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Acknowledgements

We are thankful to our scholar pool who raised the following questions that triggered us to conceptualize the theme of estuarine acidification (EA):

1. How can we beat EA and have a well-balanced aquatic ecosystem?
2. Why is EA an adverse by-product of rapid industrial development?
3. How are the population explosion and subsequent urban development related to EA?
4. What is the actual price of regulating service of mangroves in context to carbon scrubbing? And will the expansion of blue carbon be able to reduce the pace of EA?
5. Are there any strategies to manage EA at a local scale?
6. What will be the cost of EA management? And who will pay those bills?

These questions basically pushed us to dive deep in the subject and collect relevant data from various sources.

We are thankful to Dr. Pardis Fazli of Department of Biological and Agricultural Engineering, University Putra, Selangor, Malaysia, for her effort in representing our data in graphical forms.

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Mrs. Kanika Mitra), younger sister (Ms. Sharmilee Zaman), brother-in-law (Kazi Dr. Sazzad Manir), her nephew (baby Diyan Kazi), her in-laws and her beloved grandmother (Late Mrs. Shibani Dhar) for their encouragement and inspiration throughout the strenuous period of manuscript preparation. Dr. Zaman still recalls her granny late Shibani Dhar, who shaped her life and always wished to see her as an author of a subject that can create mark on the society.

Finally, our goal is to analyze the potential of different verticals of blue carbon (like mangroves, saltmarsh grass, sea grass, etc.) in retarding the pace of EA. Our aim is to bring the importance of EA in the climate change domain and draw the attention of busy decision makers, political leaders establishing national priorities, funding officers allocating research projects or young couples wishing to take bath in the coastal water in a sunny day. We hope this book will be a useful source of information for people of all ranks of the society.

Contents

About the Authors

Dr. Abhijit Mitra Associate Professor and former Head, Department of Marine Science, University of Calcutta (India), has been active in the sphere of oceanography since 1985. He obtained his Ph.D. as NET qualified scholar in 1994. Since then, he joined Calcutta Port Trust and WWF (World Wide Fund for Nature-India), in various capacities to carry out research programs on environmental science, biodiversity conservation, climate change and carbon sequestration. Presently, he is serving as Director, Research of Techno India University, West Bengal. He has to his credit about 625 scientific publications in various national and international journals and 54 books of postgraduate standards. He is presently Member of several committees like PACON International, IUCN, SIOS, Mangrove Society of India, The West Bengal National University of Juridical Sciences, etc., and has successfully completed about 17 projects on biodiversity loss in fishery sector, coastal pollution, aquaculture, alternative livelihood, climate change and carbon sequestration. He also visited as Faculty Member and Invited Speaker in several universities of Singapore, Kenya, Oman and USA. In 2008, he was invited as Visiting Fellow at University of Massachusetts at Dartmouth, USA, to deliver a series of lecture on climate change. He also successfully guided 41 Ph.D. students. Presently, his research areas include environmental science, mangrove ecology, sustainable aquaculture, alternative livelihood, blue economy, climate change and carbon sequestration.

Dr. Sufia Zaman presently serving as Head, Department of Oceanography in Techno India University, West Bengal, started her career in the field of Marine Science since 2001. She worked in the rigorous region of Indian Sundarbans and has wide range of experience in exploring the floral and faunal diversity of Sundarbans. She has published five books on carbon sequestration, 265 scientific papers and contributed chapters in several books on biodiversity, environmental science, aquaculture and livelihood development. She is presently Member of Fisheries Society of India. She is also running projects on carbon sequestration by mangroves of Indian Sundarbans. She is Recipient of DST Women Scientist and Jawaharlal Memorial Doctoral fellowship awards. Her areas of research include aquaculture, fish nutrition, phytoplankton diversity, climate change mangrove ecology and alternative livelihood. She is also the first researcher in the maritime state of West Bengal (India), who initiated trial experiments on iron fertilization and subsequent enhancement of primary (phytoplankton) and secondary (fish) productions in the brackish water ponds of Indian Sundarbans with the financial assistance of Department of Science and Technology, Government of India. She is also providing consultancy on green technology to several industries, NGOs and corporate sectors.

Chapter 1
Estuarine Acidification: An Overview

Abstract Rapid industrialization, unplanned urbanization, deforestation for aquaculture and tourism in coastal areas and change in land use pattern have raised carbon dioxide level in the atmosphere, which on mixing with the coastal and estuarine waters shift the pH value left to the normal value of the aquatic phase. It is now well established that the average pH of the world ocean surface waters has already fallen by about 0.1 units from an average value of about 8.21 to 8.10 since the beginning of the industrial revolution. Many Indian estuaries today exhibit an aquatic pH of 7.9–8.0 compared to the value around 8.3 in early eighties. This has altered the biodiversity spectrum of the estuarine ecosystem particularly the shelled organisms in terms of their community structure, morphology and behavior, which have been displayed in the chapter with specific case studies from Sundarban estuaries. The decadal data bank on aquatic pH in major estuaries of Indian sub-continent is a hallmark of the chapter.

1.1 Estuary: Definition and Types

1.1.1 Definition

Estuaries are the zones of intersection between the saline water (of oceans, seas and bays) and fresh water of the rivers. An estuary is a highly dynamic system that exhibits changes in hydrological variables with tides. It is the reservoir of several living and non-living resources that run the wheel of human civilization.

Several definitions of estuary have been forwarded by researchers as highlighted here.

Cameron and Pritchard (1963) defined estuary as “a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with fresh water derived from land drainage”.

Pritchard (1967) emphasized on the tidal actions in the estuarine system and stated the ecotone as “a semi-enclosed coastal body of water, which has a free connection with the open sea; it is thus strongly affected by tidal action and within it seawater is mixed with fresh water from land drainage”.

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Table 1.1 Physico-chemical characteristics of surface water at high tide condition during 26th May, 2019

Station no.	Water temperature (°C)	Salinity (psu)	pH	Alkalinity (mg/l)	DO (mg/l)
1	35.9	2.27	7.86	148	5.40
2	35.9	4.05	7.74	159	5.17
3	36.1	5.78	7.72	163	5.80
4	35.9	12.39	8.02	189	5.20
5	35.8	11.44	8.12	175	4.78
6	35.8	12.99	8.10	169	4.82
7	36.0	14.77	8.15	194	4.79
8	35.9	14.95	8.13	189	4.66
9	35.9	17.08	8.17	203	4.72
10	35.8	18.75	8.18	220	4.81
11	36.2	19.99	8.22	229	4.91
12	35.9	25.96	8.28	278	4.85

Perillo (1995) defined estuary as "a semi-enclosed coastal body of water that extends to the effective limit of tidal influence, within which seawater entering from one or more free connections with the open sea or any other saline coastal bodies of water is significantly diluted with fresh water derived from land drainage and can sustain euryhaline biological species, either a part or whole of their life cycle".

The tidal actions in estuaries regulate the physico-chemical variables (preferably the salinity) including the species of heavy metals as all these are functions of salinity. It is observed that exactly in the same location (that can be fixed by GPS), an environmental variable alters significantly with the change in tidal phase.

A study conducted by the authors during May 2019 highlights the spatio-tidal variations of hydrological parameters (considering 12 stations) in the Indian Sundarban Hooghly estuary (a continuation of Ganga–Bhagirathi River system) as depicted in Tables 1.1 and 1.2.

A comparison between Tables 1.1 and 1.2 exhibit significant tidal variations in relation to the hydrological parameters and therefore it is strongly suggested to consider the tidal effects while monitoring the water quality of an estuary.

1.1.2 Types of Estuaries

In standard text books on oceanography or marine science, four basic types of estuaries are usually described (Table 1.3).

Table 1.2 Physico-chemical characteristics of surface water at low tide condition during 26th May, 2019

Station no.	Water temperature (°C)	Salinity (psu)	pH	Alkalinity (mg/l)	DO (mg/l)
1	35.6	1.22	7.83	154	6.10
2	35.7	2.20	7.59	167	5.94
3	35.7	3.58	7.78	181	5.92
4	35.7	9.89	7.99	195	5.95
5	35.6	9.47	8.08	178	5.50
6	35.5	10.45	8.07	179	5.70
7	35.8	11.48	8.11	208	5.98
8	35.8	12.79	8.10	199	5.80
9	35.5	14.90	8.16	206	5.24
10	35.6	15.74	8.16	230	5.75
11	35.5	17.68	8.20	240	5.77
12	35.6	21.42	8.25	273	5.58

Pritchard (1967) classified estuaries on the basis of the four important features. They are (a) Salinity (b) Geomorphology (c) Water circulation and stratification and (d) Systems energetics.

On the basis of salinity, estuaries can be grouped into three major categories (Table 1.4).

The dynamic nature of the estuaries is witnessed by the significant spatio-temporal variation of hydrological parameters in the Hooghly-Matla estuarine complex of Indian Sundarbans. The estuarine complex in this mangrove dominated deltaic complex can be sub-divided into three sectors namely western, central and eastern sectors (Fig. 1.1) each with different signatures of salinity (Fig. 1.2a, b, c). More than two decades of data (1984–2013) were compiled from the archives of the Department of Marine Science, University of Calcutta for this study. A number of studies on different aspects of the Sundarban complex have been published over the years, which include description of the data (and methods) at different times over the past three decades (Mitra et al. 1992; Chakraborty and Choudhury 1985; Mitra et al. 1987; Mitra and Choudhury 1994; Saha et al. 1999; Banerjee et al. 2002; Banerjee et al. 2003; Mondal et al. 2006; Mitra et al. 2009; Banerjee et al. 2013; Sengupta et al. 2013; Mitra and Zaman 2016). Real time data (through field sampling by the authors) were also collected simultaneously since 1998 from 18 sampling stations (Table 1.5) in the lower Gangetic region during high tide condition to assure quality and continuity to the data bank. For each observational station, at least 30 samples were collected within 500 m of each other and the mean value of 30 observations was considered for statistical interpretations.

In the western sector, the salinity decrease ranged from 0.58 psu/year (at Jambu Island) to 1.46 psu/ year (at Harinbari) (Fig. 1.2a). Considering all the six stations

Table 1.3 Types of estuaries and its characteristics

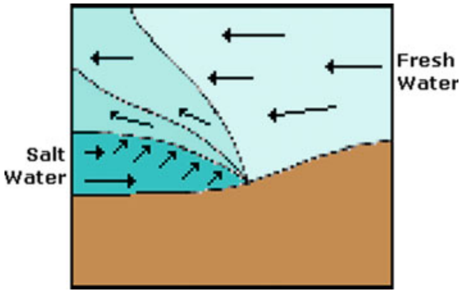
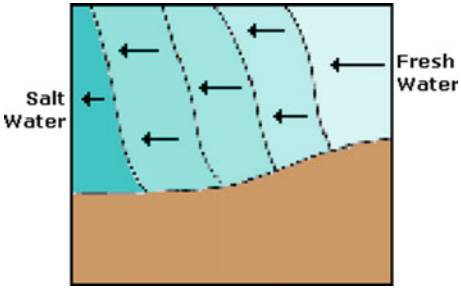
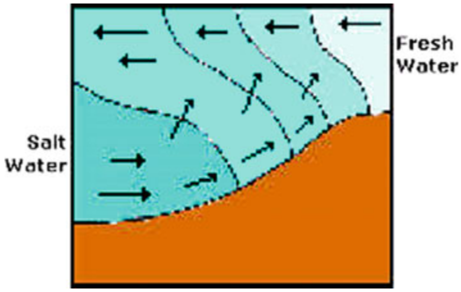
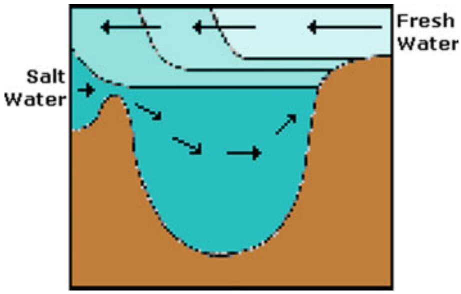
Name	Figure	Characteristic feature
Salt wedge estuary		The high flow rate of the river holds back the lesser flow of salt water. The salt water is drawn upward into the fast-moving river flow
Well-mixed estuary		Strong tidal currents distribute and mix the seawater throughout the shallow estuary. The net flow is weak and seaward at all depths
Partially-mixed estuary		Seawater enters below the mixed water that is flowing seaward at the surface. Seaward surface net flow is larger than river flow alone
Fjord-type estuary		River water flows seaward over the surface of the deeper seawater and gains salt slowly. The deeper layers may become stagnant due to the slow inflow rate of salt water

Table 1.4 Categories of estuary on the basis of salinity

Category	Description	Example
Oligohaline	In this type of estuary, the fresh water mixes with the saline water in such proportion that the water ultimately becomes uniformly saline. Such estuaries are common where small rivers meet the seas	Haldi river of West Bengal (India)
Mesohaline	In this type of estuary the aquatic phase has medium salinity due to proportional mixing of the fresh and saline water	Mahanadi river of Odisha (in the East coast of India)
Polyhaline	Such types of estuaries exhibit distinct spatial variation of salinity owing to the variation in tidal water intrusion into the river mouth. The magnitude/volume of head water discharge also regulates the salinity of estuary	Estuaries of Sundarbans

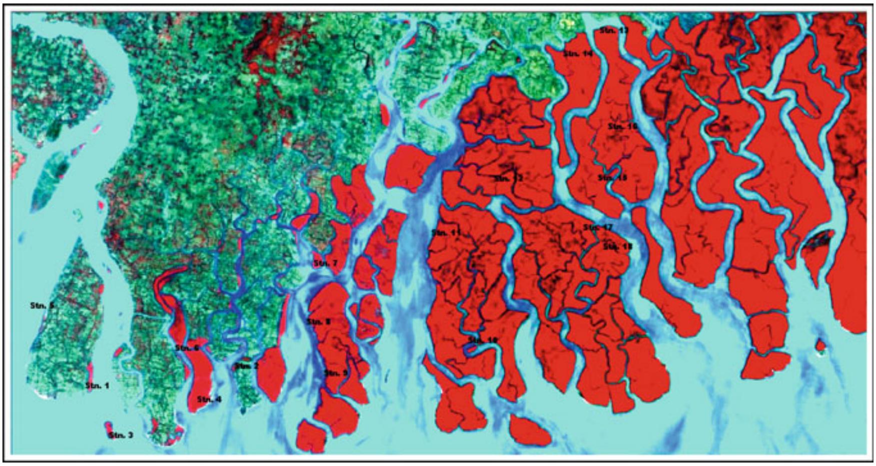


Fig. 1.1 Location of sector-wise sampling stations in Indian Sundarbans; the red colour indicates the mangrove vegetation (*Source* Mitra and Zaman 2015)

in the western sector, the decadal decrease of salinity is 7.50 psu per decade. In the western sector, the salinity intrusion is confined to 70 km from the mouth even during the dry season. The tidal variation at the mouth is from 6.1 m at springs to 0.22 m at neaps. The fresh water discharge ranges from a peak value of 4250 $m^3 s^{-1}$ to almost zero in the dry season. The average values of fresh water discharge are 3000 $m^3 s^{-1}$ during SW monsoon season (June–September) and 1000 $m^3 s^{-1}$ during a dry season (November–May). Normally, the fresh water discharges are regulated from Farakka barrage to maintain water levels at Calcutta (Biswas 1985; Sadhuram et al. 2005).

The central sector presents a completely reverse picture in terms of aquatic salinity. Irrespective of stations, salinity has increased (Fig. 1.2b between the range 1.05

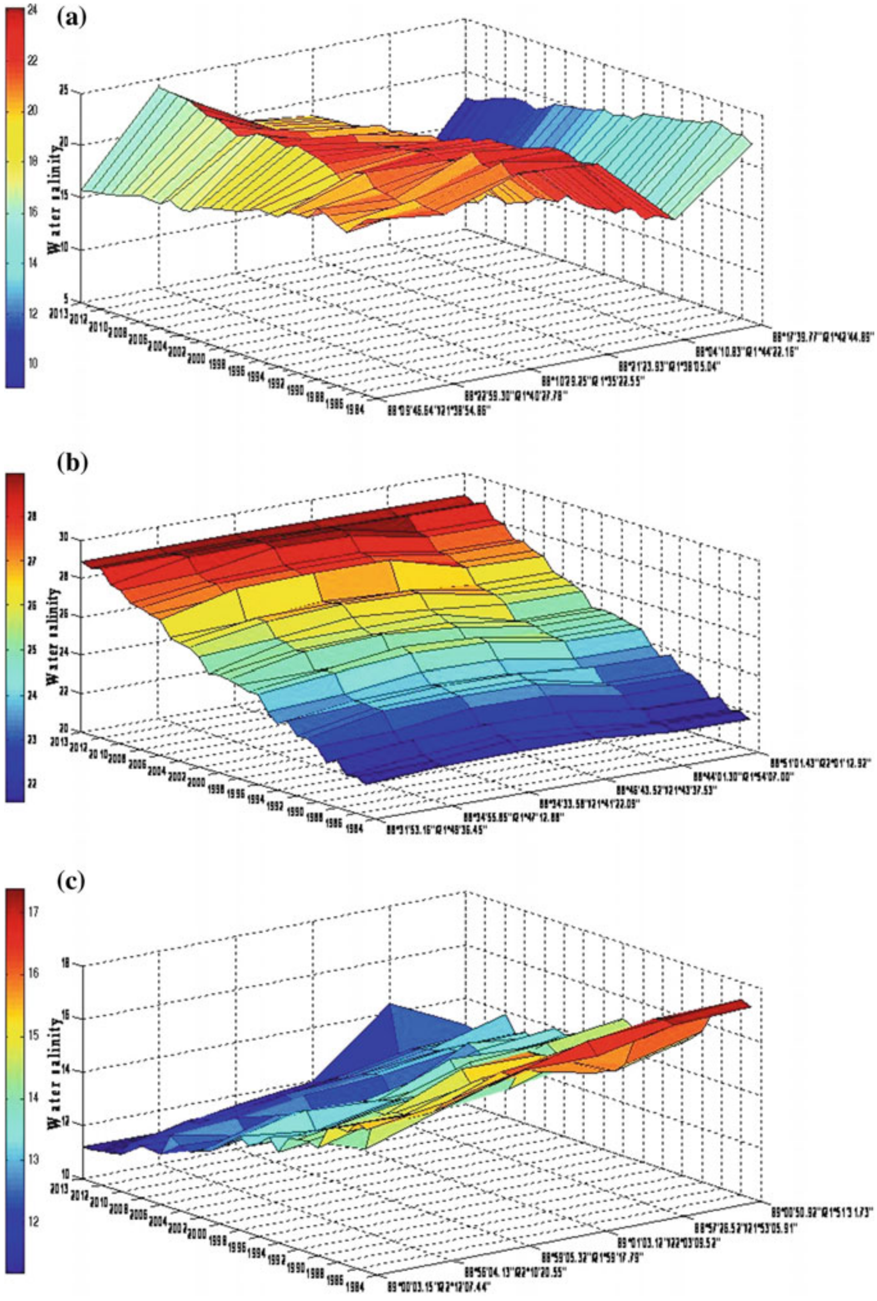


Fig. 1.2 **a** Surface water salinity in six stations of western Indian Sundarbans. **b** Surface water salinity in six stations of central Indian Sundarbans. **c** Surface water salinity in six stations of eastern Indian Sundarbans (*Source* Mitra and Zaman 2015)

Table 1.5 Sampling stations in the western, central and eastern sectors of Indian Sundarbans in the lower Gangetic delta region (*Source* Mitra and Zaman 2015)

Sectors		Sampling station	Latitude	Longitude
Western sector	Stn. 1	Chemaguri (W_1)	21° 38′ 25.86" N	88° 08′ 53.55" E
	Stn. 2	Saptamukhi (W_2)	21° 40′ 02.33" N	88° 23′ 27.18" E
	Stn. 3	Jambu Island (W_3)	21° 35′ 42.03" N	88° 10′ 22.76" E
	Stn. 4	Lothian (W_4)	21° 38′ 21.20" N	88° 20′ 29.32" E
	Stn. 5	Harinbari (W_5)	21° 44′ 22.55" N	88° 04′ 32.97" E
	Stn. 6	Prentice Island (W_6)	21° 42′ 47.88" N	88° 17′ 55.05" E
Central sector	Stn. 7	Thakuran Char (C_1)	21° 49′ 53.17" N	88° 31′ 25.57" E
	Stn. 8	Dhulibasani (C_2)	21° 47′ 06.62" N	88° 33′ 48.20" E
	Stn. 9	Chulkathi (C_3)	21° 41′ 53.62" N	88° 34′ 10.31" E
	Stn. 10	Goashaba (C_4)	21° 43′ 50.64" N	88° 46′ 41.44" E
	Stn. 11	Matla (C_5)	21° 53′ 15.30" N	88° 44′ 08.74" E
	Stn. 12	Pirkhali (C_6)	22° 06′ 00.97" N	88° 51′ 06.04" E
Eastern sector	Stn. 13	Arbesi (E_1)	22° 11′ 43.14" N	89° 01′ 09.04" E
	Stn. 14	Jhilla (E_2)	22° 09′ 51.53" N	88° 57′ 57.07" E
	Stn. 15	Harinbhanga (E_3)	21° 57′ 17.85" N	88° 59′ 33.24" E
	Stn. 16	Khatuajhuri (E_4)	22° 03′ 06.55" N	89° 01′ 05.33" E
	Stn. 17	Chamta (E_5)	21° 53′ 18.56" N	88° 57′ 11.40" E
	Stn. 18	Chandkhali (E_6)	21° 51′ 13.59" N	89° 00′ 44.68" E

psu/year (in Chulkathi) to 1.12 psu/year (in Matla and Pirkhali). The average decadal increase of salinity is 13.04 psu per decade.

In the eastern sector, salinity has decreased (Fig. 1.2c) which ranges from 0.54 psu/year (in Chamta) to 0.98 psu/year (in Jhilla). The average decadal decrease of the salinity in this sector is 10.28 psu.

On the basis of geomorphology, estuaries can be grouped into four major categories (Table 1.6).

An estuary can also be classified on the basis of water circulation and stratification as highlighted in Table 1.7.

Estuaries may also be classified as tide dominated and wave dominated (Fig. 1.3) estuary (positive and negative) on the basis of several important hydrological processes (Table 1.8).

Estuaries can be categorized on the basis of systems energetics (Table 1.9).

Impounded estuarine system causes adverse impact on the natural ecosystem services of estuaries as the water flow and tidal actions are obstructed due to which the services offered by estuaries like bioremediation, regulation of biogeochemical cycles, breeding cycle of fishes etc. are significantly impacted. In countries like India and Bangladesh, huge numbers of impounded waterbodies have been created to promote shrimp or tiger prawn (*Penaeus monodon*) culture in the coastal areas,

Table 1.6 Classification of estuaries on the basis of geomorphology (*Source* Mitra and Zaman 2015)

Type of estuary	Description	Example
Drowned river valleys	In this type, the coastlines have relatively low and extensively wide coastal plains	Chesapeake Bay on the mid-Atlantic coast of the United States
Fjord type estuaries	The deep U-shaped indentures due glacial erosion with a shallow sill at their mouth formed by terminal glacial deposits	Norway, British Columbia and Alaska
Bar-built estuaries	These are shallow basins often partly exposed at low tide enclosed by a chain of offshore bars or barrier islands, broken at intervals by inlets. These bars are sometimes deposited offshore or are remnants of former coastal dunes	North Carolina and Georgia
Estuaries produced by tectonic processes	Geological faulting or local subsidence results in the formation of coastal indented structures	San Francisco Bay

Table 1.7 Classification of estuaries on the basis of water circulation and stratification (*Source* Mitra and Zaman 2015)

Type of estuary	Description	Example
Highly stratified or 'salt-wedge' estuary	When the fresh water discharge from the rivers dominate over the tidal action, the fresh water tends to overflow the heavier salt water which forms a "wedge" extending along the bottom for a considerable distance upstream. This flow of fresh water is again governed by the Coriolis force, which forces the fresh water to move strongly along the right shore (if the observer faces the sea in the Northern Hemisphere and vice versa in the Southern Hemisphere). Such "stratified" or "bi-layered estuary will exhibit a salinity profile with a "halocline" or zone of sharp change in salinity from top to bottom	Mississippi River
Partially mixed or moderately stratified estuary	When the fresh water and the tidal water mix in equal proportion due to turbulence caused by periodicity of waves, such type of estuary is formed. Due to this, the energy is dissipated in vertical mixing thus creating a complex pattern of layers and water masses	Chesapeake Bay
Completely mixed or vertically homogenous estuary	When the tidal action is more than the fresh water discharge, the water tends to mix well from top to bottom and the salinity is relatively high. When there is wide variation in salinity and temperature, then horizontal estuaries are formed	Bar-built estuaries

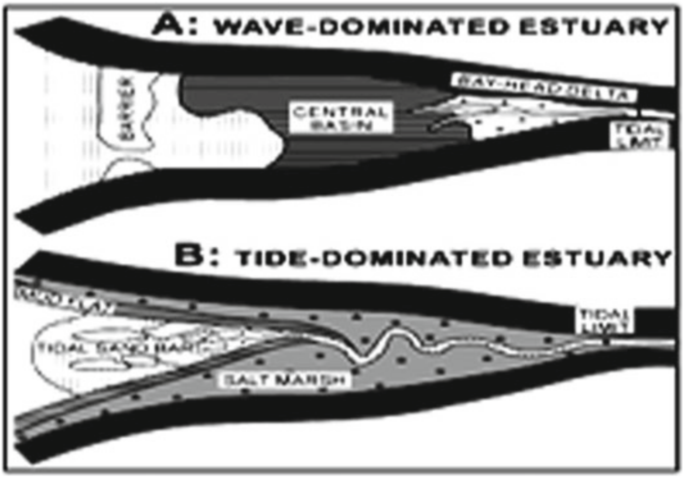


Fig. 1.3 Wave and tide dominated estuary

due to which the ecology and environment of the surrounding areas have been greatly damaged. The rate of reclamation of marshes and particularly mangrove swamps has accelerated in recent years in some parts of the tropics due to the rapid expansion of pond farming of shrimps for export (Fig. 1.4). About 50% of the mangrove forests in

Table 1.8 Comparative study of tide and wave dominated estuaries (*Source* Mitra and Zaman 2015)

Point	Tide dominated estuary	Wave dominated estuary
Catchment's input	Freshwater entering from the catchments is relatively lower. In negative estuaries, the net inflow of marine water exceeds the outflow of catchment—derived (fresh) water. In such cases, the hypersaline water is usually exported to the ocean	Freshwater enters from the catchments. Although the volume of freshwater input varies spatially and temporally (depending on local catchments and climate conditions), it is often relatively high in positive estuaries
Freshwater input	The volume of freshwater entering the estuary is too low to cause significant level of stratification. High tidal ranges may tend to accelerate mixing of any freshwater inputs, and marine water	Water circulation in wave-dominated estuaries generally ranges from well mixed to salinity-stratified, depending on the degree of wave mixing, volume of freshwater input, and climate. 'Positive' wave-dominated estuaries have lower salinity water towards their head. The volume of freshwater causes stratification (or layering) in the water column, which varies with seasonal flow. Buoyant low-salinity fresh water floats above the denser, high-salinity ocean water

(continued)

Table 1.8 (continued)

Point	Tide dominated estuary	Wave dominated estuary
Salinity	High rates of evaporation cause increases in salinity within the estuary. The resulting high-density hypersaline water sinks beneath the buoyant marine water which penetrates through the estuary mouth, and flows out of the estuarine entrance into the coastal ocean through a process known as reverse stratification. A large degree of mixing occurs between the two layers	A 'salt-wedge' or intrusion of denser saline marine water penetrates through the entrance along the bed of the estuary. Some mixing occurs at the interface between the fresh and marine water. The distance that the salt-wedge penetrates is dependent on tidal range and the amount of fluvial flow received by the estuary. During high fluvial flow events (which may be seasonal), fresh floodwater may push the salt water beyond the mouth. However, the large volume of central basins typical of wave-dominated estuaries tends to reduce this effect
Evaporation	Evaporation is the dominant process in negative tide-dominated estuaries due to arid climatic conditions, and the extensive area of shallow intertidal environments. Aridity and the degree of evaporation may vary seasonally; however by definition evaporation in 'negative' estuaries is much larger than freshwater input. Consequently, negative estuaries tend to have longer residence times than positive estuaries	While significant evaporation can occur in wave-dominated estuaries characterized by positive circulation, evaporation (by definition) does not exceed the amount of freshwater input
Water exchange	Exchange of sea water and estuarine water occurs through the wide entrance of the estuary. Flood and ebb tides may follow different routes into and out of the estuary, and the tidal prism tends to be large. In negative estuaries, the net inflow of marine water exceeds the outflow of freshwater derived from the catchments. In such cases, the hypersaline water is usually exported to the ocean	Exchange of ocean water and estuarine water occurs through the entrance of the estuary, although the magnitude of exchange depends on the size and length of the entrance channel. In positive wave-dominated estuaries, the outflow of freshwater exceeds the inflow of marine water. During dry conditions, the entrance of the estuary may be intermittently closed

the Philippines have been converted into brackishwater fish ponds (Saclauso 1989). The area converted in Thailand is estimated to be about 27% and in Ecuador about 13–14%. Such large scale conversions have aroused considerable environmental concern among the public and development agencies.

Tabuchi (2003) estimated that on a global scale, the area under mangroves is shrinking by 100,000 hectares annually due to clear cutting of timber and conversion into aquaculture projects.

Table 1.9 Classification of estuaries on the basis of systems energetics (*Source* Mitra and Zaman 2015)

Type	Salient features	Biotic community	Example
Physically stressed estuarine system	(i) Strong tidal currents (ii) Waves with high energy (breaking waves) (iii) Extreme temperature variation (iv) Extreme salinity variation (v) Low DO during night	Species diversity is extremely poor and only limited number of species survive (opportunistic species) with high adaptive potential	Rocky beach
Natural polar ecosystem	(i) Extremely low temperature (ii) Light is limiting due to short summer season (iii) Poor productivity	Species diversity of phytoplankton is extremely low and food chain is relatively short; due to extreme coldness, the phytoplankton remain in encysted condition	Arctic and Antarctic coasts
Natural temperate coastal ecosystem	(i) Moderate waves, currents and tides (ii) Environmental stress is relatively low (iii) Nutrient level is considerably high (iv) Anthropogenic activities are high due to discharge of wastes from industries, dredging activities etc.	Considerable species richness with presence of salt marshes, seaweeds, kelps, oyster beds and mud flats; dense population of clams and sea worms are observed	Long Island sound, USA
Natural tropical coastal ecosystem	(i) Minimum environmental stress (ii) Relatively less wave and tidal actions (iii) Rich in nutrients (iv) Productivity is high (v) Aquaculture is practiced in this ecosystem	Species diversity is extremely high because of congenial environment. Mangroves, sea grass, meadows, saltmarsh grass, coral reefs, seaweed communities and oyster beds are common in this ecosystem	Estuaries of Sundarbans mangrove ecosystem in India and Bangladesh
Impounded Estuarine System	(i) Estuaries are impounded at the cost of mangroves and salt marshes (Fig. 1.3) (ii) Estuarine water is stocked and impounded for aquaculture related activities (iii) Highly polluted with organic load and nutrients from shrimp farms (iv) Absence of natural capacity of waste treatment		Estuaries of Sundarban mangroves (few pockets), Philippines etc.

Fig. 1.4 Shrimp culture ponds in mangrove patches: A common scene in tropical mangrove ecosystem; Photograph taken on 04.12.2016 by Ms. Ankita Mitra (Environmentalist and a researcher)

1.2 Ecosystem Services of Estuaries

Estuaries are noted for taxonomic diversity of species, biological productivity and unique aesthetic value. The water, sediment and biotic communities of the estuaries offer several ecosystem services that provide both direct and indirect benefits to run the wheel of human civilization. Based on the living and non-living resources of the estuaries the concept of 'Blue Economy' (BE) has emerged as a new paradigm for sustainable development of marine and estuarine resources. Few common ecosystem services on which the pillars of blue economy stand are highlighted here in points:

1. Estuaries are the breeding, nursery and survival zones of a wide spectrum of finfish and shellfish species, which are commercially important and are also included in the export basket of the nation. The estuaries of Sundarbans, for example, are the survival ground for several species of finfish, shrimps and crabs that add foreign currency to the national economy.
2. Estuaries sustain mangroves, seagrasses, saltmarsh grasses and seaweeds, which have the potential to bioaccumulate conservative wastes like heavy metals in their body tissues. Reports of heavy metal accumulation by macrophytes of estuaries are plenty (Mitra et al. 1994; Trivedi et al. 1994), which show

the adaptive capability of estuarine flora to thrive in contaminated media (both water and sediment). Such biological treatments of conservative pollutants almost at zero cost have immense economic and ecological importance.

3. Estuaries are the sites for recycling of nutrients where microbes are the key players. These nutrients (preferably nitrate and phosphate) trigger the growth of phytoplankton and thereby sustain the food chain in the aquatic system.
4. Estuaries offer sustainable fisheries with high commercial value to the local population. In this context the Indian shad, *Tenualosa ilisha* needs to be mentioned as the species has demand both in the internal market and export basket.
5. The mangroves of estuaries provide timber, fuel, wax, honey and fodder to the island dwellers and local people of the fringe villages (Table 1.10). This provisional service of the estuarine vegetation plays a great role in the upliftment of local economy.
7. Estuaries are the home ground for a variety of migratory birds and endangered species that can serve as the foundation of eco-tourism in real sense. The intertidal mudflats, the aquatic system and floral communities of the estuaries attract the tourist with gorgeous and eye catching array of herons, pelicans, storks, eagles, ospreys, plovers, gulls, sandpipers and kingfishers. About 95 varieties of migratory birds come all the way in the estuaries of India from the Caspian Sea in Russia and the northern parts of the Himalayan ranges. The Sundarban estuaries are the home ground of Royal Bengal Tiger (*Panthera tigris tigris*), which can swim across the estuary over a distance of 15 km. The basking crocodiles on the intertidal mudflats of Sundarbans are special attractions for the tourists (Fig. 1.5).

Table 1.10 Traditional uses of mangrove species

Mangrove species	Use
Aegiceras corniculatum	Bark used as fish poison; also contains tannin
Avicennia alba	Used for fodder and fuel
Avicennia officinalis	Used for firewood; bark contains tannin
Bruguiera caryophylloides	Wood used for firewood and timber; bark used as tannin
Bruguiera gymnorhiza	Wood used for house posts; excellent fuel; bark contains tannin
B. parviflora	Timber used as fuel; leaves and bark contain tannin
B. sexangula	Timber used in house building
Ceriops tagal	Used for keels of boats and house posts. Provides good fuel charcoal. Bark rich in tannin used for dyeing fishing nets
Rhizophora mucronata	Bark used for tannin and cattle fodder
Sonneratia apetala	Wood used in house building, packing cases and yields excellent fuel
Xylocarpus granatum	Yields gum, resin which is used in local medicine; bark contains tannin

Fig. 1.5 Crocodile on the estuarine mudflat of Indian Sundarbans

8. The aquatic system of the estuary is extensively used for aquaculture, although in many pockets of lower Gangetic region the adverse impacts of shrimp culture have been documented with facts and figures (Mitra 1998). Aquaculture, preferably shrimp culture has upgraded the local economy in most cases, but in many places mangrove patches and saltmarsh grass beds have been destroyed in an unplanned way to construct shrimp ponds.
9. Estuaries are treated as the dumping sites of various categories of wastes. Deterioration of the water quality and commercially important fauna has been reported from many estuaries of the world. The present authors carried out a survey on the microbial load (Fecal coliform and Total coliform count) in cultured *Penaeus monodon* collected from Henry's Island and Sagar Island of western Indian Sundarbans during 2016. The count was considerably high in the shrimp samples, water and sediment (Table 1.11), which is an indication of deterioration of estuarine environment due to release of untreated wastes from coastal industries, tourism units and fish landing stations existing in the region.
10. The biotic communities of the estuarine system (particularly the mangroves, saltmarsh grass, seaweeds etc.) and the underlying soil act as the reservoir of carbon. This ecosystem service is of great relevance in context to carbon dioxide rise and subsequent climate change. A study conducted by

Table 1.11 A comparative table showing the microbial load in the ambient media and shrimp muscle sampled from the two study sites in western Indian Sundarbans during the month of May, 2016

Microbial load	Henry's Island		Sagar Island	
	Total coliform	Fecal coliform	Total coliform	Fecal coliform
(a) Water (MPN/100 ml)	22	8	4	3
(b) Sediment (MPN/ gm)	25×10^2	18×10^2	3×10^2	2×10^2
(c) *P. monodon* (MPN/gm)	6.5×10^3	4.1×10^3	2.9×10^3	1.6×10^3

the present authors (Mitra and Zaman 2016) in 24 stations of Indian Sundarbans (Fig. 1.5) exhibits considerable percentage of soil organic carbon in the intertidal mudflats ranging from 0.66 to 1.41% (Figs. 1.6 and 1.7).

11. India has taken great initiative in the sector of 'Blue Economy' through rational utilization of natural resources of oceans, seas, bays and estuaries. Researchers at Techno India University, West Bengal have developed few innovative food products from the floral species of Sundarban mangrove ecosystem. The saltmarsh grass found abundantly in the intertidal mudflats of estuaries is used for fish feed preparation. Research findings also reveal that fish feed incorporated with estuarine seaweed (*Enteromorpha intestinalis*) has resulted in improved performance, better feed efficiency, better pellet stability and improved animal (fish) product quality, which may be attributed to the enormous genetic potential of these lower group of plants with a genome that is more than twice the size of yeast. This quality has brought the seaweeds in serving many industries such as food, animal feed, cosmetics, pharmaceuticals and biofuels.
12. Flora and fauna of the estuaries are today used as sources of bioactive substances, which have immense importance in the pharmaceutical industries. Examples of **CAL** (Carcinoscorpious Amoebocyte Lysate) and **TAL** (Tachypleus Amoebocyte Lysate) are very relevant in this context. They are derived from the blue blood (amoebocyts) of horseshoe crabs (*Carcinoscorpious rotundicauda* and *Tachypleus gigas*) found abundantly in the estuaries of West Bengal and Odisha, which are the two maritime states in the North-East coast of the Indian sub-continent. CAL and TAL are used for bacterial endotoxin test.
13. Estuarine fishes are the sources of omega-3 Fatty acids, which is good for heart. Coronary heart disease occurs due to atherosclerosis and thrombosis. Atherosclerosis is initiated by endothelial damage that may result from stress related events and may finally lead to thrombosis and arrhythmia, the main cause of sudden death. The omega-3 fatty acid synthesizes with the help of enzymes, eicosanoids. The antithrombotic effect of omega-3 fatty acid is due to these eicosanoids, which inhibit platelet aggregation, vasoconstriction and adhesion and induces vasodialation. Omega-3 fatty acid is also good for diabetic patients as it improves insulin resistance syndrome that leads to heart disease. It is also reported to be good for arthritis.

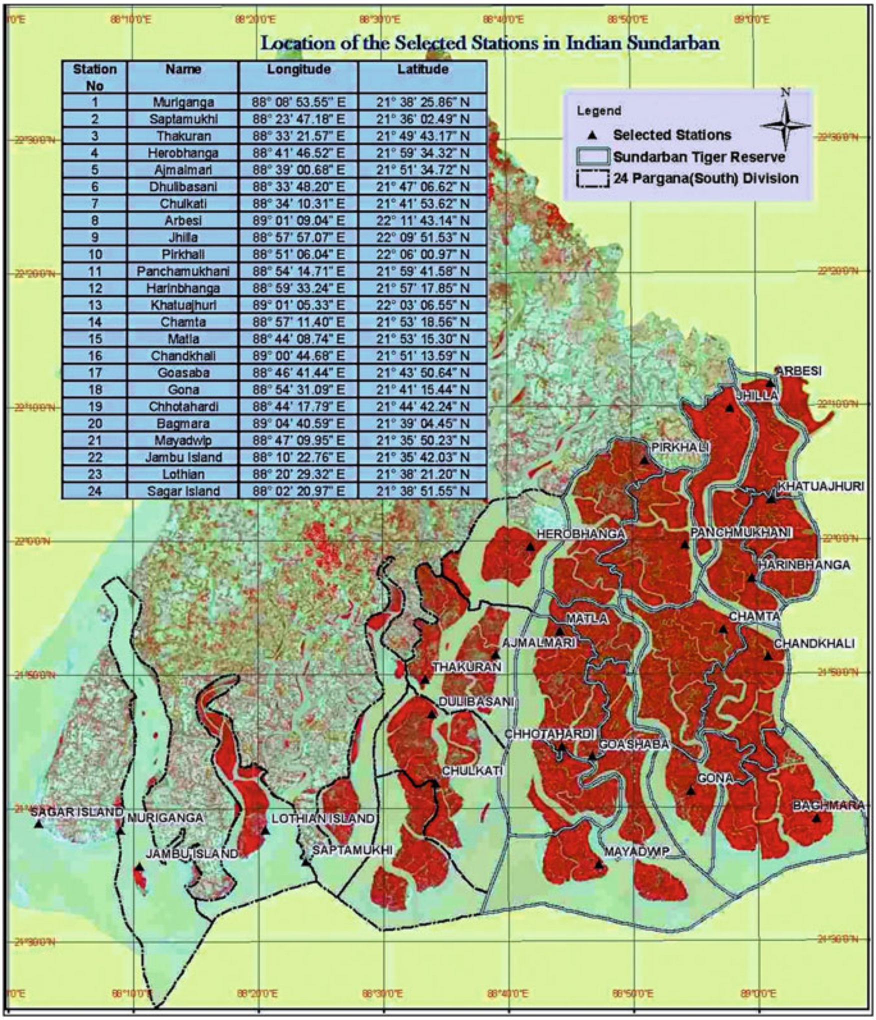


Fig. 1.6 Stations in Indian Sundarbans selected for organic carbon study (*Source* Mitra and Zaman 2016)

14. Several medicinal plants widely distributed in the coastal and estuarine regions were tested for antiviral, antifungal and mosquito larvicidal activities. In the Parangipettai coast of India (South east coast), 113 medicinal plants have been recorded. Out of 36 plants, 3 plants showed high anti-HIV activity. The anti-HIV activity of coastal population was also tested in comparison with their terrestrial counterparts. In general, coastal populations exhibited better anti-HIV activity than terrestrial ones. 23 plants were screened for antibacterial activity against 13 human pathogenic bacterial strains, of which 23 extracts showed anti-bacterial activity against one or more bacteria. 25 plants

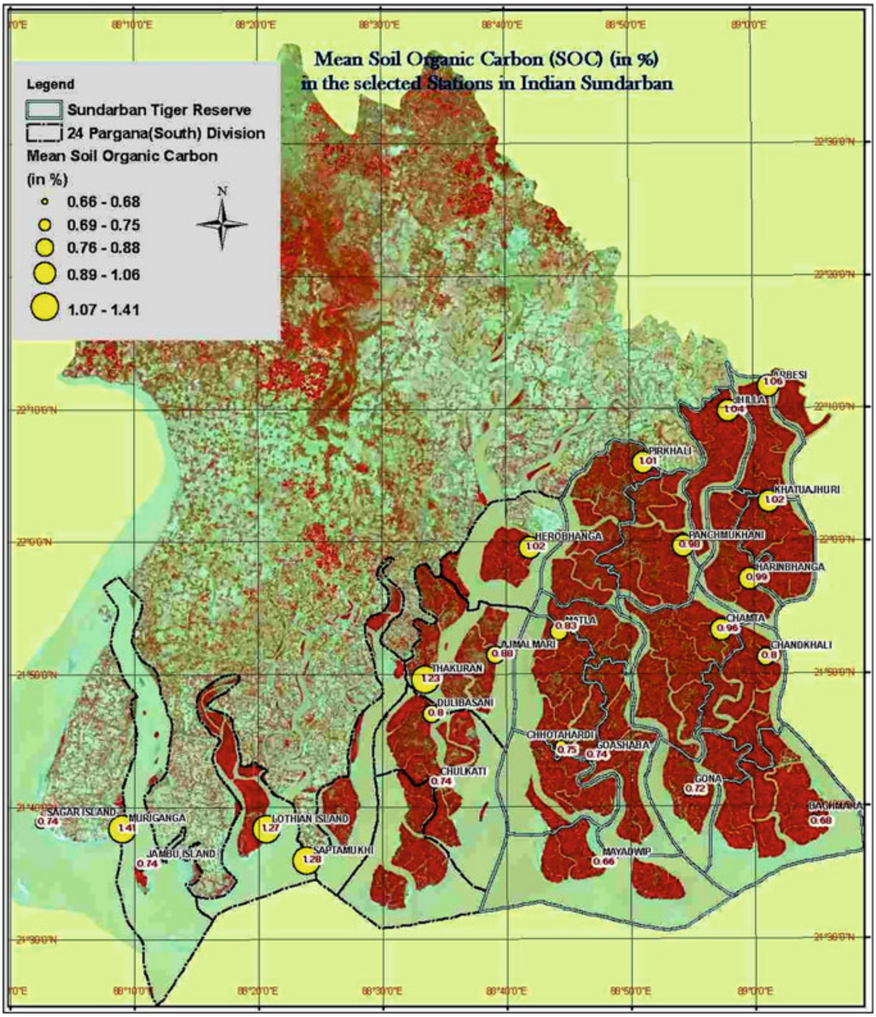


Fig. 1.7 Percentage of organic carbon in the intertidal mudflats of Indian Sundarbans (*Source* Mitra and Zaman 2016)

were screened for antifungal activity against 6 fungi. All the plant extracts examined showed activity against one or more fungi. 2 plant species exhibited high antifungal activity. In general, the coastal samples showed higher activity than terrestrial ones. 11 plants were tested for mosquito larvicidal activity against two mosquito species namely, *Culex quinquefasciatus* and *Aedes aegypti*, of which, 5 samples were effective. In addition to these services, the mangrove flora thriving in the coastal and estuarine region has unique medicinal properties (readers are advised to consult Annexure 1 for detailed information).

15. The estuarine ecosystem and surrounding island villages are unique sites of cultural and religious convergence unlike the urban areas. This may be attributed to extreme need for livelihood and adverse environmental conditions prevailing in the estuarine ecosystem that often break the barrier of caste and religion amongst the people. A relevant example in this context is the religious and cultural canvas of Indian Sundarbans. In this mangrove dominated deltaic complex, people of both religions—Islam and Hindu worship the same deities before entering into the forest for collecting their daily needs. The principal local folk deities are Dakshin Rai, Kalu Rai, Badar Sahib, Bakra Gazi, Sona Pir, Sawal Pir, Gazi Saheb and the first Goddess, Bonbibi (Fig. 1.8). Wood cutters, honey collectors and fishermen worship Dakshin Rai, Narayani Ma, Bonbibi, Gazi Saheb, Kalu Rai, Barkhan Gazi and Sa Janguli. In addition, the Goddess Manasa is worshipped with the belief to protect the people from venomous snakes, and Jagatguru from cobras. Makal Thakur and Biswalakshmi are treated as the God and Goddess of fish respectively. Manik Pir is worshipped for the welfare of cows and Olabibi for protection against cholera.

Fig. 1.8 Bonbibi, 'the Goddess of forest' worshipped by the local people of Indian Sundarbans irrespective of religion and caste (*Source* Mitra and Zaman 2016)

For protection of the embankments, people refer to Ganga as the supreme Goddess.

Historically, people have depended on bays, estuaries and coastal regions for their living requirements; this has resulted in the establishment of major population centers along the shores of estuaries and coastal seas. In the United States today, over one-half of the population lives within 80 km (50 mi) of the coasts (including the Great Lakes). This population, with its necessary industries, energy-generating facilities, recreational activities, and waste-treatment plants has created a significant negative impact on the coastal and estuarine zones.

The ecosystem services of the estuaries are presently under threat due to rapid industrialization, urbanization and unplanned tourism. Added to the uncontrolled fishing and extraction of natural resources, estuaries and brackish waters are subjected to constant changes in their physico-chemical condition due to various anthropogenic activities. The wide spread reclamation of water areas, construction of barrages and other salt water extraction structure, dredging and aquatic pollution etc. cause substantial negative impact on the positive health of the estuaries. Days are not too far when the ecosystem services of the estuaries will be greatly squeezed.

In general, the total economic valuation of an estuarine system can be calculated as the sum of four components. These are (direct) use value, indirect use value, option value and non-use value (Table 1.12).

For monetary valuation many of these components are easier to measure, as for example, use values are easy to measure because they are observable quantities of products consumed as well as their standard market prices can be utilized to determine the economic value. Recreational use can also be measured from the log book entries maintained in the ecotourism camps, hotels, resorts, sanctuaries, eco parks, or Reserve Forest. The charges for visiting and staying in the heart of Indian Sundarbans are highlighted in Fig. 1.9 and Table 1.13.

Table 1.12 Components of economic valuation of an estuarine ecosystem

Type	Description	Example
Direct use value	Resources that provide direct benefits to the stakeholders	Fishery resources, irrigation facilities, aquaculture activities, existing tourism units etc.
Indirect use value	Users get indirect benefits and often some distance away from where they originate	Pollution filtering capacity of estuarine system, flood control, etc.
Option value	Users may be willing to pay for acquiring benefits from estuarine resources in future	May be a future source of drinking water or introduction of mangrove tourism
Non-use value	Users may be willing to pay for conservation of resources, which will never be used directly	Preservation or protection of endangered species arising out of a sense of environmental stewardship that is unrelated to the indirect and direct uses in the current or in the future

Fig. 1.9 Price for visiting and staying in a forest camp in the heart of Indian Sundarbans (*Source* Mitra and Zaman 2016)

Table 1.13 Approximate price (in $) for traveling and staying in the heart of Indian Sundarbans

Items	Price ($)
Staying charge per head per day	1
Air condition launch (per day)	33.34
General launch (per day)	10
Boat	5.83
Still camera	Free
Video camera	3.33
Cinema, documentary (per day)	250
Ethnic cottage	20
Round cottage (per day)	16.67
Govt. employee on duty (excluding forest department staffs) (per day)	6.67
Dormitory (of 10 beds)	2.5
Educational trip per student (per day)	0.17
Children under 5 years	Free

Note Conversion to $ has been done on the rate of $1 = INR.60.00

Fig. 1.10 Mangroves are potential controlling agents of erosion (*Source* Mitra and Zaman 2016)

Certain ecosystem services are extremely difficult to measure as for example the pollution control, erosion control and flood control potential of an estuarine system or the oxygen generation and carbon dioxide sequestration by the estuarine microphytes and macrophytes etc. The mangroves of estuarine system, for example, are noted for erosion control and combat sea level rise (Fig. 1.10). In such cases 'shadow value' are estimated in order to 'price' the produced services.

It is also difficult to measure the option values and non-use values of the estuary as they are not reflected as physical commodities or in any form of observable/measurable items. These values are estimated by using surveys that ask people a series of questions about their willingness to pay for ecosystem services they do not use (Table 1.14).

1.3 Acidification of Indian Estuaries

Indian estuaries are mostly subject to high degree of pollution that arises from industrial activities, sewage discharge, aquaculture farms, brick kilns, tourism units etc., and depending on the riverine discharge, the salinity and pollution load exhibit dynamic scenario.

We have made extensive studies on ten major estuaries of Indian sub-continent namely (i) Vellar estuary in southern Tamil Nadu, (ii) Ennore estuary in Tamil Nadu,

Table 1.14 Economic valuation methods for water

Method	Approach	Water service appropriate for method	Data needs	Limitations
Contingent valuation method	Ask people directly their willingness to pay (WTP)	All use values and non-use value (e.g., drinking water, fishing, protecting species)	Survey with scenario description and questions about WTP for specific services	Potential biases due to hypothetical nature of scenarios
Travel cost method	Estimate demand curve from data on travel expenditures	Recreation: boating, fishing, swimming	Survey on expenditures of time and money to travel to specific sites	Only captures recreational benefits; difficult to apply for multiple destination trips
Hedonic property value method	Identify contribution of environmental quality to land values	Water quality, wetland services	Property values and characteristics including environmental quality	Requires extensive information about ecosystem services of hundreds of specific sites
Change in productivity method	Assess impact of change in water service on produced goods	Commercial fisheries, agricultural uses	Impact of change in water service on production; net values of produced goods	Information on biological impacts of changes in ecosystem services often unavailable

Source Pagiola et al. (2004)

(iii) Adyar estuary in Tamil Nadu, (iv) Rushikulya estuary in Odisha, (v) Kali estuary in Karnataka, (vi) Mandovi estuary in Goa, (vii) Kalapet estuary in Puducherry, (viii) Mahi estuary in Gujarat, (ix) Mindhola estuary in Gujarat, (x) Tapi estuary in Gujarat. The aquatic status of each of these estuaries in terms of pH is discussed here with data.

1.3.1 Vellar Estuary

The Vellar estuary, in the Tamil Nadu State of India meets the Bay of Bengal and is approximately 200 km to the south from the city of Chennai (11° 29′ N, 79° 46′ E). The estuary is made by the Vellar River (which is more than 300 km long) and represents a narrow (200–500 m wide) and rather shallow water (the characteristic depths are 2–4 m) bay having no sharp constrictions or expansions, which is approximately 20 km long. A pronounced constriction is observed only at the entrance of the estuary due to a sandy bar deposited by the surf. The high tide in the mouth of the estuary is about 90 cm above the zero level; the littoral zone is approximately 30–100 m wide. The shores in the seaward part are low; the littoral zone is composed of sand or silted sand with sometimes occurring spots of mangrove bushes. It is pertinent to note that the restoration of mangroves in the estuary was initiated about 20 years ago; previously, the shores were open and the littoral zone was mostly sandy. In the lower part of the estuary, the coasts are populated. In the estuary and neighboring marine area, there is an intensive fishery using nets casted from fishing vessels and trawlers. We made an extensive study at the mouth of the Vellar estuary and observed a decrease in pH value in all the three seasons (Table 1.15).

Table 1.15 Mean seasonal surface water pH values at the mouth of the Vellar estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.32	8.31	8.32
1985	8.32	8.30	8.31
1986	8.33	8.31	8.32
1987	8.32	8.30	8.32
1988	8.33	8.31	8.33
1989	8.32	8.32	8.32
1990	8.32	8.29	8.32
1991	8.32	8.31	8.32
1992	8.31	8.30	8.31
1993	8.33	8.31	8.33
1994	8.32	8.31	8.32
1995	8.32	8.29	8.32
1996	8.33	8.32	8.31
1997	8.31	8.31	8.32
1998	8.32	8.30	8.32
1999	8.31	8.30	8.28
2000	8.31	8.29	8.31
2001	8.31	8.30	8.31

(continued)

Table 1.15 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
2002	8.32	8.30	8.32
2003	8.31	8.30	8.30
2004	8.32	8.30	8.30
2005	8.30	8.30	8.32
2006	8.32	8.29	8.31
2007	8.30	8.29	8.30
2008	8.30	8.28	8.30
2009	8.34	8.29	8.28
2010	8.29	8.28	8.30
2011	8.30	8.28	8.30
2012	8.28	8.27	8.28
2013	8.27	8.26	8.27
2014	8.27	8.25	8.27
2015	8.26	8.23	8.25
2016	8.24	8.22	8.23
2017	8.24	8.21	8.23
2018	8.23	8.20	8.22
2019	8.24	8.17	8.21
Mean	8.3022	8.2833	8.2967
Decrease	$-0.0023\ yr^{-1}$	$-0.0040\ yr^{-1}$	$-0.0031\ yr^{-1}$

1.3.2 Ennore Estuary

Ennore is located on the northeast coast of Chennai and Ennore coast consists of alluvial tracts, beach dunes, tidal flats and creek in the eastern part. Ennore comprises of lagoons, with salt marshes and backwaters, which are submerged under water during high tide and form an arm of the sea opening in to the Bay of Bengal. Ennore coast receives major amount of untreated domestic sewage from Royapuram area, untreated or treated industrial effluents from Manali Industrial Belt, which houses many refineries and chemical industries. The dredging activities in Ennore area result in changes in the landscape, sediment transport and dust pollution to the coast by quarrying process taking place. Southern arm of the creek is well developed with industries, utilities, suburban residential areas and fishing hamlets. Northern section of the creek is connected to the Pulicat lagoon and has two major developments North Chennai Thermal power Core (NCTPS) and Ennore satellite port has chocked the mouth of the Ennore creek. Raw municipal sewage, industrial trade effluents industrial cooling waters all of them make it through Buckingham canal, enters into Ennore estuary and eventually drains into the Bay of Bengal of Chennai coast. The surface water pH values at the mouth of Ennore estuary is presented in Table 1.16.

Table 1.16 Mean seasonal surface water pH values at the mouth of the Ennore estuary

Year	Premonsoon Hhigh tide	Monsoon high tide	Postmonsoon high tide
1984	8.34	8.32	8.33
1985	8.33	8.33	8.34
1986	8.34	8.32	8.33
1987	8.33	8.31	8.33
1988	8.34	8.32	8.34
1989	8.33	8.33	8.33
1990	8.33	8.30	8.33
1991	8.33	8.32	8.33
1992	8.32	8.31	8.32
1993	8.34	8.32	8.34
1994	8.33	8.32	8.33
1995	8.33	8.30	8.33
1996	8.34	8.33	8.32
1997	8.32	8.32	8.33
1998	8.33	8.32	8.33
1999	8.32	8.31	8.29
2000	8.32	8.30	8.32
2001	8.32	8.31	8.32
2002	8.33	8.31	8.33
2003	8.32	8.31	8.31
2004	8.33	8.31	8.31
2005	8.31	8.31	8.33
2006	8.33	8.30	8.32
2007	8.31	8.30	8.31
2008	8.31	8.29	8.31
2009	8.35	8.30	8.29
2010	8.30	8.29	8.31
2011	8.31	8.29	8.31
2012	8.29	8.28	8.29
2013	8.28	8.27	8.28
2014	8.28	8.26	8.28
2015	8.27	8.24	8.26
2016	8.25	8.23	8.24

(continued)

Table 1.16 (continued)

Year	Premonsoon Hhigh tide	Monsoon high tide	Postmonsoon high tide
2017	8.25	8.22	8.24
2018	8.26	8.21	8.23
2019	8.27	8.21	8.23
Mean	8.3136	8.2950	8.3075
Decrease	$-0.0020\ yr^{-1}$	$-0.0031\ yr^{-1}$	$-0.0029\ yr^{-1}$

1.3.3 Adyar Estuary

The present study was carried out for Adyar estuary in the coastal water of East coast of Tamil Nadu. The Adyar estuary is situated in the southern part of Chennai city at Lat. 13° 06′ N, Long 80° 18′ E of south east coast of India. The mean seasonal data of surface water pH at the mouth of the Adayar estuary is presented in Table 1.17.

Table 1.17 Mean seasonal surface water pH values at the mouth of the Adyar estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.34	8.31	8.33
1985	8.34	8.34	8.35
1986	8.33	8.33	8.34
1987	8.34	8.32	8.34
1988	8.33	8.33	8.35
1989	8.34	8.34	8.34
1990	8.34	8.31	8.34
1991	8.34	8.33	8.34
1992	8.33	8.32	8.33
1993	8.35	8.33	8.35
1994	8.34	8.33	8.34
1995	8.34	8.31	8.34
1996	8.35	8.34	8.33
1997	8.33	8.33	8.34
1998	8.34	8.33	8.34
1999	8.33	8.32	8.30
2000	8.33	8.31	8.33
2001	8.33	8.32	8.33
2002	8.34	8.32	8.34
2003	8.33	8.32	8.32
2004	8.34	8.32	8.32

(continued)

Table 1.17 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
2005	8.32	8.32	8.34
2006	8.34	8.31	8.33
2007	8.32	8.31	8.32
2008	8.32	8.30	8.32
2009	8.36	8.31	8.30
2010	8.31	8.30	8.32
2011	8.32	8.30	8.32
2012	8.30	8.29	8.30
2013	8.29	8.28	8.29
2014	8.29	8.27	8.29
2015	8.28	8.25	8.27
2016	8.26	8.24	8.25
2017	8.26	8.23	8.25
2018	8.25	8.22	8.24
2019	8.26	8.19	8.23
Mean	8.3211	8.3036	8.3169
Decrease	$-0.0023\ yr^{-1}$	$-0.0034\ yr^{-1}$	$-0.0029\ yr^{-1}$

1.3.4 Rushikulya Estuary

River Rushikulya originates from the Rushimala mountains of Eastern Ghat. Geographically it located in the state of Odisha between 19° 22′–19° 24′ N and 85° 02′–85° 05′ E and discharges into Bay of Bengal near Ganjam. The estuary has a depth of 3.2 m and it is influenced by the semidiurnal tide. The nutrient supply in the estuary is mainly from freshwater flow. The estuarine ecosystem is facing a serious warning in recent time due to natural hazards and mean sea level rise phenomenon. The frequent storms at Odisha Coast have driven wave further inland into the deeper estuarine zone. At Rushikulya estuary, a long sand spit which was running parallel to the coast, separating the estuary from the sea, was eroded significantly due to the strong surge exerted by cyclone Phailin, which affected many species of fishes, shrimps and birds. Hence the cyclonic surge-induced coastal morphological changes could be one of the major reasons for decline in the number (failure of mass nesting) of these migratory endangered species. The surface water pH values at the confluence of the estuary and Bay of Bengal are presented in Table 1.18.

Table 1.18 Mean seasonal surface water pH values at the mouth of the Rushikulya estuary

Year	Premonsoon High tide	Monsoon High tide	Postmonsoon High tide
1984	8.29	8.26	8.29
1985	8.29	8.27	8.28
1986	8.30	8.26	8.29
1987	8.29	8.27	8.29
1988	8.30	8.28	8.30
1989	8.29	8.29	8.29
1990	8.29	8.26	8.29
1991	8.29	8.28	8.29
1992	8.28	8.27	8.28
1993	8.30	8.28	8.30
1994	8.29	8.28	8.29
1995	8.29	8.26	8.29
1996	8.30	8.29	8.28
1997	8.28	8.28	8.29
1998	8.29	8.28	8.29
1999	8.28	8.27	8.25
2000	8.28	8.26	8.28
2001	8.28	8.27	8.28
2002	8.29	8.27	8.29
2003	8.28	8.27	8.27
2004	8.29	8.27	8.27
2005	8.27	8.27	8.29
2006	8.29	8.26	8.28
2007	8.27	8.26	8.27
2008	8.27	8.25	8.27
2009	8.31	8.26	8.25
2010	8.26	8.25	8.27
2011	8.27	8.25	8.27
2012	8.25	8.24	8.25
2013	8.24	8.23	8.24
2014	8.24	8.22	8.24
2015	8.23	8.20	8.22
2016	8.21	8.19	8.20
2017	8.21	8.18	8.21
2018	8.22	8.17	8.22

(continued)

Table 1.18 (continued)

Year	Premonsoon High tide	Monsoon High tide	Postmonsoon High tide
2019	8.23	8.14	8.21
Mean	8.2733	8.2525	8.2686
Decrease	$-0.0017\ yr^{-1}$	$-0.0034\ yr^{-1}$	$-0.0023\ yr^{-1}$

1.3.5 Kali Estuary

The River Kali is northern most important estuarine system in Uttara Kannada district of Karnataka state. The estuary has considerable impact on adjoining coastal waters and also influences the fishery, fish and shellfish seeds and molluscan resources. The estuary spreads approximately about 23 km in axis until the edge of the elevated plateau of Sahyadri (14° 54′ 25" N and 74° 19′ 30" E) and drains into the Karwar Bay (14° 50′ 21" N and 74° 10′ 05" E) on the central west coast of India. An extensive survey made on the aquatic pH at estuarine mouth shows a decreasing trend (Table 1.19).

Table 1.19 Mean seasonal surface water pH values at the mouth of the Kali estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.35	8.33	8.34
1985	8.34	8.34	8.35
1986	8.35	8.33	8.34
1987	8.34	8.32	8.34
1988	8.35	8.33	8.35
1989	8.34	8.34	8.34
1990	8.34	8.31	8.34
1991	8.34	8.33	8.34
1992	8.33	8.32	8.33
1993	8.35	8.33	8.35
1994	8.34	8.33	8.34
1995	8.34	8.31	8.34
1996	8.35	8.34	8.33
1997	8.33	8.33	8.34
1998	8.34	8.33	8.34
1999	8.33	8.32	8.30

(continued)

Table 1.19 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
2000	8.33	8.31	8.33
2001	8.33	8.32	8.33
2002	8.34	8.32	8.34
2003	8.33	8.32	8.32
2004	8.34	8.32	8.32
2005	8.32	8.32	8.34
2006	8.34	8.31	8.33
2007	8.32	8.31	8.32
2008	8.32	8.30	8.32
2009	8.36	8.31	8.30
2010	8.31	8.30	8.32
2011	8.32	8.30	8.32
2012	8.30	8.29	8.30
2013	8.29	8.28	8.29
2014	8.29	8.27	8.29
2015	8.28	8.25	8.27
2016	8.26	8.24	8.25
2017	8.26	8.23	8.25
2018	8.25	8.22	8.24
2019	8.27	8.20	8.22
Mean	8.3228	8.3044	8.3169
Decrease	$-0.0023\ yr^{-1}$	$-0.0037\ yr^{-1}$	$-0.0034\ yr^{-1}$

1.3.6 Mandovi Estuary

The Mandovi River/Mahadayi River is described as the lifeline of the Indian state of Goa. The river has a length of ~80 km, 29 km in Karnataka and 52 km in Goa. It originates from a cluster of 30 springs at Bhimgad in the Western Ghats in the Belgaum district of Karnataka. The river has a 2032 km^2 catchment area in Karnataka and a 1580 km^2 catchment area in Goa. With its cerulean waters, Dudhsagar Falls and Varapoha Falls, it is also known as the Gomati in a few places. The Mandovi and the Zuari are the two primary rivers in the state of Goa.

The Mandovi enters Goa from the north via the Sattari Taluka in Goa and from Uttara Kannada District of Karnataka near the Castle Rock Railway station. The Mandovi flows through Belgaum, Uttara Kannada in Karnataka and Cumbarjua, Divadi and Chodné in Goa, eventually pouring into the Arabian Sea. Mandovi joins with the Zuari at a common point at Cabo Aguada, forming the Mormugao harbour. The river Mapusa is a tributary of the Mandovi. We made several visits at Mandovi

Table 1.20 Mean seasonal surface water pH values at the mouth of the Mandovi estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.33	8.31	8.32
1985	8.32	8.32	8.33
1986	8.33	8.31	8.32
1987	8.32	8.30	8.32
1988	8.33	8.31	8.33
1989	8.32	8.32	8.32
1990	8.32	8.29	8.32
1991	8.32	8.31	8.32
1992	8.31	8.30	8.31
1993	8.33	8.31	8.33
1994	8.32	8.31	8.32
1995	8.32	8.29	8.32
1996	8.33	8.32	8.31
1997	8.31	8.31	8.32
1998	8.32	8.31	8.32
1999	8.31	8.30	8.28
2000	8.31	8.29	8.31
2001	8.31	8.30	8.31
2002	8.32	8.30	8.32
2003	8.31	8.30	8.30
2004	8.32	8.30	8.30
2005	8.30	8.30	8.32
2006	8.32	8.29	8.31
2007	8.30	8.29	8.30
2008	8.30	8.28	8.30
2009	8.34	8.29	8.28
2010	8.29	8.28	8.30
2011	8.30	8.28	8.30
2012	8.28	8.27	8.28
2013	8.27	8.26	8.27
2014	8.27	8.25	8.27
2015	8.26	8.23	8.25
2016	8.24	8.22	8.23

(continued)

Table 1.20 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
2017	8.24	8.21	8.23
2018	8.23	8.20	8.22
2019	8.24	8.20	8.22
Mean	8.3025	8.2850	8.2975
Decrease	$-0.0026\ yr^{-1}$	$-0.0031\ yr^{-1}$	$-0.0029\ yr^{-1}$

estuary and made an extensive survey on aquatic pH at the mouth of estuary. The seasonal data are highlighted in Table 1.20.

1.3.7 Kalapet Estuary

The study area is the region along Puducherry situated on the east coast of India, between 79.87° E and 79.79° E longitudes and 12.05° N and 11.75° N latitudes. Nearly 40% of the land area is used for industrial, residential and commercial purposes. Fishing villages are scattered along the estuary.

The three major physiographic units generally observed are coastal plain (younger and older), alluvial plain and uplands. The entire area, except the northeastern corner, is mostly covered by sedimentary formations ranging in age from cretaceous to recent. The Kalapet coast of Puducherry has been selected in the present study and a declining trend of surface water pH is observed in the present study (Table 1.21).

Table 1.21 Mean seasonal surface water pH values at the mouth of the Kalapet estuary/Kalapet coast

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.34	8.32	8.33
1985	8.33	8.33	8.34
1986	8.34	8.32	8.33
1987	8.33	8.31	8.33
1988	8.34	8.32	8.34
1989	8.33	8.33	8.33
1990	8.33	8.30	8.33
1991	8.33	8.32	8.33
1992	8.32	8.31	8.32
1993	8.34	8.32	8.34
1994	8.33	8.32	8.33
1995	8.33	8.30	8.33
1996	8.34	8.33	8.32

(continued)

Table 1.21 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1997	8.32	8.32	8.33
1998	8.33	8.32	8.33
1999	8.32	8.31	8.29
2000	8.32	8.30	8.32
2001	8.32	8.31	8.32
2002	8.33	8.31	8.33
2003	8.32	8.31	8.31
2004	8.33	8.31	8.31
2005	8.31	8.31	8.33
2006	8.33	8.30	8.32
2007	8.31	8.30	8.31
2008	8.31	8.29	8.31
2009	8.35	8.30	8.29
2010	8.30	8.29	8.31
2011	8.31	8.29	8.31
2012	8.29	8.28	8.29
2013	8.28	8.27	8.28
2014	8.28	8.26	8.28
2015	8.27	8.24	8.26
2016	8.25	8.23	8.24
2017	8.25	8.22	8.24
2018	8.24	8.21	8.23
2019	8.25	8.19	8.22
Mean	8.3125	8.2944	8.3072
Decrease	$-0.0026\ \mathrm{yr}^{-1}$	$-0.0037\ \mathrm{yr}^{-1}$	$-0.0031\ \mathrm{yr}^{-1}$

1.3.8 Mahi Estuary

Mahi River is one of the major rivers of Gujarat. The estuarine stretch extends up to 50 km upstream (Fajalpur latitude 22° 26′ N and longitude 73° 04′ E) and opens into Gulf of Khambhat at Kamboi (latitude 22° 12′ N and longitude 72° 36′ E). Being funnel shaped (width 200 km at mouth of Gulf terminating to 6 km at the extreme end of Gulf, the Mahi estuary); the Gulf of Khambhat shows high tidal amplitude (up to 12 m), extreme water current and churning of bed material. Moreover, sediment input from major rivers like Narmada, Tapi and Mahi contribute to high turbidity. Owning to these peculiarities, the geomorphology and hydrodynamics of the Gulf of Khambhat makes the estuary very specific in terms of sedimentology as well as water quality. The downstream area can be recognized as estuarine mudflats with silty-clayey composition while, the upstream area has coarse sand and gravel bed. The seasonal variation of surface water pH showed a declining trend (Table 1.22).

Table 1.22 Mean seasonal surface water pH values at the mouth of the Mahi estuary

Year	Premonsoon high tide	Monsoon High tide	Postmonsoon High tide
1984	8.35	8.33	8.34
1985	8.34	8.34	8.35
1986	8.35	8.33	8.34
1987	8.34	8.32	8.34
1988	8.35	8.33	8.35
1989	8.34	8.34	8.34
1990	8.34	8.31	8.34
1991	8.34	8.33	8.34
1992	8.33	8.32	8.33
1993	8.35	8.33	8.35
1994	8.34	8.33	8.34
1995	8.34	8.31	8.34
1996	8.35	8.34	8.33
1997	8.33	8.33	8.34
1998	8.34	8.33	8.34
1999	8.33	8.32	8.30
2000	8.33	8.31	8.33
2001	8.33	8.32	8.33
2002	8.34	8.32	8.34
2003	8.33	8.32	8.32
2004	8.34	8.32	8.32
2005	8.32	8.32	8.34
2006	8.34	8.31	8.33
2007	8.32	8.31	8.32
2008	8.32	8.30	8.32
2009	8.36	8.31	8.30
2010	8.31	8.30	8.32
2011	8.32	8.30	8.32
2012	8.30	8.29	8.30
2013	8.29	8.28	8.29
2014	8.29	8.27	8.29

(continued)

Table 1.22 (continued)

Year	Premonsoon high tide	Monsoon High tide	Postmonsoon High tide
2015	8.28	8.25	8.27
2016	8.27	8.24	8.25
2017	8.28	8.23	8.25
2018	8.28	8.22	8.24
2019	8.28	8.20	8.22
Mean	8.3247	8.3044	8.3169
Decrease	$-0.0020\ yr^{-1}$	$-0.0037\ yr^{-1}$	$-0.0034\ yr^{-1}$

1.3.9 Mindhola Estuary

Mindhola Estuary which originates in the Western Ghats follows a westward and maundering course joining the Arabian Sea at Danti. It broadens into a wide estuary below Nanod, 25 km inland. The estuarine region has extensive sand banks and mudflats. The estuary receives large quantities of mostly untreated sewage and industrial effluents from urban areas and industrial units respectively. The estuary is under considerable tidal influence (tide 0.5–5.5 m) with extended ebb periods. Currents are 0.8–1.9 m/s with the excursion of 3–17 km inside the estuary. There is a general tendency of increase in BOD associated with low DO content which reverses during high tide. Nitrite and ammonia are often higher than expected for the estuaries along the coast. Chlorophyll *a* and zooplankton vary widely. Macrobenthos is low with few species. The aquatic pH also shows a decreasing trend through seasons (Table 1.23).

Table 1.23 Mean seasonal surface water pH values at the mouth of the Mindhola estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.33	8.32	8.33
1985	8.33	8.33	8.33
1986	8.34	8.32	8.33
1987	8.33	8.31	8.33
1988	8.34	8.32	8.32
1989	8.33	8.33	8.33
1990	8.33	8.30	8.33
1991	8.33	8.32	8.33
1992	8.32	8.31	8.32
1993	8.34	8.32	8.34
1994	8.33	8.32	8.33
1995	8.33	8.30	8.33

(continued)

Table 1.23 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1996	8.34	8.33	8.32
1997	8.32	8.32	8.33
1998	8.33	8.32	8.33
1999	8.32	8.31	8.29
2000	8.32	8.30	8.32
2001	8.32	8.31	8.32
2002	8.33	8.31	8.33
2003	8.32	8.31	8.31
2004	8.33	8.31	8.31
2005	8.31	8.31	8.33
2006	8.33	8.30	8.32
2007	8.31	8.30	8.31
2008	8.31	8.29	8.31
2009	8.35	8.30	8.29
2010	8.30	8.29	8.31
2011	8.31	8.29	8.31
2012	8.31	8.28	8.29
2013	8.31	8.27	8.28
2014	8.31	8.26	8.28
2015	8.31	8.24	8.28
2016	8.30	8.23	8.27
2017	8.31	8.22	8.27
2018	8.31	8.21	8.28
2019	8.31	8.15	8.27
Mean	8.3222	8.2933	8.3114
Decrease	$-0.0006\ yr^{-1}$	$-0.0049\ yr^{-1}$	$-0.0017\ yr^{-1}$

1.3.10 Tapi Estuary

Tapi, a major perennial river of the west coast of India, is an important source of freshwater to the region. The 720 km long river originates near Multai in the Betoul district of Madhya Pradesh with a catchment area of 65,145 km^2 of which around 4000 km^2 is in Gujarat. During seaward course, the river meanders through the hilly terrain of the Western Ghats before entering the coastal alluvial plains of Gujarat to meet the Arabian Sea near Hazira. The shallow and wide lower segment of the river exhibits characteristics of a typical estuary with strong currents associated with significantly high tidal influence upto 25 km upstream. Further inland however, the seawater excursion is restricted due to creation of a causeway at Rander which also hinders the freshwater outflow. The estuary and nearshore areas of Hazira exhibit a typical character of South Gujarat coast with (a) vast intertidal regions composed of poorly sorted sediment made up sand silt and clay with isolated rocky outcrops, (b) supra-littoral region either barren or dominated by salt tolerant plant species of P*rosopis, Acacia and Zyphus*, (c) gently sloping continental shelf with uneven seafloor often strewn with sand bars, and (d) high tidal influence due to the proximity to the Gulf of Khambhat.

The riverine discharge to the sea is controlled by the Ukai and Kakrapar dams constructed on the river at 141 and 115 km upstream respectively. Mean runoff of Tapi was 1.7982×10^{10} m^3/y in 1975. After the construction of dams, it has reduced to an average of 7.301×10^9 m^3/y during 1982–91. In 1995 a weir-cum-causeway was constructed across the river at Rander that prevented seawater incursion further inland. In recent years the river discharge of 8000 m^3 /s during monsoon decreases to 10 to 45 m^3/s during November–May leading to stagnation in the riverine and inner estuarine segments, during the dry season. Due to proximity of the Gulf, the region experiences significantly high tidal influence with mean spring and neap tidal ranges of 5.7 and 4.3 m respectively at Hazira. The tidal influence however decreases with distance into the estuary with spring and neap tidal ranges of 2.3 and 0.4 m respectively at Surat. During the period of freshwater dominance the flood duration of 6 h in the open shore reduces to 4 to 5 h in the mouth segment of the estuary and decreases to barely 2 h at Surat with corresponding increase in the ebb period. Decrease in flood period though to a lesser extent occurs in the landward direction during the dry season also. The Tapi River is subjected to sporadic floods associated with heavy rainfall in the catchment area during July–September. When the flood coincides with spring tide, the water level increases substantially inundating vast areas. A level of 10 m with respect to CD has been recorded at Magdalla during one such flood in the past. The construction of two dams on the river has however reduced the flood fury to a great extent. The mean seasonal surface water pH at the estuarine mouth shows a declining trend with time (Table 1.24).

The decrease of pH follows a unique trend with highest value in monsoon followed by postmonsoon and premonsoon (Figs. 1.11, 1.12, and 1.13). We presume that run-off during monsoon brings lots of land based wastes in the estuary, which dips the pH value to a minimum. The process of estuarine acidification is primarily linked to land based activities like emission from industries, wastes from urban settlements, aquacultural farms etc. The spatial variation as observed in Tables 1.15, 1.16, 1.17, 1.18, 1.19, 1.20, 1.21, 1.22, 1.23, and 1.24 is because of the variation in the magnitude of anthropogenic activities in the coastal, upstream and downstream zones surrounding the estuaries.

Coastal upwelling can also lead to formation of hotspots of coastal pH change because of naturally high levels of CO_2 coupled with the increased anthropogenic CO_2 content of these waters. In some regions, an increase in the intensity of upwelling, which amplifies the effects on pH, is associated with anthropogenic climate change. However, the upwelling phenomenon is not detailed as the book primarily addresses estuarine acidification.

Table 1.24 Mean seasonal surface water pH values at the mouth of the Tapi estuary

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
1984	8.35	8.34	8.35
1985	8.35	8.35	8.36
1986	8.34	8.34	8.35
1987	8.35	8.33	8.35
1988	8.33	8.34	8.36
1989	8.35	8.35	8.35
1990	8.35	8.32	8.35
1991	8.35	8.34	8.35
1992	8.34	8.33	8.34
1993	8.34	8.34	8.36
1994	8.35	8.34	8.35
1995	8.35	8.32	8.35
1996	8.36	8.35	8.34
1997	8.34	8.34	8.35
1998	8.35	8.34	8.35
1999	8.34	8.33	8.31
2000	8.34	8.32	8.34
2001	8.34	8.33	8.34
2002	8.35	8.33	8.35
2003	8.34	8.33	8.33
2004	8.35	8.33	8.33
2005	8.33	8.33	8.35
2006	8.35	8.32	8.34
2007	8.33	8.32	8.33
2008	8.33	8.31	8.33
2009	8.37	8.32	8.31
2010	8.32	8.31	8.33
2011	8.33	8.31	8.33
2012	8.31	8.30	8.31
2013	8.30	8.29	8.30
2014	8.30	8.28	8.30
2015	8.29	8.26	8.28
2016	8.27	8.25	8.26
2017	8.27	8.24	8.26

(continued)

Table 1.24 (continued)

Year	Premonsoon high tide	Monsoon high tide	Postmonsoon high tide
2018	8.26	8.23	8.25
2019	8.25	8.20	8.24
Mean	8.3297	8.3142	8.3272
Decrease	$-0.0029\ yr^{-1}$	$-0.0040\ yr^{-1}$	$-0.0031\ yr^{-1}$

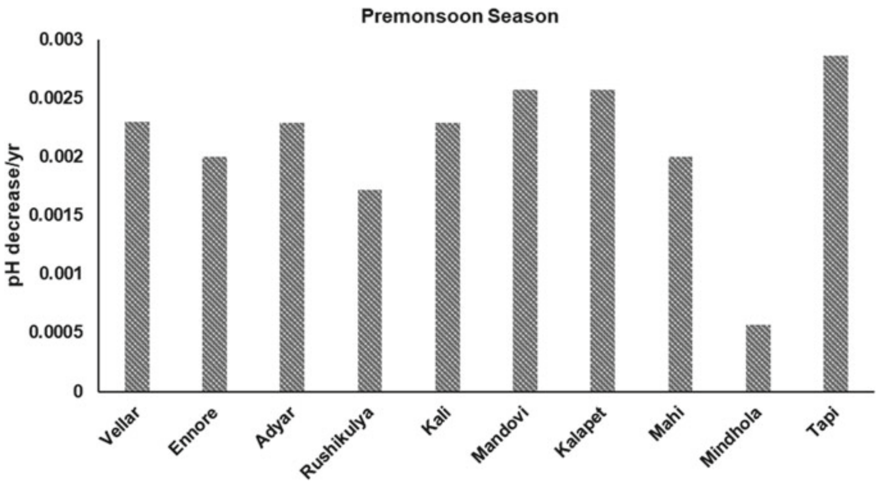


Fig. 1.11 Surface water pH decrease/yr in premonsoon season in ten imortant Indian Estuaries

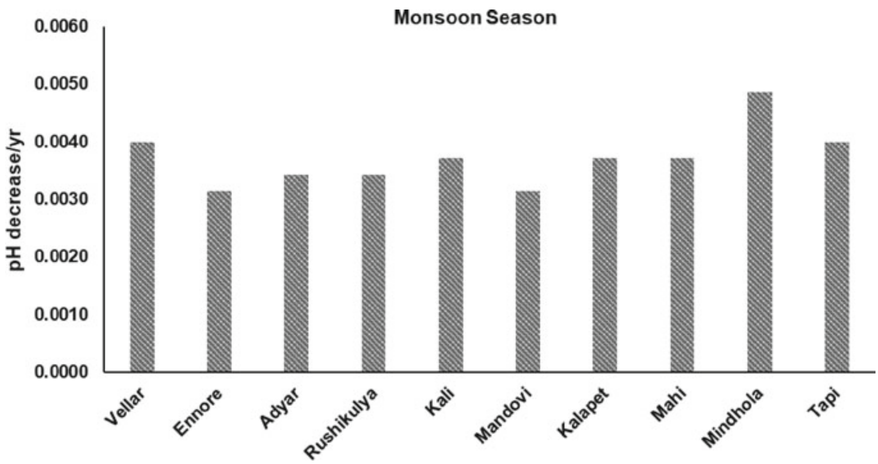


Fig. 1.12 Surface water pH decrease/yr in monsoon season in ten imortant Indian Estuaries

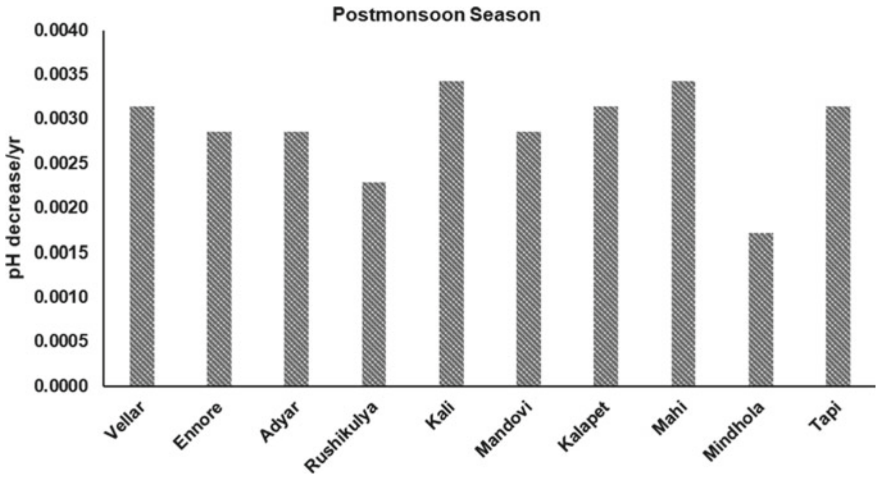


Fig. 1.13 Surface water pH decrease/yr in postmonsoon season in ten imortant Indian Estuaries

1.4 Take Home Messages

A. Estuaries are unique spots on our planet, which are situated and sandwiched between the continents and the seas. Penetrated by the sea through the recurring tides and flushed by the freshwater outflows of the lotic system, an estuary is a dynamic system where the freshwater meets seawater. Blessed by the fertile flows of both the seas and the rivers, these fascinating biotopes are by far the most productive ecosystem on our planet, the abode of unique species of plants and animals, the cradle of several species of finfish, the nursery of commercially important shellfish, the reservoir of food, chemicals, mineral, oils and natural gas and the ideal spots for tourism and aquaculture. Several definitions have been forwarded to depict the features of estuarine compartment of which most of the definitions focus on the mixing of fresh and salt water as a zone of intersection between the river and sea. Estuaries of the world have been classified from various points of views like salinity profile, circulation pattern, geomorphology, energetic etc.

B. Estuaries are noted for unique taxonomic diversity of species, biological productivity and aesthetic value. The water, sediment and biotic communities of the estuaries offer several ecosystem services that provide both direct and indirect benefits to run the wheel of human civilization. They provide ecosystem services in the domains of provisioning services (fishes, minerals, mangrove based plants etc.), regulating services (water quality maintenance, biogeochemical cycles, carbon sink, flood control etc.), supporting services (biodiversity, life cycle stages of several species of shell fish and finfish, route for various rare fauna like turtles, dolphins etc.) and cultural services (religious convergence and rituals).

C. Indian estuaries are mostly subject to high degree of pollution that arises from industrial activities, sewage discharge, aquaculture farms, brick kilns, tourism units etc., and depending on the riverine discharge, the salinity and pollution load exhibit dynamic scenario. Extensive studies have been conducted on ten major estuaries of Indian sub-continent namely (i) Vellar estuary in southern Tamil Nadu, (ii) Ennore estuary in Tamil Nadu, (iii) Adyar estuary in Tamil Nadu, (iv) Rushikulya estuary in Odisha, (v) Kali estuary in Karnataka, (vi) Mandovi estuary in Goa, (vii) Kalapet estuary in Puducherry, (viii) Mahi estuary in Gujarat, (ix) Mindhola estuary in Gujarat, (x) Tapi estuary in Gujarat. In all the estuaries a decreasing trend of pH has been observed, which can be considered as foot print of acidification.

Annexure 1: List of True Mangrove Flora with Medicinal Properties

The mangrove dominated Indian Sundarbans is the survival ground of a variety of endemic plants, which have great medicinal potential (Table 1.25).

The present annexure is an attempt to add another colored feather on the provisioning service cap of Sundarban estuarine mangrove floral species in the field of pharmacology, especially relevant in the COVID phase. Knowledge on the medicinal property of mangroves can help to cure diseases of the island dwellers locally, whose access to the city hospitals and clinics have totally been cut-off in the COVID period due to irregular transport system. Even the passenger vessel/boat, which is the only mode of transport for the Sundarban people has posed restrictions on the number of passengers to avoid the probability of contamination.

