Chapter 15
The Indian Sundarbans: Biogeochemical Dynamics and Anthropogenic Impacts

Andrew C. G. Henderson, Sourav Das, Tuhin Ghosh, Virginia N. Panizzo, Heather L. Moorhouse, Lucy R. Roberts, Richard E. Walton, Ying Zheng, Adrian M. Bass, and Suzanne McGowan

Abstract The Sundarbans region is one of the richest ecosystems in the world and is located on one of the world's largest deltas – the Ganges–Brahmaputra–Meghna system. The Indian Sundarbans have exceptional biodiversity, including rare and globally threatened species, and is made up of a mangrove forest ecosystem with an interconnected network of rivers. The hydrology of the Sundarbans underpin ecosystem health and the potential impact of humans on the region, as the tidal cycle changes water salinity diurnally and freshwater supply changes seasonally with the monsoon. The Indian Sundarbans face multiple pressures with both a reduction in freshwater supply and rising relative sea-level, leading to increased salinization of the mangrove forest. Human-driven alteration of the Sundarbans river catchments is reducing sediment flow, and when coupled with land-use change, is leading to subsidence, deforestation, nutrient enrichment, and heavy metal pollutants impacting the health of the ecosystem. All of these impacts have important ramifications for carbon fluxes that could exacerbate climate change and ecosystem health. In this chapter, we present an overview of our current understanding of biogeochemical dynamics and anthropogenic impacts on the Indian Sundarbans, with a particular focus on water quality, aquatic ecology, and carbon dynamics.

Keywords Indian Sundarbans · Ganges–Brahmaputra–Meghna delta · Water quality · biogeochemistry · carbon · pollutants · ecology · sediments

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A. C. G. Henderson (✉) · R. E. Walton
School of Geography, Politics & Sociology, Newcastle University, Newcastle upon Tyne, UK
e-mail: andrew.henderson@ncl.ac.uk

S. Das · T. Ghosh
School of Oceanographic Studies, Jadavpur University, Kolkata, India

V. N. Panizzo · L. R. Roberts · S. McGowan
School of Geography, University of Nottingham, Nottingham, UK

H. L. Moorhouse
Lancaster Environment Centre, Lancaster University, Lancaster, UK

Y. Zheng · A. M. Bass
School of Geographical & Earth Sciences, University of Glasgow, Glasgow, UK

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15.1 Introduction

The Sundarbans region is one of the richest ecosystems in the world and is located on one of the world's largest deltas – the Ganges–Brahmaputra–Meghna (GBM) system. The Sundarbans is located in the estuarine phases of the Rivers Ganga, Brahmaputra, and Meghna between 21°32′N and 21°40′N and 88°05′E and 89°E, spanning regions in both India and Bangladesh (Spalding et al. 1997) and contains arguably the world's largest remaining area of mangroves (an area of ~2529 km^2, Bhattacharyya 2015). The Indian Sundarbans have exceptional biodiversity, including rare and globally threatened species, for example, the northern river terrapin (*Batagur baska*, Lesson 1831), the Irrawaddy dolphin (*Orcaella brevirostris*, Owen in Gray 1866), the Ganges River dolphin (*Platanista gangetica*, Lebeck 1801), the brown-winged kingfisher (*Pelargopsis amauroptera* Pearson 1841), and the Royal Bengal tiger (*Panthera tigris*, Linneaus 1785) – the only mangrove tiger on Earth (RAMSAR 2019). The mangrove ecosystem, which makes up the Indian Sundarbans, is an interconnected network of rivers, creeks, rivulets, and semi-diurnal tides. The lower delta is dominated by a network of tributary rivers, creeks, and channels, with direct marine influence on the most seaward part of the Indian Sundarbans (Fig. 15.1). As a result, there are a range of hydrological influences (including both freshwater and coastal water) on the mangrove system, and when coupled with its topographic heterogeneity it results in a rich biodiversity (Gopal and Chauhan 2006). This has led to the Sundarbans mangrove forest being designated a World Heritage Site by the International Union for Conservation of Nature (IUCN) in 1987; a Biosphere Reserve by United Nations Educational, Scientific and Cultural Organization (UNESCO) in 1989; and a wetland of international importance according to the RAMSAR convention in the year 2019.

Despite its international designation, the Indian Sundarbans face multiple pressures. As the freshwater discharge originating from the Himalayan uplands has decreased in recent decades (Raha et al. 2012), this has led to increased salinization of soil and groundwater within the Sundarbans, leading to the degradation of mangrove ecosystem health (Chowdhury et al. 2019). In addition, anthropogenic activities continue to alter hydrology and sediment flow, while land-use change is leading to deforestation, nutrient enrichment, and heavy metal pollutants causing many mangrove species to become threatened or extinct (Gopal and Chauhan 2006), triggering an overall degraded ecosystem. This, in turn, has important ramifications for carbon fluxes in the Indian Sundarbans that could further exacerbate climate change and ecosystem health. The following sections aim to explore these different pressures and the impacts they are having on the current and future state of this vital ecosystem.

