Sourav Das
Tuhin Ghosh *Editors*

Estuarine Biogeochemical Dynamics of the East Coast of India

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In the loving memory of

Late Prof. Ananda Deb Mukhopadhyay
(3 May 1938 – 8 October 2020)

Prof. Ananda Deb Mukhopadhyay was an eminent academician and a renowned researcher in multifarious fields of geology, oceanography, and environmental studies. He was a well-loved teacher with father-like character and guided a number of students in academia and their personal lives. His love and affection towards the student community is still cherished by many who came in touch with him. Being a professor in the Department of Geological Sciences at Jadavpur University, West Bengal, India, he founded the School of Oceanographic Studies. He has also served as the Vice Chancellor of Vidyasagar University, West Bengal, India. Till his last day, he was actively involved with the National Council of Education, India.

Preface

Estuaries, located at the interface between land and coastal oceans, are dynamic, highly productive systems that, in many cases, have been historically associated with the development of many of the great centers of early human civilization. Biogeochemistry of estuaries offers a comprehensive and interdisciplinary approach to understanding biogeochemical cycling in estuaries. Estuary and river systems play a critical role in the natural self-regulation of Earth's surface conditions by serving as a significant sink for anthropogenic CO_2. Approximately 90% of global carbon burial occurs in ocean margins, and the majority of this carbon remains buried in large delta-front estuaries. Many of the existing books in estuarine science comprise a suite of edited volumes, typically focused on specific topics in estuaries all over the world. However, the present book entitled *Estuarine Biogeochemical Dynamics of the East Coast of India* provides a unique foundation for the first time on the east coast of India. This book utilizes numerous illustrations and an extensive literature base to impart the current state-of-the-art knowledge in this field on the east coast of India adjacent to the Bay of Bengal. We collated chapters on geomorphology, carbon dynamics, bacterial population, estuarine pollution, and nutrient cycling of this region. The book also comprised the role of microbial diversity, microzooplankton variability in estuaries, CDOM dynamics of the east coast of India, and anthropogenic impacts of Indian Sundarbans (the largest mangrove forest in the world) with linkages to physical and biological processes in estuarine sciences. Consequentially, these systems have and continued to be severely impacted by anthropogenic inputs. This timely book can act as the foundational basis of elemental cycling in estuaries of the east coast of India and estuarine management issues. Estuarine and marine scientists, ecologists, biogeochemists, and environmentalists around India and other parts of the world would find interest in the present title. Intermediate to advanced level students can benefit by going through this book. This book presents both review and original study findings involving estuaries on the east coast of India. The future state of all of these estuaries may be a sensitive indicator of shifts in global weather patterns.

The book opens with an introductory chapter by the editors (Dr. Sourav Das and Prof. Tuhin Ghosh). Then, Mr. B. K. Saha (Former Senior Deputy Director-General, Geological Survey of India) presents a brief account of the geology of the east coast of India. Studies about the estuarine carbon dynamics along the east coast of India have seen tremendous growth over the past decade. Dr. Kunal Chakraborty (Scientist-E, INCOIS, Govt. of India) has reviewed these works in one of the chapters. A synthesis of previous research works on the biogeochemistry of the Mahanadi estuarine ecosystem is presented in one of the chapters by Dr. Tamoghna Acharyya (focusing on increased anthropogenic interferences). Dr. Abhra Chanda (Assistant Professor, School of Oceanographic Studies, Jadavpur University) has reviewed different pollution parameters along the east coast of India in three of the chapters (focusing on persistent organic pollutants, heavy metals, eutrophication, algal bloom, fecal coliform, organic matter, and petroleum hydrocarbon). Dr. Anirban Mukhopadhyay illustrated the variability of suspended particulate matter with the help of geo-statistical analysis. Dr. Rajdeep Roy (Scientist-E, National Remote Sensing Centre, India) has described the nutrient cycling, phytoplankton community structure, and seasonal dynamics of primary production of the estuarine waters of the east coast of India. Mercury-resistant marine bacterial population has been synthesized by Dr. Surajit Das. Dr. Biraja Kumar Sahu covered the microzooplankton studies carried out in estuaries, mangroves, and lagoons of the east coast of India. The book continues with a chapter by Dr. Sudarsanarao Pandi covering all the information and gap on CDOM-related researches carried out in estuaries and rivers draining into the Bay of Bengal. The book closes with an overview of the current understanding of biogeochemical dynamics and anthropogenic impacts on the Indian Sundarbans ecosystems by A. C. G. Henderson (Faculty, School of Geography, Politics & Sociology, Newcastle University, UK), Dr. S. Das, Prof. T. Ghosh, Dr. V. N. Panizzo, Dr. H. L. Moorhouse, Dr. L. R. Roberts, Dr. R. E. Walton, Dr. Y. Zheng, Dr. A. M. Bass, and Dr. S. McGowan.