Table 1.25 Common true mangrove flora of Indian Sundarbans with medicinal values

Mangrove species	Identifying features	Medicinal Values
 *Acanthus ilicifolius* Common name: Hargoja	1. Shrub like morphology with prominent stilt roots, usually found in sheltered mangrove areas; thrive on the supralittoral zone 2. Leaves lanceolate with serrated margins armed with spines 3. Flowers with long spike inflorescence, light blue or violet in colour	1. The root is expectorant, and is used in coughs and asthma 2. The root, boiled in milk, is largely used in leucorrhoea and general debility 3. The plant extract has anti- inflammatory property
 *Aegiceros corniculatum* Common name: Khalsi	1. Shrub tolerant to high saline areas 2. Bark reddish brown with leaves elliptical, leaf-tip notched, cuneate at base 3. Fruit green to reddish in maturation, sharply curved 4. Fragrant white flowers, curved yellow	1. It is used for curing asthma 2. It has anti diabetic property 3. It is used to cure rheumatism

(continued)

Table 1.25 (continued)

Mangrove species	Identifying features	Medicinal Values
 *Avicennia alba* Common name: Kalo baen	1. Trees are tolerant to high salinity, pneumatophores spongy, narrowly pointed with slender stilt roots 2. Bark dark brown or even black 3. Leaves lanceolate to elliptical, leaf-tip acute, lower surface silver grey to white 4. Curved fruit with relatively long beak	1. Paste prepared from seeds helps to relieve small pox ulceration 2. Wood ash after burning wood is given in dysentery 3. The plant extract is used to cure snake bites
 *Avicennia marina* Common name: Piara baen	1. Trees are tolerant to high salinity 2. Pneumatophores pencil like 3. Bark yellowish brown 4. Leaves elliptical, leaf-tip rolling, lower surface white to light grey 5. Inflorescence terminal or axillary, orange yellow in colour	1. Bark decoction applied on "Haza" (a kind of sore due to wet sand and saline water) for curing purpose 2. Paste prepared from seeds helps to relieve small pox ulceration 3. Resinous exude is used for birth control purposes

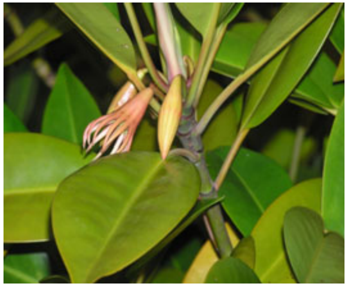
(continued)

Table 1.25 (continued)

Mangrove species	Identifying features	Medicinal Values
 *Avicennia officinalis* Common name: Sada baen	1. Trees are tolerant to high salinity, pneumatophores pencil like 2. Bark yellowish brown. Leaves elliptical, leaf-tip rolling, lower surface white to light grey 3. Inflorescence terminal or axillary, orange yellow	1. Ash obtained after burning the dried bark is used as antacid 2. Paste of green (raw) fruits is applied to cure boils and skin diseases 3. It is used to cure hepatitis
 *Sonneratia apetala* Common name: Keora	1. Trees are with long, corky, forked pneumatophores 2. Stem light brown in colour 3. Leaves thick, coriaceous, narrowly elliptic oblong tapering towards apex 4. Flowers are cream coloured in axilliary cymes with globose berry seated in flattened calyx tube	1. Fruit contains 28 g/100gm of Vitamin C and hence helps to fight cough and cold 2. Consumption of *S. apetala* fruit reduces the risk of cardiovascular disease 3. It is used to cure neurodegenerative diseases, such as Parkinson's and Alzheimers's

(continued)

Table 1.25 (continued)

Mangrove species	Identifying features	Medicinal Values
 *Bruguiera gymnorrhiza* Common name: Kankra	1. Trees generally found on elevated interior parts of mangrove forest with prominent buttress roots 2. Bark dark grey. Leaves simple, elliptical-oblong, leathery and leaf-tip acuminate 3. Flowers axillary, single with red calyx, red in colour and almost 16 lobed; fruits are cigar shaped, stout and dark green	1. Bark decoction with coconut oil is applied to cure dermatological problems 2. The extract is used to cure eye diseases 3. Leaves and stems are used to treat diarrhea, fever, diabetes and pain
 *Ceriops decandra* Common name: Goran	1. Stilt roots arising from pyramidal stem base 2. Light grey barked stem 3. Leaves elliptic-oblong, emarginate at apex, cuneate at base 4. Flowers axillary in condensed cymes 5. Fruit is berry, dark red when mature, warty towards tip, ridged, not hanging down	1. Obstetric and haemorrhage cases are treated with an infusion of *Ceriops* bark 2. It is used to cure hepatitis 3. It is used to cure ulcers

(continued)

Table 1.25 (continued)

Mangrove species	Identifying features	Medicinal Values
 *Excoecaria agallocha* Common name: Genwa	1. Prominent main root absent, many laterally spreading snake like roots producing elbo-shaped pegs 2. Bark greyish Poisonous milky latex highly irritating to eyes 3. Leaves light green with wavy margin 4. Catkin inflorescence terminal or axillary, orange yellow	1. Latex applied on leprotic wounds 2. Leaf decoction is claimed as medicine in epilepsy 3. It is used to treat conjunctivitis
 *Heritiera fomes* (Sterculiaceae) Common name: Sundari	1. Trees with numerous peg-like pneumatophores and blind root suckers 2. Young branches covered with shining golden-brown scales 3. Leaves elliptic with lower surface shining with silvery scales 4. Flowers golden yellow with reddish tinge inside and fruits sub-globose, woody, indehiscent with longitudinal and transverse ridges	1. It has antiviral property 2. It has antibacterial property 3. It has anticarcinogen property

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Chapter 2
Estuaries of Indian Sundarbans: A Test Bed for Acidification Study

Abstract Indian Sundarban delta, at the apex of Bay of Bengal is noted for the presence of seven dynamic estuaries. The estuaries in the western sector of the delta complex are hyposaline in nature with relatively low surface water pH (mean pH value = ~7.90) as they receive the industrial effluents from multifarious industrial units. On contrary, the estuaries of central Indian Sundarbans are hypersaline with relatively high pH as the freshwater discharge from the mighty River Ganga is blocked due to massive siltation. These hypersaline estuaries receive saline water from Bay of Bengal and exhibit a pH value around 8.28 throughout the year. Considering the contrasting nature of the estuaries of western and central Indian Sundarbans, the impacts of aquatic pH on several physico-chemical and biological components have been highlighted in this chapter on a comparative scale. The significant spatio-temporal variation of aquatic pH can be attributed to factors like seawater intrusion into the estuary from Bay of Bengal, sewage discharge (from point and nonpoint sources) and photosynthetic activity by the mangrove vegetation that exhibit variable biomass and distribution in and around the experimental sites.

2.1 Estuaries of Indian Sundarbans

An estuary may be considered as the zone of intersection of fresh and marine waters with unique physico-chemical and biological characteristics. Estuaries generally occupy those areas of the coasts, which are least subject to marine features/activities and wave actions and thus are major sites for development of harbours, recreational activities and aquacultural farms. In estuaries, fresh water collected over vast regions of the land pours into the ocean, which sends salt water upstream far beyond the river mouth. According to Odum (1971), estuaries belong to different class of "fluctuating water level ecosystems".

Each estuary has its respective identity in terms of the amount of river discharge, depth and general topography, specific circulation pattern, climatic regime and vertical tide range that influence its ecology and biodiversity, e.g. the estuaries of Indian Sundarbans has a salinity range from 4.0 to 30.0 psu depending on season

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and locations unlike the Mandovi and Zuari estuaries of Goa, where the salinity oscillation is not so significant.

The estuaries are the live matrix of deltaic complex, on which the unique spectrum of biological diversity is embedded. In Indian Sundarbans, approximately 2069 km^2 area is occupied by tidal river system or estuaries, which finally end up in the Bay of Bengal. The seven main estuaries, from west to east are highlighted in Table 2.1 along with their important characteristics.

The major estuaries of lower Gangetic delta are depicted in Fig. 2.1.

The estuaries of Indian Sundarbans exhibit distinct variation in salinity in the same time period. We observed that salinity in the Matla estuary flowing through central Indian Sundarbans exhibit higher salinity than Hooghly estuary in the western Indian Sundarbans (*Vide* Tables 2.2 and 2.3 and Figs. 2.2 and 2.3).

It is clearly visualized from the data sets that the central sector experiences a high saline aquatic sub-system, which is the result of complete obstruction of the fresh water flow from the upstream region owing to Bidyadhari siltation since the late fifteenth century (Chaudhuri and Choudhury 1994; Banerjee et al. 2013; Mitra 2013; Sengupta et al. 2013). The Matla estuary in the central Indian Sundarban cannot be referred to as an ideal estuary as there is no head on discharge or dilution of the system with fresh water. Thus Matla can be designated as a tidal channel, whose survival depends on the tidal flow from Bay of Bengal.

The hyposaline environment of western Indian Sundarbans may be attributed to Farakka barrage discharge situated in the upstream region of Ganga-Bhagirathi-Hooghly river system. 10-year surveys (1999–2008) on water discharge from Farakka dam revealed an average discharge of $(3.7 \pm 1.15) \times 10^3$ m^3s^{-1}. Higher discharge values were observed during the monsoon with an average of $(3.81 \pm 1.23) \times 10^3$ m^3s^{-1}, and the maximum of the order 4524 m^3s^{-1} during freshet (September). Considerably lower discharge values were recorded during premonsoon with an average of $(1.18 \pm 0.08) \times 10^3$ m^3s^{-1}, and the minimum of the order 846 m^3s^{-1} during May. During postmonsoon discharge, values were moderate with an average of $(1.98 \pm 0.97) \times 10^3$ m^3s^{-1} (Mitra 2013).

An attempt has also been taken to visualize the salinity profile of the region after a span of 30 years (forecasting) on the basis of present trend. The exponential smoothing method that produces maximum-likelihood estimate of the variable predicts a salinity value of 13.05 psu in 2043, which is a decrease of 38.4% since 1984 in western Indian Sundarban estuary (over a span of 60 years).

Considering the observed data set of 30 years (1984–2013), it can be predicted that salinity will be around 36 psu after a period of 30 years in the central sector of Indian Sundarbans, which is an indication of alarming hypersaline condition (a rise by 67.1%) in 2043 in this sector.

Table 2.1 Important tidal rivers of Indian Sundarbans

Estuary	Description
Hooghly	• It forms the western border of Indian Sundarbans and is exposed to considerable anthropogenic activities • It is the main river of West Bengal and is a direct continuation of the River Ganges • Most of the coastal industries of West Bengal are concentrated along the western bank of this river
Muriganga	• It is a branch of the Hooghly River • It flows along the east of Sagar Island, the largest island in the deltaic complex • Unique mangrove vegetation with dominancy of *Sonneratia apetala*, *Avicennia* spp. and *Excoecaria agallocha* is found along the bank of this river
Saptamukhi	• It has relatively high salinity compared to Hooghly estuary • It is connected with the Muriganga (Bartala) branch of the Hooghly River through Hatania-Duania canal
Thakuran	• It begins near Jayanagar in South 24 Parganas and has a number of connections with the Saptamukhi • It was connected in the earlier times with the Kolkata canal through the Kultali and the Piyali rives, which exist today in a dying state
Matla	• This river originates at the confluence of Bidyadhari, Khuratya and the Rampur Khal close to the town of Canning in 24 Parganas (South) • Matla is connected to Bidya and ultimately flows to the Bay of Bengal. The fresh water connection and discharge to this river has been lost in the recent times • Salinity of the river water is relatively high (in comparison to Hooghly or Muriganga) owing to fresh water cut-off from the upstream region
Bidyadhari*	• This was flourishing branch of the Bhagirathi during the fifteenth and sixteenth century, but now serves only as a sewage and excess rainwater outlet from the city of Kolkata • The river bed is completely silted and presently it is almost in dying condition

(continued)

Table 2.1 (continued)

Estuary	Description
Goashaba	• The waters of Matla and Harinbhanga (Raimangal) through a large number of canals form the estuary • The estuary and its numerous creeks flow through the reserve forests
Harinbhanga	• The salinity of Harinbhanga estuary is relatively low compared to Matla estuary in the central Indian Sundarbans • The Harinbhanga (also known as Ichamati and Raimangal) forms a natural demarcation between India and Bangladesh

* Presently a dying estuary and not considered within the seven major types

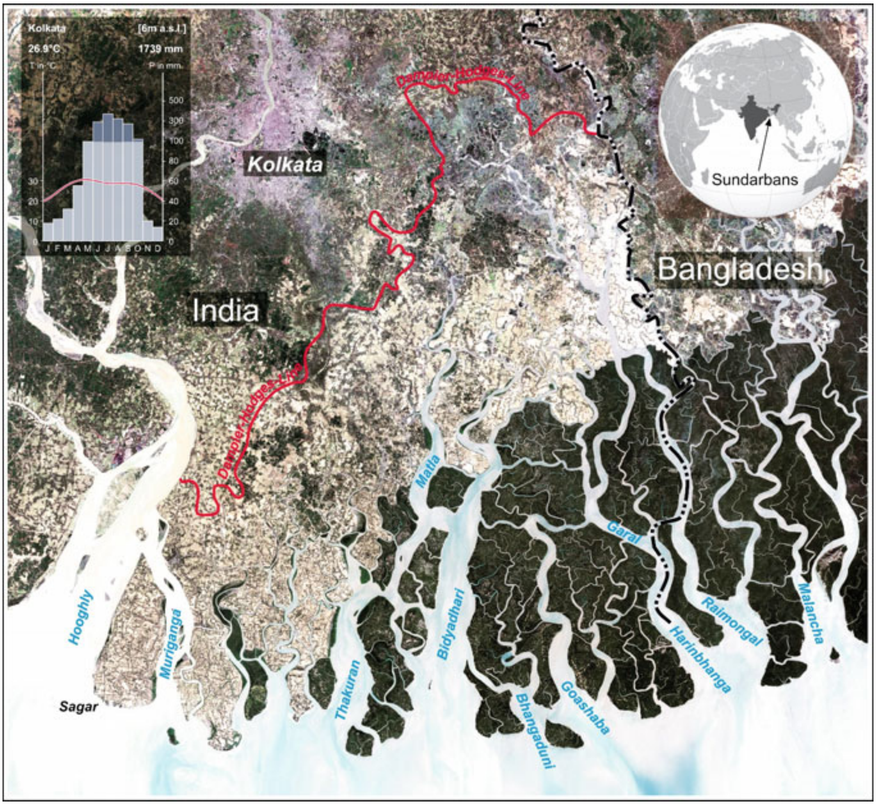

Fig. 2.1 Major estuaries in the lower Gangetic delta complex

Table 2.2 Surface water salinity (psu) in the Jharkhali station along the Matla Estuary of central Indian Sundarbans

Year	Premonsoon	Monsoon	Postmonsoon
1984	22.07	20.67	21.81
1985	23.59	20.74	22.08
1986	24.34	20.80	22.02
1987	24.22	20.14	22.67
1988	25.04	20.03	22.40
1989	25.69	20.35	23.08
1990	25.84	21.02	23.54
1991	25.01	21.67	23.57
1992	24.72	21.73	23.96
1993	25.60	21.86	23.77
1994	26.00	21.74	24.21
1995	26.04	21.99	24.99
1996	26.08	21.61	25.05
1997	26.83	22.01	24.92
1998	26.81	22.06	25.43
1999	26.75	20.64	25.41
2000	26.98	21.37	25.51
2001	27.04	22.60	25.96
2002	27.13	22.92	26.42
2003	27.45	22.98	26.48
2004	27.20	23.04	26.45
2005	27.18	23.16	27.56
2006	27.86	23.78	27.38
2007	27.69	23.83	27.69
2008	28.34	23.92	27.72
2009	31.68	22.87	28.30
2010	29.87	22.96	28.54
2011	30.13	23.37	28.89
2012	30.08	23.52	28.72
2013	30.46	23.69	28.92
2014	30.73	24.04	29.28
2015	30.81	23.89	29.80
2016	31.09	24.03	29.88
2017	30.80	25.03	29.30
2018	30.96	25.41	30.68

Table 2.3 Surface water salinity (psu) in the Diamond Harbour station along the Hooghly Estuary adjacent to theWestern Indian Sundarbans

Year	Premonsoon	Monsoon	Postmonsoon
1984	11.68	7.14	9.17
1985	11.04	7.10	9.11
1986	10.87	6.97	9.13
1987	10.99	6.00	8.17
1988	11.55	5.84	8.81
1989	11.02	5.56	8.33
1990	10.85	6.02	7.67
1991	10.32	5.13	7.14
1992	10.07	5.07	7.37
1993	9.97	4.99	7.96
1994	9.45	4.84	6.83
1995	9.63	5.04	6.40
1996	8.86	4.97	6.44
1997	8.31	4.66	6.67
1998	7.70	4.44	6.12
1999	7.95	3.96	6.14
2000	7.04	3.78	6.19
2001	7.43	3.42	5.43
2002	6.51	3.29	5.41
2003	6.25	3.55	5.77
2004	6.20	2.99	5.84
2005	6.39	2.47	5.23
2006	5.77	2.76	5.35
2007	5.17	2.34	5.43
2008	5.07	2.99	4.40
2009	11.04	3.35	4.20
2010	5.00	2.23	4.17
2011	4.66	2.06	4.00
2012	5.01	1.99	4.09
2013	4.93	1.95	3.93
2014	4.26	1.92	3.86
2015	5.07	1.87	3.71
2016	4.09	1.08	3.87
2017	4.12	1.01	3.55
2018	3.06	0.85	2.17

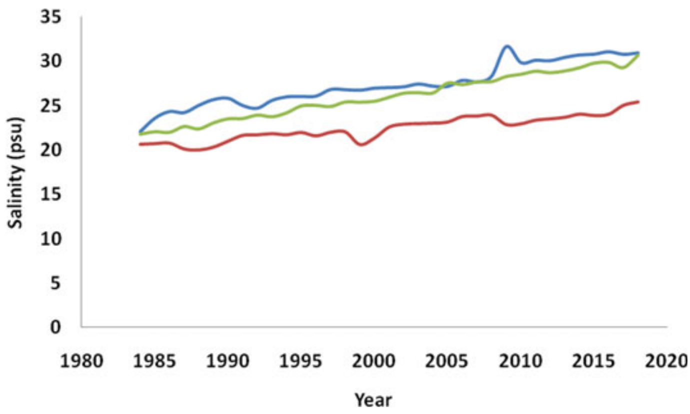

Fig. 2.2 Surface water salinity (psu) in the Jharkhali station along the Matla Estuary of central Indian Sundarbans; the blue, green and red lines represent the salinity values during premonsoon, postmonsoon and monsoon seasons respectively and the peak in blue line is the extreme salinity witnessed during the supercyclone Aila that hit Indian Sundarbans on 25th May, 2009

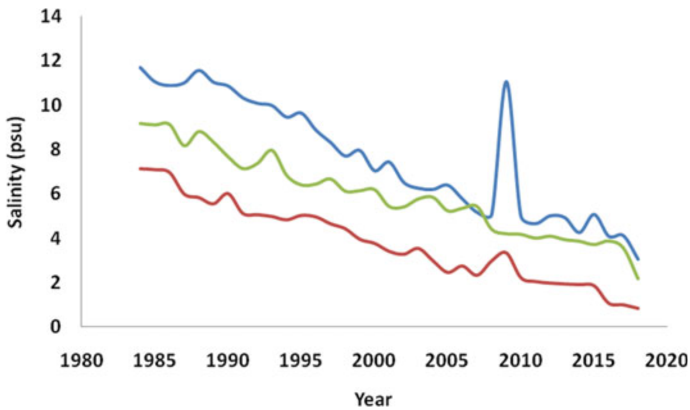

Fig. 2.3 Surface water salinity (psu) in the Diamond Harbour station along the Hooghly Estuary of western Indian Sundarbans; the blue, green and red lines represent the salinity values during premonsoon, postmonsoon and monsoon seasons respectively and the peak in blue line is the extreme salinity witnessed during the supercyclone Aila that hit Indian Sundarbans on 25th May, 2009

2.2 Climate of Indian Sundarbans

The deltaic lobe of Indian Sundarbans experiences a moderate type of climate because of its location adjacent to the Bay of Bengal as well as due to regular tidal flushing in the estuaries. Wave actions, micro and macro tidal cycles, long shore currents are recorded in most of the islands of the ecosystem. Coastal processes are very dynamic and are accelerated by tropical cyclones, which is locally called “Kal Baisakhi”

(Norwesters). Average annual maximum atmospheric temperature is around 35 °C. The seasons in study area may be conveniently categorized into premonsoon (March-June), monsoon (July–October) and postmonsoon (November- February). Each season has a characteristic feature of its own, which is very distinct and unique. The oscillations of various physico-chemical variables in different seasons of the year are discussed here in brief.

2.2.1 Wind

The direction and velocity of wind system in the coastal West Bengal are mainly controlled by the north-east and south-west monsoons. The wind from the north and north-east commences at the beginning of October and continues till the end of March. The month of January and February are relatively calm with an average wind speed around 3.5 km/h. Violent wind speed recommences from the south-west around the middle of March and continues till September. During this period, several low pressure systems occur in this region, a number of which takes the form of depressions and cyclonic storms of varying intensity. On 25th May, 2009, a type of tropical cyclone named "AILA" hit the Sundarbans region. It was formed in the central Bay of Bengal as the net output of several factors. Around May 20th, 2009 monsoon initiated at mid Andaman Islands. The moisture—laden south westerlies accelerated the moisture content in the winds of the Bay of Bengal (Fig. 2.4).

A preliminary Indian Meteorological Department report stated that the cyclone retained its intensity for about 15 h after it hit the landmasses as it was close to the Bay

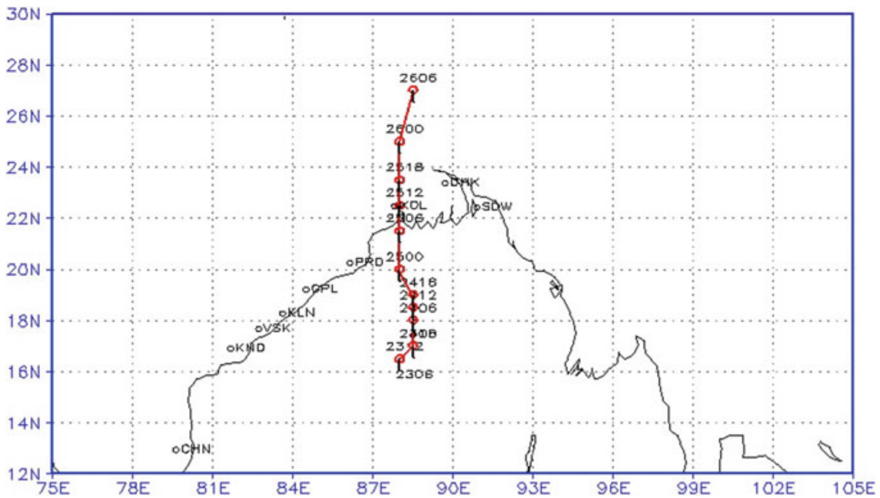

Fig. 2.4 Track of AILA during 23rd to 26th May, 2009. *Source* Regional Specialized Meteorological Center—Tropical Cyclone, New Delhi

of Bengal. It lay centered over the Gangetic delta for quite some time, ascertaining the availability of moisture. This is peculiar nevertheless because premonsoon storms rarely hit the maritime state of West Bengal with such severity. A large number of mangroves were uprooted during the AILA period, but this vegetation acted as bioshield and reduced the vulnerability of island villages.

The variations in the wind speed in the northern and southern sector of Bay of Bengal had led to the curling of winds, which is known as positive relative vortices. Basically an area of depression developed in the Bay of Bengal on May 20, 2009 which transformed into a cyclone on May 23, 2009 and hit the deltaic complex of Indian Sundarbans on May 25, 2009 destroying the lives and properties of island dwellers. It lay centered over the Gangetic delta for quite some time, ascertaining the availability of moisture. This is peculiar nevertheless because premonsoon storms rarely hit the maritime state of West Bengal with such severity.

Natural hazards are keenly related to the lives and livelihoods of Sundarban people. Bulbul, one of the most recent tropical cyclonic storms, wreaked havoc in southern West Bengal along with parts of Odisha on 8th and 9th November 2019. The storm is said to have triggered losses between INR 15,000 and 19,000 crores, as per official projections.

The storm surges primarily affected the districts of North and South Parganas and East Midnapore in West Bengal, claiming several lives, destroying houses, physical assets and sweeping away ripe agricultural harvests. Despite the adequacy of pre-arranged assistance, reliefs and contingencies provisioned by the state, Bulbul led to significant devastations for marginal rural communities in the districts—primarily subsistence agriculturalists.

Extreme climate-change events and frequent cyclones like Bulbul and Fani calls for a conscious recognition of the need of productive ecosystems like mangroves and an effective governance mechanism working towards long term environmental sustainability.

In recent time, another natural disaster in the form of cyclone Amphan, hit West Bengal on May 20, 2020 claiming 86 lives and affecting over 10 million people in the eastern Indian state. The powerful storm ripped through eastern India and neighbouring Bangladesh. The storm in West Bengal caused massive damage to standing crops, thousands of trees were uprooted, and power and water supply was interrupted in the state capital Kolkata. Many in the state have lost their entire homes as well.

Cyclone Amphan made its landfall in West Bengal between Digha and Hatiya on the afternoon of May 20, as a very severe cyclonic storm with sustained wind speeds of 155–165 kms per hour spiraling up to 185 kms per hour. The coastal state of Odisha and the neighbouring country of Bangladesh were also impacted by the cyclone.

It is estimated that about 3900 km^2 in the Sundarbans suffered damage, with over 10 lakh homes and shops being devastated, trees being uprooted, and roads being cracked open. The storm also damaged creeks and embankments, bringing saline water into villages and destroying 109,577 hectares of cultivable land and impacting 443,144 farmers.

It has been observed that saline inundation in agricultural fields has destroyed standing crops and set back any prospects of cultivation to at least two years. The incoming monsoon also brings with it new challenges for rehabilitation. Freshwater and potable water availability has been affected and it is now up to the residents to begin picking up from what's left due to the damage.

Basically the inshore region of Bay of Bengal is prone to several categories of storms in frequent intervals of time. The table here reflects the frequency of occurrence of cyclonic storm in the Indian Sundarbans during 1990–2020 (Table 2.4).

Table 2.4 A brief summary of extremely severe cyclonic storms (ESCSs) over the Bay of Bengal region during 1990–2020

S. no.	Year	Name year-wise	Lifetime	MSW (knots)	Duration during ESCS (h)
	1990[a]	1990	6 days 6 h	127	60
	1991[a]	1991	5 days 12 h	127	36
	1992[b]	1992	5 days 12 h	102	48
	1993[b]	1993	3 days 6 h	90	3
	1994[a]	1994	3 days 3 h	102	18
	1995[b]	1995	3 days 21 h	102	15
	1997[a]	1997	4 days 6 h	90	12
	1999[b]	1999	4 days	90	3
	1999[b]	Orissa SuCS	5 days 21 h	140	24
	2000[b]	2000	4 days 3 h	102	12
	2000[b]	2000	5 days 9 h	90	3
	2004[a]	2004	3 days	90	6
	2006[a]	Mala	4 days 15 h	100	24
	2007[b]	Sidr	4 days 18 h	115	63
	2008[a]	Nargis	6 days 6 h	90	9
	2009[a]	Aila	2 days	67	24
	2010[b]	Giri	2 days 18 h	105	6
	2013[b]	Phailin	6 days 3 h	115	54
	2014[b]	Hudhud	7 days 6 h	100	27
	2019	Bulbul	3 days	72	2
	2019[a]	Fani	8 days 9 h	116	27
	2020[a]	Amphan SuCS	5 days 12 h	102	60

VSCS very severe cyclonic storm (wind speed between 64 and 89 knots); ESCS extremely severe cyclonic storm (wind speed between 90 and 119 knots); SuCS super cyclonic storm (wind speed more than 120 knots); [a]During premonsoon period (March–May); [b]During post-monsoon period (October–December); One knot is equal to 1.8 kmph

2.2.2 Waves and Tides

The wind is the basic driving force for generating surface waves in the coastal zone of West Bengal. Sea waves in this region rarely become destructive except during cyclonic storms. During Norwesters', the wind speed rises above 100 km/h and is usually accompanied by huge tidal waves. When the cyclonic incidences coincide with the spring tides, wave height can rise over 5 m above the mean sea level. Ripple waves appear in the month of October, November and December when wind generated wave height varies approximately between 0.20 and 0.35 m. In the month of April to August, large wavelets are formed in the shelf region and they start breaking when they approach towards the coastal margin.

Wave height rises up to 2 m during this period, which causes maximum scouring of land masses. Wave actions, micro and macro-tidal cycles and long shore currents are recorded in most of the islands in this ecosystem. With the change in seasons, tidal pattern in the estuarine systems of coastal West Bengal also changes. During the monsoon month, the effect of flood tide is more or less countered and nullified by freshets and there is a strong predominance of ebb tide. The strength of flood tide over ebb tide is at a minimum during the postmonsoon season. Conversely, during the premonsoon season, the effect of flood tide is considerably stronger than that of the ebb tide.

2.2.3 Water Temperature

In coastal West Bengal, the seasonal variation of surface water temperature is not so drastic between premonsoon and monsoon seasons. The premonsoon period (March to June) is characterized by a mean surface water temperature around 34 °C. The monsoon period (July to October) shows a mean surface water temperature around 32 °C and the postmonsoon period (November to February) is characterized by cold weather with a mean surface water temperature around 23 °C (Mitra 2000).

2.2.4 Rainfall

Rainfall is usually maximum during the month of August/September and then monsoon period lasts from July to October. The south-west wind triggers precipitation in the monsoon period with an average rainfall of about 165 mm. The postmonsoon period (November to February) is characterized by negligible rainfall and the premonsoon period (March to June) is basically dry, but occasionally accompanied by rains and thunderstorms. Rough weather with frequent cyclonic depressions lasts from mid March to mid September. Average annual rainfall is 1920 mm. Average humidity is about 82% and is more or less uniform throughout the year.

Table 2.5 highlights the average rainfall data for three decades (1981–2018). The average monthly data of rainfall has been computed on the basis of secondary data available from Canning station (Source: IMD—Indian Meteorological Department) and it is observed that monsoon in the lower Gangetic delta region starts from June and continues till October.

2.3 Pulse of Acidification in Hooghly and Matla Estuaries of Indian Sundarbans

Over the last century, the atmospheric concentration of carbon dioxide has risen at a rate 100 times faster than any change observed during the past 650,000 years (Siegenthaler et al. 2005). There is broad consensus that this ongoing change is a direct result of human activity, principally by fossil fuel burning, cement production and changing land use (Hansen et al. 2007). Atmospheric levels of carbon dioxide have consequently increased from pre-industrial levels of 280 ppm to a concentration of approximately 380 ppm (Feely et al. 2004). Almost 50% of all anthropogenic carbon dioxide emitted to the atmosphere has diffused passively into the ocean, thereby significantly decreasing the rate of global warming (Sabine et al. 2004). Concentrations of atmospheric carbon dioxide are rising at a rate of 3.3% per year and will continue this rising trend (Canadell et al. 2007). Hydrological models predict that, based on proposed future emissions of carbon dioxide, the average oceanic pH will decline by 0.3–0.5 by the year 2100 and by 0.7 within the next 300 years (Caldeira and Wickett 2003). Leakage from carbon dioxide seabed storage would create locally faster and stronger acidification than that induced by atmospheric carbon dioxide (Hawkins 2004). Estuaries, being the arms of oceans and seas are also exposed to the process of acidification.

On the basis of the global trend of acidification, we have tried to focus on the issue at the local level in the Hooghly and Matla estuaries situated in the western and central Indian Sundarbans respectively in the lower Gangetic delta region.

We conducted a study in these two estuaries of Indian Sundarbans during 1984 to 2014 using aquatic pH as proxy in three stations of Indian Sundarbans namely Diamond Harbour and Namkhana in western Indian Sundarbans along the Hooghly estuary and Ajmalmari in the central Indian Sundarbans along the Matla estuary.

The pH ranged from 8.10 (during 2014 low tidal phase) to 8.33 (during 1984 high tide condition) at Diamond Harbour (Fig. 2.5a, b).

The pH ranged from 8.18 (during 2014 low tide phase) to 8.34 (during 1984 high tide condition) (Fig. 2.6a, b).

The pH ranged from 8.20 (during 2014 low tide phase) to 8.33 (during 1984 high tide condition (Fig. 2.7a, b).

The surface water pH is an important environmental parameter on which the life of any aquatic organism depends. It shows more or less a uniform value throughout the seasons with minor fluctuations mainly in the monsoon months, when, dilution

Table 2.5 Average monthly rainfall data (in mm) collected for Canning region, 24 Parganas, South (West Bengal)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	–	–	–	–	–	–	–	–	–	–	0	0.38
1982	0	1.69	1.65	2.77	0.85	5.69	8.49	10.4	4.23	0.36	0.87	0
1983	0.14	1.67	1.2	1.08	2.51	11.22	6.42	17.79	9.96	3.61	0.25	0.18
1984	0.57	0.03	0	2.29	3.19	23.81	7.26	15.55	6.69	3.28	0	0
1985	0.88	0.21	0.2	1.12	5.11	9.25	9.25	12.2	7.69	3.86	0	0
1986	0.33	0	0.05	1.04	6.2	6.34	10.66	3.35	27.91	8.55	7.54	0.05
1987	0	0.7	0.6	5.8	4.21	4.73	11.55	13.41	9.58	0.81	2	0.32
1988	0	0.92	0.12	0.71	5.49	20.29	17.4	9.28	6.38	4.89	4.66	0
1989	0.07	0.25	0.32	0	5.15	2.83	9.1	10.35	11.34	6.63	0.39	0.08
1990	0	2.48	6.35	3.27	4.79	10.18	16.6	10.77	10.4	5.72	2.41	0.06
1991	2	0.64	0.55	1.13	0.49	16.21	8.64	8.07	8.02	4.56	0.02	0.57
1992	0.92	1.73	0	0.59	6.1	13.31	12.13	13.51	16.1	3.8	0	0
1993	0.03	0	2.75	0.77	4.61	10.34	11.34	11.55	17.73	3.97	0.43	0
1994	0.11	0.84	0.25	3.82	2.35	8.21	14.93	9.12	6.46	2.52	1.92	0
1995	0.23	1.36	0.08	0.61	7.39	11.37	17.6	10	17.84	3.08	6.68	0
1996	0.29	0.3	0.07	0.89	2.56	18.97	11.88	16.72	5.09	9.94	0	0
1997	0.57	0.49	1.36	6.64	3.41	7.12	12.98	15.78	9.36	0.16	0.49	0.48
1998	0.98	0.14	5.97	2.13	5.86	4.94	12.07	12.09	10.41	5.31	5.84	0
1999	0.08	0	0.01	0.05	6.72	8.94	16.47	13.38	14.91	5.96	0.07	0
2000	0.05	1.96	0	2.29	10.79	7.79	15.21	6.34	11.69	4.22	0.06	0.06
2001	0.09	0.01	0.8	3.43	6.8	14.54	10.63	6.87	5.84	5.14	0.62	0
2002	0.85	0	0.53	2.66	4.01	19.81	8.78	10.05	8.31	3.97	4.62	0
2003	0	0.51	0.9	2.26	4.36	10.65	11.9	11.49	9.37	17.09	0.67	1.29
2004	0.15	0.25	0.13	2.26	2.42	8.96	13.35	14.93	7.75	8.77	0	0
2005	1.47	0	4.25	1.24	2.27	8.3	17.89	9.17	11.73	16.74	0	0.03
2006	0	0	0.11	2.06	3.9	4.08	21.16	14.55	17.35	1.045	0.03	0
2007	–	2.8	0.07	1.74	5.63	5.32	20.25	8.97	21.39	3.9	2.13	0
2008	3.46	0.34	0.15	1.4	2.26	12.22	7.16	8.96	9.62	6	–	–
2009	0	0	0.53	0.03	6.52	1.79	13.19	11.47	10.05	4.93	0.34	0
2010	0	0.13	0	0.72	4.25	8.44	8.53	7.56	7.24	4.51	0.12	0.36
2011	0	0.24	1.2	7.31	3.34	14.09	8.98	22.56	7.86	3.1	–	0
2012	1.57	1.01	0.17	3.15	1.52	6.08	10.2	14.78	8.35	4.28	1.86	1.15
2013	0.12	0.18	0.15	0.63	6.36	8.25	8.65	22.08	14.84	9.3	0	0
2014	0	2.33	1.77	0	–	5.78	7.35	–	11.37	1.7	0	0
2015	0.14	0.19	1.83	0.74	4.24	8.21	6.80	13.14	20.14	2.85	0	0

(continued)

Table 2.5 (continued)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2016	0	0.07	1.09	0	5.10	4.98	5.93	9.68	12.65	3.10	0.12	0
2017	0	0.14	0	0	1.26	11.02	7.80	12.65	9.89	4.02	0	0.14
2018	0.10	1.02	1.21	0.35	3.58	13.65	11.66	14.20	8.42	5.17	0	1.02

Source IMD (Indian Meteorological Department; '–' means data not available; Jan—January; Feb—February; Mar—March; Apr—April; May—May; Jun—June; Jul—July; Aug—August; Sep—September; Oct—October; Nov—November; Dec—December

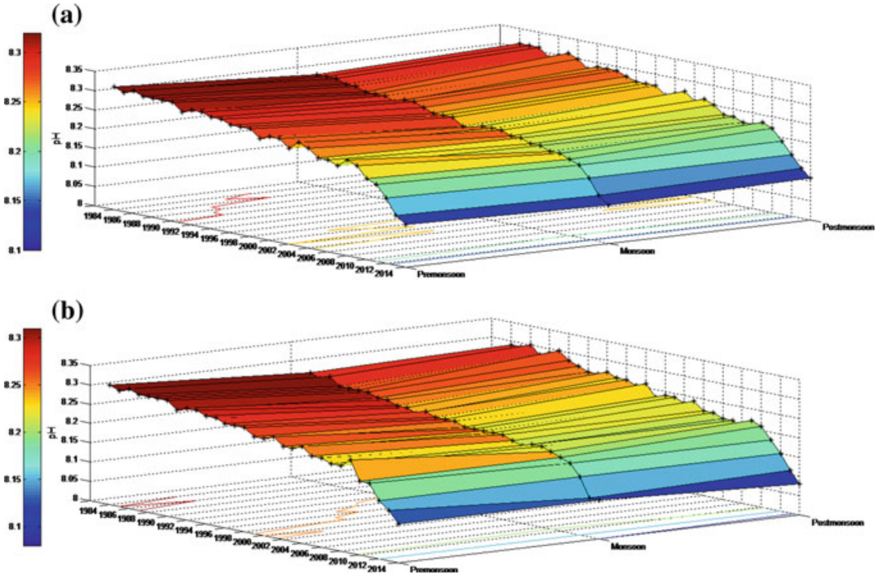

Fig. 2.5 **a** Surface water pH at Diamond Harbour during high tide condition for three decades (1984–2014). **b** Surface water pH at Diamond Harbour during low tide condition for three decades (1984–2014)

by run-off, precipitation and water discharge suppress the surface water pH. Looking on the time series data of 31 years (1984–2014), the trend of acidification becomes quiet pronounced. In all the selected stations, an almost uniform decrease in surface water pH was observed. At Diamond Harbour, the pH value has decreased at the rate of 0.081 unit/decade in premonsoon, 0.074 unit/decade in monsoon and 0.077 unit/decade in postmonsoon (Fig. 2.5a, b). At Namkhana, the rate of decrease is 0.024 unit/decade in premonsoon and monsoon and 0.019 unit/decade in postmonsoon (Fig. 2.6a, b). The decrease of surface water pH at Ajmalmari is 0.012 unit/decade in premonsoon, 0.023 unit/decade in monsoon and 0.019 unit/decade in postmonsoon (Fig. 2.5a, b). This decrease is quite close to the observations recorded in several oceans and estuaries. For further research work in this vertical, we present here the backup data of Figs. 2.5, 2.6 and 2.7 as Table 2.6.

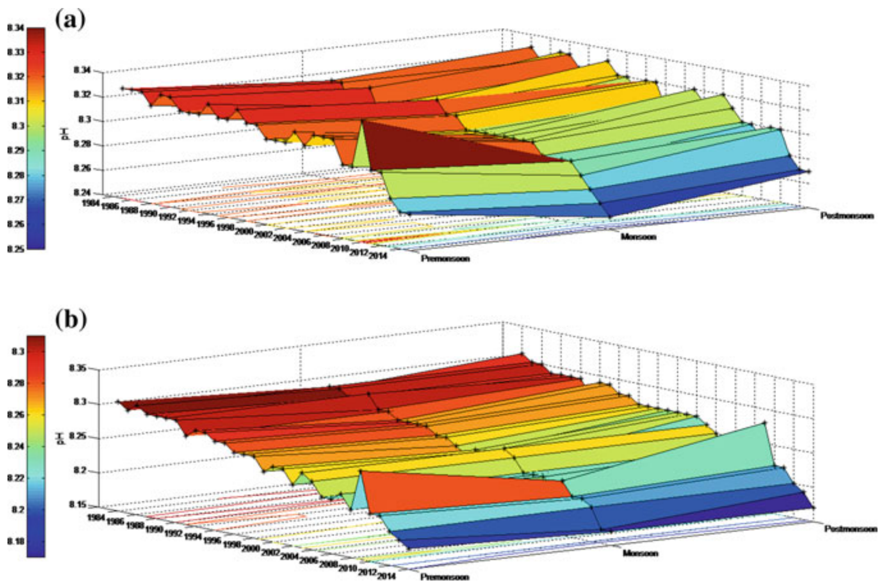

Fig. 2.6 **a** Surface water pH at Namkhana during high tide condition for three decades (1984–2014). **b** Surface water pH at Namkhana during low tide condition for three decades (1984–2014)

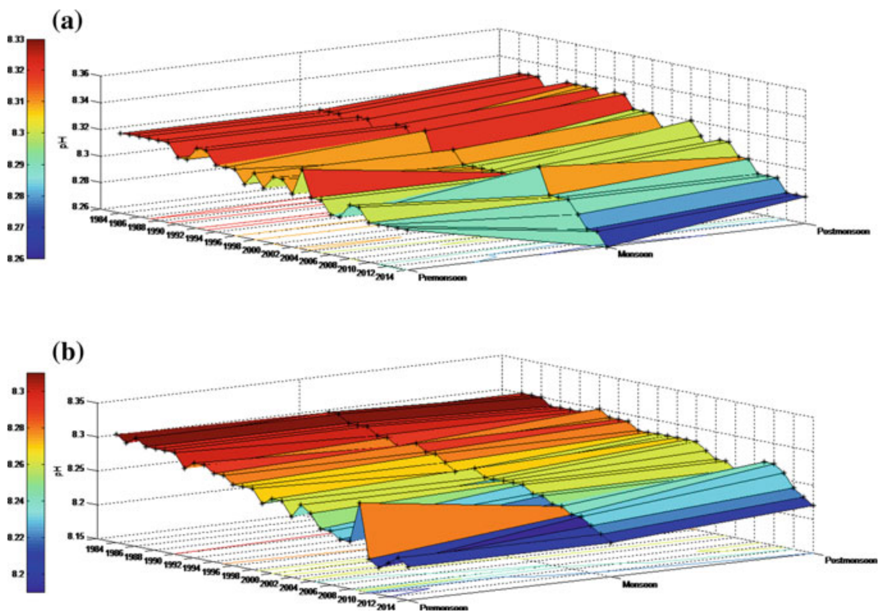

Fig. 2.7 **a** Surface water pH at Ajmalmari during high tide condition for three decades (1984–2014). **b** Surface water pH at Ajmalmari during low tide condition for three decades (1984–2014)

Table 2.6 Mean value of surface water pH at three sampling stations in Indian Sundarbans. Diamond Harbour and Namkhana are in western Indian Sundarbans along the Hooghly estuary and Ajmalmari is in the central Indian Sundarbans along the Matla estuary; Diamond Harbour is adjacent to western Indian Sundarbans

Year	Ajmalmari		Namkhana		Diamond harbour	
	High tide	Low tide	High tide	Low tide	High tide	Low tide
1984	8.33	8.31	8.34	8.31	8.33	8.31
1985	8.32	8.30	8.33	8.30	8.31	8.30
1986	8.32	8.31	8.33	8.31	8.32	8.31
1987	8.32	8.30	8.32	8.30	8.31	8.30
1988	8.32	8.30	8.33	8.30	8.31	8.30
1989	8.32	8.30	8.33	8.30	8.31	8.30
1990	8.31	8.30	8.32	8.30	8.31	8.30
1991	8.31	8.28	8.32	8.28	8.29	8.28
1992	8.32	8.29	8.32	8.29	8.30	8.29
1993	8.32	8.29	8.33	8.29	8.30	8.29
1994	8.31	8.28	8.32	8.28	8.29	8.28
1995	8.31	8.28	8.32	8.28	8.29	8.28
1996	8.31	8.27	8.33	8.27	8.28	8.27
1997	8.30	8.27	8.32	8.27	8.28	8.27
1998	8.31	8.27	8.32	8.27	8.28	8.27
1999	8.30	8.25	8.31	8.25	8.26	8.25
2000	8.31	8.26	8.31	8.26	8.27	8.25
2001	8.31	8.26	8.31	8.26	8.27	8.26
2002	8.30	8.24	8.32	8.24	8.25	8.24
2003	8.32	8.26	8.31	8.26	8.27	8.24
2004	8.30	8.25	8.32	8.25	8.26	8.25
2005	8.30	8.23	8.32	8.23	8.24	8.23
2006	8.29	8.23	8.32	8.23	8.24	8.23
2007	8.29	8.22	8.30	8.22	8.23	8.22
2008	8.30	8.22	8.30	8.22	8.25	8.22
2009	8.30	8.28	8.34	8.28	8.24	8.24
2010	8.29	8.20	8.30	8.20	8.21	8.19
2011	8.29	8.19	8.30	8.19	8.20	8.19
2012	8.29	8.20	8.28	8.20	8.17	8.15
2013	8.29	8.21	8.27	8.19	8.13	8.13
2014	8.29	8.20	8.27	8.18	8.11	8.10

We also made a seasonal survey for more than three decades at Sagar Island and Bali Island to confirm our previous data in spatio-temporal scale in a different anthropological scenario. (Tables 2.7 and 2.8). Sagar Island, in western Indian Sundarbans is noted for pilgrims (Figs. 2.8 and 2.9), tourism and fish landing activities, where as Bali Island in central Indian Sundarbans is adjacent to Reserve forest with minimum anthropogenic activities, except occasional tourism.

The Kapil Muni temple in Sagar South of western Indian Sundarban attracts about 10 lakhs devotees every year during Makar Sankranti (in mid-January) for taking holy bath in the estuarine water (Mitra and Zaman 2020), which also plays a major role in alteration of aquatic characteristics and can be considered as 'noise' in the domain of acidification of Sundarban estuaries. Apart from such sporadic anthropogenic impact, the western sector is also exposed to continuous discharge of wastes from industries, fish landing stations and busy markets that mix wastes of complex characters and alter the pH of the aquatic phase.

The seasonal behavior and decreasing trend of surface water pH are depicted in Figs. 2.10 and 2.11.

This decreasing trend is in alignment with the global trend. It has been documented that surface ocean pH has fallen by about 0.11 pH units from pre-industrial times till date. As pH is a measure of H^+ concentration and the pH scale is logarithmic, therefore for a decrease of 1 pH unit, the H^+ concentration increases by a factor of 10. Thus the decrease of 0.11 pH units is equivalent to about 29% increase in ocean H^+ concentration. It has been forecasted that if the burning of fossil fuels follows the present trend resulting in the rise of atmospheric CO_2, then the pH is likely to drop by 0.3–0.4 units by the end of the twenty-first century and increase ocean H^+ concentration by 100–150% above what it was in the pre-industrial times (http://www.us-ocb.org).

A small drop in pH value has great implication in the domain of biotic community. A very simple example may illustrate the fact. In human being, the arterial blood flow normally lies within the pH range of 7.35–7.45. A drop of 0.2–0.3 pH units can result in several health hazards like seizures, heart arrhythmia or coma. Similar modification has high probability to affect the marine organisms. Fundamental physiological processes of marine biota like photosynthesis, respiration, reproduction, calcification etc. are influenced by alternation of pH and carbonate ion concentration of the ambient aquatic phase.

The formation of calcareous skeletons or shells in the marine and estuarine molluscan species is an internal process where most organisms appear to convert HCO_3^- to $CO_3^=$ to form calcium carbonate. However, this conversion creates protons (H^+) and hence the organisms must exert energy to transport the H^+ into the external environment (ambient water). One hypothesis is that as the pH of the ambient aquatic phase decreases, there is building of protons in the external environment due to which the organisms have to exert more energy to get rid of the protons resulting into lowering of calcification rate.

The process of ocean acidification happens through a stepwise manner as stated below:

Table 2.7 Seasonal variation of surface water pH in Sagar Island (88° 04′ 0.51″E and 21° 37′ 49.90″N), a station in the western sector of Indian Sundarbans

Year	Premonsoon	Monsoon	Postmonsoon
1984	8.33 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1985	8.33 ± 0.03	8.32 ± 0.03	8.33 ± 0.03
1986	8.33 ± 0.03	8.32 ± 0.03	8.32 ± 0.03
1987	8.32 ± 0.03	8.3 ± 0.03	8.32 ± 0.03
1988	8.33 ± 0.03	8.31 ± 0.03	8.33 ± 0.03
1989	8.32 ± 0.03	8.32 ± 0.03	8.33 ± 0.03
1990	8.32 ± 0.03	8.3 ± 0.03	8.32 ± 0.03
1991	8.32 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1992	8.32 ± 0.03	8.3 ± 0.03	8.32 ± 0.03
1993	8.33 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1994	8.32 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1995	8.32 ± 0.03	8.3 ± 0.03	8.32 ± 0.03
1996	8.33 ± 0.03	8.32 ± 0.03	8.31 ± 0.03
1997	8.32 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1998	8.32 ± 0.03	8.31 ± 0.03	8.32 ± 0.03
1999	8.31 ± 0.03	8.3 ± 0.03	8.3 ± 0.03
2000	8.31 ± 0.03	8.3 ± 0.03	8.31 ± 0.03
2001	8.31 ± 0.03	8.3 ± 0.03	8.31 ± 0.03
2002	8.32 ± 0.03	8.3 ± 0.03	8.30 ± 0.03
2003	8.31 ± 0.03	8.3 ± 0.03	8.31 ± 0.03
2004	8.31 ± 0.03	8.29 ± 0.03	8.3 ± 0.03
2005	8.32 ± 0.03	8.3 ± 0.03	8.32 ± 0.03
2006	8.31 ± 0.03	8.3 ± 0.03	8.31 ± 0.03
2007	8.3 ± 0.03	8.29 ± 0.03	8.3 ± 0.03
2008	8.3 ± 0.03	8.28 ± 0.02	8.3 ± 0.03
2009	8.34 ± 0.04	8.29 ± 0.03	8.29 ± 0.03
2010	8.3 ± 0.03	8.29 ± 0.03	8.3 ± 0.03
2011	8.3 ± 0.03	8.28 ± 0.02	8.3 ± 0.03
2012	8.28 ± 0.02	8.27 ± 0.02	8.28 ± 0.02
2013	8.27 ± 0.02	8.26 ± 0.02	8.27 ± 0.02
2014	8.27 ± 0.02	8.25 ± 0.02	8.27 ± 0.02
2015	8.28 ± 0.02	8.25 ± 0.02	8.26 ± 0.02
2016	8.27 ± 0.02	8.23 ± 0.02	8.26 ± 0.02
2017	8.25 ± 0.03	8.21 ± 0.03	8.24 ± 0.01
2018	8.23 ± 0.02	8.17 ± 0.04	8.21 ± 0.02
Mean	8.30 ± 0.03	8.28 ± 0.02	8.30 ± 0.02
Decrease	0.003/yr	0.004/yr	0.003/yr

Table 2.8 Seasonal variation of surface water pH in Bali Island (88° 39′ 46″E and 22° 15′ 45.00″N), a station in the central sector of Indian Sundarbans

Year	Premonsoon	Monsoon	Postmosoon
1984	8.34 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1985	8.34 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1986	8.34 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1987	8.33 ± 0.04	8.31 ± 0.04	8.32 ± 0.04
1988	8.32 ± 0.04	8.32 ± 0.04	8.32 ± 0.04
1989	8.32 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1990	8.33 ± 0.04	8.31 ± 0.04	8.33 ± 0.04
1991	8.33 ± 0.04	8.31 ± 0.04	8.33 ± 0.04
1992	8.33 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1993	8.33 ± 0.04	8.32 ± 0.04	8.32 ± 0.04
1994	8.33 ± 0.04	8.31 ± 0.04	8.33 ± 0.04
1995	8.31 ± 0.04	8.32 ± 0.04	8.33 ± 0.04
1996	8.31 ± 0.04	8.3 ± 0.03	8.32 ± 0.04
1997	8.3 ± 0.03	8.3 ± 0.03	8.32 ± 0.04
1998	8.31 ± 0.04	8.31 ± 0.04	8.32 ± 0.04
1999	8.3 ± 0.03	8.3 ± 0.03	8.31 ± 0.04
2000	8.31 ± 0.04	8.3 ± 0.03	8.31 ± 0.04
2001	8.31 ± 0.04	8.3 ± 0.03	8.31 ± 0.04
2002	8.32 ± 0.04	8.3 ± 0.03	8.32 ± 0.04
2003	8.32 ± 0.04	8.3 ± 0.03	8.31 ± 0.04
2004	8.3 ± 0.03	8.3 ± 0.03	8.3 ± 0.03
2005	8.3 ± 0.03	8.3 ± 0.03	8.3 ± 0.03
2006	8.29 ± 0.03	8.3 ± 0.03	8.29 ± 0.03
2007	8.29 ± 0.03	8.31 ± 0.04	8.3 ± 0.03
2008	8.3 ± 0.03	8.29 ± 0.03	8.3 ± 0.03
2009	8.34 ± 0.04	8.3 ± 0.03	8.3 ± 0.03
2010	8.31 ± 0.04	8.29 ± 0.05	8.29 ± 0.03
2011	8.31 ± 0.04	8.28 ± 0.03	8.29 ± 0.03
2012	8.31 ± 0.04	8.27 ± 0.03	8.28 ± 0.03
2013	8.29 ± 0.04	8.27 ± 0.03	8.28 ± 0.03
2014	8.29 ± 0.04	8.26 ± 0.03	8.28 ± 0.03
2015	8.28 ± 0.03	8.25 ± 0.03	8.27 ± 0.03
2016	8.27 ± 0.03	8.24 ± 0.03	8.25 ± 0.02
2017	8.26 ± 0.04	8.21 ± 0.02	8.25 ± 0.02
2018	8.26 ± 0.03	8.19 ± 0.02	8.22 ± 0.01
Mean	8.31 ± 0.04	8.29 ± 0.03	8.30 ± 0.03
Decrease	0.002/yr	0.004/yr	0.003/yr

Fig. 2.8 Kapil Muni Ashram at Sagar Island

Step 1: In the first step, the atmospheric CO_2 dissolves in seawater to form aqueous CO_2 along with H_2CO_3

$$CO_2 + H_2O \leftrightarrow H_2CO_3$$

Step 2: In this step H_2CO_3 dissociates to produce HCO_3^- and protons (H^+)

$$H_2CO_3 \leftrightarrow HCO_3^- + H^+$$

Step 3: In this step HCO_3^- has the tendency to dissociate into $CO_3^=$ and protons (H^+), which results in the lowering of pH

$$HCO_3^- \leftrightarrow CO_3^= + H^+$$

It is to be noted in this context that the total dissolved inorganic carbon (DIC) in seawater is the sum total of aqueous CO_2, HCO_3^- and $CO_3^=$. Thus,

$$DIC = CO_2(aq) + HCO_3^- + CO_3^=$$

The distribution of DIC between the species varies with seawater pH. Typically surface water of today's ocean have a pH around 8.1, which means that HCO_3^- is the

Fig. 2.9 Inside view of Kapil Muni Ashram at Sagar Island. About 10–15 lakhs people visit this place every year at Makar Sankranti (during mid January)

dominant species representing about 90% of DIC whereas, CO_2 (aq) represents about <1% of the DIC. DIC in the marine and estuarine system shifts with season. The three major seasons in the tropical estuaries are premonsoon (with lowest discharge), monsoon (with highest discharge) and postmonsoon (with moderate discharge). It has been documented that freshwater input in the coastal and estuarine ecosystem lowers the pH value. This hypothesis is confirmed after the observation of Trenton, Schuylkill and Christina rivers in the Delaware Bay (Table 2.9).

In the deltaic complex of Sundarbans similar results were seen when the data of Tables 2.7 and 2.8 were analyzed. In both Sagar Island (along the Hooghly estuary) and Bali Island (along the Matla estuary) the pH level decreased maximum in monsoon (0.004/yr), when the dilution factor is maximum in the Sundarban estuary. These two major estuaries have significantly different physico-chemical characteristics. The Hugli estuary in the western sector of Indian Sundarbans receives freshwater from the Farakka discharge. The Matla estuary in the central sector of the Indian Sundarbans practically receives no freshwater due to blockage of the Bidyadhari River by excessive siltation since the late fifteenth century (Chaudhuri and Chaudhury 1994; Mitra 2013).

The hyposaline environment of western Indian Sundarbans is primarily the result of Farakka barrage discharge situated in the upstream region of Ganga-Bhagirathi-Hooghly river system. 10-year surveys (1999–2008) on water discharge from Farakka

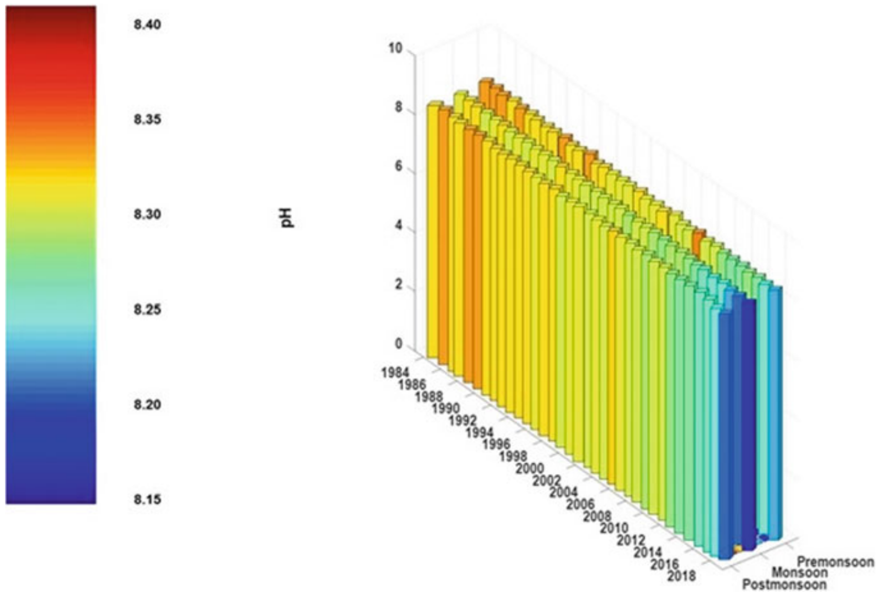

Fig. 2.10 Seasonal variation of surface water pH in Sagar Island (88° 04′ 0.51″E and 21° 37′ 49.90″N), a station in the western sector of Indian Sundarbans

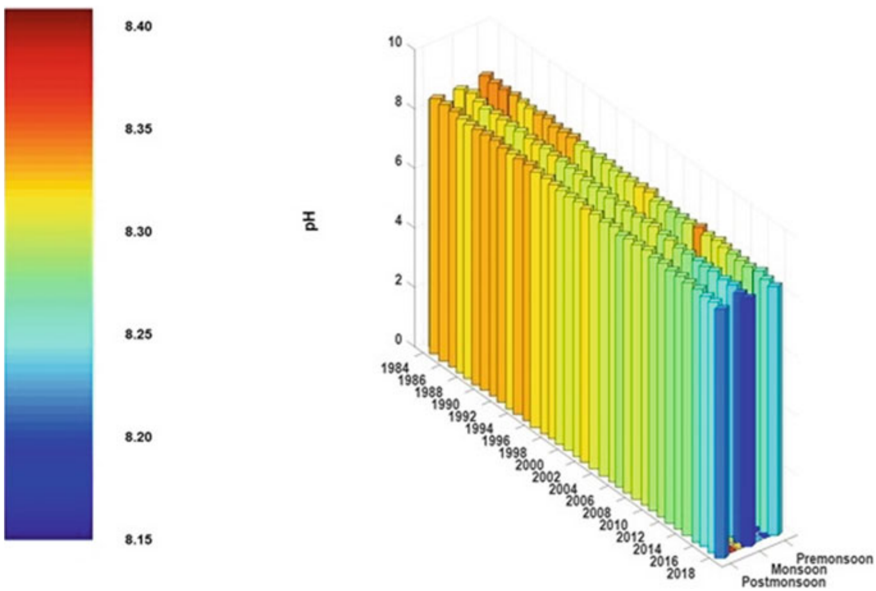

Fig. 2.11 Seasonal variation of surface water pH in Bali Island (88° 39′ 46″E and 22° 15′ 45.00″N), a station in the central sector of Indian Sundarbans

Table 2.9 Seasonal variability of physico-chemical parameters in three river estuaries in the Delaware Bay

Location	Month	Discharge (m^3s^{-1})	pH (at 25 °C)	DIC (μmolkg^{-1})
Trenton	March	182	8.8	973.4
	April	442	7.8	745.2
	May	190	8.8	856.5
	June	199	8.2	857.8
	July	1127	7.2	783.5
	September	183	8.2	454.2
	October	170	8.1	1095.2
Schuylkill	March	52	8.9	1421.2
	April	32	8.1	1682.9
	May	105	7.9	1400.1
	June	271	7.7	1095.3
	July	60	7.8	1506.1
	September	19	8.1	2071.3
	October	34	8.3	1869.3
Christina	March	14	7.7	1056.5
	April	15	7.5	1076.4
	May	11	7.7	1134.1
	June	32	7.5	1089.4
	July	6	7.9	1326.9
	September	7	8.0	1188.6
	October	7	8.0	1199.6

dam revealed an average discharge of $(3.7 \pm 1.15) \times 10^3$ m^3s^{-1}. Higher discharge values were observed during the monsoon with an average of $(3.81 \pm 1.23) \times 10^3$ m^3s^{-1}, and the maximum of the order 4524 m^3s^{-1} during freshet (September). Considerably lower discharge values were recorded during premonsoon with an average of $(1.18 \pm 0.08) \times 10^3$ m^3s^{-1}, and the minimum of the order 846 m^3s^{-1} during May. During postmonsoon discharge, values were moderate with an average of $(1.98 \pm 0.97) \times 10^3$ m^3s^{-1} (Mitra 2013).

The central sector represents a hypersaline environment due to complete obstruction of the fresh water flow from the upstream region owing to Bidyadhari siltation since the late fifteenth century (Chaudhuri and Choudhury 1994; Banerjee et al. 2013; Mitra 2013; Sengupta et al. 2013). The Matla estuary in the central Indian Sundarban cannot be referred to as an ideal estuary as there is no head on discharge or dilution of the system with fresh water. Thus Matla can be designated as a tidal channel, whose survival depends on the tidal flow from Bay of Bengal.

The salinity profiles of these two estuaries stand as proxy to freshwater discharge. The average salinity of the stations along the Hooghly estuarine stretch in western

Indian Sundarbans is less compared to the stations in central Indian Sundarbans along the Matla estuary. We have recorded the surface water salinity of ten stations, five along each of the two estuaries (Table 2.10 and Fig. 2.12).

It is observed from the data sets of aquatic salinity that during 2016, 2017 and 2018 the average salinity in western Indian Sundarbans are 20.67 psu, 18.6 psu and 17.18 psu respectively. In case of central Indian Sundarbans the average salinity during 2016, 2017 and 2018 are 21.66 psu, 22.98 psu and 24.37 psu respectively (Table 2.11). It is to be noted in this context that in western Indian Sundarbans the salinity has decreased with the passage of time, but the order is reverse in case of central Indian Sundarbans where the salinity showed an increase with time.

The comparatively higher inflow of freshwater in the western sector than central sector has decreased the pH also, which implies that apart from climate induced acidification freshwater also regulates the pH in an estuarine system, which is not the case in high seas and oceans. The regulatory role of freshwater in pH oscillation can be confirmed while critically analyzing the lowering of pH in eastern Indian Sundarbans, which is in the Reserve Forest zone with minimum anthropogenic influence. The region is hyposaline as it receives the fresh water due to inter-connection with several creeks and channels of Harinbhanga estuary (the aquatic border of India and Bangladesh Sundarbans) with the tributaries of Bangladesh Sundarbans that arise from Padma Meghna river system. Also the quantum of coastal and estuarine vegetation as mostly concentrated in the Reserve Forest area of eastern Indian Sundarbans do play a great role in altering the pH level of the aquatic phase.

The direct influence of anthropogenic activities on the pace of acidification is confirmed through an interesting study conducted by the present authors in three stations in the lower Gangetic delta region during the pre-COVID-19 lockdown (18th–22nd March, 2020) and COVID-19 lockdown phases (26th March–30th April, 2020) as discussed in details in Annexure 2. The results of this study are the outcomes of an acid test on the confirmatory role of anthropogenic activities in the process of acidification.

2.4 Take Home Messages

A. Estuaries are the live matrix of Indian Sundarban deltaic complex, on which the unique spectrum of biological diversity is embedded. In Indian Sundarbans, approximately 2069 sq. km area is occupied by tidal river system or estuaries, which finally end up in the Bay of Bengal. The seven main estuaries, from west to east are Hooghly, Muriganga, Saptamulki, Thakuran, Matla, Goashaba and Haribhanga. The estuaries of Indian Sundarbans exhibit distinct variation in salinity in the same time period.

B. The deltaic lobe of Indian Sundarbans experiences a moderate type of climate because of its location adjacent to the Bay of Bengal as well as due to regular tidal flushing in the estuaries. Wave actions, micro and macro tidal cycles, long shore currents are recorded in most of the islands of the ecosystem. Coastal

Table 2.10 Sampling stations in western (stations 1–5) and central Indian (6–10) Sundarbans with salient features

Study site	Longitude and latitude	Site description
Harinbari (Stn. 1)	88° 04′ 22.88″E 21° 46′ 53.07″N	Situated in the western region of Indian Sundarbans almost in the middle of the Sagar Island; receives the water of the Hooghly River
Chemaguri (Stn. 2)	88° 08′ 49.01″E 21° 39′ 42.88″N	Situated on the south-eastern side of Sagar Island and receives the water of the Mooriganga River
Sagar South (Stn. 3)	88° 04′ 0.51″E 21° 37′ 49.90″N	Situated on the south-western part of the Sagar Island at the confluence of the River Hooghly and the Bay of Bengal. Anthropogenically stressed zone due to presence of passenger jetties, fishing activities and pilgrimage
Lothian Island (Stn. 4)	88° 19′ 8.47″E 21° 39′ 08.04″N	Situated east of Bakkhali island; a Wildlife Sanctuary; faces the River Saptamukhi
Prentice Island (Stn. 5)	88° 17′ 3.62″E 21° 42′ 43.31″N	Situated north of Lothian island; receives the water of the Saptamukhi River
Canning (Stn. 6)	88° 41′ 04.43″E 22° 19′ 03.20″N	Situated in the central part of the Indian Sundarbans and faces the mighty River Matla, a tide-fed river. Due to presence of fish landing stations, passenger jetties and busy market, the area is anthropogenically stressed
Sajnekhali (Stn. 7)	88° 48′ 15.78″E 22° 06′ 34.19″N	A Wildlife Sanctuary and a part of Sundarban Tiger Reserve; adjacent to River Bidhya and Gomor. Tourism pressure is extremely high in this station particularly during postmonsoon
Chotomollakhali (Stn. 8)	88° 54′ 26.71″E 22° 10′ 40.00″N	Situated in the upper portion of Central Indian Sundarban adjacent to Jhila forest; receives the water of Rangabelia and Korankhali Rivers
Satjelia (Stn. 9)	88° 52′ 49.51″E 22° 05′ 17.86″N	Situated adjacent to River Duttar in the upper region of Central Indian Sundarban facing western part of the Jhilla forest
Pakhiralaya (Stn. 10)	88° 48′ 29.00″E 22° 07′ 07.23″N	Situated adjacent to River Gomor; opposite to Sajnekhali Wild Life Sanctuary

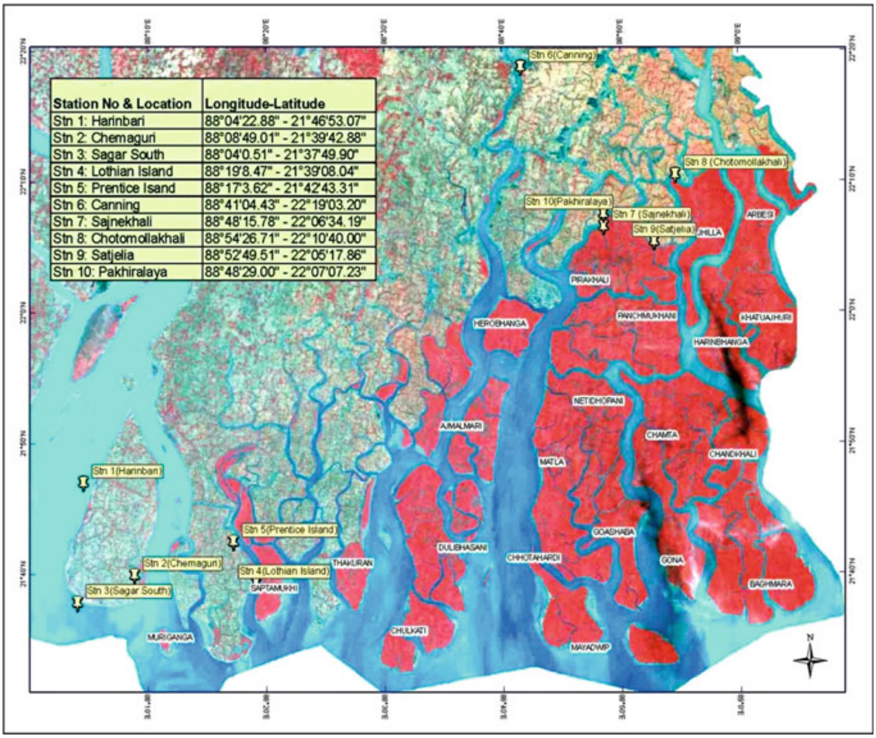

Fig. 2.12 Selected stations in Indian Sundarbans

processes are very dynamic and are accelerated by tropical cyclones, which is locally called “Kal Baisakhi” (Norwesters). Average annual maximum atmospheric temperature is around 35 °C. The seasons in study area may be conveniently categorized into premonsoon (March–June), monsoon (July–October) and postmonsoon (November–February). Each season has a characteristic feature of its own, which is very distinct and unique.

C. The surface water pH is an important environmental parameter on which the life of any aquatic organism depends. It shows more or less a uniform value throughout the seasons with minor fluctuations mainly in the monsoon months, when, dilution by run-off, precipitation and water discharge suppress the surface water pH. Looking on the time series data of 31 years (1984–2014), the trend of acidification becomes quiet pronounced in Indian Sundarban estuaries. In all the selected stations, an almost uniform decrease in surface water pH was observed.

D. The comparatively higher inflow of freshwater in the western sector than central sector of Indian Sundarbans has decreased the pH, which implies that apart from climate induced acidification freshwater also regulates the pH in an estuarine system, which is not the case in high seas and oceans. In the deltaic

Table 2.11 Water salinity (in psu) in the selected stations of western and central Indian Sundarbans

S. no.	Name	2016	2017	2018	Average	Sector
	Harinbari (Stn. 1)	8.34	6.49	5.24	6.69	Western sector average water salinity = 18.84 psu
	Chemaguri (Stn. 2)	18.75	15.38	14.94	16.36	
	Sagar South (Stn. 3)	24.69	22.88	20.91	22.83	
	Lothian island (Stn. 4)	25.74	24.68	22.42	24.28	
	Prentice island (Stn. 5)	25.81	23.99	22.39	24.06	
Average salinity		20.67	18.68	17.18		
	Canning (Stn. 6)	9.54	11.63	12.51	11.23	Central sector average water salinity = 23.05 psu
	Sajnekhali (Stn. 7)	24.90	26.31	28.42	26.54	
	Chotomollakhali (Stn. 8)	23.11	25.79	26.03	24.98	
	Satjelia (Stn. 9)	25.95	26.10	28.75	26.93	
	Pakhiralaya (Stn. 10)	24.79	25.08	26.13	25.57	
Average salinity		21.66	22.98	24.37		

complex of Sundarbans similar results were seen when the data of stations along two major estuaries, Hooghly and Matla were analyzed. In both Sagar Island (along the Hooghly estuary) and Bali Island (along the Matla estuary) the pH level decreased maximum in monsoon (0.004/yr), when the dilution factor is maximum in the Sundarban estuary.

E. A small drop in pH value has great implication in the domain of biotic community. Fundamental physiological processes of marine biota like photosynthesis, respiration, reproduction, calcification etc. are influenced by alternation of pH and carbonate ion concentration of the ambient aquatic phase. The formation of calcareous skeletons or shells in the marine and estuarine molluscan species is an internal process where most organisms appear to convert HCO_3^- to $CO_3^=$ to form calcium carbonate. However, this conversion creates protons (H^+) and hence the organisms must exert energy to transport the H^+ into the external environment (ambient water). One hypothesis is that as the pH of the ambient aquatic phase decreases, there is building of protons in the external environment due to which the organisms have to exert more energy to get rid of the protons resulting into lowering of calcification rate.

Annexure 2: How the COVID Lockdown Phase Impacted the Pace of Acidification?

Introduction

The mighty River Ganges flowing through the city of Kolkata serves as the life line of the people of the megacity. The River provides several ecosystem services like production of fishes, mode of transportation, recreational activities, sports, performance of religious rituals etc. (Mitra 2019). However, the river is still treated as the bin of all the wastes arising from domestic and industrial activities. In addition to this, wastes from automobile repairing units, emission of Green House Gases (GHGs) from industrial units and air-condition machines have made the city atmosphere highly polluted. Increased emission of CO_2 from anthropogenic sources (Mitra et al. 2020) has enhanced the entry of atmospheric CO_2 to the river water resulting in the formation of carbonic acid, thereby shifting the pH to a lower value. This is commonly referred as acidification and has been reported in several estuaries in the state of West Bengal (Mitra 2013; Mitra and Zaman 2014; Mitra and Zaman 2016; Mitra 2019). In this study, we have carried out a comparative analysis on surface water pH of the River Ganges between the pre-COVID-19 (18th March–22nd March, 2020) and COVID-19 lockdown phase (25th March–30th April, 2020). The COVID-19 pandemic provided an unique opportunity to venture in to such comparative picture as there is no movements of vessels, boats and trawlers in the river and also all the industrial operations have been ceased during the lockdown phase of the state—a condition of retrieving the natural parameters with the withdrawal of anthropogenic influences. This paper, therefore, can be treated as a comparative account of natural versus human induced factors using River Ganges as the test bed.

Materials and Methods

Study Site

Kolkata, Capital city of the maritime state of West Bengal, is the third largest city in India and situated in the east bank of the Hooghly River with an area of 187.33 km^2. Three sites along the bank of the River Ganges were selected for the present study namely Ramkrishna Ghat (22° 34′ 19.8″N; 88° 20′ 17.0″E), Botanical Garden (22° 33′ 06.4″N; 88° 18′ 06.6″E) and Babughat (22° 34′ 10.3″N; 88° 20′ 28.5″E).

Measurement of Aquatic pH

pH of the surface water in the selected sampling station was measured during high tide condition with a portable pH meter (sensitivity $= \pm 0.02$). The measurement was carried out during pre-COVID-19 lockdown (18th–22nd March, 2020) and COVID-19 lockdown phases (26th March–30th April, 2020).

Statistical Analysis

ANOVA was carried out to know whether significant variation of aquatic pH exists between sites and time phase (pre-COVID-19 and COVID-19 lockdown phases).

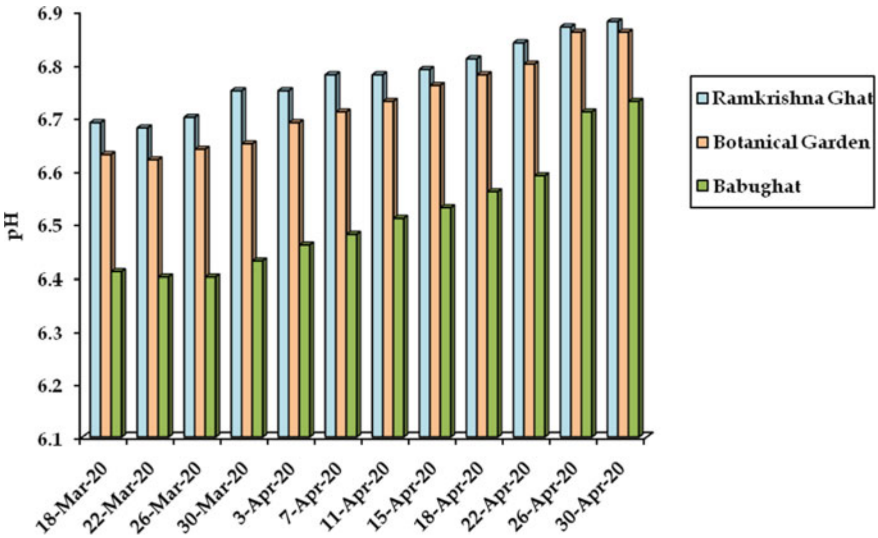

Fig. 2.13 Spatio-temporal variation of pH duirng the study period

Results

The spatio-temporal variations of aquatic pH in the three study sites are highlighted in Fig. 2.13. In the lockdown phase due to COVID-19, the pH value increases in three selective sites (Fig. 2.14).

Results of ANOVA show significant variations between stations and between pre-COVID-19 and COVID-19 lockdown phases ($p < 0.01$) (Table 2.12).

Discussion

The increase of atmospheric carbon dioxide in West Bengal, a maritime state in northeast coast of India has touched almost 51% since 1980 (Mitra 2019). The gradual increase of carbon dioxide coupled with unplanned expansion of shrimp culture in places like Sundarbans (adjacent to the city), unplanned urban development and industrial activities has lowered the aquatic pH considerably (Mitra and Zaman 2016). It is interesting to note that in all the sampling stations selected in the present study, the pH has increased by 2.84%, 3.46% and 4.99% at Ramkrishna Ghat, Botanical garden and Babughat respectively. This may be due to complete closure of all industrial operations along the bank of the River Ganges. Also the movements of vessels, floatels (a boat or ship that serves as a hotel, sometimes permanently moored to a dock) and other recreational activities have also been ceased to abide by the rules of mass gathering and social distancing during the COVID—19 lock down phase. The CO_2 level of the atmosphere also showed a considerable dip in the value (Mitra et al. 2020). All these have posed a joint impact on pH level of the aquatic phase (synergistic effect) due to which a sudden turn in the trend of acidification has taken place.

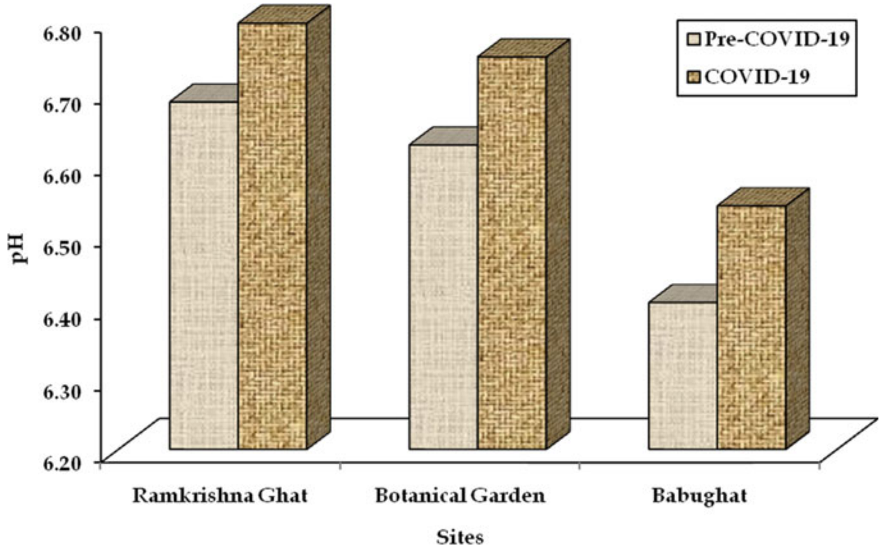

Fig. 2.14 pH variation in the three selected sampling sites between pre-COVID-19 and COVID-19 lockdown period

Table 2.12 ANOVA of the pH value between sites and between pre-COVID-19 and COVID-19 period

Source of variation	SS	df	MS	F	P-value	F crit
Between Pre-COVID-19 and COVID-19	0.022571	1	0.022571	288.7505	0.003445	18.51282
Between Sites	0.080143	2	0.040071	512.6418	0.001947	19
Error	0.000156	2	7.82E-05			
Total	0.10287	5				

The phenomenon of acidification due to climate change is never supportive and congenial for the aquatic organisms preferably for the survival of molluscs and other aquatic organisms with calcareous shell. Thus COVID-19 lockdown phase served as a boon to these faunal communities by providing a reverse swing in the process of acidification.

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Chapter 3
Impact of Acidification on Fishes

Abstract Fish protein is one of the primary sources that provide food security to the rapidly rising population of the planet Earth. It has been documented that several fish species exhibit a change in their sensory behavior during their stay in water bodies with low pH. The spawning pattern of fish is also affected if the pH level changes. A significant variation in finfish juvenile diversity and population size is observed in few experimental sites in the mangrove dominated Indian Sundarbans over a period of more than three decades (1984–2018), which is directly related to gradual lowering of pH as depicted through a time series analysis of aquatic pH in and around the deltaic complex. The chapter also presents an interesting change in the spawning zone of Indian shad (*Tenualosa ilisha*) which has shifted towards the downstream direction of the Hooghly estuary with the passage of time.

3.1 Taxonomic Diversity of Fish in Indian Sundarbans

Biodiversity refers to all life on the planet Earth and ranges from the microbes in the human gut to blue whale of the ocean. So far 1.7 millions species have been indentified and recorded on the Earth, but the total number is thought to be somewhat between 5 to 100 million. Biodiversity encompasses three important tiers or segments of biosphere, namely, habitat diversity, species diversity and genetic diversity. The major portion of the coastal zone of Bay of Bengal in the maritime state of West Bengal (India) is covered with luxuriant mangrove vegetation and the brackish-cum-saline aquatic phase of this environment nourishes the world's most famous mangrove chunk- the Sundarbans. In fact, mangroves forest, mangrove swamps and backwater of Sundarbans form a productive and protective margin of coastal West Bengal which is also the breeding ground and nursery of a wide spectrum of fish. We will be discussing in this section about the finfish variety of the estuarine waters of Indian Sundarbans.

Several researches have been carried out on the taxonomic diversity of fish species in the lower Gangetic delta. Pillay (1967) estimated the species number to be more than 120. Jhingran (1982) documented a total of 172 species and stated that the diversity is comparatively more in the high saline zone of the mangrove dominated

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Indian Sundarbans. His estimate reveals 73 species of fresh water origin and 99 species of marine/higher salinity origin. Mandal and Nandi (1989) documented 141 species under 100 genera, while Chaudhuri and Choudhury (1994) recorded 250 species under 96 genera in the aquatic sub-system of Indian Sundarbans. Khan (2003) recorded 107 species from Sundarban Biosphere Reserve region, but this figure does not include the species restricted in the low saline upper zone of the Hooghly-Matla estuarine complex. The fish fauna of the estuarine waters around Sundarbans has been classified into residents and transients (migrants). The species which are present in all stages of their life cycle in all the seasons of the year in any zone of the estuary are referred to as resident species. Examples of resident species are *Mugil parsia, Mugil tade, Polynemus paradiseus, Polydactylus indicus, Otolithoides biauritus, Lates calcarifer, Hilsa toli, Arius jella, Harpodon nehereus, Setipinna taty, Ilisha elongata, Setipinna phasa, Coilia ramcarati, Pama pama* and *Sillaginopsis panijus*. The transient or migratory fishes enter and stay in the inshore region of Bay of Bengal and associated estuaries for a short period of time. Depending on their migratory pattern and direction, the migrants may be divided into three categories (Jhingran 1982).

(1) Marine forms that migrate downstream to upstream and spawn in freshwater areas of the estuary (where there is about zero salinity) like *Tenualosa ilisha, Polynemus paradiseus, Sillaginopsis panijus and Pama pama* is one of the transient varieties (2) Freshwater species, which spawn in saline area of the estuary like *Pangasius pangasius* (3) Marine species, that spawns in less saline water of the estuary (salinity range 5.0–10.0 psu) like *Arius jella*, *Osteogeneious militaris* and *Polydactylus indicus*.

An updated checklist of fishes available in the mangrove creeks, estuaries and bays is highlighted here.

A CHECKLIST OF SUNDARBAN FISH (BOTH CHONDRICHTHYES AND OSTEICHTHYES) IN BRACKISH WATER AND FRESH WATER PONDS.

1. **ORDER: CARCHARHINIFORMES (GROUND SHARKS)**

Family: *Carcharhinidae* (Requiem sharks)
White cheek shark *Carcharhinus dussumieri*
Bull shark *Carcharhinus leucas*
Black tip shark *Carcharhinus limbatus*
Black tip reef shark *Carcharhinus melanopterus*
Tiger shark *Galeocerdo cuvier*
Ganges shark *Glyphis gangeticus*
Milk shark *Rhizoprionodon acutus*
Indian dog shark or Spadenose shark *Scoliodon laticaudus* Whale shark *Rhincodon typus*
Grey bamboo shark *Chiloscyllium griseum*
Slender bambooshark *Chiloscyllium indicum*
Family: *Sphyrnidae* (Hammerhead, bonnethead or scoophead sharks)
Winghead shark, *Eusphyra blochii*

Scalloped hammerhead *Sphyrna lewini*
Great hammerhead *Sphyrna mokarran.*

2. **ORDER: PRISTIFORMES (SAWFISHES)**

Family: *Pristidae*
Knifetooth sawfish *Anoxypristis cuspidata*
Largetooth sawfish *Pristis microdon*
Smalltooth sawfish *Pristis pectinata.*

3. **ORDER: RAJIFORMES (SKATES AND RAYS)**

Family: *Dasyatidae* (Stingrays)
Small-eye stingray *Dasyatis microps*
Pale-edged stingray *Dasyatis zugei*
Bleeker's whipray *Himantura bleekeri*
Ganges stingray *Himantura fluviatilis*
Scaly whipray *Himantura imbricata*
Pointed-nose stingray *Himantura jenkinsii*
Blackedge whipray *Himantura marginatus*
Honeycomb stingray *Himantura uarnak*
Family: *Myliobatidae* (Eagle and manta rays)
Spotted eagle ray *Aetobatus narinari*
Banded eagle ray *Aetomylaeus nichofii*
Family: *Rhinobatidae* (Guitarfishes)
Annandale's guitarfish *Rhinobatos annandalei*
Smoothback guitarfish *Rhinobatos lionotus*
Giant guitarfish *Rhynchobatus djiddensis.*

4. **ORDER: TORPEDINIFORMES (ELECTRIC RAYS)**

Family: *Narcinidae* (Numbfishes)
Brown numbfish *Narcine brunnea.*

5. **ORDER: OSTEOGLOSSIFORMES (BONY TONGUES)**

Family: *Notopteridae* (Featherbacks or knifefishes)
Clown knifefish *Chitala chitala*
Bronze featherback *Notopterus notopterus.*

6. **ORDER: ELOPIFORMES (TARPONS AND TENPOUNDERS)**

Family: *Elopidae* (Tenpounders and ladyfishes)
Tenpounder *Elops machnata*
Family: *Megalopidae* (Tarpons)
Indo-Pacific tarpon *Megalops cyprinoides.*

7. **ORDER: ALBULIFORMES (BONE FISHES) Family: *Albulidae* (Bone-fishes)** Roundjaw bonefish *Albula glossodonta*
8. **ORDER: ANGUILLIFORMES (EELS AND MORAYS)**

Family: *Anguillidae* (Freshwater eels)
Indian mottled eel *Anguilla bengalensis*
Indonesian shortfin eel *Anguilla bicolor*
Mottled eel *Anguilla nebulosa*
Family: *Moringuidae* (Worm and spaghetti eels)
Moringua macrocephalus
Purple spaghetti eel *Moringua raitaborua*
Family: *Muraenidae* (Moray eels)
Freshwater moray *Gymnothorax tile*
Family: *Ophichthidae* (Snake eels and worm eels)
Finny snake eel *Caecula pterygera*
Rice paddy eel *Pisodonophis boro*
Greenspot snake eel *Pisodonophis hijala*
Maimed snake eel *Muraenichthys schultzei*
Family: *Muraenesocidae* (Pike conger eels)
Yellow pike conger *Congresox talabon*
Indian pike conger *Congresox talabonoides*
Common pike conger *Muraenesox bagio*
Daggertooth pike conger *Muraenesox cinereus.*

9. **ORDER: CLUPEIFORMES (HERRINGS)**

Family: *Clupeidae* (Herrings, shads, sardines and menhadens)
Chacunda gizzard shad *Anodontostoma chacunda*
Thai gizzard shad *Anodontostoma thailandiae*
Ganges river sprat *Corica soborna*
White sardine *Escualosa thoracata*
Ganges river gizzard shad *Gonialosa manmina*
Indian river shad *Gudusia chapra*
Kelee shad *Hilsa kelee*
Bloch's gizzard shad *Nematalosa nasus*
Tardoore *Opisthopterus tardoore*
Raconda *Raconda russeliana*
Indian oil sardine *Sardinella longiceps*
Hilsa shad, River shad *Tenualosa ilisha*
Toli shad *Tenualosa toli*
Family: *Pristigasteridae*
Elongate ilisha *Ilisha elongata*
Coromandel ilisha *Ilisha filigera*
Kampen's ilisha *Ilisha kampeni*
Bigeye ilisha *Ilisha megaloptera*
Indian ilisha *Ilisha melastoma*
Indian pellona *Pellona ditchela*
Family: *Engraulidae* (Anchovies)
Goldspotted grenadier anchovy *Coilia dussumieri*
Ramcarat grenadier anchovy *Coilia ramcarati*

Reynald's grenadier anchovy *Coilia reynaldi*
Shorthead hairfin anchovy *Setipinna breviceps*
Dusky hairfin anchovy *Setipinna melanochir*
Gangetic hairfin anchovy *Setipinna phasa*
Scaly hairfin anchovy *Setipinna taty*
Indian anchovy *Stolephorus indicus*
Dussumier's thryssa *Thryssa dussumieri*
Hamilton's thryssa *Thryssa hamiltonii*
Malabar thryssa *Thryssa malabarica*
Moustached thryssa *Thryssa mystax*
Oblique jaw thryssa *Thryssa purava*
Bengal thryssa *Thryssa spinidens*
Slender thryssa *Thryssa stenosoma*
Orangemouth anchovy *Thryssa vitrirostris*
Family: *Chirocentridae* (Wolf herrings)
Dorab wolf herring *Chirocentrus dorab*
Whitefin wolf herring *Chirocentrus nudus.*

10. **ORDER: GONORHYNCHIFORMES (MILK FISH)**

Family: *Chanidae*
Milkfish White mullet *Chanos chanos.*

11. **ORDER: CYPRINIFORMES (CARPS)**

Family: *Cyprinidae* (Minnows, carps, barbs)
Mola carplet *Amblypharyngodon mola*
Mrigal *Cirrhinus cirrhosus*
Sind danio *Devario devario*
Silver razorbelly minnow *Salmostoma acinaces (Chela argentea)*
Large razorbelly minnow *Salmostoma bacaila*
Finescale razorbelly minnow *Salmostoma phulo*
Bengala barb *Bengala elanga*
Zebra danio *Danio rerio*
Flying rasbora (barb) *Esomus danricus*
Slender rasbora *Rasbora daniconius*
Silver hatchet danio *Chela cachius*
Indian glass barb *Chela laubuca*
Catla *Catla catla*
Reba *Labeo ariza*
Bata *Labeo bata*
Kalbosu (Orange-fin labeo) *Labeo calbasu*
Rohu *Labeo rohita*
Swamp barb *Puntius chola*
Rosy barb *Puntius conchonius*
Golden barb *Puntius gelius*
Olive barb *Puntius sarana*

Pool barb *Puntius sophore*
Onespot barb *Puntius terio*
Ticto barb *Puntius ticto.*

12. **ORDER: SILURIFORMES (CAT FISH)**

Family: *Bagridae* (Bagrid cat fishes)
Menoda cat fish *Hemibagrus menoda*
Day's mystus *Mystus bleekeri*
Gangetic mystus *Mystus cavasius*
Long whiskers cat fish *Mystus gulio*
Striped dwarf cat fish *Mystus vittatus*
Rita *Rita rita*
Long whiskered cat fish *Sperata aor*
Giant river cat fish *Sperata seenghala*
Family: *Siluridae* (Sheat fishes)
Butter cat fish *Ompok bimaculatus*
Pabdah cat fish *Ompok pabda*
Wallago *Wallago attu*
Family: *Schilbeidae* (Schilbeid cat fishes)
Gangetic ailia *Ailia coila*
Garua cat fish *Clupisoma garua*
Sharpnose cat fish *Eutropiichthys vacha*
Indian potasi *Pseudeutropius atherinoides*
Silond cat fish *Silonia silondia*
Family: *Pangasiidae* (Shark cat fishes)
Yellowtail cat fish, River pangus *Pangasius pangasius*
Family: *Sisoridae* (Sisorid cat fishes)
Dwarf goonch *Bagarius bagarius*
Goonch *Bagarius yarrelli*
Indian gagata *Gagata cenia*
Gagata gagata
Glyptothorax botius
Glyptothorax telchitta
Gogangra viridescens
Kosi nangra *Nangra nangra*
Sisor cat fish *Sisor rabdophorus*
Family: *Clariidae* (Airbreathing cat fishes)
Walking cat fish *Clarias batrachus*
Family: *Chacidae* (Squarehead cat fishes)
Squarehead cat fish *Chaca chaca*
Family: *Ariidae* (Sea cat fishes)
T hreadfin sea cat fish *Arius arius*
Engraved cat fish *Arius caelatus*
Blacktip sea cat fish *Arius dussumieri*
Gagora cat fish *Arius gagora*

Blackfin sea cat fish *Arius jella*
Spotted cat fish *Arius maculatus*
Smooth headed cat fish *Arius nenga*
Flat mouth cat fish *Arius platystomus*
Sagor cat fish *Arius sagor*
Sona sea cat fish *Arius sona*
Shovelnose sea cat fish *Arius subrostratus*
Beardless sea cat fish *Batrachocephalus mino*
River cat fish *Hemipimelodus jatius*
Soldier cat fish *Osteogeneiosus militaris*
Family: *Heteropneustidae* (Airsac cat fishes)
Stinging cat fish *Heteropneustes fossilis*
Family: *Plotosidae* (Eeltail cat fishes)
Gray eel cat fish *Plotosus canius*
Striped eel cat fish *Plotosus lineatus.*

13. **ORDER: AULOPIFORMES (GRINNERS)**

Family: *Synodontidae* (Lizard fishes, Bombay duck)
Greater lizard fish *Saurida tumbil*
Brushtooth lizard fish *Saurida undosquamis*
Bombay duck *Harpadon nehereus.*

14. **ORDER: BATRACHOIDIFORMES (TOAD FISHES)**

Family: *Batrachoididae*
Grunting toad fish *Allenbatrachus grunniens.*

15. **ORDER: GADIFORMES (CODS)**

Family: *Bregmacerotidae* (Codlets)
Spotted codlet Bregmaceros mcclellandi.