15.2 Hydrological Regime and Sediment Flow

The Indian Sundarbans landscape has evolved from the subduction of the Asian plate under the Burma plate to neotectonic tilting creating a hydrological gradient leading to river discharge from the highlands (Morgan and McIntire 1959). As a

Fig. 15.1 A Sentinel-2 satellite natural color image taken in March 2018 of the Sundarbans region West Bengal, India, generated through the Sentinel Hub. The main rivers that influence the biogeochemistry and anthropogenic impact of the Sundarbans are labelled and major cities and towns are labelled. Inset map shows the location of the Sundarbans within in India

result, there are seven major estuarine rivers flowing through the Indian Sundarbans – the Hooghly, the Muriganga, the Saptamukhi, the Thakuran, the Matla, the Gosaba, and the Harinbhanga (also known as Ichamati and Raimangal) (Fig. 15.1). The combination of freshwater and tidal flow shape the deposition and erosion of sediments across the Sundarbans region, creating the dynamic nature of this deltaic environment. The climate of the Sundarbans is sub-humid and characterized by hot summers and mild winters (Fig 15.2a). The mean monthly temperature varies between 30 °C to 40 °C in the summer (June to September) and 15 °C to 20 °C in winter (October to March). Precipitation from the annual monsoon during June to September is the major freshwater source to the Indian Sundarbans as it represents 80% of all annual rainfall (1750–1800 mm per annum) for the region. As a result, changes in freshwater inputs from monsoon rains, baseline river discharge during the rest of the year and tidal hydrology strongly influence the Sundarban region.

15.2.1 Hydrological Regime

15.2.1.1 Freshwater Hydrology

Despite the Indian Sundarbans being part of the GBM system (Chatterjee et al. 2013), year-round continuous flow is limited to a few river channels. The Hooghly River discharges the most freshwater into the Indian Sundarbans and is the western

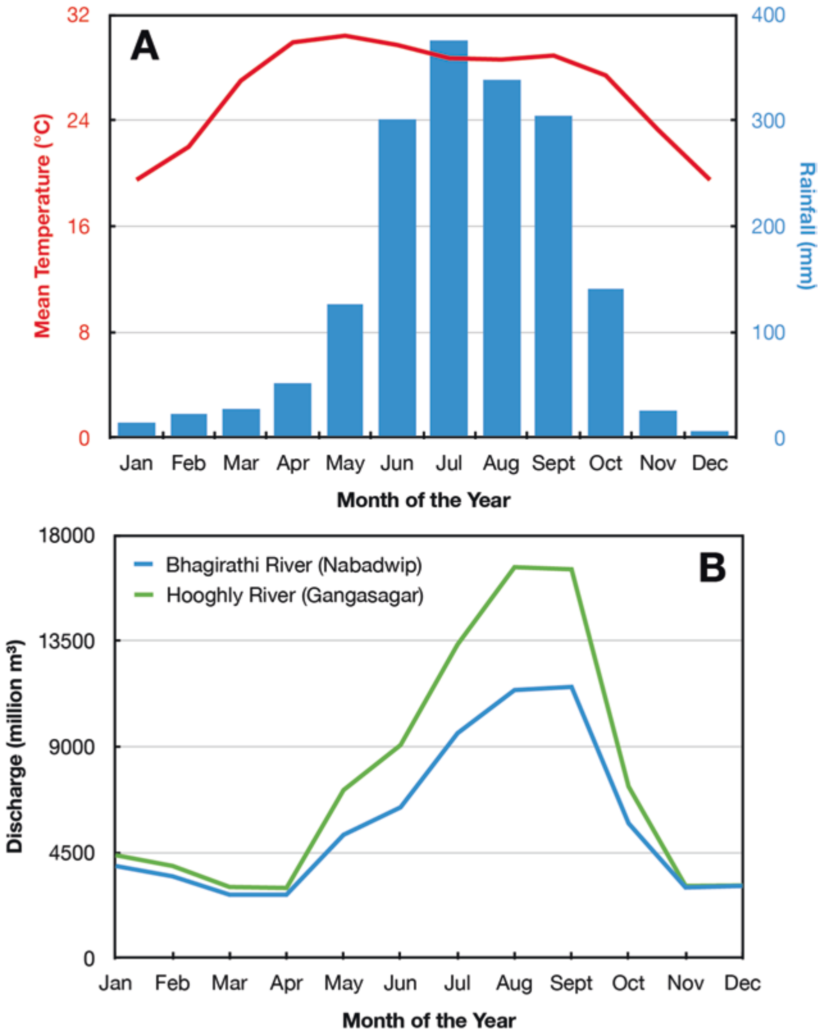

Fig. 15.2 (**a**) Summary of mean monthly temperature and precipitation data from Kolkata, West Bengal, from 1982 to 2012. Data from climate-data.org and is based on an interpolated model of weather station data; (**b**) Mean monthly discharge of the Bhagirathi and Hooghly River systems, West Bengal. (Data from Rudra (2014) and is derived from a rainfall-runoff model)

most branch of the River Ganges reaching the Bay of Bengal (Fig. 15.1) (Rudra 2018). The Raimangal River at the eastern edge of the Indian Sundarbans also brings additional freshwater as a tributary channel of the Ichamati River, and in turn this influences the discharge of the Gosaba, Harinbhanga, and Jhila Rivers (Chatterjee et al. 2013; Sarkar et al. 2013). While the monsoon seasons create variation throughout the year (Fig 15.2b), the Hooghly River has a more consistent input of freshwater than the Raimangal River (Chatterjee et al. 2013; Ghosh et al. 2013) due to the construction of the Farakka Barrage that diverts 7% of the annual flow of the Ganges to provide a regulated stream of freshwater throughout the dry season to support the operation of the Port of Kolkata (Ghosh et al. 2013).

