

Variation of salinity in the Sundarbans Estuarine System during the Equinoctial Spring tidal phase of March 2011

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Short title: Salinity variation in the Sundarbans Estuarine System, India

Abstract

The Sundarbans Estuarine System (SES), comprising the southernmost part of the Indian portion of the Ganga-Brahmaputra delta bordering the Bay of Bengal, is India's largest monsoonal, macro-tidal, delta-front estuarine system. The Sundarbans Estuarine Programme (SEP), covering six semi-diurnal tidal cycles during 18–21 March 2011 (the Equinoctial Spring Phase), was the first comprehensive observational programme in the SES. The 30 observation stations, spread over more than 3600 km², covered the seven inner estuaries of the SES: the Saptamukhi, Thakuran, Matla, Bidya, Gomdi, Harinbanga, and Raimangal. At all stations or time-series locations (TSLs), the water level was measured

every 15 minutes and water samples were collected every hour for estimating salinity. We report the observed spatio-temporal variations of salinity in this paper.

The mean salinity over the six tidal cycles decreased upstream and the mean range of salinity over a tidal cycle increased upstream. In addition to this along-channel variation, the mean salinity also varied zonally across the SES. Salinity was lowest in the eastern SES, with the lowest value occurring at the TSLs on the Raimangal. Though higher than at the Raimangal TSLs, the mean salinity was also low at Mahendranagar, the westernmost TSL located on the West Gulley of the Saptamukhi. Salinity tended to be higher in the central part of the SES. CTD (conductivity-temperature-depth) measurements at three stations on the Matla show a well-mixed profile.

Only the Raimangal has a freshwater source at its head. Therefore, the upstream decrease of salinity in the SES is likely to be the effect of the preceding summer monsoon, which would have freshened the estuary, and the ingress of salt from the seaward end due to the tide following the cessation of the monsoon rains. The freshwater inflow from the Raimangal leads to the lowest salinities occurring in the eastern SES. The lower salinity in the western SES also suggests inflow from the Hoogly estuary, whose freshwater source is regulated via the Farakka Barrage.

At 20 of the 30 TSLs, the salinity varied semi-diurnally, like the water level, and the maximum (minimum) salinity tended to occur at or around high (low) water. The temporal variation was more complex at the other 10 TSLs. Even at the TSLs at which a tidal stand exceeding 75 minutes was seen in the water level, the salinity oscillated with a semi-diurnal period. Thus, the salinity variation was unaffected by the stand of the tide that has been reported from the SES.

Keywords: Estuaries; Sundarbans; Salinity; Stand of the Tide; Hoogly; Mangroves.

1 Introduction

The world's largest delta, shared by India and Bangladesh, is formed by the distributaries of the rivers Ganga and the Brahmaputra (Seidensticker and Hai, 1983); its western boundary is R. Hoogly (also written "Hooghly" or "Hugli"), eastern boundary is R. Meghna, and the southern boundary is the Bay of Bengal (figure 1). The southern fringes of the delta constitute the Sundarbans, which are dense natural mangrove forests. The Indian part of the Sundarbans delta is about 40% (9630 km²) of the total area. Chatterjee *et al.* (2013, hereafter referred to as C2013) referred to this region lying between 21.25–22.50°N and 88.25–89.50°E as the Sundarbans Estuarine System (hereafter abbreviated SES; figure 2). Spread over the entire South 24 Parganas and the southern parts of the adjoining North 24 Parganas, the two southernmost districts of West Bengal (figure 1), the SES constitute the largest monsoonal (Vijith *et al.*, 2009), macrotidal, delta-front, estuarine system in India.

The SES is bounded on the west by R. Hoogly, the westernmost estuary of the SES and the first deltaic offshoot of R. Ganga (figure 1). R. Raimangal forms the eastern boundary of the SES (figure 2). This trans-national river is the downstream part of the Ichhamati-Kalindi river, an easterly distributary of the Ganga and rises north of the SES. The northern limit of the Sundarbans and the SES is defined by the Dampier-Hodges Line (figure 2), an imaginary line based on a survey conducted during 1829–1832. The principal estuaries of the SES lying east of the Hoogly are the north–south-flowing rivers: the Saptamukhi, Thakuran, Matla, Bidya, Gomdi (often called the Gomdi *Khaal* or the Gomor), Gosaba, Harinbhanga, and Raimangal (figure 2). The Saptamukhi is split into two channels just north of its mouth by an island: the western and eastern channels are called the Saptamukhi West Gulley (SWG) and Saptamukhi East Gulley (SEG), respectively.