16. **ORDER: CYPRINODONTIFORMES (RIVULINES, KILLI FISHES AND LIVE BEARERS)**

Family: *Aplocheilidae* (Killi fishes)
Blue panchax *Aplocheilus panchax.*

17. **ORDER: BELONIFORMES (NEEDLE FISHES)**

Family: *Belonidae*
Banded needle fish *Strongylura leiura*
Spottail needle fish *Strongylura strongylura*
Freshwater gar fish *Xenentodon cancila*
Family: *Hemiramphidae*
Gangetic half beak *Dermogenys brachynotopterus*
Wrestling half beak *Dermogenys pusilla*
Jumping half beak *Hemiramphus archipelagicus*
Congaturi half beak *Hyporhamphus limbatus*

Long billed half beak *Rhynchorhamphus georgii*
Ectuntio half beak *Zenarchopterus ectuntio*
Family: *Adrianichthyidae* (Ricefishes)
Rice fish *Oryzias carnaticus.*

18. **ORDER: SYNGNATHIFORMES (PIPEFISHES AND SEAHORSES)**

Family: *Syngnathidae*
Freshwater pipefish *Ichthyocampus carce*
Crocodile tooth pipefish *Microphis cuncalus*
Deocata pipefish *Microphis deocata.*

19. **ORDER: SYNBRANCHIFORMES (SWAMP AND SPINY EELS)**

Family: *Synbranchidae* (Swamp eels)
Cuchia, Gangetic mud eel *Monopterus cuchia*
Bengal eel *Ophisternon bengalense*
Family: *Mastacembelidae* (Spiny eels)
Lesser spiny eel *Macrognathus aculeatus*
One-stripe spinyeel *Macrognathus aral*
Barred spiny eel *Macrognathus pancalus*
Zig-zag eel, Tire-track spiny eel *Mastacembelus armatus.*

20. **ORDER: SCORPAENIFORMES (SCORPION FISHES & FLAT HEADS)**

Family: *Platycephalidae* (Flatheads)
Bartail flathead *Platycephalus indicus.*

21. **ORDER: PERCIFORMES (PERCH-LIKE)**

Family: *Latidae* (Perches)
Barramundi, Giant seaperch *Lates calcarifer*
Waigieu seaperch *Psammoperca waigiensis*
Family: *Ambassidae* (Glass fishes)
Bald glassy Ambassis *gymnocephalus*
Elongate glass-perchlet *Chanda nama*
Highfin glassy perchlet *Parambassis lala*
Indian glassy fish *Parambassis ranga*
Family: *Serranidae* (Sea basses: groupers and fairy basslets)
Orange spotted grouper *Epinephelus coioides*
Giant grouper *Epinephelus lanceolatus*
Family: *Terapontidae* (Grunters and tigerperches)
Fourlined terapon *Pelates quadrilineatus*
Jarbua terapon *Terapon jarbua*
Small-scaled terapon *Terapon puta*
Largescaled therapon *Terapon theraps*
Family: ***Sillaginidae*** {**Sillagos (Smelt-whitings)**} Flathead sillago *Sillaginopsis panijus*

Clubfoot sillago *Sillago chondropus*
Silver sillago, *Sillago sihama*
Soringa sillago *Sillago soringa*
Family: *Carangidae* (Jacks and pompanos)
Indian threadfish *Alectis indicus*
Razorbelly scad *Alepes kleinii*
Longnose trevally *Carangoides chrysophrys*
Malabar trevally *Carangoides malabaricus*
Bigeye trevally *Caranx sexfasciatus*
Japanese scad *Decapterus maruadsi*
Golden trevally *Gnathanodon speciosus*
Torpedo scad *Megalaspis cordyla*
Black pomfret, Brown pomfret *Parastromateus niger*
Barred queen fish *Scomberoides tala*
Bigeye scad *Selar crumenophthalmus*
Yellowstripe scad *Selaroides leptolepis*
Family: *Menidae* (Moonfishes, bat fishes)
Moonfish *Mene maculata*
Family: *Leiognathidae* (Pony fishes)
Goldstripe pony fish *Leiognathus daura*
Common pony fish *Leiognathus equulus*
Striped pony fish *Leiognathus fasciatus*
Splendid pony fish *Leiognathus splendens*
Pugnose pony fish *Secutor insidiator*
Deep pugnose pony fish *Secutor ruconius*
Family: *Lutjanidae* (Snappers)
Mangrove red snapper *Lutjanus argentimaculatus* Humpback red snapper *Lutjanus gibbus*
John's snapper *Lutjanus johnii*
Malabar blood snapper *Lutjanus malabaricus*
Russell's snapper *Lutjanus russellii*
Family: *Datnioididae*
Fourstripe perch *Datnioides polota*
Family: *Lobotidae* (Tripletails)
Atlantic tripletail *Lobotes surinamensis*
Family: *Gerreidae* (Mojarras)
Whipfin silver-biddy *Gerres filamentosus*
Saddleback silver-biddy *Gerres limbatus*
Slender silver-biddy *Gerres oblongus*
Common silver-biddy *Gerres oyena*
Strong spine silver-biddy *Gerres phaiya*
Small Bengal silver-biddy *Gerres setifer*
Family: *Haemulidae* (Grunts)
Bluecheek silver grunt *Pomadasys argyreus*
Silver bream *Pomadasys hasta*

Family: *Sparidae* (Porgies and sea breams)
Yellowfin seabream *Acanthopagrus latus*
King soldierbream *Argyrops spinifer*
Goldlined seabream *Rhabdosargus sarba*
Family: *Nemipteridae* (Threadfin breams and spinycheeks)
Japanese threadfin bream *Nemipterus japonicus*
Family: *Sciaenidae* (Croakers and drums)
Chaptis bahaba *Bahaba chaptis*
Reeve's croaker *Chrysochir aureus*
Bengal corvina *Daysciaena albida*
Goatee croaker *Dendrophysa russelii*
Belanger's croaker *Johnius belangerii*
Karut croaker *Johnius carutta*
Coitor croaker *Johnius coitor*
Cuja croaker *Macrospinosa cuja*
Soldier croaker *Nibea soldado*
Bronze croaker *Otolithoides biauritus*
Pama croaker *Otolithoides pama*
Hooghly croaker *Panna heterolepis*
Pennahia ovata
Blackspotted croaker *Protonibea diacanthus* Blotched tiger-tooth croaker *Pterotolithus maculatus*
Family: *Polynemidae* (Threadfins)
Fourfinger threadfin *Eleutheronema tetradactylum*
Indian threadfin *Leptomelanosoma indicum*
Striped threadfin *Polydactylus plebeius*
Sixfinger threadfin *Polydactylus sexfilis*
Paradise threadfin *Polynemus paradiseus*
Family: *Mullidae* (Goat fishes)
Sulphur goatfish *Upeneus sulphureus*
Family: *Toxotidae* (Archerfishes)
Largescale archerfish *Toxotes chatareus*
Family: *Drepaneidae* (Sicklefishes)
Concertina fish *Drepane longimana*
Spotted sicklefish *Drepane punctata*
Family: *Monodactylidae* (Moonyfishes or fingerfishes)
Silver moony *Monodactylus argenteus*
Family: *Nandidae* (Asian leaf fishes)
Gangetic leaf fish *Nandus nandus*
Family: *Badidae*
Badis *Badis badis*
Family: *Kurtidae* (Nurseryfishes)
Indian hump head *Kurtus indicus*
Family: *Mugilidae* (Mullets)
Largescale mullet *Liza macrolepis*

Gold-spot mullet *Liza parsia*
Greenback mullet *Liza subviridis*
Tade mullet *Liza tade*
Flathead mullet *Mugil cephalus*
Corsula *Rhinomugil corsula*
Cascasia mullet, Yellowtail mullet *Sicamugil cascasia*
Bluetail mullet *Valamugil buchanani*
Bluespot mullet *Valamugil seheli*
Speigler's mullet *Valamugil speigleri*
Family: *Cichlidae* (Cichlids)
Green chromide *Etroplus suratensis*
Family: *Uranoscopidae* (Stargazers)
Uranoscopus guttatus
Family: *Callionymidae* (Dragonets)
River dragonet *Callionymus fluviatilis*
Arrow dragonet *Callionymus sagitta*
Family: *Eleotridae* (Sleepers)
Duckbill sleeper *Butis butis*
Gangetic sleeper *Odonteleotris macrodon*
Dusky sleeper *Eleotris fusca*
Lutea sleeper *Eleotris lutea*
Family: *Gobiidae* (Gobies)
Tropical sand goby *Acentrogobius caninus,*
Acentrogobius cyanomos
Spotted green goby *Acentrogobius viridipunctatus*
Dragon goby *Apocryptes bato*
Scribbled goby *Awaous grammepomus*
Largesnout goby *Awaous melanocephalus*
Bathygobius ostreicola
Bumblebee goby *Brachygobius nunus*
Boddart's goggle-eyed goby *Boleophthalmus boddarti* Mudskipper *Boleophthalmus dussumieri*
Tank goby *Glossogobius giuris*
Glass goby *Gobiopterus chuno*
Rubicundus eelgoby *Odontamblyopus rubicundus*
Maned goby *Oxyurichthys microlepis*
Taileyed goby *Parachaeturichthys polynema*
Giant mudskipper *Periophthalmodon schlosseri*
Periophthalmodon septemradiatus
Atlantic mudskipper *Periophthalmus barbarus*
Pearse's mudskipper *Periophthalmus novemradiatus*
Elongate goby *Pseudapocryptes elongatus*
Many-finned eelgoby *Pseudotrypauchen multiradiatus*
Walking goby *Scartelaos histophorus*
Knight goby *Stigmatogobius sadanundio*

Eel worm goby *Taenioides anguillaris*
Burmese gobyeel *Taenioides buchanani*
Bearded worm goby *Taenioides cirratus*
Burrowing goby *Trypauchen vagina*
Family: *Scatophagidae* (Scats)
Spotted scat *Scatophagus argus*
Family: *Siganidae* (Rabbit fishes)
Streaked spinefoot *Siganus javus*
Family: *Sphyraenidae* (Barracudas)
Great barracuda *Sphyraena barracuda*
Family: *Trichiuridae* (Cutlass fishes and scabbard fishes)
Longtooth hairtail *Eupleurogrammus glossodon*
Smallhead hairtail *Eupleuroarammus muticus*
Coromandel hairtail *Lepturacanthus pantului*
Savalani hairtail *Lepturacanthus savala*
Gangetic hairtail *Trichiurus gangeticus*
Largehead hairtail *Trichiurus lepturus*
Family: *Scombridae* (Mackerels, tunas and bonitos)
Kawakawa *Euthynnus affinis*
Indian mackerel *Rastrelliger kanagurta*
Narrow-barred Spanish mackerel *Scomberomorus commerson* Indo-Pacific king mackerel *Scomberomorus guttatus*
Family: *Stromateidae* (Butterfishes)
Silver pomfret *Pampus argenteus*
Chinese silver pomfret *Pampus chinensis*
Pampus cinereus
Family: *Anabantidae* (Climbing gouramies)
Climbing perch *Anabas testudineus*
Family: *Osphronemidae* (Gouramies)
Banded gourami *Colisa fasciata*
Spiketail paradise fish *Pseudosphromenus cupanus* Dwarf gourami *Colisa lalia*
Frail gourami *Ctenops nobilis*
Honey gourami *Trichogaster chuna*
Family: *Channidae* (Snakeheads)
Barca snakehead
Channa barca
Channa gachua
Great snakehead *Channa marulius*
Walking snakehead *Channa orientalis*
Spotted snakehead *Channa punctata*
Snakehead murrel *Channa striata.*

22. **ORDER: PLEURONECTIFORMES (FLATFISHES)**

Family: *Psettodidae* (Psettodids)

Indian spiny turbot *Psettodes erumei*
Family: *Paralichthyidae* (Largetooth flounders)
Largetooth flounder *Pseudorhombus arsius*
Deep flounder *Pseudorhombus elevatus*
Malayan flounder *Pseudorhombus malayanus*
Three spotted flounder *Pseudorhombus triocellatus*
Family: *Citharidae* (Chitarids)
Yellow-dabbled flounder *Brachypleura novaezeelandiae*
Family: *Soleidae* (Soles)
Oriental sole *Brachirus orientalis*
Pan sole *Brachirus pan*
Eyed sole *Heteromycteris oculus*
Kaup's sole *Synaptura albomaculata*
Highfin sole *Zebrias altipinnis*
Family: *Cynoglossidae* (Tongue fishes)
Largescale tongue-sole *Cynoglossus arel*
Bengal tongue-sole *Cynoglossus cynoglossus*
Long tongue-sole *Cynoglossus lingua*
Malabar tongue-sole *Cynoglossus macrostomus*
Speckled tongue-sole *Cynoglossus puncticeps*
Bengal tongue-sole *Cynoglossus semifasciatus*
Doublelined tongue-sole *Paraplagusia bilineata.*

23. **ORDER: TETRADONTIFORMES (PUFFERS AND FILEFISHES)**

Family: *Triacanthidae* (Triplespines) Short-nosed tripodfish *Triacanthus biaculeatus*
Family: *Tetraodontidae* (Puffers)
Immaculate puffer *Arothron immaculatus*
Milkspotted puffer *Chelonodon patoca*
Green rough-backed puffer *Lagocephalus lunaris*
Lattice blaasop *Takifugu oblongus*
Ocellated pufferfish *Tetraodon cutcutia*
Green pufferfish *Tetraodon fluviatiles.*

3.2 Threats to Indian Sundarban Fishery in the Backdrop of Climate Change

Climate change is a bitter truth associated with the planet Earth in the present century and has both direct and indirect impacts on the fishery sector.

In this chapter we present the evidences of direct impact of climate change induced alteration of salinity and temperature on the fish community. Alteration of aquatic salinity and temperature have considerable impact on (i) spawning and larval recruitment, (ii) metabolic activity and growth and (ii) microbial load in fish tissues leading to several types of diseases.

3.2.1 Alteration of Spawning and Larval Recruitment

The metabolic activities, physiology, reproductive success, spawning and larval recruitment of fish are considerably governed by ambient environmental parameters like water temperature, salinity, pH etc. We have documented a study in the coastal zone of West Bengal at three different sites with contrasting salinity on the fish juvenile number.

West Bengal is a maritime state in the northeast part of the Indian sub-continent adjacent to Bangladesh. The coastal zone of this state spreads over an area of 10,158.22 sq. km. and is restricted within the latitude 21° 30′N to 22° 30′N and longitude 87° 25′E to 89° 10′E. The river Harinbhanga or Heronbhanga of the Indian Sundarbans (India- Bangladesh border) is the eastern border while the New Digha coast of Orissa-West Bengal border constitutes the western boundary of coastal West Bengal. With considerable degree of marine characteristics in the major portion of the ecosystem, the important morphotypes of coastal West Bengal are sand flats, coastal dunes, beaches, mudflats, estuaries, creeks, inlets and mangrove flats. There is a drastic variation of salinity and dilution factor between different horizontal transects of the ecosystem. The dilution factor, salinity and pH reveal significant variations at the same time in different locations of the coastal zone. The recent emergence of Haldia industrial complex and various fish landing stations in the coastal zone has also opened the gateway of input of various categories of wastes in this ecosystem.

Geographically, the study area encompasses three major districts of the state of West Bengal namely, 24 Parganas (North), 24 Parganas (South) and Medinipur (East). The Indian Sundarbans declared as the World Heritage Site by UNESCO in the year of 1989 fall within the North and South 24 Parganas districts. Three sampling stations were selected in and around this deltaic ecosystem namely, Diamond Harbour (station 1), Sagar light house (station 2) and Junput (station 3). Each of these sampling stations is markedly different from the other with respect to aquatic salinity due to their location and proximity to the Bay of Bengal.

Diamond Harbour (station 1) is situated in the low saline upper stretch of Hooghly estuary, just outside the northern boundary of Indian Sundarbans. The station is very near to the Haldia port-cum-industrial complex. Salinity of surface water is less around the station owing to its location in the extreme upstream region, far away from the Bay of Bengal and also due to huge fresh water discharge from the Hooghly River, which is perennial in nature.

Sagar light house (station 2) is situated in the south western tip of the Sagar Island and falls in the western sector of Indian Sundarbans. The station has rich mangrove vegetation and extensive mudflats. Although there are no industrial activities in this station, but the presence of sizeable number of shrimp farms (presently carrying

Table 3.1 Mean seasonal variation in standing stock/fish juvenile count (N) of finfish species in three selected sampling stations during Jan' 2009 to Dec' 2018

Year	Monthly average standing stock (N) of finfish species								
	Stn 1			Stn 2			Stn 3		
	Prm	Mon	Pom	Prm	Mon	Pom	Prm	Mon	Pom
2009	394	161	245	1598	134	522	1593	260	767
2010	322	133	291	1315	122	422	1303	213	625
2011	202	82	183	1273	99	416	1290	213	631
2012	197	79	175	1279	99	413	1229	201	596
2013	217	89	197	1090	84	361	1055	172	651
2014	219	89	198	716	56	233	679	123	333
2015	226	93	204	639	51	209	601	103	291
2016	223	92	201	545	42	180	521	89	255
2017	227	93	204	910	178	442	934	153	440
2018	392	38	67	936	73	304	1020	81	367

on shrimp culture by traditional method with a very low stocking density of prawn seeds) has enriched the surrounding water with nutrients and organic load.

Junput (Station 3) is situated in the Medinipur (East) district of coastal West Bengal, which is noted for its high aquatic salinity owing to its proximity to Bay of Bengal. The extremely high salinity has posed an inhibitory effect on the growth and survival of mangroves in this station. Although the station has no industry around its vicinity, but the presence of Digha tourist center and Shankarpur fishing harbour close to the station has multiplied the anthropogenic pressure around the zone.

Considering fish juvenile number as an indicator of reproductive success, egg development and spawning, we observed significant spatial difference of fish juvenile number in the study zone (Table 3.1).

Table 3.2 exhibits the abundance of finfish juvenile species in the three sampling stations. Members of genus *Coilia* sp., *Thryssa* sp., *Mugil* sp., *Tenualosa* sp., *Liza* sp., *Scatophagus* sp., *Stolephorus* sp., *Cynoglossus* sp., *Sillago* sp. are dominant (in terms of standing stock or biomass) in all the stations and in all the seasons of the study period, which suggests the wide range of tolerance of this genus in the present geographical locale. The study clearly depicts the regulation of finfish juveniles by aquatic salinity. The number of finfish juvenile is highest at station 3 (Junput) which is followed by station 2 (Sagar light house) and station 1 (Diamond Harbour). The highest juvenile number at Junput confirms the positive role of aquatic salinity in maintaining the fish germplasm in the study area. Diamond Harbour is an extremely low saline zone in the upstream area with an average aquatic salinity of 2.76 psu during premonsoon, 1.02 psu during monsoon and 2.32 during postmonsoon and hence chance of getting stenohaline fish juvenile species or saline water loving individuals is rare.

Table 3.2 Distribution of finfish juvenile species in 10 gm composite wasted sample collected from three selected sampling stations during January, 2009 to December, 2018

S. No	Species	Station 1	Station 2	Station 3
1	*Coilia* sp.	++	++	+++
2	*Thryssa hamiltonii (Gray)*	+	++	+++
3	*Thryssa baelama*	+	++	+++
4	*Torquigener oblongus*	+	+	++
5	*Rhinomugil corsula*	+	+	+
6	*Mugil cephalus*	+	+	+
7	*Sillaginopsis panijus*	+	+	+
8	*Sillago sihama*	+	+	+
9	*Sillago soringa*	+	+	+
10	*Zenarchopterus dispar*	+	+	+
11	*Glossogobius quiris*	+	+	+
12	*Pseudapocryptes lanceolatus*	+	+	+
13	*Eupleurogrammus glossodon*	+	+	+
14	*Pseudorhombus* sp.	+	++	+++
15	*Pisodonophis boro*	+	+	+
16	*Tenualosa ilisha*	+++	+	–
17	*Cynoglossus arel*	+	++	+++
18	*Cynoglossus* sp.	+	+	+++
19	*Leiognathus blochii*	–	+	+
20	*Leiognathus equalus*	+	+	+
21	*Hilsa* sp.	++	+	–
22	*Scatophagus argus*	+	+	+
23	*Liza parsia*	+++	+	+
24	*Liza tade*	+++	+	+
25	*Stolephorus commersonii*	+	+	+
26	*Stolephorus baganensis*	+	+	+
27	*Stolephorus kammalensis*	+	+	+
28	*Lutjanus johni*	+	+	+
29	*Setipinna taty*	+	+	+
30	*Lagocephalus lunaris*	–	+	+
31	*Escualosa thoracata*	–	+	+
32	*Epinephelus tauvina*	–	+	+
33	*Epinephelus coioides*	–	+	+
34	*Sphyraena* sp.	–	+	+
35	*Pomadasys* sp.	–	+	+

(continued)

Table 3.2 (continued)

S. No	Species	Station 1	Station 2	Station 3
36	*Sardinella longiceps*	–	+	+
37	*Periophthalmus* sp.	–	+	+
38	*Macrognathus* sp.	–	+	+
39	*Tetradon cutcutia*	–	+	+
40	*Bregmaceros meclellandii*	–	+	+
41	*Ichthyocampus carce*	–	+	+
42	*Stigmatogobius* sp.	–	+	+
43	*Channa* sp.	–	+	–
44	*Kurtus indicus*	–	+	–
45	*Harpodon nehereus*	–	+	–
46	*Moringua raitaborua*	–	+	–
47	*Suggrundus rodricensis*	–	+	–

'–' means absent, '+' means present in small number, '++' means present in moderate level and '+++' means high abundance

In the maritime state of West Bengal preferably in central Indian Sundarbans sea level rise is about 3.00 mm/yr, which has increased the salinity value in the region (Table 3.3). This has resulted in more abundance of trash fishes like *Harpodon nehereus*, *Thryssa hamiltonii (Gray)*, *Thryssa baelama* etc. and less availability of commercially important fishes like *Tenualosa ilisha.*

Table 3.3 Rising trend of salinity (in psu) in central Indian Sundarbans

Year	Premonsoon	Monsoon	Postmonsoon
1984	22.07	20.67	21.81
1985	23.59	20.74	22.08
1986	24.34	20.80	22.02
1987	24.22	20.14	22.67
1988	25.04	20.03	22.40
1989	25.69	20.35	23.08
1990	25.84	21.02	23.54
1991	25.01	21.67	23.57
1992	24.72	21.73	23.96
1993	25.60	21.86	23.77
1994	26.00	21.74	24.21
1995	26.04	21.99	24.99
1996	26.08	21.61	25.05

(continued)

Table 3.3 (continued)

Year	Premonsoon	Monsoon	Postmonsoon
1997	26.83	22.01	24.92
1998	26.81	22.06	25.43
1999	26.75	20.64	25.41
2000	26.98	21.37	25.51
2001	27.04	22.60	25.96
2002	27.13	22.92	26.42
2003	27.45	22.98	26.48
2004	27.20	23.04	26.45
2005	27.18	23.16	27.56
2006	27.86	23.78	27.38
2007	27.69	23.83	27.69
2008	28.34	23.92	27.72
2009	31.68	22.87	28.30
2010	29.87	22.96	28.54
2011	30.13	23.37	28.89
2012	30.08	23.52	28.72
2013	30.46	23.69	28.92
2014	30.73	24.04	29.28
2015	30.81	23.89	29.80
2016	31.09	24.03	29.88
2017	30.80	25.03	29.30
2018	30.96	25.41	30.68

With this salinity data in the central part of Indian Sundarbans, we carried out a time series modeling to visualize the trend of salinity level using a nonlinear autoregressive model (NAR) treating seasonal salinity values as inputs and 32—year lead-time (Fig. 3.1) and observed significant rising trend in salinity with a base of 70% training, 15% validation and 15% testing (Fig. 3.2). This increased salinity due to reduced fresh water inflow in the central part of Indian Sundarbans coupled with sea level rise may significantly impact the spawning and larval development of Indian shad, *Tenualosa ilisha.*

Rising sea levels is a direct arm of climate change, which may inundate wetlands and other low-lying lands, erode beaches, intensify flooding, and increase the salinity of rivers, bays and estuaries. Salinity alteration due to seawater intrusion has been reported from various parts of the world. The rising trend of salinity over a period of 27 years has also been documented in the Matla River in the central part of Indian Sundarbans (Mitra et al. 2009). The biogeographic distribution of certain fish species is influenced by such alteration of aquatic salinity.

On the basis of this three decade data bank, we used Nonlinear Autoregressive Neural Network Model to forecast the salinity levels in central Indian Sundarbans

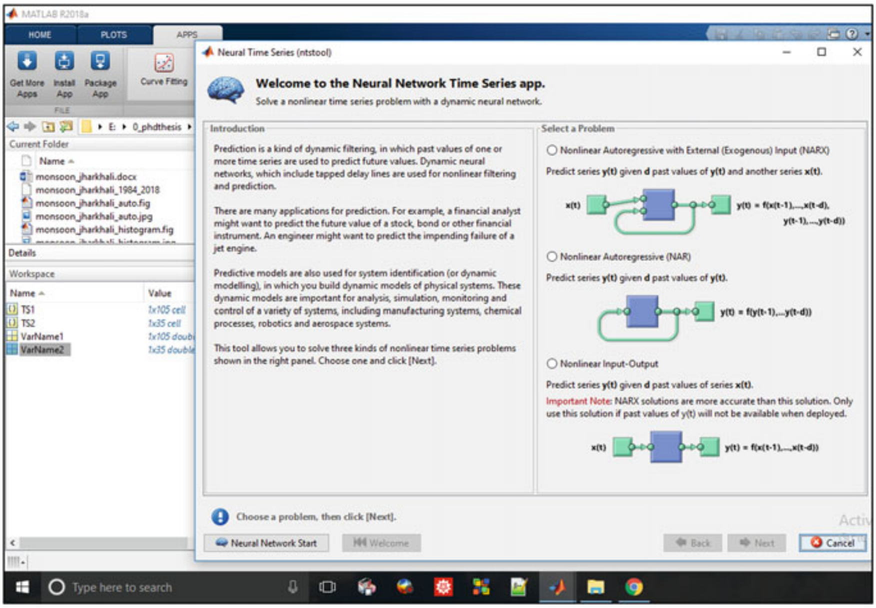


Fig. 3.1 Nonlinear Autoregression (NAR) model for evaluating the salinity trend

(with 32 years ahead time steps) for three seasons and observed a significant rise in all the seasons (Tables 3.4, 3.5 and 3.6; Figs. 3.3, 3.4 and 3.5).

The picture in the western Indian Sundarbans is totally reverse. There is a decrease of salinity in this region with the passage of time (Table 3.7), which is a congenial situation for the spawning of *Tenualosa ilisha.*

The salinity data in western Indian Sundarbans was also used to observe salinity trend using NAR considering seasonal salinity values as inputs and 32—year lead-time with a base of 70% training, 15% validation and 15% testing (Fig. 3.6). The output exhibits a significant decreasing trend of salinity, which is highly favourable for the spawning of *Tenualosa ilisha* during migration through this route of Hooghly-Bhagirathi River system from the inshore region of Bay of Bengal.

On the basis of this three decade data bank, we used Nonlinear Autoregressive Neural Network Model to forecast the salinity levels in western Indian Sundarbans (with 32 years ahead time steps) for three seasons and observed a significant decrease in salinity in all the seasons during 2050 (Tables 3.8, 3.9 and 3.10; Figs. 3.7, 3.8 and 3.9). It can, therefore, be forecasted that a congenial environment is ahead for the spawning and larval recruitment of *Tenualosa ilisha* in western sector of Indian Sundarbans.

An interesting observation in this context is the extension of the spawning ground of *Tenualosa ilisha* in more upstream zone after the construction of the Farakka barrage on the Gangetic stretch of India. The studies conducted during 1982–1992

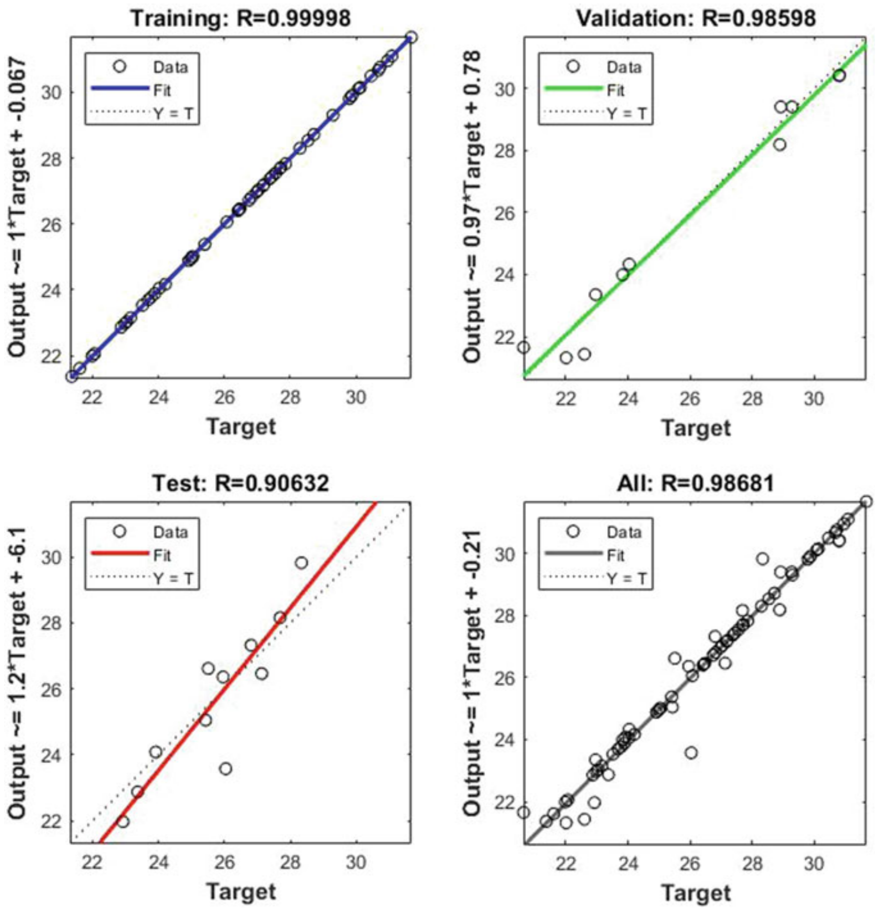


Fig. 3.2 Outputs of Nonlinear Autoregression (NAR) model showing the trend of aquatic salinity in central Indian Sundarbans

clearly reveal that the ecology of Hooghly estuary (downstream zone of Ganga-Bhagirathi system) has undergone a major change due to construction of the Farakka barrage in 1975. The increased freshwater discharge in the western part of Indian Sundarbans has resulted in considerable decrease in salinity throughout the estuary. The fresh water zone has extended toward the mouth of the estuary and the marine and estuarine zone has been pushed almost towards the end of the lower stretch of the estuary (Sinha et al. 1996). This has resulted in the expansion of the spawning ground of *Tenualosa ilisha* in the post Farakka barrage period (De and Saigal 1989). Prior to 1975 (before the installation of the Farakka barrage), the spawning ground was restricted from Calcutta to Medgachi, but survey conducted during 1987 to 1989 showed that the spawning ground has expanded more in the upstream zone almost

Table 3.4 Forecasting of salinity (in psu) in central Indian Sundarbans during premonsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in premonsoon
2019	30.87
2020	30.89
2021	30.87
2022	30.87
2023	30.86
2024	30.86
2025	30.86
2026	30.86
2027	30.86
2028	30.86
2029	30.86
2030	30.86
2031	30.86
2032	30.86
2033	30.86
2034	30.86
2035	30.86
2036	30.86
2037	30.86
2038	30.86
2039	30.86
2040	30.86
2041	30.86
2042	30.86
2043	30.86
2044	30.86
2045	30.86
2046	30.86
2047	30.86
2048	30.86
2049	30.86
2050	30.86

towards Nabadwip. This case study clearly confirms that biogeographic distribution of fish (preferably migratory fish) and even their spawning ground coordinates are regulated by aquatic salinity (Mitra 2000).

Table 3.5 Forecasting of salinity (in psu) in central Indian Sundarbans during monsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in monsoon
2019	25.67
2020	25.93
2021	25.98
2022	27.05
2023	24.41
2024	30.28
2025	17.89
2026	23.60
2027	19.99
2028	21.15
2029	22.29
2030	22.62
2031	22.30
2032	21.81
2033	21.58
2034	21.73
2035	21.85
2036	21.79
2037	21.71
2038	21.74
2039	21.78
2040	21.77
2041	21.75
2042	21.75
2043	21.76
2044	21.76
2045	21.75
2046	21.75
2047	21.76
2048	21.76
2049	21.76
2050	21.76

3.2.2 *Alteration of Metabolic Activity and Growth*

The enzymatic activities of fishes are greatly regulated by ambient aquatic temperature. It has been documented that at higher temperature the structure and function of protein are significantly impaired in fishes. In case of fish it has been observed that

Table 3.6 Forecasting of salinity (in psu) in central Indian Sundarbans during postmonsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in postmonsoon
2019	29.38
2020	31.03
2021	29.31
2022	31.45
2023	29.12
2024	31.90
2025	28.83
2026	32.29
2027	28.58
2028	32.61
2029	28.43
2030	32.81
2031	28.38
2032	32.91
2033	28.36
2034	32.95
2035	28.35
2036	32.97
2037	28.35
2038	32.97
2039	28.35
2040	32.97
2041	28.35
2042	32.97
2043	28.35
2044	32.97
2045	28.35
2046	32.97
2047	28.35
2048	32.97
2049	28.35
2050	32.97

increase of aquatic temperature within thermal range for a particular species leads to increased growth rate provided that food is not a limiting factor. The feeding rates of fishes increase at higher temperatures due to which the biomass enhances. This is reflected through the Feed Conversion Ratio (FCR) of the fish, which exhibits a decrease with increase of temperature. We performed a pilot project in the Bali

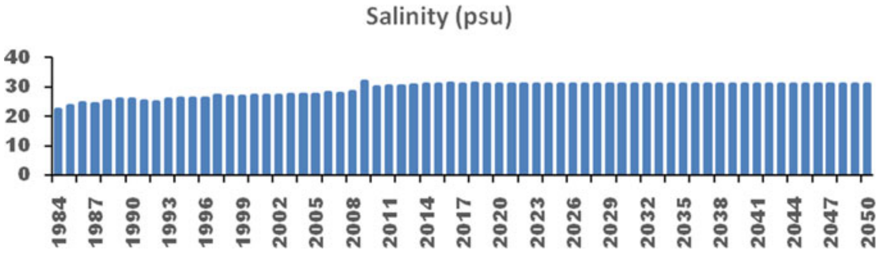


Fig. 3.3 Predicted salinity (in psu) in central Indian Sundarbans during premonsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training in the model

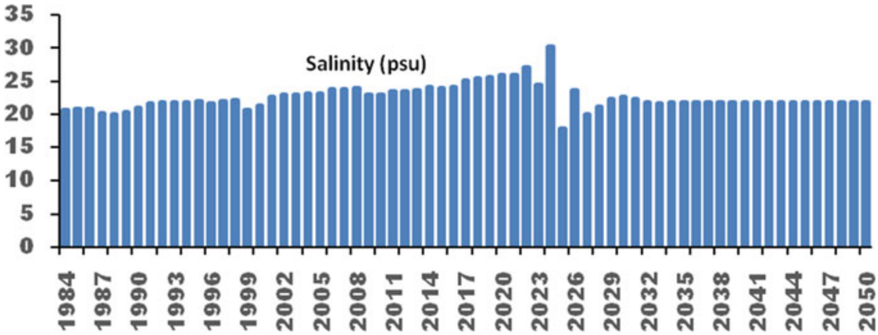


Fig. 3.4 Predicted salinity (in psu) in central Indian Sundarbans during monsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training in the model

Fig. 3.5 Predicted salinity (in psu) in central Indian Sundarbans during postmonsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training in the model

Table 3.7 Decreasing trend of salinity (in psu) in western Indian Sundarbans

	Premonsoon	Monsoon	Postmonsoon
1984	28.68	20.02	23.31
1985	28.34	19.67	21.03
1986	28.97	19.55	20.98
1987	28.00	19.42	21.02
1988	27.34	18.66	21.10
1989	26.57	18.44	21.24
1990	26.12	18.73	20.66
1991	26.07	18.53	20.54
1992	25.85	17.59	20.57
1993	25.81	17.97	20.43
1994	25.59	17.65	20.17
1995	25.34	16.95	20.29
1996	26.00	17.06	19.86
1997	26.05	17.13	19.91
1998	25.99	16.99	19.64
1999	25.57	16.87	19.54
2000	25.35	16.35	19.13
2001	25.20	16.13	19.23
2002	25.03	16.10	19.00
2003	24.90	16.41	18.84
2004	24.70	16.08	18.58
2005	24.35	16.19	18.18
2006	24.34	15.96	18.35
2007	24.20	15.78	18.11
2008	24.02	15.86	18.09
2009	28.07	17.04	18.02
2010	24.34	16.19	17.91
2011	24.00	15.94	17.78
2012	24.26	15.45	17.56
2013	23.23	15.13	18.44
2014	23.11	14.97	17.15
2015	22.91	12.78	19.40
2016	24.99	11.55	17.06
2017	23.09	10.57	18.33
2018	22.96	9.89	17.33

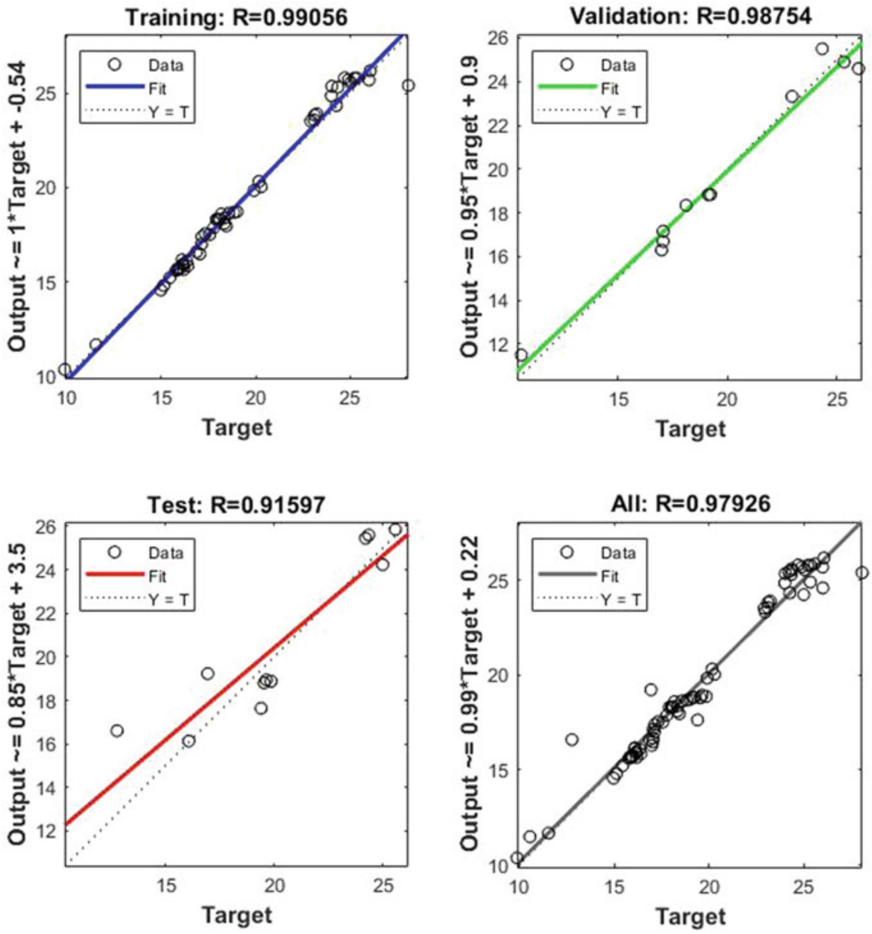


Fig. 3.6 Outputs of Nonlinear Autoregression (NAR) model showing the trend of aquatic salinity in western Indian Sundarbans

island of Indian Sundarbans in a shrimp culture farm and monitored the FCR value of *Penaeus monodon* of three months age over a period of three decades (1990–2020). We observed a significant inverse relationship between ambient water temperature and FCR values (Table 3.11).

The decrease of FCR values with increase of water temperature (Fig. 3.10) is due to better conversion of feed into biomass of cultured shrimp with the rise of temperature. Thus, it can be concluded that at an increased temperature, within a specific thermal range the enzyme–substrate complex binds effectively, which poses a positive effect on the metabolic activities of the species leading to better growth.

Table 3.8 Forecasting of salinity (in psu) in western Indian Sundarbans during premonsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in premonsoon
2019	24.99
2020	23.12
2021	22.53
2022	25.31
2023	21.52
2024	23.12
2025	25.18
2026	23.15
2027	22.48
2028	25.34
2029	21.39
2030	23.28
2031	24.86
2032	23.98
2033	23.78
2034	24.27
2035	24.68
2036	24.43
2037	24.36
2038	24.44
2039	24.48
2040	24.45
2041	24.44
2042	24.45
2043	24.45
2044	24.45
2045	24.45
2046	24.45
2047	24.45
2048	24.45
2049	24.45
2050	24.45

3.2.3 Alteration of Microbial Load in Fish Tissues

Fish diseases are mostly seasonal and are regulated by environmental parameters preferably water temperature. Kawasaki (2001) provided specific evidence of the effects of global warming on world fisheries production, particularly on tuna and

Table 3.9 Forecasting of salinity (in psu) in western Indian Sundarbans during monsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in monsoon
2019	8.71
2020	8.51
2021	10.40
2022	11.32
2023	10.59
2024	8.24
2025	7.01
2026	9.62
2027	11.44
2028	11.21
2029	8.82
2030	6.91
2031	8.34
2032	11.37
2033	11.44
2034	9.26
2035	7.00
2036	7.65
2037	11.25
2038	11.46
2039	9.51
2040	7.11
2041	7.38
2042	11.14
2043	11.47
2044	9.70
2045	7.23
2046	7.22
2047	11.02
2048	11.47
2049	9.90
2050	7.36

sardines. The triggering of the fish disease due to warming of atmosphere was seen in American lobster. Massive, catastrophic summer-fall mortalities of lobsters in Long Island Sound began in August 1999, and the incidence continued to occur to a greater or lesser degree in subsequent summers. An extensive federally sponsored research program has identified summer warming of Long Island Sound bottom

Table 3.10 Forecasting of salinity (in psu) in Western Indian Sundarbans during postmonsoon using Autoregressive Neural Network Model

Year	Predicted salinity (in psu) in postmonsoon
2019	18.99
2020	17.24
2021	19.43
2022	17.27
2023	18.65
2024	17.22
2025	19.41
2026	17.26
2027	18.68
2028	17.22
2029	19.43
2030	17.26
2031	18.62
2032	17.22
2033	19.40
2034	17.26
2035	18.73
2036	17.22
2037	19.46
2038	17.27
2039	18.54
2040	17.23
2041	19.33
2042	17.25
2043	18.90
2044	17.21
2045	19.46
2046	17.27
2047	18.53
2048	17.23
2049	19.31
2050	17.25

waters, coupled with hypoxia, as the most likely causes of the outbreak of disease. One of these diseases called "excretory calcinosis", discovered by scientists at Stony Brook University, is a gill tissue blood disorder resulting directly from warm water temperatures (Dove et al. 2004). Other lobster diseases also appear to result from the stress of high temperature and hypoxia. The result of these multiple stresses has

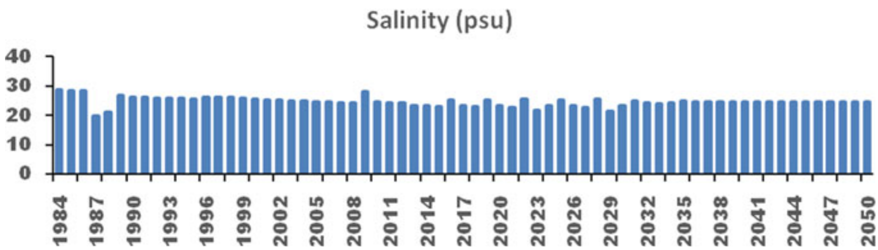


Fig. 3.7 Predicted salinity (in psu) in western Indian Sundarbans during premonsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training

Fig. 3.8 Predicted salinity (in psu) in western Indian Sundarbans during monsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training in the model

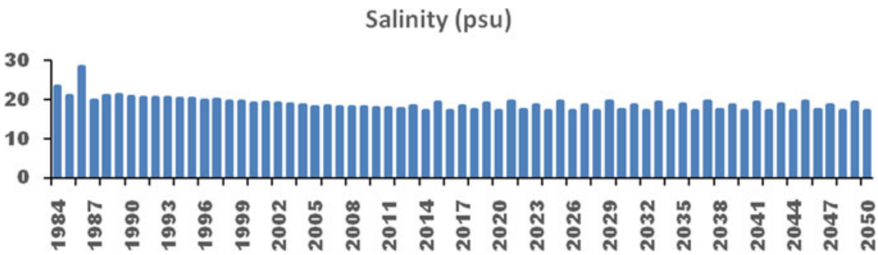


Fig. 3.9 Predicted salinity (in psu) in western Indian Sundarbans during postmonsoon using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2018 has been used as training in the model

been a 75% reduction in total landings and 85% reduction in the overall abundance of the population. These diseases now appear to be moving northward.

An experiment conducted by the authors at the roof-top tank of Techno India University, West Bengal (India) exhibited higher levels of total coliform and fecal coliform bacteria in the muscle, gill and hepatopancreas of *Macrobrachium rosenburgii* in 2019 compared to 2018 in all the three seasons (premonsoon, monsoon, postmonsoon). The increased microbial load during 2019 may be attributed to higher

Table 3.11 Surface water temperature and FCR values of shrimps cultured at Bali island of Indian Sundarbans

Year	Water temperature (°C)	FCR value
1990	32.7±0.5	2.05
1991	33.1±0.5	1.98
1992	32.9±0.3	2.02
1993	33.0±0.4	1.96
1994	33.3±0.5	1.90
1995	33.0±0.4	2.00
1996	32.9±0.4	1.88
1997	33.0±0.6	1.85
1998	33.2±0.6	1.79
1999	33.5±0.6	1.74
2000	33.6±0.6	1.87
2001	33.8±0.6	1.69
2002	33.6±0.5	1.68
2003	33.4±0.5	1.71
2004	33.7±0.7	1.64
2005	33.5±0.7	1.52
2006	34.1±0.7	1.49
2007	34.0±0.7	1.46
2008	34.3±0.6	1.44
2009	36.0±0.6	1.35
2010	34.4±0.6	1.33
2011	34.6±0.6	1.41
2012	34.7±0.6	1.28
2013	34.8±0.5	1.30
2014	34.8±0.7	1.33
2015	35.1±0.7	1.29
2016	35.3±0.7	1.26
2017	35.8±0.7	1.28
2018	36.1±0.7	1.22
2019	36.5±0.7	1.27
2020	36.8±0.7	1.21

temperature witnessed in 2019 (average yearly temperature = 38.8 °C) compared to 2018 (average yearly temperature = 36.6 °C) in the city of Kolkata (Figs. 3.11, 3.12 and 3.13).

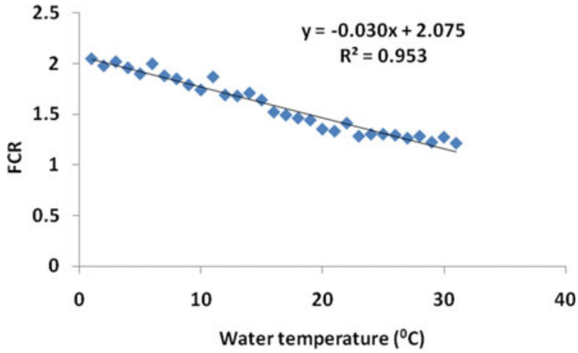


Fig. 3.10 Decrease of FCR values with increase of water temperature

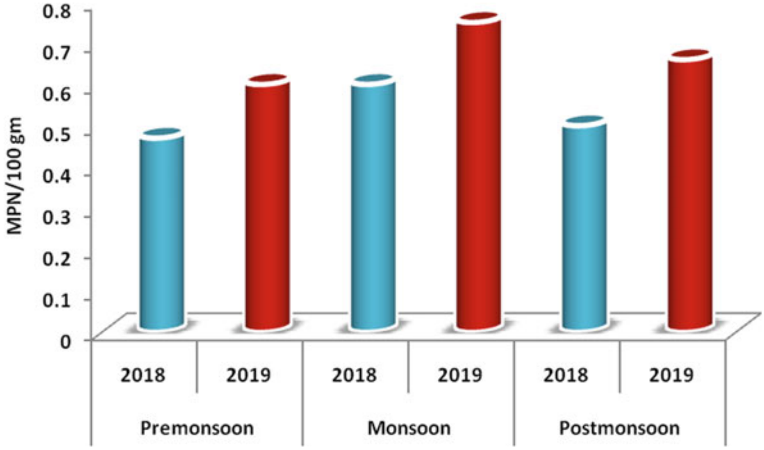


Fig. 3.11 Total coliform (MPN/100gm) in the muscle of *Macrobrachium rosenburgii* in the roof-top tank of Techno India University, West Bengal (India)

3.3 Acidification—Effect on Fish Community of Indian Sundarbans

The atmospheric CO_2 has accelerated with a high magnitude since the pre-industrial scenario and has exceeded 400 ppm. Approximately 30% of the excess CO_2 in the atmosphere has been absorbed by the oceans (Sabine et al. 2004), which, owing to their expansive surface area, experience a parallel increase in the partial pressure of CO_2 (PCO_2) with the atmosphere (Doney 2010). If the current trajectory is maintained, increases in atmospheric CO_2 levels are predicted to exceed 900 ppm by 2100 (Meinshausen et al. 2011). Increasing PCO_2 of marine systems is often accompanied by a decrease in pH of the water, termed ocean acidification (OA) (Doney 2010).

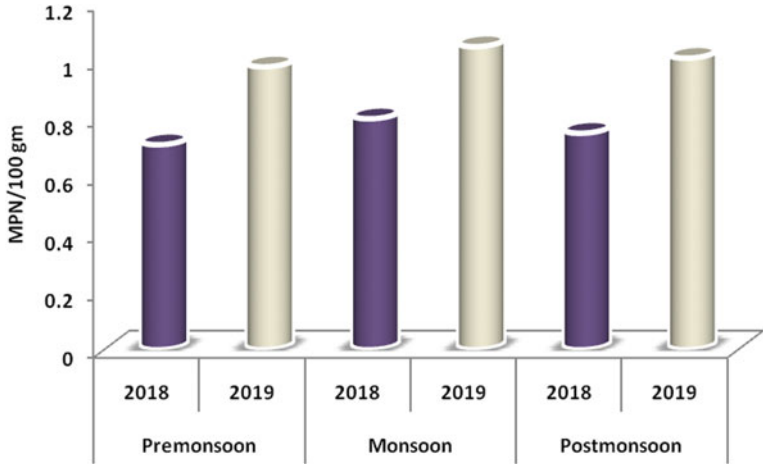


Fig. 3.12 Total coliform (MPN/100gm) in the gills of *Macrobrachium rosenburgii* in the roof-top tank of Techno India University, West Bengal (India)

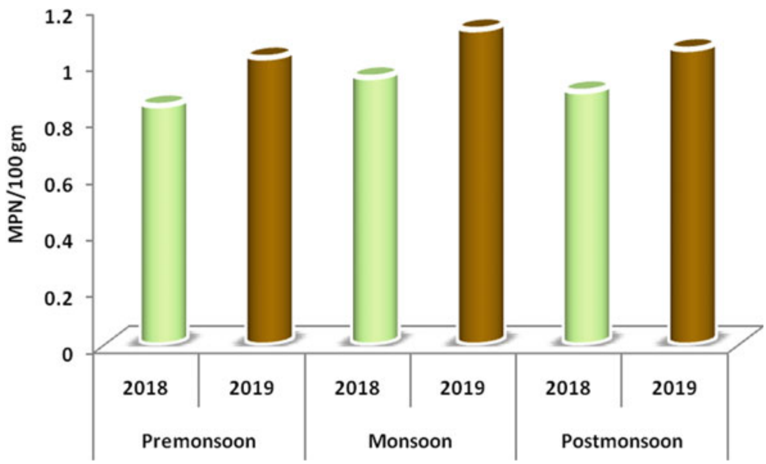


Fig. 3.13 Total coliform (MPN/100gm) in the hepatopancreas of *Macrobrachium rosenburgii* in the roof-top tank of Techno India University, West Bengal (India)

The scenario in mangrove dominated Indian Sundarban estuaries is no exception to this global trend.

We carried out a seasonal study on atmospheric carbon dioxide concentration at Sagar Island at 18 m above the ground on the campus of Youth Hostel at Sagar South (21° 38′ 51.55″ N and 88° 02′ 20.97″ E), with a non-dispersive infrared gas analyzer (LI6262, LI-COR Inc., USA). We installed and air intake at 1 m above the roof of the building. A diaphragm pump was used to draw air through a ¼ inch Teflon tube at a rate of 10 L per minutes with most of the air being vented

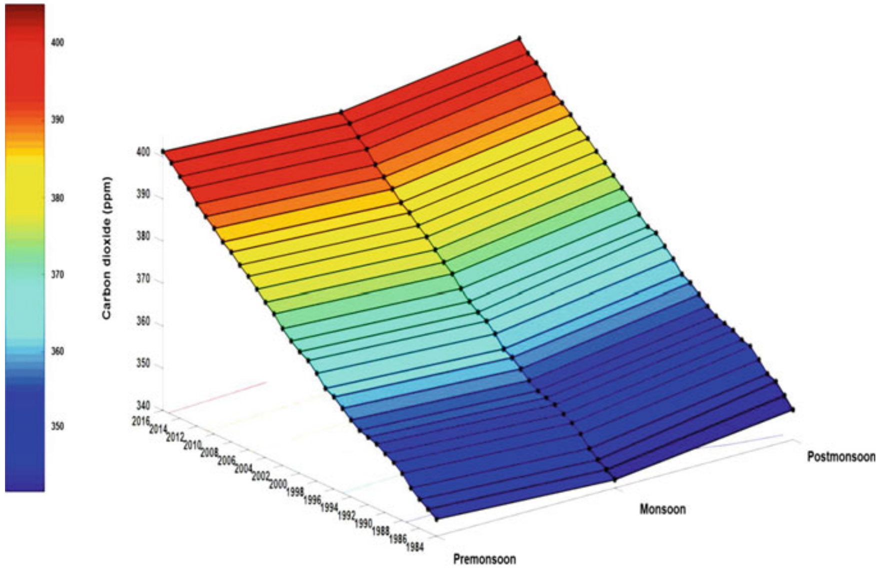


Fig. 3.14 Temporal variation of atmospheric CO_2 at Sagar Island in western Indian Sundarbans

off. The step of removal of water vapour was performed and the air sample was introduced into a sample cell of the NDIR analyzer, and the output voltage of the NDIR analyzer was integrated at five-minute interval. The analyzer was calibrated every four hours by successively introducing four calibrated working gases (340, 380, 410 and 450 ppm carbon dioxide in dry air) into the NDIR analyzer cell for five minutes each. The experiment was performed in every year (1984–2016) in three fixed months namely May (premonsoon), September (monsoon) and December (postmonsoon). A linear increase in atmospheric carbon dioxide concentration was observed (Fig. 3.14), which may be attributed to factors like intense industrialization, urbanization, proliferation of shrimp farms and brick kilns (Fig. 3.15 and 3.16) at the cost of mangrove habitat, which could otherwise be a potential sink of CO_2.

Massive destruction of mangroves in Indian Sundarbans since mid eighties has squeezed the reservoir of mangrove storage due to which Estuarine Acidification (EA) has gradually crept in the lower Gangetic water. Sundarban, being a rich habitat for marine and estuarine fishes cannot escape the situation. Impacts of acidification on organisms with calcareous parts are highly identifiable, but in most fishes with efficient adaptive mechanism the impact is mostly masked. We have highlighted here few probable impacts of EA on the fish community.

Fig. 3.15 Shrimp farms in Indian Sundarbans at the cost of mangroves

Fig. 3.16 Brick kilns in Indian Sundarbans have come up on the mangrove habitat

3.3.1 Effect on Calcareous Structures

Fish are not ideally considered as calcifying organisms, but they produce $CaCO_3$ precipitates in the intestinal lumen and otoliths in the inner ear. Otoliths are $CaCO_3$ concretions that serve the purpose of sound detection and gravity sensing (Tohse and Mugiya 2004; Tohse et al. 2001), whereas intestinal $CaCO_3$ precipitates are produced to provide service like water absorption in the intestine and subsequent osmoregulation. It has been documented that there is an increase in the size and density of at elevated level of CO_2. A study on sea bass put forward the hypothesis that reduced aragonite saturation states in water with elevated CO_2 would impair otolith growth and demonstrated increased rather than decreased otolith size in larval fish exposed to environmentally realistic CO_2 levels of 993 µAtm (Checkley et al. 2009).

3.3.2 Effect on Growth and Condition Index

The growth and condition index of fishes are highly species- specific and life cycle stage-specific. At elevated level of CO_2 no significant change in condition factor was observed, but a reduction in condition factor was demonstrated in juvenile Atlantic cod (Moran and Støttrup 2011). We made a thorough study on the condition index of few dominant adult finfish species in both Hooghly and Matla estuary and observed a decrease in condition index with the decrease in aquatic pH. Individual length and weight of the selected species were measured to evaluate the condition factor[3] as per the following expression:

$$K = \frac{\overline{w}}{(\overline{TL})^3} \times 10^3$$

where K is the condition factor, $\overline{w}$ is the average weight (g) and $\overline{TL}$ is the average total length (cm). Condition factor is an indication of the well being of an organism and is based on the hypothesis that heavier fish of a given length are in a better condition than light weighed fish of the same species. It has been used as an index of growth and feeding intensity, decreases with increase in length and also influences the reproductive cycle in fish. On this background we have used this parameter/index as proxy to detect the impact of lowering of pH in the two major estuaries of Indian Sundarbans namely Hooghly and Matla.

Our first order analysis clearly reflects a pronounced variation in condition factor of the selected species between the two sectors and also between the two time periods (Table 3.12). Significantly higher condition factor of commercially important finfish was observed in the species collected from the Hooghly estuary, where the rate of pH decrease is less (0.0016) compared to Matla estuary (0.0025). We interpret from

Table 3.12 Condition factor of the selected fin fish species in the Hooghly and Matla estuaries of Indian Sundarbans

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
	pH = 8.30	pH = 8.24	pH = 8.34	pH = 8.25
 *Tenualosa ilisha* (Family: Clupeidae)	0.934	0.652	0	0
 *Pama pama* (Family: Sciaenidae)	1.102	0.429	0.901	0.328
 *Pampus* spp. (Family: Stromateidae)	0.932	0.544	0.872	0.431

(continued)

Table 3.12 (continued)

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
 *Ilisha elongata* (Family: Pristigasteridae)	0.878	0.613	0	0
 *Lates calcarifer* (Family: Centropomidae)	1.401	0.560	1.050	0.477

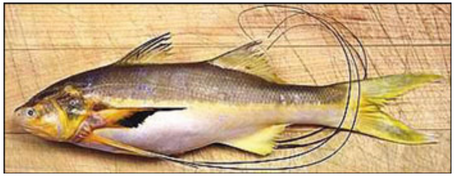
(continued)

Table 3.12 (continued)

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
 *Pangasius pangasius* (Family: Pangasiidae)	0.938	0.475	0.766	0.405
 *Liza parsia* (Family: Mugilidae)	0.957	0.516	0.623	0.385
 *Liza tade* (Family: Mugilidae)	1.008	0.933	0.918	0.864

(continued)

Table 3.12 (continued)

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
 *Tenualosa toli* (Family: Clupeidae)	1.326	0.733	1.004	0.667
 *Polynemus paradiseus* (Family: Polynemidae)	0.994	0.705	0.718	0.540

(continued)

Table 3.12 (continued)

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
 *Otolithoides biauritus* (Family: Sciaenidae)	1.105	0.917	0.889	0.520
 *Tachysurus jella* (Family: Ariidae)	0.982	0.764	0.653	0.388
 *Sciaena biauritus* (Family: Sciaenidae)	1.117	0.955	1.006	0.553

(continued)

Table 3.12 (continued)

Commercially important fin fish	Western sector (Hooghly estuary)		Central sector (Matla estuary)	
	1984	2019	1984	2019
 *Eleutheronema tetradactylum* (Family: Polynemidae)	1.006	0.489	0.919	0.475

Note The value 0 (zero) represents the non availability of the species in the estuarine water this data sets that stability in aquatic pH is a major driver in providing a congenial environment of fish species.

3.3.3 *Effect on Bioaccumulation*

Acidification has been observed to increase the bioaccumulation in the fish tissue. Our data bank since 1980 reflects an increasing trend of dissolved Cu in western Indian Sundarbans (Table 3.13), which is an indication of water quality variation. It is very difficult to relate the oscillation of dissolved Cu with climate change due to noise created by recent industrialization and urbanization in the Haldia industrial complex in the upstream zone. We also lack data on the effect of temperature increase on Cu toxicity. It has been documented that lowering of pH (which is a consequence of CO_2 increase) favours transference of Cu from the sediment (bed material) to aquatic phase (Mitra et al. 1994; Mitra 1998a, 1998b) and thus an indirect, but feeble string of Cu bioaccumulation and elevation of atmospheric CO_2 can be sketched.

Statistical analyses of our 18 years data set on aquatic pH, dissolved Cu and biologically available Cu in sediment of western Indian Sundarbans (Table 3.13) confirm the process of transference of Cu from the sediment bed to the upper aquatic

Table 3.13 Concentrations of dissolved Cu, biologically available Cu in sediment and surface water pH in western Indian Sundarbans

Year	Dissolved Cu (ppb)	Biologically available Cu (ppm)	pH
2000	38.73	24.66	8.33
2001	41.84	20	8.33
2002	50.93	15.81	8.32
2003	49.65	18.24	8.32
2004	49.94	20.66	8.32
2005	50.41	16.96	8.31
2006	55.07	16.65	8.32
2007	55.87	14.7	8.31
2008	54.85	15.19	8.31
2009	62.96	12.97	8.31
2010	66.02	13.41	8.3
2011	65.95	14.29	8.3
2012	61.12	15.72	8.3
2013	69.73	11.98	8.29
2014	66.93	13.83	8.29
2015	57.4	16.4	8.29
2016	66.96	14.69	8.28
2017	69.94	11.87	8.28

phase ($\mathbf{r}_{\text{dissolved Cu} \times \text{sediment Cu}} = -0.903, p < 0.01$; $\mathbf{r}_{\text{dissolved Cu} \times \text{pH}} = -0.887, p < 0.01$ and $\mathbf{r}_{\text{sediment Cu} \times \text{pH}} = 0.747$, $p < 0.01$) in a condition of low pH value. Considering dissolved Cu as variable 1 (VAR_1), biologically available Cu as variable 2 (VAR_2) and pH as variable 3 (VAR_3), the scatter plot generated through SYSTAT reflects that higher pH favours the precipitation of Cu from water to sediment, whereas lower pH increases the concentrations of dissolved Cu (Fig. 3.17). The vulnerability of the increasing trend of dissolved heavy metals cannot be ignored as the process is related to bioaccumulation and biomagnification leading to human health hazard.

We have also observed increasing trend of heavy metals since 2000 (Table 3.14a–c), which is inversely proportional to trend of pH in the same period of time. A long term research needs to be undertaken to investigate the interrelationship between the heavy metal level in fish tissue and indicators of climate change (like water temperature or pH). Simulation experiment may be an effective approach in this context.

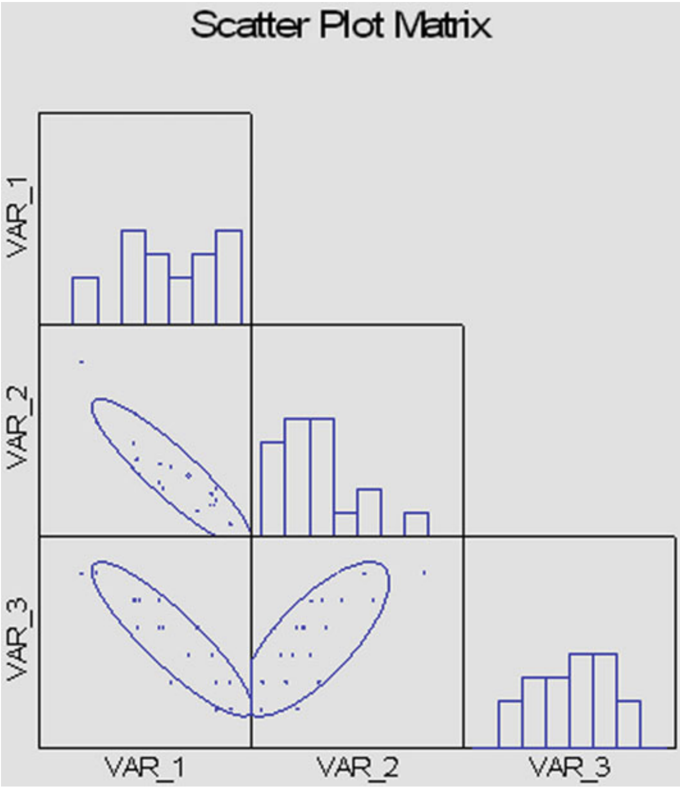


Fig. 3.17 Scatter plot matrix showing the inter-relationship between dissolved Cu (VAR_1), biologically available Cu in sediment (VAR_2) and surface water pH (VAR_3)

Table 3.14 **a** Zn concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary, **b** Cu concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary, **c** Pb concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary

(a) Zn concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary

Species	2015	2016	2017	2018	2019
Coilia sp.	21.12	28.00	30.59	29.71	27.11
Thryssa hamiltonii	17.61	25.77	26.96	23.71	32.5
Rhinomugil corsula	19.23	29.23	29.12	38.73	38.1
Mugil cephalus	25.21	27.88	29.98	41.94	44.88
Sillago sihama	12.85	19.41	18.86	24.32	21.12
Pisodonophis boro	28.7	39.31	41	57.79	54.99
Tenualosa ilisha	21.9	29	28.47	33.6	34.08
Liza parsia	29.34	35.5	38.13	42.93	39.2
Liza tade	33.11	46.21	49.22	52.89	48.65
Stolephorus commersonii	14.23	20.35	12.66	18.24	10.84

(b) Cu concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary

Species	2015	2016	2017	2018	2019
Coilia sp.	3.19	6.34	6.68	7.78	9.98
Thryssa hamiltonii	6.68	10.27	10.21	7.13	11.33
Rhinomugil corsula	5.82	7.25	6.81	8.63	9.44
Mugil cephalus	10.49	15.04	19.45	16.06	20.59
Sillago sihama	3.08	6.08	4.95	6.40	5.04
Pisodonophis boro	13.60	18.09	17.47	18.64	21.21
Tenualosa ilisha	4.84	7.44	7.83	7.62	9.38
Liza parsia	5.42	9.26	8.74	7.98	10.0
Liza tade	6.49	10.82	10.80	13.41	9.10
Stolephorus commersonii	3.83	0	5.45	4.46	5.0

(c) Pb concentrations (in ppm dry wt.) in fin fish muscles collected from Hooghly estuary

Species	2015	2016	2017	2018	2019
Coilia sp.	1.05	0.32	2.21	3.20	2.94
Thryssa hamiltonii	3.05	3.35	3.05	2.69	4.57
Rhinomugil corsula	4.22	4.63	4.98	2.53	2.28
Mugil cephalus	7.28	7.53	5.08	5.77	7.36
Sillago sihama	2.1	1.43	1.50	2.54	2.34
Pisodonophis boro	4.53	3.32	5.97	7.08	4.80
Tenualosa ilisha	4.17	3.60	2.37	4.65	4.65
Liza parsia	2.06	2.67	2.08	2.53	1.97
Liza tade	2.83	2.23	3.33	2.67	1.96
Stolephorus commersonii	2.04	1.38	1.17	1.84	1.60

Table 3.15 Egg diameter of *Mystus gulio* in relation to pH of ambient aquatic phase

Year	Sagar Island		Bali Island	
	Mean Egg diameter (in mm); Sample size = 1875	Mean pH (mean of 50 readings covering three seasons)	Mean Egg diameter (in mm); Sample size = 1655	Mean pH (mean of 50 readings covering three seasons)
2010	1.5	8.30±0.03	1.7	8.31±0.04
2011	1.3	8.30±0.03	1.8	8.31±0.04
2012	1.4	8.28±0.02	1.3	8.32±0.04
2013	1.2	8.27±0.02	1.4	8.32±0.04
2014	0.8	8.27±0.02	1.6	8.30±0.03
2015	0.9	8.28±0.02	1.2	8.30±0.03
2016	1.1	8.27±0.02	1.0	8.29±0.03
2017	0.7	8.25±0.03	0.9	8.29±0.03
2018	0.1	8.23±0.02	1.0	8.30±0.03
2019	0.6	8.21±0.03	0.8	8.28±0.02

3.3.4 Effect on Spawning

Researchers have documented that acidification of the ocean, seas and estuarine waters are likely to interfere in the spawning process of fish. It is known that both the male and the female gonads exhibit cyclic morphological and histological changes before reaching full maturity and becoming ripe. The release of gametes from the body into ambient aquatic phase is called spawning. During spawning the egg diameter attains maximum value. We have documented the egg diameter of *Mystus gulio*, the estuarine cat fish in the waters adjacent to Sagar island and Bali island for a decade of 2010–2019 and observed a decrease in egg diameter in both the stations (Table 3.15). Our result clearly confirms the adverse impact of estuarine acidification on the egg diameter which may pose a negative effect on the spawning process of the species. Detailed literature on this subject is still scanty and needs to be studied to fill the gap area.

3.4 Take Home Messages

A. The fish fauna of the estuarine waters around Sundarbans has been classified into residents and transients (migrants). The species whose individuals of different sizes are present during all the months of the year in any zone of the estuary are referred to as resident species. The important resident species of fish are *Mugil parsia, Mugil tade, Polynemus paradiseus, Polydactylus indicus, Otolithoides biauritus, Lates calcarifer, Hilsa toli, Arius jella, Harpodon nehereus, Setipinna taty, Ilisha elongata, Setipinna phasa, Coilia ramcarati, Pama pama* and

Sillaginopsis panijus. The transient or migratory fishes enter and stay in the Bay of Bengal associated estuaries for a short period. Depending on nature of migration, the migrants may be divided into three categories like (1) Marine forms that migrate upstream and spawn in freshwater areas of the estuary like *Tenualosa ilisha, Polynemus paradiseus, Sillaginopsis panijus and Pama pama* (2) Freshwater species, which spawn in saline area of the estuary like *Pangasius pangasius* (3) Marine species, that spawns in less saline water of the estuary like *Arius jella*, *Osteogeneious militaris* and *Polydactylus indicus*.

B. Climate change is a bitter truth associated with the present century and has both direct and indirect impacts on fish stocks which are exploited commercially. Direct effects act on physiology and behaviour of fishes and alter their growth, reproduction, mortality and distribution. Indirect effects encompass events like alteration of aquatic productivity, biotic community structure and composition of the marine and estuarine ecosystems on which fishes depend for food and survival. Changes in primary and secondary production will obviously have a major effect on fisheries production, but it is not possible in the current state of knowledge to make accurate quantitative predictions of changes in global marine primary production solely due to climate.

C. Ocean acidification due to increased CO_2 level is a well accepted concept. Most of our knowledge on the direct effects of ocean acidification on marine organisms focuses on species known as "marine calcifiers" (e.g., corals, molluscs etc.) that build skeletons or shells made of calcium carbonate. Many of these species will suffer impaired ability to build skeletons as pH decreases. We know less about the direct impacts of acidification on harvested species like fishes and squids. In these species, the response to acidification is likely to involve physiological diseases including acidosis of tissue and body fluids leading to impaired metabolic function. Egg and larval stages are likely to be much more susceptible than adults, suggesting that reduced reproductive success will be among the first symptoms to appear. The indirect effects of acidification on fisheries will include loss of reef habitat and breeding ground constructed by marine calcifiers.

D. Massive destruction of mangroves in Indian Sundarbans since mid eighties has squeezed the reservoir of mangrove storage due to which Estuarine Acidification (EA) has gradually crept in the lower Gangetic water. Sundarban, being a rich habitat for marine and estuarine fishes cannot escape the situation. Impacts of acidification on organisms with calcareous parts are highly identifiable, but in most fishes with efficient adaptive mechanism the impact is mostly masked. Few identifiable indicators to assess the impact of EA on fish community of Indian Sundarbans are otolith growth, condition index, bioaccumulation in fish tissue and spawning related parameters.

Annexure 3: Compartmentation of Heavy Metals due to Acidification in Matla Estuary of Indian Sundarbans

Background of the Study

Over the last century, the atmospheric concentration of carbon dioxide has risen at a rate 100 times faster than any change observed during the past 650,000 years (Siegenthaler et al. 2005). There is broad consensus that this ongoing change is a direct result of human activity, principally by fossil fuel burning, cement production and changing land use (Hansen et al. 2007). Atmospheric levels of carbon dioxide have consequently increased from pre-industrial levels of 280 ppm to a concentration of approximately 380 ppm (Feely et al. 2004). Almost 50% of all anthropogenic carbon dioxide emitted to the atmosphere has diffused passively into the ocean, thereby significantly decreasing the rate of global warming (Sabine et al. 2004). Concentrations of atmospheric carbon dioxide are rising at a rate of 3.3% per year and will continue this rising trend (Canadell et al. 2007). Hydrological models predict that, based on proposed future emissions of carbon dioxide, the average oceanic pH will decline by 0.3–0.5 by the year 2100 and by 0.7 within the next 300 years (Caldeira and Wickett 2003). Leakage from carbon dioxide seabed storage would create locally faster and stronger acidification than that induced by atmospheric carbon dioxide (Hawkins 2004).

The process of acidification largely regulates the concentration of conservative pollutants (primarily heavy metals) in the water and sediments. It has been documented by several researchers that aquatic pH controls the process of dissolution / precipitation and there by regulates the level of heavy metals in the aquatic phase and the underlying sediment compartments (Mitra et al. 1992; Mitra and Choudhury 1993; Byrne 2002). Depending on the aquatic pH, bioaccumulation and subsequent toxic effects occur in plankton, nekton or benthic community.

On the basis of the global trend of acidification, we try to focus on the issue at the local level in the Matla River situated in the central Indian Sundarbans of the lower Gangetic delta region and evaluat e the role of the phenomenon on the compartmentation of selected heavy metals (Zn, Cu and Pb), that are dominant in the present geographical locale (Mitra 1998a, 1998b; Mitra et al. 2011).

Materials and Methods

Study Area

The lower Gangetic delta region, at the apex of Bay of Bengal sustains the famous mangrove dominated ecosystem, the Sundarbans. The deltaic complex has an area of 9630 sq. Km and houses 102 islands. The western sector of the deltaic lobe receives the snowmelt water of mighty Himalayan glaciers after being regulated through several barrages on the way. The central sector on the other hand, is fully deprived from such supply due to heavy siltation and clogging of the Bidyadhari channel since the late fifteenth century (Chaudhuri and Choudhury 1994). The lower part of the deltaic complex has multifarious industries such as paper, textiles, chemicals, pharmaceuticals, plastic, shellac, food, leather, jute, tyres and cycle rims (UNEP 1982). These units are point sources of heavy metals in the estuarine water (Mitra et al. 1992). The central part of the delta complex receives the water of the Matla River. Industries are almost absent along the bank of the river, but the water is contaminated with sewage from the highly urbanized city of Kolkata. Reports of considerable concentrations of Zn, Cu and Pb are also available in this region, which originates mainly from the antifouling paints used for conditioning the fishing vessels and trawlers (Mitra et al. 1992, 2011; Mitra and Choudhury 1993; Mitra 1998a, 1998b). The present study was conducted 1.5 km off Bonnie camp (21° 49′42.9″ N/88° 37′13.7″ E) in the Ajmalmari river (local name) that receives the water from the Matla River.

A total of 30 samples (for both water and sediment) were collected for each parameter in May (summer season in the present geographical locale) of every year (1984–2013) during high tide condition and the average results of every parameter were considered for statistical analyses.

Measurement of Aquatic pH

pH of the surface water in the selected sampling station was measured with a portable pH meter (sensitivity = ± 0.02).

Analysis of Dissolved Zn, Cu and Pb

Surface water samples were collected from the sampling station using 10-l Teflon-lined Go-Flo bottles, fitted with Teflon taps and deployed on a rosette or on Kevlar line, with additional surface sampling carried out by hand. Shortly after collection, samples were filtered through Nuclepore filters (0.4 μm pore diameter) and aliquots of the filters were acidified with sub-boiling distilled nitric acid to a pH of about 2 and stored in cleaned low-density polyethylene bottles. Dissolved heavy metals were separated and pre-concentrated from the seawater using dithiocarbamate complexation and subsequent extraction into Freon TF, followed by back extraction into HNO_3 as per the procedure of Danielsson et al (1978). Extracts were analyzed for Zn, Cu and Pb by Atomic Absorption Spectrophotometer (Perkin Elmer: Model 3030). The accuracy of the dissolved heavy metal determinations is indicated by good agreement between our values and reported for certified reference seawater materials (CASS 2) (Table 3.16).

Analysis of Biologically Available Zn, Cu and Pb

Sediment samples from surface (1 cm depth) were collected by scrapping using a pre-cleaned and acid washed plastic scale and immediately kept in clean polythene

Table 3.16 Analysis of reference material for near shore seawater (CASS 2)

Element	Certified value ($\mu g\ l^{-1}$)	Laboratory results ($\mu g\ l^{-1}$)
Zn	1.97±0.12	2.01±0.14
Cu	0.675±0.039	0.786±0.058
Pb	0.019±0.006	0.029±0.009

Table 3.17 Analysis of reference material (NIES Sargasso sample) for sediments obtained from the National Institute of Environmental Studies, Japan

Element	Certified value (μg g^{-1})	Laboratory results (μg g^{-1})
Zn	28.6	26.2
Cu	14.9	13.7
Pb	2.4	2.9

bags, which were sealed. The samples were washed with metal free double distilled water and dried in an oven at 105 °C for 5–6 h, freed from visible shells or shell fragments, ground to powder in a mortar and stored in acid washed polythene bags. Analyses of biologically available metals were done after re-drying the samples, from which 1 gm was taken and digested with 0.5 (N) HCl as per the standard procedure outlined by Malo (1977). The resulting solutions were then stored in polythene containers for analysis. The solutions were finally aspirated in the flame Atomic Absorption Spectrophotometer (Perkin Elmer: Model 3030) for the determination of metal concentrations. No detectable trace metals were found in the reagent blank. Analysis of the NIES Sargasso sample was carried out to assure the quality of the data (Table 3.17).

Statistical Analysis

Inter-relationships between aquatic pH, selected dissolved heavy metals and biologically available heavy metals in sediment were determined through correlation coefficient values, scatter plots and allometric equations for all possible combinations. All statistical calculations were performed with SPSS 9.0 for Windows.

Results

1. **Surface water pH**

The surface water pH exhibited variation within a small range. Highest value was recorded during 1985 (8.32) and lowest value (8.29) was recorded during 2013 (Fig. 3.18). The gradual lowering of pH (0.001/yr) clearly confirms the phenomenon of acidification in the Matla estuarine system.

2. **Dissolved metal**

The order of dissolved heavy metals in the estuarine water is Zn > Cu > Pb. Dissolved Zn ranged from 123.66 ppb during (1984) to 265.00 ppb during (2013) (Fig. 3.19). Dissolved Cu ranged from 44.75 ppb during (1984) to 97.14 ppb during (2013) (Fig. 3.20). During the study period the value of dissolved Pb ranged from 7.39 ppb (1984) to 17.39 ppb (2013). All the selected dissolved metals thus exhibit an increasing trend.

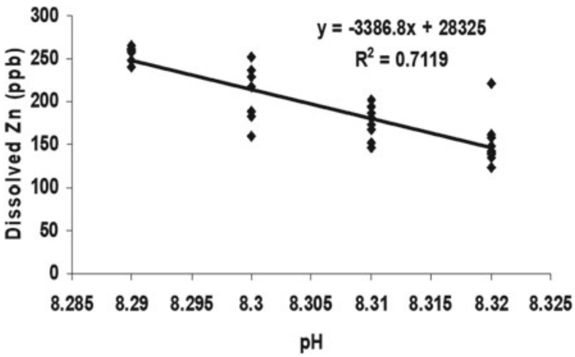


Fig. 3.18 Inter-relationship between dissolved Zn and pH

3. Sediment metal

In sediment compartment, the biologically available metals exhibited a decreasing trend. In case of Zn, the value decreased from 64.71 ppm (during 1984) to 29.66 ppm (during 2013). In case of Cu, the value ranged from 7.31 ppm (during 2013) to 23.61 ppm (during 1984). In case of Pb, the lowest value was observed during 2013 (1.08 ppm) and the highest value was recorded during 1984 (10.78 ppm). It is also noted that the order of biologically available heavy metals in sediment is similar to that of dissolved heavy metals (Zn > Cu > Pb).

Discussion

Ocean acidification is predicted to occur under current IPCC CO_2 emissions scenarios (Houghton et al. 2001). Around 50% of the emissions of carbon dioxide are being absorbed by the oceans, increasing the pCO_2 with a concomitant decrease in the surface pH by 0.3–0.4 units by the end of the century (Feely et al. 2004; Caldeira and Wickett 2005; Orr et al. 2005). At present, the carbon dioxide interaction with seawater reduces the carbonate ion concentration, which is thought to regulate the calcification of extracellularly calcifying organisms (Spero et al. 1997; Marubini et al. 2008). This process is governed by the $CaCO_3$ saturation state (Ω $(CO_3{}^{2-})(Ca^{2+})/K^*_{sp}$), where K^*_{sp} is the apparent stoichiometric solubility product. For values of $\Omega < 1$ (undersaturated), seawater is corrosive, and dissolution may proceed (Isaji 1995). The process triggers the rate of dissolution of precipitated heavy metals from the sediment compartment to the water column and alters the speciation of selected heavy metals in the study area. The scatter plots (Figs. 3.18, 3.19, 3.20, 3.21, 3.22 and 3.23) explain the significant negative and positive relationships of aquatic pH with dissolved and biologically available heavy metals in surface sediments respectively. The R^2 values stated in Figs. 3.18, 3.19, 3.20, 3.21, 3.22 and 3.23 indicate strong inverse relationships between aquatic pH and dissolved heavy metals. However, with biologically available heavy metals, the positive relationship is highly significant for Zn, and moderately significant for Cu and Pb.

The present findings may serve as baseline report to link the climate change induced aquatic pH variation with pollution level of the estuarine and coastal waters. The results of the study also suggest that heavy metal concentrations in coastal and

Fig. 3.19 Inter-relationship between dissolved Cu and pH

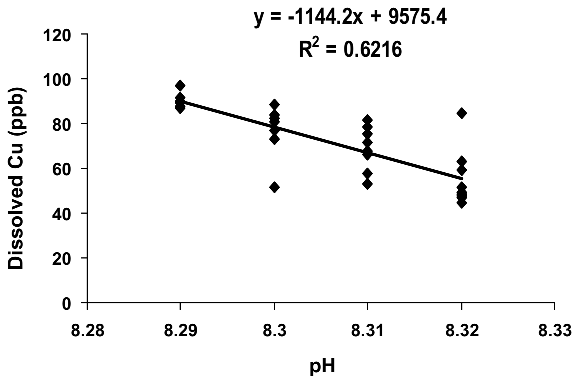


Fig. 3.20 Inter-relationship between dissolved Pb and pH

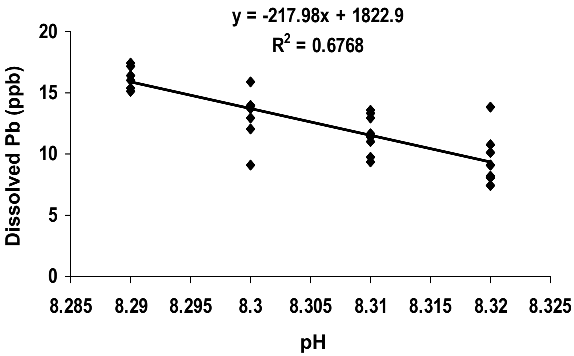
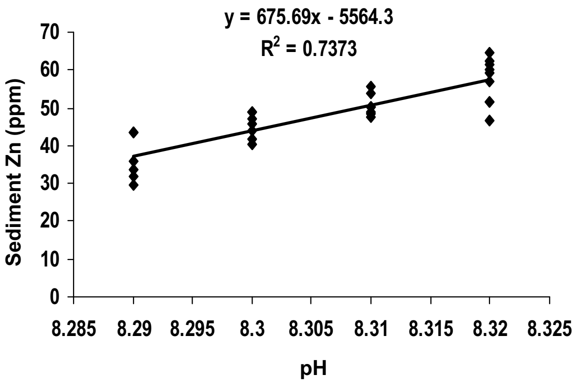


Fig. 3.21 Inter-relationship between sediment Zn and pH



estuarine waters need to be monitored considering the phenomenon of acidification, which is a major driver in altering the species of heavy metals in the coastal and estuarine ecosystem. The subject needs further studies and researches as acidification may trigger the process of bioaccumulation of heavy metals in edible estuarine

Fig. 3.22 Inter-relationship between sediment Cu and pH

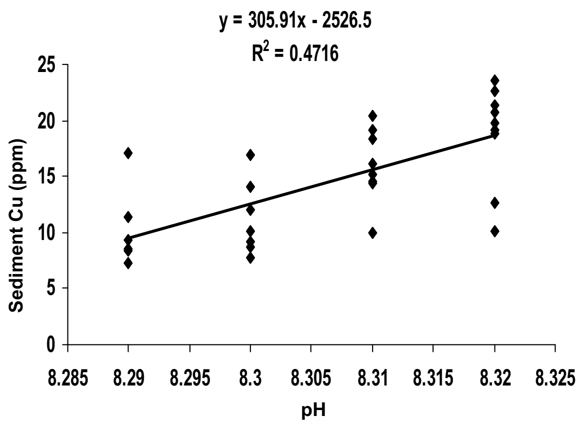
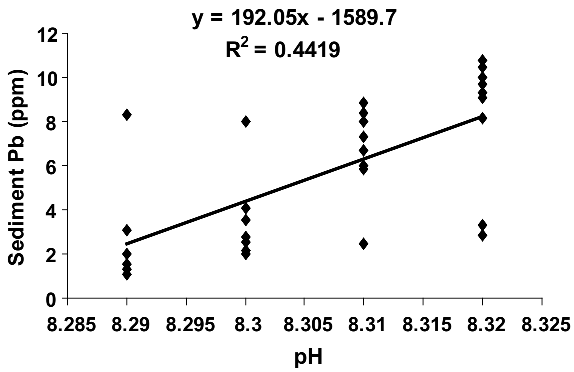


Fig. 3.23 Inter-relationship between sediment Pb and pH



species (like fishes, crabs, oysters, shrimps etc.) and pose subsequent vulnerability to human health.