15.2.1.2 Tidal Influence on Hydrology

The Sundarbans are macrotidal (range: 1.8 to 5.2 m between neap and spring high tides) and it experiences a semi-diurnal tide cycle (Gole and Vaidyaraman 1967; Rogers and Goodbred 2014; Sinha et al. 1996). Despite the large volumes of freshwater from the Hooghly and Raimangal Rivers, rising tides still influence the upstream hydrology of the Sundarbans, with tides regularly travelling up to 120 km from the mouth of the Hooghly River during the pre-monsoon season (Gole and Vaidyaraman 1967). In the post-monsoon, the tide can travel 250 km up the Hooghly (Sinha et al. 1996) with the tidal limit at Kalna, West Bengal, during the monsoon (Chatterjee et al. 2013).

As the tides bring saline water with them, they impact both anthropogenic access to freshwater and affect ecological functioning. The incursion of saline waters by flood tides is also controlled by the season in which it happens. For example, the extent of saline waters during the monsoon is low, as the increased freshwater delivered by seasonal rains acts as a barrier to flood tide penetration, with the upper limit typically as far as Nayachar Island in the upper mouth of the Hooghly River (Chatterjee et al. 2013; Ghosh et al. 2013; Sharma et al. 2018). Another effect is the stratification of freshwaters over the saline/brackish waters in the river during the monsoon season (Sadhuram et al. 2005; Chatterjee et al. 2013). In the non-monsoon seasons there is a significant rise in salinity levels within the Hooghly River with 30 ppt (parts per thousand) observed near Diamond Harbour and saline waters reach as far north as Kolkata (Gole and Vaidyaraman 1967), although during ebb tides the limit of saline water moves back down to the mouth of the estuary near Sagar Island (Sinha et al. 1996).

15.2.2 Sediment Flow

All river channels flow into the Indian Sundarbans, including freshwater rivers and tidal inflows, carrying sediments that affect the whole mangrove ecosystem. Sediments carried by the freshwater Hooghly River consist predominantly of sand and silt (Somayajulu et al. 2002; Massolo et al. 2012) and less than 10% of the sediment consists of clay particles. These sediments are predominantly derived from rain-driven terrestrial erosion to the Ganges (Somayajulu et al. 2002; Rudra 2018) and because of the high discharge of the Ganges and Hooghly Rivers these sediments do not experience much water-column weathering before they reach the Sundarbans and the Bay of Bengal (Somayajulu et al. 2002; Flood et al. 2016). While the Hooghly carries a large volume of sediment, there is a notable seasonal variation in sediment loads because of monsoon-driven changes in freshwater discharge (Gole and Vaidyaraman 1967).

Each year flood tides deposit ~12 cm of fresh sediment in to the Indian Sundarbans (Rudra 2018) and tides carry sediments that are more fine-grained than those transported by freshwater rivers (Allison et al. 2003; Flood et al. 2016, 2018). Sediments transported and deposited by flood tides in the Indian Sundarbans also originate from the mouth of the Ganges–Brahmaputra–Meghna River system approximately 275 km to the east (Flood et al. 2016, 2018; Rudra 2018), where >1 billion tons of sediment are discharged each year (Somayajulu et al. 2002; Rogers and Goodbred 2014; Rudra 2018). These sediments are carried by coastal currents westward along the coastline through suspension (Rogers and Goodbred 2014; Flood et al. 2018), where they undergo weathering and degradation in the water column, resulting in fine-grained sediments being transported in suspension by flood tides in to the Sundarbans (Flood et al. 2016, 2018). Sediments are deposited and retained because of lateral accretion along mangrove tree roots (Manna et al. 2012; Flood et al. 2018) and tidal creeks (Rudra 2018).

Resuspension of sediments occurs as a result of bioturbation in intertidal mudflats (Rogers and Goodbred 2014), dredging, winds, and tides. These resuspended sediments are redistributed or carried from the Sundarbans through flooding and wave action. Approximately 430 km^2 of the Indian Sundarbans were eroded between 1917–2016, which is offset by 220 km^2 of sediment accumulation over the same period (Rudra 2018). The dynamics of rivers, tides, and sediment movement means these are key processes that drive Sundarbans water quality, ecology, and overall ecosystem health (Gole and Vaidyaraman 1967; Sinha et al. 1996; Rogers and Goodbred 2014).

15.3 Ecology and Water Quality

The Indian Sundarbans are home to a number of endemic enigmatic and globally vulnerable species. By looking at the biology of these fragile Sundarbans ecosystems and the interface with hydrology and biogeochemistry we can document and understand the threats to the Sundarbans wetland ecosystem and its iconic inhabitants.

15.3.1 Aquatic Ecology

15.3.1.1 Primary Producers

Aquatic primary production in the Sundarbans is a function of nutrient loading and light penetration, with the latter often constrained by river turbidity (Chaudhuri et al. 2012). Large river and estuarine channels are dominated by the

Bacillariophyceae algal group – biosiliceous diatoms, followed by *Pyrrophyceae* – dinoflagellates, and *Chlorophyceae* – chlorophytes (Biswas et al. 2010; Manna et al. 2010; De et al. 2011). There are still large gaps in our knowledge about the role of these primary producers in mangrove ecosystems, especially diatoms (Samanta and Bhadury 2018). However, the biovolume of primary produces is highest in the post-monsoon winter months supporting colonies of long-chain diatoms, whereas there are low biovolumes during the monsoon season because of increased total suspended solids (TSS) (derived from rain-driven catchment erosion), reducing light penetration and photosynthesis (Chaudhuri et al. 2012; Bhattacharjee et al. 2013). Prior to the monsoon season the diatom assemblage is dominated by saline-tolerant species (Manna et al. 2010) and this may become a feature of upstream diatom communities as saline intrusion into the delta region becomes more widespread.