Interconnecting these estuaries and forming a complex estuarine network are numerous west-east flowing channels, canals, and creeks, which are locally known as *Khaal* (meaning a narrow canal or creek) or *Gaang* and *Nadi* (both meaning wide rivers). Some of these interlinking channels are wide and the flow in them is strong enough for them to be considered

as estuaries by themselves. The principal estuaries are funnel-shaped: they have very wide mouths, but their widths decrease rapidly northward after short, wide stretches. For example, the Matla is ~ 26 km wide at the mouth, but its width is less than 1 km at Port Canning (figure 2). Except in the vicinity of the seafloor, the estuaries follow meandering courses with sharp bends. East of the Matla, the interconnections become so complicated that they are often difficult to identify as belonging to a particular estuary.

Though all are former distributaries of the Ganga, the seven inner estuaries of the SES lying between the Hoogly and the Raimangal are at present saline, tidal rivers because geological changes during the 16th century caused the main flow of the Ganga to shift progressively eastward, severing these inner estuaries completely from the freshwater source at their upstream heads (Seidensticker and Hai, 1983). The Hoogly and the Raimangal, however, still carry the freshwater discharge of the Ganga into the Bay of Bengal throughout the year. Following the withdrawal of the summer monsoon (Attri and Tyagi, 2010), the freshwater flow through the Hoogly is augmented during the lean period by the diversion of regulated amounts of the Gangetic main flow through the Farakka Barrage (figure 1) in order to keep the Hoogly navigable and Kolkata port functional in accordance with the Indo-Bangladesh Water Sharing Treaty (Anonymous, 2017).

The absence of a direct freshwater source at their head implies that the estuarine character of the SES estuaries is now maintained by the semi-diurnal tides at their mouths and the freshwater received as local runoff. Indeed, the tide so completely influences all the basic estuarine processes operating in the region that the tides are intricately woven into the fabric of life in the Sundarbans; hence, the Sundarbans is often referred to as the *Bhatir Desh* or “tidal country” (Abul-Fazl-Allami, 1589–1598; Roy, 1949; Ghosh, 2004; Chakarabarti, 2009; Bhattacharyya, 2011).

Most of the local runoff is derived from the rainfall, ranging between 1500–2500 mm year⁻¹ (Attri and Tyagi, 2010) during the summer monsoon (June–September), and from the floods that are a consequence of the freshwater accumulation in the upstream parts of the Ganga during this season. Rainfall accompanying the frequently occurring pre-monsoon thunderstorms (known as “Norwesters” or, locally, *Kaal Baisakhi*) is another source of freshwater runoff during the dry season (Attri and Tyagi, 2010).

Surface salinities in the Hoogly, as known from earlier studies (table 1), follow a seasonal pattern (Oag, 1939). The maximum salinities occur during the dry pre-monsoon period (March–May), the minimum salinities occur during the wet summer-monsoon period, and low to medium salinities occur following the summer monsoon (October–February). It is reasonable to believe that surface salinities in the inner estuaries of the SES also follow the same seasonal pattern. Yet, unlike in the Hoogly, even during the peak monsoon months, complete flushing of the inner estuaries of the SES is never observed because they lack a direct freshwater source at their head. The only exception is the Raimangal. Hence, the estuarine water in the SES remains brackish throughout the year. Nevertheless, the monsoonal regime and the seasonality of the runoff imparts a time dependence to the salinity distribution and the salinity field in the SES is always unsteady. This temporal restriction of the freshwater supply and the resulting unsteadiness of the salinity is commonly observed in all Indian estuaries falling within the summer-monsoon regime. Such estuaries were classified as monsoonal estuaries by Vijith *et al.* (2009).