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Chapter 4
Impact of Acidification on Molluscs

Abstract The lowering of pH of the coastal and estuarine waters lead to a shortage of carbonate, which is the primary building block to build the shells of corals and molluscs. The main groups of animals that are highly vulnerable to acidification, apart from corals are oysters, clams, crabs and lobsters. The present chapter depicts the vulnerability of these shelled organisms to acidification with special focus on edible oyster (*Saccostrea* spp.) in which thinning of shell is observed with the lowering of ambient aquatic pH. The ground zero data obtained directly from the field study in Indian Sundarbans shows a direct relationship between aquatic pH and thickness of the oyster shell.

4.1 Estuarine Molluscan Community: An Overview

Mollusca constitutes a very large phylum in the domain of invertebrate animals with around 1,25,000 living species. This phylum encompasses of about 23% of all marine organisms and has six major classes (Table 4.1).

Members of this phylum have soft body with hard calcareous shell. However, in some groups of terrestrial slugs the shell is greatly reduced and sometimes internal which is basically functionless. Marine shelled molluscs have a complex life cycle in which the larval stage is pelagic and the adult stage is benthic in nature. Molluscs provide several ecosystem services which can be categorized into provisioning, regulating, supporting and cultural services (Table 4.2).

The major species of gastropods found in coastal and estuarine waters are listed in Table 4.3

Bivalves are amongst the important classes of phylum mollusca. They constitute a large class of molluscs, also known as pelecypods and possess hard calcareous shell made of two parts or 'valves'. Few bivalves are carnivorous in nature, eating much larger prey than the tiny microalgae eaten by other bivalves. The best known examples of bivalves are clams, mussels, scallops and oysters. Gigantic shaped bivalves weighing about 5 kg are also seen in the marine and coastal ecosystems. Some common bivalves of the coastal and estuarine waters are listed in Table 4.4.

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Table 4.1 Major classes of phylum mollusca with examples

Class	Example
Bivalvia	*Saccostrea cucullata, Crassostrea cuttackensis, C. madrasensis, Macoma birmanica*
Gastropoda	*Telescopium telescopium, Cerithedia obtusa, C. cingulata*
Cephalopoda	*Loligo indica*, *Octopus rugosus*, *Octopus alatus*
Polyplacophora	*Cryptochiton stelleri*, *Chaetopleura apiculata*
Scaphopoda	*Dentalium laqueatum*
Monoplacophora	*Neopilina galathea*

Table 4.2 Ecosystem services of molluscs

Ecosystem service type	Description
Provisioning	Molluscan meat/flesh is a source of food, shells of molluscs are used as decorative items, calcium of molluscan shell is used in pharmaceutical industries
Regulating	Bioremediation, carbon sequestration
Supporting	Oyster bed serves as substratum of several marine and estuarine organisms like sea anemone, barnacles, seaweeds etc.
Cultural	Conch is used in several religious rituals

Apart from class gastropoda and bivalvia, phylum mollusca also encompasses class cephalopoda, which has representatives in coastal and marine ecosystems. They are characterized by a completely merged head and foot, with a ring of arms and/or tentacles surrounding the head. Few estuarine cephalopods are listed in Table 4.5.

The mangrove ecosystem is highly dynamic as water covers almost one-third of the tree during high tide (Fig. 4.1), but it is also noted for its vast intertidal mudflats that get exposed during low tide (Fig. 4.2).

In mangrove forest, molluscs occupy almost all the levels in the food web such as predators, herbivores, detritus and filter feeders, and thus they play an important role in maintaining the function and productivity of mangroves. Gastropods and bivalves are the two major classes of phylum mollusca occupying mangrove forest areas. These macrobenthic molluscs can be broadly grouped under three categories on the basis of their niche preference namely (i) epifauna—those living on mud or surface area of the land, (ii) infauna—those burying themselves in the substratum, and (iii) arboreal—mostly living on the vegetation.

Examples of epifauna are *Telescopium telescopium*, *Cerithedia cingulata* etc. (Fig. 4.3).

Macoma birmanica is an infauna widely found in the intertidal mudflat of Sundarbans, which is under class bivalvia and possesses inhalant and exhalent siphons for in-taking of food materials and expulsion of wastes respectively (Fig. 4.4). *Cerithedia obtusa* is a very common arboreal gastropod that is found grazing on the algal mat on mangrove stem (Fig. 4.5).

Table 4.3 Major gastropod species found in coastal and estuarine waters

S. No.	Gastropod species
1	*Amaea acuminate*
2	*Assiminea beddomeana*
3	*Assiminea brevicula*
4	*Assiminea francesiae*
5	*Assiminea hungerfordiana*
6	*Assiminea microsculpta*
7	*Assiminea nitida*
8	*Assiminea theobaldiana*
9	*Assiminea woodmasoniana*
10	*Auricula translucens*
11	*Batillaria sordid*
12	*Bulla ampulla*
13	*Canarium erythrinum*
14	*Cassidula aurisfelis*
15	*Cassidula bensoni*
16	*Cassidula mustelina*
17	*Cassidula nucleus*
18	*Cerithidea alata*
19	*Cerithidea cingulata*
20	*Cerithidea decollate*
21	*Cerithidea djadjariensis*
22	*Cerithidea fluviatilis*
23	*Cerithidea obtuse*
24	*Cerithidea quadrata*
25	*Cerithidea weversi*
26	*Cerithium citrinum*
27	*Cerithium columna*
28	*Cerithium coralium*
29	*Cerithium scabridum*
30	*Cerithium trailli*
31	*Cerithium zonatum*
32	*Chicoreus brunneus*
33	*Cithon oualaniensis*
34	*Clathrella clathrata*
35	*Clithon bicolor*
36	*Clithon corona*
37	*Cuthona annandalei*

(continued)

Table 4.3 (continued)

S. No.	Gastropod species
38	*Cyclostrema (Tubiola) innocens*
39	*Dolomena variabilis*
40	*Dostia crepidularia*
41	*Drupella margariticola*
42	*Ellobium aurisjudae*
43	*Ellobium gangeticum*
44	*Elysia bangtawaensis*
45	*Engina alveolata*
46	*Ergalatax contracta*
47	*Ergalatax heptagonalis*
48	*Gangetica milicea*
49	*Haminoea crocata*
50	*Hemifusus pugilinus*
51	*Indoplanorbis exustus*
52	*Lambis (Lambis) lambis*
53	*Littoraria carinifera*
54	*Littoraria melanostoma*
55	*Littoraria scabra*
56	*Littoraria undulate*
57	*Littorina intermedia*
58	*Lunella cinerea*
59	*Mainwaringia paludomoidea*
60	*Mauritia Arabica*
61	*Melampus caffer*
62	*Melampus castaneus*
63	*Melampus ceylonicus*
64	*Melampus coffea*
65	*Melampus pulchella*
66	*Melampus singaporensis*
67	*Melampus striatus*
68	*Melanoides tuberculata*
69	*Mitra (Strigatella) paupercula*
70	*Mitra (Strigatella) scutulata*
71	*Monodonta (Monodonta) labio*
72	*Morula (Morula) anaxeres*
73	*Muricopsis bombayanus*
74	*Naquetia capucina*

(continued)

Table 4.3 (continued)

S. No.	Gastropod species
75	*Nassarius foveolatus*
76	*Nassarius globosus*
77	*Nassarius immerse*
78	*Nassarius olivaceus*
79	*Nassarius orissaensis*
80	*Nassarius stolatus*
81	*Nassarius subconstrictus*
82	*Nerita albicilla*
83	*Nerita articulate*
84	*Nerita chamaeleon*
85	*Nerita chameleon*
86	*Nerita crepidularia*
87	*Nerita insculpta*
88	*Nerita planospira*
89	*Nerita polita*
90	*Nerita semirugosa*
91	*Nerita squamulata*
92	*Nerita undulate*
93	*Neritina depressa*
94	*Neritina smithi*
95	*Neritina violacea*
96	*Nodilittorina*
97	*Notocochlis qualteriana*
98	*Notocochlis tigerina*
99	*Onchidium tenerum*
100	*Onchidium tigrinum*
101	*Onchidium typhae*
102	*Pascula ochrostoma*
103	*Peronia verruculata*
104	*Pila virens*
105	*Pila globosa*
106	*Planaxis sulcatus*
107	*Polinices tumidus*
108	*Potamacmaea fluviatilis*
109	*Potamides cingulatus*
110	*Pseudanachis duclosiana*
111	*Pseudonerita obtuse*

(continued)

Table 4.3 (continued)

S. No.	Gastropod species
112	*Pseudonerita sulculosa*
113	*Pugilina cochlidium*
114	*Purpura bufo*
115	*Purpura persica*
116	*Pythia plicata*
117	*Rhinoclavis (Rhinoclavis) sinensis*
118	*Rhinoclavis aspera*
119	*Rhinoclavis vertagus*
120	*Salinator burmana*
121	*Septaria caerulescens*
122	*Stenothyra blanfordiana*
123	*Stenothyra deltae*
124	*Syncera brevicula*
125	*Telescopium telescopium*
126	*Terebralia palustris*
127	*Thais (Thalessa) virgata*
128	*Thaisella blanfordi*
129	*Thaisella lacera*
130	*Thaisella tissoti*
131	*Thiara scabra*
132	*Umbonium vestiarium*
133	*Vanikoro cancellata*

Molluscs are known for their unique property to serve as indicator species. Macrobenthic molluscs can tolerate a wide range of environmental oscillation although to some molluscs like oyster, low salinity (below 10 psu) often poses stress on their survival. We have made an extensive study on the macrobenthic molluscan diversity in the estuaries of east coast of Indian sub-continent during May 2014–April 2015. The intertidal mudflats in four maritime states of India namely West Bengal (Shankarpur coast), Odisha (Bahuda estuary), Andhra Pradesh (East Godavari estuary) and Puducherry (Kalapet coast) were our selected sites. A total of 17 dominant species were observed under the molluscan community encompassing two major classes namely bivalvia and gastropoda. Population density by quadrat method was enumerated in all the sites to evaluate the magnitude of environmental stress (Figs. 4.6, 4.7, 4.8, 4.9, 4.10, 4.11, 4.12, and 4.13).

From the data of population density of each sites, we evaluated the Shannon—Weiner species diversity index as per the standard expression.

Table 4.4 Major bivalve species found in the coastal and estuarine waters

S. No.	Bivalve species
1	*Anadara granosa*
2	*Anadara rhombea*
3	*Bactronophorus thoracites*
4	*Bankia bipennata*
5	*Bankia campanellata*
6	*Bankia carinata*
7	*Bankia nordi*
8	*Bankia rochi*
9	*Barbatia candida*
10	*Barnea candida*
11	*Cardites bicolor*
12	*Codakia tigerina*
13	*Crassostrea cuttackensis*
14	*Crassostrea gryphoides*
15	*Crassostrea madrassensis*
16	*Crassostrea palmipes*
17	*Dicyathifer manni*
18	*Donax cuneatus*
19	*Donax incarnatus*
20	*Donax lubricus*
21	*Dosinia (Asa) tumida*
22	*Enigmonia aenigmatica*
23	*Gafrarium pectinatum*
24	*Geloina galatheae*
25	*Geloina siamica*
26	*Glauconome cerea*
27	*Glauconome chinensis*
28	*Isognomon ephippium*
29	*Katelysia opima*
30	*Laternula truncata*
31	*Lyrodus massa*
32	*Lyrodus pedicellatus*
33	*Macoma birmanica*
34	*Macoma qubernaculum*
35	*Mactra cuneata*
36	*Marcia opima*
37	*Martesia striata*

(continued)

Table 4.4 (continued)

S. No.	Bivalve species
38	*Meretrix attenuata*
39	*Meretrix casta*
40	*Meretrix meretrix*
41	*Modiolus americanus*
42	*Modiolus modulaides*
43	*Modiolus striatulus*
44	*Modiolus traillii*
45	*Modiolus undulatus*
46	*Nausitora dunlopei*
47	*Nausitora hedleyi*
48	*Nausitora hedleyi*
49	*Neotrapezium sublaevigatum*
50	*Nototeredo edax*
51	*Nuculana mauritiana*
52	*Paphia malabarica*
53	*Paphia undulata*
54	*Pelecyora trigona*
55	*Perna perna*
56	*Perna viridis*
57	*Pharella javanicus*
58	*Placenta placenta*
59	*Placuna placenta*
60	*Polymesoda bengalensis*
61	*Potamocorbula abbreviata*
62	*Saccostrea cucullata*
63	*Siliqua albida*
64	*Solen annandalei*
65	*Solen brevis*
66	*Solen kempi*
67	*Sphenia pedata*
68	*Strigilla splendida*
69	*Tanysiphon rivalis*
70	*Tegillarca granosa*
71	*Tellina ala*
72	*Tellina bruguieri*
73	*Tellina iridescens*
74	*Teredo furcifera*

(continued)

Table 4.4 (continued)

S. No.	Bivalve species
75	*Theora opalina*
76	*Uperotus rehderi*
77	*Villorita cyprinoides*

Table 4.5 Major cephalopods found in the coastal and estuarine waters

S. No.	Species
1	*Loligo indica*
2	*Octopus rugosus*
3	*Sepia aculeata*
4	*Sepia inermis*

Fig. 4.1 Mangrove forest almost under water during high tide

$$\text{Species diversity index } (H) = -\sum_{i=1}^{-s} Pi \log_e Pi$$

$$or, \quad (H) = -\sum_{i=1}^{-s} ni/N \text{ loge } ni/N$$

Fig. 4.2 Exposed inter-tidal mudflats in mangrove forest during low tide

where,

Pi = Importance probability for each species

ni = Importance value for each species

N = Total of importance values

S = Total number of species.

The Shannon—Weiner species diversity index, which is a mirror of degree of stress/congeniality ranged from 2.180 to 2.226 (in Shankarpur coast of West Bengal), 2.693 to 2.765 (in Bahuda estuary of Odisha), 2.176 to 2.474 in (East Godavari estuary of Andhra Pradesh) and 2.138 to 2.578 (in Kalapet coast of Puducherry). Considering the mean values of Shannon-Weiner species diversity index, it is observed that the value is highest in Bahuda estuary (2.787), followed by East Godavari estuary (2.638), Kalapet coast (2.599) and Shankarpur coast (2.278). The picture of lowest diversity index of macrobenthic molluscs in Shankarpur coast despite of considerable population density is the outcome of uneven distribution of population amongst the species, which is an indication of high degree of environmental stress in and around the selected sampling site (Figs. 4.14, 4.15, 4.16, and 4.17). The high degree of environmental stress may be attributed to lowering of pH as witnessed by us in a nearby station known as Digha (*vide* Table 4.6 for the long term data set), which is a popular tourist spot in the maritime state of West Bengal (21° 0.62′ 22″ N, 87° 50′ 66″ E).

Fig. 4.3 *Telescopium telescopium*—a common epifauna (under class gastropoda) in mangrove ecosystem of Indian Sundarbans

The present study has great implications as macrobenthic molluscan community is noted for its notable ecosystem services mainly in the verticals of bioremediation, biomonitoring (as indicator species), carbon storage, livelihood etc.

4.2 Effect of Acidification on Oyster Community

We have carried out an extensive literature survey to find out the researches related to the effects of acidification on marine and estuarine molluscan species and documented that the first study on this subject was performed by Loosanoff and Tommers (1947). In the present geographical locale impact of lowering of pH on molluscan community was documented by (Mitra and Zaman 2015). A thorough literature survey on the impact of acidification on shelled molluscs reveal several adverse impacts on the community as listed in Table 4.6.

Oyster is widely distributed in the coastal and estuarine waters of the maritime state of West Bengal. A long term study carried out for 35 years on the condition index (CI) of *Saccostrea cucullata* sampled from Digha sea beach in the maritime state of West Bengal revealed significant direct relationship between aquatic pH and condition index of the species (Table 4.7).

Fig. 4.4 *Macoma birmanica*—a common infauna (under class bivalvia) in the mangrove ecosystem of Indian Sundarbans

On the basis of more than three decade data bank (Table 4.8), we used Non-linear Autoregressive Neural Network Model to forecast the aquatic pH levels in Digha (with 30 years ahead time steps) and observed a significant decrease of pH in the coastal water of Digha as time progresses (Table 4.8 and Fig. 4.18).

In this study we have used condition index as proxy to evaluate the role of pH on the oyster health. More value of this index is an indication of congenial environmental variables for the growth and survival of the species. We observed a significant decrease of CI with the passage of time (Table 4.9) and using Nonlinear Autoregressive Neural Network Model to forecast the CI, we observe the adverse impact of coastal acidification on the health of the oyster species, *Saccostrea cucullata* from the output data. The CI value has decreased with time and has touched 4.93 in 2050 (Fig. 4.19).

Another important impact of acidification on molluscan species is the enhancement of heavy metal level in the body tissues of bivalves and gastropods. We have made a time series analysis on the heavy metal levels in selective molluscan species and observed that the values increased in the species inhabiting Hooghly estuary, but decreased in the species sampled from Matla estuary (Tables 4.10, 4.11, 4.12, 4.13, 4.14, and 4.15). This variation may be attributed to a number of factors like distribution, mobility, biological availability of chemical elements (*i.e.* it's chemical or physical association), pH, redox potential and availability of reactive species such

Fig. 4.5 *Cerithedia obtusa*—an arboreal gastropod in the mangrove ecosystem of Indian Sundarbans

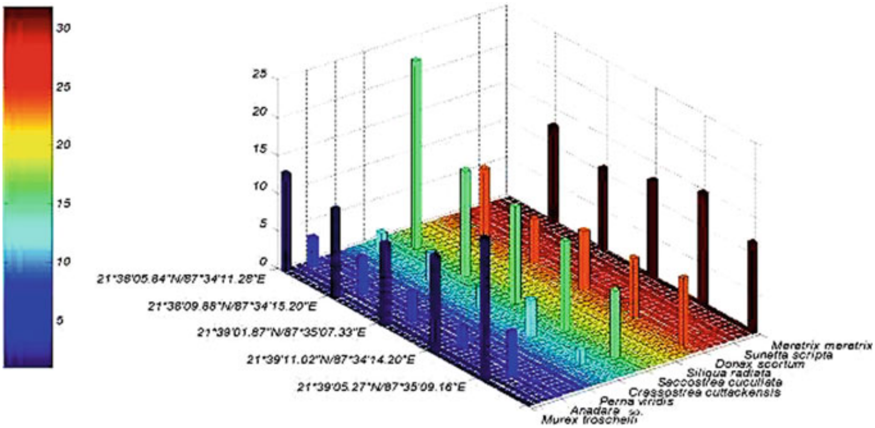

Fig. 4.6 Population density of bivalve species in the Shankarpur coast of West Bengal; value for each coordinate represents the mean value of 10 quadrates

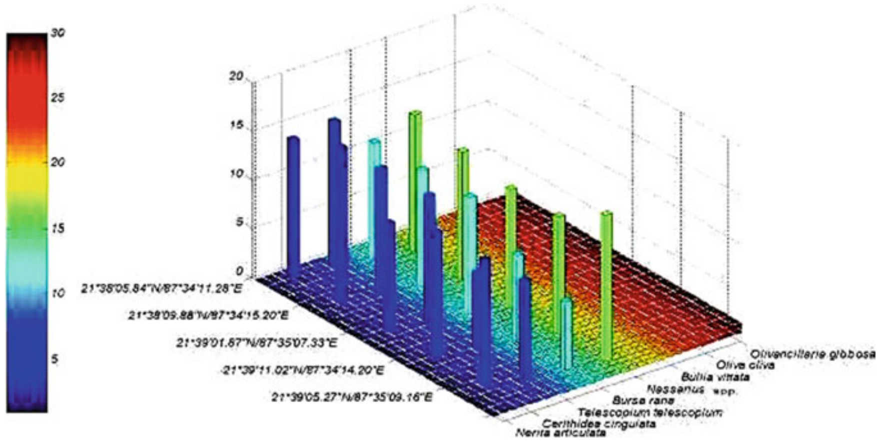

Fig. 4.7 Population density of gastropod species in the Shankarpur coast of West Bengal; value for each coordinate represents the mean value of 10 quadrates

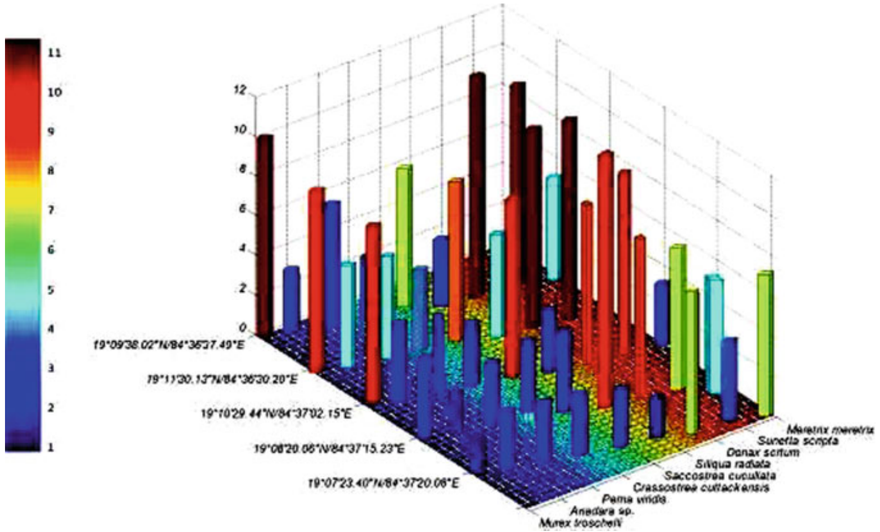

Fig. 4.8 Population density of bivalve species in the Bahuda estuary of Odisha; value for each coordinate represents the mean value of 10 quadrates

as complexing ligands (organic and inorganic), particle surface for adsorption and colloidal matter etc. In the present study, such in-depth effort has not been attempted, but significant negative correlations between aquatic pH and dissolved heavy metals confirm the role of pH as one of the major factors influencing chemical speciation of the heavy metals in the present geographical locale. The lowering of pH might

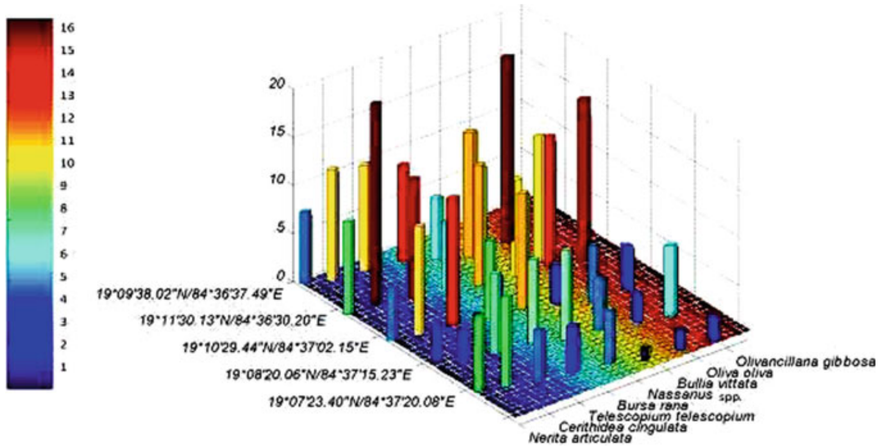

Fig. 4.9 Population density of gastropod species in the Bahuda estuary of Odisha; value for each coordinate represents the mean value of 10 quadrates

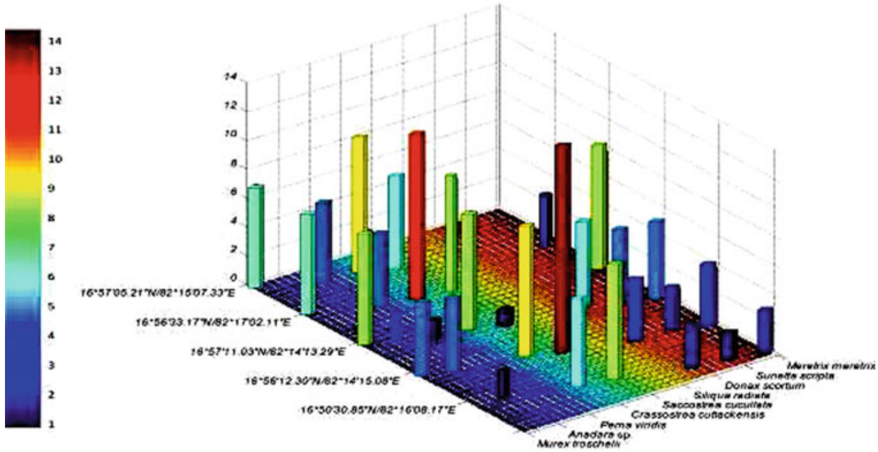

Fig. 4.10 Population density of bivalve species in the East Godavari estuary of Andhra Pradesh; value for each coordinate represents the mean value of 10 quadrates

facilitate the dissolution of the precipitated form of metals and increase the amount of metallic ions in solutions, which has great role in the process of bioaccumulation.

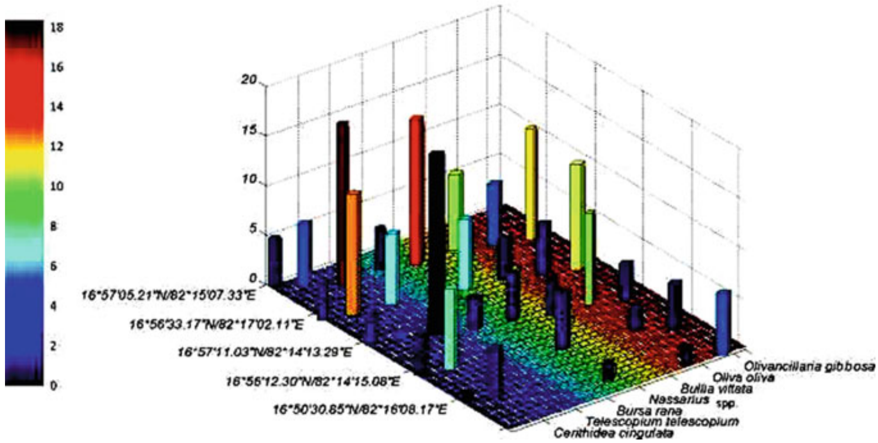

Fig. 4.11 Population density of gastropod species in the East Godavari estuary of Andhra Pradesh; value for each coordinate represents the mean value of 10 quadrates

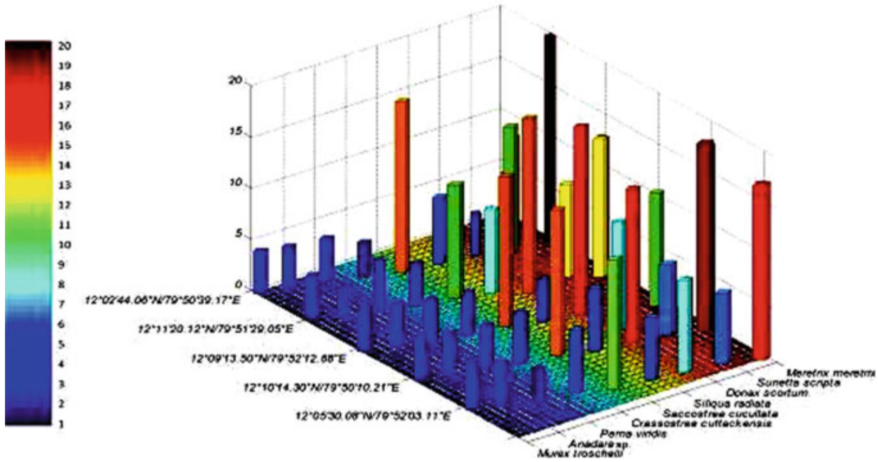

Fig. 4.12 Population density of bivalve species in the Kalapet coast of Puducherry; value for each coordinate represents the mean value of 10 quadrates

4.3 Molluscs as Potential Sink of Carbon

The present work stands on the consideration of the molluscan community under the banner of blue carbon primarily because of their habitat in the marshy wetlands, mangroves, sea grass bed, saltmarsh grass bed, coastal zones, estuaries, river mouths and seas and also their ability to store carbon. Carbon is a major constituent of the calcareous hard shell over the body of molluscan organisms. However, acidification, a strong arm of climate change has posed a negative impact on this community by

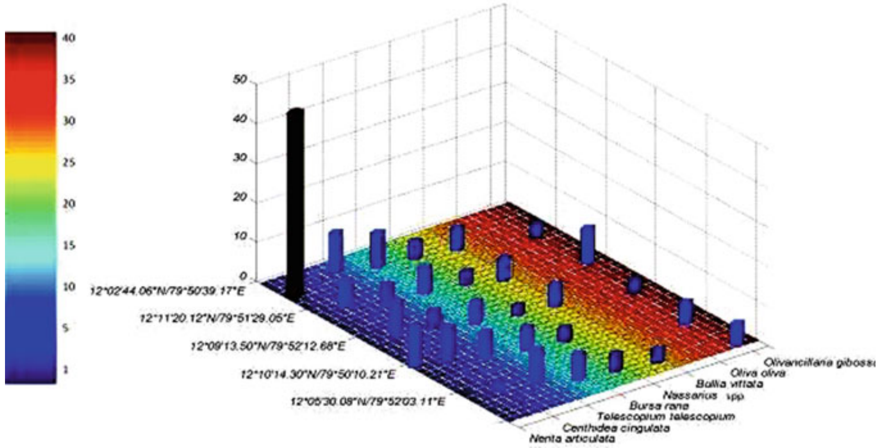

Fig. 4.13 Population density of gastropod species in the Kalapet coast of Puducherry; value for each coordinate represents the mean value of 10 quadrates

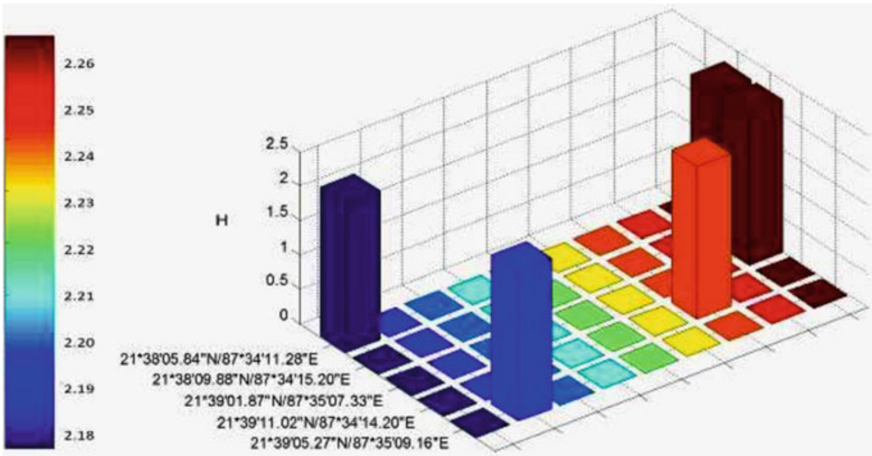

Fig. 4.14 Shannon—Weiner species diversity index of macrobenthic molluscan community in the Shankarpur coast of West Bengal

way of dissolving and thinning their calcareous shell. Filter-feeding oysters, clams or mussels sequester significant amounts of carbon by consuming phytoplankton and absorbing dissolved organic matter. Carbon is a primary component of oyster shell and it has been observed that for every kilogram of live clams or oysters grown in Florida waters approximately 114 g of carbon are removed from the water column and benthos. Stored carbon has also been documented in gastropod species (Jurkiewicz-Karnakowska 2005), which are mostly detritivores. On this background

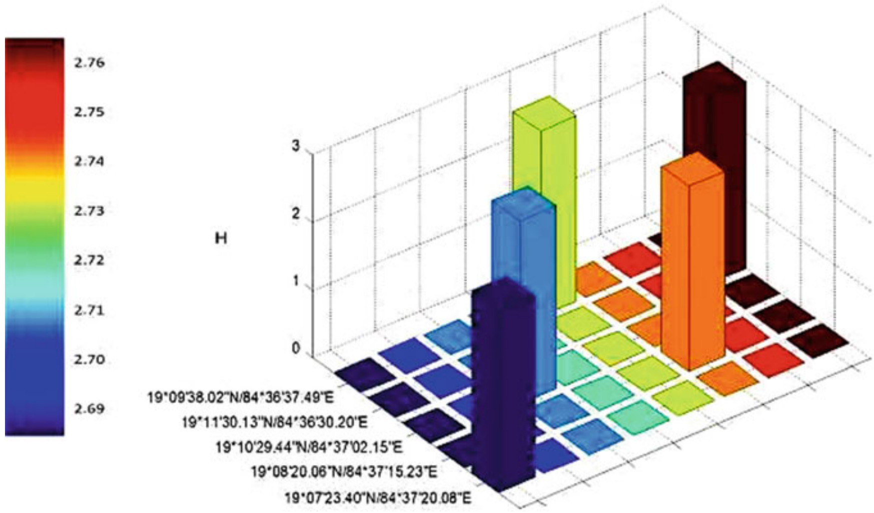

Fig. 4.15 Shannon—Weiner species diversity index of macrobenthic molluscan community in the Bahuda estuary of Odisha

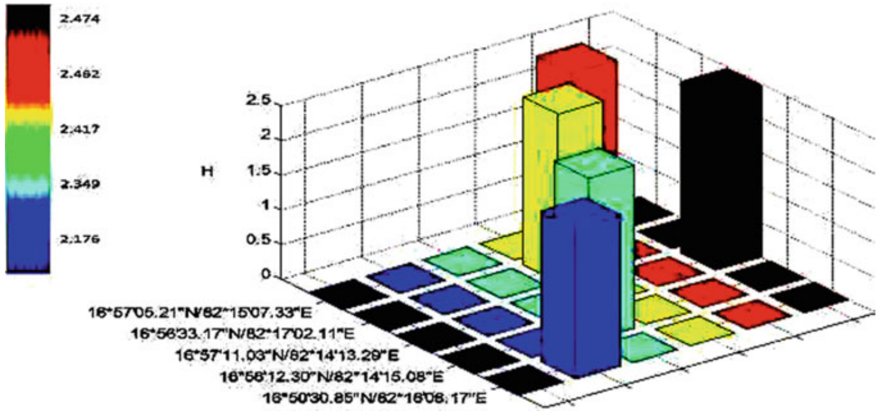

Fig. 4.16 Shannon—Weiner species diversity index of macrobenthic molluscan community in the East Godavari estuary of Andhra Pradesh

the present section aims to quantify the stored carbon in major (dominant) macrobenthic species of molluscs preferably bivalves and gastropods sampled from the intertidal mudflats selected in two maritime states and one Union territory of India namely West Bengal (Hooghly estuary of Indian Sundarbans), Puducherry (Kalapet coast) and Goa (Mandovi estuary) during 2014 and 2015 (Tables 4.16, 4.17, 4.18, 4.19, 4.20, 4.21 and Figs. 4.20, 4.21, 4.22, 4.23, 4.24, 4.25).

The results for the present programme are summarized below in Table 4.22 shows

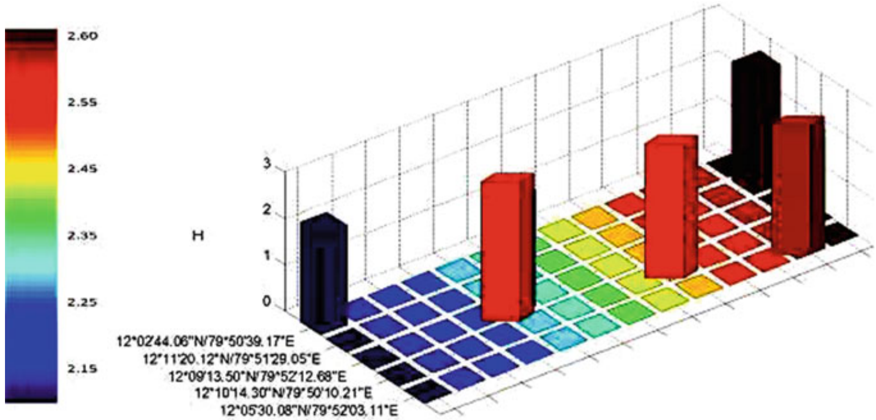

Fig. 4.17 Shannon—Weiner species diversity index of macrobenthic molluscan community in the Kalapet coast of Puducherry

Table 4.6 Probable adverse impact of acidification on shelled molluscs due to alteration of aquatic pH

pH alteration	Impact
Lesser than 7.5	• Increase of shell dissolution • Decrease of growth rate • Decrease of condition index
Less than 7	• Reduction of filtration rate • Increase of heart beat • Reduction of feeding rate and flesh weight
Less than 6.5	• Increased mortality • Abnormal behavior • Decrease of condition index

the ANOVA results that depict the spatio-temporal variation of stored carbon in flesh (Fig. 4.21) and shell of the selected molluscan species.

The significant difference in stored carbon in the flesh of the selected macrobenthic molluscs is primarily due their food preference. *Saccostrea cucullata*, a dominant bivalve is common in almost all the coastal zones of Indian sub-continent. They are filter feeding bivalves and obtain their carbon from phytoplankton. The gastropods are also the store house of carbon as evidenced from the concentrations of total carbon (% dry weight) in their soft tissues and shells. One of the most important sources of carbon in marine and estuarine gastropods is their diets, which mainly are macroalgae or seaweeds on the mangrove vegetation (preferably on mangrove trunk/stem) or detritus on the intertidal mudflats. *Cerithedia obtusa* is fully dependent on algal matter for nutrition and *N. articulata* prefers both algal feed as well as detritus. *T. telescopium* and *C. cingulata* are detritivores.

Table 4.7 Aquatic pH and condition index of *Saccostrea cucullata* sampled during the month of May (premonsoon season) from the Digha sea beach (21° 0.62′ 22″ N, 87° 50′ 66″ E) of coastal West Bengal

Year	Aquatic pH	Condition index (CI)
1984	8.33	16.35
1985	8.33	15.98
1986	8.33	15.88
1987	8.32	16.05
1988	8.31	15.42
1989	8.32	13.39
1990	8.31	14.65
1991	8.30	15.08
1992	8.30	13.55
1993	8.28	12.80
1994	8.26	12.95
1995	8.28	11.98
1996	8.27	12.60
1997	8.25	12.45
1998	8.26	11.90
1999	8.24	10.67
2000	8.24	10.50
2001	8.22	11.26
2002	8.21	11.45
2003	8.19	10.78
2004	8.20	9.88
2005	8.17	9.70
2006	8.20	9.66
2007	8.19	8.78
2008	8.18	8.59
2009	8.35	8.44
2010	8.16	8.38
2011	8.16	8.95
2012	8.15	8.20
2013	8.14	8.15
2014	8.17	7.69
2015	8.14	8.25
2016	8.14	6.90
2017	8.14	6.82
2018	8.13	6.35
2019	8.12	6.37
2020	8.32	6.20

Table 4.8 Forecasting of aquatic pH in Digha using Autoregressive Neural Network Model

Year	Predicted pH in May (premonsoon season)
2021	8.17
2022	8.18
2023	8.19
2024	8.22
2025	8.21
2026	8.23
2027	8.21
2028	8.22
2029	8.21
2030	8.22
2031	8.21
2032	8.22
2033	8.21
2034	8.22
2035	8.21
2036	8.22
2037	8.21
2038	8.22
2039	8.21
2040	8.22
2041	8.21
2042	8.22
2043	8.21
2044	8.22
2045	8.21
2046	8.22
2047	8.21
2048	8.22
2049	8.21
2050	8.22

The shelled organisms preferably the molluscs are important store houses of carbon. A number of physical, chemical, and biological processes/factors carry out carbon sequestration in molluscs. The filter feeding bivalves like oysters source their carbon from their diet (phytoplankton) and ambient aquatic phase. Gastropods also play a significant role both in accumulation and circulation of carbon, especially in habitats where they are numerous and their biomass is high. However, studies concerning these problems are scarce.

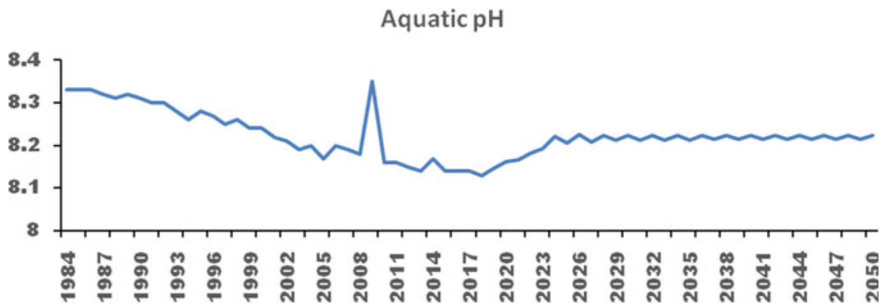

Fig. 4.18 Predicted aquatic pH in Digha coast during May (premonsoon season) using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2020 has been used as training in the model

Table 4.9 Forecasting decrease of CI of *Saccostrea cucullata* using Non-linear Autoregressive Neural Network Model to forecast the CI

Year	Predicted CI value of *Saccostrea cucullata* in May (premonsoon season)
2021	4.06
2022	5.34
2023	6.03
2024	5.74
2025	4.98
2026	4.41
2027	4.65
2028	5.47
2029	5.82
2030	5.51
2031	4.92
2032	4.60
2033	4.91
2034	5.51
2035	5.69
2036	5.37
2037	4.90
2038	4.73
2039	5.07
2040	5.52
2041	5.58

(continued)

Table 4.9 (continued)

Year	Predicted CI value of *Saccostrea cucullata* in May (premonsoon season)
2042	5.27
2043	4.90
2044	4.84
2045	5.17
2046	5.51
2047	5.50
2048	5.20
2049	4.91
2050	4.93

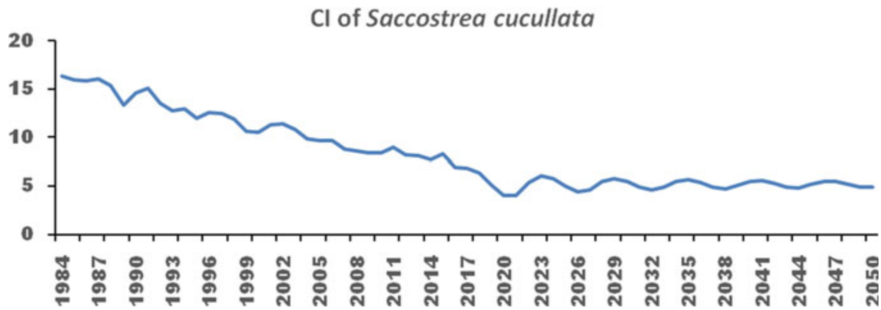

Fig. 4.19 Predicted CI values of oyster sampled from Digha coast during May (premonsoon season) using Nonlinear Autoregressive Neural Network Model; real time data from 1984 to 2020 has been used as training in the model

Terrestrial gastropods ingest water from multiple sources, including dew, soil moisture, standing water, and precipitation, all of which contain some amount of dissolved inorganic carbon (DIC). Water is taken up through the foot of the gastropod by contact rehydration (Balakrishnan and Yapp 2004) and introduced to the hemolymph before being passed on to the extrapallial fluid. The soft fleshy meat and shells of gastropods and bivalves is store house of carbon as evidenced from the concentrations of total carbon (% dry weight) in the soft tissues and shells of these organisms.

There is a need to estimate the carbon storage potential of molluscs so that in the future policy programme on climate change this phyla constituting about 23% of identified marine organisms can be an important vertical.

Table 4.10 Zn concentrations (in ppm dry wt.) in molluscan flesh collected from Hooghly estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	411.05	413.84	417.37	411.87	419.18	423.09	427.12	417.43	418.95	427.56
Nerita articulata	213.38	216.65	219.90	215.76	230.76	226.85	232.76	231.89	233.05	235.71
Cerithedia cingulata	118.78	119.17	122.56	121.09	133.88	136.89	141.34	147.21	140.66	150.82
C. obtusa	124.55	130.99	134.11	137.05	140.66	141.88	143.90	149.06	152.67	159.25
Saccostrea cucullata	664.23	669.34	711.34	778.45	787.98	808.33	837.99	847.21	858.48	1110.34

Table 4.11 Zn concentrations (in ppm dry wt.) in molluscan flesh collected from Matla estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	219.66	213.50	189.54	176.32	168.88	163.95	155.87	139.43	141.12	127.94
Nerita articulata	176.44	170.05	166.58	162.96	160.18	153.22	141.78	126.90	133.85	114.20
Cerithedia cingulata	103.45	112.56	98.34	91.07	89.22	87.15	77.95	71.02	66.29	55.12
C. obtusa	107.35	111.20	100.66	114.67	103.88	99.67	89.22	84.28	73.17	62.08
Saccostrea cucullata	487.45	434.76	423.98	411.90	398.45	346.77	338.31	332.97	317.56	298.93

Table 4.12 Cu concentrations (in ppm dry wt.) in molluscan flesh collected from Hooghly estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	29.61	27.89	25.20	30.19	37.18	41.45	59.38	64.81	73.44	87.98
Nerita articulata	17.38	18.65	19.90	21.76	27.76	25.85	36.76	47.89	58.05	68.71
Cerithedia cingulata	14.56	15.09	14.99	16.56	20.98	18.02	28.34	39.42	49.67	53.14
C. obtusa	15.12	16.65	18.12	18.70	19.02	20.56	32.87	39.99	52.65	55.05
Saccostrea cucullata	47.88	55.34	65.15	70.05	77.34	50.10	61.97	74.08	80.53	91.22

Table 4.13 Cu concentrations (in ppm dry wt.) in molluscan flesh collected from Matla estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	21.09	25.85	22.28	28.32	27.61	24.66	23.78	21.90	25.78	20.27
Nerita articulata	14.33	12.50	11.76	11.84	14.39	12.62	11.35	10.55	9.21	8.56
Cerithedia cingulata	13.02	12.17	11.80	11.63	10.98	8.02	8.28	7.06	6.44	5.14
C. obtusa	14.75	13.70	15.55	15.70	13.33	9.71	11.94	11.60	10.65	7.05
Saccostrea cucullata	33.95	35.06	34.28	30.15	27.08	30.79	26.42	21.01	20.57	18.40

Table 4.14 Pb concentrations (in ppm dry wt.) in molluscan flesh collected from Hooghly estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	6.09	6.15	6.98	7.84	8.05	9.11	12.18	11.65	14.44	15.43
Nerita articulata	5.12	5.88	6.04	6.66	6.97	8.05	7.94	9.16	11.98	12.75
Cerithedia cingulata	3.76	3.11	4.99	5.30	5.51	6.08	6.49	6.35	7.09	7.45
C. obtusa	4.08	4.76	5.45	5.87	6.91	6.28	7.78	7.60	8.12	8.39
Saccostrea cucullata	10.34	16.72	16.41	17.23	20.90	18.55	22.30	15.65	23.92	25.63

Table 4.15 Pb concentrations (in ppm dry wt.) in molluscan flesh collected from Matla estuary during June of every year

Species	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Telescopium telescopium	5.12	4.85	3.70	3.84	2.05	2.11	2.02	1.96	1.87	BDL
Nerita articulata	3.56	2.27	2.88	1.75	1.32	1.05	BDL	BDL	BDL	BDL
Cerithedia cingulata	2.08	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
C. obtusa	2.97	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL
Saccostrea cucullata	8.03	7.59	7.27	6.68	5.49	3.21	3.85	2.99	3.62	2.85

Table 4.16 Concentrations of total carbon (% dry wt) in the soft tissues of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during premonsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	36.02 ± 0.63	35.13 ± 0.68	34.98 ± 0.74
Nerita articulata	36.99 ± 0.64	36.38 ± 0.76	35.19 ± 0.74
Cerithedia cingulata	35.15 ± 0.66	33.28 ± 0.65	33.02 ± 0.72
C. obtusa	39.14 ± 0.91	38.46 ± 0.89	37.33 ± 0.86
Saccostrea cucullata	40.15 ± 0.92	39.83 ± 0.90	38.17 ± 0.87

Table 4.17 Concentrations of total carbon (% dry wt) in the soft tissues of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during monsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	35.23 ± 0.63	34.41 ± 0.68	33.20 ± 0.74
Nerita articulata	34.98 ± 0.64	33.05 ± 0.76	32.49 ± 0.74
Cerithedia cingulata	33.03 ± 0.66	32.14 ± 0.65	32.05 ± 0.72
C. obtusa	37.29 ± 0.91	35.30 ± 0.89	34.93 ± 0.86
Saccostrea cucullata	38.24 ± 0.92	36.21 ± 0.90	34.99 ± 0.87

Table 4.18 Concentrations of total carbon (% dry wt) in the soft tissues of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during postmonsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	35.00 ± 0.63	34.20 ± 0.68	34.20 ± 0.74
Nerita articulata	35.96 ± 0.62	34.06 ± 0.77	33.50 ± 0.75
Cerithedia cingulata	34.04 ± 0.67	33.15 ± 0.66	33.06 ± 0.73
C. obtusa	38.30 ± 0.92	36.31 ± 0.90	33.94 ± 0.87
Saccostrea cucullata	39.25 ± 0.93	37.22 ± 0.91	35.98 ± 0.88

Table 4.19 Concentrations of total carbon (% dry wt) in the calcareous shell of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during premonsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	12.98 ± 0.11	12.56 ± 0.12	12.33 ± 0.13
Nerita articulata	13.03 ± 0.12	13.00 ± 0.14	12.96 ± 0.15
Cerithedia cingulata	12.59 ± 0.09	12.43 ± 0.10	12.05 ± 0.12
C. obtusa	13.99 ± 0.18	13.83 ± 0.17	13.05 ± 0.16
Saccostrea cucullata	14.23 ± 0.19	13.97 ± 0.18	13.55 ± 0.17

Table 4.20 Concentrations of total carbon (% dry wt) in the calcareous shell of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during monsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	12.98 ± 0.11	12.56 ± 0.12	12.33 ± 0.13
Nerita articulata	13.03 ± 0.12	13.00 ± 0.14	12.96 ± 0.15
Cerithedia cingulata	12.59 ± 0.09	12.43 ± 0.10	12.05 ± 0.12
C. obtusa	13.99 ± 0.18	13.83 ± 0.17	13.05 ± 0.16
Saccostrea cucullata	13.09 ± 0.17	12.98 ± 0.16	12.57 ± 0.14

Table 4.21 Concentrations of total carbon (% dry wt) in the soft tissues of the investigated gastropod and bivalve species (mean values and standard deviations) collected from three selected sampling sites during postmonsoon 2014–2015

Species	Station		
	Hooghly estuary (Indian Sundarbans)	Mandovi estuary (Goa)	Kalapet coast (Puducherry)
	Carbon (%)		
Telescopium telescopium	35.00 ± 0.63	34.20 ± 0.68	34.20 ± 0.74
Nerita articulata	35.96 ± 0.62	34.06 ± 0.77	33.50 ± 0.75
Cerithedia cingulata	34.04 ± 0.67	33.15 ± 0.66	33.06 ± 0.73
C. obtusa	38.30 ± 0.92	36.31 ± 0.90	33.94 ± 0.87
Saccostrea cucullata	39.25 ± 0.93	37.22 ± 0.91	35.98 ± 0.88

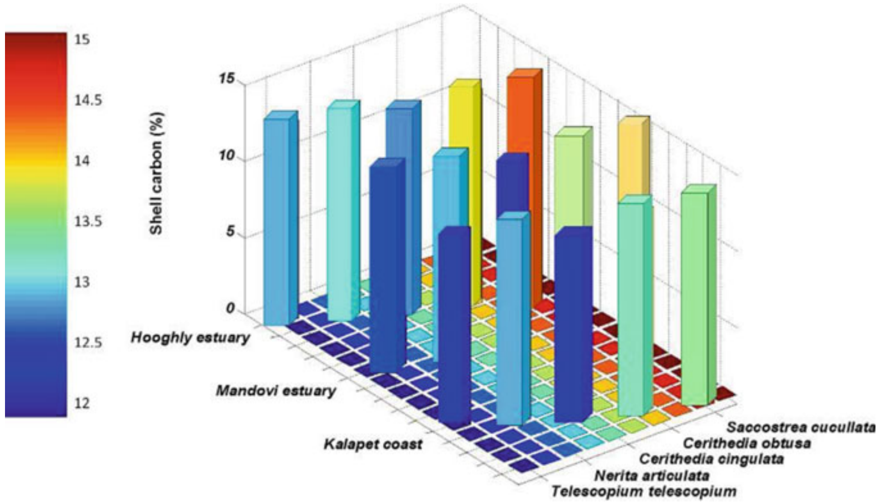

Fig. 4.20 Stored carbon percentage in flesh of dominant molluscan species in premonsoon season during 2014–15

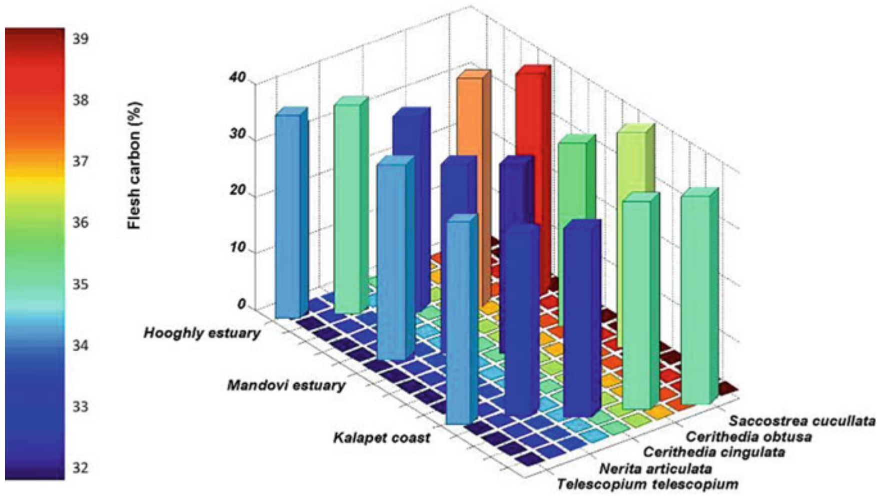

Fig. 4.21 Stored carbon percentage in flesh of dominant molluscan species in monsoon season during 2014–15

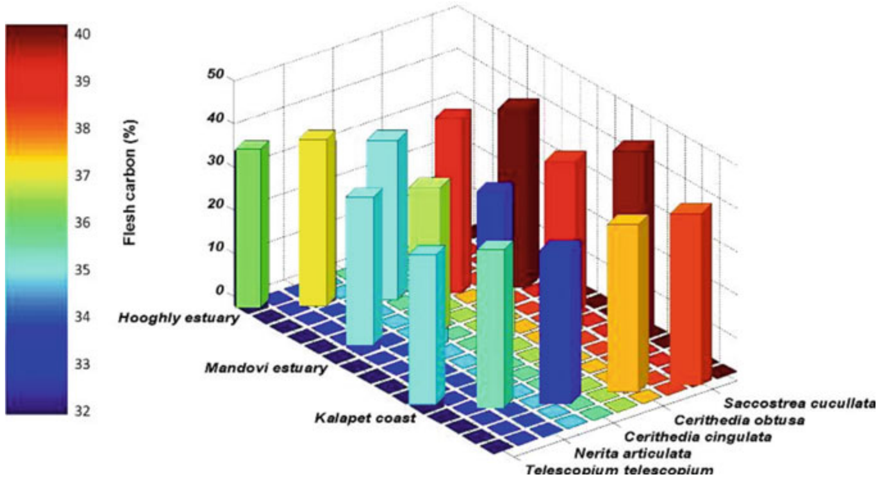

Fig. 4.22 Stored Carbon Percentage in Flesh of Dominant Molluscan Species in postmonsoon Season during 2014–15

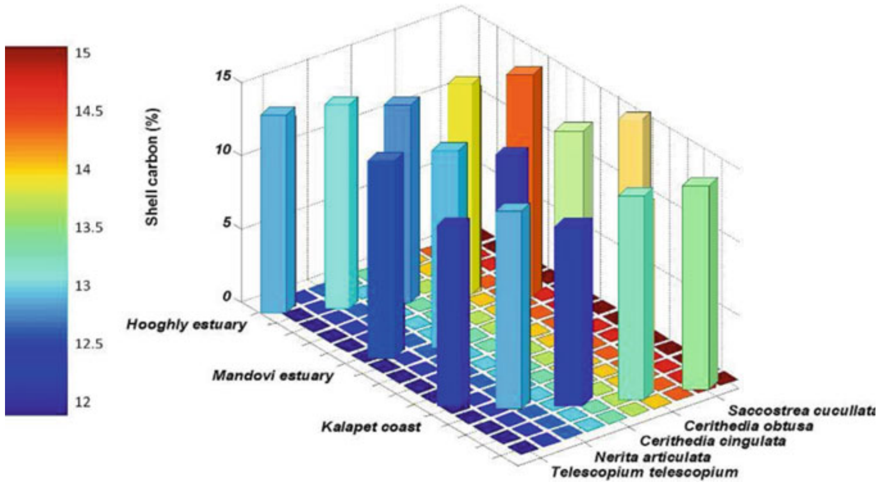

Fig. 4.23 Stored carbon percentage in shell of dominant molluscan species in premonsoon season during 2014–15

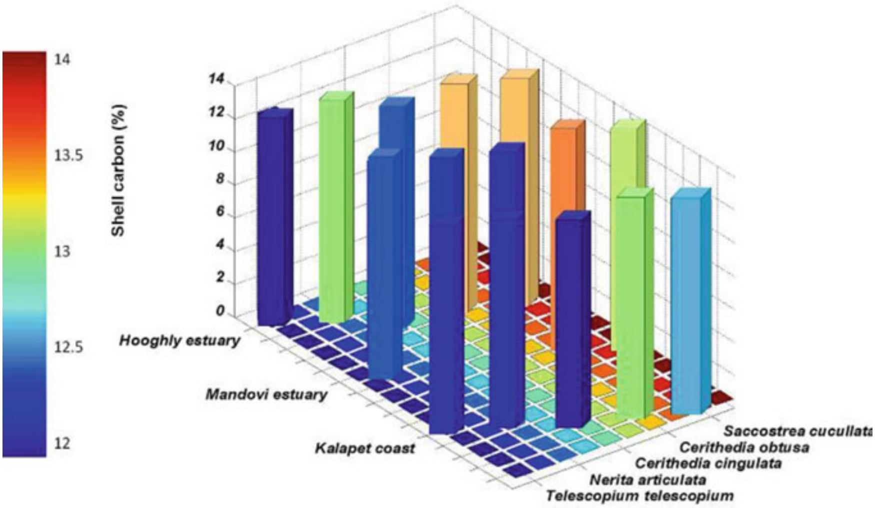

Fig. 4.24 Stored carbon percentage in shell of dominant molluscan species in monsoon season during 2014–15

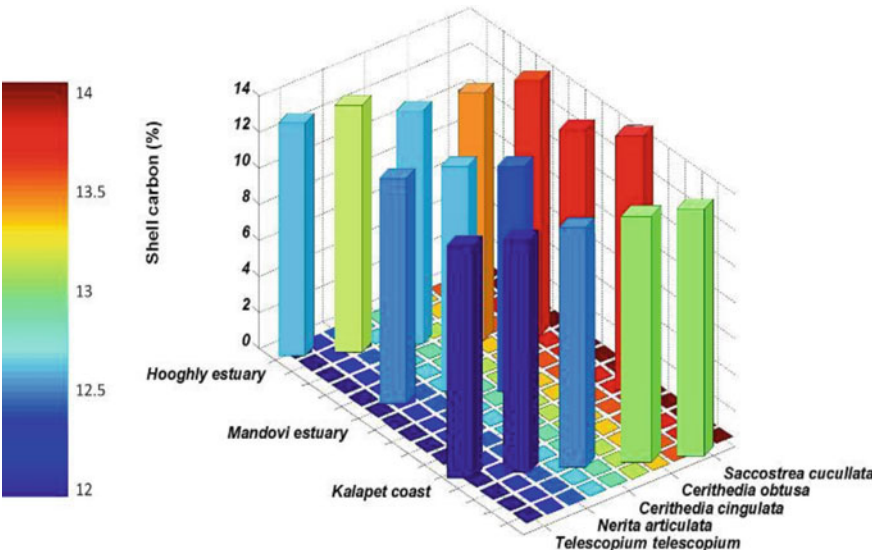

Fig. 4.25 Stored carbon percentage in shell of dominant molluscan species in postmonsoon season during 2014–15

Table 4.22 ANOVA results of flesh and shell carbon of selected molluscan species

Parameter	F_{obs}	F_{crit}	*p*-value
Species			
Telescopium telescopium (flesh)			
Between stations	8.939198	6.944272	0.033426
Between seasons	7.185884	6.944272	0.047404
Telescopium telescopium (shell)			
Between stations	59.69737	6.944272	0.001051
Between seasons	26.61842	6.944272	0.004884
Nerita articulata (flesh)			
Between stations	27.61633	6.944272	0.00456
Between seasons	38.73566	6.944272	0.002411
Nerita articulata (shell)			
Between stations	0.438143	6.944272	0.67286
Between seasons	17.72404	6.944272	0.010282
Cerithedia cingulata (flesh)			
Between stations	13.08253	6.944272	0.017584
Between seasons	12.33403	6.944272	0.019468
Cerithedia cingulata (shell)			
Between stations	0.528864	6.944272	0.625474
Between seasons	0.025349	6.944272	0.975125
Cerithedia obtusa (flesh)			
Between stations	10.75582	6.944272	0.024583
Between seasons	9.499951	6.944272	0.030246
Cerithedia obtusa (shell)			
Between stations	4.288894	6.944272	0.101137
Between seasons	14.99093	6.944272	0.013856
Saccostrea cucullata (flesh)			
Between stations	22.83252	6.944272	0.006487
Between seasons	24.72919	6.944272	0.005599
Saccostrea cucullata (shell)			
Between stations	4.581158	6.944272	0.092354
Between seasons	87.22928	6.944272	0.000502

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Mitra A, Zaman S (2015) Blue carbon reservoir of the blue planet. Publisher, Springer India, Book ID 322214_1_En Book, Book, ISBN- 978-81-322-2106-7; Copyright Holder Name Springer India Copyright Year 2015, pp 1–299. https://doi.org/10.1007/978-81-322-2107-4

Chapter 5
Impact of Acidification on Plankton

Abstract Plankton are unique sensors to climate change induced alteration in temperature, salinity and pH of coastal and estuarine waters. They are considered as one of the best proxies to understand the effect of climate change due to their very short life cycle, quick response to alteration of water quality and less exploitation by humans, unlike fishes. Hence the pulse of acidification can be clearly evaluated through change in plankton composition and productivity. The present chapter highlights how the community structure of plankton along with their productivity changes as an effect of acidification in estuarine water.

5.1 Plankton Community: Overview and Types

Phytoplankton community encompasses unicellular, free floating organisms whose sizes usually range between 1 μm to 1 mm. The cells of these organisms are characterized by the presence of chlorophyll pigment, which is the core pigment in the process of photosynthesis. Phytoplankton are mainly confined in the photic zone of the ocean as they require sunlight, nutrients and carbon dioxide to form glucose that provides these tiny organisms with energy to perform various life processes. Phytoplankton forms the base of the marine and estuarine food web or in other words they support half of the global primary production, which directly or indirectly forms the foundation of all marine life. The Potential Fishing Zone (PFZ), which is the region for maximum fish catch is detected on the basis of pigment characterization that is assessed through Remote Sensing Technique.

Phytoplankton, the tiny aquatic floral entities provide several ecosystem services as listed here:

(i) Phytoplanton form the foundation stone of World fishery. It has been estimated that the total annual primary production of the World seas is around 20×10^9 tonnes of carbon which has the capacity to yield 240 million tonnes of fish although our present harvest is only about 60 million tones.
(ii) The distribution and abundance of the commercially important fish and shellfish and their larvae are dependent on some species of the phytoplankton besides serving as their main food source. Among the species of diatoms,

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*Fragilaria oceanic*a and *Hemidiscus hardmannianus* have been recorded to indicate the abundance of the clupeid fish, Hilsa in the Hooghly estuary and oil sardine, *Sardinella longiceps* in the west coast of India. The 'white water phenomenon' due to abundance of the coccolithophores has been a good sign for the herring fisheries in the British waters. Similarly, the colonial diatom, *Fragilaria antartica* is known to indicate the abundance of the Antartic krill, *Euphausia superba.* Nowadays the distribution and abundance of fish is detected through remote sensing technology, where the abundance of phytoplankton and their pigments are used as proxy to forecast the density/abundance of fish population.

(iii) Phytoplankton are sources of fossil fuels. It has been reported that some species of phytoplankton store extra food as oil rather than starch to get an advantage in terms of buoyancy. When oil-storing forms phytoplankton die and descend to the bottom of the sea and undergo microbial degradation, they are often covered by huge sediment load and subjected to enormous pressure. Such conditions are supposed to change the deposited phytoplankton into fossil fuel after hundreds and millions of ten years. Thus human World is benefitted from these tiny organisms even after their death.

(iv) The diatoms are commercially important as 'diatomaceous Earth' (diatomite or kielselghur), a congregation of dead silicon-rich diatom frustules in the sea beds like protozoan oozes. This material is employed in the filtration of fruit juice, syrup and varnish; in the boilers, electric ovens and refrigerators as insulators; as polishing agent for precious metals; in the separation of paraffin wax from petroleum and in the manufacture of concrete. Because of the presence of the hydrocarbon compound 'diatomin' the diatoms serve as the indicators of rich petroleum grounds. Present day scientists are of the opinion that these tiny free-floating producers are the chief precursors of the petroleum rich fields of Venezuela at Los Angeles.

(v) The dinoflagellates also at times play an important role in the fishery sector as by virtue of their power of luminescence they can emit 'cold living light' which though lasts for about one-tenth of a second, helps in identifying certain fish shoals during night.

(vi) Phytoplankton can also be used to reflect the water quality in terms of certain pollutants other than sewage (that contribute considerable amount of nitrate and phosphate in the ambient water). It has been reported that an increase in cell volume occurs in certain species (like *Dunaliella tertiolecta* and *Phaeodactylum tricornutum*) due to copper pollution (Stauber and Florence 1987).

(vii) Phytoplankton play an important role in maintaining the global carbon cycle. The elemental composition of phytoplankton is C:N:P = 106:16:1, which is commonly referred as the Red Field Ratio' (Redfield 1934, 1958). This ratio clearly explains that about 100 units of carbon is delivered to the deep sea for every sixteen units of nitrogen and one unit of phosphorous. As such, the biological pump delivers carbon from the atmosphere to the deep sea, where it is concentrated and sequestered for centuries.

(viii) Diatoms are important components contributing to the stability of intertidal mudflats. They excrete polysaccharides, which trap sediment sediment grains and stabilize sediment (http://www.nioo.know.hl/cemo/ecoflat/work.htm).

(ix) Mass culture of phytoplankton may be undertaken in closed systems of the space capsules. The nitrogenous wastes of the travelers could be diluted and circulated as algal nutrients and the respired air as a source of carbon dioxide. In exchange, the travelers could utilize the oxygen released by the photosynthesis of algae and benefit from the food value cultured phytoplankton.

(x) Phytoplankton has a major role to play in the pharmaceutical sector of blue economy. They can serve as a good source of omega-3 and omega-6 polyunsaturated fatty acids (PUFAs) and can be alternative to fish oil, which has been the main human source of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA).

The recent inclination of the scientists towards the phytoplankton community is mainly due to their paramount importance in various spheres of life, as pointed below (http://www.bigelow.or/sci_overview).

1. Oceans cover more than 70% of Earth's surface, containing all but 3% of the World's water and this saline water mass supports huge quantum of phytoplankton.
2. Dissolved gases in seawater regulate the composition of our atmosphere through phytoplankton compartment.
3. The World's phytoplankton generate half of the oxygen we breathe and absorb half of the carbon dioxide that may be contributing to global warming.
4. Phytoplankton constitute the base of the marine and estuarine food web and are the dominant producers of the aquatic ecosystem.
5. Phytoplankton act as the sink of anthropogenic wastes (specially nitrate and phosphate) that are contributed by sewage and agricultural operations.

Phytoplankton community may be divided into five major categories as listed in Table 5.1.

Depending on the nature of valves and pattern of ornamentation in the valve surface, the diatoms are grouped into **centric** and **pennate** diatoms. The major differences between these two groups are given in Table 5.2.

On the basis of size, the phytoplankton may be grouped under five categories (Table 5.3).

(a) Phytoplankton may also be classified on the basis of the cell characteristics (Table 5.4).

The zooplankton occupy the tier next to phytoplankton in the marine and estuarine food web. They either graze on phytoplankton or feed on other members of zooplankton. Foraminifera and radiolarians are members of zooplankton community who possess only one cell. Copepods and euphausiids are widely distributed zooplankton in the marine and estuarine environments. Zooplankton exhibit the phenomenon of **vertical migration** in which some species migrate towards the

Table 5.1 Different categories of phytoplankton

Category	Salient features	Example
Diatoms	(1) Presence of shell/frustules, which, is composed of translucent silica (2) The shell resembles a 'pillbox' bottom and lid; the lid is called the epitheca and the bottom is known as hypotheca (3) Many species of diatoms exhibit sculptured shells that look like beautiful ornaments (4) On the basis of nature of values and pattern of ornamentation on the surface of the value the diatoms are grouped into centric and pinnate diatom, the differences between which are highlighted in Table 5.2	*Thallassiosira pacifica, Stephanopyxis nipponica*
Dinoflagellates	(1) Unicellular organisms (2) Same are without any cover while others are armoured with plates of cellulose (3) Presence of two flagella for locomotion (4) Many species of dinoflagellates exhibit bioluminescence	*Skeletonema costatum* and *Coscinodiscus eccentricus*
Coccolithophores	(1) Extremely tiny having a range between 5 and 20 microns (2) Flagella are present in several forms (3) Body covered with tiny calcified circular plates having wide variety of designs (4) Coccolithophores are the preferred diet for filter feeding animals like bivalves	*Isochrysis galbana* and *Coccolithus* sp.
Blue green algae	(1) Prokaryotic in nature (2) Unicellular, or multicellular organisms (3) Presence of phycocyanin which imparts blue colour to the organism (4) Contributes greatly in 'bloom' formation	*Trichodesmium erythraeum*
Green algae	(1) Eukaryotic in nature (2) Dominate in the coastal water, rich in nutrients (3) Presence of chloroplasts which imparts green colour (4) Noted for high protein, carotenoid, vitamin and mineral content	*Chlorella marina* and *Chlorella salina*

Table 5.2 Differences between centric and pennate diatoms

Point	Centric diatom	Pennate diatom
Cell shape	Discoid, solenoid or cylindrical	Elongated and fusiform, oval, sigmoid or roughly circular
Ornamentation	Radial in nature i.e., the arrangement of markings is radiating from the centre	Bilateral in nature i.e., the arrangement of the markings is on either side of the apical (main) axis

Table 5.3 Classification of phytoplankton on the basis of size

Plankton category	Maximum dimension (μm)
Ultraplankton	<2
Nanoplankton	2–20
Microplankton	20–200
Macroplankton	200–2000
Megaplankton	>2000

Table 5.4 Classification of phytoplankton on the basis of cell characteristics

Class	Common name	Area(s) of predominance	Common genera
Cyanophyceae (cyanobacteria)	Blue-green algae	Tropical	*Oscillatoria, Synechococcus*
Rhodophyceae	Red algae	Cold temperate	*Rhodella*
Cryptophyceae	Cyptomonads	Coastal	*Cryptomonas*
Chrysophyseae	Chrysomonads Silicoflagellates	Coastal Cold waters	*Aureococcus* *Dictyocha*
Bacillariophyceae (Diatomophyceae)	Diatoms	All waters, especially coastal waters	*Coscinodiscus, Chaetoceros, Rhizosolenia*
Raphidophyceae	Chloromonads	Brackish	*Heterosigma*
Xanthophyceae	Yellow-green algae	Brackish	Very rare
Eustigmatophyceae	Yellow-green algae	Estuarine	Very rare
Prymnesiophyceae	Coccolithophorids Prymnesiomonads	Oceanic Coastal	*Emiliania* *Isochrysis* *Prymnesium*
Euglenophyceae	Euglenoids	Coastal	*Eutreptiella*
Prasinophyceae	Prasinomonads	All waters	*Tetraselmis* *Micromonas*
Chlorophyceae	Green algae	Coastal	Rare
Pyrrophyceae (Dinophyceae)	Dinoflagellates	All waters, especially warm	*Ceratium* *Gonyaulax* *Protoperidinium*

sea surface during the night time and return back to their original depth during day. The span of daily migration varies between 10 and 500 m and this change of zone is keenly related to their nutritional requirement or maintenance of their light level. The zooplankton are mainly filter feeding in nature and are the prey of many shore-dwelling species. The zooplankton also exhibits various adaptations to keep them in floating condition. In many protozoa, the cilia act as blade of the rotor of a helicopter which enables the ciliates to move up and down the water. The scyphomedusae floats and moves in the direction of current by the rhythmic contraction and relaxation of their umbrella. Although these are large and heavy, but 99% of their mass is due to the presence of a jelly-like substance, due to which their density is reduced. *Vellela* sp. has chambers filled with air that keeps it afloat. The zoea of many arthropods have well developed uropods and these help them to remain in floating condition or buoy up by swimming. The molluscan larvae are important component of zooplankton community. The *Lanthina* sp. remains afloat by creating froath of bubbles, which contract the surface film of water and the animal hangs on froth. The zooplankton usually produce 3 to 5 generations in warm water where there is plenty of food supply and optimum temperature. At higher latitudes, where the phytoplankton growth is restricted within a brief period of time, the zooplankton produce only a single generation in a year.

The most abundant members of marine zooplankton are crustaceans called copepods. In coastal waters, the population density of copepods can be as high as 100,000 individuals per cubic metre of water. The main reasons for such large numbers are the tremendous reproductive capacity of these animals and the rich food supply. Copepods are the primary consumers of diatoms. A single copepod can consume as many as 120,000 diatoms per day.

There are major contributions of zooplankton to the marine and estuarine environments as highlighted here in points.

1. Among the various levels of production in the sea, the secondary production contributed by zooplankton is an important linkage between the primary and tertiary productions. The zooplankton mainly consumes the primary producers and forms the major food source for tertiary producers. An important food for the Antarctic baleen whales is the krill, which are important zooplankton in the Antarctic region.
2. In certain parts of the world, the zooplankton are directly consumed as food, e.g., certain species of *Mysids* are consumed as food in West Indies. A deep-water copepod (*Euchaeta norvegica*) is delicious food item in West Indies.
3. In many places of the world, zooplankton are treated as source of bioactive substances.
4. Certain species of zooplankton are used as bio-indicators of water quality.
5. The zooplankton contribute substantial biogenic material to ooze formation, which has wide application in instrument related industry where the ooze is used as thermal insulators, chromatographic column filters etc.

Zooplankton are found in almost all the layers of the photic zone of the ocean. They are potentially limited by two factors in the coastal and estuarine zones. Firstly by turbidity which can limit phytoplankton production and thus restrict the ration supply for the zooplankton community, and secondly by currents which, particularly in small estuaries are dominated by high river flow that usually carries the zooplankton out to the sea. The zooplankton biomass can increase the fishery productivity because they chiefly consume the primary producers (phytoplankton) and form the major food source for members of higher trophic levels in which several species of osteichthyes and chondrichthyes exist. Zooplankton are classified according to their habitat, depth distribution, size and duration of planktonic life (Tables 5.5, 5.6, 5.7 and 5.8).

Table 5.5 Classification of zooplankton on the basis of habitat

Type	Description
Oceanic plankton	These are marine zooplankton that inhabit beyond the continental shelf
Neritic plankton	These zooplankton inhabit waters overlying continental shelves. These waters are often very productive as they receive the runoff from the adjacent landmasses that triggers the phytoplankton growth in these regions
Brackish water plankton	These zooplankton inhabit estuarine regions, where there is a continuous mixing of fresh water and sea water. The zooplankton species of this category have wide range of tolerance to different dilution factors. Such zooplankton are very common in the shrimp culture farms and form important diet of the prawns

Table 5.6 Classification of zooplankton on the basis of depth distribution

Type	Description
Neuston	The zooplankton of this category are restricted at the top few millimeters (usually 10 mm) of the surface micro layer
Pleuston	These are widely distributed at the surface of the sea (with parts of the body sometime projecting above the water)
Epipelagic	These are distributed between 0 and 300 m water column e.g. siphonophores, arrow worms etc.
Mesopelagic	The zooplankton of this category are restricted within the depth 300–1000 m e.g. euphausiids, chaetognath etc.
Bathypelagic	These are restricted within the depth 1000 and 3000 m e.g., foraminifera, euphausiids etc.
Abyssopelagic	The waters overlying the vast abyssal plains of the ocean are inhabited by a variety of zooplankton species, which are often referred to as abyssopelagic zooplankton. These zooplankton are thus restricted between 3000 and 4000 m

Source Srinivasan and Santhanan (1998)

Table 5.7 Classification of zooplankton on the basis of size

Type	Size range
Nannozooplankton	<20 μm
Microzooplankton	20–200 μm
Mesozooplankton	200 μm–2 mm
Macrozooplankton	2–20 mm
Megazooplankton	>20 mm

Source Srinivasan and Santhanam (1998)

Table 5.8 Classification of zooplankton on the basis of duration of planktonic life

Type	Description
Holoplankton	This group includes organisms which are planktonic throughout their life cycle e.g., tintinnids, cladocerans, copepods, chaetognaths etc.
Meroplankton	This group encompasses those organisms which remain planktonic only for a portion of their life cycle e.g., larvae of benthic invertebrates and fish larvae (ichthyoplankton)

Source Santhanam and Srinivasan (1998)

5.2 Common Plankton of Indian Sundarban Estuaries

The estuaries of Indian Sundarbans are noted for their unique spatio-temporal variations of salinity (Mitra 2000, 2013; Mitra et al. 2009, 2011; Banerjee et al. 2013; Sengupta et al. 2013; Chakraborty et al. 2013; Mitra and Zaman 2014, 2015,2016. This variation has resulted to a wide range of adaptability to plankton community.

The list of phytoplankton species has increased more than 150 in recent times in Indian Sundarban estuaries (Tables 5.9, 5.10 and 5.11).

In aquatic sub-system of deltaic Sundarbans, the zooplankton community comprises a heterogenous assemblage of animals covering many taxonomic groups including copepods, mycids, lucifers, gammarid, cladocerae, ostracods, cumacea, hydromedusae, ctenophores and chaetognaths among holoplankters and polychaete larvae, molluscan and echinoderm larvae, crustacean larvae and fish eggs and larvae among meroplankters Among the zooplankton, calaniod copepods constitute the major bulk, followed by cyclopoids, copepods and harpecticoids (Chaudhuri and Choudhury 1994). In general, higher abundance of zooplankton is encountered during the premonsoon periods. The main cause of the high species diversity index of zooplankton during the premonsoon months may be attributed to the coincidence of the breeding period of the coastal and estuarine fishes in the months of late February and March in the tropical mangrove ecosystem (Mitra 2000). A wide range of species under zooplankton community is available in the Indian Sundarban waters (Table 5.12).

We conducted a field survey during June 2017, 2018 and 2019 on ichthyoplankton abundance and aquatic pH at ten different stations in Indian Sundarbans (Table

Table 5.9 Checklist of diatoms in Indian Sundarban estuarine water

S. No.	Species
1	*Coscinodiscus eccentricus*
2	*Coscinodiscus jonesianus*
3	*Coscinodiscus lineatus*
4	*Coscinodiscus radiates*
5	*Coscinodiscus gigas*
6	*Coscinodiscus oculus-iridis*
7	*Coscinodiscus concinnus*
8	*Coscinodiscus perforates*
9	*Coscinodiscus asteromphalus*
10	*Coscinodiscus thorii*
11	*Coscinodiscus granii*
12	*Cyclotella* sp.
13	*Cyclotella striata*
14	*Cyclotella stylorum*
15	*Thalassiosira subtilis*
16	*Thalassiosira* sp.
17	*Thalassiosira decipiens*
18	*Thalassiosira punctigera*
19	*Thalassiosira hyaline*
20	*Thalassiosira eccentric*
21	*Skeletonema costatum*
22	*Paralia sulcata*
23	*Planktoniella sol*
24	*Planktoniella blanda*
25	*Rhizosolenia setigera*
26	*Rhizosolenia alata*
27	*Rhizosolenia hebetate*
28	*Rhizosolenia styliformis*
29	*Rhizosolenia robusta*
30	*Rhizosolenia stolterfothii*
31	*Rhizosolenia cylindrus*
32	*Rhizosolenia shrubsolei*
33	*Rhizosolenia imbricata:*
34	*Lauderia annulata*
35	*Bacteriastrum* sp.
36	*Bacteriastrum delicatulum*
37	*Bacteriastrum varians*

(continued)

Table 5.9 (continued)

S. No.	Species
38	*Bacteriastrum comosum*
39	*Bacteriastrum hyalinum*
40	*Chaetoceros dydymus*
41	*Chaetoceros curvisetus*
42	*Chaetoceros diversus*
43	*Chaetoceros messanensis*
44	*Chaetoceros peruvianus*
45	*Chaetoceros eibenii*
46	*Chaetoceros lorenzianus*
47	*Chaetoceros compressus*
48	*Chaetoceros decipiens*
49	*Chaetoceros atlanticus*
50	*Chaetoceros subtilis*
51	*Chaetoceros convolutes*
52	*Chaetoceros holsaticum*
53	*Chaetoceros gracile*
54	*Chaetoceros cinctum*
55	*Chaetoceros affinis*
56	*Chaetoceros danicus*
57	*Chaetoceros constrictus*
58	*Ditylum sol*
59	*Ditylum brightwelli*
60	*Lithodesmium undulatum*
61	*Triceratium favus*
62	*Triceratium reticulatum*
63	*Triceratium* sp.
64	*Biddulphia sinensis*
65	*Biddulphia mobiliensis*
66	*Biddulphia regia*
67	*Eucampia zodiacus*
68	*Hemidiscus cuneiformis*
69	*Climacosphenia elongate*
70	*Fragilaria oceanic*
71	*Rhaphoneis amphiceros*
72	*Thalassionema nitzchioides*
73	*Thalassionema* sp.
74	*Thalassiothrix longissima*

(continued)

Table 5.9 (continued)

S. No.	Species
75	*Thalassiothrix fraunfeldii*
76	*Thalassiothrix* sp.
77	*Thalassiothrix nitzchioides*
78	*Asterionella japonica*
79	*Asterionellopsis glacialis*
80	*Diatoma vulgare*
81	*Diatoma* sp.
82	*Cocconeis* sp.
83	*Cocconeis soutellrem*
84	*Gyrosigma balticum*
85	*Gyrosigma* sp.
86	*Pleurosigma normanii*
87	*Pleurosigma elongatum*
88	*Pleurosigma directum*
89	*Diploneis smithii*
90	*Navicula longa*
91	*Navicula rhombic*
92	*Navicula pennata*
93	*Navicula* sp.
94	*Nevicula cancellata*
95	*Cymbella marina*
96	*Nitzschia sigma*
97	*Nitzschia longissima*
98	*Nitzschia closterium*
99	*Nitzschia striata*
100	*Nitzschia seriata*
101	*Pseudo-nitzschia pungens*
102	*Pseudo-nitzschia australis*
103	*Pinnularia alpine*
104	*Pinnularia* sp.
105	*Pinnularia Trevelyan*
106	*Bacillaria paradoxa*
107	*Bacillaria paxilifer*
108	*Triceratium spinosum*
109	*Phaeocystis* sp.
110	*Amphora hyaline*
111	*Amphipleura* sp.

(continued)

Table 5.9 (continued)

S. No.	Species
112	*Amphiprora constrica*
113	*Halosphera viridis*
114	*Halosphera* sp.
115	*Corethron crinophyllum*
116	*Guinerdia flacida*
117	*Hemiaulus sinensis*
118	*Melosira numuloides*
119	*Melosira granulate*
120	*Melosira variance*
121	*Melosira* sp.
122	*Bellerochea malleus*
123	*Ceratualina pelagic*
124	*Leptocylindrius danicum*
125	*Leptocylindrius minimus*
126	*Asteromphalus* sp.
127	*Hyalodiscus* sp.
128	*Actinocyclus octanarius*
129	*Actinoptychus* sp.
130	*Eunotia* sp.
131	*Tabellaria* sp.
132	*Grammatophora marina*
133	*Closterium* sp.
134	*Striatella* sp.
135	*Striatella unipunctata*
136	*Diplosalis* sp.
137	*Licmophora chrenbergii*

Source Mitra and Zaman (2015)

5.13 and Fig. 5.1) to interpret the impact of pH on ichthyoplankton community comprising of fish juveniles, which cannot move against the current and are basically meroplankton (Fig. 5.2).

The standing stock of ichthyoplankton (N) per haul was determined during 2017, 2018 and 2019 using standard procedure and expressed in gm. Simultaneously the aquatic pH was also determined with a portable pH meter (sensitivity = ±0.01). The data for each of the 10 selected stations are presented in Table 5.14.

The data of Table 5.14 reflects three important facts (i) both ichthyoplankton standing stock (N) and pH decreased with time (ii) ichthyoplankton standing stock (N) was relatively high in stations like Lothian Island, Prentice Island and Sajnekhali, and (iii) pH values were almost uniform in Lothian Island, Prentice Island and

Table 5.10 Checklist of dinoflagellates in Indian Sundarban estuarine water

S. No.	Species
1	*Prorocentrum gracile*
2	*Prorocentrum micans*
3	*Prorocentrum concavum*
4	*Ceratium furca*
5	*Ceratium fusus*
6	*Ceratium teres*
7	*Ceratium minutum*
8	*Ceratium tripose*
9	*Ceratium trichoceros*
10	*Ceratium horridum*
11	*Ceratium inflatum*
12	*Ceratocorys horrida*
13	*Protoperidinium* sp.
14	*Protoperidinium crassipes*
15	*Protoperidinium depressum*
16	*Protoperidinium ovatum*
17	*Protoperidinium pellucidum*
18	*Protoperidinium conicum*
19	*Pyrocystis fusiformis*
20	*Pyrocystis* sp.
21	*Dinophysis caudata*
22	*Dinophysis acuta*
23	*Dinophysis norvegica*
24	*Dinophysis* sp.
25	*Alexandrium* sp.
26	*Preperidinium meunieri*

Source Mitra and Zaman (2015)

Sajnekhali. The reasons behind these outputs may be many, but our first order analysis points towards the presence of rich mangrove vegetation at Lothian Island, Prentice Island and Sajnekhali compared to other stations, which imparted a buffering capacity to adjacent estuarine water in terms of pH and nutrient rich water, mostly derived from mangrove litter and detritus. The abundance of mangroves in these stations is presented in Fig. 5.3.

Ten stations selected in the present work can be categorized into two major sectors in the study area namely (i) western sector encompassing stations 1 to 5 and (ii) central sector with stations 6–10 (see Fig. 5.1). These two sectors are significantly different in terms of salinity, pH, and mangrove vegetation, which resulted in the variation of ichthyoplankton in these two sectors (Table 5.15). The western sector

Table 5.11 Checklist of other algae in Indian Sundarban estuarine water

S. No.	Species
1	*Trichodesmium* sp.
2	*Trichodesmium thiebautii*
3	*Oscillatoria* sp.
4	*Oscillatoria limosa*
5	*Gleocapsa* sp.
6	*Stigonema* sp.
7	*Cylindrospermopsis raciborskii*
8	*Anabaena* sp.
9	*Dictyocha* sp.
10	*Ditylum sol*
11	*Chlorella salina*
12	*Amphora hyaline*
13	*Netrium* sp.
14	*Drapamaldia* sp.
15	*Gleocapsa* sp.

Source Mitra and Zaman (2015)

of Indian Sundarbans exhibited greater abundance of ichthyoplankton of commercially important fishes like *Tenualosa* sp., *Liza* sp., *Scatophagus* sp. etc., whereas ichthyoplankton of trash fish variety like *Coilia* sp., *Thryssa* sp. etc., dominated the estuarine water of central Indian Sundarbans.

To sum up it can be stated that mangrove vegetation acts as a unique buffer against pH fall and serves as a nursery ground for ichthyoplankton by offering safe shelter through wave attenuation by root systems and nutrition derived from mangrove detritus (Fig. 5.4).

Hence, it is the need of the hour to conserve and propagate this unique forest of halophytes to retard the pace of acidification and subsequent impact on plankton community.

5.3 Plankton: Effect of Acidification

The growing population coupled with industrial development at large scale has scratched the stability of the environment. The level of carbon dioxide has increased even in the atmosphere of Indian Sundarbans through seasons (Fig. 5.5), probably due to massive destruction of mangroves (Fig. 5.6), the major sink of carbon dioxide in the region.