15.3.1.2 Macroinvertebrates

The main consumers of primary producers are the zooplankton, who play an integral role in the transfer of organic matter between trophic levels and export organic carbon to sediments (Bhattacharya et al. 2015a). As macroinvertebrate species occupy distinct trophic levels they respond rapidly to environmental change and are relatively quick and easy to identify, making them effective water-quality indicators (Gannon and Stemberger 1978). Copepods are small cosmopolitan crustaceans, which dominate zooplankton in tidal river systems in the Indian Sundarbans (Bir et al. 2015). Whereas in tidal flats, polychaetes and mollusks are important macrozoobenthic groups, whose spatiotemporal distribution is driven by salinity, the nature of the substrate (e.g., mudflats exhibit greater diversity than sandflats), and anthropogenic activity (Khan 2003; Roy and Nandi 2012).

In the Sundarbans, compositional changes in zooplankton communities are primarily driven by the quantity and quality of primary producer prey, as well as salinity and water transparency, which can vary seasonally and interannually (Bhattacharya et al. 2015a). Much like primary producers, zooplankton biomass is highest during the post-monsoon season when water currents, salinity, and temperature are at their lowest (Bir et al. 2015). However, extreme climate events, such as cyclone "*Aila*" in 2009, can lead to increased suspended particulates and nutrients, reductions in transparency, and primary photosynthesis. As a result there is a decrease in zooplankton diversity, biomass, and abundance (Bhattacharya et al. 2014a). If extreme events across the region worsen, this could modify phytoplankton–zooplankton interactions and threaten the viability of both open-water and aquaculture fisheries, whose stock require good quantity and quality of these prey organisms. Indeed, continued saltwater intrusion may reduce macrozoobenthic diversity due to reductions in decomposition rate of photosynthetic organic matter following higher sediment salinities, which may modify macrozoobenthic feeding behaviors and consequently impact the higher organisms which they support, for example, wading birds (Bandopadhyay and Burman 2006; Roy and Nandi 2012).

15.3.1.3 Microbial Biodiversity

Mangrove environments are hotspots of microbial diversity because of the complexity of habitats they provide and the fluxes in salinity, nutrients, labile organic compounds, and water levels across daily to seasonal timescales (Chakraborty et al. 2015). Seasonal variations in freshwater flow are an important determinant of community diversity, specifically of the bacterioplankton, where diversity is found to be greater in monsoon seasons compared to post-monsoon (Ghosh and Bhadury 2018). These microbes play a profound role in biogeochemical cycling from metabolizing the considerable allochthonous organic matter inputs of mangrove vegetation (Chakraborty et al. 2015), and therefore the sustenance, productivity, and recovery of this ecosystem (Ghosh et al. 2010; Roy et al. 2002; Santos et al. 2011). While there remains a significant gap in the knowledge of microbial diversity and abundance in the Sundarbans (Ghosh et al. 2010), modifications in microbial abundance, diversity, and community composition have been identified (Ghosh and Bhadury 2018). For example, industrial and boating activity has increased polyaromatic hydrocarbons (PAHs), heavy metal, and nutrient pollution detected by bacterial strains with heavy metal resistance and those involved in hydrocarbon degradation processes (Chakraborty et al. 2015). Eutrophication of these waters has meant bacterial productivity exhibits an exponential relationship to temperature as they are no longer nutrient-limited (Manna et al. 2010, 2012).

15.3.2 Water Quality

15.3.2.1 Nutrients

One of the key factors determining the biodiversity of the Indian Sundarbans is water and the role it plays in transporting nutrients and pollutants in the mangrove ecosystem (Sarkar et al. 2004). In general, phosphorus (P) availability is low in tropical regions where soils have been weathered for millions of years (Yang et al. 2013). Nitrogen (N) can be generated and removed from ecosystems by microbes and so mangroves are important sites for N (and C) cycling with mangrove plants being significant stores of N (Kamruzzaman et al. 2019; Purvaja et al. 2008). In coastal zones, P and N availability changes along the freshwater–marine transition, because sediments retain less P in marine environments, releasing P to the waters (Blomqvist et al. 2004). Primary production in freshwaters tends to be limited by P, whereas marine waters are generally N-limited and P-replete. Therefore, the tidal cycle in the Sundarbans is a key influence on nutrient distribution in estuaries, and the nutrient status of waters change seasonally to become P-limited after the monsoon when the influence of freshwaters increases, and N-limited during the monsoon and pre-monsoon periods (Chaudhuri et al. 2012). The main source of nutrients are from either freshwater runoff, for example, dissolved silica, nitrate, and phosphate, and/or from intertidal flats, for example, ammonium, nitrate/nitrite, and phosphate (Singh et al. 2016). During low tides, there is an increase in freshwater input into the northern Bay of Bengal, which dilutes nutrient concentration across the continental shelf and the mangrove ecosystem and vice versa during high tides, and these tidal dynamics play a crucial role in regulating short-term variability in nutrient concentrations (Das et al. 2015, 2017). Atmospheric deposition of P also constitutes a major source in the Sundarbans mangroves, comprising >50% of the annual P inputs (Ray et al. 2018a). P is hypothesized to be transported from arid regions of western India by pre-monsoonal northwesterly (and westerly) winds (Ray et al. 2018a). This seasonal P transport seems likely to either drive or exacerbate the observed seasonal differences in estuaries, but thus far there has been little research into the interplay of monsoonal rainfall, river discharge, and the consequences of desertification in arid regions on nutrient cycling of the Sundarbans.