The network of estuaries comprising the SES is the transportation lifeline of the region. In recent years, there has also been a significant increase in the traffic between West Bengal and the northeastern states of India via Bangladesh, raising the importance of the channels for navigation (<https://iwai.nic.in/>, <https://www.mea.gov.in/>). Yet, in spite of the tides exercising a controlling influence on the life of its over four million inhabitants (Ghosh, 2004; Bhattacharyya, 2011), the SES remained poorly studied till 2011 (C2013). The complex network of estuaries and the difficulty of making measurements limited the studies to sporadic observations that were largely restricted to the Hoogly (hydrodynamical, morphological, chemical,

and biological observations) and a few sporadic observations, mostly biological and chemical, conducted in the Matla and the Saptamukhi. As noted by C2013, even water-level measurements in the SES were restricted to the vicinity of jetties. Salinity measurements were even more limited and sporadic (see table 1 for a summary) than water-level measurements (C2013) in spite of its obvious implications: the Dampier-Hodges line, which marks the northern limit of the SES (figure 2), is based on salinity.

The first comprehensive measurements in the SES were carried out under the Sundarbans Estuarine Programme in March 2011 (C2013); hereafter, this set of measurements is referred to as SEP2011. The water-level measurements from SEP2011 were reported by C2013, but the programme also included measurements of salinity. Though earlier studies had suggested that salinity decreases during the summer monsoon and increases during the dry season (table 1), the changes over a tidal cycle and in space were mapped for the first time during SEP2011. A brief description of SEP2011 is deferred to section 2, but we note here the importance of salinity measurements in the SES.

First, salinity data are required for the management and adequate distribution of sweet or potable water for domestic and agricultural use. Nearly 3155 km² (~59%) of the northern settlements have been cleared for cultivation (Department of Sundarban Affairs, Government of West Bengal; <https://www.sundarbanaffairswb.in/>). The main crop grown consists of three varieties of rice in three cropping seasons: *Aman*, cultivated during the summer monsoon (*Kharif*), is completely rainfed; *Aus*, cultivated soon after the summer monsoon withdraws, and *Boro*, cultivated during the winter (*Rabi*), depend heavily on irrigation. All three are freshwater varieties of rice, have some salinity tolerance (2 psu), but perish completely when salinities increase to 7 psu (Debnath, 2014). Water for irrigation, drinking and other domestic use is obtained mostly through freshwater (rainwater harvested) or from brackish water ponds present in every agricultural field or through river lift irrigation. Freshwater is also extracted through medium- and high-capacity deep-water tube wells that tap water from freshwater aquifers situated more than 300 m below ground level (Water Investigation and Development Department, Government of West Bengal Economic Review 2011–2012; <https://bengalchamber.com/economics/west-bengal-statistics-2011-2012.pdf>), but this method cannot work in the southern, seaward part of the delta. While saline water ingress occurs periodically owing to the very high tidal water levels and also remotely generated swell waves, a greater threat is posed by extreme weather events like depressions and cyclones and the surges due to these events (Das, 1972; Murty *et al.*, 1986; Mohapatra *et al.*, 2012; Dube, 2012).

Second, salinity matters for the fishery of the Sundarbans, which also serve as the spawning grounds for the fish. The important species include shrimps, prawns, crabs, and the *Hilsa* (*Hilsa ilisha*). The salinity and water temperature tolerance is species-specific. The fish normally inhabit the seaward regime of the estuaries and the foreshore areas of the sea and migrate upstream for spawning (Kuttyamma, 1982; Chanda *et al.*, 2015). The *Hilsa*, perhaps the most popular fish in West Bengal and Bangladesh (De, 1986), prefers the Sundarbans owing to the presence of sub-surface oxygen, relatively low salinity, strong tidal action, high turbidity, heavy siltation, and rich growth of plankton (Pillay and Rosa, 1963). It too migrates upstream for spawning (Hora, 1938; Pillay, 1958; De, 1986). Though the *Hilsa* is very tolerant of changes in salinity (Bhaumik and Sharma, 2011), its yield has declined in recent years, necessitating an analysis of the causes.