Table 5.12 Zooplankton in Indian Sundarban estuarine water (ichthyoplankton community has not been considered in the list)

Class	Species
Acantharia	*Acanthometron* sp.
Spirotrichea	*Leprotintinnus nordqvisti*
	Tintinnopsis beroidea
	T. butschlii
	T. cylindrica
	T. mortensenii
	T. tocantinensis
	T. tubulosa
	T. uruguayensis
	Codonellopsis ostenfeldi
	Dictyocysta seshaiyai
	Metacylis jorgenseni
	Rhabdonella sp.
	Amphorellopsis sp.
	Eutintinnus tenue
	Favella philippinensis
Polythalamea	*Globigerina bulloides*
	G. rubescense
	Globigerina sp.
	Asterorotalia trispinosa
	Quinqueloculina sp.
Hydrozoa	*Cladonema* sp.
	Sarsia sp.
	Podocoryne sp.
	Obelia sp.
	Phialella quadrata
	Liriope tetraphylla
	Aglaura hemistoma
	Aequorea vitrina
	Agalma elegans
	Sulculeolaria sp.
	Diphyes chamissonis
	D. dispar
	Diphyes sp.
	Lensia sp.
	Eudoxoides mitra
	Muggiaea sp.

(continued)

Table 5.12 (continued)

Class	Species
	Abylopsis sp.
	Bassia bassensis
Tentaculata	*Pleurobrachia pileus*
Nuda	*Beroe* sp.
Gastropoda	*Atlanta* sp.
	Janthina sp.
	Limacina bulimoides
	Limacina inflata
	Cresis acicula
	Hyalocylix striata
Branchiopoda	*Evadne tergestina*
	Penilia avirostris
Maxillipoda	*Pleuromamma* sp.
	Acartia. centrura
	A. danae
	A. erythraea
	A. spinicauda
	A. negligens
	A. southwelli
	Acartia sp.
	Candacia catula
	Candacia sp.
	Paracandacia truncata
	Paracandacia sp.
	Centropages alcocki
	C. furcatus
	C. calaninus
	C. dorsispinatus
	C. orsinii
	C. tenuiremis
	Centropages sp.
	Calanopia minor
	C. elliptica
	Labidocera acuta
	L. detruncata
	L. minuta
	L. pectinata

(continued)

Table 5.12 (continued)

Class	Species
	Labidocera sp.
	Pontella fera
	P. securifer
	Pontellina platychela
	Temora discaudata
	T. turbinata
	T. stylifera
	Tortanus barbatus
	T. forcipatus
	T. gracilis
	Mesocalanus tenuicornis
	Canthocalanus pauper
	Nannocalanus minor
	Undinula vulgaris
	Acrocalanus gracilis
	A. longicornis
	A. gibber
	Acrocalanus sp.
	Calocalanus pavo
	Paracalanus aculeatus
	P. parvus
	Paracalanus sp.
	Eucalanus attenuates
	E. monachus
	Eucalanus sp.
	Subeucalanus crassus
	S. mucronatus
	S. pileatus
	S. subcrassus
	S. subtenuis
	Undeuchaeta sp.
	Metacalanus aurivilli
	Clausocalanus arcuicornis
	Euchaeta concinna
	E. marina
	Euchaeta sp.
	Scolecithrix danae

(continued)

Table 5.12 (continued)

Class	Species
	Scolecithricella minor
	Pseudodiaptomus aurivilli
	P. serricaudatus
	P. annandalei
	Pseudodiaptomus sp.
	Haloptilus sp.
	Oithona nana
	O. oculata
	O. setigera
	O. similis
	O. simplex
	O. tenuis
	O. rigida
	O. brevicornis
	O. spinirostris
	Oithona sp.
	Miracia efferata
	Macrosetella gracilis
	M. oculata
	Microsetella norvegica
	M. rosea
	Clytemnestra scutellata
	Euterpina acutifrons
	Longipedia weberi
	Oncaea conifera
	O. media
	O. mediterranea
	O. venusta
	Oncaea sp.
	Copilia quadrata
	Sapphirina auronitens
	S. maculosa
	S. ovatolanceolata
	Sapphirina sp.
	Corycaeus agilis
	C. andrewsi
	C. catus

(continued)

Table 5.12 (continued)

Class	Species
	C. danae
	C. erythraeus
	C. lautus
	C. longistylis
	C. ovalis
	C. robustus
	C. speciosus
	Corycaeus sp.
	Farranula carinata
	F. concinna
	F. curta
	F. gibbula
	F. gracilis
Ostracoda	*Macrocypridina castanea*
	Conchoecia elegans
	Euconchoecia chierchiae
	Mesopodopsis orientalis
	Leucothoe spinicarpa
	Hyperia sp.
	Caprella sp.
	Metacaprella sp.
	Orchestoidea sp.
	Campylaspis costata
	Euphausia tenera
	Euphausia sp.
	Lucifer hanseni
	Sergestes sp.
Sagittoidea	*Pseudosagitta maxima*
	Sagitta bedoti
	S. bipunctata
	S. enflata
	Sagitta sp.
	Adinosagitta bedfordii
Appendicularia	*Oikopleura dioica*
	O. parva
	Fritillaria sp.
Thaliacea	*Doliolum* sp.
	Salpa fusiformis

Table 5.13 Selected sampling stations (for the determination of average ichthyoplankton standing stock and mangrove density) in Indian Sundarbans with salient features

Study Site	Latitude and Longitude
Harinbari (Stn. 1)	21° 46′ 53.07″ N and 88° 04′ 22.88″ E
Chemaguri (Stn. 2)	21° 39′ 42.88″ N and 88° 08′ 49.01″ E
Sagar South (Stn. 3)	21° 37′ 49.90″ N and 88° 04′ 0.51″ E
Lothian Island (Stn. 4)	21° 39′ 08.04″ N and 88° 19′ 8.47″ E
Prentice Island (Stn. 5)	21° 42′ 43.31″ N and 88° 17′ 3.62″ E
Canning (Stn. 6)	22° 19′ 03.20″ N and 88° 41′ 04.43″ E
Sajnekhali (Stn. 7)	22° 06′ 34.19″ N and 88° 48′ 15.78″ E
Chotomollakhali (Stn. 8)	22° 10′ 40.00″ N and 88° 54′ 26.71″ E
Satjelia (Stn. 9)	22° 05′ 17.86″ N and 88° 52′ 49.51″ E
Pakhiralaya (Stn. 10)	22° 07′ 07.23″ N and 88° 48′ 29.00″ E

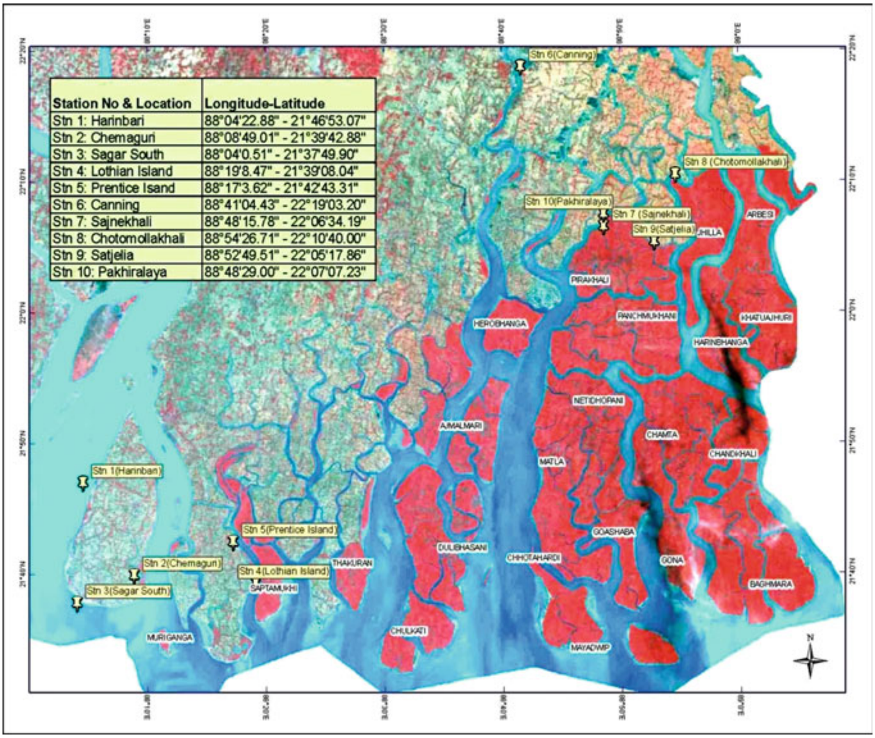


Fig. 5.1 Map showing the ten stations in Indian Sundarbans selected for the determination of inter-relationship between ichthyoplankton standing stock and aquatic pH

Fig. 5.2 Ichthyoplankton in the estuarine water of Indian Sundarbans

Table 5.14 Spatio-temporal variation of average standing stock of ichthyoplankton (N) per haul (in gm) and surface water pH recorded during high tide

S. No.	Station name	2017		2018		2019	
		N	pH	N	pH	N	pH
1	Harinbari (Stn. 1)	467	8.17	401	8.17	380	8.15
2	Chemaguri (Stn. 2)	454	8.26	358	8.24	307	8.24
3	Sagar South (Stn. 3)	491	8.28	397	8.27	295	8.24
4	Lothian Island (Stn. 4)	566	8.27	481	8.27	428	8.27
5	Prentice Island (Stn. 5)	593	8.27	467	8.27	439	8.27
6	Canning (Stn. 6)	402	8.05	361	8.02	134	8.00
7	Sajnekhali (Stn. 7)	565	8.24	405	8.23	365	8.23
8	Chotomollakhali (Stn. 8)	305	8.13	302	8.09	217	8.06
9	Satjelia (Stn. 9)	366	8.11	313	8.09	207	8.07
10	Pakhiralaya (Stn. 10)	417	8.11	395	8.08	287	8.07

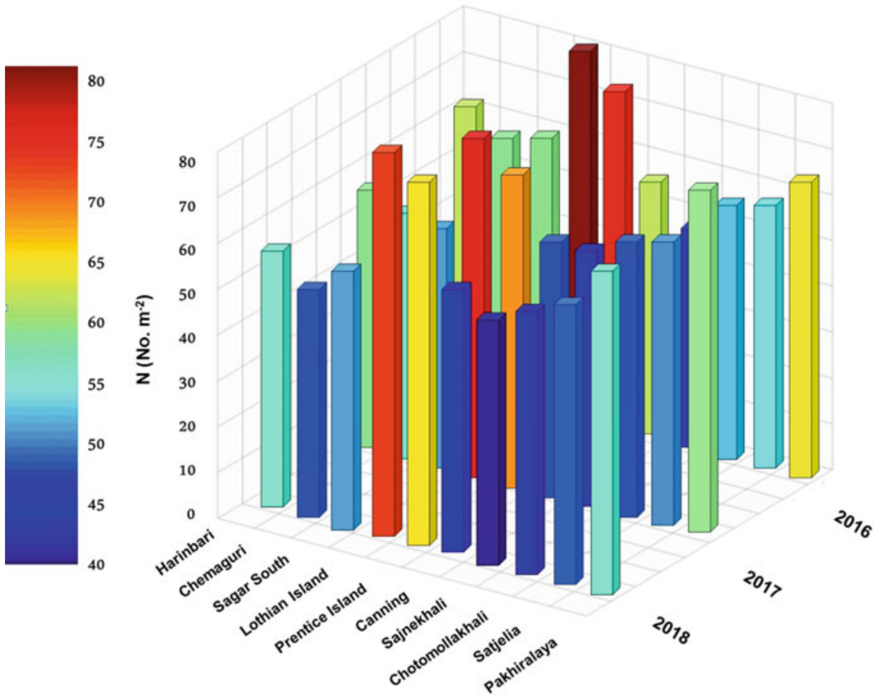


Fig. 5.3 Spatio-temporal variation of population density of mangroves (in No./100 m^2) in the 10 selected stations during 2016, 2017 and 2018

The estuaries of Indian Sundarbans synchronized with the pace of rising atmospheric carbon dioxide (5.13) and exhibited a simultaneous decrease of aquatic pH (Tables 5.16 and 5.17).

A significant negative relationship witnessed between the two variables (near surface atmospheric carbon dioxide level and aquatic pH) clearly confirms the pulse of acidification in the estuaries of Indian Sundarbans.

It is interesting to note in this context that the pace of acidification differs considerably between the western and eastern Indian Sundarbans, the former having a higher pace than the latter. This may be attributed to contrasting anthropogenic-cum-environmental set-ups. The western Indian Sundarbans is exposed to high degree of aquatic pollution from the chain of factories and industries situated at the bank of Hooghly estuary (Table 5.18), which mostly release untreated/partially treated wastes.

The eastern Indian Sundarbans, on contrary, is basically a Reserve Forest (RF) area, where there are minimum anthropogenic footprints. The presence of rich mangrove vegetation in this sector is also the factor to reduce the rate of acidification (Fig. 5.7).

Table 5.15 Abundance of ichthyoplankton species in 10 gm composite sample collected from two sectors of Indian Sundarbans

S. No.	Species	Western Sector (composite samples of Stations 1–5)	Central Sector (composite samples of Stations 6–10)
1	*Coilia* sp.	++	+
2	*Thryssa hamiltonii (Gray)*	+	+++
3	*Thryssa baelama*	+	+++
4	*Torquigener oblongus*	+	+
5	*Rhinomugil corsula*	+	+
6	*Mugil cephalus*	+++	+
7	*Sillaginopsis panijus*	+++	+
8	*Sillago sihama*	+++	+
9	*Sillago soringa*	+++	+
10	*Zenarchopterus dispar*	+	+
11	*Glossogobius quiris*	+	+
12	*Pseudapocryptes lanceolatus*	+	+++
13	*Eupleurogrammus glossodon*	+	+
14	*Pseudorhombus* sp.	+	+
15	*Pisodonophis boro*	+	+
16	*Tenualosa ilisha*	++	+++
17	*Cynoglossus arel*	+	+++
18	*Cynoglossus* sp.	+	+++
19	*Leiognathus blochii*	+	++
20	*Leiognathus equalus*	+	+
21	*Scatophagus argus*	+	+
22	*Liza parsia*	+++	+
23	*Liza tade*	+++	+
24	*Stolephorus commersonii*	+	+
25	*Stolephorus baganensis*	+	+
26	*Stolephorus kammalensis*	+	+
27	*Lutjanus johni*	+	+
28	*Setipinna taty*	+	+++
29	*Lagocephalus lunaris*	+	+

(continued)

Table 5.15 (continued)

S. No.	Species	Western Sector (composite samples of Stations 1–5)	Central Sector (composite samples of Stations 6–10)
30	*Escualosa thoracata*	+	+
31	*Epinephelus tauvina*	+	+
32	*Epinephelus coioides*	+	+
33	*Sphyraena* sp.	+	+
34	*Pomadasys* sp.	+	+
35	*Sardinella longiceps*	+	+
36	*Periophthalmus* sp.	+	+
37	*Macrognathus* sp.	+	+
38	*Tetradon cutcutia*	+	+
39	*Bregmaceros meclellandii*	+	+
40	*Ichthyocampus carce*	+	+
41	*Stigmatogobius* sp.	+	+
42	*Channa* sp.	+	+
43	*Kurtus indicus*	+	+
44	*Harpodon nehereus*	+	+++
45	*Moringua raitaborua*	+	+
46	*Suggrundus rodricensis*	+	+

'+' abundance < 10%; '++' abundance = 10–20%; '+++' abundance = 21–80%

The phytoplankton diversity (measured in terms of Shannon-Weiner Species Diversity Index) in these two sectors also exhibited different spatio-temporal scores (Table 5.19), which may be due variations in Total Suspended Solid (TSS), nitrate and phosphate (Tables 5.20, 5.21 and 5.22 respectively). For interested readers, with a little bit of knowledge on programming, we have highlighted the computation of Shannon-Weiner Species Diversity Index of phytoplankton by using C programming language (*Vide* Annexure 5). This is an imperative procedural language which is designed to be compiled using a relatively straight forward compiler, to provide low level access to memory, and to provide language, constructs the map efficiently to machine instructions. This language requires minimum run-time support.

Similar trends were also observed in Haldia and Bali Island (Tables 5.23, 5.24, 5.25 and 5.26) where significant negative correlation values were observed between phytoplankton diversity and suspended solids. The presence of more suspended solid on the water mass prohibits the primary producer, phytoplankton in getting sunlight at optimum level due to which their survival and growth are adversely impacted. The gradual decrease of Shannon- Weiner Index values in all the selected stations (Tables 5.19 and 5.23) with the passage of time is a clear indication of the adverse role played by increased suspended solid and decreased pH, both of which are

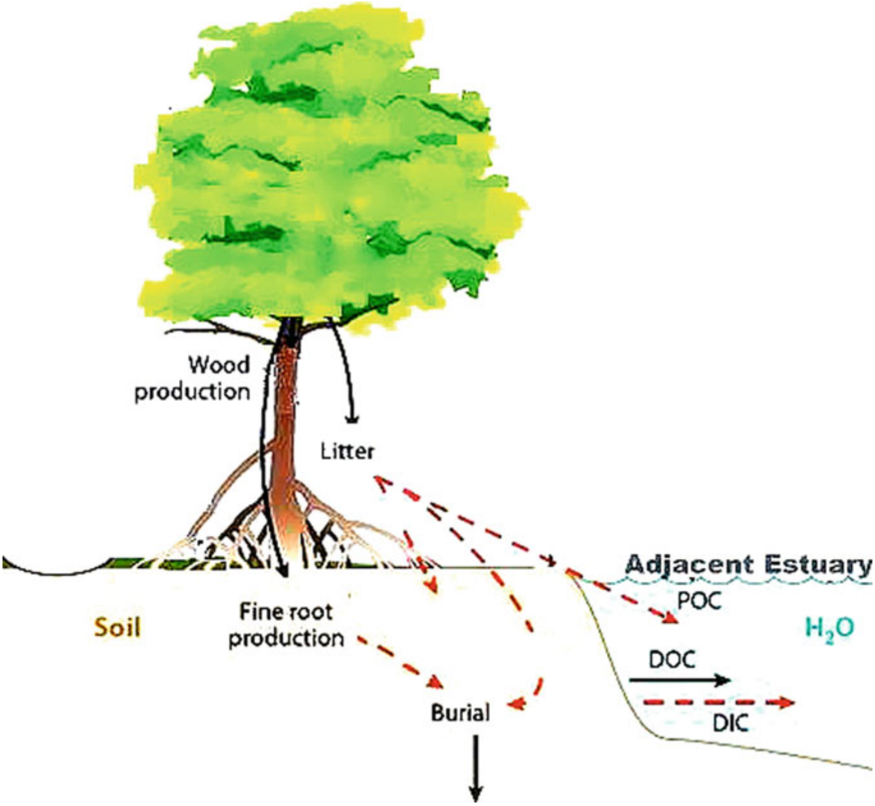


Fig. 5.4 Mangrove vegetation provides nutrients to adjacent water body that supports the ichthyoplankton in the system

anthropogenically sourced in the region. The decrease in phytoplankton diversity and standing stock results in the un-utilization of nutrients (nitrate and phosphate) in the aquatic phase due to which the levels increase with time.

Acidification is the net result of climate change induced carbon dioxide rise in the atmosphere. With the rise of carbon dioxide, surface waters have become more susceptible to acidification. Anthropogenic carbon dioxide from the burning of fossil fuels has increased the uptake of the green house gas, causing the pH to drop from 8.2 to 8.1 (Chu 2015).

Ocean acidification has high probability to pose negative impact on the marine life. It is well known that coral bleaching, reduced calcification and thinning of oyster shells are the direct effects of acidification. However, the species abundance and diversity of phytoplankton are also impacted by the pH level of the aquatic ecosystem, (Fabry et al. 2008). The uptake of Fe (iron) by phytoplankton, such as diatoms and coccolithophores, decreases with increasing acidification (Shi et al. 2010). On this background, we carried out an outdoor experiment in the Kadwip region of western

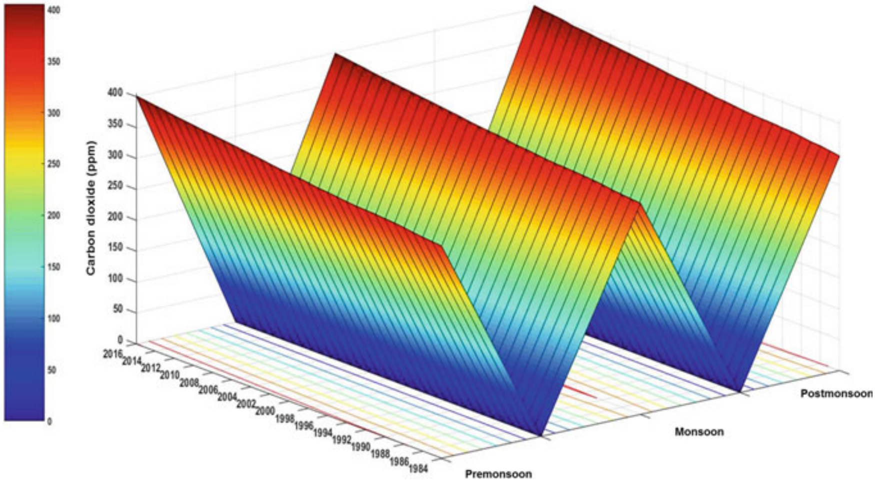


Fig. 5.5 Near Surface atmospheric carbon dioxide (in ppm) in the Kakdwip area of Indian Sundarbans

Fig. 5.6 Cutting of mangroves for fuel wood and deforestation for settlement in Indian Sundarbans

Table 5.16 Temporal variation of near surface atmospheric carbon dioxide through seasons at Kakdwip in Western Indian Sundarbans

Year	Premonsoon	Monsoon	Postmonsoon
1984	345.07	342.87	348.38
1985	346.55	344.35	350.86
1986	347.97	345.77	353.24
1987	349.71	347.51	354.12
1988	352.23	350.03	356.54
1989	353.88	351.68	358.79
1990	355.06	352.86	359.37
1991	356.38	354.18	360.69
1992	357.08	354.88	361.39
1993	357.8	355.6	362.2
1994	359.29	357.09	363.6
1995	361.11	358.91	365.42
1996	362.88	360.68	367.19
1997	363.99	361.79	368.3
1998	366.64	364.44	370.95
1999	368.72	366.52	373.03
2000	369.9	367.7	375.22
2001	371.5	369.3	375.81
2002	373.5	371.3	377.81
2003	376.05	373.85	380.36
2004	377.87	375.67	382.18
2005	379.9	377.7	384.21
2006	382.02	379.82	386.33
2007	383.76	381.56	388.07
2008	385.87	383.67	390.18
2009	387.37	385.17	391.68
2010	389.65	387.45	393.96
2011	391.53	389.33	395.84
2012	393.54	391.34	397.19
2013	396.28	394.08	400.59
2014	398.21	396.01	402.52
2015	400.5	398.3	403.86
2016	402.31	400.09	406.4

A = Premonsoon, B = Monsoon and C = Postmonsoon

Table 5.17 Temporal variation of surface water pH through seasons at different tidal phase at Kakdwip in Western Indian Sundarbans

	A1	A2	B1	B2	C1	C2
1984	8.32 ± 0.03	8.31 ± 0.03	8.29 ± 0.03	8.28 ± 0.03	8.31 ± 0.03	8.29 ± 0.03
1985	8.31 ± 0.03	8.3 ± 0.03	8.29 ± 0.03	8.27 ± 0.03	8.31 ± 0.03	8.29 ± 0.03
1986	8.32 ± 0.03	8.31 ± 0.03	8.29 ± 0.03	8.28 ± 0.03	8.31 ± 0.03	8.3 ± 0.03
1987	8.31 ± 0.03	8.3 ± 0.03	8.28 ± 0.03	8.26 ± 0.03	8.29 ± 0.03	8.28 ± 0.03
1988	8.31 ± 0.03	8.3 ± 0.03	8.28 ± 0.03	8.26 ± 0.03	8.3 ± 0.03	8.29 ± 0.03
1989	8.31 ± 0.03	8.3 ± 0.03	8.27 ± 0.03	8.26 ± 0.03	8.31 ± 0.03	8.3 ± 0.03
1990	8.31 ± 0.03	8.3 ± 0.03	8.27 ± 0.03	8.26 ± 0.03	8.3 ± 0.03	8.28 ± 0.03
1991	8.29 ± 0.03	8.28 ± 0.03	8.27 ± 0.03	8.25 ± 0.03	8.28 ± 0.03	8.27 ± 0.03
1992	8.3 ± 0.03	8.29 ± 0.03	8.26 ± 0.03	8.25 ± 0.03	8.29 ± 0.03	8.26 ± 0.03
1993	8.3 ± 0.03	8.29 ± 0.03	8.27 ± 0.03	8.24 ± 0.02	8.29 ± 0.03	8.26 ± 0.03
1994	8.29 ± 0.03	8.28 ± 0.03	8.27 ± 0.03	8.24 ± 0.02	8.29 ± 0.03	8.27 ± 0.03
1995	8.29 ± 0.03	8.28 ± 0.03	8.26 ± 0.03	8.23 ± 0.02	8.28 ± 0.03	8.26 ± 0.03
1996	8.28 ± 0.03	8.27 ± 0.03	8.25 ± 0.03	8.24 ± 0.02	8.27 ± 0.03	8.26 ± 0.03
1997	8.28 ± 0.03	8.27 ± 0.03	8.25 ± 0.03	8.23 ± 0.02	8.27 ± 0.03	8.25 ± 0.03
1998	8.28 ± 0.02	8.27 ± 0.03	8.25 ± 0.03	8.23 ± 0.02	8.27 ± 0.03	8.26 ± 0.03
1999	8.26 ± 0.03	8.25 ± 0.03	8.23 ± 0.02	8.23 ± 0.02	8.25 ± 0.03	8.23 ± 0.02
2000	8.27 ± 0.03	8.25 ± 0.03	8.23 ± 0.02	8.22 ± 0.02	8.26 ± 0.03	8.24 ± 0.02
2001	8.27 ± 0.03	8.26 ± 0.03	8.24 ± 0.02	8.22 ± 0.02	8.27 ± 0.03	8.24 ± 0.02
2002	8.25 ± 0.03	8.24 ± 0.02	8.24 ± 0.02	8.22 ± 0.02	8.25 ± 0.03	8.23 ± 0.02
2003	8.27 ± 0.03	8.24 ± 0.02	8.24 ± 0.02	8.22 ± 0.02	8.26 ± 0.03	8.24 ± 0.02
2004	8.26 ± 0.03	8.25 ± 0.02	8.23 ± 0.02	8.22 ± 0.02	8.25 ± 0.03	8.22 ± 0.02
2005	8.24 ± 0.02	8.23 ± 0.02	8.23 ± 0.02	8.21 ± 0.02	8.23 ± 0.02	8.22 ± 0.02
2006	8.24 ± 0.02	8.23 ± 0.02	8.22 ± 0.02	8.2 ± 0.02	8.23 ± 0.02	8.21 ± 0.02
2007	8.23 ± 0.02	8.22 ± 0.02	8.22 ± 0.02	8.21 ± 0.02	8.22 ± 0.02	8.21 ± 0.02
2008	8.25 ± 0.03	8.22 ± 0.02	8.21 ± 0.02	8.21 ± 0.02	8.22 ± 0.02	8.2 ± 0.02
2009	8.24 ± 0.05	8.24 ± 0.04	8.21 ± 0.02	8.2 ± 0.02	8.23 ± 0.02	8.22 ± 0.02
2010	8.21 ± 0.02	8.19 ± 0.02	8.2 ± 0.02	8.19 ± 0.02	8.22 ± 0.02	8.21 ± 0.02
2011	8.2 ± 0.02	8.19 ± 0.02	8.19 ± 0.02	8.18 ± 0.02	8.19 ± 0.02	8.18 ± 0.02
2012	8.17 ± 0.02	8.15 ± 0.02	8.16 ± 0.02	8.15 ± 0.02	8.16 ± 0.02	8.15 ± 0.02
2013	8.13 ± 0.02	8.13 ± 0.02	8.12 ± 0.02	8.1 ± 0.02	8.13 ± 0.02	8.11 ± 0.02
2014	8.11 ± 0.02	8.1 ± 0.02	8.1 ± 0.02	8.1 ± 0.02	8.11 ± 0.02	8.08 ± 0.01
2015	8.13 ± 0.02	8.1 ± 0.02	8.09 ± 0.01	8.07 ± 0.01	8.1 ± 0.02	8.09 ± 0.01
2016	8.12 ± 0.02	8.08 ± 0.01	8.09 ± 0.01	8.04 ± 0.01	8.1 ± 0.02	8.07 ± 0.01

A1 = Premonsoon high tide condition, B1 = Monsoon high tide condition and C1 = Postmonsoon high tide condition, A2 = Premonsoon low tide condition, B2 = Monsoon low tide condition and C2 = Postmonsoon low tide condition

Table 5.18 List of major industries along the lower stretch of the Hooghly estuary

S. No.	Name of Industry	Product
1	Indian Oil Corporation Ltd., Haldia	L.P.G., Motor Gasoline, Naptha, ATF, MTO, HSD, JBO, Kerosene, Furnace Oil, Lubes, Bitumen
2	KoPT/Haldia Dock Complex	Port Services
3	Tata Chemicals Ltd., Haldia	Industrial Phosphate and Acids
4	Exide Industries Ltd., Haldia	Automotive Batteries, Heavy Duty Batteries, Containers, Special Types of Separators, etc.
5	Shaw Wallace, Haldia	Pesticides
6	MCC PTA India Corpn. Pvt. Ltd., Haldia	P.T.A
7	Haldia Petrochemicals Ltd., Haldia	LLDPE, HDPE, Naptha Cracker etc.
8	IOCL, Paradip-Haldia Oil Pipeline	Petroleum Storage and Transportation
9	IOC Petronas Ltd., Haldia	L.P.G
10	Shamon Ispat Ltd.	Steel Rolling
11	Dhunseri Petrochem and Tea Ltd.	PET Resin
12	Greenways Shipping Agencies Pvt. Ltd.	Containers Freight Station (CFS)
13	IOC Ltd., Haldia	Petroleum Storage
14	Hindustan Petroleum Corporation Ltd	Petroleum and allied products
15	Bharat Petroleum Corporation Ltd., Haldia	Petroleum and allied products
16	Hindustan Unilever Limited	Detergents
17	Marcus Oils and Chemical Pvt. Ltd.	Polyehylene Waxes
13	IOC Ltd., Haldia	Petroleum Storage
18	Ruchi Soya Industries Ltd.	Edible Oil
19	Manaksia Ltd.	Aluminum and Steel
20	Sanjana Cryogenic Storages Ltd.	Ammonia Storage and handling terminal
21	R. D. B. Rasayans Ltd.	PP Jumbo Bag and Small bag
22	Reliance Industries Limited	Storage and handling Petroleum Product
23	Adani Wilmar Ltd.	PEdible Oil Refinery
24	Electrosteel Castings Ltd.	Coke Oven Plant, sponge iron plant, power plant
25	URAL India Ltd.	Automobile

(continued)

Table 5.18 (continued)

S. No.	Name of Industry	Product
26	K.S. Oils Ltd.	Edible Oil Refinery
27	DPM Net Pvt. Ltd.	Fishing net
28	Hooghly Met Coke and Power Co. Ltd.	Coke Oven Plant
29	Ruchi Infrastructure Pvt. Ltd.	3rd Party liquid storage tank terminal
30	Shree Renuka Sugars Ltd.	Sugar Refinery and Food Complex
31	Gokul Refoils and Solvent Ltd.	Edible Oil Refinery
32	Emami Biotech Ltd.	Bio-diesel Plant
33	Ennore Coke Private Ltd.	Coke Oven Plant
34	West Bengal Waste Management Ltd.	Industrial waste/municipal waste management complex
35	Lalbaba Seamless Tubes Pvt. Ltd.	Seamless Tube
36	Modern India Con-cast Ltd.	Ferro Alloy Plant
37	Rohit Ferro Tech Ltd.	Ferro Alloy

Fig. 5.7 Dense mangrove vegetation in eastern Indian Sundarbans

Table 5.19 Temporal variation of phytoplankton species diversity (Shannon Weiner Species Diversity Index) at Chemaguri (in Western Indian Sundarbans) and Jhilla (in Eastern Indian Sundarbans)

Year	Chemaguri (Western Indian Sundarbans)	Jhilla forest (Eastern Indian Sundarbans)
	21° 38′ 25.86″ N 88° 08′ 53.55″ E	22° 09′ 51.53″ N 88° 57′ 57.07″ E
1984	2.614	3.088
1985	2.587	3.087
1986	2.543	3.085
1987	2.511	3.083
1988	2.497	3.080
1989	2.478	3.079
1990	2.452	3.077
1991	2.311	3.075
1992	2.297	3.072
1993	2.846	3.069
1994	2.777	3.064
1995	2.718	3.062
1996	2.679	3.060
1997	2.637	3.059
1998	2.599	3.055
1999	2.543	3.054
2000	2.507	3.051
2001	2.476	3.050
2002	2.401	3.048
2003	2.347	3.047
2004	2.296	3.043
2005	2.243	3.040
2006	2.176	3.039
2007	2.119	3.037
2008	2.017	3.033
2009	2.915	3.135
2010	2.142	3.061
2011	1.907	3.058
2012	1.843	3.051
2013	1.612	3.039
2014	1.407	3.012
2015	1.245	2.986
2016	1.016	2.925
2017	0.963	2.919
2018	0.875	2.917

Table 5.20 Temporal variation of Total Suspended Solid (in mg/l) at Chemaguri (in Western Indian Sundarbans) and Jhilla (in Eastern Indian Sundarbans)

Year	Chemaguri (Western Indian Sundarbans)	Jhilla forest (Eastern Indian Sundarbans)
1984	127	98
1985	131	102
1986	133	104
1987	129	100
1988	130	101
1989	138	109
1990	143	114
1991	147	118
1992	140	111
1993	146	117
1994	150	121
1995	153	124
1996	159	130
1997	162	133
1998	165	136
1999	168	139
2000	158	129
2001	167	138
2002	161	132
2003	166	137
2004	170	141
2005	172	143
2006	175	146
2007	177	148
2008	171	142
2009	230	201
2010	184	155
2011	186	157
2012	180	151
2013	181	152
2014	189	160
2015	193	164
2016	195	166
2017	197	168
2018	192	163

Table 5.21 Temporal variation of nitrate (in µg at/l) at Chemaguri (in Western Indian Sundarbans) and Jhilla (in Eastern Indian Sundarbans)

Years	Chemaguri (Western Indian Sundarbans)	Jhilla forest (Eastern Indian Sundarbans)
1984	19.76	11.9
1985	21.54	13.68
1986	18.85	10.99
1987	20.66	12.8
1988	22.08	14.22
1989	24.71	16.85
1990	25.63	17.77
1991	26.22	18.36
1992	26.89	19.03
1993	27.13	19.27
1994	24.69	16.83
1995	25.44	17.58
1996	27.89	20.03
1997	29.02	21.16
1998	29.76	21.9
1999	30.35	22.49
2000	30.95	23.09
2001	31.08	23.22
2002	31.23	23.37
2003	31.75	23.89
2004	32.68	24.82
2005	33.01	25.15
2006	33.9	26.04
2007	34.15	26.29
2008	34.66	26.8
2009	40.21	32.35
2010	33.98	26.12
2011	34.85	26.99
2012	35.02	27.16
2013	35.11	27.25
2014	36.76	28.9
2015	37.39	29.53
2016	37.56	29.7
2017	38.07	30.21
2018	38.19	30.33

Table 5.22 Temporal variation of phosphate (in μg at/l) at Chemaguri (in Western Indian Sundarbans) and Jhilla (in Eastern Indian Sundarbans)

Years	Chemaguri (Western Indian Sundarbans)	Jhilla forest (Eastern Indian Sundarbans)
1984	0.98	0.87
1985	1.05	0.94
1986	1.16	1.05
1987	1.25	1.14
1988	1.39	1.28
1989	1.88	1.77
1990	1.93	1.82
1991	2.04	1.93
1992	2.11	2
1993	2.19	2.08
1994	2.37	2.26
1995	2.65	2.54
1996	2.73	2.62
1997	2.81	2.7
1998	2.56	2.45
1999	2.69	2.58
2000	2.93	2.82
2001	3.02	2.91
2002	3.15	3.04
2003	3.44	3.33
2004	3.58	3.47
2005	3.72	3.61
2006	3.86	3.75
2007	3.9	3.79
2008	3.97	3.86
2009	6.05	5.94
2010	4.18	4.07
2011	3.95	3.84
2012	4.05	3.94
2013	4.23	4.12
2014	4.36	4.25
2015	4.49	4.38
2016	4.58	4.47
2017	4.61	4.5
2018	4.75	4.64

Table 5.23 Temporal variation of phytoplankton species diversity at Haldia (adjacent to Western Indian Sundarbans) and Bali Island (in Central Indian Sundarbans)

Year	Haldia (adjacent to Western Indian Sundarbans)	Bali Island (Central Indian Sundarbans)
	22° 01′ 18.30″ N 88° 03′ 11.40″ E	22° 04′ 35.17″ N 88° 44′ 55.70″ E
1984	1.717	2.832
1985	1.69	2.831
1986	1.646	2.829
1987	1.614	2.827
1988	1.6	2.824
1989	1.581	2.823
1990	1.555	2.821
1991	1.414	2.819
1992	1.400	2.816
1993	1.949	2.813
1994	1.88	2.808
1995	1.821	2.806
1996	1.782	2.804
1997	1.74	2.803
1998	1.702	2.799
1999	1.646	2.798
2000	1.61	2.795
2001	1.579	2.794
2002	1.504	2.792
2003	1.45	2.791
2004	1.399	2.787
2005	1.346	2.784
2006	1.279	2.783
2007	1.222	2.781
2008	1.12	2.777
2009	2.018	2.879
2010	1.245	2.805
2011	1.01	2.802
2012	0.946	2.795
2013	0.715	2.783
2014	0.51	2.756
2015	0.348	2.73

(continued)

Table 5.23 (continued)

Year	Haldia (adjacent to Western Indian Sundarbans)	Bali Island (Central Indian Sundarbans)
	22° 01′ 18.30″ N 88° 03′ 11.40″ E	22° 04′ 35.17″ N 88° 44′ 55.70″ E
2016	0.119	2.669
2017	0.066	2.663
2018	0.022	2.661

Indian Sundarbans (21° 52′ 35.7″ N and 88° 11′ 55.0″ E) considering water bodies with varying pH levels. Our experimental design consisted of raising the pH of the three selected ponds by applying lime. Three ponds with aquatic pH 7.5, 7.8 and 8.1 were prepared for the experimental purpose by stocking the same source water having salinity 10.58 psu, nitrate 28.32 μg at L^{-1}, PO_4 2.95 μg at L^{-1} and SiO_3 145.75 μg at L^{-1}. The entire experiment was carried out during March 2020 to May 2020, the period of complete lockdown due to COVID-19 pandemic. We selected this period intentionally to minimize the external sources of pollution in our experimental ponds. During this three months period there was almost minimum anthropogenic influence due to complete closures of industries, fishing activities, fish landing stations and tourism units, which are common in the present study area and could provide external inputs to our experimental systems. At the end of the experiment, the water samples were collected to enumerate the phytoplankton density and diversity. The water samples were collected within bucket of a known volume, filtered through the bolting silk cloth and the plankton was concentrated. Centrifugation was carried out to concentrate the sample. The final volume of plankton concentrate was recorded to achieve the result of plankton density in terms of cells/litre or cells/m^3. In the next step, counting of plankton through Sedgwick Rafter was carried out. 1 ml of plankton sample obtained from the stock through the pipette was transferred to the Sedgwick Rafter counting cell. The sample for counting in this chamber was spread evenly in the form of a thin layer and this was done by placing a cover slip diagonally across the counting cell and the sample was then introduced at one of its corner. The total number of phytoplankton (standing stock) present in a litre of water sample was calculated using the formula:

$$\mathbf{N = nv/V}$$

where,

N= total number plankton cells per litre of water filtered.

n = average number of plankton cells in 1 ml of plankton sample.

v = volume of plankton concentrate (ml)

V= volume of total water filtered (l).

Table 5.24 Temporal variation of Total Suspended Solid (in mg/l) at Haldia (adjacent to Western Indian Sundarbans) and Bali (in Central Indian Sundarbans)

Year	Haldia (adjacent to Western Indian Sundarbans)	Bali Island (Central Indian Sundarbans)
1984	176	115
1985	180	119
1986	182	121
1987	178	117
1988	179	118
1989	187	126
1990	192	131
1991	196	135
1992	189	128
1993	195	134
1994	199	138
1995	202	141
1996	208	147
1997	211	150
1998	214	153
1999	217	156
2000	207	146
2001	216	155
2002	210	149
2003	215	154
2004	219	158
2005	221	160
2006	224	163
2007	226	165
2008	220	159
2009	279	218
2010	233	172
2011	235	174
2012	229	168
2013	230	169
2014	238	177
2015	242	181
2016	244	183
2017	246	185
2018	241	180

Table 5.25 Temporal variation of nitrate (in µg at/l) at Haldia (adjacent to Western Indian Sundarbans) and Bali (in Central Indian Sundarbans)

Years	Haldia (adjacent to Western Indian Sundarbans)	Bali Island (Central Indian Sundarbans)
1984	23.21	14.76
1985	24.99	16.54
1986	22.3	13.85
1987	24.11	15.66
1988	25.53	17.08
1989	28.16	19.71
1990	29.08	20.63
1991	29.67	21.22
1992	30.34	21.89
1993	30.58	22.13
1994	28.14	19.69
1995	28.89	20.44
1996	31.34	22.89
1997	32.47	24.02
1998	33.21	24.76
1999	33.8	25.35
2000	34.4	25.95
2001	34.53	26.08
2002	34.68	26.23
2003	35.2	26.75
2004	36.13	27.68
2005	36.46	28.01
2006	37.35	28.9
2007	37.6	29.15
2008	38.11	29.66
2009	43.66	35.21
2010	37.43	28.98
2011	38.3	29.85
2012	38.47	30.02
2013	38.56	30.11
2014	40.21	31.76
2015	40.84	32.39
2016	41.01	32.56
2017	41.52	33.07
2018	41.64	33.19

Table 5.26 Temporal variation of phosphate (in μg at/l) at Haldia (adjacent to Western Indian Sundarbans) and Bali Island (in Central Indian Sundarbans)

Years	Haldia (adjacent to Western Indian Sundarbans)	Bali (Central Indian Sundarbans)
1984	1.8	1.08
1985	1.87	1.15
1986	1.98	1.26
1987	2.07	1.35
1988	2.21	1.49
1989	2.7	1.98
1990	2.75	2.03
1991	2.86	2.14
1992	2.93	2.21
1993	3.01	2.29
1994	3.19	2.47
1995	3.47	2.75
1996	3.55	2.83
1997	3.63	2.91
1998	3.38	2.66
1999	3.51	2.79
2000	3.75	3.03
2001	3.84	3.12
2002	3.97	3.25
2003	4.26	3.54
2004	4.4	3.68
2005	4.54	3.82
2006	4.68	3.96
2007	4.72	4
2008	4.79	4.07
2009	6.87	6.15
2010	5	4.28
2011	4.77	4.05
2012	4.87	4.15
2013	5.05	4.33
2014	5.18	4.46
2015	5.31	4.59
2016	5.4	4.68
2017	5.43	4.71
2018	5.57	4.85

The units of standing crop are N/l or N $\times$ $10^3/m^3$.

Shannon Wiener Species Diversity Index (H) of 1949 was computed by using the formula

$$(\overline{\mathbf{H}}) = -\sum_{\mathbf{i}=1}^{\mathbf{S}} \frac{\mathbf{n_i}}{\boldsymbol{N}} \log_{\mathbf{e}} \frac{\mathbf{n_i}}{\boldsymbol{N}}$$

where,

n_i = importance probability for each species.

N = total of importance values.

The results of the experiment are presented in Table 5.27.

The Shannon Weiner Species Diversity Index is a reflection of environmental health. It is observed that the index follows the trend pH 8.1 (3.6346) > pH 7.8 (3.5855) > pH 7.5 (3.4827), which implies that with the decrease of pH, the stress increases more on the phytoplankton community, if other factors like salinity and nutrient levels are kept more or less uniform.

The subsequent level of Chlorophyll *a* in the order 10.55 mg m^{-3} in pond with aquatic pH = 8.1 > 7.25 mg m^{-3} in pond with aquatic pH = 7.8 > 4.60 mg m^{-3} in pond with aquatic pH = 7.5 confirms the adverse impact of acidification on the primary productivity of the estuarine ecosystem. This is also confirmed through fluorescence microscopic images. Maximum fluorescence was observed in pond with aquatic pH = 8.1, followed by pond with aquatic pH = 7.8 and pond with aquatic pH = 7.5 (Fig. 5.8a–c).

Zooplankton constitute an important tier in the marine and estuarine food web. The effect of climate change on the zooplankton community of estuarine system has not been studied by many researchers. A study conducted by Taucher et al. (2017) documented the dominancy of calanoid copepod *Pseudocalanaus acuspes* in simulated condition of ocean acidification. However, majority of studies have confirmed the resilient property of copepod to increasing carbon dioxide level (Weydmann et al. 2012; McConville et al. 2013; Hildebrandt et al. 2014). Several researchers have pointed negative physiological effects of ocean acidification on *Pseudocalanaus acuspes* by increasing respiration and decreasing ingestion and fecundity (Thor and Oliva 2015; Thor and Dupont 2015). Our work on the impact of lowering of aquatic pH on the ichthyoplankton community (a major component of zooplankton) as discussed in Table 5.14 confirms with confidence the adverse role of estuarine acidification on the floating juvenile community of bony fishes. It can also be inferred from the entire discussion that in the present geographical locale the role of anthropogenic activities in triggering the process of acidification cannot be ruled out due to presence of an industrial hub in the lower stretch of the Hooghly estuary preferably at Haldia (refer Table 5.18), which mostly discharge un-treated or partially treated wastes in the Hooghly estuary (Mitra and Zaman 2020).

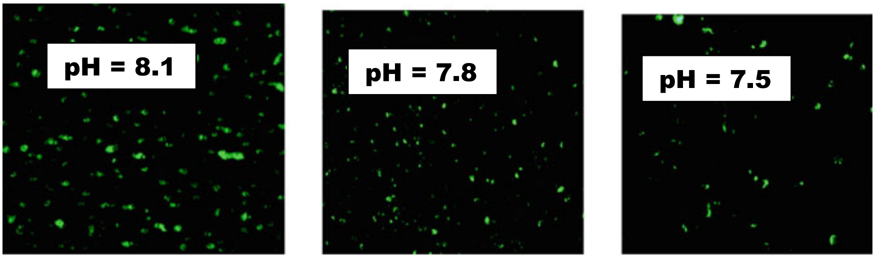
Table 5.27 Standing stock of the phytoplankton (N × $10^3/m^3$) in the selected brackish water ponds with variable pH

S. No.	Species	pH = 8.1	pH = 7.8	pH = 7.5
1	*Coscinodiscus eccentricus*	29.12	26.92	17.77
2	*Coscinodiscus jonesianus*	23.32	22.27	17.27
3	*Coscinodiscus lineatus*	21.55	19.47	20.15
4	*Coscinodiscus radiates*	26.09	24.47	20.92
5	*Coscinodiscus gigas*	17.65	12.87	15.47
6	*Coscinodiscus oculusiridis*	14.12	12.47	12.07
7	*Planktoniella sol*	15.72	14.92	13.02
8	*Cyclotella striata*	18.02	15.22	13.32
9	*Thalassiosira subtilis*	20.22	15.97	18.17
10	*Ceratium tripos*	10.19	9.47	7.62
11	*Skeletonema costatum*	10.82	9.07	8.12
12	*Paralia sulcata*	12.52	11.32	11.12
13	*Rhizosolenia crassipina*	10.29	9.02	8.02
14	*Rhizosolenia setigeara*	8.15	8.27	9.12
15	*Rhizosolenia alata*	10.89	9.77	7.22
16	*Ceratium teres*	8.75	6.72	5.82
17	*Ceratium trichoceros*	10.02	9.37	6.32
18	*Bacteriastrum delicatulum*	11.59	10.22	7.82
19	*Bacteriastrum varians*	13.35	11.12	9.47
20	*Bacteriastrum comosum*	9.99	8.67	8.07
21	*Chaetoceros didymus*	10.65	8.87	7.02
22	*Chaetoceros peruvianus*	8.89	7.37	7.37
23	*Chaetoceros compressus*	8.45	7.37	7.87
24	*Ditylum sol*	12.39	10.42	10.02
25	*Triceratium favus*	16.79	15.07	13.77
26	*Triceratium reticulatum*	14.72	11.67	11.07
27	*Biddulphia sinensis*	11.12	10.02	8.92
28	*Biddulphia mobiliensis*	12.89	11.32	9.82
29	*Hemidiscus hardmannianus*	11.42	9.27	7.82
30	*Climacosphenia elongate*	6.37	6.08	6.13
31	*Fragillaria oceanic*	12.15	9.97	9.77
32	*Rhaphoneis amphiceros*	6.2	5.97	5.94
33	*Thalassionema nitzschioides*	9.85	8.37	8.32
34	*Thalassiothrix longissima*	13.79	11.47	11.47
35	*Thalassiothrix fraunfeldii*	12.75	11.47	9.37

(continued)

Table 5.27 (continued)

S. No.	Species	pH = 8.1	pH = 7.8	pH = 7.5
36	*Asterionella japonica*	7.89	6.92	6.62
37	*Ceratium extensum*	9.55	7.52	6.57
38	*Gyrosigma balticum*	10.92	9.37	8.52
39	*Pleurosigma normanii*	16.82	13.32	13.42
40	*Pleurosigma elongatum*	10.55	7.87	6.77
41	*Diploneis smithii*	13.62	11.42	10.27
42	*Cymbella marina*	11.49	9.87	7.97
43	*Nitzschia sigma*	8.72	7.97	7.72
44	*Nitzschia closterium*	10.29	8.52	7.62
45	*Ceratium furca*	8.89	7.72	6.72
46	*Trichodesmium erythraea*	26.45	22.87	25.47
47	*Chlorella marina*	13.15	9.91	11.82
	Total (N)	619.14	535.59	491.05
	Shannon Weiner Index (H)	3.6346	3.5656	3.4827



a **b** **c**

Fig. 5.8 Fluorescence microscopic view of phytoplankton standing stock in three ponds with varying pH

5.4 Take Home Messages

A. Phytoplankton community encompasses unicellular, free floating organisms whose sizes usually range between 1 μm and 1 mm. The cells of these organisms are characterized by the presence of chlorophyll pigment, which is the core pigment in the process of photosynthesis. Phytoplankton are mainly confined in the photic zone of the ocean as they require sunlight, nutrients and carbon dioxide to form glucose that provides these tiny organisms with energy to perform various life processes. Phytoplankton forms the base of the marine and estuarine food web or in other words they support half of the global primary production, which directly or indirectly forms the foundation of all marine life. The Potential Fishing Zone (PFZ), which is the region for maximum fish catch is detected on the basis of pigment characterization that is assessed through Remote Sensing Technique. The estuaries of Indian Sundarbans are noted for their unique spatio-temporal variations of salinity. This variation has resulted to a wide range of adaptability to plankton community. The list of phytoplankton species has increased more than 150 in recent times in Indian Sundarban estuaries.

B. The zooplankton occupy the tier next to phytoplankton in the marine and estuarine food web. They either graze on phytoplankton or feed on other members of zooplankton. Foraminfera and radiolarians are members of zooplankton community who possess only one cell. Copepods and euphausiids are widely distributed zooplankton in the marine and estuarine environments. Zooplankton exhibit the phenomenon of vertical migration in which some species migrate towards the sea surface during the night time and return back to their original depth during day. The amount of daily migration varies between 10 and 500 m and this change of zone is keenly related to their nutritional requirement or maintenance of their light level. The zooplankton are mainly filter feeding in nature and are the prey of many shore-dwelling species. In aquatic sub-system of deltaic Sundarbans, the zooplankton community comprises a heterogenous assemblage of animals covering many taxonomic groups including copepods, mycids, lucifers, gammarid, cladocerae, ostracods, cumacea, hydromedusae, ctenophores and chaetognaths among holoplankters and polychaete larvae, molluscan and echinoderm larvae, crustacean larvae and fish eggs and larvae among meroplankters. Among the zooplankton, calaniod copepods constitute the major bulk, followed by cyclopoids, copepods and harpecticoids.

C. Acidification is the net result of climate change induced carbon dioxide rise in the atmosphere. With the rise of carbon dioxide, surface waters have become more susceptible to acidification. Anthropogenic carbon dioxide from the burning of fossil fuels has increased the uptake of the green house gas, causing the pH to drop from 8.2 to 8.1. Ocean acidification has high probability to pose negative impact on the marine life. It is well known that coral bleaching, reduced calcification and thinning of oyster shells are the direct effects of acidification. However, the species abundance and diversity of plankton are also adversely impacted by the pH level of the aquatic ecosystem as evidenced by our indoor experiments and field data.

Annexure 5: Program to Evaluate Shannon-Weiner Species Diversity Index

deci Shannon.c

```c

#include <stdio.h>
#define MAX_SIZE 1000 // Maximum array size
#include<math.h>
int main()
{
    float arr[MAX_SIZE]; // Declare an array of MAX_SIZE
    int  i,N,sum=0,j,temp=-1;
float l, k,s=0,s1=0;
    /* Input array size */
    printf("Enter total number of species: ");
    scanf("%d", &N);

    /* Input elements in array */

    for(i=0; i<N; i++)
    {
       printf("Enter No. of individuals of species: ", N,i+1);
        scanf("%f", &arr[i]);
    }


    /*
     * Print all elements of array
     */

   for(i=0;i<N;i++)
   {
    sum=sum+arr[i];
   }
```

deci Shannon.c

```c
   l=sum;
    printf("\n Percentage of species are: ");
    for(i=0; i<N; i++)
    {
        printf("\n  No. %d  percentage is %f ", i+1,arr[i]*100/l);
    }



   for(i=0;i<N;i++)
   {

     j=arr[i];
    k=j/l;

   s=s+k*log(k)*temp;
  s1=s1+pow(k,2);

          }









     if(s>0 && s<=0.5)
{
    printf("\n SHANNON INDEX IS %lf WHICH IS WORST",s);
}

```

```


else if(s>0.5 && s<=1.5)
{


    printf("\nSHANNON INDEX IS %lf WHICH IS MODERATE",s);
}
else if(s>1.5 && s<=2.5)
{


    printf("\nSHANNON INDEX IS %lf WHICH IS GOOD",s);
}

else if(s>2.5 && s<=3.5 )
{


printf("\nSHANNON INDEX IS %lf WHICH IS BETTER",s);

}
else
{
    printf("\nSHANNON WEINER INDEX IS %lf WHICH IS BEST",s);
}
printf("............................................. \n");
printf("\n EVENNESS INDEX is %f",s/log(N));
printf("\n INDEX OF DOMINANCE=%f",s1);

```

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Chapter 6
Impact of Acidification on Ecosystem Services of Sundarban Estuaries

Abstract Estuaries, being the zone of interaction between the sea and the river offer a wide spectrum of ecosystem services under the categories of provisioning services (fishes, minerals, oil and natural gas, products from mangroves, marsh grass etc.), regulating services (water quality maintenance, flood control, bioremediation, carbon sink etc.), supporting services (biodiversity, life cycle stages of fish and several aquatic organisms) and cultural services (religious convergence and rituals). Acidification poses an adverse impact on these ecosystem services primarily by disturbing the estuarine food webs where several categories of finfish and shellfish species are intricately linked. Lowering of pH also triggers the transference of the precipitated heavy metals from the underlying sediment bed to the overlying water column and thus the regulating services are affected. This chapter throws light on various disturbances caused by acidification on several ecosystem services provided by estuaries to mankind considering the mangrove dominated Indian Sundarbans as the case study zone.

6.1 Concept of Ecosystem Services: Focus Sundarban Mangroves

Ecosystem comprising of biotic and abiotic components provide a wide range of services to mankind. In addition to meet the daily needs of human beings, the floral community of ecosystem is the source of several life saving drugs. Disasters like super cyclones, landslides, tsunamis etc. are often checked by ecosystem and plays great role in reducing their intensities. However, the services are mostly unmarked and therefore the concept is not known to many. For this reason, we have carried out a respondent analysis in Sect. 6.2 of this chapter to get the people's feedback involving individuals across different tiers of the society. Today the concept of ecosystem services has become an important model for linking the functioning of ecosystems to societal benefits. With the progress of civilization, human beings have attempted to depend on nature for the supply of items like food, timber, fuel wood, fiber etc. (Foley et al. 2005; Kareiva et al. 2007; Monfreda et al. 2008; Ramankutty et al. 2008). In coastal areas and islands, people are depending on mangroves for procuring

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fishes, honey, fodder, timber, wax etc. However these attempts have been masked as nature simultaneously generate multiple ecosystem services that interrelate in complex dynamic ways (Peterson et al. 2003; Chan et al. 2006; Rodriguez et al. 2006; Brauman et al. 2007). It has been found that the scale of different ecosystem services is highly variable in nature, e.g., few ecosystem services like food and timber have great values compared to services like pollination or bioremediation.

Ecosystem services have been defined from various points of views. According to Millennium Ecosystem Assessment (2003, 2005) the benefits that people obtain from ecosystem including provisioning services such as food, timber, fresh water fiber; cultural services that provide non-material benefits, such as places for recreation, meditation and inspiration; and regulating services such as flood control and climate regulation together constitute the ecosystem services. This definition of ecosystem services encompasses gifts of nature like aesthetic beauty, carbon storage or oxygen generation etc.

Several research papers have explored the spatial patterns of provision of multiple services across landscapes by mangroves. This unique floral community acts as agent of shoreline protection in some areas, where as the same species plays significant role in bioremediation in some other zone (preferably in the coastal industrial belts).

In the domain of ecosystem services 'driver' is a very important term, which is basically a factor often directly modified by human management and affects one or more ecosystem services (Table 6.1). It has been observed that certain service of ecosystem affects the other through synergistic or antagonistic mechanism, e.g., afforestation enhance the process of carbon sequestration but at the same time the evapotranspiration increases the growth of the trees, which ultimately decreases the water availability. Thus it is an example of antagonistic mechanism. Again by maintaining forest patches close to agricultural land generates two services simultaneously namely pollination and crop production. This is an example of synergistic mechanism. It is therefore important to analyze the drivers and interactions among the multiple services and find a road map to create synergies and avoid antagonistic process by manipulating ecosystem service drivers.

Lot of works have been done on the valuation methods, data and classification systems for ecosystem services for terrestrial ecosystems compared to the mangrove ecosystems in the coastal and estuarine regions of the world. Peer review literature on global economic valuations of coastal forest like mangrove ecosystems, sea grass ecosystems is rather limited. Mangrove ecosystems are widely distributed at the land-sea interface and it has been projected that the number of people living within 10 km of significant mangrove areas might rise to 120 million (Van Bochove et al. 2014).

There are certain confusion to pinpoint the exact ecosystem services offered by mangroves because the ecosystem is often overlapped or combined with tidal marshes, sea grasses community, coral reefs etc. (Figs. 6.1 and 6.2).

Table 6.2 lists the ecosystem services categories identified by the mangrove Delphi, grouped according to the Common International Classification of Ecosystem Services (CICES).

Table 6.1 Examples of ecosystem service relationships

Sector	Driver	Service A	Service B	Shared driver	Response type	Interaction type	Synergy or trade-off	References
1.	Trail building	Cultural tourism	Agricultural production	No	–	None	None	Brscic (2006)
2.	Fertilizer use	Crop production	Water quality	Yes	Opposite	None	Trade-off	Carpenter et al. (1998)
3.	Wolf re-introduction (For Indian Sundarban mangroves, the present author considers it as deer re-introduction)	Nature tourism	Flood plain maintenance	Yes	Similar	None	Synergy	Wolf et al. (2007)
4.	Restoring riparian vegetation	Flood control	Crop production	No	–	Uni-directional, positive	Synergy	Kramer et al. (1997)
5.	Maintaining forest patches close to coffee plantations (For Indian Sundarban mangroves, the present author considers salt tolerant paddy plantations)	Pollination	Crop production	No	–	Uni-directional, positive	Synergy	Ricketts et al. (2008)

(continued)

Table 6.1 (continued)

Sector	Driver	Service A	Service B	Shared driver	Response type	Interaction type	Synergy or trade-off	References
6.	Wetland restoration	Flood control	Water quality	Yes	Similar	Uni-directional, positive	Synergy	Zedler (2003)
7.	Afforestation	Carbon sequestration	Water quantity	Yes	Opposite	Uni-directional, negative	Trade-off	Engel et al. (2005)
8.	Marine protected area development	Regulation of algae growth	Tourism	Yes	Similar	Uni-directional, positive	Synergy	Hughes et al. (2005)
9.	Dry spells	C sequestration/soil organic matter	Crop yield	No	–	Bi-directional, positive	Synergy	Enfors et al. (2008)
10.	Pesticide spraying	Wood production	Pest control	No	–	Bi-directional, negative	Trade-off	Clark et al. (1979)
11.	Cloud forest land clearing	Moisture retention	Carbon sequestration and tree growth	Yes	Similar	Bi-directional, positive	Synergy	del-Val et al. (2006)

Fig. 6.1 Overlapping of mangrove associate species (*Suaeda* sp.) with true mangrove flora

The total spectrum of ecosystem services offered by mangroves may be broadly divided into four major categories as presented in Fig. 6.3.

The valuation method for mangrove ecosystem services has not been standardized fully. Economist generally divide the total economic value of mangrove into three major groups namely (i) Direct use value (ii) Indirect use value and (iii) Non-use value. Direct use values refer to consumptive and non-consumptive uses that encompass physical interaction with the mangroves and their services as for example revenues generated from fishery, timber, fuel wood, fodder, honey, wax, recreation and transport. Indirect use values include regulatory ecological functions like flood control, storm protection, nutrient retention and erosion control. Non-use values include existence and bequest values of mangroves. Table 6.3 summarizes these three types of services as well as the methods most commonly used in their valuation.

Over the past few decades, research articles on mangrove ecosystem primarily focused on four major services namely (1) nursery services of mangrove forest, (2) fuel, fodder and timber production as sources of livelihood for adjacent coastal population and island dwellers, (3) Shoreline stabilization and land-building capacity and (4) carbon storage and subsequent sequestration. In recent time considerable progress has been made in the field of bioprospecting of mangrove derived microbes. Mangrove actinomycetes are the promising source for secondary metabolites.

Fig. 6.2 Overlapping of mangrove trees with saltmarsh grass (*Porteresia coarctata*)

The various forms of ecosystem services provided by mangroves are highlighted here in points.

1. Mangrove vegetations and their associates are economically very important for their products like timber, fire-wood, honey, wax, alcohol, tannins (Table 6.4) and even extracts having surprising medicinal properties.
2. Mangroves are thought to possess the ability to control coastal water quality. The complexity of the mangrove forest habitat increases the residence time, which assists in the assimilation of inorganic nutrients and traps suspended particulate matter. The mangroves also function as flood control barrier and binder of sediment particles (http://www.fao.org/gpa/sediments/habitat.htm).
3. The ecosystem forms an ideal ecological asset because the production of leaf litter and detrital matter from mangrove plants fulfill the nutritional requirements of prawn juveniles, adult shrimps, molluscs and fishes of high economic value. Because of this, mangrove ecosystem is recognized as the world's most potential nursery. There are three main factors to justify the nursery role of the mangrove habitat. They are:

    - High levels of water turbidity, which increases the survival rate of larvae through reduced perception distance of predators.

Table 6.2 Ecosystem service categories identified by the mangrove Delphi, grouped according to the Common International Classification of Ecosystem Services (CICES) v4.3 (http://cices.eu/)

Section	Division	Group	Class	Class type	Delphi technique categories
Provisioning	Nutrition	Biomass	Wild animals and their outputs	Animals by amount, type	Fisheries (food)
					Honey
			Animals from in-situ aquaculture	Animals by amount, type	Fisheries (aquaculture)
	Materials	Biomass	Fibres and other materials from plants, algae and animals for direct use or processing	Material by amount, type, use, media (land, soil, freshwater, marine)	Wood and timber
			Materials from plants, algae and animals for agricultural use		Fodder
	Energy	Biomass-based energy sources	Plant-based resources	By amount, type, source	Energy resources
Regulation and maintenance	Mediation of waste, toxics and other nuisances	Mediation by biota	Bio-remediation by micro-organisms, algae, plants, and animals	By amount, type, use, media (land, soil, freshwater, marine)	Water bioremediation
		Mediation by ecosystems	Filtration/sequestration/ storage/ accumulation by ecosystems	By amount, type, use, media (land, soil, freshwater, marine)	Pollution abatement, Environmental risk indicator
	Mediation of flows	Mass flows	Mass stabilization and control of erosion rates	By reduction in risk, area protected	Protection from sedimentation
			Buffering and attenuation of mass flows		Protection from salt intrusion

(continued)

Table 6.2 (continued)

Section	Division	Group	Class	Class type	Delphi technique categories
		Gaseous/air flows	Storm protection	By reduction in risk, area protected	Coastal protection
	Maintenance of physical, chemical, biological conditions	Lifecycle maintenance, habitat and gene pool protection	Maintaining nursery populations and habitats	By amount and source	Fisheries (nursery)
		Soil formation and composition	Decomposition and fixing processes		Carbon sequestration
		Atmospheric composition and climate regulation	Global climate regulation by reduction of greenhouse gas concentrations	By amount, concentration or climatic parameter	Carbon sequestration
Cultural	Physical and intellectual interactions with biota, ecosystems, and land-/seascapes (environmental settings)	Intellectual and representative interactions	Entertainment		Ecotourism and recreation
			Aesthetic		Aesthetic value

The first five columns belong to the CICES framework and the results of the Delphi technique are included in the last column. https://doi.org/10.1371/journal.pone.0107706.t001

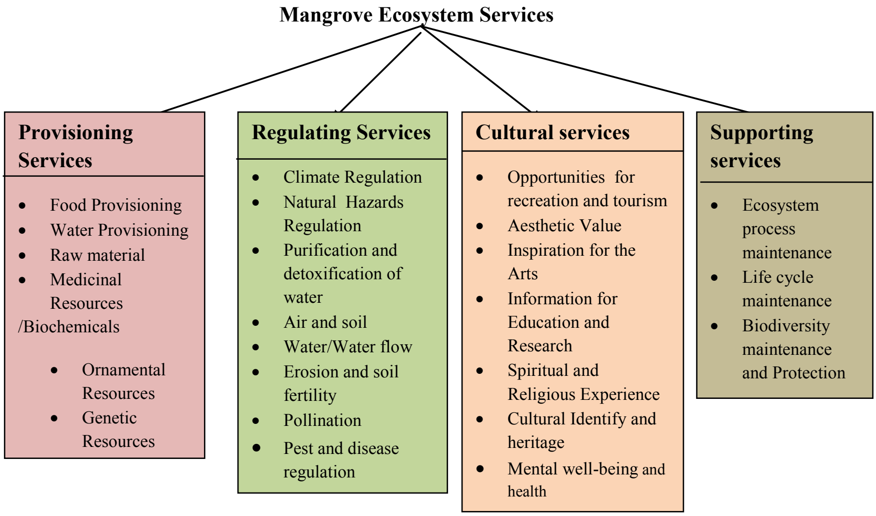

Fig. 6.3 Ecosystem services of mangroves

- Tidal mixing, nutrient trapping and fresh water inflow that result in considerable primary productivity and provide base of a food web from zooplankton to post larval fishes and juveniles.
- The physical and structural complexity of the habitat itself provides a variety of niches favourable to survival of juveniles. Niche segregation often leads to minimization of inter-and intra-specific competition resulting in a high survival rate of finfish and shellfish juveniles.

4. The vibrating mangrove ecosystem provides nutritional inputs to adjacent shallow channels and bay system that constitute the primary habitat of a large number of aquatic species, algae of commercial importance, seaweeds, phytoplankton etc. Mangroves and mangrove habitats contribute significantly to the global carbon cycle. Twilley et al. (1992) estimated the total global mangrove biomass to be approximately 8.70 gigatons dry weight (which is equivalent to 4.00 gigatons of carbon). Accurate biomass estimation however needs the measurement of the volumes of individual trees.
5. Mangroves trap debris and silt, leading to the stabilization of the near shore environment. (http://www.reefrelief.org/Documents/mangrove.html).
6. The highly specialized mangrove ecosystem also acts as the protector of the coastal landmass from storm surges, tropical cyclone, high winds, tidal bores, seawater seepage and intrusion.
7. Bioaccumulation of heavy metals by certain mangrove species reveals a most surprising feature about these plants as they can act as bio-purifier or bio-filter. Certain mangrove species are highly efficient in detecting or assessing the change of ambient environment. The concentration of heavy metal pollutants

Table 6.3 Ecological mangrove functions, economic goods and services, types of value, and commonly applied valuation methods

Ecological function	Economic goods and services	Value type	Commonly used valuation method(s)*
Flood and flow control	Flood protection	Indirect use	RCM MP
Storm buffering/ sediment	Storm protection	Indirect use	RCM PF
Water quality maintenance/nutrient retention	Improved water quality	Indirect use	CVM
	Waste disposal	Direct use	RCM
Habitat and nursery for plant and animal species	Commercial fishing and hunting	Direct use	MP NFI
	Recreational fishing and hunting	Direct use	TCM CVM
	Harvesting of natural materials	Direct use	MP NFI
	Energy resources	Direct use	MP NFI
Biodiversity	Appreciation of species existence	Non-use	CVM
Carbon sequestration	Reduced global warming	Indirect use	RCM
Natural environment	Recreation, tourism	Direct use	CVM TCM
	Existence, bequest, option values	Non-use	CVM

Source Brander et al. (2006) who adapted with modifications from Barbier (1991), Barbier et al. (1997), Brouwer (2000) and Woodward and Wui (2001)

*Abbreviations represent: market prices (MP), production function method (PFM), travel cost method (TCM), contingent valuation method (CVM), replacement cost method (RCM), and net factor income (NFI)

in different parts of mangrove plants may act as a pathfinder for water quality monitoring programme (Mitra et al. 2004).

8. Mangroves filter ground water and storm water run-off that often contain harmful pesticides, herbicides and hydrocarbons. Mangroves also recharge underground water table by collecting rain water and slowly releasing it into the underground reservoir.
9. Mangrove prop roots protect and offer habitat for mammals, amphibians, reptiles, countless unique plants, juvenile fish and invertebrates that filter water such as sponges, barnacles, oysters, mussels, crabs, shrimps etc.
10. Mangroves are ideal nesting grounds for many water birds such as the great white heron, reddish egrets, roseate spoonbills, white-crowned pigeons, cuckoos and frigate birds. The excretory materials of these birds serve as the

Table 6.4 Some traditional uses of true mangrove species

Mangrove species	Uses
Aegiceras corniculatum	Bark used as fish poison. Also contains tannin
Avicennia alba	Used as fodder and fuel
Bruguiera caryophylloides	Wood used for firewood and timber. Bark used for tannin production
Bruguiera gymnorrhiza	Wood used for house posts. Bark used as tannins. Also provides fuel
Bruguiera parviflora	Source of fuel. Leaves and barks contain tannin
Bruguiera sexangula	Timber used in house building
Ceriops tagal	Used for keel of boats and house posts. Provides good fuel charcoal. Bark is rich in tannin, used for dyeing fishing nets
Rhizophora mucronata	Bark is used for tannin and cattle fodder
Sonneratia apetala	Wood used in house building, packing cases and yield excellent fuel
Xylocarpus granatum	Yields gum, resin which are used in local medicines. Bark contains tannin

Source Mangroves of the Sundarbans, Vol. 1: India, by A. B. Chaudhuri and A. Choudhury, IUCN publication, 1994

fertilizers of the adjacent water bodies on which the primary production of the aquatic phase depends.

11. Mangrove forests are the housing complexes for bees, birds, mammals and reptiles from which honey, wax, food etc. are obtained.
12. The molluscan species in the mangrove ecosystem (under gastropoda and bivalvia) are the rich sources of lime (Fig. 6.4).
13. Mangrove leaves are used as fodder and green manure. The cyanobacterial strains present on the forest floor of mangrove ecosystem are important sources of biofertilizer.
14. Extracts from mangrove and mangrove dependent species have proven activity against some animal and plant pathogens. Moreover, mangrove extracts kill larvae of the mosquitoes *e.g.*, a pyrethrin like compound in stilt roots of *Rhizophora apiculata* shows strong mosquito larvicidal activity (Thangam 1990).
15. Bioactive compound (ecteinascidin) extracted from the mangrove ascidian *Ecteinascidia turbinata* have shown strong in vivo activity against a variety of cancer cells.
16. Phenols and flavonoids in mangroves leaves serve as UV-screening compounds. Hence, mangroves can tolerate solar UV radiation and create a UV-free, under-canopy environment (Moorthy 1995).
17. Bark of *Ceriops* sp. is an excellent source of tannin and a decoction of it is used to stop haemorrhage and as an application to malignant ulcers. Flowers of this plant are a rich source of honey and bee wax.

Fig. 6.4 Oysters in the mangrove ecosystem are rich sources of high quality lime

18. Mangrove ecosystem affords recreation to hunters, fishermen, bird-watchers, photographers and others who treasure natural areas. However, the intrusive actions of noisy jet-skis, happy campers and others, which disturb nesting and breeding areas, chop down mangroves and otherwise damage this fragile environment, threaten its existence.
19. Mangroves are potential vegetation from the point of carbon storage and sequestration. Despite the large number of case studies dealing with various aspects of organic matter cycling in mangrove systems (Kristensen 2008), there is very limited consensus on the carbon sequestering potential of mangroves. Not only the vegetative and reproductive parts of the mangrove tree species, but the soil below on which the mangroves thrive is also a unique carbon reservoir. The term blue carbon encompasses this carbon pool in the biotic and abiotic components in the mangrove forests (Fig. 6.5).
20. Oxygen production is one of the most common but under-researched benefits of mangroves. Most of the mangrove forests are usually oxygen-neutral or oxygen-negative system as they produce equal or less oxygen compared to what they consume. The dead mangrove trees and the mangrove litter along with detritus consume oxygen to carry out the process of decomposition,

Fig. 6.5 Mangrove forests with adjacent mudflats—a potential sink of carbon

which pushes the mangrove system toward oxygen-negative. In order to make the system oxygen-positive, it is essential to retard the process of decomposition. An in-depth study conducted on the oxygen production potential of mangroves shows that the dominant mangrove species in Indian Sundarbans can release on an averge about 7.7 tonnes of oxygen per hecatre in 1 year, which amounts to INR 841,533 for filling 1295 cylinders of 6 L capacity. The net oxygen release (tonnes/ha/yr) of mangroves is a function of carbon sequestration (10 years considered in this study) and Table 6.5 presents the net oxygen release (tonnes/ha/yr) of five dominant species namely *Sonneratia*

Table 6.5 Sector-wise net O_2 release (in tonnes ha^{-1} y^{-1}) by dominant mangrove floral species in Indian Sundarbans

Sector	Carbon sequestration (tonnes ha^{-1} y^{-1})	Net O_2 release (tonnes ha^{-1} y^{-1})	No. of O_2 cylinders needed to fill up by the O_2 gas (capacity 6 lt.)	Total price of cylinder (INR)
Central	3.014	8.047	1341	871,650
Western	2.800	7.476	1246	809,900
Eastern	2.916	7.785	1297	843,050

apetala, *Avicennia marina*, *Avicennia alba*, *Avicennia officinalis*, and *Exoce-caria agallocha.* The values are average of five species (for each of the three sectors in Indian Sundarbans.

21. Mangrove based fungi degrade the vegetation and play major roles in ecological and biogeochemical processes. They contribute significantly to the degradation process of mangrove–derived organic matter and thereby generate food/nutrients for benthic fauna. The major phyla under fungi are Basidiomycota, Ascomycota, Glomeromycota, Microsporidia, Blastocladiomycota, Neocallimastigomycota and Chytridiomycota.
22. Flora and fauna of the estuaries are today used as sources of bioactive substances, which have immense importance in the pharmaceutical industries. Examples of CAL (Carcinoscorpious Amoebocyte Lysate) and TAL (Tachypleus Amoebocyte Lysate) are very relevant in this context. They are derived from the blue blood of horseshoe crabs (*Carcinoscorpious rotundifolia* and *Tachypleus gigas*) found abundantly in the estuaries of West Bengal and Odisha, which are two maritime states in the North-East coast of the Indian sub-continent. CAL and TAL are used for bacterial endotoxin test.
23. Several mangrove medicinal plants widely distributed in the coastal and estuarine regions were tested for antiviral, antifungal and mosquito larvicidal activities. In the Parangipettai coast of India (South east coast), 113 medicinal plants have been recorded. Out of 36 plants, 3 plants showed high anti-HIV activity. The anti-HIV activity of coastal population was also tested in comparison with their terrestrial counterparts. In general, coastal populations exhibited better anti-HIV activity than terrestrial ones. 23 plants were screened for antibacterial activity against 13 human pathogenic bacterial strains, of which 23 extracts showed anti-bacterial activity against one or more bacteria. 25 plants were screened for antifungal activity against 6 fungi. All the plant extracts examined showed activity against one or more fungi. 2 plant species exhibited high antifungal activity. In general, the coastal samples showed higher activity than terrestrial ones. 11 plants were tested for mosquito larvicidal activity against two mosquito species namely, *Culex quinquefasciatus* and *Aedes aegypti*, of which, 5 samples were effective. In addition to these services, the mangrove flora thriving in the coastal and estuarine regions are rich sources of antioxidants.
24. In recent time considerable progress has been made in the field of bioprospecting of mangrove derived microbes. Mangrove actinomycetes are the promising source for secondary metabolites. Novel indolocarbazoles identified from a mangrove streptomycete present unprecedented cyclic N-glycosidic linkages between 1,3-carbon atoms of the glycosyl moiety and two indole nitrogen atoms of the indolocarbazole core with anticancer activity.
25. The vegetative structures of mangroves offer considerable resistance to the magnitude of natural disasters. Features of mangrove vegetation like presence of pneumatophores or complex prop root systems, the density of the forest and the diameter of the tree stems regulate the magnitude of damage caused by storms and cyclones. The spatial dimensions of the forest, in particularly

Fig. 6.6 Pneumatophores of mangroves act as structures against wave attenuation

how far it reaches inland from the shore, are considered some of the most important determinants of protective capabilities with regards to tsunamis and cyclones. Mangroves are also capable to reduce wind related damage from large cyclone, storms by directly attenuating the energy of wind that passes through there dense canopies. The dense pneumatophores of mangroves serve as natural agents of wave attenuation (Fig. 6.6).

India with coast line of approximately 7517 km including the Island territories has a mangrove cover of 6749 km^2.

The Indian mangrove habitats may be classified into three distinct categories (Table 6.6).

Considering the geomorphologic characters the mangrove habitat in India can be sub-divided into three categories (Table 6.7).

In Indian subcontinent a total of 82 very common true mangrove and associate species, distributed in 52 genera and 36 families have been recorded (Table 6.8).

In Indian sub-continent, mangrove biodiversity is extremely rich in regions like Indian Sundarbans and Bhitarkanika. In these two maritime states in the northeast part of the country, some 36 species of true mangroves have been documented.

The Indian Sundarbans appears as a continuous green carpet in aerial surveys, consisting of dense low trees ranging from 3 to 5 m in height comprising of *Excoecaria agallocha* and *Avicennia* spp. *Rhizophora apiculata* and *R. mucronata* are found in the creeks, often in association with *Nypa fruticans*. Three common

Table 6.6 Classification of Indian mangroves habitats

Sl No	Category	Description	Example
(a)	Deltaic mangrove habitat	High tidal actions along with tidal amplitude are the characteristic features associated with deltaic mangrove habitat. In this habitat strong tidal currents are seen which are responsible for the dispersion of sediments brought to the coasts by the rivers and the main river channels	Sundarban mangrove forest in West Bengal, mangrove forest in Mahanadi delta in Odisha, mangrove forest in the Bhavnagar estuary in Gujarat
(b)	Coastal mangrove habitat	The tidal range is not very high in the coastal mangrove habitat. This habitat is formed by the deposition of terrigenous sands, silts and clays brought by the river discharges	It includes the inter- tidal coastlines, minor river mouths, sheltered bays and back water areas of the west coast
(c)	Island mangrove habitat	This type of mangrove habitat is seen at the mouths where rivers are seen to border the open sea	It includes shallow but protected inter tidal zones of bay island and Lakshadweep Atoll

Table 6.7 Geo-morphological character- based categorization of Indian mangroves

Sl No	Category	Example
(a)	East coast mangrove habitats	Sundarban mangrove forest (West Bengal), Bhitarkanika mangrove forest (Odisha), Mahanadi delta mangrove forest (Odisha), Godavari and Krishna delta mangrove forest (Andhra Pradesh), Pichavaram mangrove forest (Tamilnadu) etc.
(b)	West coast mangrove habitats	Mangrove forest along Cochin estuary, mangrove forests along Zuari and Mandovi estuaries in Goa, Mangrove forest along Bhavnagar estuaries in Gujarat etc.
(c)	Andaman & Nicobar and Lakshadweep Island	Andamam & Nicobar Islands and Lakshadweep Atoll, comprising more than 200 and 37 islands, respectively, harbour island mangroves

species of *Bruguiera* are present, comprising *B. cylindrica*, *B. gymnorrhiza* and *B. sexangula*. These genera have been over-exploited and regeneration is poor. *Kandelia candel*, a fourth genus of the family *Rhizophoraceae*, is very rare. *Avicennia alba*, *Avicennia marina* and *Avicennia officinalis* are members of the family *Avicenniaceae*, which are abundantly found in the Indian Sundarbans. These species represent a

Table 6.8 Most common Indian mangrove flora (including mangrove associate species)

Sl. No	Scientific names	Families
1	*Acanthus ilicifolius* L	Acanthaceae
2	*A. ebracteatus* Vahl	Acanthaceae
3	*A. volubilis* Wall	Acanthaceae
4	*Aegialitis rotundifolia* Roxb	Aegialitidaceae
5	*Sesuvium portulacastrum* L	Aizoaceae
6	*Crirtum defixum* Ker. Gawler	Amaryllidaceae
7	*Cerbera manghas* L	Apocynaceae
8	*C. odolum* Gaertner	Apocynaceae
9	*Cryptocoryne ciliata* Fish ex Schott	Araceae
10	*Nypa fruticans* Roxb	Arecaceae
11	*Phoenix paludosa* Wurmb	Arecaceae
12	*Sarcolobus globosus* Wall	Asclepiadaceae
13	*S. carinatas* Wall	Asclepiadaceae
14	*Hoya parasitica* Wall	Asclepiadaceae
15	*Pentatropis capensis* (L.f.) Bullock	Asclepiadaceae
16	*Avicennza alba* Blume	Avicenniaceae
17	*A. marina* (Forsk.) Vier	Avicenniaceae
18	*A. officinalis* L	Avicenniaceae
19	*Dolichandrone spathaceae* (L.f.) Schum	Bignoniaceae
20	*Heliotropium curassavicum* L	Boraginaceae
21	Caesalpinia bonuc L	Caesalpiniaceae
22	*C. crista* L	Caesalpiniaceae
23	*Suaeda nudiflora* Roxb	Chenopodiaceae
24	*S. mritima* Dumort	Chenopodiaceae
25	*S. monoica* Forssk	Chenopodiaceae
26	*Salicornia brachiata* Roxb	Chenopodiaceae
27	*Lumnitzera racemosa* Willd	Combretaceae
28	*L. littorea* (Jack.) Voigt	Combretaceae
29	*Ipomoea pes-caprae* L	Convolvulaceae
30	*Excoecaria agallocha* (L.) Sweet	Euphorbiaceae
31	*Barringtonia racemosa* (L.) Sprengal	Lecythidaceae
32	*Viscum orientale* Willd	Loranthaceae
33	*Dendrophthoe falcata* (L.f.) Etting	Loranthaceae
34	Hibiscus liliaceous L	Malvaceae
35	*Viscum orientale* Willd	Malvaceae

(continued)

Table 6.8 (continued)

Sl. No	Scientific names	Families
36	*Thespesia populnea* (L.) Soland ex Correa	Malvaceae
37	*T. populnoides* (Roxb.) Kostel	Malvaceae
38	*Xylocarpus granetum* Koenig	Meliaceae
39	*X. moluccensis* (Lamk.) Roem	Meliaceae
40	*X. mekongensis* Pierre	Meliaceae
41	Aglaia cucullata Pellegrin	Meliaceae
42	*Cynometra ramiflora* L	Mimosaceae
43	*Aegiceras corniculatum* (L.) Blanco	Myrsinaceae
44	*Ardisia littoralis* SW	Myrsinaceae
45	*Pandanus foetidus* Roxb	Pandanaceae
46	*Derris scandens* Benth	Fabaceae
47	*D. trifoliata* Lour	Fabaceae
48	*D. indica* Bennett	Fabaceae
49	*Dalbergia spinosa* L	Fabaceae
50	*Porteresia coarctata* (Roxb.) Takeoka	Poaceae
51	*Aehiropus legopoides* (L.) Trin	Poaceae
52	*Myriostachya wightiana* Hk.f	Poaceae
53	*Urochandra setulosa* (Trin.) Hubbard	Poaceae
54	*Acrostichum aureum* L	Pteridaceae
55	*Rhizophora mucronata* Lamk	Rhizophoraceae
56	*R. apiculata* Blume	Rhizophoraceae
57	*R. stylosa* Griff	Rhizophoraceae
58	*R.lamarkii* Montr	Rhizophoraceae
59	*R. annamalayana* Kathir	Rhizophoraceae
60	*Bruguiera gymnorrhiza* (L.) Lamk	Rhizophoraceae
61	*B. sexangula* (Lour.) Poir	Rhizophoraceae
62	*B. parviflora* W. & A	Rhizophoraceae
63	*B. cylindrica* (L.) Blume	Rhizophoraceae
64	*Ceriops decandra* (Griff.) DingHou	Rhizophoraceae
65	*C. tagal* Robinson	Rhizophoraceae
66	*Kandelia candel* (L.) Druce	Rhizophoraceae
67	*Scyphiphora hydrophyllacae* Gaertn. F	Rubiaceae
68	*Hydrophylax maritima* L	Rubiaceae

(continued)

Table 6.8 (continued)

Sl. No	Scientific names	Families
69	*Atalantia correa* M.Roem	Rutaceae
70	*Salvadora persica* L	Salvadoraceae
71	*Solarium trilobatum* L	Solanaceae
72	*Sonneratia apetala* Buch. Ham	Sonneratiaceae
73	*S. alba* Smith	Sonneratiaceae
74	*S. caseolaris* (L.) Engler	Sonneratiaceae
75	*S. griffithii* Kurz	Sonneratiaceae
76	*Heritiera fames* Buch. Ham	Sterculiaceae
77	*H. littoralis* Ait. Ex Dry	Sterculiaceae
78	*H. kanikensis*	Sterculiaceae
79	*Tamarix gallica* L	Tamaricaceae
80	*Tamarix dioica* Roxb	Tamaricaceae
81	*Brownlowia tersa* (L.) Koesterm	Tiliaceae
82	*Clerodendron inerme* (L.) Gaertn	Verbenaceae

pioneer genus in mangrove plant succession and occur in association with the salt marsh grass *Porteresia coarctata*, in areas of accretion. *Avicennia* spp. also occurs in gregarious forms along the stretches of channels and creeks. *Sonneratia apetala* occurs in fringe areas in discontinuous strips while *S. caseolaris* occurs only in the western Sundarbans. These two species thrive luxuriantly in areas with high dilution factor. *Xylocarpus granatum* and *X. mekongensis*, which were once common species in the Sundarbans, are found scattered and have become scarce because of selective felling and poor regeneration. Stunted trees of *Heritiera fomes* are found scattered all over the forest. In the central Indian Sundarbans, which is extremely hypersaline in nature, the species is on the verge of extinction (Mitra 2013; Mitra and Zaman 2014, 2015, 2016). *Amoora cucullata* is also found in association with *Heritiera*, in freshwater conditions. *Aegialites rotundifolia*, representing a monoypic genus, is found in low-lying areas with *Acanthus ilicifolius*. Both *Amoora cucullata* and *Aegialites rotundifolia*, together with *Aegiceras corniculatum*, are present in very small numbers and are a cause for concern. *Aegiceras*, found on the banks of narrow creeks, are exploited for timber and fuel wood. *Lumnitzera racemosa* is sparsely distributed in areas of high salinity. *Nypa fruticans* is found in the creeks although this species has been over-exploited and regeneration is poor. *Brownlowia tersa* and *Cynometra ramiflora* are scarce. On high areas above tide level, thick patches of pure *Phoenix paludosa* occur and are increasing in number (Fig. 6.7). The species can thrive luxuriantly in high saline environment and offers a congenial shelter for Royal Bengal tiger.

The Bhitarkanika mangrove forest is the second largest mangrove forest in India. In April, 1975 mangroves of Bramhani and Baitarani delta of Kendrapara district have been declared as the Bhitarkanika Wild Life Sanctuary (BWLS), which covers an area of 145 km^2. Bhitarkanika is endowed with three major types of ecosystem

Fig. 6.7 *Phoenix paludosa* patches in the Indian Sundarbans on high areas of the tide level

namely brackish water, marine and terrestrial—intricately mixed with each other. The community structure of mangrove vegetation is greatly influenced by dilution factor, tidal inflow, degree of inundation and salinity gradient. Several works have been carried out on the distribution of mangroves in the Bhitarkanika region (Banerjee and Das 1972; Mishra and Panigrahi 1987; Pattanaik and Choudhury 1989; Banerjee and Rao 1990; Dani et al. 1999; Mishra et al. 2005; Pattnaik et al. 2008; Upadhyay et al. 2008).

In Indian literatures most of the mangrove related studies focused on their taxonomic status. In course of time, the dimension of research shifted towards their ecosystem services. Since the last decade, mangrove related researches took a bent/turn towards climate change and carbon sequestration. In many countries, policy makers attempted to link mangrove plantation with carbon sequestration as a road map towards Clean Development Mechanism (CDM).