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Chapter 1
Introduction: An Overview of Biogeochemical Cycle of Estuarine System

Sourav Das and Tuhin Ghosh

Abstract Estuaries are one of the most dynamic regions of the world where a suite of biogeochemical phenomena drives the ecosystem functions. This chapter has provided a brief overview of the role of estuaries as a fragile ecosystem and the environmental processes involved in this regime. The most significant topics which have gained impetus from the viewpoint of research are introduced in the chapter. These topics include the effect of climate change, nutrient dynamics, sedimentation, and the carbon cycle. India encompasses a long coastline, and the eastern side of the Indian peninsula has an intricate network of estuaries. This chapter has set up a background of the present book giving special emphasis on the estuaries of the east coast of India. The scope of the entire book along with the chapter summary is also included in this chapter to engage the readers. Overall, this chapter can be considered as a brief introduction to the book.

Keywords Overview of estuarine system · Coast · Estuarine nutrient dynamics · Estuarine carbon cycle · Sedimentation in estuarine ecosystems · Estuaries of India

1.1 Coast and Estuaries

Coastal environments are areas of substantial productivity and high convenience. Despite their comparatively small areal cover (only 7% of the biosphere ocean surface), coastal regions play a significant role in the global carbon cycle and defending from human impacts on ocean systems. They are contributing to 12–16% of the biosphere ocean net annual productivity and approximately responsible for more than 40% of the yearly carbon sequestration (Muller Karger et al. 2005). The coastal sector characterizes more than 85% of the biosphere fish catch (Pauly and Christensen 1995), and Costanza et al. (1997) estimate its economic value, i.e., >40% of the

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value of the world ecosystem services. Alongi et al. (1998) quantified the coastal area as a zone of severe human impact on the marine environs, and more than 60% of the world population survive along the shoreline. The present book is based on the biogeochemical characteristics of major coastal and estuarine regions (adjoining to the Bay of Bengal) of the east coast of India.

However, the estuary is an integral sector of the coastal environment. An estuary is a transitional zone between the fluvial and marine environments and the outfall province of the river. The estuarine ecosystem is the most dynamic and delivers a direct source of natural resources to humankind. These ecosystems are also used for industrial, commercial, and recreational purposes. Bianchi (2007) defines an estuarine system as a resource for commercially valuable estuarine species.

Estuaries also provide shelter and food for the juvenile stages of the economically important species. More than 85% of the world's land surface is joined to the sea by rivers (Ludwig and Probst 1998). Present-day estuaries were shaped during the last 5000–5500 years in a stable interglacial period. Only 12–15% of the world's 180 prominent rivers that empty freely from the source to the ocean form different types of estuaries (Wang et al. 2007). The Ganges River – one of the largest rivers (~2510 km in length) in the world – stands in the third position (first one is Amazon and second is the Congo River) for draining freshwater to the Bay of Bengal from terrestrial through the Hooghly estuary, one of the estuarine systems presented in the book.