Third, though the exact number of the mangrove species is still debated and reported variously as 69 (Gopal and Chauhan, 2006; Mandal and Naskar, 2008) to 84 (Raha *et al.*, 2013; Barik and Chowdhury, 2014; Ghosh *et al.*, 2015), the mangroves in the Indian Sundarbans are known to harbour the richest species diversity. Their natural forest resources provide the means of livelihood for the majority of the inhabitants of the region. All mangrove plants in the SES have medicinal value, which is well-known locally, but is yet to receive serious scientific attention (Bandaranayake, 1998; Pattanaik *et al.*, 2008; Sarkar, 2011). The mangroves of the Sundarbans

also act as a buffer that absorbs and mitigates the effect of the storms, providing protection to the densely populated city, Kolkata, to the north (figure 1). In addition, the mangroves are the biggest sink of carbon in the region and function as a natural filter for pollutants, including heavy metals released in its industrialised northern reaches (Maiti and Chowdhury, 2013). Mangroves dominate the Sundarbans because the conditions required for their proliferation are fulfilled there, but an increase in salinity can lead to either changes in species or drive some to extinction. The most striking example is the once prolific *Sundari* Tree (*Heritiera fomes*), from which the Sundarbans got its name. The *Sundari* grows fastest in low-salinity (0–5 psu) water, and is usually found in the northern (headward) stretches of the SES estuaries. Though human exploitation has contributed to its decline, a gradual increase in salinity, driven by natural geological changes over the last few centuries, in the western part of the SES has led to the gradual disappearance of the *Sundari* from these parts. At present, the *Sundari* is an endangered species and is found only eastward of the Matla (Kathiresan *et al.*, 2010), where salinities are lower, and are relatively more abundant in the easternmost parts of the Bangladesh Sundarbans (Das, 2012).

Therefore, a good understanding of the spatio-temporal variations of salinity in the SES over short (daily, sub-tidal) and long (seasonal, annual) time scales is essential for gaining insight into and resolving several issues that have become critical for this region. The focus of this paper is on the changes seen over a tidal cycle. The rest of this paper is organised as follows. In section 2, we present a brief description of SEP2011. The salinity variation during SEP2011 is described in section 3 and the results are discussed in section 4.

2 The Sundarbans Estuarine Programme 2011 (SEP2011)

This section begins with a brief description of SEP2011 and the astronomical and weather conditions during the observations. This background information is followed by a description of the observational and analytical methods. The section ends with a summary of the results of C2013, who described the water-level measurements.

2.1 SEP2011 overview

SEP2011, conducted during 18–21 March 2011, was a systematically planned observational programme aimed at mapping the nature and characteristics of tidal propagation and spatio-temporal variation of surface salinity in the SES, an area of ~ 9600 km² lying between 88.25–89.50°E and 21.25–22.50°N. A comprehensive description is provided in C2013 and we provide but a brief overview in this paper. C2013 divided the SES region into two sectors: Sector 1 (88.250–88.625°E, 21.625–22.022°N), covering ~ 1814 km², was located in the southwestern portion of the SES, with the Bay of Bengal as its southern boundary, and Sector 2 (88.625–89.017°E, 22.022–22.375°N), covering ~ 1800 km², was located in the northwestern portion of the SES (figure 2).

The observations consisted of simultaneous and continuous measurements of water level, surface temperature, air temperature, and surface salinity for 72 hours at 30 selected time-series locations (called TSLs hereafter). These TSLs, spread over ~ 3600 km² of the SES and therefore representing $\sim 40\%$ of its total area, provide a comprehensive coverage of the region and the data obtained represent a wide range of estuarine and environmental conditions. The choice of the TSLs was dictated by logistic considerations such as existence of settlements and jetties, which, in turn, were mostly located at or near channel confluences. This constraint and the prolific existence of channel confluences, a consequence of the high channel density, led to many of the TSLs being located at or near channel confluences. 14 of the TSLs lay in Sector 1: eight on the Saptamukhi System, two on the Thakuran and four are on the southern stretch of the Matla, extending downstream of M14 (Kaikhali) up to its mouth. The remaining 16 TSLs

were located in Sector 2: three on the northern stretch of the Matla, four on the Bidya, two each on the Gomdi and Harinbhanga, and five on the Raimangal. Since the mouth of the Matla is the southernmost, its latitude, 21.603°N , has been taken to represent the seaface. All distances north of the seaface are measured along the respective channels from this latitude (table 2). Following C2013, the first letter of the name of the estuary on which it is situated has been prefixed to the TSL number, implying a two-letter prefix for TSLs located at the confluence of two estuaries. For example, ST13 (Raidighi) is at the confluence of the Saptamukhi (S) and the Thakuran (T) and GH21 (Melmelia) is at the confluence of the Gomdi (G) and Harinbhanga (H).