A survey was carried out at Bhitarkanika Wild Life Sanctuary (BWLS) by the present author during August 2016 to estimate stored carbon in the stem region of true mangrove and mangrove associate floral species. The stored carbon exhibited direct proportionality with stem biomass irrespective of the species. The stored carbon in the stem of the selected species varied from 0.03 t ha^{-1} in *Thespesia populnea* to 11.32 t ha^{-1} in *Avicennia officinalis* as shown in Fig. 6.8. The total stored carbon in the stems of the selected species is 61.97 t ha^{-1}, which synchronizes well with values (extrapolated through thumb rule) obtained from different mangrove regions of the

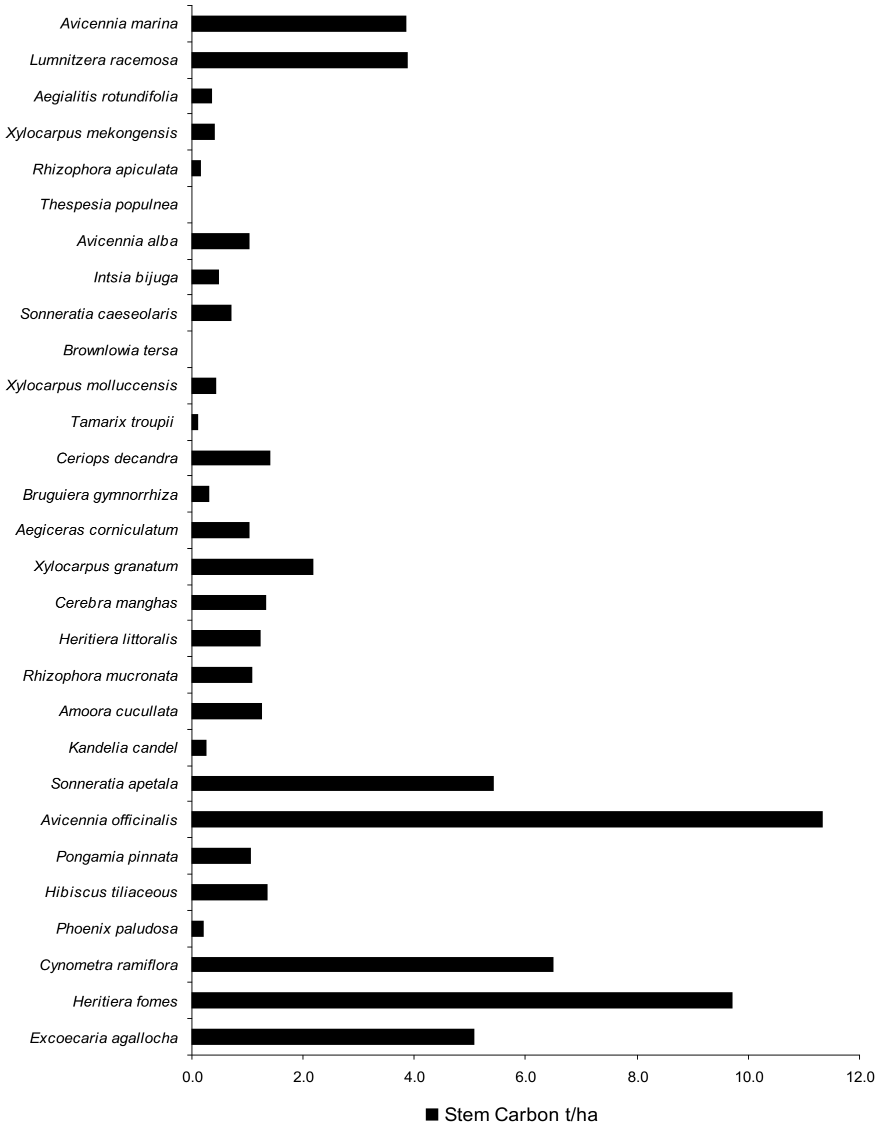

Fig. 6.8 Stem carbon of mangrove trees in Bhitarkanika as recorded during August, 2016

World. The present study establishes the potential of BWLS mangrove flora in the domain of carbon sequestration, which is a new dimension in the ecosystem services of mangroves thriving in the deltaic complex of Brahmani and Baitarani Rivers.

It is interesting to note that few cutting edge researches are gradually taking a formative stage in the domain of ecosystem services of Indian Sundarban mangroves, which have direct linkage with the livelihood of coastal population. Fruit jelly, has been prepared from *S. apetala* fruit. Ice creams, cookies, breads have been prepared from mangrove associate seaweeds *Enteromorpha intestinalis* (Mitra et al. 2016; Pramanick 2017). There are also reports of preparing breakfast snacks like samosa and kachuri from mangrove associate species like *Suaeda maritima* and *Salicornia brachiata* (Biswas et al. 2019). All these are few innovations under the umbrella of provisioning services of mangroves, and are yet to see the light of mass scale production and proper marketing facility.

In addition to true mangrove species there are also associate species in the same ecosystem which also play great role in terms of ecosystem services. The floral species in mangrove ecosystem can be categorized into true mangroves and mangrove associates. The species which are adapted to mangrove habitat and do not extend into other terrestrial plant communities are referred to as true mangrove species. On contrary, plants that occur in the coastal environment and also within the mangroves are referred to as mangrove associate species. It has been observed that mangrove associate species can also thrive luxuriantly in terrestrial region far away from mangroves. Seaweeds often associated with the mangrove ecosystem and distributed in shallow water adjacent to intertidal mudflats have wide application in the health care services. Several mangrove associated seaweeds are used for manufacturing cosmetics (Table 6.9) due to presence of nutritional elements, antioxidant and iodine in their thallus body.

Table 6.9 Use of mangrove associate species in health care products

Product name	Company name	Country	Seaweed used
Super Moisturizing Hand Cream	Balance Me	UK	*Chondrus crispus*
Pacific Seaweed Soak	Beauty through Balance	Canada	*Macrocystis integrifolia*
Gentle Foaming Facial Cleanser	Be Natural Organic	U.S	*Ascophyllum nodosum*
Your Best Baby Bump Duo (containing Elasticity Belly Oil and All Day Moisture Body Lotion)	Belli Skincare	U.S	*Chondrus crispus*
Detoxifying Soap Bar with Grapefruit, Lemon and Seaweed	Bentley Organic	UK	*Fucus vesiculosus*
Brow Boost	Billion Dollar Brows	U.S	*Laminaria digitata*
Bliss Fabulous Every Day Eye cream	Bliss World LLC	U.S	*Laminaria digitata*

(continued)

Table 6.9 (continued)

Product name	Company name	Country	Seaweed used
Beeswax and Royal Jelly Eye Cream	Burt's Bees	U.S	*Chondrus crispus*
Scottish Intensive Seaweed Conditioner	Diana Drummond	UK	*Laminaria digitata, Chondrus crispus, Ascophyllum nodosum, Ulva lactuca*
Sea Plus Renewal Night Cream	Alba Botanica	U.S	*Chondrus crispus*, *Laminaria digitata*, *Macrocystis pyrifera*, *Ulva compressa*, *Ulva lactuca*

6.2 Respondent Analysis on Acidification of Sundarban Estuaries

Little quantitative information is available regarding the impact of acidification on the ecosystem services of estuaries. Very few people are aware of the phenomenon and its impact on the ecosystem. Considering this knowledge gap, the concept of acidification of Indian Sundarban estuaries and its subsequent impacts on biodiversity and livelihoods were brain stormed amongst the stakeholders associated with the mangrove ecosystem in the frame work of Indian Sundarbans during 2017–2019 through a set of questionnaires (*Vide* Table 6.16). The entire network of the study consisted of three stages (i) identification of respondents (policy maker, researcher, fisherman, agriculturist and local inhabitant) (ii) identification of major impacts of acidification (8 in numbers) and iii) evaluation of the respondent's response to construct the Acidification Impact Scale (AIS) through ranking (IR) and voting. Although impacts can be of various types, the present list captures the major impacts caused by lowering of aquatic pH in three sectors of Indian Sundarbans (western, central and eastern) and was ranked in terms of their importance by building an Acidification Assessment Matrix (AAM). However, as there is high probability of variation of this ranking with the category of respondents, therefore the views of the respondents were also considered (by inclusion of the % of voting along with their respective ranking factor) and finally Composite Acidification Impact Scale (CAIS) in context to Indian Sundarban estuaries was constructed as per the expression (Tables 6.10, 6.11, 6.12, 6.13, 6.14 and 6.15).

$$\mathrm{CAIS} = \mathrm{AIS1} + \mathrm{AIS2} + \mathrm{AIS3} + \mathrm{AIS4} + \mathrm{AIS5}$$

where, AIS = Impact Rank (IR) × % of Vote.

It is to be noted in this context that the sample size of respondents are variable e.g., for policy maker it is 65, but for other groups of respondents n = 90 for each group.

Table 6.10 Impact of acidification on estuarine water with scaling in western Indian Sundarbans

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
pH level of estuarine water	7	23.1	161.7
Pollution level	7	22.2	155.4
Fishes	2	9.1	18.2
Molluscs	5	10.2	51.0
Plankton	4	9.7	38.8
Mangrove flora	3	6.2	18.6
Livelihood	6	11.3	67.8
Socio-economic profile	5	8.2	41.0
Impact	**Researcher (respondent type 2)**		
	IR	**% of vote**	**AIS2**
pH level of estuarine water	7	23.7	165.9
Pollution level	7	23.0	161.0
Fishes	2	8.1	16.2
Molluscs	5	10.2	51.0
Plankton	4	9.1	36.4
Mangrove flora	3	7.4	22.2
Livelihood	6	11.5	69.0
Socio-economic profile	5	7.0	35.0
Impact	**Fisherman (respondent type 3)**		
	IR	**% of vote**	**AIS3**
pH level of estuarine water	8	23.5	188.0
Pollution level	8	21.8	174.4
Fishes	1	9.7	9.7
Molluscs	8	10.0	80.0
Plankton	2	8.9	17.8
Mangrove flora	5	6.0	30.0
Livelihood	7	11.1	77.7
Socio-economic profile	6	9.0	54.0
Impact	**Agriculturist (respondent type 4)**		
	IR	**% of vote**	**AIS4**
pH level of estuarine water	7	26.2	183.4
Pollution level	7	24.7	172.9
Fishes	2	8.9	17.8
Molluscs	5	11.7	58.5
Plankton	2	3.7	7.4

(continued)

Table 6.10 (continued)

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
Mangrove flora	2	4.2	8.4
Livelihood	5	12.1	60.5
Socio-economic profile	6	8.5	51.0
Impact	**Local inhabitant (respondent type 5)**		
	IR	**% of vote**	**AIS5**
pH level of estuarine water	5	29.3	146.5
Pollution level	8	21.5	172.0
Fishes	1	8.7	8.7
Molluscs	6	14.2	85.2
Plankton	3	5.6	16.8
Mangrove flora	6	3.2	19.2
Livelihood	7	10.3	72.1
Socio-economic profile	5	7.2	36.0

Table 6.11 ANOVA results showing variations between impact of acidification and respondent's views on the impact in the western Indian Sundarbans

Source of variation	SS	df	MS	F	P-value	F_{crit}
Between impact	138,973.3	7	19,853.33	161.5015	6.48E-21	2.35926
Between respondents	568.949	4	142.2372	1.157062	0.350728	2.714076
Error	3442.031	28	122.9297			
Total	142,984.3	39				

Table 6.10 reflects the results of respondent analysis in the western sector of Indian Sundarbans, which is almost semi-urbanized with fish landing stations/harbours, tourism units and pilgrims. The mangroves in this sector have been mostly sacrificed for shrimp farms, which is one of the major livelihoods in this area.

The western sector of Indian Sundarbans is in the zone of 'noise' as there is the presence of industries, fish landing stations, tourism units, shrimp farms that discharge wastes of complex nature and causes the lowering of pH. Policy makers, researchers, fishermen, agriculturists and local inhabitants are aware of the phenomenon and imparted maximum weightage on lowering of the pH and pollution (Table 6.10). The sequence of CAIS, which is the combined opinion of all categories of stakeholders ranked the impact of acidification as pH level of estuarine water (845.5) > pollution level of the estuarine water (835.7) > livelihood (347.1) > molluscan community (325.7) > socio-economic profile (217.0) > plankton community (117.2) > mangrove flora (38.4) > fishes (70.6). The stakeholders also feel that

Table 6.12 Impact of acidification on estuarine water with scaling in central Indian Sundarbans

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
pH level of estuarine water	7	36.3	254.1
Pollution level	8	19.3	154.4
Fishes	1	6.9	6.9
Molluscs	6	12.8	76.8
Plankton	4	4.2	16.8
Mangrove flora	3	1.8	5.4
Livelihood	6	11.2	67.2
Socio-economic profile	6	7.5	45.0
Impact	**Researcher (respondent type 2)**		
	IR	**% of vote**	**AIS2**
pH level of estuarine water	8	22.9	183.2
Pollution level	7	20.7	144.9
Fishes	4	9.0	36.0
Molluscs	8	19.9	159.2
Plankton	1	4.6	4.6
Mangrove flora	2	3.8	7.6
Livelihood	8	10.1	80.8
Socio-economic profile	8	9.0	72.0
Impact	**Fisherman (respondent type 3)**		
	IR	**% of vote**	**AIS3**
pH level of estuarine water	7	21.9	153.3
Pollution level	7	22.8	159.6
Fishes	3	9.1	27.3
Molluscs	8	17.2	137.6
Plankton	4	6.0	24.0
Mangrove flora	5	5.9	29.5
Livelihood	8	11.7	93.6
Socio-economic profile	8	5.4	43.2
Impact	**Agriculturist (respondent type 4)**		
	IR	**% of vote**	**AIS4**
pH level of estuarine water	7	27.0	189.0
Pollution level	8	12.7	101.6
Fishes	5	9.2	46.0
Molluscs	8	15.8	126.4
Plankton	2	6.2	12.4

(continued)

Table 6.12 (continued)

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
Mangrove flora	2	8.0	16.0
Livelihood	8	12.0	96.0
Socio-economic profile	7	9.1	63.7
Impact	**Local inhabitant (respondent type 5)**		
	IR	**% of vote**	**AIS5**
pH level of estuarine water	7	24.3	170.1
Pollution level	8	21.6	172.8
Fishes	3	8.2	24.6
Molluscs	8	16.1	128.8
Plankton	3	5.5	16.5
Mangrove flora	7	4.0	28.0
Livelihood	7	9.1	63.7
Socio-economic profile	8	11.2	89.6

Table 6.13 ANOVA results showing variations between impact of acidification and respondent's views on the impact in the central Indian Sundarbans

Source of variation	SS	df	MS	F	P-value	F_{crit}
Between Impact	148,517.1	7	21,216.72	37.0189	1.64E-12	2.35926
Between Respondents	383.129	4	95.78225	0.167121	0.953315	2.714076
Error	16,047.7	28	573.1323			
Total	164,947.9	39				

the phenomenon of acidification will have substantial impact on livelihood as most of the livelihood of Indian Sundarbans is aqua-centric (Fig. 6.9).

ANOVA carried out with the data sets of Table 6.10 shows that there are no statistically significant differences between the views of stake holders on the impact of acidification in the western Indian Sundarbans (Table 6.11). However, the type of impact varied at 5% level of significance as F_{obs} (161.5015) > F_{crit} (2.35926).

The central Indian Sundarbans is noted for erosion and hypersaline ambient environment (due to blockage of fresh water on account of massive siltation (Fig. 6.10).

Tourism is one of the major livelihoods of the local inhabitants. The respondents' views towards the impact of acidification in this sector are presented in Table 6.12.

In the central Indian Sundarbans, the result of respondent analysis is bit different. With maximum weightage to pH level of the estuarine water, the adverse impact on the molluscan community is visible in this zone through thinning of the oyster shell and mortality and hence impact of molluscan community has been given considerable

Table 6.14 Impact of acidification on estuarine water with scaling in eastern Indian Sundarbans

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
pH level of estuarine water	7	19.7	137.9
Pollution level	7	13.7	95.9
Fishes	2	17.3	34.6
Molluscs	8	19.0	152.0
Plankton	4	5.2	20.8
Mangrove flora	1	6.6	6.6
Livelihood	6	11.0	66.0
Socio-economic profile	7	7.5	52.5
Impact	**Researcher (respondent type 2)**		
	IR	**% of vote**	**AIS2**
pH level of estuarine water	7	44.5	311.5
Pollution level	7	12.8	89.6
Fishes	1	5.2	5.2
Molluscs	8	15.8	126.4
Plankton	4	1.2	4.8
Mangrove flora	1	1.8	1.8
Livelihood	7	11.2	78.4
Socio-economic profile	7	7.5	52.5
Impact	**Fisherman (respondent type 3)**		
	IR	**% of vote**	**AIS3**
pH level of estuarine water	7	29.5	206.5
Pollution level	7	26.3	184.1
Fishes	4	7.1	28.4
Molluscs	7	13.9	97.3
Plankton	2	5.5	11.0
Mangrove flora	1	2.8	2.8
Livelihood	8	8.0	64.0
Socio-economic profile	8	6.9	55.2
Impact	**Agriculturist (respondent type 4)**		
	IR	**% of vote**	**AIS4**
pH level of estuarine water	7	30.5	213.5
Pollution level	8	11.5	92.0
Fishes	3	4.3	12.9
Molluscs	5	11.5	57.5
Plankton	1	5.9	5.9

(continued)

Table 6.14 (continued)

Impact	**Policy maker (respondent type 1)**		
	IR	**% of vote**	**AIS1**
Mangrove flora	1	2.7	2.7
Livelihood	4	24.4	97.6
Socio-economic profile	7	9.2	64.4
Impact	**Local inhabitant (respondent type 5)**		
	IR	**% of vote**	**AIS5**
pH level of estuarine water	8	16.3	130.4
Pollution level	6	20.5	123.0
Fishes	2	6.9	13.8
Molluscs	5	19.3	96.5
Plankton	4	4.2	16.8
Mangrove flora	2	3.4	6.8
Livelihood	8	11.9	95.2
Socio-economic profile	5	17.5	87.5

Table 6.15 ANOVA results showing variations between impact of acidification and respondent's views on the impact in the eastern Indian Sundarbans

Source of variation	SS	df	MS	F	P-value	F_{crit}
Between impact	153,306.5	7	21,900.93	18.08322	7.62E-09	2.35926
Between respondents	1531.927	4	382.9816	0.316221	0.864691	2.714076
Error	33,911.32	28	1211.118			
Total	188,749.7	39				

score. It is to be noted that many local inhabitants of central Indian Sundarbans are engaged in lime generation from molluscs (Fig. 6.11) and hence people are quite aware of that situation. The CAIS values in this region varies as per the order pH level of estuarine water (947.7) > adverse impact on molluscan population (733.3) > pollution level of the estuarine water (628.8) > livelihood (401.3) > socio-economic profile (313.5) > fishes (140.8) > mangrove flora (86.5) > plankton (74.0) (Table 6.12).

We have also carried out ANOVA with the data set of Table 6.12 and observed that there are no significant differences in opinion between the stakeholders of the central sector of Indian Sundarbans in context to impact of acidification as F_{obs} is less than F_{crit} (Table 6.13). However, the type of impact varied at 5% level of significance as F_{obs} (37.0189) > F_{crit} (2.35926).

The eastern Indian Sundarban is a pristine zone with Reserve Forest and minimum anthropogenic pressure. The mangrove forest is luxuriant in this sector (Fig. 6.12).

Table 6.16 Questionnaires to evaluate the impact of acidification through respondent's analysis

1	What is your name and profession?
2	Have you heard the term acidification? What is the normal pH of estuarine water around you?
3	What are the major effects of acidification?
4	How acidification impacts fishes in Sundarban estuaries? Rank the impact with the score from 1 to 8, where 1 stands for very least impact and 8 stands for highest degree of impact
5	How the molluscan community is helpful in context of livelihood?
6	How acidification impacts oysters (kasturi in local language), snails and other molluscs in Sundarban estuaries? Rank the impact with the score from 1 to 8, where 1 stands for very least impact and 8 stands for highest degree of impact
7	Do you have any idea on the bioremediation potential of mangroves?
8	What are the sources of pollutants in the estuaries of Indian Sundarbans?
9	Do you think that lowering of pH is related to release of industrial and domestic wastes in the estuaries of Sundarbans?
10	Do you have any idea about climate change and Green House Gas (GHG) emission?
11	Which is the major GHG in your area and what are its sources?Do you believe that excess carbon dioxide emission causes acidification of Sundarban estuaries?
12	Do you believe that excess carbon dioxide emission causes acidification of Sundarban estuaries?
13	How mangroves are useful in minimizing the GHG level in Sundarban atmosphere?
14	What is your major source of income? Does it get affected with acidification?
15	Do you have any idea about alternative livelihood and its relation with acidification?

The respondent analysis, however, highlighted the CAIS values as per the order pH of the estuarine water (999.8) > pollution of the estuarine water (529.7) > livelihood (401.2) > socio-economic profile (312.1) > adverse impact on fish (94.9) > plankton (59.3) > mangrove (20.7). The least weightage of acidification on mangrove as provided by the stakeholders confirm that the stakeholders are quite aware of the resilience of mangrove vegetation to acidification (Table 6.14).

Results of ANOVA with the data sets of Table 6.14 exhibit no significant variations between stakeholders' views, but the impact of acidification differed greatly at 5% level of significance (Table 6.15).

6.3 Status of Heavy Metals in Context to Acidification of Sundarban Estuaries

Conservative wastes are non-biodegradable in nature and include heavy metals like Zn, Cu, Pb, Cr, Hg etc. Unlike common domestic wastes having organic matter, conservative wastes are not degraded by microbes, and hence remain in the ambient media almost permanently. We are concerned of this long residence time and hence

Fig. 6.9 Aqua-centric livelihood in Sundarbans

in this section we have tried to focus on the effect of acidification on heavy metals considering Indian Sundarbans as our case study zone. This Indo-Gangetic plain is the biggest alluvial tract of the World, and this alluvial fill is essentially of Quaternary age. The lower Ganga delta in the undivided Sundarbans was built up in the seaboard by the alluvium fine clay, silt and sand particles, carried down from the Great Himalaya and Chotanagpur hills. In this silt and clay transport the two rivers Ganga and Brahmaputra and their numerous tributaries has taken active part. The stretch of coastal quaternaries exhibits varied geomorphological signatures (like sand dunes, beach ridge, intertidal clayey/sandy flats, tidal shoals etc.) evolved out of dynamic and varied interactions of marine agencies like waves, tides and littoral currents, combined with fluvial and aeolin components. These silt, clay and sand particles have been deposited step by step or layer by layer in the sea board and due to rapid formation have also resulted in uneven thickness and width or surface of the horizons in the estuarine mouths, facing the Bay of Bengal. The macrotidal (tidal range > 4 m) Sundarbans is characterized by embroidery of tidal creeks, encompassing the islands and offshore linear tidal shoals, aligned perpendicular to the shore line and separated by swales.

In the present day scenario, the Hooghly-Matla estuary has became the most anthropogenically stressed ecosystem due to presence of multifarious industries that discharge wastes in to aquatic system mostly without any treatment. Presence of heavy metals in the ambient media of Sundarbans has been reported by a number of

Fig. 6.10 Erosion of inter-tidal mudflats—A major threat to mangrove vegetation

researchers and extensive studies have been carried out by our team since last few decades (Mitra et al. 1994, 2000, 2013; Trivedi et al. 1995; Mitra 1998; Bhattacharyya et al. 2001; Das et al. 2005; Barua et al. 2011; Ray Chaudhuri et al. 2014; Zaman et al. 2014).

Three stations namely Diamond Harbour (Station 1), Namkhana (Station 2) and Ajmalmari (Station 3) were selected for the present programme, which are located in South 24 Parganas district of West Bengal. The latitude and longitude of the three sampling stations are presented in Table 6.17.

Surface water pH was measured by using a portable pH meter (sensitivity = ±0.02). Analysis of dissolved heavy metals was done with samples collected during high tide condition from all the three stations. Before analysis, each water sample was collected and stored in clean TARSON bottles and was filtered through a 0.45 μm Millipore membrane. The filtrate was treated with diethyl dithiocarbamate and extracted in carbon tetrachloride (Chakraborti et al. 1987). The extracted was evaporated to dryness and the residue was mineralized with 0.1 ml of concentrated nitric acid. Analytical blank was prepared and treated with the same reagents. Analyses were done in triplicate by direct aspiration into AAS (Perkin-Elmer Model: 3030) equipped with a HGA-500 graphite furnace atomizer and a deuterium background corrector. The accuracy of the dissolved heavy metal determinations is indicated by good agreement between our values and reported for certified reference seawater materials (CASS 2) (Table 6.18).

Fig. 6.11 Collected molluscan shell for lime generation

In order to analyse biologically available heavy metals in sediments, samples from surface (1 cm depth) were collected by scrapping using a pre-cleaned and acid washed plastic scale and immediately kept in clean polythene bags, which were sealed. The samples were washed with metal free double distilled water and dried in an oven at 105 °C for 5–6 h, freed from visible shells or shell fragments, ground to powder in a mortar and stored in acid washed polythene bags. Analyses of biologically available metals were done after re-drying the samples, from which 1 gm was taken and digested with 0.5 (N) HCl as per the standard procedure outlined by Malo (1977). The resulting solutions were then stored in polythene containers for analysis. The solutions were finally aspirated in the flame Atomic Absorption Spectrophotometer (Perkin Elmer: Model 3030) for the determination of metal concentrations. No detectable trace metals were found in the reagent blank. Analysis of the NIES Sargasso sample was carried out to assure the quality of the data (Table 6.19).

The pH ranged from 8.11 (during 2014) to 8.32 (during 1984) at Diamond Harbour during HT (Fig. 6.13).

The pH ranged from 8.27 (during 2013–2014) to 8.33 (during 1984–1986; 1988–1989) at Namkhana during HT (Fig. 6.14).

The pH ranged from 8.29 (during 2006–2007; 2010–2014) to 8.32 (during 1984–1989; 1992–1993) at Ajmalmari during HT (Fig. 6.15).

The surface water pH is an important environmental parameter on which the life of any aquatic organism depends. It showed more or less a constant value throughout

Fig. 6.12 Luxuriant mangrove forest in eastern Indian Sundarbans

Table 6.17 Stations with coordinates

Stations	Geographical locations	
	Latitude	Longitude
Diamond Harbour	22° 11′ 4.2″ N	88° 11′ 22.2″ E
Namkhana	21° 45′ 53.7″ N	88° 13′ 51.5″ E
Ajmalmari	21° 49′ 42.9″ N	88° 37′ 13.7″ E

Table 6.18 Analysis of reference material for near shore seawater (CASS 2)

Element	Certified value ($\mu g\ l^{-1}$)	Laboratory results ($\mu g\ l^{-1}$)
Zn	1.97 ± 0.12	2.01 ± 0.14
Cu	0.675 ± 0.039	0.786 ± 0.058
Pb	0.019 ± 0.006	0.029 ± 0.009

Table 6.19 Analysis of reference material (NIES Sargasso sample) for sediments obtained from the National Institute of Environmental Studies, Japan

Element	Certified value ($\mu g\ g^{-1}$)	Laboratory results ($\mu g\ g^{-1}$)
Zn	28.6	26.2
Cu	14.9	13.7
Pb	2.4	2.9

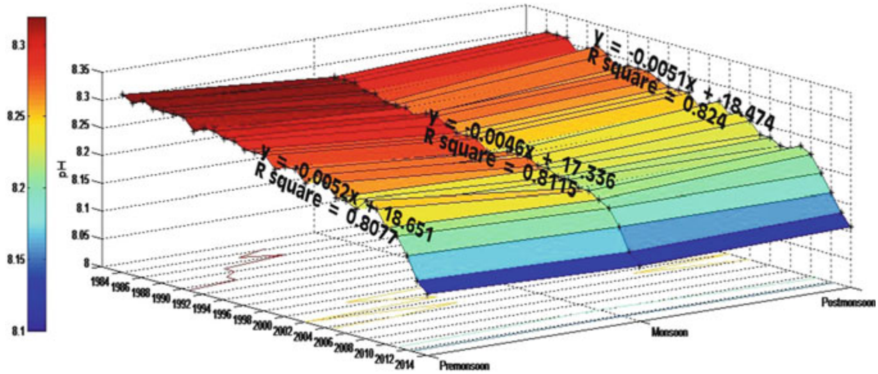

Fig. 6.13 Temporal variation of surface water pH in Diamond Harbour (Stn. 1)

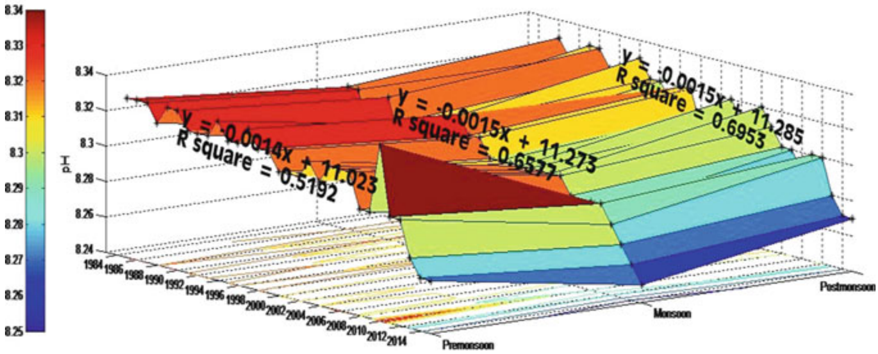

Fig. 6.14 Temporal variation of surface water pH in Namkhana (Stn. 2)

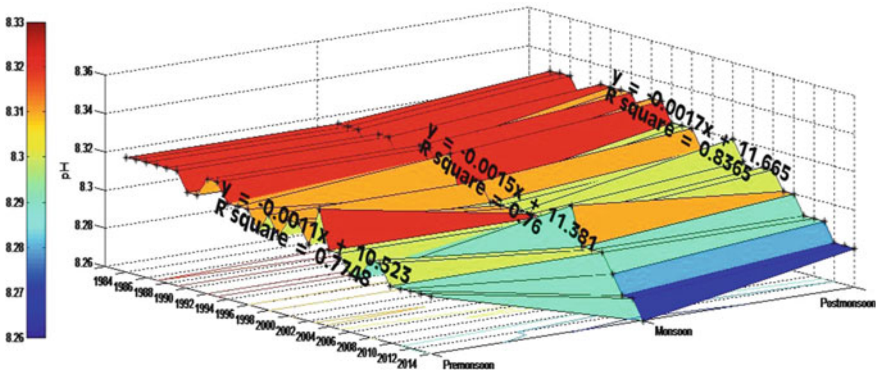

Fig. 6.15 Temporal variation of surface water pH in Ajmalmari (Stn. 3)

the study period in all the stations with minor fluctuations mainly in the monsoon months, when, dilution by run-off, precipitation and water discharge suppressed the surface water pH in all the sampling stations.

Looking on the time series data of 31 years, the trend of acidification becomes quiet pronounced. Acidification of marine and estuarine water is usually a direct function of rise of carbon dioxide in the atmosphere. In all the selected stations, an almost uniform decrease in surface water pH was observed. At Diamond Harbour, the pH value has decreased at the rate of 0.081 unit/decade in premonsoon, 0.074 unit/decade in monsoon and 0.077 unit/decade in postmonsoon (Fig. 6.13). At Namkhana, the rate of decrease is 0.024 unit/decade in premonsoon and monsoon and 0.019 unit/decade in postmonsoon (Fig. 6.14). The decrease of surface water pH at Ajmalmari is 0.012 unit/decade in premonsoon, 0.023 unit/decade in monsoon and 0.019 unit/decade in postmonsoon (Fig. 6.15). This decrease is quite close to the observations recorded in several oceans and estuaries.

At Diamond Harbour, dissolved Zn ranged from 201.00 ppm (during premonsoon in 1984) to 626.89 ppm (during monsoon in 2014) (Table 6.20). At Namkhana, dissolved Zn ranged from 187.55 ppm (during premonsoon in 1984) to 527.88 ppm (during monsoon in 2014) (Table 6.21), whereas at Ajmalmari, it was observed to range from 104.85 ppm (during premonsoon in 1984) to 286.61 ppm (during monsoon in 2014) (Table 6.22).

At Diamond Harbour, the sediment Zn concentration ranged from 18.99 μg/g (during monsoon in 2014) to 94.98 μg/g (during premonsoon in 1984) (Table 6.23). At Namkhana, the sediment Zn concentration ranged from 16.54 μg/g (during monsoon in 2014) to 92.75 μg/g (during premonsoon in 1984) (Table 6.24), whereas at Ajmalmari, it ranged from 12.98 μg/g (during monsoon in 2014) to 64.71 μg/g (during premonsoon in 1984) (Table 6.25).

At Diamond Harbour, dissolved Cu ranged from 63.25 ppm (during premonsoon in 1984) to 319.37 ppm (during monsoon in 2014) (Table 6.26), whereas at Namkhana, dissolved Cu ranged from 50.95 ppm (during premonsoon in 1984) to 297.98 ppm (during monsoon in 2014) (Table 6.27). In case of Ajmalmari, dissolved Cu ranged from 39.68 ppm (during premonsoon in 1984) to 140.12 ppm (during monsoon in 2014) (Table 6.28).

At Diamond Harbour, the sediment Cu concentration ranged from 9.86 μg/g (during monsoon in 2014) to 39.85 μg/g (during premonsoon in 1984) (Table 6.29). At Namkhana, the sediment Cu concentration was found to range from 7.93 μg/g (during monsoon in 2014) to 36.23 μg/g (during premonsoon in 1985) (Table 6.30), whereas at Ajmalmari, the sediment Cu concentration ranged from 1.08 μg/g (during monsoon in 2013) to 15.55 μg/g (during premonsoon in 1984) (Table 6.31).

At Diamond Harbour, dissolved Pb ranged from 9.54 ppm (during premonsoon in 1984) to 108.88 ppm (during monsoon in 2014) (Table 6.32). At Namkhana, dissolved Pb ranged from 8.59 ppm (during premonsoon in 1984) to 89.42 ppm (during 2014) (Table 6.33). In case of Ajmalmari, it was observed to range from 4.65 ppm (during premonsoon in 1984) to 24.83 ppm (during monsoon in 2014) (Table 6.34).

At Diamond Harbour, the sediment Pb concentration ranged from 0.93 μg/g (during monsoon in 2014) to 24.09 μg/g (during premonsoon in 2009) (Table

Table 6.20 Average yearly variation of dissolved Zn (in ppm) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	201	263.64	250.64
1985	212.55	274.68	261.68
1986	232.05	315.54	302.54
1987	300.34	349.37	336.37
1988	315.68	354.05	341.05
1989	322.98	359.22	346.22
1990	305.78	362.85	349.85
1991	331.89	363.31	350.31
1992	340.06	375.83	362.83
1993	351.17	402.33	389.33
1994	378.9	414.55	401.55
1995	389.99	448.46	435.46
1996	395.52	453.84	440.84
1997	399.27	466.14	453.14
1998	406.57	410.84	397.84
1999	398.99	414.66	401.66
2000	410.29	430.35	417.35
2001	413.59	441.22	428.22
2002	402.44	444.55	431.55
2003	413.78	447.71	434.71
2004	417.78	457.06	444.06
2005	423.89	427.75	414.75
2006	434.56	475.22	462.22
2007	436.89	453.85	440.85
2008	450	496.91	483.91
2009	365.21	403.22	390.22
2010	468.89	491.44	478.44
2011	456.22	499.31	486.31
2012	471.89	515.21	502.21
2013	489.02	525.75	512.75
2014	491.54	626.89	601.89

6.35). At Namkhana, the sediment Pb concentration ranged from 0.89 μg/g (during monsoon in 2014) to 21.12 μg/g (during premonsoon in 1984) (Table 6.36). At Ajmalmari, it was observed to range from 0.44 μg/g (during monsoon in 2013) to 10.79 μg/g (during premonsoon in 1984) (Table 6.37).

The distribution of dissolved metals followed the order Zn > Cu > Pb in all the three sampling stations and exhibited a significant seasonal pattern with high values during monsoon and lowest during premonsoon. In the present study the significant

Table 6.21 Average yearly variation of dissolved Zn (in ppm) in Namkhana during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	187.55	247.27	234.29
1985	191.9	255.53	242.55
1986	195.98	306.84	293.86
1987	203.67	312.93	299.95
1988	213.89	316.08	303.1
1989	227.8	328.74	315.76
1990	231.11	346.83	333.85
1991	246.67	356.2	343.22
1992	264.89	359.86	346.88
1993	276.9	404.83	391.85
1994	283.59	410.97	397.99
1995	293.77	418.7	405.72
1996	299.62	434.8	421.82
1997	312.5	449.82	436.84
1998	345.87	456.08	443.1
1999	333.51	436.27	423.29
2000	382.05	415.2	402.22
2001	393.44	432.83	419.85
2002	399.75	434.87	421.89
2003	401.44	442.93	429.95
2004	412.52	449.64	436.66
2005	416.56	443.2	430.22
2006	418	463.83	450.85
2007	405.23	465.19	452.21
2008	426.91	482.98	470
2009	302.21	381.82	368.84
2010	417.88	478.76	465.78
2011	456	483.96	470.98
2012	461.09	511.32	498.34
2013	470.59	514.88	501.9
2014	489.05	527.88	513.66

temporal variation of heavy metals in all the stations may be attributed to huge run-off from the adjacent landmasses during the monsoon and also due to chemical speciation (Mitra and Choudhury 1998; Chakraborty et al. 2006). During monsoon, the dilution factor (df) of all the sampling stations in the coastal and estuarine zone of West Bengal increases many folds that results in the decrease of salinity and pH. The lowering of pH might facilitate the dissolution of the precipitated form of metal and increase the amount of metallic ions in solution. The increase of Cu concentrations

Table 6.22 Average yearly variation of dissolved Zn (in ppm) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	104.85	136.55	123.66
1985	107.32	139.82	133.84
1986	111.66	141.2	138.43
1987	117.54	143.65	140.66
1988	131.65	144.78	142.44
1989	140.82	148.32	147.18
1990	142.33	153.55	146.45
1991	147.94	168.21	151.94
1992	149.2	170.12	156.88
1993	152	172.42	161.43
1994	154.75	175.21	167.39
1995	158.66	177.39	172.85
1996	162.32	184.46	180.05
1997	166.81	195.35	182.66
1998	168.45	199.85	185.91
1999	170.3	204.61	189.23
2000	175	211.32	194.21
2001	177.21	212.02	202.54
2002	179.06	220.4	217.36
2003	181.25	226.77	221.41
2004	185.5	235.75	229.5
2005	187.22	241.82	235.89
2006	189.17	244.09	240.62
2007	193.45	252.15	248.22
2008	195.62	254.1	251.33
2009	121.42	201.29	159.85
2010	198.63	260.05	257.21
2011	199.13	267.25	259.5
2012	201.35	266.5	261.22
2013	207.42	270.13	265
2014	213.44	286.61	280.02

with the decrease of salinity was also reported by several workers while working in the Porto Novo (India) waters (Sundararaj and Krishnamurthy 1972). Again the maximum run-off occurs during monsoon season (UNESCO 2012).

The distribution of biologically available heavy metals in sediment followed the order: Zn > Cu > Pb in all the three selected sampling stations and exhibited unique seasonal pattern with high values during premonsoon and lowest during monsoon.

Table 6.23 Average yearly variation of sediment Zn (in ppm dry wt) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	94.98	76.5	83.44
1985	94.65	74.32	80.61
1986	93.56	71.29	78.23
1987	93.5	73.62	73.55
1988	93.49	64.31	65.42
1989	91.88	60.22	67.61
1990	91.22	55.75	60.21
1991	90.77	51.49	62.15
1992	89.85	49.63	55.5
1993	83.85	46.4	49.66
1994	82.82	38.32	40.41
1995	81.65	35.55	40.66
1996	76.51	31.68	39.32
1997	76.29	30.32	39.49
1998	73.22	28.73	35.66
1999	71.84	26.55	36.82
2000	71.22	25.08	35.75
2001	70.44	24.81	29.8
2002	70.39	23.95	30.02
2003	69.84	23.36	30.32
2004	69.22	27.52	31.31
2005	68.59	26	31.25
2006	67.81	21.15	27.21
2007	66.85	20.08	29.95
2008	64.79	20	29.66
2009	83.88	44.55	65.88
2010	61.21	27.56	29.21
2011	57.85	21.39	22.45
2012	56.02	19.73	21.41
2013	51.9	19.05	21.32
2014	46.44	18.99	20.66

The increase of metallic ions in the aquatic phase resulted in the decrease of metal concentration in the sediment bed, which is a pure case of compartmentation of heavy metals in the estuarine systems. Estuarine bottom sediments accumulate metals and affect the near bottom water layer due to re-suspension or dissolution processes (Li et al. 1984; Khan et al. 1998).

The significant negative correlations between dissolved metals and biologically available metals (especially in case of Zn) in all the three stations (for Diamond

Table 6.24 Average yearly variation of sediment Zn (in ppm dry wt) in Namkhana during 1984–2014

Year	Premonsoon	monsoon	Postmonsoon
1984	92.75	73.21	80.77
1985	92.08	73.05	79.43
1986	90.5	69.83	76
1987	89.22	66.55	72.13
1988	87.99	63.89	71.02
1989	86.22	60.02	63.29
1990	85.66	52.43	62.88
1991	80.39	50.99	60
1992	79.23	46.44	59.43
1993	78.15	45.89	51.84
1994	76	37.36	47.35
1995	74.82	33.28	39.83
1996	74.21	30.41	39
1997	73.85	29.49	38.64
1998	71.22	27.32	33.24
1999	70.33	25.16	31.85
2000	69.44	25	34.32
2001	69.21	23.97	28.78
2002	68.72	22.02	29.1
2003	64.88	21.58	29.36
2004	64.55	24.68	27.41
2005	64.21	25.51	30.31
2006	62.88	19.83	24.85
2007	62.29	19.01	23.32
2008	60.29	17.99	27.88
2009	59.73	39.36	27.48
2010	54.55	25.62	28.32
2011	50.33	20.38	20.49
2012	49.88	18.7	21
2013	42.44	18.62	20.15
2014	40.39	16.54	20.05

Harbour, dissolved Zn × sediment Zn = −0.4887, $p < 0.05$; for Namkhana, dissolved Zn × sediment Zn = −0.6352, $p < 0.01$; for Ajmalmari, dissolved Zn × sediment Zn = −0.7152, $p < 0.01$) stand as proof of the compartmentation process. But in case of other two metals the correlations between dissolved concentration and biologically available concentration are at 10% level of signiicance.

Finally the present results conclude that the process of acidification largely regulates the concentration of conservative pollutants (primarily heavy metals) in the

Table 6.25 Average yearly variation of sediment Zn (in ppm dry wt) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	64.71	52.85	60.41
1985	62.31	50.4	59.83
1986	61.35	50.22	55.41
1987	60.08	49.65	53.22
1988	59.15	46.32	54.44
1989	57.16	50.05	52
1990	55.72	43.35	49.71
1991	53.83	41.85	46.83
1992	51.65	40.61	46.01
1993	51.65	40.85	44.43
1994	50.17	33.78	44
1995	50.15	32.72	38.39
1996	50.12	29.36	37.85
1997	49.12	26.45	33.24
1998	49.1	25.38	32.24
1999	48.75	24.32	29.85
2000	48.32	21.41	26.32
2001	47.54	20.08	24.49
2002	46.93	19.9	25.02
2003	46.71	17.39	24.36
2004	45.88	17	23.88
2005	43.85	16.82	23.41
2006	43.42	16.71	21.47
2007	43.34	15.99	20.33
2008	51.66	15.31	19.71
2009	40.32	15	17.83
2010	35.81	13.98	16.55
2011	33.44	14.02	16.32
2012	31.88	13.65	17.05
2013	29.66	13.34	15.08
2014	26.44	12.98	14.96

water and sediments. Depending on the aquatic pH, bioaccumulation and subsequent toxic effects may occur in plankton, nekton or benthic community. Hence during the planning process of cleaning the lower Gangetic delta region focus and proper weightage should be given on the role of acidification and/or aquatic pH as this parameter seems to be a major driver in the domain of aquatic health of Indian Sundarbans.

Table 6.26 Average yearly variation of dissolved Cu (in ppm) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	63.25	70.08	68.33
1985	67.82	72.44	70.22
1986	69.33	79.32	73.85
1987	73.21	81.55	79.61
1988	76.85	87.32	80.1
1989	79.83	88.1	82.15
1990	82.91	93.41	87.63
1991	93.44	116.38	98.41
1992	97.88	123.5	102.86
1993	113.23	130.88	117.55
1994	121.55	139.41	128.3
1995	111.86	142.88	138.55
1996	137.44	153.65	141.62
1997	142.65	168.22	150.02
1998	158.44	180.93	160.11
1999	173.85	199.99	175.33
2000	189.93	208.85	191.44
2001	195.21	214.32	197.88
2002	200.24	231.45	205.66
2003	211.42	242.66	217.85
2004	217.33	251.75	219.22
2005	220.64	260.08	224.75
2006	223.54	265.73	226.82
2007	214.54	268.82	217.34
2008	241.34	271.35	252.55
2009	137.85	283.1	255.75
2010	253.65	290.09	258.32
2011	261.73	295.45	265.71
2012	273.54	297.98	280.31
2013	281.99	314.2	285.93
2014	299.50	319.37	301.32

6.4 Take Home Messages

A. Ecosystem comprising of biotic and abiotic components provide a wide range of services to mankind. In addition to meet the daily needs of human beings, the floral community of ecosystem is the source of several life saving drugs. Disasters like super cyclones, landslides, tsunamis etc. are often checked by

Table 6.27 Average yearly variation of dissolved Cu (in ppm) in Namkhana during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	50.95	59.75	52.85
1985	52.68	61.78	54.71
1986	58.43	63.75	60.2
1987	69.21	75.88	71.55
1988	71.44	79.23	75.23
1989	74.44	85.44	76.09
1990	75.79	89.41	79.82
1991	80.96	93.22	82.45
1992	85.93	102.85	87.88
1993	99.81	109.31	101.66
1994	105.71	116.42	107.22
1995	107.83	120.85	111.35
1996	120.69	127.39	123.79
1997	117.55	129.88	125.68
1998	140.39	151.33	143.42
1999	148.72	158	149.85
2000	151.65	163.45	156.23
2001	165.39	175.22	166.38
2002	188.54	191.83	189.95
2003	195.25	205.78	197.05
2004	205.71	213.44	206.82
2005	212.86	224.78	217.85
2006	218.54	234.88	219.32
2007	220.79	242.71	222.43
2008	238.21	258.05	240.8
2009	132	262.31	242.45
2010	248.76	271.86	253.85
2011	255.55	283.22	257.39
2012	260.08	291.01	263.03
2013	264	295	265.43
2014	270.06	297.98	271.88

ecosystem and plays great role in reducing their intensities. However, the services are mostly unmarked and therefore the concept is not known to many. Today the concept of ecosystem services has become an important model for linking the functioning of ecosystems to societal benefits. However, little quantitative information is available regarding the impact of acidification on the ecosystem services of estuaries due to which a sound management policy could

Table 6.28 Average yearly variation of dissolved Cu (in ppm) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	39.68	55.38	44.75
1985	40.22	57.84	46.82
1986	41.31	59.93	47.33
1987	43.15	62.08	49.44
1988	46.32	65.77	48.14
1989	48.11	69.81	51.33
1990	49.05	72.44	53.45
1991	52.14	73.1	57.61
1992	54.63	74.98	59.22
1993	56.15	79.1	63.15
1994	59.81	82.4	65.77
1995	61.41	87.3	67.89
1996	63.02	89.28	71.42
1997	65.07	94.46	73.21
1998	68.72	97.1	75.15
1999	70.15	99.2	77.2
2000	72.43	103.14	78.14
2001	76.81	107.51	81.21
2002	78.41	111.62	82.65
2003	79.21	114.41	84.27
2004	79.99	116.08	80.51
2005	82.69	117.31	83.66
2006	84.65	121.55	87.1
2007	87.91	123.78	89.21
2008	87.99	127.08	88.55
2009	43.91	129.36	91.63
2010	86.66	131.05	87.41
2011	87.2	132.13	89.93
2012	89.21	135.62	91.66
2013	94.05	137	97.14
2014	96.12	140.12	98.23

not be undertaken for Estuarine Acidification (EA) preferably for Sundarban estuaries.

B. Considering the knowledge gap in the domain of acidification of Indian Sundarban estuaries and its subsequent impacts on biodiversity and livelihoods, a brain storming was carried out involving the stakeholders associated with the mangrove ecosystem in the frame work of Indian Sundarbans during 2017–2019 through a set of questionnaires. The entire network of the study consisted

Table 6.29 Average yearly variation of sediment Cu (in ppm dry wt) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	39.85	32.16	37.82
1985	35.55	29.44	33.43
1986	36.24	29	33.94
1987	37.83	26.84	36.41
1988	30.22	24.32	29.88
1989	31.44	23.98	30.41
1990	34.31	23	33.2
1991	31.15	24.16	29.95
1992	33.62	22.89	32.86
1993	29.23	22.14	27.46
1994	30.05	21.95	27.89
1995	27.14	19.77	26.44
1996	26.23	19.21	26.05
1997	25.75	18.65	25.15
1998	25	18.34	24.84
1999	24.13	17.49	23.66
2000	24.02	16.32	23.88
2001	23.19	16.21	22.49
2002	22.48	15.84	21.83
2003	25.78	15.21	24.32
2004	29.2	14.66	26.41
2005	21.15	13.21	20.72
2006	22	13.05	20.44
2007	19.99	12.88	20.91
2008	19.05	12.23	18.94
2009	31.44	11.64	17.49
2010	22.39	11.21	21.36
2011	20.56	10.94	19.22
2012	18.98	10.63	17.85
2013	17.64	10.05	16.43
2014	14.55	9.86	13.22

of three stages (i) identification of respondents (policy maker, researcher, fisherman, agriculturist and local inhabitant) (ii) identification of major impacts of acidification (8 in numbers) and (iii) evaluation of the respondent's response to construct the Acidification Impact Scale (AIS) through ranking and voting. It is observed from the results of this exercise that all the stakeholders are aware of the deterioration of estuarine ecosystem services, but they are confused about the exact causes of such impacts. Fisherman, agriculturist and local inhabitant

Table 6.30 Average yearly variation of sediment Cu (in ppm dry wt) in Namkhana during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	36.23	28.49	31.1
1985	33.41	26.22	32.49
1986	34.82	27.14	31.15
1987	35.39	24.34	30.02
1988	29.14	23	29.11
1989	28.66	22.8	28.44
1990	29.81	22.41	28.35
1991	28.99	21.36	27.31
1992	24.82	21.08	22.65
1993	24.96	21	21.49
1994	24.33	19.45	20.14
1995	23.85	18.71	23
1996	23.06	19	22.09
1997	23.12	17.48	21
1998	22.94	17	20.41
1999	22.13	16.15	20.69
2000	21.95	15.99	21.45
2001	21.03	15.34	20.6
2002	20.69	14.98	19.21
2003	20.94	14.64	18.38
2004	20.12	13.32	17.95
2005	19.74	13.08	18.33
2006	19.44	12.31	16.39
2007	18.31	11.66	20.66
2008	18.49	11.41	17.72
2009	23.48	10.45	15.85
2010	16.42	9.62	14.68
2011	15.19	9.48	14.93
2012	15.36	9.81	13.68
2013	16.08	8.85	12.05
2014	13.12	7.93	11.89

imparted weightage on the adverse impacts on shelled organisms, molluscs, and all of them also opined on the alteration of aquatic pH level and pollution of Sundarban estuaries, but the very term EA is not very transparent to them.

C. Conservative wastes are non-biodegradable in nature and include heavy metals like Zn, Cu, Pb, Cr, Hg etc. Unlike common domestic wastes having organic matter, conservative wastes are not degraded by microbes, and hence remain in the ambient media almost permanently. We are concerned of this long residence

Table 6.31 Average yearly variation of sediment Cu (in ppm dry wt) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	15.55	10.28	10.79
1985	14.83	9.52	10.43
1986	13.36	9.93	10.02
1987	13	8.83	9.33
1988	12.84	9.19	9.69
1989	11.65	8.56	9.06
1990	11.39	7.81	8.41
1991	10.85	8.22	8.82
1992	9.84	7.55	7.88
1993	8.63	2.38	8.15
1994	9.01	6.39	7.33
1995	7.89	6.06	6.66
1996	9.44	6.73	7.99
1997	8.1	5.28	2.54
1998	7.65	2.04	5.88
1999	8.75	7.41	8.01
2000	7.02	5.37	5.97
2001	6.69	3.58	4.43
2002	6.6	1.93	4.08
2003	5.44	2.84	3.34
2004	4.88	3.05	3.55
2005	4.93	2.27	2.77
2006	5.14	2.73	3.06
2007	4.78	2.56	3.33
2008	4.85	1.63	2.13
2009	8.32	1.52	2.02
2010	3.98	1.48	1.98
2011	3.04	1.52	1.57
2012	2.96	1.43	1.33
2013	2.08	1.08	1.46
2014	2.13	1.19	1.25

time and hence in Sect. 6.3 we have tried to focus on the effect of acidification on heavy metals considering Indian Sundarbans as our case study zone. The results of our study with a data bank of 31 years conclude that the process of acidification largely regulates the concentration of conservative pollutants (primarily heavy metals) in the water and sediments of Indian Sundarban estuaries. Depending on the aquatic pH, bioaccumulation and subsequent toxic effects may occur in plankton, nekton or benthic community. Hence during the

Table 6.32 Average yearly variation of dissolved Pb (in ppm) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	9.54	14.73	11.48
1985	11.23	17.85	13.65
1986	13.41	21.32	15.83
1987	15.66	27.65	19.23
1988	17.85	30.33	20.44
1989	14.93	34.88	23.85
1990	19.21	39.21	26.33
1991	19.64	42.65	26.98
1992	20.95	47.83	28.22
1993	20.89	49.95	31.35
1994	22.54	52.16	35.46
1995	23.31	57.65	38.32
1996	27.73	59.99	40.05
1997	28.15	60.23	41.78
1998	28.33	64.79	46.35
1999	29.71	68.66	44.82
2000	30.62	70.23	49.33
2001	32.05	74.39	50.05
2002	33.89	76.82	51.78
2003	34.73	79.99	54.32
2004	35.11	80.23	55.69
2005	35.85	84.88	57.31
2006	37.34	87.31	56.43
2007	37.39	89.02	59.78
2008	38.32	93.41	61.28
2009	23.21	96.46	63.43
2010	38.43	97.23	67.88
2011	40.6	99.1	68.01
2012	41.44	101.61	72.44
2013	43.34	107.35	75.18
2014	47.98	108.88	77.28

planning process of cleaning the lower Gangetic delta region focus and proper weightage should be given on the role of acidification and/or aquatic pH as this parameter seems to be a major driver in the domain of aquatic health of Indian Sundarbans.

Table 6.33 Average yearly variation of dissolved Pb (in ppm) in Namkhana during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	8.59	12.44	10.69
1985	9.21	13.31	11.31
1986	10.08	13.65	12.18
1987	10.99	15.83	13.09
1988	11.44	17.31	13.54
1989	12.66	17.99	14.76
1990	13.85	19.22	15.95
1991	14.79	20.05	16.89
1992	15.66	21.46	17.76
1993	17.94	23.98	20.04
1994	18.55	24.73	20.65
1995	19.21	27.62	21.31
1996	21.33	28.31	23.43
1997	24.79	29.35	26.89
1998	23.83	30.44	25.93
1999	25.97	35.63	28.07
2000	27.88	41.38	29.98
2001	28.22	44.75	30.32
2002	30.65	46.82	32.75
2003	32.41	50.35	34.51
2004	30.79	53.44	32.89
2005	33.81	57.81	39.91
2006	35.42	60.05	41.52
2007	36.21	64.66	38.31
2008	38	70.91	40.1
2009	19.49	77.41	21.59
2010	35.48	78.35	37.58
2011	37.79	80.21	43.89
2012	40.83	84.68	45.93
2013	42	87.38	44.1
2014	45.15	89.42	48.37

Table 6.34 Average yearly variation of dissolved Pb (in ppm) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	4.65	9.12	7.39
1985	4.82	9.75	8.1
1986	5.13	9.83	8.15
1987	5.15	10.21	8.06
1988	6	10.72	9.11
1989	6.73	10.54	9.15
1990	6.85	10.98	9.34
1991	7.12	11.2	9.76
1992	7.66	11.44	10.1
1993	8.15	12.65	10.71
1994	8.31	13.1	11.02
1995	9	13.44	11.66
1996	9.54	13.93	11.44
1997	9.63	14.75	12.08
1998	9.88	15.01	12.95
1999	10.01	15.63	12.99
2000	10.53	16.17	13.33
2001	10.77	16.7	13.55
2002	11.21	17	13.78
2003	11.78	17.44	13.83
2004	12.02	18.23	13.97
2005	12.14	19.01	14.02
2006	12.99	19.39	15.11
2007	13.61	20.55	15.44
2008	13.45	22.05	15.92
2009	8.16	21.38	16.08
2010	14.32	22.88	16.05
2011	15.15	23.67	16.37
2012	15.73	24.04	17.15
2013	16.02	24.78	17.39
2014	17.14	24.83	20.56

Table 6.35 Average yearly variation of sediment Pb (in ppm dry wt) in Diamond Harbour during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	23.19	15.65	22.69
1985	21.21	14.32	18.61
1986	19.93	14.01	17.94
1987	21.44	13.98	16.04
1988	16.64	12.64	15.43
1989	15.33	13.05	14.73
1990	19.05	12.01	18.45
1991	15.02	11.64	14.42
1992	18.09	9.83	17.49
1993	14.88	8.44	14.28
1994	14.96	8.12	14.36
1995	13.94	7.75	13.34
1996	11.54	6.62	7.6
1997	9.2	6.01	7.94
1998	13.18	5.98	12.58
1999	9.98	5.44	9.52
2000	10.02	5.23	9.48
2001	14.33	5.01	13.73
2002	11.2	4.86	10.7
2003	9.81	3.85	9.22
2004	9.72	3.63	9.31
2005	8.56	3.54	7.83
2006	9.33	3.3	7.16
2007	10.66	3.21	8.06
2008	9.21	3.09	8.71
2009	14.09	2.89	7.59
2010	7.05	1.93	6.55
2011	6.29	1.44	5.79
2012	5.83	1.01	5.33
2013	5.75	1.06	5.25
2014	5.01	0.93	4.88

Table 6.36 Average yearly variation of sediment Pb (in ppm dry wt) in Namkhana during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	21.12	13.34	19.87
1985	20.47	13.01	17.52
1986	17.49	12.86	16.89
1987	16.83	11.55	16.23
1988	16	12.04	15.4
1989	15	12	14.4
1990	14.19	11.54	13.59
1991	13.6	11.21	13
1992	13.44	8.85	12.84
1993	12.49	7.79	11.89
1994	12.05	8	11.45
1995	9.97	7.23	9.47
1996	11.37	5.61	10.87
1997	8.66	5	8.16
1998	9.08	4.96	8.84
1999	9.34	4.33	8.58
2000	9.11	4.02	8.61
2001	10.41	3.98	9.91
2002	8.13	3.34	7.63
2003	7.5	3.01	6.9
2004	7.05	3.15	6.55
2005	11.2	3.21	7
2006	6.85	2.97	5.7
2007	8.95	2.68	8.45
2008	6.2	2.44	6.35
2009	5.32	2.33	4.82
2010	4.88	2.31	4.38
2011	4.79	1.85	4.29
2012	3.96	1.4	3.46
2013	3.88	0.98	3.38
2014	3.2	0.89	2.98

Table 6.37 Average yearly variation of sediment Pb (in ppm dry wt) in Ajmalmari during 1984–2014

Year	Premonsoon	Monsoon	Postmonsoon
1984	10.79	9.41	10.28
1985	10.43	9.32	9.52
1986	10.02	8.85	9.93
1987	9.33	7.79	8.83
1988	9.69	7.02	9.19
1989	9.06	7	8.56
1990	8.41	7.33	7.81
1991	8.82	6.89	8.22
1992	8.71	6.54	7.55
1993	8.15	4.28	4.38
1994	7.33	3.35	7.39
1995	6.66	5.82	6.06
1996	7.99	5.79	6.73
1997	5.54	4.85	5.28
1998	5.88	4.89	5.04
1999	8.01	2.98	7.41
2000	5.97	2.63	5.37
2001	5.43	2.54	3.58
2002	4.08	2.33	2.93
2003	3.34	1.85	2.84
2004	3.55	2.02	3.05
2005	5.77	2.19	2.27
2006	5.06	2.17	5.73
2007	5.33	3.35	3.56
2008	2.13	2.08	2.63
2009	2.02	1.54	1.62
2010	1.98	1.31	1.48
2011	1.57	0.96	1.07
2012	1.33	0.62	0.83
2013	1.11	0.48	0.68
2014	1.05	0.44	0.59

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Chapter 7
Regulatory Role of Blue Carbon in Estuarine Acidification

Abstract Blue carbon comprising the coastal vegetation (mangroves, marsh grass, sea grass etc.) exerts a regulatory effect on the pH of the estuarine water as these halophytes absorb carbon dioxide for photosynthesis. The key biochemical actor in the process is Ribulose-1,5-Biphosphate Carboxylase Oxygenase (RuBisCo), present in the halophytes that fixes the carbon and push shift the pH towards alkaline value. The present chapter critically addresses the role of blue carbon in maintaining an equilibrium condition of estuarine water in context to pH.

7.1 Mangroves

Mangrove forest area accounts for 0.7% of the total tropical forest in the world. Most mangroves are concentrated in Asia (42%), followed by Africa (20%), North and Central America (15%), Oceania (12%) and South America (15%). The entire mangrove spectrum of the world encompasses 31 families under which 48 genera and 96 species are included as documented in the site http://www.bsienvis.nic.in/Database/IndianMangroves_3941.aspx#WORLD DISTRIBUTION OF MANGROVES (Annexure 7). According to a study conducted by a team of U.S. Forest Service and university scientists coastal mangrove forests store more carbon than almost any other forest on Earth. Their findings are published online in the journal *Nature Geoscience* (www.nature.com/naturegeoscience.com). The potential of mangrove forest to store such large amounts of carbon may be attributed, in part, to the deep organic-rich soils on which it thrives (Fig. 7.1).

The soil depth mostly increases with time as the silt of the overlying aquatic phase deposit on the existing soil bed (intertidal mudflats). This happens because the intertidal mudflats suffer total submergence by silty water during high tide (Fig. 7.2).

Mangrove-sediment/substratum stores carbon on an average five times larger than those typically observed in temperate, boreal and tropical terrestrial forests, on a per-unit-area basis. The mangrove forest's complex root systems, which anchor the plants into underwater sediment, slow down incoming tidal waters allowing organic and inorganic material to settle on the sediment surface. Low oxygen conditions slow decay rates, resulting in much of the carbon accumulating in the soil. In fact,

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Fig. 7.1 Organic carbon—rich soil (substratum) of mangrove ecosystem

Fig. 7.2 Complete submergence of intertidal mudflats during high tide

mangroves have more carbon in their soil alone than most tropical forests have in all their biomass and soil combined.

The capacity of mangroves, sea grasses, and salt marshes to sequester carbon dioxide from the atmosphere is becoming increasingly recognized at an international level. Of all the biological carbon, also termed as 'green carbon', captured in the world, over half (55%) is captured by mangroves, sea grasses, salt marshes, and other marine living organisms, which are also known more specifically as 'blue carbon'. Mangroves, salt marshes, and sea grasses form much of the earth's blue carbon sinks (http://www.recoftc.org/site/resources/Mangroves-more-Carbon-Rich-and-Important-for-Climate-Change.php).

It has been reported that mangroves are among the most carbon-dense forests in the tropics (sample-wide mean: 1023 MgC $ha^{-1} \pm 88$ s:e:m:) and exceptionally high compared to mean carbon storage of the world's major forest domains (Donato et al. 2011). Estuarine sites contained a mean of 1074 MgC ha^{-1} ($\pm$171 s:e:m:); oceanic sites contained 990 $\pm$ 96 MgC ha^{-1}. AGC pools are sizeable (mean 159 MgC ha^{-1}, maximum 435 MgC ha^{-1}), but Below Ground Storage in soils dominate, accounting for 71–98% and 49–90% of total storage in estuarine and oceanic sites, respectively. High per-hectare carbon storage coupled with a pan-tropical distribution (total area ~14 million ha; FAO, 2007; Bouillon et al. 2009), suggests mangroves are a globally important surface carbon reserve.

Mangroves exhibit almost all the salient features of plants that follow the route of C_3 photosynthesis. However, it is interesting to note that although mangroves are considered under the umbrella of C_3 photosynthetic plants, they can also be compared with 'seaweed' as they are able to grow in submerged and high saline environment. There are four important evidences to prove that mangrove plants use C_3 photosynthetic biochemistry. These evidences are highlighted in points.

(1) Leaves of mangroves lack bundle sheath cells, which is the characteristic of plants employing C_4 photosynthesis.
(2) Carbon isotope composition of mangrove leaves offers a direct evidence of the presence mangroves under the category of C_3 photosynthetic plants. It has been documented by Smith and Epstein (1971) that the carbon isotope composition of leaves shows a range of δ^{13}C values from -23.2% to -34.3% as reported for C_3 plants.
(3) The carbon dioxide compensation point at 25 °C and saturated light intensity ranges from 45 to 60 $\mu l\, l^{-1}$, consistent with the photorespiratory activity typical of C_3 photosynthesis.
(4) In mangroves, the photosynthetic rates are maximal at leaf temperature less than 35 °C and generally become light saturated at intensities ranging from 30 to 50% of full sunlight.

Finally, there is no convincing evidence in mangroves on transformation of environmentally induced from C_3 to either C_4 or CAM photosynthetic biochemistry. The gas exchange in mangroves is strongly regulated by the amount and properties of the enzyme ribulose-1, 5-biphosphate carboxylase/oxygenase (RuBisCO), which catalyzes the combination of carbon dioxide with the acceptor molecule ribulose-1, 5-biphosphate (Fig. 7.3).

The ability of mangroves to scrub carbon from the ambient media is the key to regulate the process of acidification. Basically mangroves absorb carbon dioxide from the atmosphere and the water column and store it as carbon in their vegetative

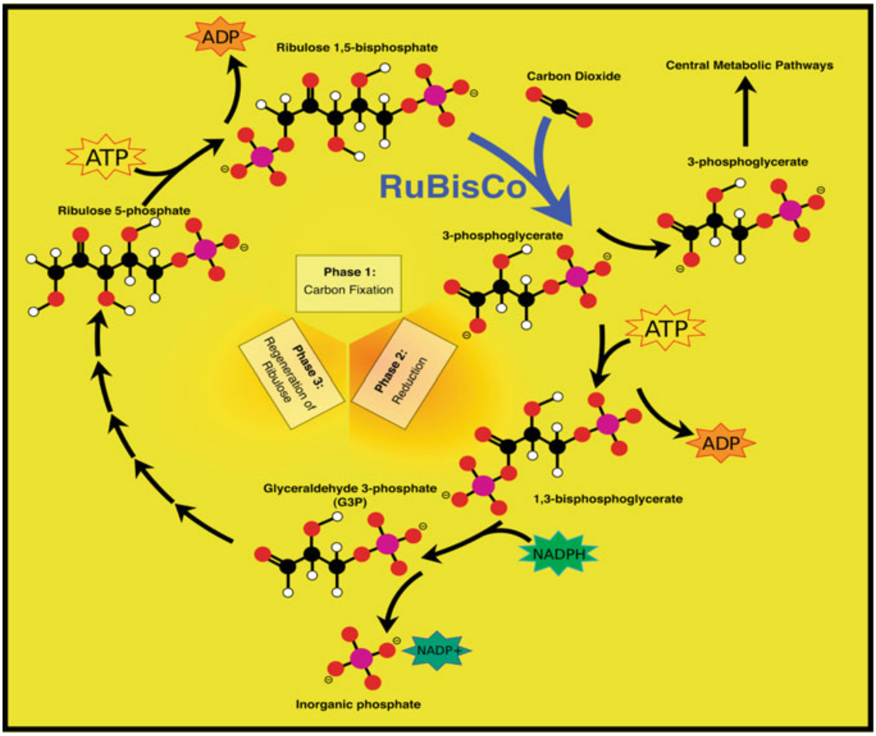


Fig. 7.3 RuBisCo action in mangrove flora (*Source* Mitra and Zaman 2016)

and reproductive parts. The principal carbon-fixing enzyme in plants is ribulose 1, 5-biphosphate carboxylase/oxygenase (RuBisCO). The magnitude of the mangrove vegetation pool thus exerts a regulatory role on the pH of the estuarine water as these halophytes absorb carbon dioxide for photosynthesis and shift the equilibrium towards alkalinity.

We have made a detailed study to assess the inter-relationship between mangrove vegetation cover-cum-biomass and ambient aquatic pH during 2019 considering six sampling stations in eastern sector of Indian Sundarbans (Table 7.1).

Table 7.1 Sampling stations with coordinates in western Indian Sundarbans

Sampling stations	Latitude	Longitude
Arbesi (Stn. 1)	22° 12′ 07.44″ N	89° 00′ 03.15″ E
Jhilla (Stn. 2)	22° 10′ 20.55″ N	88° 56′ 04.13″ E
Harinbhanga (Stn. 3)	21° 59′ 17.79″ N	88° 59′ 05.32″ E
Khatuajhuri (Stn. 4)	22° 03′ 09.52″ N	89° 01′ 03.12″ E
Chamta (Stn. 5)	21° 53′ 05.91″ N	88° 57′ 26.52″ E
Chankhali (Stn. 6)	21° 51′ 31.73″ N	89° 00′ 50.92″ E

We observed high pH reduction in areas with low mangrove pool confirming the positive role of mangroves in retarding the pace of acidification (Table 7.2).

The polynomial presented in Fig. 7.4 (considering aquatic pH as dependent variable and forest area as independent variable for six selected stations in eastern Indian Sundarbans) shows the positive role of mangrove vegetation in retarding the pace of EA.

Table 7.2 Mangrove pool (tonnes), % pH reduction in the eastern Indian Sundarbans

Station	Total biomass of dominate species (tonnes/ha) Date type: primary		Forest area (ha) Date type: primary	Mangrove pool (tonnes) Date type: primary	% pH reduction/decade Date type: primary
Arbesi (Stn. 1)	*S. apetala*	67.12	7200	1,971,000.0	1.08
	A. alba	62.2			
	E. agallocha	21.79			
	A. officinalis	63.56			
	A. marina	59.08			
		273.75			
Jhilla (Stn. 2)	*S. apetala*	65.33	8387	2,309,863.67	0.96
	A. alba	63.88			
	E. agallocha	21.97			
	A. officinalis	64.13			
	A. marina	60.1			
		275.41			
Harinbhanga (Stn. 3)	*S. apetala*	66.21	7465	1,971,357.20	0.72
	A. alba	59.31			
	E. agallocha	21.84			
	A. officinalis	62.17			
	A. marina	54.55			
		264.08			
Uajhuri (Stn. 4)	*S. apetala*	66.18	8666	24,022,648.5	0.69
	A. alba	64.77			
	E. agallocha	21.58			
	A. officinalis	64.97			
	A. marina	59.75			
		277.25			
Chamta (Stn. 5)	*S. apetala*	64.99	12,955	3,641,002.75	0.72
	A. alba	66.09			

(continued)

Table 7.2 (continued)

Station	Total biomass of dominate species (tonnes/ha) Date type: primary		Forest area (ha) Date type: primary	Mangrove pool (tonnes) Date type: primary	% pH reduction/decade Date type: primary
	E.agallocha	22.02			
	A. officinalis	67.94			
	A. marina	60.01			
		281.05			
Chandkhali (Stn. 6)	*S. apetala*	62.14	9635	2,536,895.5	0.36
	A. alba	60.54			
	E.agallocha	22.87			
	A. officinalis	62.58			
	A. marina	55.17			
		263.3			

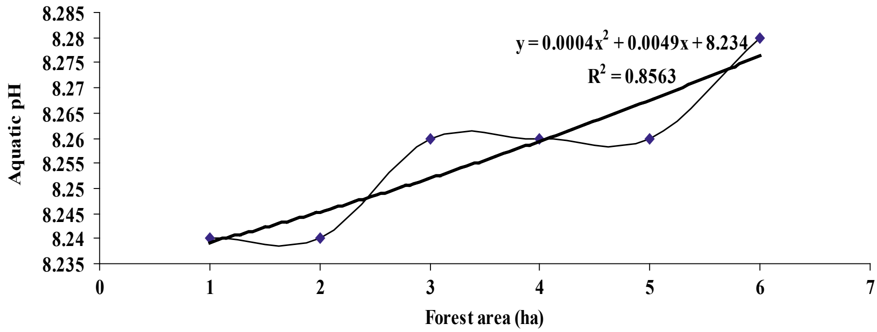


Fig. 7.4 Inter-relationships between forest area and aquatic pH in eastern Indian Sundarbans

7.2 Sea Grass and Saltmarsh Grass

The burning of fossil fuels like coal, oil etc. results in the release of carbon dioxide in to the atmosphere, which triggers the process climate change at local, regional and global scales. The atmospheric carbon dioxide is absorbed into the aquatic phase of oceans, seas, bays and estuaries where chemical reactions with the seawater produce carbonic acid that poses an adverse impact on the marine life particularly to organisms with calcareous shell. Sea grass beds provide several ecosystem services like providing food and shelter for marine organisms, erosion control, bioremediation etc. They also absorb carbon dioxide to run the process of photosynthesis and thus can buffer the pH of the oceans and estuaries thereby help neutralize the adverse effects caused by acidification.

The present authors assessed the stored carbon in major species of sea grass sampled from the Gulf of Mannar region during 2014 and documented the stored carbon both in AGB and BGB as highlighted in Tables 7.3 and 7.4 respectively. Three study sites namely Koswari (08° 52.34′N, 78° 13.04′E; Stn. 1), Kariyachalli (08° 57.36′N, 78° 14.42′E; Stn. 2) and Vilanguchalli (08° 56.22′N, 78° 15.59′E; Stn. 3) and three species (*Cymodocea serrulata, Thalassia hemprichii, Halophila ovalis*) were selected for estimation of stored carbon. Simultaneously pH values of the ambient aquatic phase were also estimated to evaluate the buffering potential of sea grass. It is observed that pH values are high in sites having more total biomass of sea grass (Table 7.5). These results confirm that sea grass meadows offer the buffering ecosystem service to prevent acidification of the aquatic phase.

In the selected quadrate, the order of abundance of the sea grass species was *Cymodocea serrulata* > *Thalassia hemprichii* > *Halophila ovalis.* Pronounced variation was observed between AGB and BGB in all the three species. The ratio of AGB and BGB ranged from 1:1.25 to 1:1.30. The Above Ground Carbon (AGC) and

Table 7.3 Species-wise above ground biomass (AGB) and above ground carbon (AGC) per unit area in Gulf of Mannar

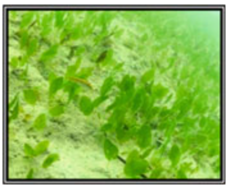
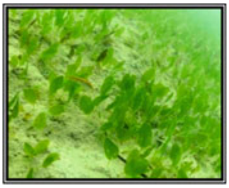
Species	AGB (g dry wt. m^{-2})			AGC (g dry wt. m^{-2})		
	Stn 1	Stn 2	Stn 3	Stn 1	Stn 2	Stn 3
 *Cymodocea serrulata*	115.23 (49.6%)	109.60 (49.7%)	101.85 (49.9%)	57.15	54.47	50.82
 *Thalassia hemprichii*	56.98 (48.5%)	49.79 (48.9%)	38.64 (47.9%)	27.63	24.35	18.51
 *Halophila ovalis*	28.87 (41.23%)	25.19 (43.05%)	19.49 (45.16%)	11.90	10.84	8.80

Table 7.4 Species-wise below ground biomass (BGB) and below ground carbon (BGC) per unit area in Gulf of Mannar

Species	BGB (g dry wt. m^{-2})			BGC (g dry wt. m^{-2})		
	Stn 1	Stn 2	Stn 3	Stn 1	Stn 2	Stn 3
 *Cymodocea serrulata*	144.04 (48.4%)	140.29 (48.6%)	132.41 (49.1%)	69.72	68.18	65.01
 *Thalassia hemprichii*	71.79 (47.9%)	63.23 (48.2%)	49.84 (48.5%)	34.39	30.48	24.17
 *Halophila ovalis*	36.31 (39.69%)	33.14 (38.43%)	24.75 (38.11%)	14.41	12.74	9.43

Below Ground Carbon (BGC) also exhibited significant variation with highest value in *Cymodocea serrulata* followed by *Thalassia hemprichii* and *Halophila ovalis.*

The coincidences of high biomass of sea grass with high pH of the surrounding water is a litmus test to prove the positive role of the sea grass species in preventing the pace of lowering the aquatic pH.

Soil Organic Carbon (SOC) was also monitored simultaneously to evaluate the amount of stored carbon in the underlying soil of the intertidal region in the study area. SOC values ranged from 0.89% (in the underlying soil of *Thalassia hemprichii* in station 3) to 1.98% (in the underlying soil of *Cymodocea serrulata* in station 1) (Table 7.6). ANOVA results also confirm significant variations ($p < 0.01$) in SOC between stations and also between underlying substrata of the respective species (Table 7.7).

Very scanty references are available on the mechanisms of carbon fixation in sea grasses and questions concerning the kinetics of the active forms of carbon utilized and possible photosynthetic pathways. Steemann Nielsen (1975) postulated that the exogenous form of carbon assimilated by sea grasses is HCO_3^-. This may

Table 7.5 Species-wise total biomass (TB) and total carbon (TC) per unit area in the Gulf of Mannar along with pH of the surrounding aquatic phase

Species	TB (g dry wt. m^{-2})			TC (g dry wt. m^{-2})			pH value		
	Stn 1	Stn 2	Stn 3	Stn 1	Stn 2	Stn 3			
 *Cymodocea serrulata*	259.27	249.89	234.26	126.87	122.65	115.83	8.34	8.32	8.32
 *Thalassia hemprichii*	128.77	111.02	88.48	62.02	54.83	42.68	8.30	8.30	8.29
 *Halophila ovalis*	65.18	58.33	44.24	26.31	23.58	18.23	8.30	8.29	8.27

Table 7.6 Soil organic carbon (SOC) level associated with the sea grass species

Species	SOC (%)		
	Stn 1	Stn 2	Stn 3
Cymodocea serrulata	1.98	1.36	1.09
Thalassia hemprichii	1.07	0.98	0.89
Halophila ovalis	1.13	0.97	1.01

Table 7.7 ANOVA results showing variations of AGB, BGB, AGC and BGC of Seagrass between species and stations in Gulf of Mannar

Variables	F_{cal}	F_{crit}
AGB		
Between species	1104.33	6.94
Between station	27.76	6.94
BGB		
Between species	1029.25	6.94
Between station	19.57	6.94
AGC		
Between species	643.76	6.94
Between station	12.50	6.94
BGC		
Between species	999.93	6.94
Between station	13.96	6.94
SOC		
Between underlying substratum of species	4.58	6.94
Between station	2.61	6.94

be attributed to extremely low concentration of carbon dioxide in seawater compared with HCO_3^- (about 200 times less) and the slow rate at which carbon dioxide could be re-supplied to the plant from other forms of carbon. The complete dependency of few sea grass species on HCO_3^- was demonstrated by Beer et al. (1977). These species are *Halophila stipulacea*, *Thalassodendron ciliatum*, *Halodule uninervis* and *Syringodium isoetifolium*. It is of interest whether sea grass species belong to the C_3 or C_4 group of plants because many species are tropical, and hence exposed to high temperatures, especially in shallow water. This is one of the conditions which might have contributed to the evolution of C_4 plants. While certain features such as the $\delta^{13}C$ values measured by Parker (1964), Smith and Epstein (1971), Doohan and Newcomb (1976) and Benedict and Scott (1976) suggest that various sea grass species belong to the C_4 type, other features such as the high rates of photorespiration (Hough 1976) and photosynthetic inhibition by high oxygen concentrations (Downton et al. 1976) are typically associated with the C_3 pathway. Results of a more appropriate test for the determination of C_3 or C_4 photosynthesis, i.e. short-time $\delta^{14}C$ experiments, have been reported previously only by Benedict and Scott (1976). They show that *Thalassia testudinurn* is a C_4 plant. In 1979 Beer and Waisel conducted short-time $\delta^{14}C$ pulse-chase experiments on two other sea grass species. Both species show a typical C_3 pattern with phosphoglyceric acid being the first major stable substance labelled. The label is subsequently transferred to phosphorylated sugars and phosphate esters, and later to saccharose or aspartic acid. Although saccharose and aspartic acid were not separated in the scraping and counting of the chromatograms, two distinct spots could be identified on the X-ray film, the saccharose spot usually of higher density than the aspartic acid. In any case, neither malic nor aspartic acids were primary products of ^{14}C fixation showing that these sea grass species are not C_4 plants. Although ^{14}C pulse-chase experiments should ideally result in the same total activity of label in all treatments, the relative activity of fixed ^{14}C increased with increasing chase times. This is due to absorption of $H^{14}CO_3^-$ which continues to be metabolized after the plant has been transferred to a ~4C-free medium. Therefore, phosphoglyceric acid levels in 15 and 45 s chase periods are somewhat overestimated while main labelled products are underestimated. The regain of spotted ~4C activity was about 60%, including the activity of the whole plates. Some activity was lost to the running solvent in the tank and about 10% was lost as an evenly distributed smear over the whole plate. The two sea grass species investigated are unlike *Thalassia testudinum* which was shown earlier to be a C_4 plant (Benedict and Scott 1976). They are also somewhat different from *Halophila stipulacea and Thalassodendron ciliatum* plants which, although mostly resembling C_3 plants, show a relatively higher labelling into malic and aspartic acids (Beer unpublished). Sea grasses do not exhibit the structural differentiation of photosynthetic tissue (Kranz anatomy) which is usually found in C_4 plants and photosynthesis seems to be carried out mainly in the chloroplast-rich epidermis. C_4 photosynthesis as in *Thalassia testudinurn* is therefore not associated with the Kranz anatomy (Benedict and Scott 1976). It is likely that variations in photosynthetic pathways found in sea grasses are linked to the levels of photosynthetic enzymes as well as HCO_3^- and/or carbon dioxide rather than to differences in anatomy. In some freshwater angiosperms, the ratio of phosphoenolpyruvate carboxylase to ribulosebiphosphate carboxylase differs as a response to seasonal changes of the environment (Bowes et al. 1978). If this is also true for sea grasses, one could expect to find variations in photosynthetic pathways both between and within species as a response to growth conditions. Also, nothing would hinder both pathways being more or less active simultaneously. The main exogenous form of carbon utilized by six sea grass species investigated so far is HCO_3^-. This agrees well with the high HCO_3^- compared with carbon dioxide concentrations found in seawater. The former concentration (about 2.5 mM) is saturating for photosynthesis in these plants. Whether HCO_3^- is fixed directly by phosphoenolpyruvate carboxylase or transformed to carbon dioxide and fixed via ribulosebiphosphate carboxylase probably depends on the levels of these and other enzymes as well as which form of carbon is available. ^{14}C pulse-chase experiments have shown that at least one sea grass species is a C_4-plant while others are C_3 plants. Experiments based on other parameters sometimes show contradictory or intermediary photosynthetic pathways. The variations in photosynthetic pathways reflect an ability of sea grasses to adapt to various ecological conditions.

Salt marsh communities are widely distributed on the shoreward side of mud flats in temperate and subarctic regions of the world. The dominant plant life in this community on many North American shores is cordgrass (*Spartina* sp.) that has moved to the shallow intertidal area. The cordgrass *Spartina alterniflora* dominates the marshlands of the Atlantic coast, while *Spartina foliosa* is dominant along the coast of California. On the Gulf Coast of Florida, the tallest and most marsh grass is *Juncus* sp*.,* which is found in higher elevations (higher up on shore). The species found most seaward is tall cordgrass, *Spartina alterniflora.*

The estuaries of Indian sub-continent sustains an important saltmarsh grass species namely *Porteresia coarctata* (Fig. 7.5), which has a great role in stabilizing the islands. Their long network of roots binds the soil particles very intricately and retards the process of erosion. The growth, biomass and subsequent carbon storage capacity of the species is controlled by the ambient aquatic salinity. The species exhibits a luxuriant growth in relatively low saline regions (salinity range within 5–20 psu) with subsequently higher carbon content, but at salinity around 30 psu, the growth is stunted.

A time series analysis (2001–2012) was conducted by the present authors on the stored carbon of the species sampled from the east and west coasts of India. Interestingly the species sampled from the Hooghly estuary in the east coast exhibited higher biomass and carbon compared to those sampled from the Mandovi estuary in the west coast. The entire data bank of biomass and stored carbon in *P. coarctata* is presented Figs. 7.6, 7.7, 7.8 and 7.9.

In Indian Sundarbans, *Porteresia coarctata* is widely available in the intertidal zone surrounding almost all the islands. This species provides different categories of ecosystem services like provisioning services (as fodder), regulating services (bioremediation, carbon sequestration, erosion checking etc.) and supporting services

Fig. 7.5 Saltmarsh grass *Porteresia coarctata* in Indian Sundarbans

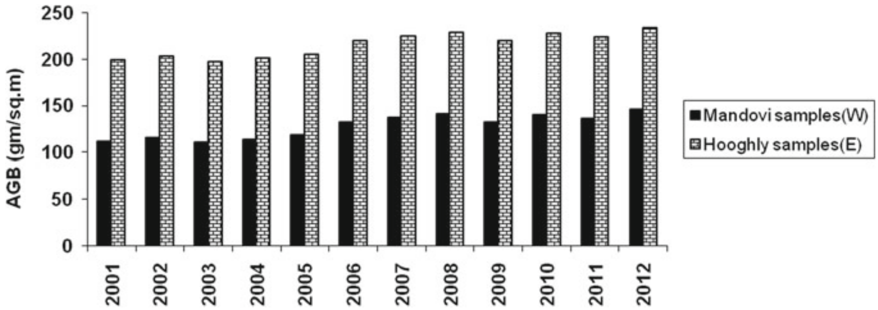


Fig. 7.6 AGB in *P. coarctata* samples from the Hooghly and Mandovi estuary during 2001–2012

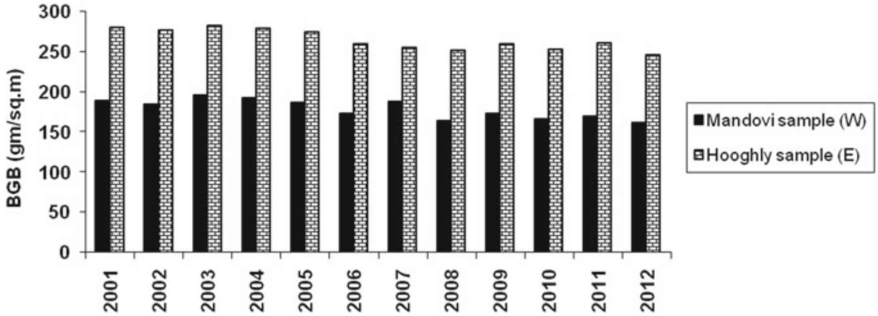


Fig. 7.7 BGB in *P. coarctata* samples from the Hooghly and Mandovi estuary during 2001–2012

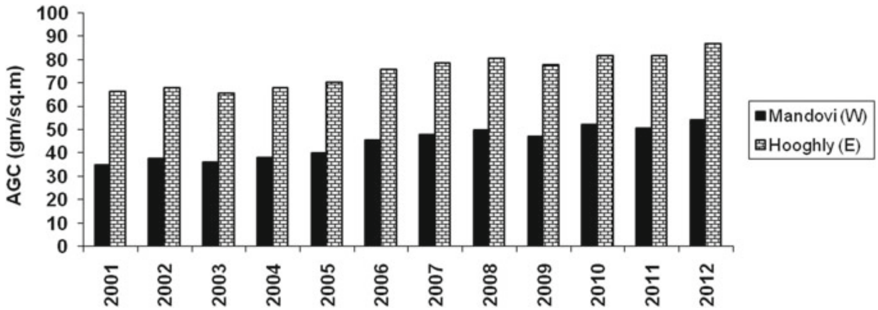


Fig. 7.8 AGC in *P. coarctata* samples from the Hooghly and Mandovi estuary during 2001–2012

(nursery and breeding ground of several fish species). In this section, we have documented the role of the species in regulating the pH of the water body surrounding the islands. The monitoring of the parameters was conducted during March, 2019 in 24 selected stations in Indian Sundarbans (Table 7.8 and Fig. 7.10).