1.2 Estuarine Processes

Estuaries represent a biogeochemically active zone since it receives massive inputs of terrestrial organic matter and nutrient and exchanges large amounts of matter and energy with the open ocean (Bouillon et al. 2007). In tropical estuaries, where the water temperature is more or less stable, a number of plants and animals are less affected. Tides are necessary for healthy estuaries as they flush the systems and provide nutrients to keep the food webs functional. However, the tides create incessantly changing conditions of exposure to air and inundation to water. Water circulation is important because it transports animals and plants; mixes nutrients, oxygen, and sediments; and removes wastes. Estuarine circulation, river and groundwater discharge, tidal flooding, re-suspension events, and exchange flow with adjacent areas (Leonard and Luther 1995) all constitute important physical variables that exert some level of control on estuarine biogeochemical cycles.

1.3 Impact of Climate Change on Estuaries

Previous studies emphasized that disturbance in natural processes limits the estuarine health and viability (Goldberg 1995), making them all the more vulnerable to the consequences of climate change. Some of the critical potential impacts of climate change on estuaries may result from changes in physical mixing characteristics

caused by changes in freshwater runoff (Scavia et al. 2002). A globally intensified hydrological cycle and regional alterations in runoff all comprehensively indicate changes in coastal water quality. Freshwater inflows into estuaries influence water residence time, nutrient delivery, vertical stratification, salinity, and control of phytoplankton growth rates. Increased freshwater inflows decrease the water residence time and enhance vertical stratification and vice versa (Moore et al. 1997). The effects of altered residence times can have significant impacts on phytoplankton populations, which have the potential to increase fourfold per day. Changes in the timing of freshwater delivery to estuaries could lead to a decoupling of the juvenile phases of many estuarine and marine fishery species from the available nursery habitat. Increased water temperature also affects a suite of microbial processes such as nitrogen fixation and denitrification in estuaries (Lomas et al. 2001). Apart from that, extreme weather events such as cyclones and flooding are likely to be a future threat to estuarine systems (Nicholls et al. 2007).

1.4 Estuarine Nutrient Dynamics

Ecosystem responses depend on several critical physicochemical characteristics and processes. The transport, transformation, retention, and export of nutrients in estuarine ecosystems are strongly influenced by estuary size (surface area), depth, volume, flushing rate, water residence time, tidal exchange, vertical mixing, and stratification. Riverine input influences estuarine hydrography by creating salinity gradients and stratification and assures large transport of silt, organic material, and inorganic nutrients to the estuaries. The open marine areas impose large-scale physical and chemical forcing on the estuarine ecosystem due to tide and wind-generated water exchange (Berner and Berner 1996; Flindt et al. 1999).

During the last six decades, global riverine C, N, and P inputs (inorganic nutrient flux) into the ocean have trebled due to regional climate, geology, and human activities, whereas the dissolved silicate stemming from natural sources was significantly reduced (Turner et al. 2005; Lohrenz et al. 2002). Changed ratios of the essential nutrients Si, N, and P entail changes of the plankton community and the biogeochemical cycles (Smith et al. 2003). These enhanced inputs of C, N, and P are due to increasing population density in the areas of major river drainage basins and close oceanic coastlines; socio-economic development and changes in land-use practices; enhanced discharges of industrial, agricultural, and municipal waste into continental margin waters via the river; groundwater discharges; and atmospheric transport (Meybeck and Vörösmarty 2005). Engineering projects (damming of the rivers) have an opposite effect by altering the hydrological regime of most of the world's major rivers. The current state of knowledge indicates that the impact of dams on estuarine ecosystems is profound, complex, varied, multiple, and mostly negative (Adams et al. 2002). By storing or diverting water, dams alter the natural distribution and timing of stream flows. This alteration in land use, in turn, changes sediment and nutrient regimes and alters water temperature and chemistry, with consequent ecological and economic impacts.

1.5 Estuarine Carbon Cycle

Recent observations have shown that river-estuary systems release a significant amount of CO_2 into the atmosphere in addition to the commonly recognized fluvial export of inorganic/organic matter (Borges et al. 2006; Hofmann et al. 2009). Over 97% of the runoff has been classified as the $Ca(HCO_3)_2$ type, making HCO_3^-, Ca^{2+}, SO_4^{2-}, and SiO_2 the dominant dissolved constituents in global surface river waters (Mehrbach et al. 1973; Bianchi 2007). Rivers are generally net heterotrophic, resulting in greater consumption of HCO_3^- by river phytoplankton (Bianchi et al. 2004). High decomposition rates in estuarine systems may result in the export of DIC that rivals that of riverine export to coastal waters (Wang and Cai 2004). Estuarine and freshwater systems are close to equilibrium with atmospheric CO_2 and are influenced by temperature and salinity (Wetzel 2001).