For convenience, in spite of the lack of a riverine source of freshwater at the head of six of the seven estuaries constituting the SES, we use the conventional term “upstream” (“downstream”) to refer to movement along the channel away from (towards) the mouth.

2.2 Astronomical and weather conditions during SEP2011

The spatio-temporal variations of surface salinity in all estuaries is known to be a result of the interactions between several oceanographic and meteorological processes: the tides, freshwater inflow, residual estuarine circulation (gravitational circulation), bathymetry and the geometry of the channels, wind, precipitation, and solar radiation (Lewis and Uncles, 2003; Eaton, 2007). It is reasonable to assume that the surface salinity in the SES will be determined by the same set of processes. Though we refrain from analysing the processes in this paper, a description of the astronomical and meteorological conditions is a necessary component of the background.

The SEP observations were conducted during the Full-Moon phase of the Equinoctial Spring, with the Full Moon (termed popularly as the Super Moon) occurring at 11 PM (Indian Standard Time or IST, which is UTC+0530) on 19 March. 18 March 2011 was unique in the sense that this was the day of maximum tidal forcing, with the semi-diurnal tidal amplitudes at 1.88 times that of the equilibrium tide (Pugh, 1987). The reason for this higher high tide was the near coincidence of the times of occurrences of zero solar declination and lunar perigee. Such an astronomical event had occurred earlier in 1980, 1993, 1997, 1998 and 2002, and the next occurrence after 2011 will be in 2028 (Pugh, 1987).

The most notable meteorological feature during the 72-hour period, which started at 4 AM on 18 March and ended at 4 AM on 21 March 2011, was the extremely strong and steady southerly-southwesterly wind that blew throughout this period. A qualitative idea of the wind speed at 10 m is obtained from the METAR (METeorological Aerodrome Reports) records (at 30-minute intervals) from the Netaji Subhash International Airport at Dumdum, Kolkata, ~ 150 km northwest of Nandakumarpur and Gadkhali (figure 1). At Dumdum, the wind speed at 10 m varied between $5\text{--}7.5$ m s $^{-1}$ and the sea-level pressure lay between 1004–1005 hPa. This strong, southerly wind, directed along the north–south orientation of the main estuarine channels, is a usual feature in March. Since SEP2011 was conducted during the peak of the dry season, there was no rainfall before or during 18–21 March 2011. Fair weather existed all over the SES, with occasional cloudiness in the late afternoons.

2.3 Observational and analytical methods

2.3.1 Water level

As described by C2013, water level was measured every 15 minutes using tide poles (C2013). At each TSL, mechanised boats, anchored firmly next to the tide poles, were used as observation platforms from which the reading on the tide poles could be taken even during the night. The position of these boats and the tide poles remained fixed throughout the 72 hours of observation. Each boat had on board a team consisting of six observers and a supervisor; several boats also had a scientist on board throughout the observation period. All observers

and supervisors consisted of local people recruited through three local non-governmental organisations: Sabuj Sangha (SS) in Sector1 and the Calcutta Wildlife Society (CWS) and the Tagore Society for Rural Development (TSRD) in Sector 2. All observation teams were trained through several training sessions organised before SEP2011 at the SS and TSRD head quarters at Nandakumarpur and Rangabelia (figure 2), respectively.

In addition, there were three supervision teams, which were expected to ensure that at least one of them visited each TSL daily to check the observations and ensure the general well-being of the observation teams. While a visit to most of the stations was possible on at least one of the three days, it proved impossible to reach M3 (Kalash), the southernmost and most remote of the TSLs.