We estimated the total biomass (sum of Above Ground Biomass and Below Ground Biomass) of the species by the standard quadrant method. Simultaneously pH of the surrounding water around the salt marsh bed was monitored in all the selected

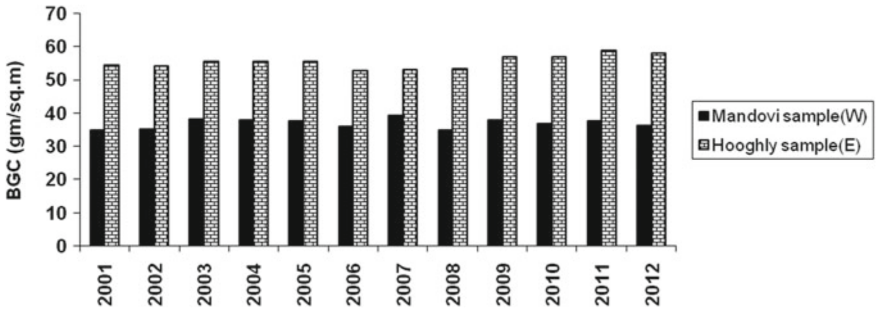
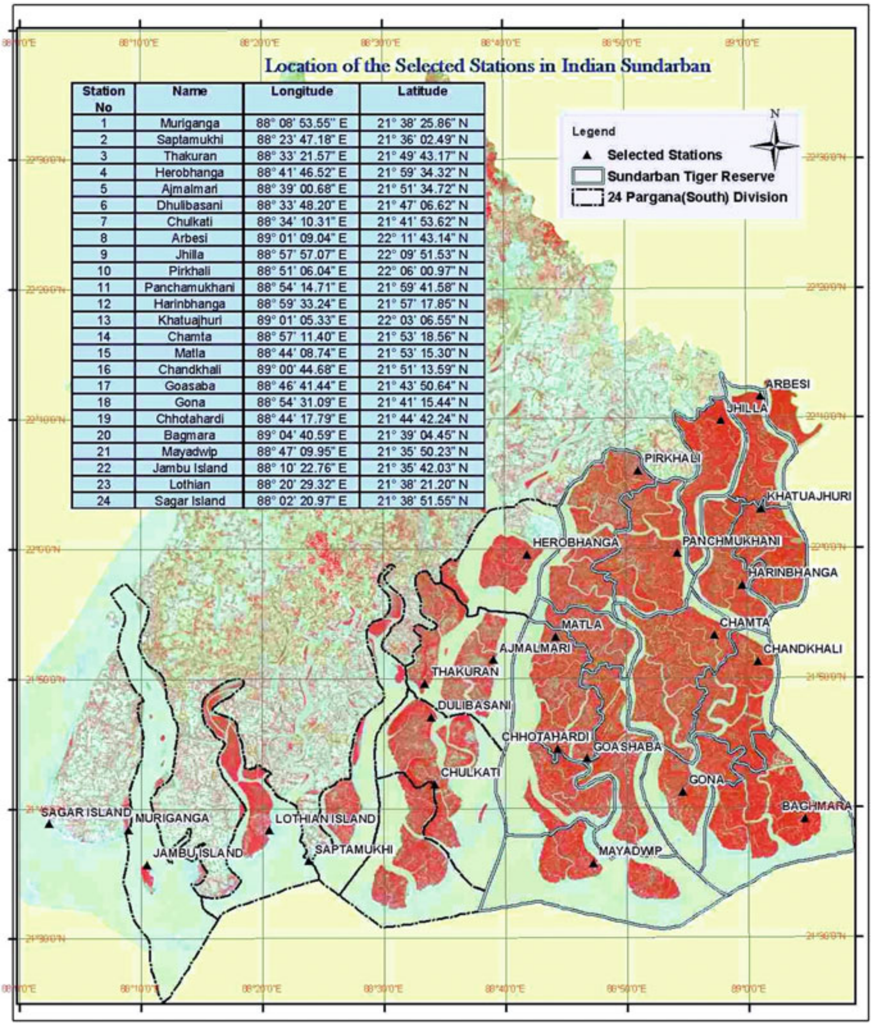


Fig. 7.9 BGC in *P. coarctata* samples from the Hooghly and Mandovi estuary during 2001–2012

Table 7.8 Sampling stations in Indian Sundarbans with Total Biomass of *Porteresia coarctata* and pH values of the ambient aquatic phase

S. No.	Sampling station	Latitude	Longitude	Total biomass (g dry wt. m^{-2})	pH value
1	Muriganga	21° 38′ 25.86″ N	88° 08′ 53.55″ E	289.54	8.05
2	Saptamukhi	21° 36′ 02.49″ N	88° 23′ 47.18″ E	301.49	8.10
3	Thakuran	21° 49′ 43.17″ N	88° 33′ 21.57″ E	335.46	8.22
4	Herobhanga	21° 59′ 34.32″ N	88° 41′ 46.52″ E	393.45	8.28
5	Ajmalmari	21° 51′ 34.72″ N	88° 39′ 00.68″ E	327.45	8.20
6	Dhulibasani	21° 47′ 06.62″ N	88° 33′ 48.20″ E	348.65	8.26
7	Chulkathi	21° 41′ 53.62″ N	88° 34′ 10.31″ E	354.70	8.27
8	Arbesi	22° 11′ 43.14″ N	89° 01′ 09.04″ E	401.68	8.33
9	Jhilla	22° 09′ 51.53″ N	88° 57′ 57.07″ E	385.29	8.31
10	Pirkhali	22° 06′ 00.97″ N	88° 51′ 06.04″ E	373.25	8.31
11	Panchmukhani	21° 59′ 41.58″ N	88° 54′ 14.71″ E	391.02	8.32
12	Harinbhanga	21° 57′ 17.85″ N	88° 59′ 33.24″ E	363.13	8.30
13	Khatuajhuri	22° 03′ 06.55″ N	89° 01′ 05.33″ E	379.85	8.30
14	Chamta	21° 53′ 18.56″ N	88° 57′ 11.40″ E	360.38	8.29
15	Matla	21° 53′ 15.30″ N	88° 44′ 08.74″ E	303.45	8.15
16	Chandkhali	21° 51′ 13.59″ N	89° 00′ 44.68″ E	329.92	8.19
17	Goashaba	21° 43′ 50.64″ N	88° 46′ 41.44″ E	311.48	8.18
18	Gona	21° 41′ 15.44″ N	88° 54′ 31.09″ E	353.66	8.28
19	Chhotahardi	21° 44′ 42.24″ N	88° 44′ 17.79″ E	343.85	8.27
20	Baghmara	21° 39′ 04.45″ N	89° 04′ 40.59″ E	356.96	8.29
21	Mayadwip	21° 35′ 50.23″ N	88° 47′ 09.95″ E	390.40	8.30
22	Jambu Island	21° 35′ 42.03″ N	88° 10′ 22.76″ E	289.43	7.99
23	Lothian	21° 38′ 21.20″ N	88° 20′ 29.32″ E	356.29	8.32
24	Sagar Island	21° 38′ 51.55″ N	88° 02′ 20.97″ E	213.45	7.98



Station No	Name	Longitude	Latitude
1	Muriganga	88° 08' 53.55" E	21° 38' 25.86" N
2	Saptamukhi	88° 23' 47.18" E	21° 36' 02.49" N
3	Thakuran	88° 33' 21.57" E	21° 49' 43.17" N
4	Herobhanga	88° 41' 46.52" E	21° 59' 34.32" N
5	Ajmalmari	88° 39' 00.68" E	21° 51' 34.72" N
6	Dhulibasani	88° 33' 48.20" E	21° 47' 06.62" N
7	Chulkati	88° 34' 10.31" E	21° 41' 53.62" N
8	Arbesi	89° 01' 09.04" E	22° 11' 43.14" N
9	Jhilla	88° 57' 57.07" E	22° 09' 51.53" N
10	Pirkhali	88° 51' 06.04" E	22° 06' 00.97" N
11	Panchamukhani	88° 54' 14.71" E	21° 59' 41.58" N
12	Harinbhanga	88° 59' 33.24" E	21° 57' 17.85" N
13	Khatuajhuri	89° 01' 05.33" E	22° 03' 06.55" N
14	Chamta	88° 57' 11.40" E	21° 53' 18.56" N
15	Matla	88° 44' 08.74" E	21° 53' 15.30" N
16	Chandkhali	89° 00' 44.68" E	21° 51' 13.59" N
17	Goasaba	88° 46' 41.44" E	21° 43' 50.64" N
18	Gona	88° 54' 31.09" E	21° 41' 15.44" N
19	Chhotahardi	88° 44' 17.79" E	21° 44' 42.24" N
20	Bagmara	89° 04' 40.59" E	21° 39' 04.45" N
21	Mayadwip	88° 47' 09.95" E	21° 35' 50.23" N
22	Jambu Island	88° 10' 22.76" E	21° 35' 42.03" N
23	Lothian	88° 20' 29.32" E	21° 38' 21.20" N
24	Sagar Island	88° 02' 20.97" E	21° 38' 51.55" N

Fig. 7.10 Location of 24 sampling stations in Indian Sundarbans

24 stations. For each observational station, at least three samples were collected from the surface during low tide condition within 500 m of each other. We observed a significant positive correlation between total biomass of the species and aquatic pH ($r = 0.9204$; $p < 0.01$). The inter-relationship between these variables is also highlighted by the scatter plot (Fig. 7.11), which confirms the regulatory role of the salt marsh grass species, *P. coarcatata* in buffering the water bodies surrounding the vegetation. The present result strongly suggests the conservation and massive plantation of the species to retard the rate of acidification in the coastal and estuarine regions.

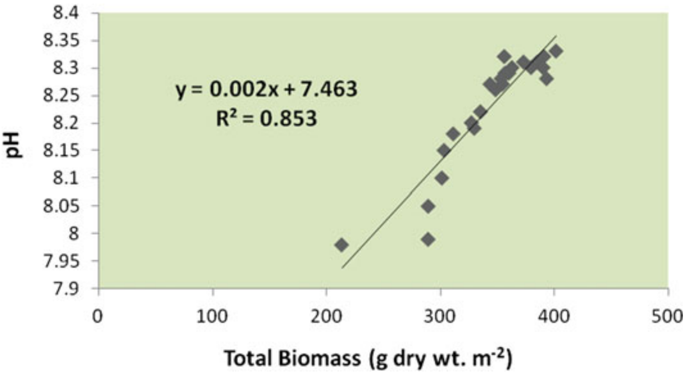


Fig. 7.11 Scatterplot showing the positive relationship between total biomass of *Porteresia coarctata* and aquatic pH

7.3 Seaweeds

Seaweeds or marine macroalgae are the group of plants that thrive either in marine or brackish water environment. They are macroalgae and contain photosynthetic pigments. Like the terrestrial producer community, the seaweeds can prepare their own food with the help of sunlight and nutrients present in the seawater. Seaweeds are found in the coastal region between high tide to low tide and in the sub-tidal region up to a depth where 0.01% photosynthetic light is available. They require hard substratum for their growth, which may be tree trunks (preferably mangroves) that get submerged during the high tide or even brick or boulders that are often laid to enter the island from the adjacent bays or estuaries.

Based on the colour of the pigmentation, the seaweeds are broadly classified into various categories like Chlorophyceae (green), Phaeophyceae (brown), Rhodophyceae (red) etc.

Chlorophyceae: Algae are typically green in colour due to the predominant presence of the green pigment, the chlorophyll *a*, contained in chloroplasts. Most of the green algae are found occurring in the littoral zones of the marine environment and produce motile reproductive bodies e.g., *Codium* sp., *Enteromorpha intestinalis*, *Enteromorpha compressa, Ulva lactuca*, *Chaetomorpha* sp., *Cladophora* sp. etc.

Phaeophyceae: The brown algae are distinguished by their colour, which varies from olive green through light golden to a deep shade of brown. Motile reproductive cells are commonly found in the brown algae e.g., Kelps like *Postelsia* sp., *Nereocystis* sp., *Macrocystis* sp., and *Laminaria* sp., *Fucus* sp., *Padina gymnospora, and Rosenvingea intricata.* Since brown algae live primarily in shallow waters or on shoreline rocks, they exhibit adaptations that protect them from the constant pounding of the waves. The body of brown algae is very flexible, which allow them to bend or orient with the wave action. Unlike red and green algae, brown algae usually do not reproduce by fragmentation because the tissues are too highly specialized to regenerate new parts. A major exception to this rule is *Sargassum* sp. Large masses of this seaweed are found floating in the Atlantic Ocean, where they tend to accumulate in an area known as the Sargasso Sea. These free-floating clumps of sargassum weed form a complex, three-dimensional habitat that sustains a diverse group of marine organisms.

Rhodophyceae: The seaweeds under this category are recognized by their bright pink colour caused by the biloprotein pigments, r-phycoerythrin and r-phycocyanin. The fresh water forms, however, are of bluish green in colour. Red algae produce large amount of polysaccharides around their cells. Several of these polysaccharides are commercially important. The majority of the marine forms occur from low tide marks to greater depths up to 100 m beneath the surface of the sea. e.g., *Porphyra* sp., *Chondrus crispus*, *Catenella repens* etc.

A list of common seaweeds (belonging to three different classes) found in the tropical regions is highlighted in Table 7.9.

Ecosystem Services of Seaweeds

Today seaweeds are used for various commercial purposes. Agar and algin extracted from the seaweeds have a variety of industrial applications. Apart from consuming the seaweed as food, they are used as fodder, manure, medicine and also as ingredients of several health products as discussed here under different headings.

As Food: In many countries like Malaysia, Indonesia, Korea, and Australia seaweeds are used for human consumption. These are used in the preparation of salads, soups, jellies and vinegar. The common species utilized for the preparation of food are *Porphyra* sp., *Gracilaria* sp., *Laurencia* sp., *Caulerpa* sp., *Sargassum* sp. etc. These algae are rich in Vitamin B.

As Fodder: Some important species of seaweeds that are used in cattle feed are *Ulva* sp., *Enteromorpha* sp., *Gracilaria* sp., *Padina* sp., *Sargassum* sp. etc. Poultry feed is also made in certain areas by mixing seaweeds with trash fishes.

As Manure: Seaweeds have unique capacity to bioaccumulate trace elements from ambient media and therefore they are rich sources of macro and micro-elements required for the growth of plants. Seaweeds like *Sargassum* sp. and *Gracilaria* sp. are used as manure for coconut plantation in India, particularly in the south Indian states.

As Medicine: Seaweeds have wide applications in the sphere of medicine. *Sargassum* sp. and *Turbinaria* sp. are good sources of alginates, which are known to prolong the period of activity of certain drugs. *Hypnea* sp. and *Acanthophora* sp. are the major sources of carrageenans, which have been found to be useful in ulcer therapy.

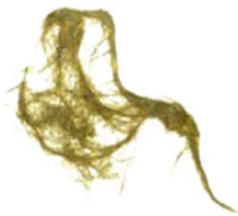
As Industrial Raw Material: Agar–agar is a gelatinous colloidal carbohydrate present in the cell wall of algae and is extracted from some members of Rhodophyceae. In India, agar has wide use in the preparation of food, ice creams, jellies, soups, bacteriological samples and cosmetics. Being a non-toxic substance

Table 7.9 Common seaweed species of marine and estuarine ecosystems

Scientific name	Systematic position	Description	Figure
Caulerpa racemosa	Division—Chlorophyta Order—Bryopsidales Family—Caulerpaceae	Plants with a horizontal rhizome like stem anchored by rhizoids. The erect branches bear clusters of small branchlets with swollen tips	
Caulerpa scalpelliformis	Division—Chlorophyta Order—Bryopsidales Family—Caulerpaceae	Flat lanceolate blades arise from the stolen anchored in sand	
Caulerpa serrulata	Division—Chlorophyta Order—Bryopsidales Family—Caulerpaceae	Spirally twisted blades with toothed edges (serrulate) arise from the stolon anchored in sand by the root like rhizoides	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Chaetomorpha linum	Division—Chlorophyta Order—Cladphorales Family—cladophoraceae	*Chaetomorpha* means 'hair-shaped' and the thick, unbranched filaments form bright green mats in mangrove channels	
Codium arabicum	Division—Chlorophyta Order—Bryopsidales Family—Codiaceae	This species forms convoluted flattened cushions	
Codium dwarkense	Division—Chlorophyta Order—Bryopsidales Family—Codiaceae	The cylindrical, spongy branches are primarily dichotomous (with regularly forked branches) with some side branches	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Codium indicum	Division—Chlorophyta Order—Bryopsidales Family—Codiaceae	Plants are spongy with irregularly forked cylindrical branches attached by a disc-shaped holdfast to rocks. *Codium* plants vary in shape from this branched type to thick crusts to flat blades	
Enteromorpha flexuosa	Division—Chlorophyta Order—Ulvales Family—Ulvaceae	*Enteromorpha* forms thin, hollow tubes which are generally small but may reach over 10 cm in length in good conditions. These fronds are mostly unbranched and flattened	
Ulva fasciata	Division—Chlorophyta Order—Ulvales Family—Ulvaceae	The blade is green divided into long and narrow strap-like lobes reaching to 15 cm on Arabian sea coasts. The margins are irregularly toothed	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Ulva grandis	Division—Chlorophyta Order—Ulvales Family—Ulvaceae	The blade is dark green, expanded to more than a meter long and grows extensively along the Mirbat peninsula on the Arabian Sea coasts	
Dictyota pardalis	Division—Phaeophyta Order—Dictyotales Family—Dictyotaceae	This species may be up to 20 cm high with branches often growing in a twisting or spiral manner. The lower branches may be covered with small proliferations	
Hormophysa cuneiformis	Division—Phaeophyta Order—Fucales Family—Cystoseiraceae	Plants to 40 cm, stiff with wide, flat margins to the branches. The margins are toothed	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Jolyna laminarioides	Division—Phaeophyta Order—Scytosiphonales Family—Scytosiphonaceae	The strap-shaped blades are usually unbranched and reach up to 30 cm	
Padina boergesenii	Division—Phaeophyta Order—Dictyotales Family—Dictyotaceae	*Padina* has fan-like blades which are attached by a discoid holdfast to rocks. This species has a double row of hairs in concentric bands	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Sargassum ilicifolium	Division—Phaeophyta Order—Fucales Family—Sargassaceae	These are long main stem bearing many leaves which are usually toothed with a distinct midrib. The spherical air bladders float the photosynthetic leaves up into the lighted surface waters	
Stoechospermum marginatum	Division—Phaeophyta Order—Dictyotales Family—Dictyotaceae	This brown seaweed, which may reach 40 cm in height, has regularly dichotomously branched blades. These are flat, stiff and strap-like with in-rolled tips. Fertile plants have characteristic marginal dark lines crowded with sporangia	
Turbinaria conodes	Division—Phaeophyta Order—Fucales Family—Sargassaceae	This stiff, erect plant has distinctive turban-like blade attached to a central stem fixed to rocks by a spreading stolon. Each blade is roughly triangular with marginal teeth and a lobed centre	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Amphiroa anceps	Division—Rhodophyta Order—Corallinales Family—Corallinaceae	This calcified, coralline red alga shows regular dichotomous branching with narrow fork angles in upper parts of the plant. There is clear articulation with segments alternating with non-calcified 'joints'. The plant is very brittle when dry and then easily falls to pieces	
Euptilota fergusonii	Division—Rhodophyta Order—Cerramiales Family—Ceramiaceae	This bushy, dark red alga grows to 15 cm. the delicate-looking branchlets end I very fine tips with 2–3 spiny outgrowths	
Galaxaura marginata	Division—Rhodophyta Order—Nemaliales Family—Galaxauraceae	This bushy, mounded seaweed grows to 10 cm or more with lightly calcified pinkish blades loosely entangled. The dichotomously branched blades show faint cross banding near the tips and have thickened margins	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Galaxaura obtusata	Division—Rhodophyta Order—Nemaliales Family—Galaxauraceae	This rose-red plant may reach 10 cm. The cylindrical branches are repeatedly forked	
Gelidium latifolium	Division—Rhodophyta Order—Geliadiales Family—Gelideaceae	This identification is not confirmed but the plant has a dense appearance with many fine branches	
Gracilaria canaliculata	Division—Rhodphyta Order—Gracilariales Family—Gracilarriaceae	These tough, fleshy plants reach a length of 7 cm tall with interwining branches throughout. The branches are cylindrical in cross section	
Haliptilon subulatum	Division—Rhodophyta Order—Cryptonemiales Family—Corallinaceae	This attractive coralline alga has brittle, heavily calcified pink segments connected by flexible joints. There is a regular arrangement of main segments like inverted triangles with cylindrical side branches	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Halymenia porphyriformis	Division—Rhodophyta Order—Cryptonemiales Family—Halymeniaceae	This striking seaweed is rosy-red with a flat, lobed leaf-like lamina with a few perforations. It reaches 20 cm or more and is attached to rocks by a small disc-shaped holdfast	
Hypnea boergesenii	Division—Rhodophyta Order—Gigartinales Family—Hypnaceae	This species grows up to 10—15 cm	
Hypnea bryoides	Division—Rhodophyta Order—Gigartinales Family—Hypnaceae	This striking plant grows to 20 cm with tough, wiry branches forming dense clumps from a holdfast. The branches have a characteristics 'hairy' appearance from a dense covering of tiny spiny outgrowths	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Martensia elegans	Division—Rhodophyta Order—Ceramiales Family—Delesseriaceae	This remarkable elegant plant grows to 10 cm. The net-like blades are divided into zones with every other zone forming a network of elongated holes resembling a cross section of wood in a tree	
Porphyra sp.	Division—Rhodophyta Order—Bangiales Family—Bangiaceae	This alga attaches itself to the rocks by multicellular rhizoidal attachments, usually disc-shaped	
Portieria hornemanni	Division—Rhodophyta Order—Cryptonemiales Family—Rhizophyllidaceae	This conspicuous, bright red alga grows up to 8 cm in tufts, It branches repeatedly to form a delicate, lacy appearance	

(continued)

Table 7.9 (continued)

Scientific name	Systematic position	Description	Figure
Sarcodia montagneana	Division—Rhodophyta Order—Gigartinales Family—Sarcodiaceae	This plant occurs as dense clusters of thick, flat triangular blades to 8 cm high. The blades are irregularly or dichotomously divided with distinctive rounded projections along the margins	
Sarconema filiforme	Division—Rhodophyta Order—Gigartinales Family—Solieriaceae	The dichotomously branched tips taper to fine points. It is coloured yellow–brown in exposed areas but dark red in shaded sites	
Sarconema scinaioides	Division—Rhodophyta Order—Gigartinales Family—Solieriaceae	The plant is up to 15 cm tall, tough and rubbery with dichotomous branching throughout. The branches are cylindrical with short tips and are thicker than other species of *Sarconema*	
Sebdenia flabellata	Division—Rhodophyta Order—Gigartinales Family—Solieriaceae	The dichotomous branches are cylindrical and very gelatinous. Large specimens found late in the season (November/December) are filled with jelly	

agar is also used for the preparation of wine, beer, hand lotions etc. Algin and alginates have extensive uses in the preparation of various medicines, cosmetics, paper products, textile products, paints, milk products etc.

As biological treatment of wastes: Seaweeds can also be utilized for the biological treatment of industrial wastes by utilising their unique bioaccumulation capacity. It has been found that *Catenella repens*, *Ulva* sp., and *Enteromorpha intestinalis* are unique absorber of Zn, Cu, Fe etc. from the ambient aquatic medium. These algae, if cultured in the treatment plant of coastal industries can trap substantial amount of metals from the released industrial wastes.

In coral reef building: Many macroalgae make important contributions to the construction of the coral reef structure or reef skeleton by depositing calcium carbonate ($CaCO_3$ or limestone). Crustose Calcareous Algae (CCA, especially the Order Corallinales: e.g. *Porolithon* sp) are considered important in building and cementing the carbonate framework of coral reefs. CCA bind adjacent substrata and provide a calcified tissue barrier against erosion. This process is particularly important on many reef crests of the Great Barrier Reef, where Crustose Coralline Algae are dominant. Estimates of calcification rates of CCA at Lizard Island indicate significant annual deposition rates (1–10.3 kg $CaCO_3$ m^{-2} yr^{-1}). Non-coralline CCA (e.g. *Peyssonnelia*) is also important in deep areas (between 80 and 120 m) at the edge of the continental platform in the Southern Reef, where they form large algal frameworks several meters high.

Seaweeds as biofuels: Prospecting macroalgae (seaweeds) as feed stocks for bioconversion into biofuels and commodity chemical compounds is limited primarily because of tractable microorganisms that can metabolize alginate polysaccharides. Today researchers have discovered a 36-kilo–base pair DNA fragment from *Vibrio splendidusen* coding enzymes for alginate transport and metabolism. The genomic integration of this ensemble, together with an engineered system for extracellular alginate depolymerization, generated a microbial platform that can simultaneously degrade, uptake and metabolize alginate. When further engineered for ethanol synthesis, this platform enables bioethanol production directly from macroalgae via a consolidated process, achieving a titer of 4.7% volume/volume and a yield of 0.281 weight ethanol/weight dry macroalgae (equivalent to ~80% of the maximum theoretical yield from the sugar composition in macroalgae).

Carbon sequestration: Unlike other blue carbon sectors (mangroves, sea grasses, and salt marshes), kelp forests and seaweed beds do not have such sedimentary substrata. Instead, their carbon-rich biomass detaches and is broken down in food chains by organisms that range in scale from grazing animals to pelagic and seabed bacteria. Knowledge on the scale of conversion of inorganic carbon into biomass, its subsequent sinking to the seabed and its sequestration over thousands of years form the basis of understanding the oceans as a potential sink for increasing levels of atmospheric carbon dioxide (CO_2). The other modes of fate of seaweed biomass depend on natural processes. The seaweed can be consumed by herbivores, whose fecal matters sink to the bottom and may remain there for a while. Moreover, distal

Table 7.10 Sampling stations with coordinates and salient features

Station	Coordinates	Salient features
Nayachar Island (Stn. 1 in the western sector)	21° 45′ 24″ N; 88° 15′ 24″ E	It is located in the Hooghly estuary and faces the Haldia port-cum-industrial complex that houses a variety of industrial units
Sagar South (Stn. 2 in the western sector)	21° 39′ 04″ N; 88° 01′ 47″ E	Situated at the confluence of the River Hooghly and the Bay of Bengal on the western sector of Indian Sundarbans
Gosaba (Stn. 3 in the central sector)	22° 15′ 45″ N; 88° 39′ 46″ E	Located in the Matla Riverine stretch in the central sector of Indian Sundarbans
Annpur in Satjelia Island (Stn. 4 in the central sector)	22° 11′ 52″ N; 88° 50′ 43″ E	Located in the central sector of Indian Sundarbans. Noted for its wilderness and mangrove diversity; selected as control zone

portions of the fronds disintegrate during the summer season and those fragments enter the detritus food chain. Exudation as a dissolved organic material can be a critical loss. Therefore, some of the seaweed carbon will return to the water column and be either recaptured during photosynthesis or eventually returned to the atmosphere. However, a significant fraction of the algal carbon can be sequestered on the sea floor for a long period, perhaps centuries depending on location, currents etc.

Compared to other vegetation, the carbon sequestration potential of seaweeds in estuarine and deltaic environments, are however poorly understood. In this section, the seasonal and spatial variations in biomass production and carbon content of three major species of seaweeds (*E. intestinalis, U. lactuca* and *C. repens*) inhabiting two different sectors of lower Gangetic delta (western and central) with contrasting salinity have been estimated during 2019 (Table 7.10).

Seasonal samplings for biomass and carbon estimation of seaweed species (*E. intestinalis, U. lactuca and C. repens*) were carried out at low tides during May, 2019 (premonsoon), September, 2019 (monsoon) and November, 2019 (postmonsoon) from the intertidal mudflats. Samples of seaweed species were scrapped and handpicked from sluice gates, mangrove trunk and concrete jetties. Immediately after collection, the thallus of each species was thoroughly washed separately in the ambient seawater, as well as with double distilled water, to remove adhering debris and sediments. Altogether 10 quadrants (area = 1 m^2) were sampled form each of the selected stations for each species, randomly mixed and weighed accurately in an electronic balance (IRD Balance; Model No. 290). The biomass was expressed in g m^{-2}.

For carbon estimation, seaweed samples were separately dried in a hot air oven (60 °C) for 72 h until a constant weight was obtained. Dried samples were ground to a fine powder. Direct estimation of percent carbon in the thallus body of each seaweed species for each season and for each sampled locations was separately carried out by Vario MACRO elementar make CHN analyzer, after grinding and random mixing the oven dried seaweed samples. At about 990 °C, the seaweed sample was mineralized separately. Formation of carbon monoxide is possible at this temperature even in the presence of excess oxygen. The complete oxidation is reached through a tungsten trioxide catalyst which is passed by the gaseous reaction products. The samples were finally analyzed through CHN mode, which is the most universal of the analysis modes because of the combination of the reagent design and the optimize combustion control parameters and expressed in percentage.

The biomass of *E. intestinalis* ranged from 2844.59 gm m^{-2} (at Stn. 3, during premonsoon 2019) to 3185.99 gm m^{-2} (at Stn. 1, during postmonsoon 2019). The carbon content exhibited lowest value at Stn. 3 (955.85 g m^{-2} during monsoon 2019) and highest at Stn. 2 (1163.93 g m^{-2} during premonsoon 2019). It is interesting to note that the mean order of biomass of *E. intestinalis* is postmonsoon (3098.68 g m^{-2}) > monsoon (3015.23 g m^{-2}) > premonsoon (2994.55 g m^{-2}) (Table 7.11). However, the carbon content varied as per the order premonsoon (1312.43 g m^{-2}) > postmonsoon (1185.03 g m^{-2}) > monsoon (1094.44 g m^{-2}) (Table 7.12). The mean seasonal values of both biomass and stored carbon are highlighted in Fig. 7.12.

The biomass of the species exhibited an almost uniform value in both the sectors and three seasons ($p < 0.01$) as revealed through ANOVA (Table 7.13), but the carbon content showed a significant spatial and seasonal variations ($p < 0.01$) (Table 7.14). The highest carbon content in premonsoon may be attributed to congenial temperature and solar radiation in the study area that have profound influence on the photosynthetic rate.

Table 7.11 Average seasonal variations in biomass or standing stock (gm m^{-2}) of seaweeds with standard deviations; the values are the average of four selected stations during 2019

Species	Season		
	Premonsoon	Monsoon	Postmonsoon
Enteromorpha intestinalis	2994.55 ± 26.85	3015.23 ± 30.63	3098.68 ± 33.25
Ulva lactuca	499.01 ± 9.01	251.66 ± 7.36	173.11 ± 5.54
Catenella repens	232.05 ± 4.52	69.05 ± 2.81	133.83 ± 1.73

Table 7.12 Average seasonal variations in carbon content (gm m^{-2}) of seaweeds with standard deviations; the values are the average of four selected stations during 2019

Species	Season		
	Premonsoon	Monsoon	Postmonsoon
Enteromorpha intestinalis	1312.43 ± 2.85	1094.44 ± 1.93	1185.03 ± 2.03
Ulva lactuca	157.08 ± 1.88	73.31 ± 1.29	49.33 ± 1.10
Catenella repens	57.21 ± 0.93	15.04 ± 0.70	29.32 ± 0.62

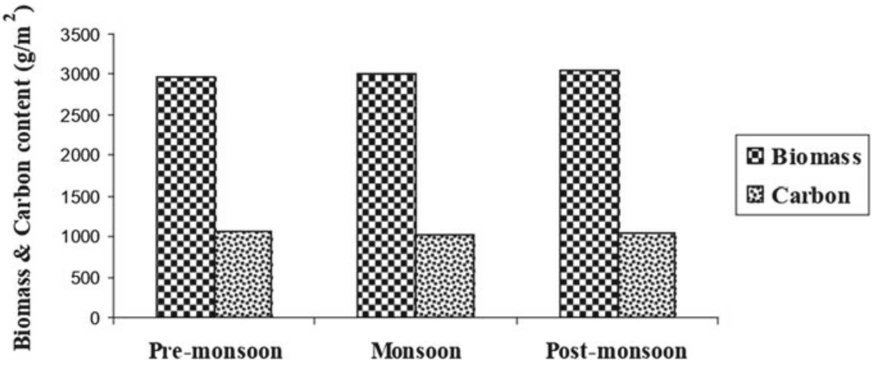


Fig. 7.12 Mean seasonal variations in biomass and carbon content of *Enteromorpha intestinalis* during 2019

Table 7.13 Results of ANOVA for seaweed standing stock (biomass) in Indian Sundarbans during premonsoon, monsoon and postmonsoon seasons considering the average values of four selected stations during 2019

Variable	$F_{calculated}$	$F_{critical}$
Enteromorpha intestinalis		
Between sectors	1.59	18.51
Between stations	7.77	4.76
Between seasons	2.03	4.14
Ulva lactuca		
Between sectors	1.12	18.51
Between stations	3.73	4.76
Between seasons	10.32	4.14
Catenella repens		
Between sectors	7.38	18.51
Between stations	6.89	4.76
Between seasons	14.70	4.14

In case of *Ulva lactuca*, the biomass ranged from 95.66 g m^{-2} (at Stn. 1, during monsoon 2019) to 793.22 g m^{-2} (at Stn. 2, during premonsoon 2019). The carbon content showed the lowest value at Stn. 1 during monsoon 2019 (25.11gm m^{-2}) and highest at Stn. 2 during premonsoon 2019 (251.02 g m^{-2}). The mean order of biomass is premonsoon (499.01 g m^{-2}) > monsoon (251.66 g m^{-2}) > postmonsoon (173.11 g m^{-2}) (Table 7.11), and the carbon content exhibited a similar trend as per the order premonsoon (157.08 g m^{-2}) > monsoon (73.31 g m^{-2}) > postmonsoon (49.33 g m^{-2}) (Table 7.12 and Fig. 7.13). The significant seasonal variations in the values of biomass and carbon in *U. lactuca* are the results of synergistic effect of temperature, solar radiation and salinity.

The biomass of *C. repens* collected from the selected stations ranged from 42.11 (at Stn. 1, during postmonsoon 2019) to 315.00 g m^{-2} (at Stn. 2, during premonsoon

Table 7.14 Results of ANOVA for carbon content in seaweeds in unit area in Indian Sundarbans during premonsoon, monsoon and postmonsoon seasons considering the average values of four selected stations during 2019

Variable	$F_{calculated}$	$F_{critical}$
Enteromorpha intestinalis		
Between sectors	25.15	18.51
Between stations	38.31	4.76
Between seasons	4.64	4.14
Ulva lactuca		
Between sectors	0.84	18.51
Between stations	3.54	4.76
Between seasons	10.34	4.14
Catenella repens		
Between sectors	5.38	18.51
Between stations	5.86	4.76
Between seasons	13.23	4.14

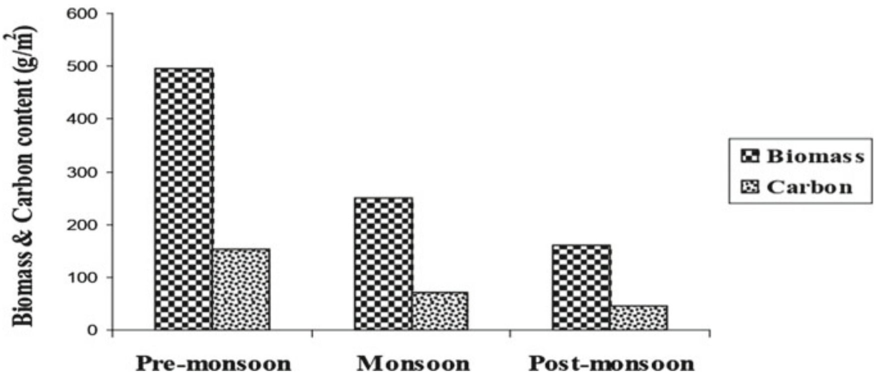


Fig. 7.13 Mean seasonal variations in biomass and carbon content of *Ulva lactuca* during 2019

2019). The mean order of biomass is premonsoon (232.05 g m^{-2}) > postmonsoon (133.83 g m^{-2}) > monsoon (69.05 g m^{-2}) for *C. repens* (Table 7.11). In the thallus body of the species, the values of stored carbon ranged from 9.01 (at Stn.1, during postmonsoon 2019) to 76.22 g m^{-2} (at Stn. 2, during premonsoon 2019). The carbon content in this species varied as per the order premonsoon (57.21 g m^{-2}) > post-monsoon (29.32 g m^{-2}) > monsoon (15.04 g m^{-2}) (Table 7.12). The mean seasonal values of both biomass and stored carbon in *C. repens* are highlighted in Fig. 7.14.

ANOVA results (Tables 7.13 and 7.14) also confirm significant spatial and seasonal variations in the biomass and carbon content of the species ($p < 0.01$).

The present study indicates that carbon storage in seaweed species is species-specific in nature. The highest value is observed in *E. intestinalis* (average 1042.77 g m^{-2}) followed by *U. lactuca* (average 89.79 g m^{-2}) and *C. repens* (average 32.64 g m^{-2}). Similar observation was also documented through a study done by

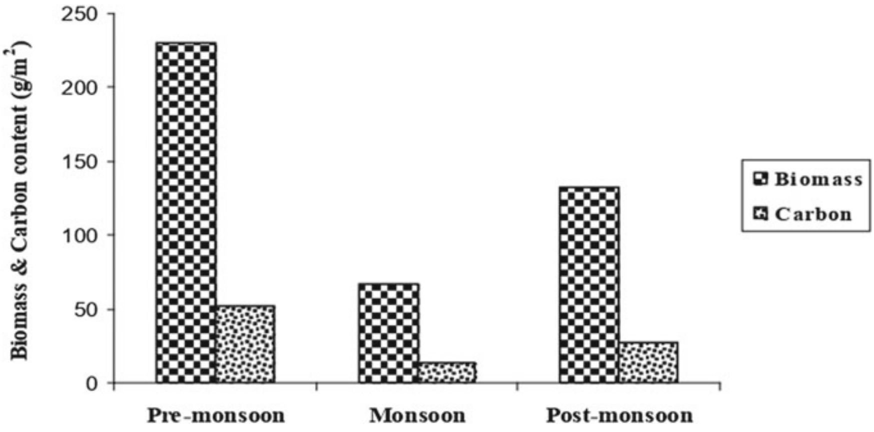


Fig. 7.14 Mean seasonal variations in biomass and carbon content of *Catenella repens* during 2019

Muraoka (2004) where the carbon absorption capacity by seaweeds varied as per the order *Laminaria* > *Ecklonia* > *Sargassum* > *Gelidium.* The species-wise variation of stored carbon may be attributed to the morphological structure of the seaweed. Unlike *U. lactuca* and *C. repens*, the extremely coiled and spiral structure of *E. intestinalis* exposes more area of the species to ambient water, which enables relatively more capture of carbon through diffusion. Due to presence of high surface area per unit volume of the *E. intestinalis* thallus, the absorption of carbon dioxide from the ambient water is more compared to *U. lactuca* and *C. repens.*

Our ground zero observations carried out during February, 2020 clearly exhibit significant coincidence of those sites having high biomass of seaweed *Enteromorpha intestinalis* with low Dissolved Inorganic Carbon (DIC) and high pH level of the estuarine water (Table 7.15). DIC encompasses three main constituents: free CO_2 (a gas), the bicarbonate ion (HCO_3^-), and the carbonate ion (CO_3^{2-}). Bicarbonate and carbonate constitute the major buffers in most natural waters and account for most of the acid neutralizing capacity. Free CO_2 is the most dynamic of the constituents of DIC and is the dominant acid in most natural waters. The ratio of CO_2 to HCO_3^- and CO_3^{2-} acts as the major driver of pH in most natural waters.

It is observed from the present field experiment that the TB of *E. intestinalis* ranged between 0.879 kg dry wt. m^{-2} (at Sagar Island) to 1.505 kg dry wt. m^{-2} (at Arbesi) (Fig. 7.15). DIC ranged from 1738 μmol/L (at Chulkathi) to 2132 μmol/L (at Sagar Island) (Fig. 7.16). The pH value, which is the primary proxy to estuarine acidification ranged from 7.98 (at Sagar Island) to 8.33 (at Arbesi) (Fig. 7.17).

The gas exchange in seaweed is strongly regulated by ribulose-1,5-biphosphate carboxylase/oxygenase (RuBisCO), which catalyzes the combination of carbon dioxide with the acceptor molecule ribulose-1,5-biphosphate. It is to be noted in this context that (aqueous dissolved carbon dioxide; CO_2 (aq)) represents only 0.5–1% of the total DIC pool, while HCO_3^- represents approximately 90% of the DIC

Table 7.15 Sampling stations in Indian Sundarbans with Total Biomass (TB) of *Enteromorpha intestinalis*, DIC and pH values of the ambient aquatic phase during February, 2020

Stn. No.	Sampling station	Coordinates	Total biomass (kg dry wt. m^{-2})	DIC (μmol/L)	pH value
1	Muriganga	21° 38′ 25.86″ N; 88° 08′ 53.55″ E	1.005	1921	8.05
2	Saptamukhi	21° 36′ 02.49″ N; 88° 23′ 47.18″ E	1.239	1863	8.10
3	Thakuran	21° 49′ 43.17″ N; 88° 33′ 21.57″ E	1.316	1802	8.22
4	Herobhanga	21° 59′ 34.32″ N; 88° 41′ 46.52″ E	1.432	1799	8.28
5	Ajmalmari	21° 51′ 34.72″ N; 88° 39′ 00.68″E	1.295	1815	8.20
6	Dhulibasani	21° 47′ 06.62″ N; 88° 33′ 48.20″E	1.416	1806	8.26
7	Chulkathi	21° 41′ 53.62″ N; 88° 34′ 10.31″ E	1.428	1738	8.27
8	Arbesi	22° 11′ 43.14″ N; 89° 01′ 09.04″ E	1.505	1775	8.33
9	Jhilla	22° 09′ 51.53″ N; 88° 57′ 57.07″ E	1.493	1769	8.31
10	Pirkhali	22° 06′ 00.97″ N; 88° 51′ 06.04″ E	1.489	1773	8.31
11	Panchmukhani	21° 59′ 41.58″ N; 88° 54′ 14.71″ E	1.491	1778	8.32
12	Harinbhanga	21° 57′ 17.85″ N; 88° 59′ 33.24″ E	1.475	1780	8.30
13	Khatuajhuri	22° 03′ 06.55″ N; 89° 01′ 05.33″ E	1.478	1800	8.30
14	Chamta	21° 53′ 18.56″ N; 88° 57′ 11.40″ E	1.445	1867	8.29
15	Matla	21° 53′ 15.30″ N; 88° 44′ 08.74″ E	1.358	1865	8.15
16	Chandkhali	21° 51′ 13.59″ N; 89° 00′ 44.68″ E	1.367	1869	8.19
17	Goashaba	21° 43′ 50.64″ N; 88° 46′ 41.44″ E	1.360	1795	8.18
18	Gona	21° 41′ 15.44″ N; 88° 54′ 31.09″ E	1.430	1799	8.28
19	Chhotahardi	21° 44′ 42.24″ N; 88° 44′ 17.79″ E	1.427	1791	8.27
20	Baghmara	21° 39′ 04.45″ N; 89° 04′ 40.59″ E	1.436	1782	8.29

(continued)

Table 7.15 (continued)

Stn. No.	Sampling station	Coordinates	Total biomass (kg dry wt. m^{-2})	DIC (µmol/L)	pH value
21	Mayadwip	21° 35′ 50.23″ N; 88° 47′ 09.95″ E	1.440	1776	8.30
22	Jambu Island	21° 35′ 42.03″ N; 88° 10′ 22.76″ E	0.987	2024	7.99
23	Lothian	21° 38′ 21.20″ N; 88° 20′ 29.32″ E	1.512	1790	8.32
24	Sagar Island	21° 38′ 51.55″ N; 88° 02′ 20.97″ E	0.879	2132	7.98

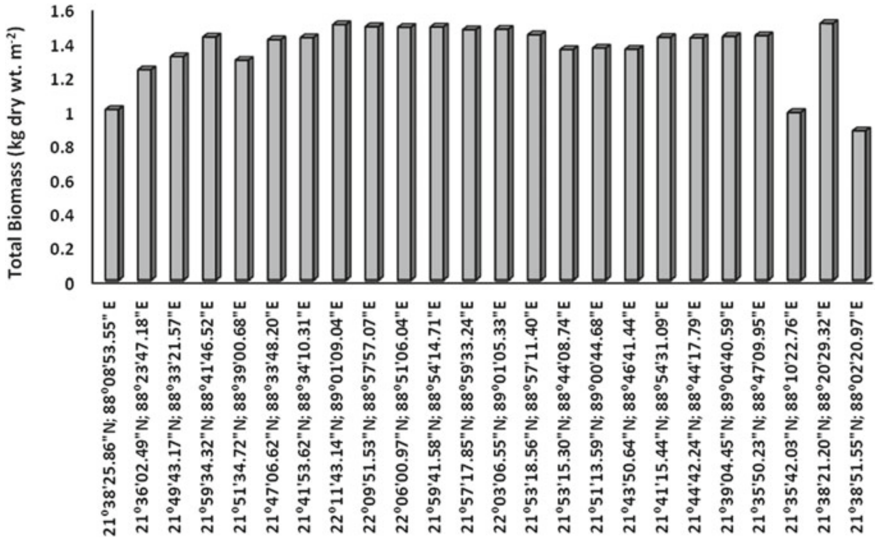


Fig. 7.15 Total Biomass (kg dry wt. m^{-2}) of *Enteromorpha intestinalis* during February 2020

pool of the aquatic phase. Thus, the need of inorganic carbon for seaweed photosynthesis is often met by HCO_3^-. This might be the reason for the coincidence of relatively high pH in the estuarine water of Indian Sundarbans with the sampling stations sustaining high biomass of the seaweed species *E. intestinalis*. The bottom line of the entire discussion is the unique potential of seaweeds to transform DIC into organic carbon through the process of photosynthesis, which can decrease the pCO_2 in the aquatic phase and retard the pace of acidification.

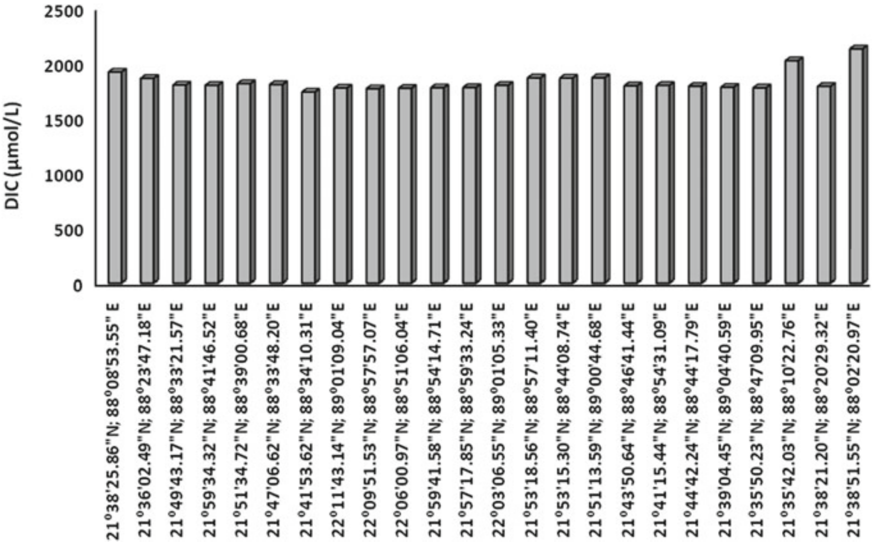


Fig. 7.16 DIC (µmol/L) of aquatic phase during February 2020

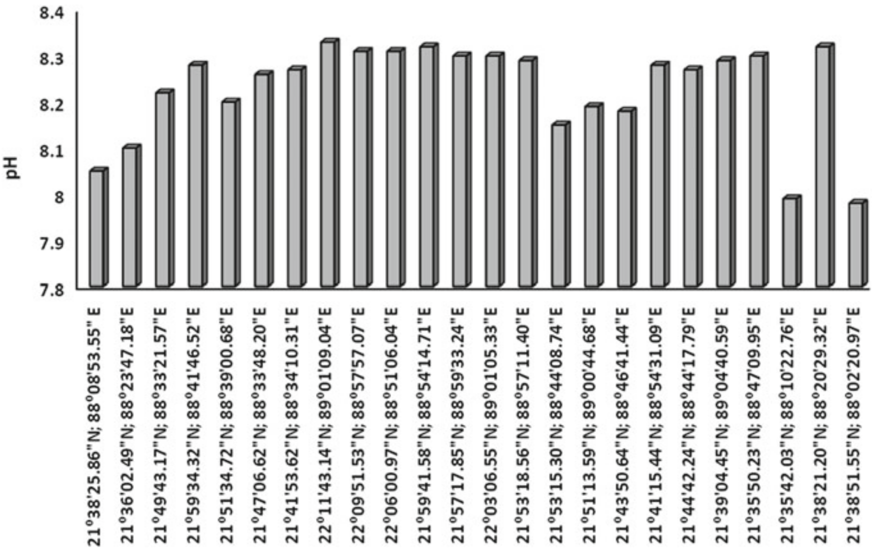


Fig. 7.17 pH value of ambient aquatic phase during February 2020

7.4 Take Home Messages

(a) Mangroves are among the most carbon-dense forests in the tropics and store exceptionally high carbon compared to different forest ecosystems in the world. The ability of mangroves to scrub carbon from the ambient media is the key to regulate the process of acidification. Basically mangroves absorb carbon dioxide from the atmosphere and the water column and store it as carbon in their vegetative and reproductive parts. The principal carbon-fixing enzyme in plants is ribulose 1,5-biphosphate carboxylase/oxygenase (RuBisco). The magnitude of the mangrove vegetation pool thus exerts a regulatory role on the pH of the estuarine water as these halophytes absorb carbon dioxide for photosynthesis and shift the equilibrium towards alkalinity.

(b) Sea grasses are marine plants that generally inhabit the protected shallow waters of temperature and tropical coastal areas and are included in the domain of blue carbon. These plants are not true grasses, and they represent several genera appear to be more closely related to members of the lily family. Very scanty references are available on the mechanisms of carbon fixation in sea grasses and questions concerning the kinetics of the active forms of carbon utilized and possible photosynthetic pathways. Researchers postulated that the exogenous form of carbon assimilated by sea grasses is HCO_3^-. This may be attributed to extremely low concentration of carbon dioxide in seawater compared with HCO_3^- (about 200 times less) and the slow rate at which carbon dioxide could be re-supplied to the plant from other forms of carbon. **Salt marsh** communities are found on the shoreward side of mud flats in temperate and subarctic regions of the world. The estuaries of Indian sub-continent sustains an important saltmarsh grass species namely *Porteresia coarctata*, which has a great role in stabilizing the islands. Their long network of roots binds the soil particles very intricately and retards the process of erosion. The growth, biomass and subsequent carbon storage capacity of the species is controlled by the ambient aquatic salinity. The species exhibits a luxuriant growth in relatively low saline regions (salinity range within 5–20 psu) with subsequently higher carbon content, but at salinity around 30 psu, the growth is stunted. The species is noted or retarding the pace of acidification in areas of low salinity in the estuarine stretch, where their growth is significantly high.

(c) Seaweeds are macroalgae and are noted for their capacity to utilize dissolved inorganic carbon (DIC) from the surrounding seawater for photosynthesis and growth, resulting in a decrease in the DIC concentration of seawater and a drop in the partial pressure of carbon dioxide (pCO_2) below atmospheric levels. Our ground zero observations show that sites with high biomass of seaweeds coincide with low DIC and high pH level of the estuarine water.

Annexure 7: Worldwide Common Mangrove and Associate Species

S. No.	Species	
1	*Acanthus ebracteatus*	
2	*Acanthus ilicifolius*	
3	*Acanthus volubilis*	
4	*Cerbera manghas*	
5	*Nypa fruticans*	

(continued)

(continued)

S. No.	Species	
6	*Phoenix paludosa*	
7	*Finlaysonia obovata*	
8	*Sarcolobus globosus*	
9	*Sarcolobus carinatus*	
10	*Tylophora tenuis*	

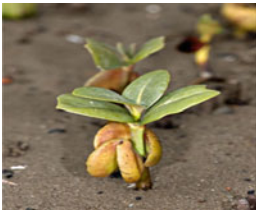
(continued)

(continued)

S. No.	Species	
11	*Avicennia alba*	
12	*Avicennia bicolour*	
13	*Avicennia germinans*	
14	*Avicennia integra*	
15	*Avicennia marina*	

(continued)

(continued)

S. No.	Species	
16	*Avicennia var. australasica*	
17	*Avicennia var. eucalyptifolia*	
18	*Avicennia officinalis*	
19	*Avicennia rumphiana*	
20	*Avicennia schaueriana*	

(continued)

(continued)

S. No.	Species	
21	*Dolichandrone spathacea*	
22	*Camptostemon philippinensis*	
23	*Camptostemon schultzii*	
24	*Caesalpinia bonduc*	
25	*Caesalpinia cristata*	

(continued)

(continued)

S. No.	Species	
26	*Cynometra iripa*	
27	*Cynometra ramiflora*	
28	*Intsia bijuga*	
29	*Conocarpus erectus*	
30	*Laguncularia racemosa*	

(continued)

(continued)

S. No.	Species	
31	*Lumnitzera littorea*	
32	*Lumnitzera racemosa*	
33	*Ipomoea tuba*	
34	*Fimbristylis ferruginea*	
35	*Scirpus littoralis*	

(continued)

(continued)

S. No.	Species	
36	*Excoecaria agallocha*	
37	*Excoecaria indica*	
38	*Excoecaria ovate*	
39	*Flagellaria indica*	
40	*Pemphis acidula*	

(continued)

(continued)

S. No.	Species	
41	*Hibiscus tiliaceous*	
42	*Thespesia populneoide*	
43	*Thespesia populnea*	
44	*Aglaia cucullata*	
45	*Xylocarpus granatum*	

(continued)

(continued)

S. No.	Species	
46	*Xylocarpus mekongensis*	
47	*Xylocarpus moluccensis*	
48	*Aegiceras corniculatum*	
49	*Aegiceras floridum*	
50	*Osbornia octodonta*	

(continued)

(continued)

S. No.	Species	
51	*Dalbergia spinosa*	
52	*Derris scandens*	
53	*Derris heterophylla*	
54	*Mucuna gigantea*	
55	*Pelliciera rhizophorae*	

(continued)

(continued)

S. No.	Species	
56	*Aegialitis rotundifolia*	
57	*Aegialitis annulata*	
58	*Myriostachya wightiana*	
59	*Porteresia coarctata*	
60	*Urochondra setulosa*	

(continued)

(continued)

S. No.	Species	
61	*Acrostichum aureum*	
62	*Acrostichum danaeifolium*	
63	*Acrostichum speciosum*	
64	*Bruguiera cylindrica*	
65	*Bruguiera exaristata*	

(continued)

(continued)

S. No.	Species	
66	*Bruguiera gymnorhiza*	
67	*Bruguiera hainesii*	
68	*Bruguiera parviflora*	
69	*Bruguiera sexangula*	
70	*Ceriops australis*	

(continued)

(continued)

S. No.	Species	
71	*Ceriops decandra*	
72	*Ceriops tagal*	
73	*Kandelia candel*	
74	*Rhizophora apiculata*	
75	*Rhizophora harrisonii*	

(continued)

(continued)

S. No.	Species	
76	*Rhizophora mangle*	
77	*Rhizophora mucronata*	
78	*Rhizophora racemosa*	
79	*Rhizophora samoensis*	
80	*Rhizophora stylosa*	

(continued)

(continued)

S. No.	Species	
81	*Scyphiphora hydrophyllacea*	
82	*Merope angulata*	
83	*Sonneratia alba*	
84	*Sonneratia apetala*	
85	*Sonneratia caseolaris*	

(continued)

(continued)

S. No.	Species	
86	*Sonneratia griffithii*	
87	*Sonneratia lanceolata*	
88	*Sonneratia ovate*	
89	*Sonneratia gulngai*	
90	*Sonneratia urama*	

(continued)

(continued)

S. No.	Species	
91	*Heritiera fomes*	
92	*Heritiera globosa*	
93	*Heritiera kanikensis*	
94	*Heritiera littoralis*	
95	*Brownlowia tersa*	

(continued)

(continued)

S. No.	Species	
96	*Clerodendrum inerme*	

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Chapter 8
Estuarine Acidification: Management and Mitigation

Abstract Acidification is one of the climate change related stressors expected to have multiple impacts on estuarine ecosystem. Considering the magnitude of the impact it is essential to identify its potential impacts to beneficial uses of the ecosystem, cost-effective monitoring strategies and management actions. However, it is important to note that all estuaries are not uniform in terms of morphology, hydrology, and biodiversity status. Hence a generalized management strategy may not yield a fruitful result to combat the process of acidification. Controlling the point sources of industrial discharge by setting Combined Effluent Treatment Plant (CETP) and expanding the dimension of blue carbon along the estuarine stretch might be some measures of first-order scale. Halophyte farming and iron fertilization in closed water bodies coupled with aquaculture are the other options to scrub carbon dioxide from the atmosphere.

8.1 Mitigation of Point Sources of Carbon Dioxide Through Clean Energy

Emission of carbon dioxide occurs from industries, urban and transport sectors and change of land use pattern for reasons like expansion of tourism, aquaculture, ports and harbours etc. All these activities cannot be completely stopped and uprooted as there is a growing demand to meet the needs of the rapidly rising population of the world. The scenario of the present day world has changed a lot since the last few centuries. The population has increased exponentially (Table 8.1) while the area (space) remained almost constant resulting in the rise of population density (Table 8.2). At present the population of the World is somewhat around 7.5 billion (https://www.census.gov/newsroom/stories/world-population-day.html) and predictions state that the figure will touch 9.0 billion by the year 2050.

The huge population pressure has posed challenges on leaving space, resources, environmental condition, job opportunity, mobility and the quality of the life. Desperate need for job opportunities/employment has opened the doors for intense industrialization, which has resulted in more emission of GHGs preferably carbon dioxide. As a result, the concentration of dissolved inorganic carbon (DIC) in the

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Table 8.1 Increase of population in 1 year

Country	2017	2018
Aruba	105,366	105,845
Afghanistan	36,296,400	37,172,386
Angola	29,816,748	30,809,762
Albania	2,873,457	2,866,376
Andorra	77,001	77,006
Arab World	411,898,965	419,790,588
United Arab Emirates	9,487,203	9,630,959
Argentina	44,044,811	44,494,502
Armenia	2,944,809	2,951,776
American Samoa	55,620	55,465
Antigua and Barbuda	95,426	96,286
Australia	24,601,860	24,992,369
Austria	8,797,566	8,847,037
Azerbaijan	9,854,033	9,942,334
Burundi	10,827,024	11,175,378
Belgium	11,375,158	11,422,068
Benin	11,175,204	11,485,048
Burkina Faso	19,193,284	19,751,535
Bangladesh	159,670,593	161,356,039
Bulgaria	7,075,947	7,024,216
Bahrain	1,494,074	1,569,439
Bahamas, The	381,761	385,640
Bosnia and Herzegovina	3,351,527	3,323,929
Belarus	9,498,264	9,485,386
Belize	375,769	383,071
Bermuda	63,874	63,968
Bolivia	11,192,854	11,353,142
Brazil	207,833,831	209,469,333
Barbados	286,233	286,641
Brunei Darussalam	424,473	428,962
Bhutan	745,568	754,394
Botswana	2,205,128	2,254,126
Central African Republic	4,596,028	4,666,377
Canada	36,540,268	37,058,856
Central Europe and the Baltics	102,738,854	102,511,922
Switzerland	8,451,840	8,516,543

(continued)

Table 8.1 (continued)

Country	2017	2018
Channel Islands	168,665	170,499
Chile	18,470,439	18,729,160
China	1,386,395,000	1,392,730,000
Cote d’Ivoire	24,437,469	25,069,229
Cameroon	24,566,045	25,216,237
Congo, Dem. Rep.	81,398,764	84,068,091
Congo, Rep.	5,110,702	5,244,363
Colombia	48,901,066	49,648,685
Comoros	813,892	832,322
Cabo Verde	537,497	543,767
Costa Rica	4,949,954	4,999,441
Caribbean small states	7,314,990	7,358,965
Cuba	11,339,259	11,338,138
Curacao	160,175	159,849
Cayman Islands	63,382	64,174
Cyprus	1,179,680	1,189,265
Czech Republic	10,594,438	10,625,695
Germany	82,657,002	82,927,922
Djibouti	944,097	958,920
Dominica	71,458	71,625
Denmark	5,764,980	5,797,446
Dominican Republic	10,513,131	10,627,165
Algeria	41,389,198	42,228,429
East Asia & Pacific (excluding high income)	2,068,155,660	2,081,651,801
Early-demographic dividend	3,207,188,541	3,249,140,605
East Asia & Pacific	2,314,202,003	2,328,220,870
Europe & Central Asia (excluding high income)	415,710,935	417,797,257
Europe & Central Asia	915,420,161	918,793,590
Ecuador	16,785,361	17,084,357
Egypt, Arab Rep.	96,442,593	98,423,595
Euro area	341,164,362	341,783,171
Eritrea		
Spain	46,593,236	46,723,749
Estonia	1,317,384	1,320,884
Ethiopia	106,400,024	109,224,559
European Union	512,191,098	513,213,363

(continued)

Table 8.1 (continued)

Country	2017	2018
Fragile and conflict affected situations	504,119,229	515,215,936
Finland	5,508,214	5,518,050
Fiji	877,459	883,483
France	66,865,144	66,987,244
Faroe Islands	48,331	48,497
Micronesia, Fed. Sts.	111,459	112,640
Gabon	2,064,823	2,119,275
United Kingdom	66,058,859	66,488,991
Georgia	3,728,004	3,731,000
Ghana	29,121,471	29,767,108
Gibraltar	33,728	33,718
Guinea	12,067,539	12,414,318
Gambia, The	2,213,894	2,280,102
Guinea-Bissau	1,828,146	1,874,309
Equatorial Guinea	1,262,001	1,308,974
Greece	10,754,679	10,727,668
Grenada	110,874	111,454
Greenland	56,171	56,025
Guatemala	16,914,936	17,247,807
Guam	164,281	165,768
Guyana	775,221	779,004
High income	1,204,429,565	1,210,312,147
Hong Kong SAR, China	7,391,700	7,451,000
Honduras	9,429,013	9,587,522
Heavily indebted poor countries (HIPC)	759,106,221	780,234,406
Croatia	4,124,531	4,089,400
Haiti	10,982,366	11,123,176
Hungary	9,787,966	9,768,785
IBRD only	4,731,120,193	4,772,284,113
IDA & IBRD total	6,335,039,629	6,412,522,234
IDA total	1,603,919,436	1,640,238,121
IDA blend	543,525,897	555,830,605
Indonesia	264,645,886	267,663,435
IDA only	1,060,393,539	1,084,407,516
Isle of Man	83,598	84,077
India	1,338,658,835	1,352,617,328

(continued)

Table 8.1 (continued)

Country	2017	2018
Not classified		
Ireland	4,807,388	4,853,506
Iran, Islamic Rep.	80,673,951	81,800,269
Iraq	37,552,781	38,433,600
Iceland	343,400	353,574
Israel	8,713,300	8,883,800
Italy	60,536,709	60,431,283
Jamaica	2,920,853	2,934,855
Jordan	9,779,173	9,956,011
Japan	126,785,797	126,529,100
Kazakhstan	18,037,776	18,276,499
Kenya	50,221,473	51,393,010
Kyrgyz Republic	6,198,200	6,315,800
Cambodia	16,009,414	16,249,798
Kiribati	114,158	115,847
St. Kitts and Nevis	52,045	52,441
Korea, Rep.	51,466,201	51,635,256
Kuwait	4,056,097	4,137,309
Latin America & Caribbean (excluding high income)	603,254,104	609,013,934
Lao PDR	6,953,035	7,061,507
Lebanon	6,811,873	6,848,925
Liberia	4,702,228	4,818,977
Libya	6,580,724	6,678,567
St. Lucia	180,955	181,889
Latin America & Caribbean	635,372,515	641,357,515
Least developed countries: UN classification	986,365,080	1,009,662,578
Low income	687,449,530	705,417,321
Liechtenstein	37,800	37,910
Sri Lanka	21,444,000	21,670,000
Lower middle income	2,981,420,591	3,022,905,169
Low & middle income	6,306,560,891	6,383,958,209
Lesotho	2,091,412	2,108,132
Late-demographic dividend	2,276,319,334	2,288,665,963
Lithuania	2,828,403	2,789,533
Luxembourg	596,336	607,728
Latvia	1,942,248	1,926,542

(continued)

Table 8.1 (continued)

Country	2017	2018
Macao SAR, China	622,585	631,636
St. Martin (French part)	36,560	37,264
Morocco	35,581,294	36,029,138
Monaco	38,392	38,682
Moldova	3,549,196	3,545,883
Madagascar	25,570,540	26,262,368
Maldives	496,402	515,696
Middle East & North Africa	441,255,234	448,912,859
Mexico	124,777,324	126,190,788
Marshall Islands	58,058	58,413
Middle income	5,619,111,361	5,678,540,888
North Macedonia	2,081,996	2,082,958
Mali	18,512,394	19,077,690
Malta	467,999	483,530
Myanmar	53,382,581	53,708,395
Middle East & North Africa (excluding high income)	376,546,755	382,896,715
Montenegro	622,373	622,345
Mongolia	3,113,779	3,170,208
Northern Mariana Islands	56,562	56,882
Mozambique	28,649,007	29,495,962
Mauritania	4,282,574	4,403,319
Mauritius	1,264,613	1,265,303
Malawi	17,670,260	18,143,315
Malaysia	31,105,028	31,528,585
North America	361,751,263	364,290,258
Namibia	2,402,603	2,448,255
New Caledonia	280,350	284,060
Niger	21,602,472	22,442,948
Nigeria	190,873,311	195,874,740
Nicaragua	6,384,855	6,465,513
Netherlands	17,131,296	17,231,017
Norway	5,276,968	5,314,336
Nepal	27,627,124	28,087,871
Nauru	12,876	12,704
New Zealand	4,793,900	4,885,500
OECD members	1,296,225,760	1,303,529,456

(continued)

Table 8.1 (continued)

Country	2017	2018
Oman	4,665,935	4,829,483
Other small states	30,148,800	30,758,989
Pakistan	207,896,686	212,215,030
Panama	4,106,771	4,176,873
Peru	31,444,297	31,989,256
Philippines	105,173,264	106,651,922
Palau	17,808	17,907
Papua New Guinea	8,438,029	8,606,316
Poland	37,974,826	37,978,548
Pre-demographic dividend	894,512,725	919,485,393
Puerto Rico	3,325,001	3,195,153
Korea, Dem. People's Rep.	25,429,985	25,549,819
Portugal	10,300,300	10,281,762
Paraguay	6,867,062	6,956,071
West Bank and Gaza	4,454,805	4,569,087
Pacific island small states	2,422,086	2,457,367
Post-demographic dividend	1,106,035,186	1,109,997,273
French Polynesia	276,103	277,679
Qatar	2,724,724	2,781,677
Romania	19,587,491	19,473,936
Russian Federation	144,496,740	144,478,050
Rwanda	11,980,937	12,301,939
South Asia	1,792,835,608	1,814,388,744
Saudi Arabia	33,099,147	33,699,947
Sudan	40,813,396	41,801,533
Senegal	15,419,381	15,854,360
Singapore	5,612,253	5,638,676
Solomon Islands	636,038	652,858
Sierra Leone	7,488,431	7,650,154
El Salvador	6,388,122	6,420,744
San Marino	33,671	33,785
Somalia	14,589,119	15,008,154
Serbia	7,020,858	6,982,084
Sub-Saharan Africa (excluding high income)	1,050,057,829	1,078,209,758
South Sudan	10,910,759	10,975,920
Sub-Saharan Africa	1,050,153,672	1,078,306,520

(continued)

Table 8.1 (continued)

Country	2017	2018
Small states	39,885,876	40,575,321
Sao Tome and Principe	207,089	211,028
Suriname	570,496	575,991
Slovak Republic	5,439,232	5,447,011
Slovenia	2,066,388	2,067,372
Sweden	10,057,698	10,183,175
Eswatini	1,124,753	1,136,191
Sint Maarten (Dutch part)	40,574	40,654
Seychelles	95,843	96,762
Syrian Arab Republic	17,068,002	16,906,283
Turks and Caicos Islands	37,115	37,665
Chad	15,016,773	15,477,751
East Asia & Pacific (IDA & IBRD countries)	2,042,687,863	2,056,064,424
Europe & Central Asia (IDA & IBRD countries)	457,810,292	459,865,205
Togo	7,698,475	7,889,094
Thailand	69,209,858	69,428,524
Tajikistan	8,880,268	9,100,837
Turkmenistan	5,757,669	5,850,908
Latin America & the Caribbean (IDA & IBRD countries)	619,460,244	625,569,713
Timor-Leste	1,243,261	1,267,972
Middle East & North Africa (IDA & IBRD countries)	372,091,950	378,327,628
Tonga	101,998	103,197
South Asia (IDA & IBRD)	1,792,835,608	1,814,388,744
Sub-Saharan Africa (IDA & IBRD countries)	1,050,153,672	1,078,306,520
Trinidad and Tobago	1,384,072	1,389,858
Tunisia	11,433,443	11,565,204
Turkey	81,101,892	82,319,724
Tuvalu	11,370	11,508
Tanzania	54,663,906	56,318,348
Uganda	41,162,465	42,723,139
Ukraine	44,831,135	44,622,516
Upper middle income	2,637,690,770	2,655,635,719
Uruguay	3,436,646	3,449,299
United States	325,147,121	327,167,434
Uzbekistan	32,388,600	32,955,400
St. Vincent and the Grenadines	109,827	110,210

(continued)

Table 8.1 (continued)

Country	2017	2018
Venezuela, RB	29,390,409	28,870,195
British Virgin Islands	29,577	29,802
Virgin Islands (U.S.)	107,268	106,977
Vietnam	94,596,642	95,540,395
Vanuatu	285,510	292,680
World	7,510,990,456	7,594,270,356
Samoa	195,352	196,130
Kosovo	1,830,700	1,845,300
Yemen, Rep.	27,834,821	28,498,687
South Africa	57,000,451	57,779,622
Zambia	16,853,688	17,351,822
Zimbabwe	14,236,745	14,439,018

near surface ocean increases, which drives a decrease in pH in order to maintain a chemical equilibrium. The various sources of GHG's that triggers the process of Estuarine Acidification (EA) are discussed here in points with particular reference to estuaries of lower Gangetic delta.

1. **Emission of Fluorine Compounds**

   (i) Various fluorine compounds (HF, F_2, SiF_4, H_2SiF_6 etc.) are emitted from phosphate fertilizer manufacturing plants (since large amounts of fluorine are present in phosphate rock).

   (ii) During aluminium extraction (where cryolite i.e., Na_3AlF_6 is used to lower the melting point of the mixture of CaF_2, Al_2O_3 and Na_3AlF_6) compounds of fluorine are released in to the atmosphere.

2. **Emission of Oxides of Carbon**

   (i) Cement manufacturing unit is one of the largest sources of industrial carbon dioxide emissions. The gas is produced when calcium carbonate ($CaCO_3$) is heated to produce the calcium oxide (CaO, also called *quick-lime*), which is the main ingredient for cement ($CaSiO_3$) production. The reaction steps in this manufacture are:

$$CaCO_3 \xrightarrow{\Delta} CaO + CO_2$$

$$CaO + SiO_2 \xrightarrow{\Delta} CaSiO_3$$

   CO_2 produced in the first step has considerable contribution to global warming. While fossil fuel combustion and deforestation each produce

Table 8.2 Country-wise area in sq. mi with population density (PD)

Country	Area (sq. mi)	PD (per sq. mi)
Afghanistan	647,500	48.0
Albania	28,748	124.6
Algeria	2,381,740	13.8
American Samoa	199	290.4
Andorra	468	152.1
Angola	1,246,700	9.7
Anguilla	102	132.1
Antigua & Barbuda	443	156.0
Argentina	2,766,890	14.4
Armenia	29,800	99.9
Aruba	193	372.5
Australia	7,686,850	2.6
Austria	83,870	97.7
Azerbaijan	86,600	91.9
The Bahamas	13,940	21.8
Bahrain	665	1050.5
Bangladesh	144,000	1023.4
Barbados	431	649.5
Belarus	207,600	49.6
Belgium	30,528	340.0
Belize	22,966	12.5
Benin	112,620	69.8
Bermuda	53	1241.0
Bhutan	47,000	48.5
Bolivia	1,098,580	8.2
Bosnia & Herzegovina	51,129	88.0
Botswana	600,370	2.7
Brazil	8,511,965	22.1
British Virgin is	153	151.0
Brunei	5770	65.8
Bulgaria	110,910	66.6
Burkina Faso	274,200	50.7
Burma	678,500	69.8
Burundi	27,830	290.7
Cambodia	181,040	76.7
Cameroon	475,440	36.5
Canada	9,984,670	3.3

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
Cape Verde	4033	104.4
Cayman Islands	262	173.4
Central African Rep.	622,984	6.9
Chad	1,284,000	7.7
Chile	756,950	21.3
China	9,596,960	136.9
Colombia	1,138,910	38.3
Comoros	2170	318.4
Congo, Dem. Rep.	2,345,410	26.7
Congo, Repub. of the	342,000	10.8
Cook Islands	240	89.1
Costa Rica	51,100	79.8
Cote d'Ivoire	322,460	54.8
Croatia	56,542	79.5
Cuba	110,860	102.7
Cyprus	9250	84.8
Czech Republic	78,866	129.8
Denmark	43,094	126.5
Djibouti	23,000	21.2
Dominica	754	91.4
Dominican Republic	48,730	188.5
East Timor	15,007	70.8
Ecuador	283,560	47.8
Egypt	1,001,450	78.8
El Salvador	21,040	324.3
Equatorial Guinea	28,051	19.3
Eritrea	121,320	39.5
Estonia	45,226	29.3
Ethiopia	1,127,127	66.3
Faroe Islands	1399	33.8
Fiji	18,270	49.6
Finland	338,145	15.5
France	547,030	111.3
French Guiana	91,000	2.2
French Polynesia	4167	65.9
Gabon	267,667	5.3
The Gambia	11,300	145.3

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
Gaza Strip	360	3968.8
Georgia	69,700	66.9
Germany	357,021	230.9
Ghana	239,460	93.6
Gibraltar	7	3989.7
Greece	131,940	81.0
Greenland	2,166,086	0.0
Grenada	344	260.8
Guadeloupe	1780	254.4
Guam	541	316.1
Guatemala	108,890	112.9
Guernsey	78	838.6
Guinea	245,857	39.4
Guinea-Bissau	36,120	39.9
Guyana	214,970	3.6
Haiti	27,750	299.4
Honduras	112,090	65.4
Hong Kong	1092	6355.7
Hungary	93,030	107.3
Iceland	103,000	2.9
India	3,287,590	333.2
Indonesia	1,919,440	127.9
Iran	1,648,000	41.7
Iraq	437,072	61.3
Ireland	70,280	57.8
Isle of Man	572	131.9
Israel	20,770	305.8
Italy	301,230	193.0
Jamaica	10,991	250.9
Japan	377,835	337.4
Jersey	116	785.2
Jordan	92,300	64.0
Kazakhstan	2,717,300	5.6
Kenya	582,650	59.6
Kiribati	811	130.0
Korea, North	120,540	191.8
Korea, South	98,480	496.0

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
Kuwait	17,820	135.7
Kyrgyzstan	198,500	26.3
Laos	236,800	26.9
Latvia	64,589	35.2
Lebanon	10,400	372.5
Lesotho	30,355	66.6
Liberia	111,370	27.3
Libya	1,759,540	3.4
Liechtenstein	160	212.4
Lithuania	65,200	55.0
Luxembourg	2586	183.5
Macau	28	16,183.0
Macedonia	25,333	80.9
Madagascar	587,040	31.7
Malawi	118,480	109.8
Malaysia	329,750	74.0
Maldives	300	1196.7
Mali	1,240,000	9.5
Malta	316	1266.5
Marshall Islands	11,854	5.1
Martinique	1100	396.5
Mauritania	1,030,700	3.1
Mauritius	2040	608.3
Mayotte	374	538.1
Mexico	1,972,550	54.5
Micronesia, Fed. St.	702	153.9
Moldova	33,843	132.0
Monaco	2	16,271.5
Mongolia	1,564,116	1.8
Montserrat	102	92.5
Morocco	446,550	74.4
Mozambique	801,590	24.6
Namibia	825,418	2.5
Nauru	21	632.7
Nepal	147,181	192.2
Netherlands	41,526	397.1
Netherlands Antilles	960	231.0

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
New Caledonia	19,060	11.5
New Zealand	268,680	15.2
Nicaragua	129,494	43.0
Niger	1,267,000	9.9
Nigeria	923,768	142.7
N. Mariana Islands	477	172.9
Norway	323,802	14.2
Oman	212,460	14.6
Pakistan	803,940	206.2
Palau	458	44.9
Panama	78,200	40.8
Papua New Guinea	462,840	12.3
Paraguay	406,750	16.0
Peru	1,285,220	22.0
Philippines	300,000	298.2
Poland	312,685	123.3
Portugal	92,391	114.8
Puerto Rico	13,790	284.8
Qatar	11,437	77.4
Reunion	2517	312.9
Romania	237,500	93.9
Russia	17,075,200	8.4
Rwanda	26,338	328.4
Saint Helena	413	18.2
Saint Kitts & Nevis	261	149.9
Saint Lucia	616	273.5
St Pierre & Miquelon	242	29.0
Saint Vincent and the Grenadines	389	303.0
Samoa	2944	60.1
San Marino	61	479.5
Sao Tome & Principe	1001	193.2
Saudi Arabia	1,960,582	13.8
Senegal	196,190	61.1
Serbia	88,361	106.3
Seychelles	455	179.2
Sierra Leone	71,740	83.7

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
Singapore	693	6482.2
Slovakia	48,845	111.4
Slovenia	20,273	99.2
Solomon Islands	28,450	19.4
Somalia	637,657	13.9
South Africa	1,219,912	36.2
Spain	504,782	80.0
Sri Lanka	65,610	308.2
Sudan	2,505,810	16.5
Suriname	163,270	2.7
Swaziland	17,363	65.5
Sweden	449,964	20.0
Switzerland	41,290	182.2
Syria	185,180	102.0
Taiwan	35,980	640.3
Tajikistan	143,100	51.2
Tanzania	945,087	39.6
Thailand	514,000	125.7
Togo	56,785	97.7
Tonga	748	153.3
Trinidad & Tobago	5128	207.9
Tunisia	163,610	62.2
Turkey	780,580	90.2
Turkmenistan	488,100	10.3
Turks & Caicos Is	430	49.2
Tuvalu	26	454.2
Uganda	236,040	119.5
Ukraine	603,700	77.4
United Arab Emirates	82,880	31.4
United Kingdom	244,820	247.6
United States	9,631,420	31.0
Uruguay	176,220	19.5
Uzbekistan	447,400	61.0
Vanuatu	12,200	17.1
Venezuela	912,050	28.2
Vietnam	329,560	256.1
Virgin Islands	1910	56.9

(continued)

Table 8.2 (continued)

Country	Area (sq. mi)	PD (per sq. mi)
Wallis and Futuna	274	58.5
West Bank	5860	419.9
Western Sahara	266,000	1.0
Yemen	527,970	40.6
Zambia	752,614	15.3
Zimbabwe	390,580	31.3

significantly more carbon dioxide in the Earth's atmosphere, cement production alone is responsible for approximately 2.5% of total worldwide emissions from industrial sources.

(iii) Automobiles like trucks, cars, scooters, motor cycles etc. produce nearly two-thirds of the carbon monoxide and one half of the hydrocarbons and nitrous oxides.

(iv) Fossil fuels are the sources of energy for cooking, heating, lightening our houses, washing clothes through washing machine, or for running TV etc. Considerable amount of CO_2 are released during coal burning. In majority of the Indian cities, towns and villages cooking is done by burning coals, which is an important cause behind the increment of carbon dioxide concentration in the atmosphere.

(v) Aircrafts are responsible for about 2.5% of the CO emissions and about 1% of the hydrocarbon emissions, along with negligible amounts of the other major air pollutants. The smoke emitted from jet aircraft is composed largely of fine particles approximately 0.5 μm in diameter, which are completely burnt. As these particles scatter light quiet well, they often reduce visibility.

(vi) Burning of forest areas, grasslands etc. for pastures and croplands produces about 60 to 65% of CO_2 in the atmosphere.

(vii) In places like Sundarbans where there are not much industrial activities, the situation has been aggravated from the emissions of fishing vessels, trawlers, passenger vessels, brick kilns, removal of antifouling paints from boats and trawlers for conditioning purpose by burning the old paints etc. (Fig. 8.1, 8.2, 8.3, 8.4 and 8.5).

3. **Emission of Oxides of Sulphur**

(i) Electrical power plants, burning fossil fuels, particularly coal and sometimes petrol or diesel, produce two-thirds of the SO_2.

(ii) SO_2 is also released from various industrial processes. These encompass activities like extracting metal from ore and the burning of fuels with high sulphur content by locomotives, large ships and non-road equipment.

Fig. 8.1 Antifouling paints (usually coal tar) are applied for conditioning fishing vessels and trawlers. Burning this coal tar releases considerable amount of carbon dioxide in the atmosphere of Sundarbans

Fig. 8.2 Tourist vessels stranded along the bank are the point sources of carbon dioxide

4. **Emission of Methane**

   (i) Methane is emitted during the production and transport of coal, natural gas, and oil.

Fig. 8.3 Passenger boats with crowds is a common scene in all the inhabitable islands of Sundarbans, which are the sources of CO_2 emission

Fig. 8.4 Black smoke with carbon dioxide is emitted from tourist vessels

Fig. 8.5 Brick kilns are the point sources of carbon dioxide

(ii) About 40% of methane is produced from paddy fields, guts of livestock and also from burning of biomass.

The mangrove vegetation of Sundarbans is a unique sink of carbon dioxide, but massive destruction of the mangrove reservoir has squeezed the potential of scrubbing atmospheric carbon dioxide, eventually resulting in the rise of carbon dioxide. The main reasons behind these deforestation activities are the setting of shrimp farms, fish landing units, tourism units etc., in which the EIAs are conducted as per the norms and acts, but EMP is hardly carried out. In many EIA reports uses of technologies to minimize and recycling of wastes are stated along with specific floral species plantation, but in practice they are not followed to that extent.

We carried out extensive studies for three decades on the near-surface carbon dioxide level in the atmosphere of Indian Sundarbans (1984–2016) and observed that our results have touched/exceeded 400 ppm (Fig. 8.6) although there are no industries or power plants in this deltaic complex. However, the Haldia—port-cum industrial complex just adjacent to Indian Sundarbans is an industrial hub (Table 8.3), from where the emissions diffuse in the atmosphere of Sundarbans.

To combat the rise of carbon dioxide it is extremely important to shift from traditional non-renewable energy (primarily coal-based) sources to renewable clean energy phase. The resources which are being continuously consumed by man but are renewed by nature constantly are called as renewable resources. These resources

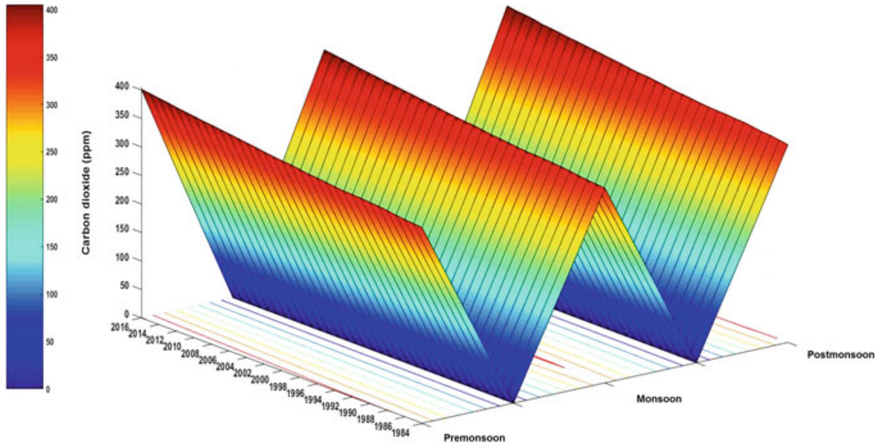

Fig. 8.6 Near-surface carbon dioxide level in the atmosphere of Indian Sundarbans (1984–2016)

are inexhaustible because they are not exhausted permanently. Renewable resources are also called as 'Non-Conventional' sources of energy. Examples of renewable resources include solar energy, wind energy, tidal energy, hydro power, geothermal energy and biofuels. These sources are highly eco-friendly and do not emit GHGs. In the southern states of Indian sub-continent, wind based energy is widely used to run the wheels of civilization (Fig. 8.7). The emission from renewable sources is practically zero/negligible.

The non-renewable resources do not replenish and cannot be renewed. It takes thousands of years of time to form the non-renewable resources which exist inside the Earth in the form of coal, fossil fuels, etc. Examples of non-renewable resources are coal, mineral ores, metal ores, crude oil, nuclear energy etc. These resources, on burning, emit GHGs, which are the main drivers of acidification of oceans, seas, bays and estuaries. A comparative account of renewable and non-renewable resources is presented in Table 8.4.

For islands and mangrove forest dominated ecosystems like Sundarbans, tidal energy is one of the best options for generation of electric current. The mechanism of working in tide-based energy conversion is not very complicated. During ingression of the water, the tidal energy works via a turbine in which the blade rotates 12–20 times per minute. The rotation of the blade is, however, a function of the tidal strength. The turbine, which is connected to a gear box, turns the generator that finally produces electric current. In this context, we would like to state that the high upfront cost is one of the greatest hindrances to implement tidal-based electric generation. Because of the high density of the water, the turbine need to bear high strength compared to wind turbines. For Sundarban deltaic ecosystem, siltation is a major problem to run the turbine as suspended particulate matter may clog the system.

The maritime state of West Bengal has a gross wind power potential of 450 MW, but the installed capacity, as of March 2013 is 2.5 MW. The Government of West

Table 8.3 Industries in Haldia port-cum-industrial complex adjacent to Indian Sundarbans

Sl. No.	Name of industry	Product
1	Indian oil corporation Ltd., Haldia	L.P.G., motor gasoline, naptha, ATF, MTO, HSD, JBO, kerosene, furnace oil, lubes, bitumen
2	KoPT/Haldia dock complex	Port services
3	Tata chemicals Ltd., Haldia	Industrial phosphate & acids
4	Exide industries Ltd., Haldia	Automotive batteries, heavy duty batteries, containers, special types of separators, etc.
5	Swal corporation Ltd., Haldia	Dimethanate fenithrothion, ethion, malathion
6	MCC PTA India corpn. pvt. Ltd., Haldia	P.T.A
7	Haldia petrochemicals Ltd., Haldia	LLDPE, HDPE, naptha cracker etc.
8	IOCL, Paradip-Haldia oil pipeline	Petroleum storage & transportation
9	IOC Petronas Ltd., Haldia	L.P.G
10	Shamon ispat Ltd.	Steel rolling
11	Dhunseri petrochem & tea Ltd.	PET resin
12	Greenways shipping agencies Pvt. Ltd.	Containers freight station (CFS)
13	IOC Ltd., Haldia	Petroleum storage
14	Hindustan petroleum corporation Ltd.	Petroleum and allied products
15	Bharat petroleum corporation Ltd., Haldia	Petroleum and allied products
16	Hindustan unilever limited	Detergents
17	Marcus oils & chemical Pvt. Ltd.	Polyethylene waxes
18	IOC Ltd., Haldia	Petroleum storage
19	Ruchi soya industries Ltd.	Edible oil
20	Manaksia Ltd.	Aluminum and Steel
21	Sanjana cryogenic storages Ltd.	Ammonia storage and handling terminal
22	R. D. B. Rasayans Ltd.	PP jumbo bag and small bag
23	Reliance industries Limited	Storage & handling petroleum product
24	Adani wilmar Ltd.	Edible oil refinery
25	Electrosteel castings Ltd.	Coke oven plant, sponge iron plant, power plant
26	URAL India Ltd.	Automobile
27	K.S. oils Ltd.	Edible oil refinery
28	DPM Net Pvt. Ltd.	Fishing net
29	Hooghly met coke & power co. Ltd.	Coke oven plant
30	Ruchi infrastructure Pvt. Ltd.	3RD Party liquid storage tank terminal
31	Shree Renuka sugars Ltd.	Sugar refinery and food complex
32	Gokul refoils & solvent Ltd.	Edible oil refinery

(continued)

Table 8.3 (continued)

Sl. No.	Name of industry	Product
33	Emami biotech Ltd.	Bio-diesel plant
34	Ennore coke private Ltd.	Coke oven plant
35	West Bengal waste management Ltd.	Industrial waste/municipal waste management complex
36	Lalbaba seamless tubes Pvt. Ltd.	Seamless tube
37	Modern India con-cast Ltd.	Ferro alloy plant
38	Rohit ferro tech Ltd.	Ferro alloy

Bengal is planning to set up a wind power station at Dadan Patra Bar near Mandarmoni in East Midnapore district of the state. The West Bengal Government has decided to set up 100 MW project with an estimated investment of INR 500 crore. The project will be developed in phases. The state government has already earmarked 1000 acre of land for the power station and in the first phase of the project a total of 700 acre land will be used. The Dadan Patra Bar area has a wind speed of 19 km per hour and the plant is expected to generate 50 MW power in its phase I (https://www.projectstoday.com/news/west-bengal-to-set-up-wind-power-station).

To mitigate the emission of carbon dioxide, West Bengal Renewable Energy Development Agency (WBREDA) has installed four aero generators each of capacity 5 kW at two existing Solar PV Power Plants at Gayen Bazar 25 kW Solar PV Power Plant and at Moushuni 55 kW Solar PV Power Plant of Sundarbans. WBREDA is facing problem in maintaining the Aero Generators. Three Aero Generators have been badly damaged due to Aila, a super cyclone that hit the lower Gangetic delta on 25th May, 2009. WBREDA already informed the matter to Ministry of New and Renewable Energy (MNRE), Government of India for providing fund in restoring the systems. Performances of Aero Generators are found well particularly for the period from March to September. It is to be noted in this context that Sundarban is a cyclone prone zone and this can pose considerable damage to installed structures for generating non-conventional energy.

To conclude, it can be stated that reduction of CO_2 emission through non-conventional energy can see the light of success if few actions as highlighted here are adopted on fast track basis.

1. **Universal access to energy**

While most part of the Indian sub-continent is on track to reach near universal access to energy, there are several islands in Indian Sundarban region with extremely low access rates. These islands require particular attention and institutional support from the side of their respective Governments, as well as from international development partners. Issues of quality and reliability of energy access, as well as availability of reliable data for monitoring of this indicator need to be controlled by the policy makers.

Fig. 8.7 Wide use of wind energy in the southern parts of Indian sub-continent. *Source* Mitra and Zaman (2020)

2. **Clean energy**

National targets for clean energy and technologies need to be established on priority basis and clean energy should be integrated into energy policy frameworks of the country.