The abiotic source of CO_2 in rivers and estuaries is the photochemical mineralization of dissolved organic carbon (DOC). This process happens either by direct photo-oxidation of DOC to CO_2 by solar UV radiation (Granéli et al. 1996) or by cleavage of DOC molecules into low molecular weight compounds available for bacterial metabolism (Bertilsson and Stefan 1998). Allochthonous DOC is preferentially photomineralized, while autochthonous DOC is preferentially mineralized by heterotrophic microbes (Obernosterer and Benner 2004). Finally, CO_2 in estuarine water also is the result of respiration by heterotrophic organisms. CO_2 loss from estuaries is supported largely by microbial decomposition of OC produced in coastal wetlands (Cai 2011).

Annually, world rivers transport large quantities of C to coastal seas (0.9 Gt C, out of which 40% is organic and 60% inorganic) (Etcheber et al. 2007). Particulate organic carbon (POC) in estuarine systems is derived from a multitude of sources. The autochthonous POC includes phytoplankton, submerged vegetation, benthic diatoms and cyanobacteria, and periphyton living on stems of emergent plants, whereas the allochthonous sources of POC consist of marginal marsh and swamp vegetation, marine- or river-borne phytoplankton and detritus, and beach, shoreline, and wind-blown material (Schlesinger 1997).

Several studies showed that nearshore ecosystems such as estuaries, mangrove waters, salt marsh waters, and coral reefs are assumed to be a net source of CO_2 (Cai et al. 2004; Borges et al. 2006; Abril and Borges 2005). In general, estuaries are CO_2-supersaturated as a result of the respiration of the riverine OC input. The overall source of CO_2 from nearshore ecosystems has been evaluated to ~0.50 Pg C y–1, mainly related to the emission of CO_2 to the atmosphere from estuaries (~0.36 Pg C y–1) (Chen and Borges 2009). Bouillon et al. (2008) reported oversaturation of CO_2 in different mangrove forests surrounding waters, suggesting that this surface water is a significant source of CO_2 to the atmosphere. The direction and magnitude of air-water CO_2 exchanges strongly depend on the type of ecosystem at the coast (Borges et al. 2006), the ocean currents dominating at a respective coast (Liu et al. 2000), and the geographical latitude (Liu et al. 2000; Borges et al. 2006). Isotopic

signatures from sediments suggest that most of the terrestrial POCs are degraded in estuaries (Hedges et al. 1997) under the strong net heterotrophic nature of the system (Gattuso et al. 1998; Hopkinson and Smith 2005).

Estuarine water and wetlands are the dominant natural source of CH_4 all over the globe and emit between 100 and 230 Tg CH_4 y^{-1} globally (Denman et al. 2007) and are expected to remain largely unchanged in the future. Bange et al. (1994) reported that up to 75% of total oceanic CH_4 emissions are from estuarine and coastal areas that contribute around 2% of global atmospheric CH_4 emission.

1.6 Sedimentation in Coastal/Estuarine Ecosystems

Sedimentation (as well as erosion) is an elementary phenomenon of nature dealing with loose sediments within the transporting cycle from source to sink locations. Sedimentation of the coastal environment is often associated with human interference in the physical system, such as land-use changes (Walling 2006), construction of artificial structures, or the dredging of sediment from the bed to increase the flow depth or width. Sedimentation affects the navigation, shoreline erosion and stability, migration of shoals, fate of nutrients, contaminants such as heavy metals and pesticides, turbidity, and the primary productivity of estuaries (Wolanski 1995).