In addition to natural variability in nutrients, anthropogenic inputs of nutrient-rich effluent have led to the eutrophication of smaller rivers, tidal creeks, and ponds in the Sundarbans, exacerbated by generally reduced flushing rates. However, such phenomena are being more commonly documented within the main estuarine channels such as the Hooghly River where anthropogenic influences has increased at a faster rate (Manna et al. 2010; De et al. 2011). Eutrophication has led to algal blooms, which reduce light penetration for benthic photosynthesis and deplete oxygen for higher trophic species (due to bloom respiration) (Biswas et al. 2014). In addition, harmful algal blooms (HABs) from toxin-producing cyanobacteria (CyanoHABs) such as *Microcystis* species and dinoflagellates have been recorded in Sundarbans aquatic habitats (Manna et al. 2010; Sen et al. 2015). CyanoHABs outcompete other algal groups due to their ability to regulate buoyancy, adaptation to low light, and higher temperatures, and are often able to fix N from the atmosphere (important in systems that are N-limited relative to P typical in these wetlands) (Paerl and Tucker 1995; Walsby and Schanz 2002; Islam et al. 2004; Paerl and Huisman 2008).

15.3.2.2 Heavy Metals

The primary source of heavy metal contamination in coastal areas of West Bengal is the major rivers that run through the Sundarbans (Mitra 1998) and even though these metals can occur naturally in the Sundarbans biogeochemical cycle (Garrett 2000), they predominantly come from industrial and domestic effluents, storm water runoff, dust, and boating activities. The mineralogy and grain size of sediments of the GBM river system has the potential to trap contaminants with silt and clays, predominantly carrying metal contamination from upstream. However, the textual composition and amount of organic matter in the sediment is critical to the sorption of transition metals (Kumar and Ramanathan 2015; Roy et al. 2018). Consequently, river sediments have become a sink of bioavailable heavy metals, with flooding and dredging leading to the resuspension of sediments, releasing their heavy metal load into the water column. Furthermore, salinity influences the partitioning, physiochemical form, and therefore bioavailability of these metals (Mitra 1998).

The Hooghly River catchment encompasses rural, agricultural, urban, and industrial land uses, including the megacity of Kolkata (population ~ 15 million) before draining into the Bay of Bengal. The metal concentrations of the riverine suspended particulate matter (SPM) ranges 7.9–29μg/g (mean: 19 ± 5.5μg/g) for Co, 17–70μg /g (mean: 49 ± 14μg /g) for Ni, and 12–55μg/g (mean: 36 ± 12μg/g) for Cu, which is higher than the average concentrations for global rivers (Samanta and Dalai 2018). The dissolved concentrations of metals in the Hooghly River estuary range 0.8–24 nM/L (mean: 6.2 ± 6 nM/L) for Co, 3.5–172 nM/L (mean: 50 ± 42 nM/ L) for Ni, and 8–178 nM/L (mean: 60 ± 37 nM/L) for Cu. Annually, these contribute up to 1.8% Co, 2.4% Ni, and up to 1.2% Cu of the global riverine metal fluxes (Samanta and Dalai 2018). The heavy metal concentrations of the Hooghly display seasonal variability with the maximum pollution load pre-monsoon and minimum load during the monsoon (Roy et al. 2018). High concentrations pre-monsoon have been attributed to high temperatures and increased evaporation rates of surface water (Bhattacharya et al. 2014a; Ghosh and Choudhury 1989; Mitra 1998).

Mixing of riverine and marine waters also contributes to changes in the speciation of metals, as well as the resuspension of sediments. Mukherjee et al. (2009) argue physicochemical changes limit the enrichment of heavy metals in river sediments and the high concentrations in the Hooghly compared to other regional rivers is because of a large sediment contribution from a bigger catchment area. The elevated concentrations in the Hooghly River are an important mechanism for elevating the amount of dissolved Ba in the river estuary via desorption with mixing of waters (Samanta and Dalai 2018). Similarly, Hg concentrations are positively correlated with pH ($r = 0.58–0.68$, $p < 0.01$) and salinity ($r = 0.52–0.79$, $p < 0.01$) (Bhattacharya et al. 2014b), and some metal concentrations in the waters of the middle and lower Hooghly estuary are significantly higher than other global estuaries in dissolved Ni and Cu (Samanta and Dalai 2018). However, upstream anthropogenic activities are still important in contributing widescale pollution across the Sundarbans.

Anthropogenic pollution within the Sundarbans itself has led to elevated levels of Cd, Cu, Zn, As, Ni, Pb, and Hg, which can cause impacts on biology (Sarkar et al. 2004; Chatterjee et al. 2007, 2009; Chowdhury et al. 2017; Mitra and Ghosh 2014). The source of these contaminants come from a mixture of industrial effluents, boat anti-fouling paint, sewage, fertilizers, and storm water drainage (Chowdhury and Maiti 2016; Mitra and Ghosh 2014; Chatterjee et al. 2007; Mitra et al. 2009; Kumar and Ramanathan 2015). Sediments within the Sundarbans have higher levels of contamination compared with sediments in the Hooghly estuary because of lower tidal energy and finer-grained sediments (Banerjee et al. 2012). Hooghly River inputs of Cu and Zn are a critical source of heavy metal pollution to the Sundarbans (Chakrabarti et al. 1993; Bhattacharya et al. 2015). Moreover, the metal concentration of fine-gained sediment in the Indian Sundarbans is higher than those in the Bangladesh Sundarbans (Kumar and Ramanathan 2015) (Table 15.1). The industrialization of the upper catchment in India compared to Bangladesh has been suggested as the primary reason for this difference (Rahman et al. 2011).