3. **Increasing the share of renewables in the energy mix**

Considering the quasi stagnation of the share of renewable energy in the energy matrix of the region, efforts at promoting renewable sources of energy should be the

Table 8.4 Comparative account of renewable and non-renewable resources

Point of comparison	Renewable resource	Non-renewable resource
Presence	The renewable resources are mostly present in the atmosphere of the Earth	The non-renewable resources are typically found in the underground layers of the Earth
Replaceable	The renewable resources are replaced by nature itself in a very short period	The non-renewable resources cannot be replaced by nature during the time of human life span
Availability	The renewable energy resources are plentiful and abundant in nature	The non-renewable resources are scarce resources and not available in an abundant manner in nature
Cost	The renewable resources are obtained free of cost or at very less cost in nature	The non-renewable resources are very costly and not easily available
Impact on environment	The renewable resources do not affect the environment of the Earth and do not cause any climate changes in the atmosphere	The non-renewable resources seriously affect the environment and cause climate changes in the environment like burning of fossil fuels cause Green House Gas emission
Pollution	The renewable resources do not cause pollution in the environment and do not release any pollutants into the environment	The non-renewable resources pollute the Earth by releasing various types of pollutants into the air, water, soil, etc. when fossil fuels are burned
Impact on atmosphere	The renewable resources are called as 'Clean and Green' energy sources because they do not produce any adverse impact to the environment	The non-renewable resources release Green House Gases into the atmosphere which leads to global warming
Impact on health	The renewable resources do not cause any health problems to the living beings of the Earth	The non-renewable resources adversely affect the health of the living beings by releasing smoke, radiations, carcinogenic or cancer causing elements into the environment
Impact on nature	The use of renewable resources promotes the balance in the nature and natural habitat of the Earth	The use of non-renewable resources disrupts the balance in nature which is due to digging the earth to take out coal, minerals, fuels, etc.

After Mitra and Zaman (2020)

need of the hour. This is primarily because of the rapid rate of industrialization and urbanization, which are presently fully fuel dependent in India. Moreover the effort can be a practical step to curb emission of GHGs.

4. **Energy efficiency**

Energy efficiency measures should be considered with high priority in the transport, industry, tourism, aquaculture and building sectors.

5. **Intergovernmental and Trans-boundary cooperation**

Member states with the support of Economic and Social Commission for Asia and the Pacific (ESCAP) and other relevant regional institutions need to develop an intergovernmental mechanism that would promote trans-boundary electricity power trade and connectivity as one of the building blocks to attain sustainable development. This is especially applicable for single large mangrove chunk like Sundarbans, in which 62% lies in Bangladesh and the remaining 38% in India.

6. **Removing policy barriers and promoting funds to innovative technology based research**

To facilitate renewable energy and energy efficiency expansion, member States need to address existing policy barriers such as restrictive permit procedures, monopolistic utility positions and restrictions in energy prices. After successful implementation of these measures, the introduction of financial incentives for clean energy projects will bring positive results. While a number of member States have made strong efforts to incentivize clean energy and have committed to phasing out fossil fuel subsidies, more improvements need to be made to reach the respective targets. Despite significant technological innovation in many industries, international energy cooperation efforts to deploy innovative technologies are limited due to lack of a coherent approach among the member states. Cutting edge innovation in the sphere of solar energy, wind energy, biomass energy, geo-thermal energy, tidal energy should be encouraged through adequate funding after a comprehensive SWOT analysis.

8.2 Expansion of Blue Carbon

Blue carbon refers to the coastal vegetation which includes mangroves, sea grass, salt marsh grass etc. In our previous publication we have also included phytoplankton and seaweeds under the domain of blue carbon (Mitra and Zaman 2016). Blue carbon has specific status in combating the process of acidification as they scrub dissolved form of carbon from the ambient aquatic phase. It is no exaggeration to state that increased level of carbon dioxide has shifted the pH of ocean, seas, bays and estuaries from the normal value ranging between 8.1–8.3 and 8.0–7.8. This shifting has posed several adverse impacts on marine and estuarine systems especially on the molluscan community with calcareous structures. It is therefore the need of the hour to expand the dimension of blue carbon and other mangrove associate species. Presently more than 90 varieties of mangrove and associate species are thriving luxuriantly in different coastal zones of the planet Earth. However, all the species do not prefer similar type of salinity. Many species like *Heritiera fomes, Sonneretia apetala, Nypa fruticans* etc. thrive in low saline zone of the estuary/coastal zone water, while some other species like *Phoenix paludosa, Rhizophora* spp. Prefer high saline water. Some species like *Exoecaria agallocha* survive and grow luxuriantly in all categories of salinity. A case study conducted by us during 2014–2016 in Indian Sundarbans exhibited the growth (in terms of biomass and carbon sequestration potential) of dominant species of mangroves in different gradients of salinity leading us to conclude that survival and growth of mangroves is significantly salinity -specific (*Vide* Annexure 8 for details).

Basically the producers of the ecosystem drive the global carbon cycle by sequestering (storing) carbon dioxide through photosynthesis and releasing it through respiration. When the uptake of carbon dioxide (photosynthesis) exceeds losses via respiration, harvest and management, then forests store carbon (C sinks). In an undisturbed forest ~74% of the carbon dioxide is stored in live stems and branches, 16% is stored in roots and 10% in soils. The global sink in forest vegetation and soils is estimated to be 1200 Gt of carbon (1 Gt = 10^9 tonnes). This increases at a rate of 1–3 Gt annually. Several researchers have estimated the carbon stored in forest vegetation in the pre-industrial and present times (Tables 8.5 and 8.6).

The tropical forest zone encompasses 1.76 billion ha or 17,600,000 Km^2, and is divided into six ecofloristic zones: the tropical rain forests, the moist deciduous forests, the dry zone, the very dry zone, the desert zone and the hill and mountain forests. Tropical rain forests are found in areas with more than 2500 mm of annual

Table 8.5 Previous global carbon storage estimates for vegetation

Storage (Gt C)	Reservoir type	Author(s)
827 Gt (1)	Present actual land vegetation	Whittaker and Likens (1975)(s)
560 Gt (2)	Present actual land vegetation	Olson et al. (1983)
550 Gt (3)	Present actual (1980s) land vegetation	IPCC (1990)(s)
610 Gt (3)	Pre-industrial (pre-1700) vegetation	IPCC (1990)(s)
1080 Gt (4)	Land vegetation, ‘prehistoric’ times	Bazilevich et al. (1971)
924 Gt	Present potential (‘prehistoric’) vegetation	Adams et al. (1990)
343 Gt (5)	Last glacial maximum vegetation	Adams et al. (1990)
350 Gt	Coarse woody debris (present potential)	Harmon et al. (pers. Comm., 1990)
591 Gt (8)	Present-actual land vegetation	Ajtay et al. (1979)(s)

Table 8.6 Carbon storage totals for global soils

Storage (Gt C)	Reservoir type	Author(s)
1115 Gt	Soils, present potential ('prehistoric')	Adams et al. (1990)
1395 Gt (1)	Peats + soils, present potential	Adams et al. (1990)
1405 Gt (3)	Soils, present-day	Bazilevich (1974)(s)
3000 Gt (4)	Soils (+ peats ?), present-day	Bohn (1978)(s)
1672 Gt (3)	Soils, present-day	Bolin et al. (1979)(s)
1477 Gt (5)	Soils, present-day	Buringh (1983)(s)
1515 Gt (6)	Soils (+peat lands?) present-day	Schlesinger (1984)
787 Gt	Forestsoils only (+fine debris)	Dixon and Krankina (1993)
1500 Gt (7)	Soils, in 1989	IPCC (1990)(s)
1560 Gt (7)	Soils, in 'pre-industrial' era	IPCC (1990)(s)
860 Gt (8)	Peats, present-day	Bohn (1976)(s)
300 Gt (8)	Peats	Sjors (1980)(s)
202 Gt (8)	Peats	Post et al. (1982)
377 Gt (8)	Peats	Bohn (1976, 82)
180–227 Gt (8)	Peats	Gorham (1990)(s)
461 Gt (9)	Subarctic and boreal peat	Gorham and Janssens (1992)
1576 Gt (10)	Global soils (present-day)	Eswaran et al. (1993)
500 Gt (11)	Global peats	Markov et al. (1988)(s)

rainfall. They are evergreen, luxuriant and rich in animal and plant species. More than half the world's 718.3 million ha of rain forests are located in two countries: Brazil (41%) and Indonesia (13%). Rain forest composition and structure vary with distance from the ocean, distance from rivers, altitude and geographic position. Moist deciduous forests occur in areas with an annual rainfall of 1000 to 2000 mm. Forest structure varies depending on the amount and distribution of rain, the type of soil and the length of the dry season. Some dominant tree species may lose their leaves towards the end of the dry season. This forest type is generally less diverse than rain forest. Dry zone forests are found in tropical areas receiving between 500 and 1000 mm of rainfall per year. They are relatively open and include thorn land, shrub land, savannah and other short and sparse woody vegetation. Dry zone forests tend to be fragile and are easily degraded. More than half are in Africa. Dry forest types include oak, mesquite, piñon-juniper, maquis and acacia. Tropical upland forests are forests above 800 m and include cloud forests (montane rain forests), which are shorter, floristically simpler and more heavily laden with mosses and lichens than lowland rain forests. Tropical upland species are similar to temperate forest species. The upland zone covers the Himalayas, parts of Myanmar, Thailand and Vietnam, the highlands of Mexico, the Andes and the highlands of Ethiopia and mountains around Lake Victoria.

Acidification of coastal waters, bays, estuaries and seas are mostly regulated and controlled by blue carbon, whose expansion is needed as a part of managing the heath of the aquatic ecosystem. We monitored the impact of massive mangrove plantation in and around the Nayachar island (latitudes 21°54′41″ N–22°01′28″ N and longitudes 88°03′02″ E–88°08′43″ E) in the western sector of lower Gangetic delta along the Hooghly estuary considering relevant parameters like DIC and surface water pH for more than three decades (1984–2016). The island is located about 56 nautical miles south of the mega city of Kolkata, directly facing the port-cum-industrial complex of Haldia and has an area of about 47 km^2 and a maximum elevation of 6.5 m above mean sea level (MSL). Length of the Island centrally measured from North to South is 15,861 m and from East to West is 4340 m (Fig. 8.8). The land topography is generally flat, with elevation ranging from a low of 1.08 m MSL to as high as 3.68 m MSL along the coastal region of the island. Average ground level of the island is 1.366 m MSL. The island is convex upward with gently sloping eastern and western flanks. The eastern flank is undergoing erosion at present while the western edge is accreting. According to recent estimation, the present accretion rate is about 1 km^2/yr on the Haldia port area and the erosion rate is about 0.05 km^2/yr on the eastern part of Nayachar. The island is exposed to strong scouring action of the running Hooghly River and hence a programme was undertaken by Calcutta Port Trust in eighties to stabilize the island and increase the draft of the adjacent navigational channel. 11 true mangrove species were planted inside and along the border of the island on geo-jute matrix and within a span of two years excellent growth of the species (particularly *Sonneratia apetala* and *Bruguiera gymnorhiza*) stabilized the boulders with considerable accretion of silt particles (Mitra 2013) (Fig. 8.9).

The biomass of the mangrove vegetation (tha^{-1}) was estimated simultaneously along with DIC and aquatic pH to evaluate the role mangrove vegetation in the domain of Estuarine Acidification (EA).

We observed that with the passage of time as the biomass of the mangroves increased in the island, the DIC values exhibited a gradual decrease (Fig. 8.10) with subsequent increase of pH values in the ambient aquatic phase.

Expansion of blue carbon can be achieved by several technologies like (i) massive mangrove afforestation programme considering the salinity of the region (salinity-specific mangrove afforestation programme), (ii) halophyte farming and (iii) triggering phytoplankton growth through artificial method like iron fertilization. Each of these methods is briefly discussed here.

(i) **Salinity-specific mangrove afforestation programme**

The survival, growth and metabolic activities of mangroves are extremely salinity-specific. In Indian Sundarbans we have recorded significant growth of *Sonneratia apetala*, *Sonneratia caseolaris*, *Heritiera fomes* and *Nypa fruticans* in low saline belt (aquatic salinity = ~5 psu). These true mangrove floral species are best suited in hypo-saline environment (Figs. 8.11, 8.12, 8.13 and 8.14).

Species like *Avicennia marina*, *Avicennia officinalis*, *Avicennia alba*, *Phoenix paludosa* thrive best in hyper-saline environment (Figs. 8.15, 8.16, 8.17 and 8.18).

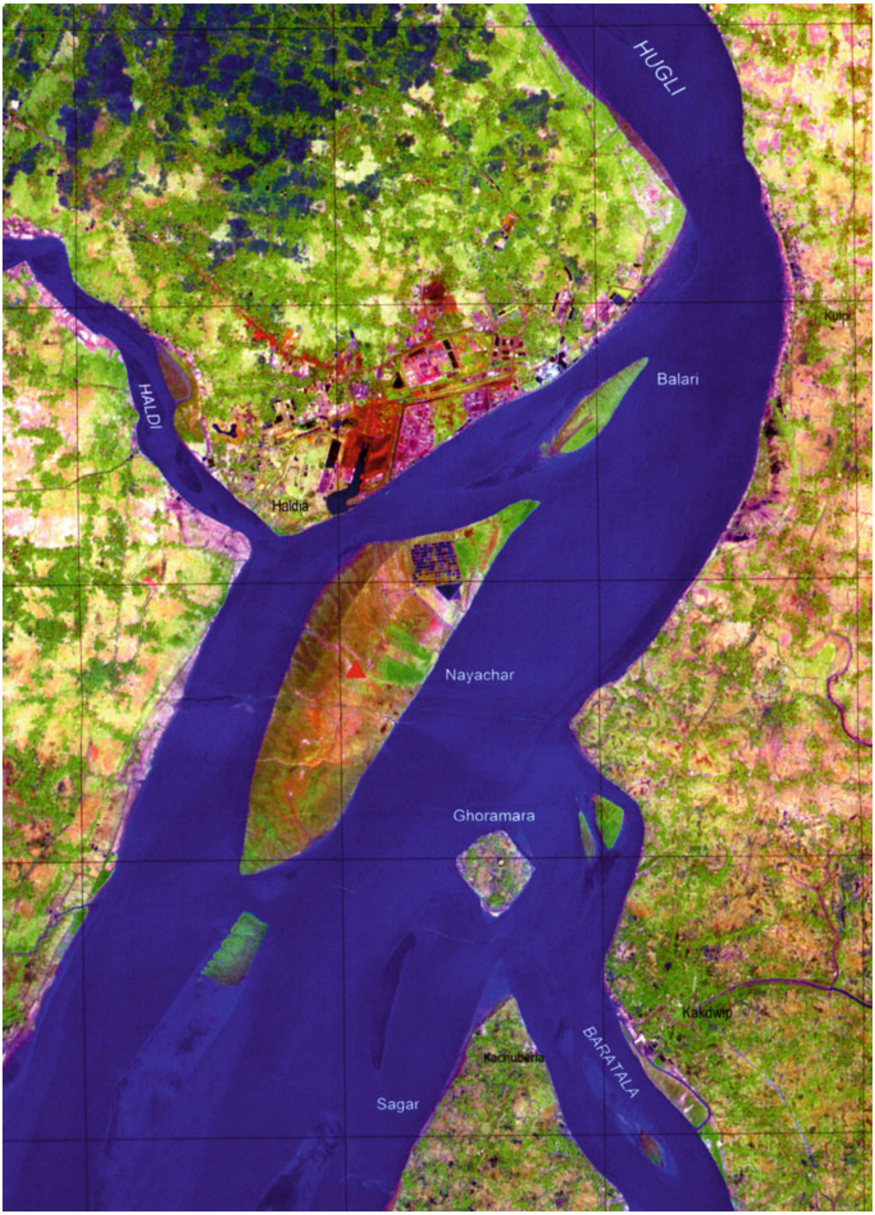

Fig. 8.8 Location of Nayachar island along the Hooghly estuary (*Source* Mitra 2013)

Fig. 8.9 Stand of *Bruguiera gymnorhiza* around Nayachar island along the Hooghly estuary

We have observed that *Excoecaria agallocha* (Fig. 8.19) grows luxuriantly in different salinity regimes.

This wide range of tolerance to salinity by the species must be considered with due weightage while transplanting mangroves from the nursery (Fig. 8.20) to the field.

The survival and growth of mangroves in the field condition can only shift the pH value of the ambient aquatic phase to its equilibrium by retarding the process of acidification.

Basically mangroves absorb carbon dioxide from the atmosphere and the water column and store it as carbon in their vegetative and reproductive parts. The principal carbon-fixing enzyme in plants is ribulose 1, 5- biphosphate carboxylase/oxygenase (RuBisco). The magnitude of the mangrove vegetation pool thus exerts a regulatory role on the pH of the estuarine water as these halophytes absorb carbon dioxide for photosynthesis and shifts the equilibrium towards alkalinity.

The fish bone model of distributing water from the source (estuaries, bays or coastal regions) can successfully result in the growth of mangroves. In this method brackish/saline water from the source is diverted to the targeted site through the feeder canal and field channels and subsequently help transforming the barren land with high salt content into the low saline zone that supports the survival of mangrove plant species. The shape of model is just like the bone of the fish with side bones which allows the brackish water to reach the region where the mangroves need to be

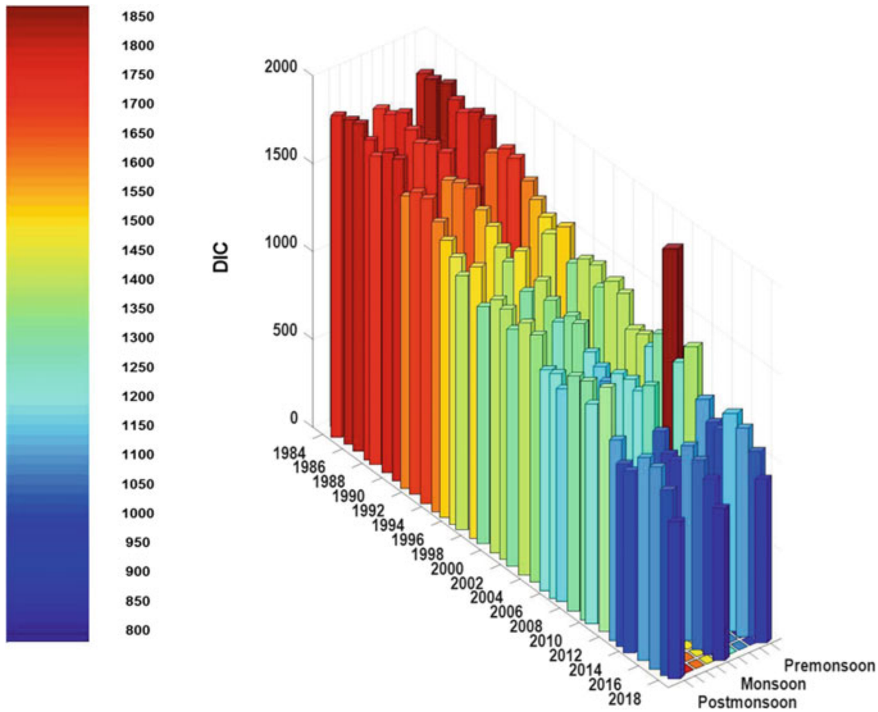

Fig. 8.10 Gradual decrease of DIC (μmol/L) in the aquatic phase around Nayachar island with the increase of mangrove vegetation (in terms of biomass)

planted. This technology has helped to eco-restore the mangrove cover in the Krishna Wild Life Sanctuary (KWS) covering about 6,000 ha since 2006. The model has been successfully standardized by M.S Swaminathan Research foundation (MSSRF).

In Indian Sundarbans brackish water channels have been excavated to transfer the source water to the plantation site and survival rate was monitored after 2 years of plantation in 2017. We conclude that the survival rates are significantly governed by salinity and hence site-specific. We observed that survival rates of *Sonneretia apetala, Aegiceros corniculatum, Bruguiera gymnorrhiza, Xylocarpus granatum, Nypa fruticans, Heritiera fomes, Derreis trifoliate* are significantly high in the low saline belt of western Indian Sundarbans (marked in the graph as Stns. 1–5). The survival rates of these hyposalinophilic species are highlighted in Figs. 8.21, 8.22, 8.23, 8.24, 8.25, 8.26 and 8.27.

In hypersaline environment of central Indian Sundarbans the survival rates of mangrove species like Avicennia alba, Avicennia marina, Avicennia officinalis, Aegiceros ilicifolius, Excoecaria agallocha, Phoenix paludosa, Ceriops decandra, Rhizophora mucronata and Aegialitis rotundifolia are relatively high (Figs. 8.28, 8.29, 8.30, 8.31, 8.32, 8.33, 8.34, 8.35 and 8.36).

Fig. 8.11 *Sonneratia apetala* prefers salinity between 5 psu and 10 psu

These results point out the fact that expansion of mangroves and other coastal vegetation need to be done considering the salinity as the primary driver.

8.3 Acceleration of Resilience of Affected Components

Estuarine acidification (EA), being a major stressor poses adverse impacts on the biotic community as well as on the ambient environmental quality. Thus both biotic and abiotic components are exposed to negative impacts of acidification. There are methods by which stressors can be reduced by employing resilience management to assist the ecological systems and dependent stakeholders, industrials and communities in resisting and recovery from EA. Very scanty works have been conducted on the specific biological attributes that can offer resilience against EA in the lower Gangetic delta region. Till date, there is limited understanding of the major drivers that impart estuarine ecosystem and its services more resilience to estuarine acidification. It is, however, confirmed that EA poses an adverse impact on the socio-economic profile of the region as the natural resources drive the economic cycle of the coastal population. In this context it is extremely important to develop a comprehensive strategy involving the major stakeholders and their respective action plans as reflected in Table 8.7.

Fig. 8.12 *Sonneratia caseolaris* prefers salinity between 1.0 psu and 8.0 psu

EA can be minimized to a great extent by following steps like imposing restrictions on recreational activities, shrimp farming at the expense of blue carbon, industrial discharges, land based activities and emissions from the surroundings. Waste discharges from fishing vessels/trawlers and fish landing stations need to be minimized or properly treated before releasing them to ambient aquatic phase. Regular monitoring needs to be undertaken to manage risks from invasive species, ballast discharge etc. Temporary closure may be done to safeguard the vulnerable spots. A schematic diagram to manage the EA in context to lower Gangetic delta estuaries is highlighted in Fig. 8.37.

To sum up this section, we feel that in Indian Sundarbans out of 10 stations we surveyed since more than three decades (Table 8.8), special restrictions should be imposed on canning in the central sector as the magnitude of stressors is highest in this station owing to presence of busy markets, fish landing sites, passenger jetties, fishing trawler and boat repairing units etc. Moreover this station is also the gateway of Indian Sundarbans forest area, which attracts large number of tourists. All these stressors have high probability to trigger EA in this station as represented in Fig. 8.38.

On contrary, due to presence of luxuriant mangrove vegetation and abundance of mangrove associate species, the environment is quiet safe in terms of EA as represented in Fig. 8.39.

The water quality in the lower Gangetic delta can be improved in context to EA through proper conservation of blue carbon. Studies throughout the world have

Fig. 8.13 *Hertiera fomes* prefers salinity between 1.0 psu and 5.0 psu

Fig. 8.14 *Nypa fruticans* prefers salinity between 4.0 psu and 12.0 psu

Fig. 8.15 *Avicennia marina* prefers salinity between 15.0 psu and 30.0 psu

shown that wetlands chemically, physically and biologically remove pollutants, sediments and nutrients from water flowing through them (Zhang 1995; Day et al. 2004; Alexander and Dunton 2006; Conkle et al. 2008; Kadlec and Wallace 2009; Vymazal 2010; Shaffer et al. 2015).

In context to the present scales represented in Figs. 8.38 and 8.39, it is therefore utmost important to carry out mass scale mangrove plantation in central sector preferably in Canning (along the Matla estuary). The barrier of high salinity can be overcome through interlinking of Matla and Hooghly estuary after a thorough EIA. Rain water harvesting in an around the Canning must be encouraged from where the stored rain water should be channelized to mangrove plantation site.

(ii) **Halophyte farming**

Halophtye farming has dual benefits in the sense that the farmed species have edible value and may serve as source material for alternative livelihood and at the same time may act as carbon sequestering mass leading to inhibition of EA. Literature survey indicates that *Suaeda maritima* and *Salicornia brachiata* when cultivated in high saline environment yield good results, which indicates that there is scope to grow these halophytes in high saline soil or sea water inundated region. The soil usually has high sodium and potassium level. Large scale farming of these mangrove associate species can help retard EA. The field level technology to grow these mangrove associate species is highlighted here in steps.

Fig. 8.16 *Avicennia officinalis* prefers salinity between 12.0 psu and 28.0 psu

1st Step

In the 1st step *Suaeda maritima* and *Salicornia brachiata* are raised in the nursery for 45 days in 3″ × 5″ polythene bags filled with garden soil. Shade net (50%) are used to reduce the light and temperature. Fresh water is used to raise the saplings in the nursery.

2nd Step

In this step the 45-day-old seedlings are transplanted and each species are grown in the saline land preferably in the supra-littoral zone. Initially fresh water is used for irrigation (2 wettings) and then brackish water from nearby creeks is used.

Remarks Since these mangrove associate plants are highly saline- and- drought-tolerant, two wettings with brackish water are given. The salinity of the brackish water used for the first wetting is around 28–30 psu whereas salinity of the brackish water given for the second wetting is around 20–25 psu.

3rd Step

In this step the final harvesting is done before the onset of the monsoon since these halophytes will die thereafter. It is to be noted in this context that these mangrove associate species thrive and grow luxuriantly in high saline condition and die when

Fig. 8.17 *Avicennia allba* prefers salinity between 10.0 psu and 30.0 psu

the dilution factor of the estuarine and coastal water increases during the monsoon season.

Halophyte farming has several benefits in terms of livelihood, but in context to CO_2 mitigation, the magnitude of stored carbon in *Suaeda maritima* and *Salicornia brachiata* (Table 8.9) speaks in favor of scrubbing the GHG at the local scale.

(iii) **Triggering phytoplankton growth through artificial method like iron fertilization**

Iron fertilization in closed water body coupled with pisciculture/aquaculture can be a food for thought to regulate EA. The recent researches on iron fertilization put forward the concept that phytoplankton growth can be stimulated by adding iron to **HNLC** waters (High Nitrate Low Chlorophyll). Many scientists also forwarded the view that the efficiency of this biological pump can be enhanced by fertilizing the oceans with iron. Increased efficiency means sucking up more carbon dioxide from the atmosphere into the oceans. This can be an effective roadmap to mitigate climate change due to rise of carbon dioxide in the atmosphere. However, such researches are based on an incomplete understanding and highly simplified interpretation of current scientific knowledge. The major drawbacks of the concept of reducing carbon dioxide level in the atmosphere by triggering the growth of phytoplankton of the ocean through iron fertilization are listed here in points:

Fig. 8.18 *Phoenix paludosa* prefers salinity between 18.0 psu and 32.0 psu

1. Ecological perturbations in the marine and estuarine environments due to iron fertilization have not been given proper importance.
2. The geophysical changes of the ecosystem that may result due to large scale iron fertilization have not been accounted in this research programme.
3. In order to remove significant amount of atmospheric carbon dioxide, a huge area of the ocean needs to be fertilized which may not be particularly feasible.
4. Iron fertilization if done, on commercial scale, may lead to harmful algal bloom (HAB), which has adverse effect on other marine lives.
5. Iron addition and subsequent phytoplankton bloom associated with increased particulate organic export and remineralization, could reduce dissolved oxygen (DO) level in sub-surface water. This has high probability to pose a negative impact on the marine organisms.
6. As the bloom will progress due to iron fertilization, the nutrient load of the ambient water will sharply decrease. This could result in a reduction of these nutrients down current from an iron fertilized area. Finally, lack of nutrients may cause a detrimental effect on phytoplankton resulting in a reduction in overall biological productivity. Predictive mathematical models have suggested that commercial scale iron fertilization of the oceans could have a significant adverse impact on marine fisheries.
7. There is also the concern that the changes in water chemistry caused by iron fertilization could lead to higher emission of nitrous oxide due to decomposition

Fig. 8.19 *Excoecaria agallocha* prefers salinity between 5.0 psu and 28.0 psu

of organic matter in deep water. Some researchers have contradicted the concern with the idea of fertilizing low-nutrient regions of the oceans instead of high—nutrient ones. This scientific school believes that excess phytoplankton density (bloom condition) could create a larger aerosol effect leading to block incoming solar radiation that may cause global cooling.

8. It is difficult to track phytoplankton blooms in the vast ocean with dynamic circulation pattern. The added iron rapidly dilutes, sinks, and reacts with seawater, becoming virtually undetectable after a few days. Researchers therefore have to add minute amounts of an inert tracer like sulphur hexafluoride (SF_6), which

Fig. 8.20 Nursery of mangroves prior to translocation on the mudflats

itself is a potent greenhouse gas. One kilogram of SF_6 added in an experiment is equivalent to releasing 7 tonnes of carbon dioxide.

Considering the drawbacks of iron fertilization in Open Ocean, we suggest similar approach in closed water body stocked with estuarine/coastal water. The merits of the programme are as follows:

1. The question of huge input of iron does not arise because the water body has a limited surface area or volume.
2. Standardization of iron fertilization can be easily done because of the closed nature of the system due to which the wave action, tidal phenomenon and other parameters can be controlled.
3. Ecological perturbations will be negligible in aquaculture ponds because unlike open oceans the species richness is not too high in this closed system. Only the target species is cultured in the pond and essentially the food chain consists of phytoplankton, zooplankton and target (cultured) species.
4. The aquaculture ponds are closed systems with depth ranging from 1 to 5 m. The substratum is basically soil. The question of massive geophysical changes does not arise when iron fertilization is done.
5. In aquaculture pond the algal bloom can be converted into animal biomass as the cultured species feed and phytoplankton and the question of dissolved oxygen (DO) fall does not arise.

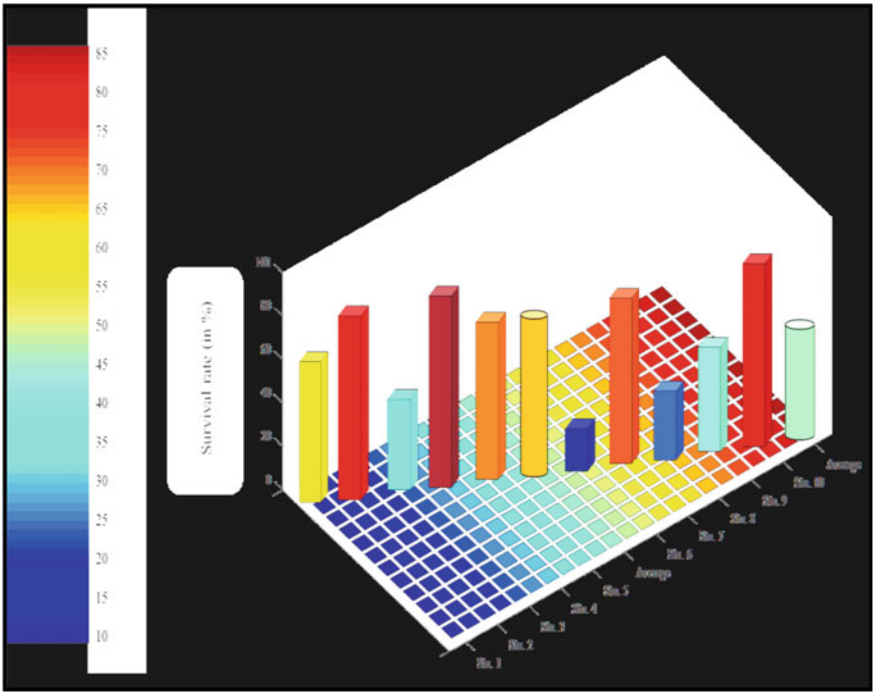

Fig. 8.21 Survival rate of *Sonneretia apetala*

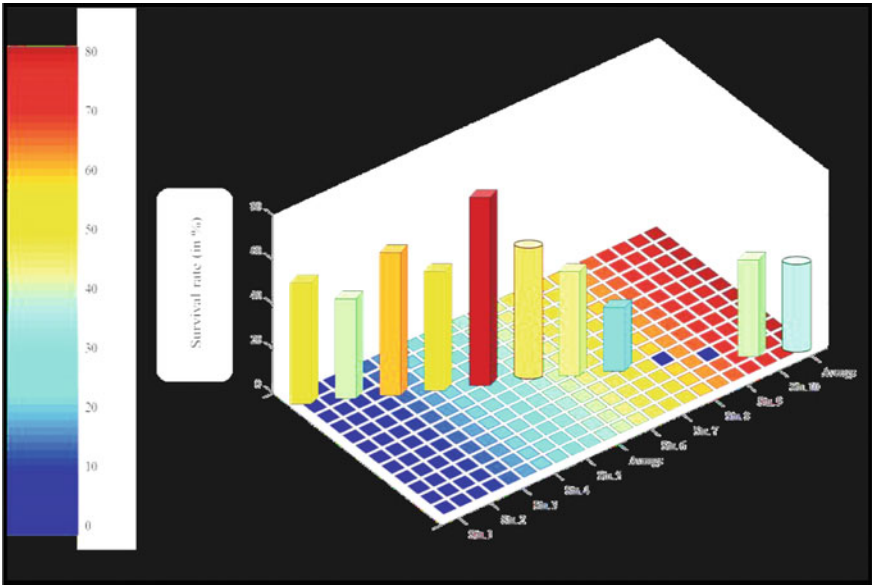

Fig. 8.22 Survival rate of *Aegiceros corniculatum*

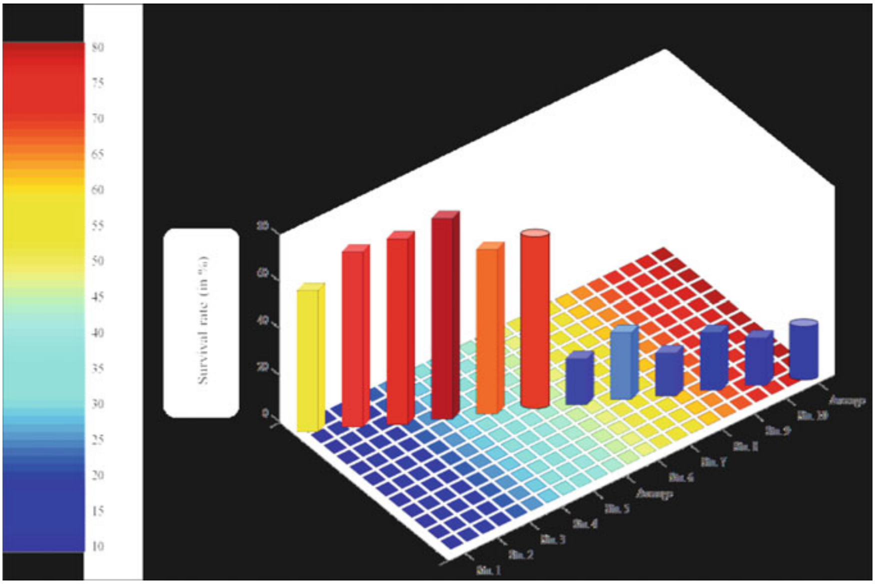

Fig. 8.23 Survival rate of *Bruguiera gymnorrhiza*

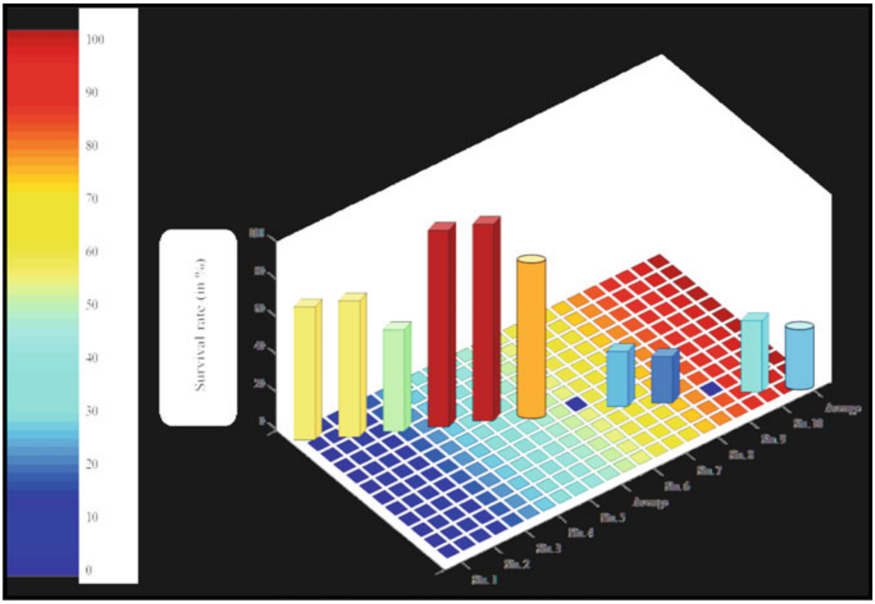

Fig. 8.24 Survival rate of *Xylocarpus granatum*

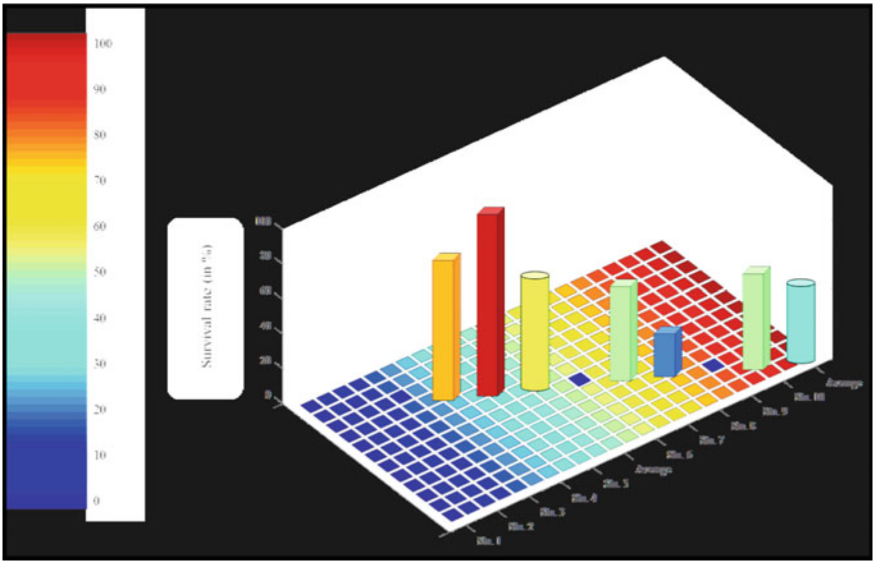

Fig. 8.25 Survival rate of *Nypa fruticans*

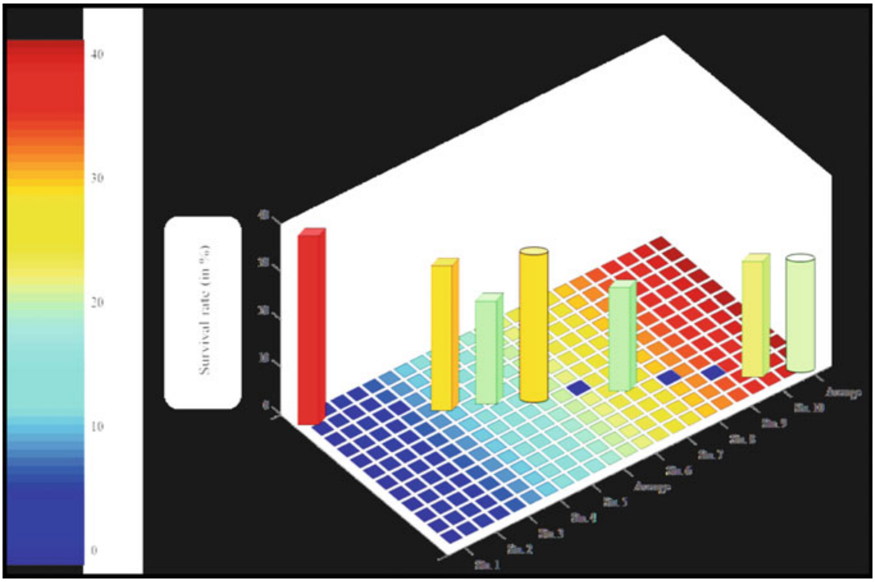

Fig. 8.26 Survival rate of *Heritiera fomes*

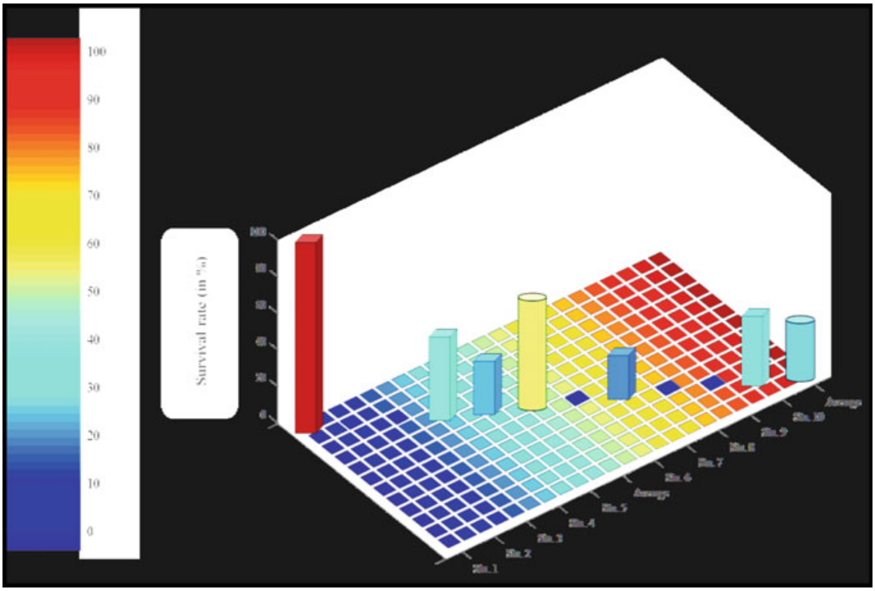

Fig. 8.27 Survival rate of *Derris trifoliate*

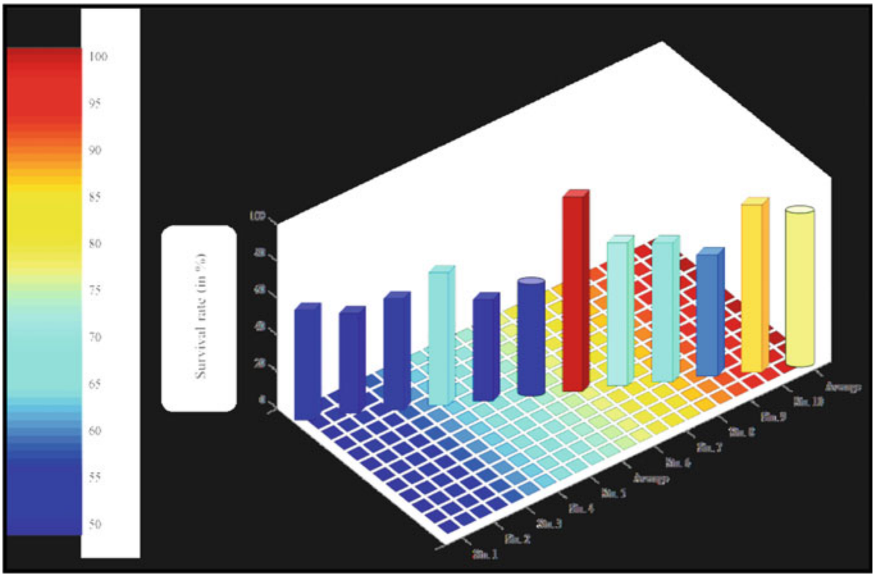

Fig. 8.28 Survival rate of *Avicennia alba*

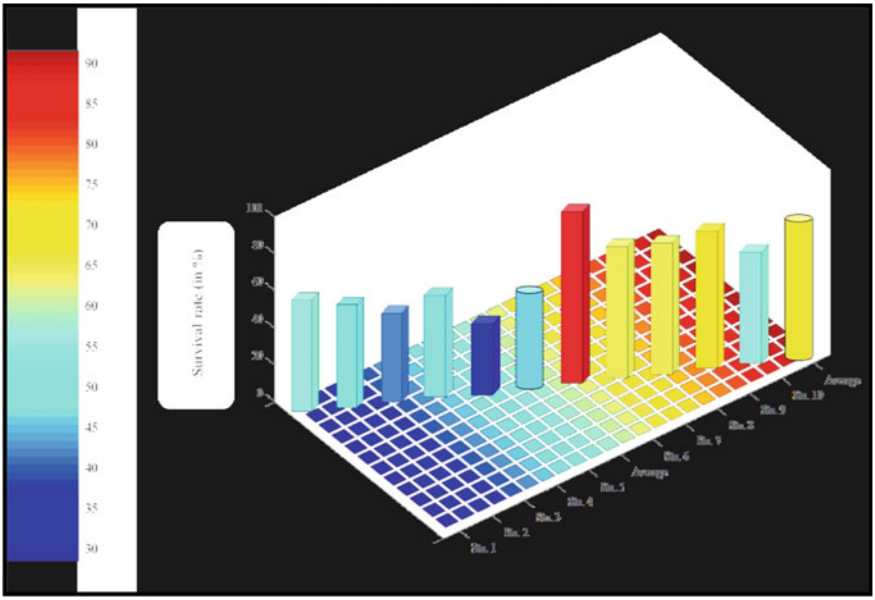

Fig. 8.29 Survival rate of *Avicennia marina*

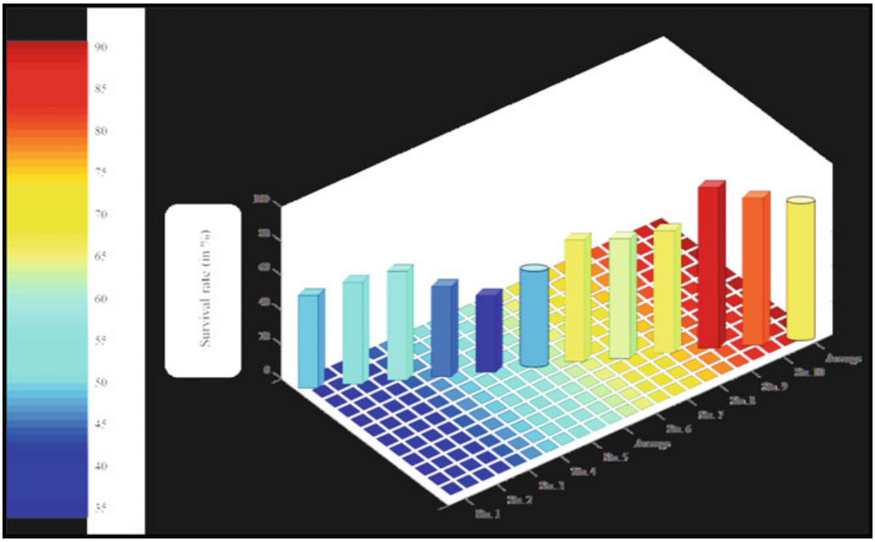

Fig. 8.30 Survival rate of *Avicennia officinalis*

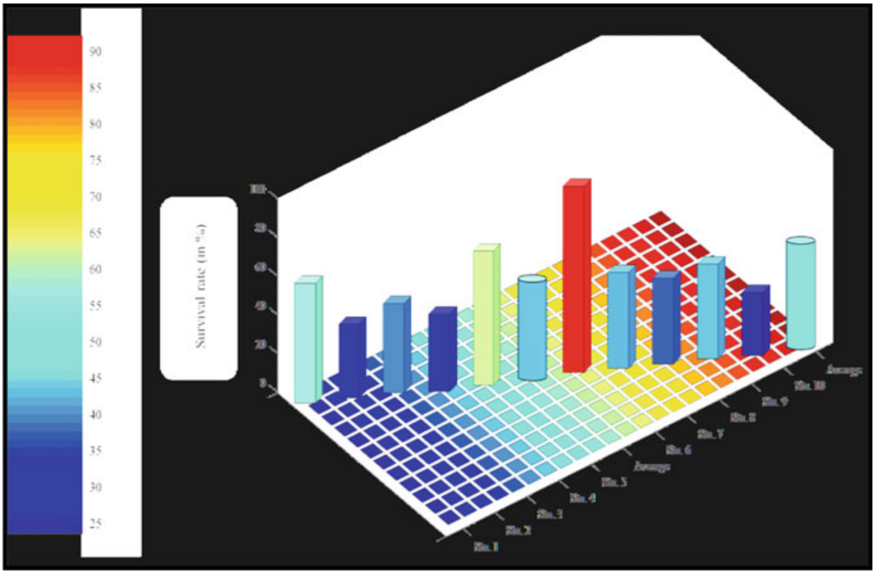

Fig. 8.31 Survival rate *Aegiceros ilicifolius*

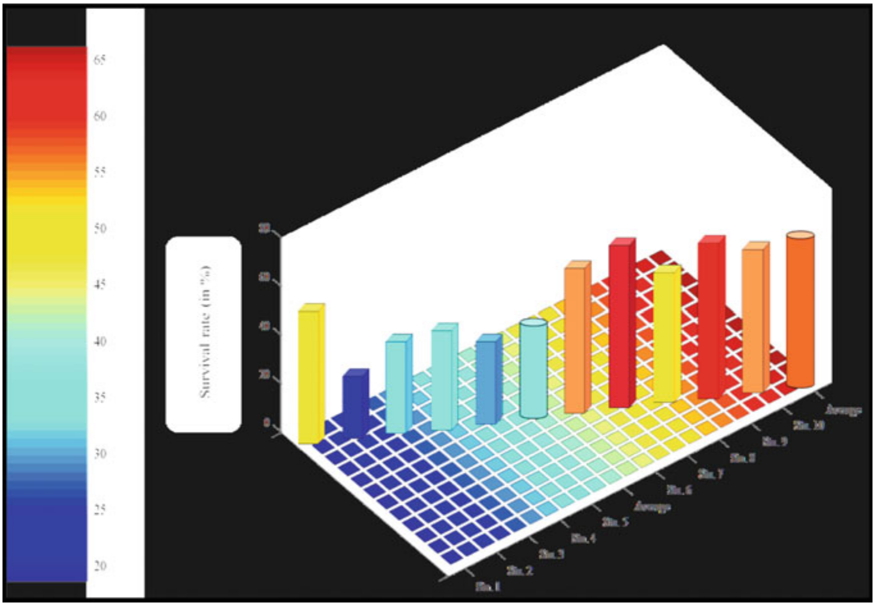

Fig. 8.32 Survival rate of *Excoecaria agallocha*

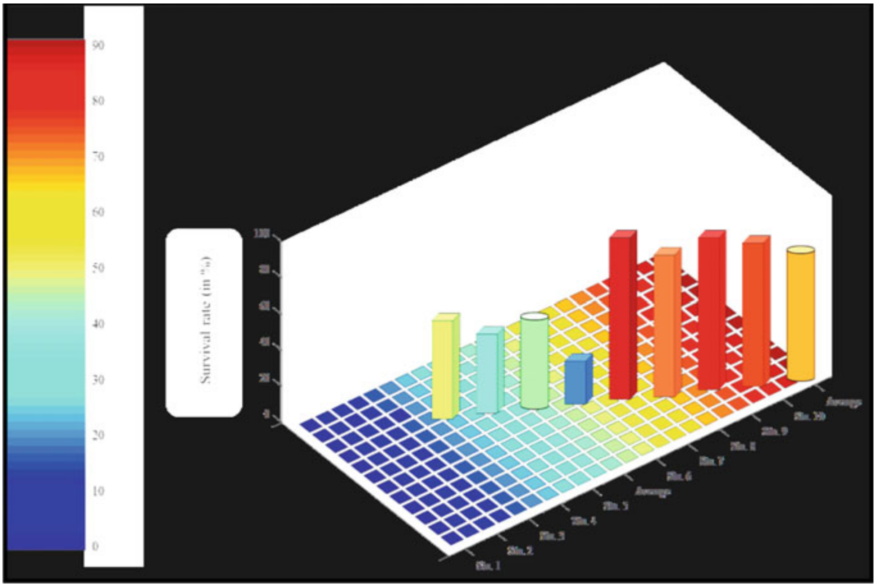

Fig. 8.33 Survival rate of *Phoenix paludosa*

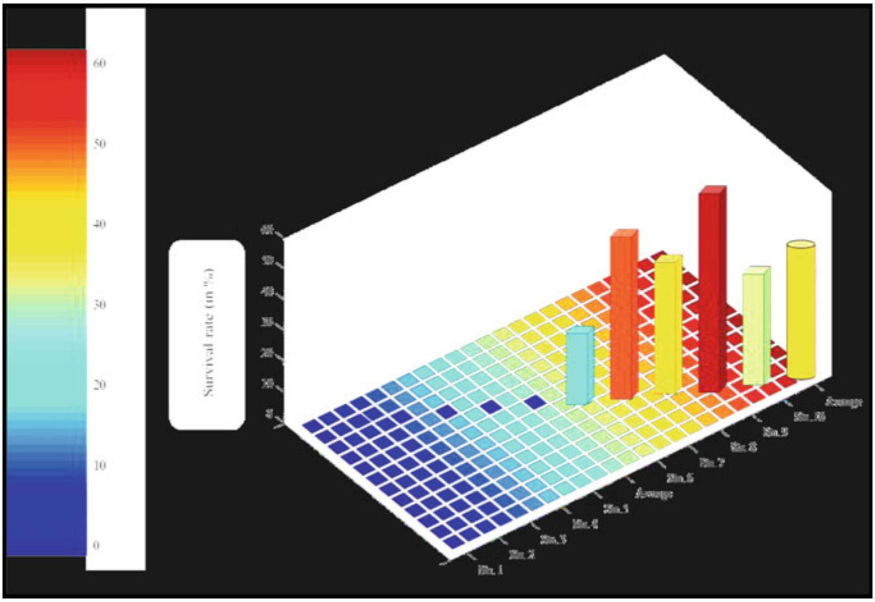

Fig. 8.34 Survival rate of *Ceriops decandra*

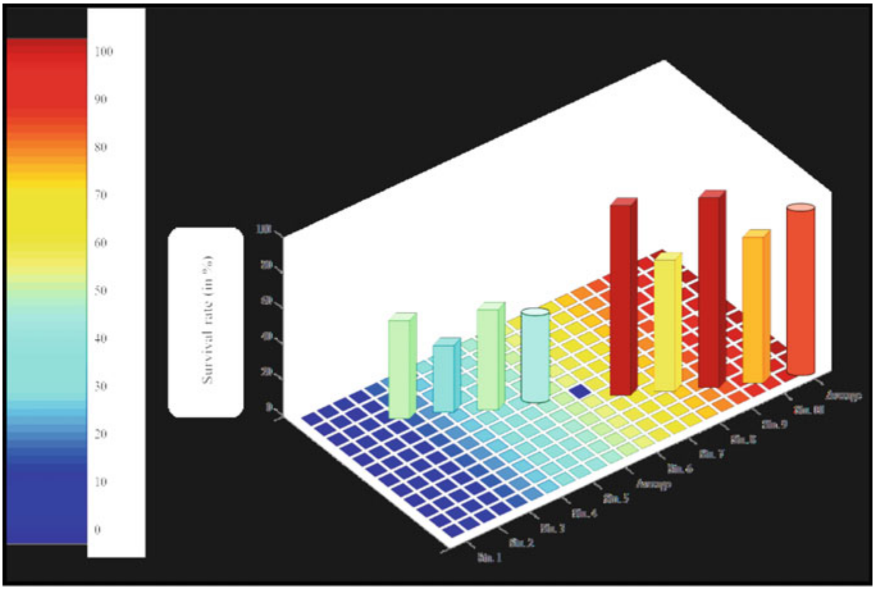

Fig. 8.35 Survival rate of *Rhizophora mucronata*

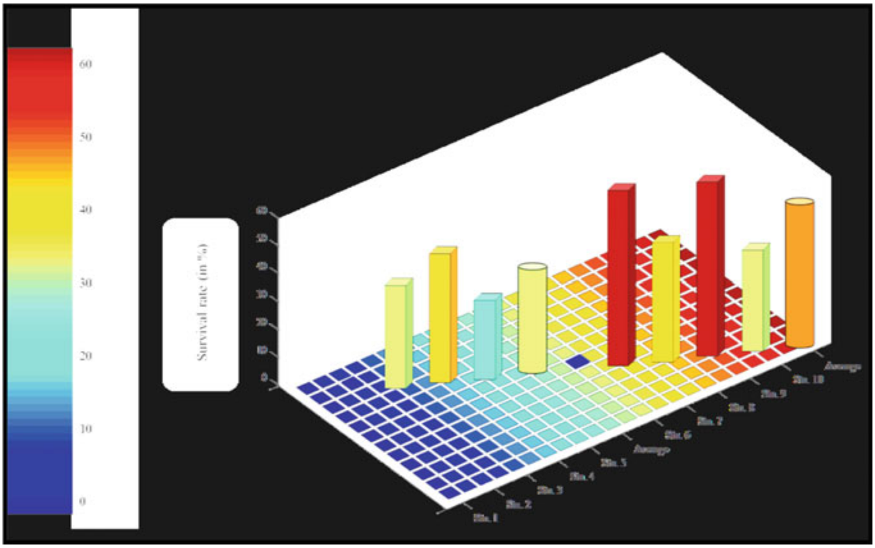

Fig. 8.36 Survival rate of *Aegialitis roduntifolia*

Table 8.7 Comprehensive strategies to manage EA with pinpointed questions and indicators in context to estuaries of lower Gangetic region

Impact	Questions	Indicators/approaches
Local anthropogenic factors like industrial discharges, municipal wastes pose considerable impact on EA. This local effect may be magnified by phenomenon like eutrophication—enhanced acidification in some locations in the lower stretch of the estuary	What are the sources, of altered water quality preferably pH? What is the relative importance of low-pH water compared to other stressors? What is the contribution of local anthropogenic sources of CO_2 like brick kiln or industrial emissions to low pH water? How massive deforestation due to shrimp culture activities or mushrooming of tourism units contribute to the process of EA?	• Conduct chemical and physical monitoring via cruises/surveys and moored sensors • Develop and test calibrated carbon models, conceptual models, and mass balance calculations • Obtain information on point sources of CO_2 at multiple locations • Obtain time series information on replication/proliferation of shrimp farms and tourism units at the cost of mangroves
Changes in phytoplankton community and food quality Adverse impact on filter feeding molluscan community	To what extent can exposure to lower-pH water change the phytoplankton community or food quality? How the molluscs preferably *Saccostrea* spp. are impacted due to compositional variation or abundance of phytoplankton?	• Evaluate changes in phytoplankton distribution and diversity along with chlorophyll content of the aquatic phase
Increased toxins from harmful algal blooms and effects on higher trophic levels	To what extent can exposure to lower-pH water increase the production of (harmful algal bloom) HAB toxins?	• Assess HABs and toxins in the relation to EA and evaluate inter-relationship preferably through regression model
Impact on fisheries and shellfish community	To what extent does exposure to lower-pH water decrease shellfish populations and fisheries? Is there any observation on oyster shell thinning?	• Assess larval quality, recruitment, and juvenile growth of bivalves, crabs, etc. • Use EA as a lens through which habitat is valued for upper trophic levels • Assess finfish otoliths • Assess oyster shell weight and thickness
Local mitigation of EA impacts by submerged aquatic vegetation (SAV)	To what extent can existing or restored SAV buffer for lower pH exposure? What is the carbon sequestration potential for different natural and restored vegetative habitats like mangrove, sea grass, saltmarsh grass etc.?	• Assess SAV health and buffer capacity, and quantify habitat suitability through evaluation of ecological indices • Overlay EA “hotspots” over the habitat- suitability maps for SAV to help prioritize restoration or other projects

(continued)

Table 8.7 (continued)

Impact	Questions	Indicators/approaches
Other considerations	Have any indicators/proxy in relation to EA in the lower Gangetic delta been standardized?	• Couple biological, chemical, and physical monitoring in association with living shoreline projects • Assess nested indicators in different trophic levels • Assess microbial community and function • Assess the buffering capacity of molluscan shells (preferably oyster) as they dissolve in low pH condition • Evaluate benthic foraminifera characteristics

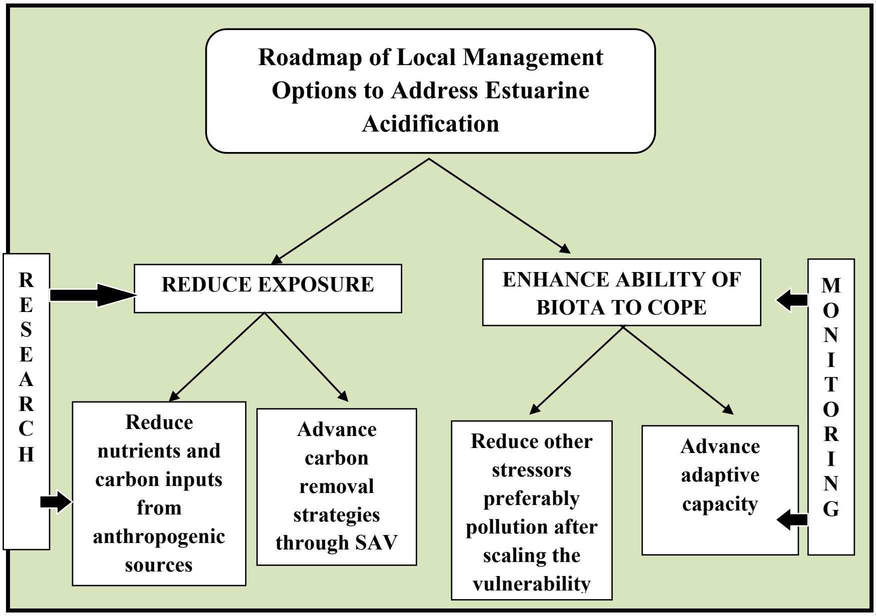

Fig. 8.37 Local management options to address estuarine acidification in the lower Gangetic estuaries

6. The HAB species can be detected and managed as aquaculturists monitor the water quality and check the pond health almost on hourly basis.
7. Hydrogen sulphide gas produced by microbial activity in the aquaculture ponds can be precipitated through application of ferrous sulphate, which may otherwise be toxic for the cultured species.

Table 8.8 Sampling stations with salient features surveyed in context to EA

Study site	Latitude and longitude	Site description
Harinbari (Stn. 1)	21°46′53.07″ N 88°04′22.88″ E	Situated in the western region of Indian Sundarbans almost in the middle of the Sagar Island; receives the water of the Hugli River
Chemaguri (Stn. 2)	21°39′42.88″ N 88°08′49.01″ E	Situated on the south-eastern side of Sagar Island and receives the water of the Mooriganga River
Sagar South (Stn. 3)	21°37′49.90″ N 88°04′0.51″ E	Situated on the south-western part of the Sagar Island at the confluence of the River Hugli and the Bay of Bengal. Anthropogenically stressed zone due to presence of passenger jetties, fishing activities and pilgrimage
Lothian island (Stn. 4)	21°39′08.04″ N 88°19′8.47″ E	Situated east of Bakkhali island; a Wildlife sanctuary; faces the River Saptamukhi
Prentice island (Stn. 5)	21°42′43.31″ N 88°17′3.62″ E	Situated north of Lothian island; receives the water of the Saptamukhi River
Canning (Stn. 6)	22°19′03.20″ N 88°41′04.43″ E	Situated in the central part of the Indian Sundarbans and faces the mighty River Matla, a tide-fed river. Due to presence of fish landing stations, passenger jetties and busy market, the area is anthropogenically stressed
Sajnekhali (Stn. 7)	22°06′34.19″ N 88°48′15.78″ E	A Wildlife Sanctuary and a part of Sundarban Tiger Reserve; adjacent to River Bidhya and Gomor. Tourism pressure is extremely high in this station particularly during postmonsoon
Chotomollakhali (Stn. 8)	22°10′40.00″ N 88°54′26.71″ E	Situated in the upper portion of Central Indian Sundarban adjacent to Jhila forest; receives the water of Rangabelia and Korankhali Rivers
Satjelia (Stn. 9)	22°05′17.86″ N 88°52′49.51″ E	Situated adjacent to River Duttar in the upper region of Central Indian Sundarban facing western part of the Jhilla forest
Pakhiralaya (Stn. 10)	22°07′07.23″ N 88°48′29.00″ E	Situated adjacent to River Gomor; opposite to Sajnekhali Wild Life Sanctuary

Ocean acidification has presently taken a faster pace, approximately 30 to100 times faster than at any time during the last several million years driven by the rapid growth rate atmospheric CO_2 that is almost unprecedented over geologic history. According to the Intergovernmental Panel on Climate Change (IPCC), economic and population scenarios predict that atmospheric CO_2 levels could reach 500 ppm by 2050 and 800 ppm or more by the end of the century. This will not only lead to significant temperature increases in the atmosphere and ocean, but will further acidify

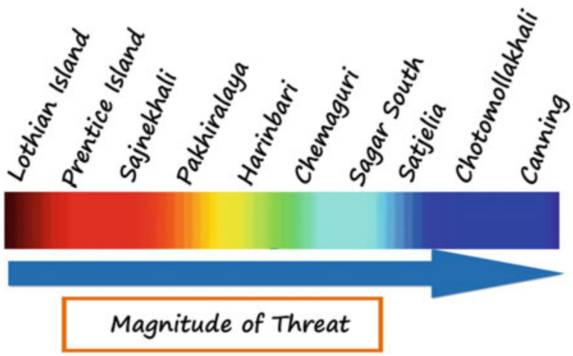

Fig. 8.38 Scaling the spatial threat on mangroves; note the order of threat is Canning > Pakhiralaya > Chotomollakhali > Satjelia > Chemaguri > Harinbari > Sagar South > Prentice island > Sajnekhali > Lothian island

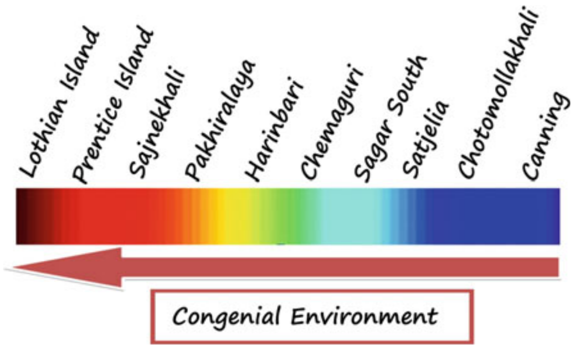

Fig. 8.39 Scaling the health and water quality in Indian Sundarban mangroves; note the order is Lothian island > Prentice island > Sajnekhali > Pakhiralaya > Harinbari > Chemaguri > Sagar South > Satjelia > Chotomollakali > Canning

ocean water, reducing the pH an estimated 0.3 to 0.4 units by 2100, a 150% increase in acidity over preindustrial times (https://www.whoi.edu/know-your-ocean/ocean-topics/ocean-chemistry/ocean-acidification/). It's a fact that phytoplankton community is a biological pump and will drag more CO_2 in the aquatic system due to iron fertilization, but if it can be scientifically carried out in closed aquacultural ponds, then these tiny floral particles can be the primary source of food for cultured species (preferably filter feeders like oysters) and will serve dual benefits (i) local scale reduction of atmospheric CO_2 thereby reducing the dissolving potential of atmospheric CO_2 and (ii) production of edible finfish and shell fish for human consumption.

In this context it is interesting to note that an experiment was performed during 2011 in Indian Sundarbans in closed brackish water body where different doses of iron were mixed to trigger up the bloom of phytoplankton and prawn species *Macrobrachium rosenbergii* was introduced simultaneously (Fig. 8.40).

Table 8.9 Biomass and Stored Carbon in *Suaeda maritima* and *Salicornia brachiata* sampled from Jharkhali region of Central Indian Sundarbans during 2018

Species	Total Biomass (kgm^{-2})	Total Carbon (kgm^{-2})
 *Suaeda maritima*	4.86	1.86 (38.2%)*
 *Salicornia brachiata*	3.52	1.25 (35.6%)*

**Note* The values within bracket represent stored carbon percentage of the biomass of the species

Fig. 8.40 Phytoplankton bloom in the experimental pond after adding ferrous sulphate

Fig. 8.41 Growth of *Macrobrachium rosenbergii* in the iron fertilized brackish water pond

Best growth of prawn (in terms of biomass) was observed after a culture period of 9 months in the culture pond when 1.5 ppm ferrous sulphate was applied in the aquatic phase (Fig. 8.41). In this experiment salinity was uniformly maintained (3.5–4.2 psu) during the experimental period.

In conclusion we strongly believe that retardation of the pace of EA requires micro-level strategies at local level as many of the estuaries flowing through different districts/states are inter-connected. These strategies need to be developed through an inter-departmental approach by involving all the relevant actors as stated in Table 8.10.

8.4 Take Home Messages

A. To retard the pace of rise of carbon dioxide it is extremely important to shift from traditional non-renewable energy (primarily coal-based) sources to renewable clean energy phase. The resources which are being continuously consumed by man but are renewed by nature constantly are called as renewable resources. These resources are inexhaustible because they cannot be exhausted permanently. Renewable resources are also called as 'Non-Conventional' sources of energy. Examples of renewable resources include solar energy, wind energy,

Table 8.10 Ten micro-level approaches to control EA

S. No.	Estuarine acidification (EA) management strategy	Institutional capacity at present	Financial investment required (INR)	Actors
1	Set up initiatives in each of the Indian coastal districts/states to assess the threat of EA to ecosystem health and services along with livelihoods of coastal people and island dwellers and develop strategies to mitigate local drivers	Partial	20 Crores	State agencies, science, policy and capacity building NGOs, academic and research institutes, port authorities, coast guard, state environment department, state fisheries department and district administration
2	For regional EA issues, leverage existing inter-district/state coalitions or form new inter-state/district task forces to facilitate multi stakeholder solutions	Absent	20 Crores	State agencies, science and policy NGOs, academic and research institutes, port authorities, coast guard, district administration
3	Continue developing a coordinated regional network of monitoring stations to map the vulnerability of coastal areas to EA, extend monitoring to near-shore systems relevant to management jurisdictions, and establish biological indicators as proxies for ecosystem health	Adequate	10 Crores	State agencies, science and policy NGOs, academic and research institutes, remote sensing agencies

(continued)

Table 8.10 (continued)

S. No.	Estuarine acidification (EA) management strategy	Institutional capacity at present	Financial investment required (INR)	Actors
4	Launch public education programs on EA and its causes to develop public awareness and stakeholder involvement in the process	Adequate	2 Crores	State agencies, NGOs meant for awareness building and science education, resources persons from academic and research institutes
5	Coordinate domestic research and communication efforts with international programs to focus attention to EA, increase international collaboration, and standardize Inter-State monitoring Protocols	Partial	5 Crores	State agencies, science and policy NGOs, academic and research institutes, port authorities, foreign high commissions
6	Integrate the threat of EA into existing and new climate change programs and state-level coastal programs under the ICZM umbrella	Mostly absent	–	State agencies, academic and research institutes, port authorities, coast guard, central and sate pollution control boards, ministry of environment & forests, ministry of earth science, ICZM authorities
7	Enforce existing regulatory measures to regulate water quality that affects enhanced EA	Absent	–	State agencies, juridical universities, advocacy or policy NGOs, central and sate pollution control boards, state police department

(continued)

Table 8.10 (continued)

S. No.	Estuarine acidification (EA) management strategy	Institutional capacity at present	Financial investment required (INR)	Actors
8	Include the impact of permitting actions on EA when conducting environmental impact assessments under the National Environmental Policy Act or under state-level environmental policy acts. EMP should be strong enough to mitigate EA	Absent	–	State agencies, academic and research institutes, port authorities, coast guard, central and sate pollution control boards, ministry of environment & forests, ministry of earth science
9	Consider and incorporate information about coastal gene pool within EA hotspots into marine protected area planning processes	Partial	20 Crores	State agencies, academic and research institutes, central and sate pollution control boards, ministry of environment & forests, ministry of earth science, central and state department of science and technology, apps developer
10	Consider implementing innovative low carbon emission innovative livelihood programmes for coastal population and island dwellers at pilot scale	Partial		State agencies, academic and research institutes, NGOs involved in capacity building, central and sate pollution control boards, ministry of environment & forests, ministry of earth science, central and state department of science and technology, ministry of agriculture, food processing units, state fisheries department

[*] *Note* '–' means financial investment could not be estimated

tidal energy, hydro power, geothermal energy and biofuels. The emission from renewable sources is practically zero/negligible. For islands and mangrove forest dominated ecosystems like Sundarbans, tidal energy is one of the best options for generation of electric current, provided adequate precautionary measures are taken during the period of cyclonic depressions.

B. Blue carbon refers to the coastal vegetation which includes mangroves, sea grass, salt marsh grass etc. Blue carbon has specific status in combating the process of acidification as they scrub dissolved form of carbon from the ambient aquatic phase. It is no exaggeration to state that increased level of carbon dioxide has shifted the pH of ocean, seas, bays and estuaries from the normal value ranging between 8.1–8.3 and 8.0–7.8. This shifting has posed several adverse impacts on marine and estuarine systems specially on the molluscan community with calcareous structures. The survival and growth of mangroves in the in the intertidal zone can shift the pH value of the ambient aquatic phase to its equilibrium by retarding the process of acidification. Basically mangroves absorb carbon dioxide from the atmosphere and the water column and store it as carbon in their vegetative and reproductive parts. The principal carbon-fixing enzyme in plants is ribulose 1, 5- biphosphate carboxylase/oxygenase (rubisco). The magnitude of the mangrove vegetation pool thus exerts a regulatory role on the pH of the estuarine water as these halophytes absorb carbon dioxide for photosynthesis and shifts the equilibrium towards alkalinity. It is therefore the need of the hour to expand the area of blue carbon and other mangrove associate species. Expansion of blue carbon can be achieved by several low cost technologies like (i) massive mangrove afforestation programme considering the salinity of the region (salinity-specific mangrove afforestation programme), (ii) halophyte farming and (iii) triggering phytoplankton growth coupled with aquaculture through artificial method like iron fertilization.

C. Estuarine acidification (EA), being a major stressor poses adverse impacts on the biotic community as well as on the ambient environmental quality. Thus both biotic and abiotic components are exposed to negative impacts of acidification. There are methods by which stressors can be reduced by employing resilience management to assist the ecological systems and dependent stakeholders, industrials and communities in resisting and recovery from EA. Very scanty works have been conducted on the specific biological attributes that can offer resilience against EA in the lower Gangetic delta region. Till date, there is limited understanding of the major drivers that impart estuarine ecosystem and its services more resilience to estuarine acidification.

D. EA can be minimized to a great extent by following steps like imposing restrictions on recreational activities, shrimp farming at the expense of blue carbon, industrial discharges, land based activities and emissions from the surroundings. Waste discharges from fishing vessels/trawlers and fish landing stations need to be minimized or properly treated before releasing them to ambient aquatic phase. Regular monitoring needs to be undertaken to manage risks from invasive species, ballast discharge etc. Temporary closure may be done to safeguard the vulnerable spots.

Annexure 8: Salinity—Specific Mangrove Distribution in Indian Sundarbans

A detailed survey was carried out during 2017 on the ground-zero level in Indian Sundarbans covering eighteen sampling stations (Table 8.11) to assess the biomass and stored carbon in five dominant species namely *Sonneratia apetala, Avicennia marina, Avicennia officinalis, Avicennia alba* and *Excoecaria agallocha.*

We observed two interesting points in the output datasets (Tables 8.12, 8.13, 8.14, 8.15 and 8.16) in terms of preference of the mangrove floral species to environment. Firstly, *Sonneratia apetala* has high preference for low saline regions as witnessed in the western and eastern Indian Sundarbans. *Avicennia* spp. grows well in the high saline zone of central Indian Sundarbans. *Excoecaria agallocha* shows a wide range of salinity tolerance. Secondly, *Excoecaria agallocha* although has wide range of tolerance to salinity, but because of the poor biomass of the species, its role in carbon sequestration is not admirable. Giving weightage to mangrove biomass in regulating EA, it is therefore suggested to plant *Sonneratia apetala* in western and eastern sectors of Indian Sundarbans and *Avicennia* spp. in central Indian Sundarbans.

On the basis of these report cards, we developed a bird's eye view (Table 8.17) for each of the selected species in terms of their adaptations to different salinity using carbon sequestration as proxy. A proxy variable is an easily measurable variable that

Table 8.11 Sampling stations in the western, central and eastern sectors of Indian Sundarbans

Sectors		Sampling stations	Longitude	Latitude
Western sector	Stn. 1	Chemaguri (W_1)	88°08′53.55″ E	21°38′25.86″ N
	Stn. 2	Saptamukhi (W_2)	88°23′27.18″ E	21°40′02.33″ N
	Stn. 3	Jambu Island (W_3)	88°10′22.76″ E	21°35′42.03″ N
	Stn. 4	Lothian (W_4)	88°20′29.32″ E	21°38′21.20″ N
	Stn. 5	Harin Bari (W_5)	88°04′32.97″ E	21°44′22.55″ N
	Stn. 6	Prentice Island (W_6)	88°17′55.05″ E	21°42′47.88″ N
Central sector	Stn. 7	Thakuran Char (C_1)	88°31′25.57″ E	21°49′53.17″ N
	Stn. 8	Dhulibasani (C_2)	88°33′48.20″ E	21°47′06.62″ N
	Stn. 9	Chulkathi (C_3)	88°34′10.31″ E	21°41′53.62″ N
	Stn. 10	Goashaba (C_4)	88°46′41.44″ E	21°43′50.64″ N
	Stn. 11	Matla (C_5)	88°44′08.74″ E	21°53′15.30″ N
	Stn. 12	Pirkhali (C_6)	88°51′06.04″ E	22°06′00.97″ N
Eastern sector	Stn. 13	Arbesi (E_1)	89°01′09.04″ E	22°11′43.14″ N
	Stn. 14	Jhilla (E_2)	88°57′57.07″ E	22°09′51.53″ N
	Stn. 15	Harinbhanga (E_3)	88°59′33.24″ E	21°57′17.85″ N
	Stn. 16	Khatuajhuri (E_4)	89°01′05.33″ E	22°03′06.55″ N
	Stn. 17	Chamta (E_5)	88°57′11.40″ E	21°53′18.56″ N
	Stn. 18	Chandkhali (E_6)	89°00′44.68″ E	21°51′13.59″ N

Table 8.12 Carbon sequestration by *Sonneratia apetala* inhabiting Indian Sundarbans

Species	Stations	AGB (tonnes/ha)		AGC (tonnes/ha)		Carbon sequestration = ΔAGC/Δt (tonnes/ha/yr)
		1 Year	11 Year	1 Year	11 Year	
Sonneratia apetala	Muriganga	0.280	121.65	0.147 (52.5%)	56.202 (46.2%)	5.606
	Saptamukhi	0.292	123.06	0.154 (52.74%)	57.223 (46.5%)	5.707
	Jambu Island	0.142	104.59	0.075 (52.82%)	48.216 (46.1%)	4.814
	Lothian Island	0.275	142.33	0.145 (52.73%)	65.472 (46%)	6.533
	Sagar Island	0.267	139.88	0.140 (52.43%)	64.764 (46.3%)	6.462
	PrenticeIsland	0.271	140.63	0.143 (52.77%)	66.096 (47%)	6.595
	Thakuran	0.105	43.62	0.053 (50.48%)	19.978 (45.8%)	1.993
	Dhulibasani	0.112	48.71	0.057 (50.89%)	22.455 (46.1%)	2.240
	Chulkathi	0.110	45.50	0.056 (50.91%)	20.885 (45.9%)	2.083
	Goashaba	0.102	41.39	0.052 (50.98%)	18.791 (45.4%)	1.874
	Matla	0.236	68.75	0.120 (50.85%)	31.281 (45.5%)	3.116
	Pirkhali	0.114	50.27	0.058 (50.88%)	23.124 (46%)	2.307
	Arbesi	0.452	166.85	0.239 (52.88%)	78.586 (47.1%)	7.835
	Jhila	0.300	158.43	0.159 (53%)	75.254 (47.5%)	7.510
	Harinbhanga	0.296	155.29	0.157 (53.04%)	73.452 (47.3%)	7.330
	Khatuajhuri	0.289	152.71	0.153 (52.94%)	72.690 (47.6%)	7.254
	Chamta	0.300	160.05	0.159 (53.00%)	76.024 (47.5%)	7.587
	Chandkhali	0.281	149.99	0.149 (53.02%)	70.645 (47.1%)	7.050

Table 8.13 Carbon sequestration by *Avicennia marina* inhabiting Indian Sundarbans

Species	Stations	AGB (tonnes/ha)		AGC (tonnes/ha)		Carbon sequestration = ΔAGC/Δt (tonnes/ha/yr)
		1 Year	11 Year	1 Year	11 Year	
Avicennia marina	Muriganga	0.151	39.863	0.077 (51.0%)	18.018 (45.2%)	1.794
	Saptamukhi	0.159	42.334	0.080 (50.3%)	19.347 (45.7%)	1.927
	Jambu Island	0.313	45.781	0.159 (50.8%)	21.013 (45.9%)	2.085
	Lothian Island	0.313	44.663	0.159 (50.8%)	20.366 (45.6%)	2.021
	Sagar Island	0.309	43.284	0.157 (50.8%)	19.651 (45.4%)	1.949
	PrenticeIsland	0.155	45.004	0.079 (51%)	20.567 (45.7%)	2.049
	Thakuran	0.533	66.281	0.279 (52.3%)	31.749 (47.9%)	3.147
	Dhulibasani	0.357	64.385	0.187 (52.4%)	30.969 (48.1%)	3.078
	Chulkathi	0.358	64.224	0.187 (52.2%)	30.699 (47.8%)	3.051
	Goashaba	0.366	66.883	0.191 (52.2%)	32.104 (48%)	3.191
	Matla	0.363	67.991	0.190 (52.3%)	32.568 (47.9%)	3.238
	Pirkhali	0.555	70.224	0.290 (52.3%)	33.778 (48.1%)	3.349
	Arbesi	0.157	39.112	0.078 (49.7%)	17.718 (45.3%)	1.764
	Jhila	0.152	35.668	0.076 (50%)	16.122 (45.2%)	1.605
	Harinbhanga	0.301	37.885	0.151 (50.2%)	17.427 (46%)	1.728
	Khatuajhuri	0.151	38.447	0.075 (49.7%)	17.609 (45.8%)	1.753
	Chamta	0.148	40.299	0.074 (50%)	18.336 (45.5%)	1.826
	Chandkhali	0.142	41.326	0.071 (50%)	18.886 (45.7%)	1.882

Table 8.14 Carbon sequestration by *Avicennia alba* inhabiting Indian Sundarbans

Species	Stations	AGB (tonnes/ha)		AGC (tonnes/ha)		Carbon sequestration = ΔAGC/Δt (tonnes/ha/yr)
		1 Year	11 Year	1 Year	11 Year	
Avicennia alba	Muriganga	0.415	41.224	0.212 (51.0%)	18.716 (45.4%)	1.850
	Saptamukhi	0.270	43.081	0.138 (51.1%)	19.731 (45.8%)	1.959
	Jambu Island	0.442	47.112	0.226 (51.1%)	21.719 (46.1%)	2.149
	Lothian Island	0.437	45.998	0.223 (51.0%)	21.067 (45.8%)	2.084
	Sagar Island	0.287	45.110	0.146 (50.8%)	20.705 (45.9%)	2.056
	PrenticeIsland	0.288	47.117	0.147 (51.0%)	21.580 (45.8%)	2.143
	Thakuran	0.326	68.130	0.170 (52.1%)	32.771 (48.1%)	3.260
	Dhulibasani	0.483	70.223	0.252 (52.1%)	33.918 (48.3%)	3.367
	Chulkathi	0.652	68.441	0.340 (52.1%)	32.852 (48.0%)	3.251
	Goashaba	0.653	67.965	0.341 (52.2%)	33.099 (48.7%)	3.276
	Matla	0.665	70.416	0.347 (52.2%)	34.011 (48.3%)	3.366
	Pirkhali	0.493	73.103	0.258 (52.3%)	35.747 (48.9%)	3.549
	Arbesi	0.264	43.269	0.132 (50.0%)	19.817 (45.8%)	1.969
	Jhila	0.263	39.808	0.132 (50.1%)	18.192 (45.7%)	1.806
	Harinbhanga	0.134	38.615	0.067 (50.0%)	17.917 (46.4%)	1.785
	Khatuajhuri	0.397	40.109	0.199 (50.1%)	18.450 (46.0%)	1.825
	Chamta	0.136	41.967	0.068 (50.0%)	19.263 (45.9%)	1.920
	Chandkhali	0.277	41.326	0.139 (50.2%)	18.969 (45.9%)	1.883

Table 8.15 Carbon sequestration by *Avicennia officinalis* inhabiting Indian Sundarbans

Species	Stations	AGB (tonnes/ha)		AGC (tonnes/ha)		Carbon sequestration = ΔAGC/Δt (tonnes/ha/yr)
		1 Year	11 Year	1 Year	11 Year	
Avicennia officinalis	Muriganga	0.428	42.008	0.220 (51.4%)	19.786 (47.1%)	1.957
	Saptamukhi	0.574	44.116	0.295 (51.3%)	20.690 (46.8%)	2.040
	Jambu Island	0.420	49.004	0.215 (51.2%)	23.032 (47.0%)	2.282
	Lothian Island	0.447	46.137	0.230 (51.4%)	21.177 (45.9%)	2.095
	Sagar Island	0.451	46.220	0.231 (51.2%)	21.631 (46.8%)	2.140
	PrenticeIsland	0.415	48.217	0.213 (51.3%)	22.517 (46.7%)	2.230
	Thakuran	0.970	68.995	0.509 (52.4%)	31.600 (45.8%)	3.109
	Dhulibasani	0.649	75.116	0.340 (52.4%)	36.131 (48.1%)	3.579
	Chulkathi	0.505	72.553	0.265 (52.5%)	34.680 (47.8%)	3.442
	Goashaba	0.672	70.134	0.352 (52.3%)	33.664 (48.0%)	3.331
	Matla	0.859	73.228	0.450 (52.4%)	34.857 (47.6%)	3.441
	Pirkhali	0.683	75.004	0.358 (52.4%)	35.102 (46.8%)	3.474
	Arbesi	0.272	42.819	0.137 (50.4%)	20.467 (47.8%)	2.033
	Jhila	0.283	36.208	0.143 (50.5%)	17.380 (48.0%)	1.724
	Harinbhanga	0.143	37.191	0.072 (50.3%)	17.666 (47.5%)	1.759
	Khatuajhuri	0.297	40.120	0.150 (50.5%)	18.816 (46.9%)	1.867
	Chamta	0.140	38.178	0.070 (50.0%)	17.791 (46.6%)	1.772
	Chandkhali	0.283	41.227	0.142 (50.2%)	19.418 (47.1%)	1.928

Table 8.16 Carbon sequestration by *Excoecaria agallocha* inhabiting Indian Sundarbans

Species	Stations	AGB (tonnes/ha)		AGC (tonnes/ha)		Carbon sequestration = ΔAGC/Δt (tonnes/ha/yr)
		1 Year	11 Year	1 Year	11 Year	
Excoecaria agallocha	Muriganga	0.256	38.112	0.132 (51.6%)	18.103 (47.5%)	1.797
	Saptamukhi	0.131	40.667	0.068 (51.9%)	19.154 (47.1%)	1.909
	Jambu Island	0.252	42.814	0.130 (51.5%)	19.823 (46.3%)	1.969
	Lothian Island	0.261	43.559	0.135 (51.7%)	19.950 (45.8%)	1.982
	Sagar Island	0.129	40.664	0.066 (51.1%)	18.421 (45.3%)	1.836
	PrenticeIsland	0.127	42.917	0.066 (51.9%)	19.742 (46.0%)	1.968
	Thakuran	0.273	62.35	0.142 (52.0%)	28.307 (45.4%)	2.817
	Dhulibasani	0.260	59.581	0.135 (51.9%)	28.003 (47.0%)	2.787
	Chulkathi	0.123	58.017	0.064 (52.0%)	27.442 (47.3%)	2.738
	Goashaba	0.256	62.206	0.133 (51.9%)	29.610 (47.6%)	2.948
	Matla	0.122	63.459	0.063 (51.6%)	29.826 (47.0%)	2.976
	Pirkhali	0.278	65.883	0.145 (52.1%)	30.636 (46.5%)	3.049
	Arbesi	0.131	36.497	0.066 (50.3%)	17.081 (46.8%)	1.702
	Jhila	0.123	33.22	0.063 (51.2%)	15.713 (47.3%)	1.565
	Harinbhanga	0.130	34.426	0.066 (50.7%)	16.215 (47.1%)	1.615
	Khatuajhuri	0.125	36.108	0.063 (54.4%)	16.790 (46.4%)	1.673
	Chamta	0.126	37.515	0.064 (50.7%)	17.294 (46.0%)	1.723
	Chandkhali	0.259	38.777	0.131 (50.5%)	18.186 (46.8%)	1.806

Table 8.17 Species-wise carbon sequestration potential of mangroves inhabiting three different sectors of Indian Sundarbans with variable salinity

Species	Western Indian Sundarbans	Central Indian Sundarbans	Eastern Indian Sundarbans
Sonneratia apetala			
Avicennia marina			
Avicennia alba			
Avicennia officinalis			
Excoecaria agallocha			

Index (based on carbon sequestration values stated in tables 8.11 to 8.16)

1.000- 2.900- **Not recommended for plantation**

3.000- 4.900- **Recommended for plantation**

5.000- 6.900- **Strongly recommended for plantation**

7.000- 8.900- **Most strongly recommended for plantation**

is used in place of a variable that cannot be measured or is difficult to measure. The proxy variable can be something that is not of any great interest itself, but has a close correlation with the variable of interest (here the adaptation of mangroves to different salinity gradients). Our approach to expand mangrove vegetation in different sectors of lower Gangetic delta as a function of salinity (Table 8.17) may be a viable road map for mitigation of carbon dioxide rise at local level.

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