All together, six tidal cycles — from low water (LW) to high water (HW) to LW — occurred during the period of observation; the 72-hour period started around low tide on 18 March. Logistic problems, however, delayed the start at M3 (Kalash) and G12 (Durgaduani), and the observations at M4 (Bonnie Camp) had to be abandoned after the fifth tidal cycle because the tide pole broke and could not be repaired. The few data gaps that existed in the time series of the water levels were filled following the harmonic analysis of the data. The harmonic analysis was carried out using Tidal Analysis Software Kit (TASK-2000) software (Bell *et al.*, 1998). Since the measurements were restricted to just 72 hours, we determined only eight constituent bands (following Shetye *et al.*, 1995). We assumed the period of the semi-diurnal and diurnal bands to be 12.42 hours (M_2) and 23.92 hours (K_1), respectively. The frequencies of the eight constituent bands are available in table 7 of C2013.

The mean tide level was computed as the arithmetic mean of the hourly water levels extracted from the 15-minute time series. The mean tidal ranges, however, are as reported in C2013, and were computed from the 15-minute time series as the difference between HW level (HWL) and LW level (LWL) during a tidal cycle. Thus, the range for each tidal cycle, R_{WL} , has been calculated as the difference in the maximum and minimum values attained in that cycle, and the mean range is the arithmetic mean of the six values.

2.3.2 Salinity

Water samples were collected every hour for subsequent analysis to estimate the surface salinity. The temperature was read from the bucket (figure 3a) and the samples were collected in 200 ml PET (Polyethylene terephthalate) bottles (figure 3b) with an inner lid and cap that were pre-labelled with the station name, sample number, and date. To avoid contamination of the samples by unwanted sediment and the flotsam washed up at the edge of the bank, each team was instructed to collect the water sample a little away from the bank. This distance implied the need to get down from the boat, which led to difficulties during low tide, when a significant part of the islands tends to become exposed (figure 3c), and also at night. At S2 (Dhanchi), for example, the samples were collected by the team even at night in spite of the danger posed by crocodiles. In total, 2190 water samples were collected.

The method of sample collection generally followed Shetye *et al.* (1995), but the Sundarbans posed problems that demanded additional steps for each observation. The new bucket supplied for the purpose was at first thoroughly rinsed at least thrice with the estuarine water. The PET bottle, lid, and cap were rinsed with the water in the bucket at least three times. The water sample was then poured into the bottle through a fine muslin cloth to filter out sediment and other particulates. To prevent evaporation and crystallisation of dissolved salts, the bottle was then filled up to the neck and the inner lid and inner sides of the neck were wiped clean with tissue paper. Care was taken to avoid contact with the bottled water or hands. Once the inner lid was in place, the inner side of the cap was dried similarly and the bottle was capped. The outer surface of the capped bottle was then wiped dry, and, as a precaution against leakages during subsequent transportation to the laboratory, the cap was sealed by winding cellotape around it (figure 3d).

In addition to the water samples, salinity data were collected at three stations on the Matla using a portable SeaBird CTD (conductivity-temperature-depth) of make SBE19plus; moving upstream from the seaface, these stations were Kalash, Kaikhali, and Purandar (figure 2). The CTD was deployed at all three stations from a separate boat that moved to roughly the middle of the Matla channel at each station to ensure sufficient depth of water for the deployment. At Kalash, logistical problems precluded deployment of the CTD on the 18 March, the first day; hence, the CTD data are available for only two days at this station.

2.3.3 Analysis of water samples

The water samples were analysed using an autosal (Make Guildline 8400B) at CSIR-NIO, Goa and the regional centre of CSIR-NIO at Visakhapatnam. In spite of the filtering with the muslin cloth, several samples, particularly those collected during low tide (see, for example, figure 3c), were turbid. All samples were allowed to settle for over 12 hours before the autosal analysis.

Mean salinities were computed as time averages over each tidal cycle using the trapezoidal rule. The mean salinities and the mean values of R_{WL} are listed in table 2.