Table 15.1 Comparison of heavy metal concentrations (Fe, Mn, Cu, Zn) across the Indian and Bangladesh Sundarbans

Heavy metal	Indian Sundarban	Bangladesh Sundarban
Fe ($\mu g\ g^{-1}$)	38,760–52,829	29,081–45,025
Mn ($\mu g\ g^{-1}$)	424–770	342–792
Cu ($\mu g\ g^{-1}$)	36–82	12–45
Zn ($\mu g\ g^{-1}$)	55–83	29–75

Data from Kumar and Ramanathan (2015)

Table 15.2 Heavy metal concentrations in water, sediments, and macrobenthos from the Sundarbans. Concentrations in the macrobenthos exceed toxic levels

Heavy metal	Water	Sediment	Macrobenthos
Cd ($\mu g\ g^{-1}$)	0.04–0.10	6.25–7.38	14.63
Zn ($\mu g\ g^{-1}$)	0.01–9.66	24.91–62.0	268.91
Pb ($\mu g\ g^{-1}$)	0.03–0.16	33.7–50.33	174.84
Fe ($\mu g\ g^{-1}$)	14.3–170.0		
Cr ($\mu g\ g^{-1}$)		46.8–78.50	18.76
Cu ($\mu g\ g^{-1}$)		20.38–42.01	90.02

Data from Rahman et al. (2009)

15.3.2.3 Bioaccumulation and Health

Heavy metal pollution of the Sundarbans has important implications for the health of the ecosystem, aquatic organisms, and the local communities (Bhattacharya et al. 2015). River water in the region is largely unpotable due to the dissolved concentrations of Mn, Pb, and Ni (Bhattacharya et al. 2015). River water is also not suitable for irrigation due to the high concentration of Mn (Bhattacharya et al. 2015) and the large-scale metal pollution in riverine water and sediments is a serious concern as fish, prawns, and crabs have been reported to contain significant toxic metals (Dutta et al. 2017a; Mitra et al. 2012). Bioaccumulation of metals in these organisms occurs through the food chain until top level predators accumulate ions at a level that can develop neuronal, abdominal, and cardiovascular diseases. Table 15.2 shows the increase in metal accumulation between water, sediment, and macro benthos. At low concentrations, effects such as diarrhea, vomiting, and skin irritation are common. However, at high concentrations and continued exposure, there are serious health considerations with the International Agency for Research on Cancer (IARC) classifying Cd as a human carcinogen, Pb as possible human carcinogen, and Cr to be the cause of a rare sino-nasal cancer (Dayan and Paine 2001; Järup 2003).

15.4 Carbon Biogeochemistry

The Sundarbans contain nearly 3% of the total area of the world's mangrove ecosystems and have been an important region for understanding carbon cycle dynamics in estuarine delta ecosystems over the past 20 years. In particular, the biogeochemical cycling of different carbon species including dissolved organic carbon (DOC), particulate organic carbon (POC), dissolved inorganic carbon (DIC), and dissolved greenhouse gases (CO_2; CH_4) in different environments including estuarine water (e.g., Biswas et al. 2004; Dutta et al. 2019a, b), sediment (e.g. Dutta et al. 2013; Dutta et al. 2017b), mangrove soil and forests (e.g. Rahman et al. 2015; Chanda et al. 2016; Das et al. 2016).

15.4.1 Carbon Fluxes in the Sundarbans

Mangrove estuaries have been recognized as important organic C sources for the ocean and atmosphere (Rosentreter et al. 2018; Ray et al. 2015), with an estimated flux of 55 Tg C yr.$^{-1}$ (Sippo et al. 2017) derived from plant litter, phytoplankton, and microphytobenthos (Ray et al. 2015). However, the Sundarbans have a conspicuous lack of data related to its carbon budget. In particular, measurements of POC and DOC have only been taken in the last few years (Ray et al. 2018b; Dutta et al. 2019a, b). Ray et al. (2018b) provide the first baseline data of C export (DOC, POC, and DIC) from the Sundarbans mangroves into the Bay of Bengal, which accounts for 3.03 Tg C yr.$^{-1}$, 0.58 Tg C yr.$^{-1}$, and 3.69 Tg C yr.$^{-1}$, respectively. DIC is the major form of C exported in the Sundarbans region, contributing to >50% of the fluvial C budget (Fig. 15.3), with DIC concentration ([DIC]) varying between 1.92 to 2.19 mM