Estuaries are recognized as a trap for fine, cohesive coastal sediments (FitzGerald and Knight 2005; Syvitski et al. 2005). Coastal sedimentary processes are inherently dynamic, but significant changes have been related to anthropogenic activities in upland areas (Syvitski et al. 2005). Estuaries are associated with rivers or other forms of runoff from land. They are the immediate recipients of sediment carried by those rivers, as manifest by the formation of river deltas. In the long term, sediment build-up in estuaries is limited by a dynamic balance between the effects of tides, waves, and rivers on sediment inputs and outputs in different parts of an estuary. Estuarine export of fine and coarse sediment is poorly understood because of the tidal pumping mechanism involved in estuarine sediment import (Wolanski et al. 2006). The Hooghly is a macro-tidal estuary that receives high sediment loads from the river Ganges, majorly filled with fluvial sediments. Particle settling in this estuary can be enhanced by the change from fresh to saltwater, the rise and fall of the water level with the tides, and the presence of turbidity maxima during slack tides.

1.7 Estuaries of India

The length of the total coastline in India is approximately 7515 km, and estuaries cover about 27,000 square km area. The Indian subcontinent has 160 minor, 45 medium, and 14 major rivers with an overall catchment region of 3.12×10^6 square km. The combined length of all rivers is 4.5×10^4 km. Kumar et al. (2006) stated

Table 1.1 Major estuaries in the east coast of India

States in the east coast of India	Estuaries	Average discharge (m^3/s/day)
West Bengal	Ganges delta	35,217
Odisha	Mahanadi	2100
Andhra Pradesh	Godavari	3500
	Krishna	2100
	Pennar	200
Tamil Nadu	Cauvery	600
	Ponnaiyar	21
	Vaigai	28

Source: http://iomenvis.nic.in

Table 1.2 The status of important ecologically sensitive areas along the east coast of India

Sensitive area	State	Area (sq km)	Coast length	Status of inlet/ channels	Importance
Indian Sundarban	West Bengal (40%), Bangladesh	4260	85 km inland	Cluster of 102 islands	World's largest mangrove, erosion
Chilika (Asia's largest lagoon)	Odisha	906–1155	64	North shifting/ opening and closing inlets	Aqua catch, dolphins, birds
Kolleru (Asia's largest freshwater body)	Andhra Pradesh	308–954	Inland lake	60 km long river Upputeru joining sea and lake	Aquaculture, agriculture, birds
Pulicat Lake (Asia's second largest lagoon)	Andhra Pradesh (84%)/Tamil Nadu (16%)	350–450	60	Three inlets – Tupili Palem, Pulicat, Rayadoruvu	Mangroves, aqua culture
Golf of Mannar	Tamil Nadu	10,500	63.22	21 islands, coral reefs, estuaries, mangrove	Coral hub

Source: Mishra (2016)

that about 26% of the total population survive within 100 km from the coast in India. There are five major rivers, namely, Ganges, Mahanadi, Godavari, Krishna, and Cauvery, on the east coast (Table 1.1) and Narmada and Tapti on the west coast. The Ganges estuary is considered the largest estuary on the east coast of India as well as in India. Geological processes along with various physical processes like wave, wind, current, tide, and also sediment influx play a crucial role in the formation of the coastal domain and for the development of the estuarine system as well to characterize the water quality of the coastal water of India. The coast is experiencing varying tidal ranges of 4.3 m at Sagar Island (the mouth of Hooghly River), 1.3 m at Kakinada, 1.0 m at Chennai, and 0.9 m at Pondicherry (Nayak and Hanamgond 2010). Besides, there are several ecologically sensitive zones along the east coast of India (Table 1.2). The Ganges estuary, also known as the Hooghly-

Matla estuarine systems, deserves a special mention in this regard. Millions of people are directly and indirectly dependent on this estuarine system, which is also one of the most polluted estuaries of this country as well. This estuarine system also exhibits unique carbon dynamics. The eastern part of the estuary essentially acts as a source of CO_2, whereas the other counterpart acts as transient sinks, especially in the post-monsoon season (Akhand et al. 2016). Due to its vast north to south as well as east to west stretch, the spatial variability in the carbon dynamics depends on an array of biogeochemical and metrological factors.