2.4 Variation of water level in the SES during SEP2011

In this subsection, we summarise the results of C2013. The water-level data and their harmonic analysis showed a dominant semi-diurnal tide (figure 4). The three-day time series is not sufficient to separate the two dominant semi-diurnal constituents, M_2 and S_2 , but the dominance of the M_2 tide in the northern Bay of Bengal (Sindhu and Unnikrishnan, 2013) implies that the semi-diurnal oscillation observed in the water level in the SES is due to this constituent. In general, the tidal range, R_{WL} , increased upstream with distance from the mouth (figures 2,5a). The minimum HWL, 3.61 m, was observed at S2 (Dhanchi) on the SEG and the maximum HWL, 7.08 m, was observed at M26 (Canning), ~ 98 km from the seaface (figure 2). R_{WL} varied between a minimum of 4.32 m at S2 and a maximum of 6.73 m at M26 (table 2). The upstream amplification of the tide along the main north–south-oriented channels, all of which are funnel-shaped, convergent channels, can be attributed to the dominance of the channel geometry over frictional dissipation (Friedrichs and Aubrey, 1994; Shetye *et al.*, 1995). A different pattern of tidal amplification existed in the two parallel channels, the Bidya and the Gomdi (Gomor). The Bidya is a long, highly meandering channel, while the Gomdi is the narrowest and shortest of the channels surveyed. Tidal amplitudes increased and decreased without any fixed pattern over the various tidal cycles at each of the observation locations situated in these two estuaries. The complexity of the estuarine network also led to complex patterns of the observed rates of tidal amplification and decay in various estuarine stretches.

Harmonic analysis of the observed tidal water-level data from the SES revealed that the M_2 constituent was dominant. For the majority of the 30 locations, the next two bands were the 6-hourly M_4 and 4-hourly M_6 bands. Upstream amplification in these bands was stronger (factor of 4–5) compared to the amplification of the M_2 band (factor of ~ 2). As noted by C2013, the generation of these two higher harmonic bands suggests the existence of nonlinear effects that are a consequence of the interaction of the semi-diurnal tide with the channel geometry: for example, the interaction of the semi-diurnal tide with the bottom of the channel (nonlinear friction), can generate the M_4 and M_6 bands, which amplify as the tide progresses headward (see, for example, Pingree and Griffiths, 1979; Speer and Aubrey, 1985; Speer *et al.*, 1991; Song *et al.*, 2011). This superposition of the M_4 and M_6 bands on the M_2 band led to asymmetries of the tide, of which two types were evident in the data.

The first asymmetry is the better-known tidal-duration asymmetry (Pugh, 1987), which is of two types, flow-dominant and ebb-dominant. For water level, the asymmetry was of the flow-dominant type in the SES, but at some locations and during some tidal cycles, existence of

ebb-dominance and the vanishing of the tidal-duration asymmetry were also observed (C2013, table 3).

The second type of tidal asymmetry is referred to as the tidal stand or stand of the tide or a platform tide and is known to exist in other parts of the world (Pugh, 1987). Its identification in the SES was, however, the first report of a tidal stand from an Indian estuary. In this type of asymmetry of the tide, water levels near the times of HW and LW change so slowly that the change appears to be imperceptible, resulting in an apparent stationarity of the water level to the observer. HW stands exceeding 30 minutes were seen at 27 of the 30 TSLs, the exceptions being M3, M26, and B16, but longer stands with duration exceeding 75 minutes, implying that the water level changed imperceptibly around the HWL for 105 minutes, were seen in the northeastern TSLs on the Bidya, Gomdi, Harinbhanga, and Raimangal (figure 4).

C2013 pointed out that the existence of the tidal stand in the SES, which is prone to cyclones and storm surges, would increase the duration over which high water levels are experienced during a storm surge. This increased duration has implications for engineering constructions such as jetties, embankments, and bridges.

3 Variation of salinity in the SES

The spatial and temporal variation of surface salinity in the SES is described in this section, which ends with a brief description of the vertical structure seen in the CTD data.

3.1 Spatial variation of mean surface salinity

The mean salinity, S_{mean} , over the observation period varied spatially. We split this variation into two parts, along the channels, which are generally oriented north–south (the exceptions are the Bidya and Gomdi, which are oriented more northeast–southwest), and zonally (east–west) across the SES.