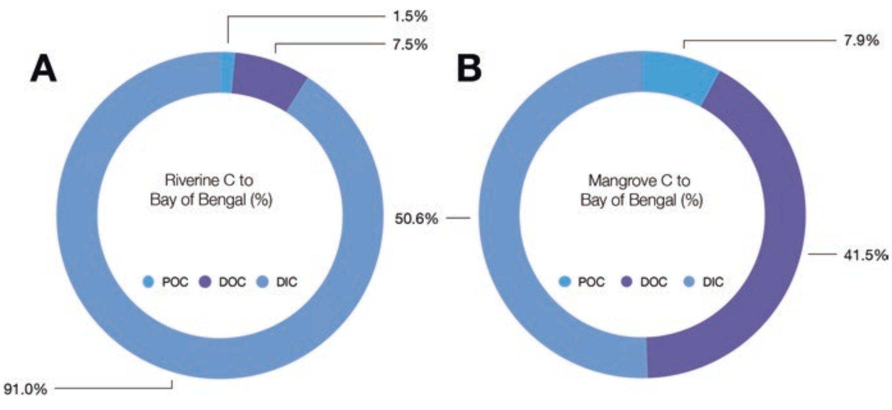

Fig. 15.3 Percentage contribution of the different carbon fractions – dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) – (**a**) riverine C export from the Hooghly River into the Bay of Bengal during the monsoon season with maximum discharge; (**b**) mangrove-derived C export into the Bay of Bengal. (Data from Ray et al. 2018b)

during a 24-hour period (Dutta et al. 2019a). However, compared to the Hooghly estuary, the major river draining into the Bay of Bengal, the percent contribution and flux of [DIC] from the Sundarbans is much smaller and it has a greater amount of organic-C flux (as DOC and POC). DOC concentration ([DOC]) was monitored in different seasons, with similar values observed during the pre- and post-monsoon (pre-monsoon: 294.3 ± 34 uM; post-monsoon: 262.5 ± 48.2 uM) (Ray et al. 2018b), 235 ± 49 (Dutta et al. 2019b). [POC] is much smaller than [DOC], ranging from 28.0 ± 8.6 uM during pre-monsoon to 45.4 ± 7.5 uM post-monsoon (Ray et al. 2018b). When more locations were monitored, a higher post-monsoon [POC] of 173 ± 111 uM was observed by Dutta et al. (2019b), reflecting the spatial variability of C flux within the Sundarbans region. DIC removal in the Sundarbans is facilitated by phytoplankton uptake, CO_2 outgassing and export to the adjacent continental shelf (Ray et al. 2018b), although significant uncertainty remains.

Much of the work on C biogeochemistry in the Sundarbans has focused on the CO_2 flux from river surface waters (Mukhopadhyay et al. 2002a, b; Biswas et al. 2004; Akhand et al. 2016; Vinh et al. 2019) (Table 15.3). While the mangrove forest is an autotrophic ecosystem and acts as a net C sink (Rodda et al. 2016), more temporal and spatial C flux data is needed to understand its potential to be a large C store. This is important as mangroves can export C to adjacent water bodies, increasing the fraction of CO_2 in water, which can control water-to-air emissions (Akhand et al. 2012) (Table 15.3). A study of the outer part of the Sundarbans found this area to be a CO_2 sink at a rate of 16×10^6 kg C year^{-1} (Mukhopadhyay et al. 2000), while other studies suggest mangrove estuaries are a net CO_2 source at a rate of 13.8 kg C ha^{-1} year^{-1} (Biswas et al. 2004), or it varies between a net source and sink through the seasons as influenced by the monsoon (Mukhopadhyay et al. 2002a, b) (Table 15.3).

The significance of CH_4 production and export from the Sundarbans has been recently documented (e.g., Mukhopadhyay et al. 2002a; Jha et al. 2014; Dutta et al. 2017b). Its importance to the Sundarbans biogeochemical cycle lies in the nature of intertidal mangrove sediments, which are generally anoxic and rich in organic carbon, and therefore favorable environments for methanogenesis (Dutta et al. 2017b). While in the riverine and standing waters, the production of CH_4 is linked to the stratification of the water column and anoxic bottom waters (Koné et al. 2010; Borges and Abril 2011). As a result, dissolved CH_4 concentrations ([CH_4]) are 11.0–129.0 nM throughout the year (Biswas et al. 2007) (Table 15.3), with a distinct increase in CH_4 in the post-monsoon period and maximum recorded values in December across all Sundarbans sites. Higher mean concentration for CH_4 is found in surface waters (69.9 nM) compared to subsurface (56.1 nM) (Dutta et al. 2017b) (Table 15.3).

In mangroves and wetlands, sedimentary-derived CH_4 can escape to the adjacent water and/or atmosphere via plant vascular system–mediated transport, ebullition, and molecular diffusion (Chanton and Dacey 1991), among which ebullition is the dominant pathway (Maher et al. 2019) and is rarely accounted for in the water–air CH_4 budget (Jeffrey et al. 2019). While the [CH_4] in water columns can be partly oxidized to CO_2 via physical and biochemical processes (Hanson and Hanson 1996), this will be limited in well-mixed water bodies, allowing for CH_4 to be emit-

Table 15.3 A summary of CO_2 and CH_4 fluxes and concentration estimates from the Sundarban ecosystem

Place	CO_2 flux (mmol m^{-2} d^{-1})	[CH_4] (nM)	CH_4 flux (umol m^{-2} d^{-1})	Reference
Sundarbans	-3.65×10^9			a.
Hooghly estuary	−2.78–84.4			a.
Sundarbans	0.315			b.
Hooghly-Matla	−0.337			c.
Sundarbans (inner)	0.675			d.
Sundarbans (middle)	0.536			
Sundarbans (outer)	−0.759			
Hooghly estuary	88.8			e.
Matla estuary	6.3			
Saptamukhi estuary (surface water)		69.9		f.
Saptamukhi estuary (sub-surface water)		56.1		
Sundarbans (Muriganga, Saptamukhi, Thakuran)		11.0–129.0	1.97–134.6	g.
Hooghly estuary		10.3–59.3	0.88–148.6	

Data sources: a. Mukhopadhyay et al. 2000, 2002b. Biswas et al. 2004; c. Akhand et al. 2012; d. Akhand et al. 2013; e. Akhand et al. 2016; f. Dutta et al. 2017b; g. Biswas et al. 2007

ted (Abril et al. 2007). The CH_4 emission rate from surface waters was between 1.97 and 134.6μmol m^{-2} d^{-1} in three distributaries in the Sundarbans with clear seasonal variation – minimum during the monsoon and maximum in the post-monsoon (Biswas et al. 2007) (Table 15.3).