1.8 Scope of the Book

The biogeochemical properties from upland to coastal margin ecosystems of the northeastern flank of the Indian Ocean (east coast of India) are least understood. There are various research carried out along the east coast of India, while one or two estuaries encompassed most of those studies. Several small to large estuaries, like the Hooghly, Mahanadi, Godavari, Krishna, and Cauvery (Table 1.1), intersperse the east coast of India facing the Bay of Bengal (BoB). This coastal region is one of the most dynamic regimes in the world. A significant amount of river discharge from several perennial estuaries vis-à-vis the effect of monsoon and frequent depression and tropical cyclones makes the estuarine and coastal waters of the east coast of India unique from various perspectives. These physical forcing and extreme atmospheric events exert a substantial impact on the biogeochemistry of the water column in the east coast estuaries and nearshore waters. The purpose of the present work (book) is to understand the water quality parameters and their biogeochemical interaction within the estuarine ecosystem of the east coast of India.

Therefore, it is necessary to identify the principal anthropogenic activities impacting the estuaries of the east coast of India, including the physicochemical variability, nutrient fluxes, organic carbon loading, and heavy metal pollution. It is worth examining these in detail to develop effective management strategies to mitigate their impacts. Moreover, this book addresses a few critical global change problems on the regional estuarine ecosystem, emphasizing their interactions with water quality.

Because of the complex nature of the processes (geologic or anthropogenic) occurring in the coastal zone of the east coast of India, a multi-disciplinary effort is necessary to find a holistic solution for their implementable management options, and the present book is a step forward in that direction (Table 1.3).

Table 1.3 Chapter outline of the present book

Chapter no.	Outline of the chapters
Chapter 2	A brief account of the geology of the east coast of India is presented to describe the geological processes which play an important role in the development of the different type of estuarine systems
Chapter 3	Discusses the present state of the art of several biogeochemical parameters in the estuaries along the east coast of India under normal conditions and the impact of different physical forcing in modulating these parameters. Moreover, it defines a stark difference between the northern estuaries of the east coast and the southern estuaries concerning biogeochemical characteristics
Chapter 4	Discusses the understanding of estuarine carbon dynamics along the east coast of India
Chapter 5	Synthesizes previous research works on the biogeochemistry of the Mahanadi estuarine ecosystem concerning increased anthropogenic interferences
Chapter 6	Presents a detailed study on the mercury-resistant marine bacterial (MRMB) population along the Odisha coast and the effect of the physicochemical parameters on the population dynamics
Chapter 7	The chapter focuses on the persistent organic pollutant (POP) accumulation in the sediments, water column, and selected biotas in the estuaries along the east coast of India
Chapter 8	Discusses the present state of the art of heavy metal contamination in the water column, sediments, and marine organisms adjoining the estuaries of the east coast of India as well as assesses the human health risk
Chapter 9	Confers on the suspended particulate matter concentration variability along the northwestern coastal waters of Bay of Bengal to explain the regionalized coastal phenomenon affecting the environmental state by geo-statistical analysis
Chapter 10	Discusses all the principal findings observed concerning pollutions (eutrophication, algal bloom, fecal coliform, organic matter, and petroleum hydrocarbon) in the estuaries and nearshore waters along the east coast of India
Chapter 11	Describes the nutrient cycling, phytoplankton community structure, and seasonal dynamics of primary production of the estuarine waters of the east coast of India
Chapter 12	The chapter describes all the information on microzooplankton studies carried out in estuaries, mangroves, and lagoons to give a holistic view of the microzooplankton of the east coast of India
Chapter 13	This chapter addresses the impact of physical forcing mechanisms on spatiotemporal variation of biological productivity aided by nutrient dynamics in the coastal waters of the Bay of Bengal (east coast of India)
Chapter 14	The chapter describes all the information and gap on CDOM related researches carried out in estuaries of the east coast of India
Chapter 15	The present chapter presents an overview of our current understanding of biogeochemical dynamics and anthropogenic impacts on the Indian Sundarbans ecosystems

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