15.4.2 Temporal and Spatial Variations of C Flux

The biogeochemical processes in the Sundarbans can be significantly different in the monsoon seasons compared to the dry periods of the year. For example, water in the Matla River was found to be marginally oversaturated in CO_2 throughout the year, but transitioned to a CO_2 sink during the post-monsoon season (Akhand et al. 2016). The difference results from the high discharge during the monsoon seasons creating a well-mixed water column, meaning that CO_2 diffusion was limited and there was little organic-rich sediment deposition. Furthermore, the concentrations and fluxes of different forms of C in the Sundarbans are often compared to the Hooghly River estuary, the main artery to the Sundarbans mangroves meaning you are comparing freshwater with coastal saline/brackish waters, which provides a different C dynamic. For [DOC], [POC], and [DIC] there is no distinct or consistent spatial pattern between three Sundarbans estuaries (Dutta et al. 2019b), although

[DIC] and [DOC] were both lower on average than the Hooghly River. Akhand et al. (2013) shows water in the inner and middle Sundarbans regions is oversaturated in CO_2, but undersaturated in the outer region during the summer. As a result, the inner and middle Sundarbans act as a CO_2 source (29.7 and 23.6 mg CO_2 m^{-2} day^{-1}, respectively) while the outer Sundarbans is a net sink (−33.4 mg CO_2 m^{-2} day^{-1}). This change of carbon sink and source results from higher nutrient availability and chlorophyll *a* concentrations, reflecting primary productivity in the outer mangrove system. Variations in the fluxes of CO_2 also demonstrate the heterotrophic nature of the inner mangrove ecosystems at the land–ocean interface and the C-sink character of the outer mangrove on continental shelves (Chen and Borges 2009).

15.4.3 Source of C in the Indian Sundarbans

Very few studies have explored the source of different C species in the Sundarbans water, but a modelling study of the Hooghly–Matla river system by Ray et al. (2015) shows plant litter production and the breakdown of detritus from adjacent Sundarbans mangrove forests are a major source of dissolved inorganic N and C to river waters, and potentially C exports to the continental shelf. In addition, phytoplankton is a leading source of C near Sagar Island, while this is not the case for the Saptamukhi estuary in the Sundarbans, where POC is mainly sourced from riverine suspended sediments and soils, but less from marine plankton, as indicated by their C/N ratios (Dutta et al. 2019a). Higher carbon isotope values in POC ($\delta^{13}C_{POC}$) in estuarine waters compared to mangroves indicate the modification of POC. Ray et al. (2018b) also demonstrate mangrove forests (including plant litter, eroded soil) are the major source of C exported from Sundarbans to the Bay of Bengal, compared to upstream C-inputs and marine phytoplankton. In addition, the negative relationship between [DIC] and its carbon isotope value ($\delta^{13}C_{DIC}$) during low tide, highlights respiration of marine plankton-derived organic carbon may be an important source of DIC rather than exchange of C-rich porewaters derived from terrestrial sources.

15.4.4 Influence of Salinity and Tide on C

In general, CO_2 flux decreases with increasing salinity toward the open sea (Akhand et al. 2012). In the Matla River, the highest fraction of aqueous CO_2 (fCO_2) coincides with the lowest neap tide, overriding CO_2 uptake by photosynthesis. The hydrological change during the ebb and low tide leads to the mixing of sediment porewater and groundwater with brackish/saline estuary waters. The subsequent biogeochemical interaction that leads to increasing fCO_2 and the extent of CO_2 efflux highlights the role of salinity in C-dynamics over the Sundarbans (Akhand et al. 2016). The importance of tidal stage in controlling dissolved greenhouse gas efflux from water is also demonstrated by Padhy et al. (2020), who show the concentrations of dissolved CH_4 and CO_2 are higher in stagnant water during low tide compared to high tide water. This implies the effect of stagnation and lower salinity and therefore less SO_4^{2-} availability, which increases CO_2 emissions. Apart from high pCO_2 during low tide, Dutta et al. (2019b) also suggest there is a strong influence from estuarine mixing on DIC and $\delta^{13}C_{DIC}$ during the low tide, both of which correlate with salinity. This can be explained by the impacts of this biogeochemistry on denitrification, sulfate reduction, and aerobic organic matter mineralization to DIC, along with possible organic contributions from porewater.

15.5 Conclusions

This overview of biogeochemical dynamics and anthropogenic impacts on the Indian Sundarbans highlights the importance of the hydrological regime in driving variability in ecosystem health. Diurnal and seasonal changes in salinity, which are driven by the tides and monsoon-driven freshwater availability, influence biological responses, biogeochemical cycling, and carbon dynamics. Also, high concentrations of heavy metals mean they are bioavailable within the major rivers running into the Sundarbans, but there is little evidence of the short- and long-term implications of this pollution for mangrove health, aquatic organisms, and local communities. Overall, there remains a paucity of research into water-quality impacts on aquatic ecology, including nutrient enrichment and heavy metal pollution, carbon cycling through the mangrove system, and how climate change has and will continue to affect the Indian Sundarbans.

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