3.1.1 Along-channel variation

The S_{mean} values in the SES are expected to be high during March, which marks the local peak of the dry season; there was also no precipitation before and during the observation period. The highest value of S_{mean} , 28.015 psu, occurred at the southernmost TSL, S1 (Indrapur), which is located 8 km north of the seafloor (table 2). Though S_{mean} was higher (28.35 psu) at M3 (Kalash), the duration of measurement there was less than 72 hours. This salinity is lower than, but comparable to, the mean climatological salinity of ~ 31 psu in the northern Bay of Bengal (Chatterjee *et al.*, 2012). Therefore, though we do not have a measure of the salinity in March 2011 in the northern bay at the mouths of the SES estuaries, it is likely that even the maximum salinity in the SES during the peak of the dry season is lower than the salinity at the mouths, suggesting that the estuaries of the SES can be classified as positive estuaries (Pugh, 1987).

S_{mean} decreased upstream along the estuary, with the minimum S_{mean} , 18.373 psu, recorded at R29 (Sahebkhal), which is located ~ 108 km from the seafloor (table 2, figure 5b). Use of triangulation permits a spatial view of the mean salinity field: the upstream decrease of S_{mean} is clearly evident in this map (figure 6). The difference of 9.642 psu between S1 and R29 implies a salinity gradient of ~ 0.096 psu km^{-1} . This gradient is merely indicative of the overall trend, however, because the northward decrease was not uniform (figure 5b, table 2): S_{mean} decreased by just 4.493 psu from S1 to M26 (Canning), which is located 98 km from the seafloor, but the decrease from M26 to R29, which is located 108 km from the seafloor or just ~ 10 km farther from the seafloor compared to M26, was higher (5.149 psu, figure 5b). The variation of S_{mean} with distance from the seafloor was not smooth and showed considerable fluctuations, with pockets

of low S_{mean} evident in all the estuaries: an example is S5 (Mahendranagar), which had a lower S_{mean} than ST13 (Raidighi), on the Saptamukhi (table 2, figures 5b,6).

In general, the mean of the salinity range over the tidal cycles, R_S , tended to increase upstream from the seaface, but this variation was not uniform (table 2, figure 5c). The minimum value of R_S , 0.337 psu, occurred not at S1, but at S7 (Pakhirala), located ~ 28 km upstream of the seaface, and the maximum value, 5.208 psu, occurred at R24 (Bagna), located ~ 87 km upstream (table 2). As seen from the data in table 2, clusters of eight and seven TSLs (i.e., half the TSLs), respectively could be identified for values of R_S around 0.5 psu (S7, S1, S2, M3, and S9 in Sector 1 and G12, B16, and B23 in Sector 2) and 1 psu (S6, T10, T11, and M14 in Sector 1 and M22, M26, and B20 in Sector 2). R_S was much higher than 1 psu at the other 15 TSLs: S30, S5, and ST13 on the Saptamukhi and Thakuran, M8, M4, and M15 on the Matla, B19 on the Bidya, H17, G18, and GH21 on the Harinbhanga and Gomdi, and all the five TSLs on the Raimangal. Only five of the TSLs (S30, S5, ST13, M4, and M8) with $R_S > 1$ psu were in Sector 1; the remaining 10 TSLs were located in Sector 2.

3.1.2 Zonal variation across the SES

The spatial map generated by triangulation suggests that the salinity did not merely decrease upstream in the SES (figure 6). A zonal variation across the SES was superimposed on the along-channel, largely meridional, variation. The lowest values of S_{mean} occurred at the five eastern TSLs on the Raimangal (table 2, figures 5b,6), with the minimum value of 18.373 psu occurring at R29 (Sahebkhal). S_{mean} at S5 (Mahendranagar) on the SWG was lower (23.873 psu) than that at S6 (Ramganga) farther east on the SEG.

Large changes in salinity occurred over short distances: for example, S5, on the SWG, and S6 (Ramganga), on the SEG (figure 6), were separated by just ~ 6 km, but S_{mean} increased by 3.795 psu from S5 to S6 (table 2, figure 5b). The zonal salinity changes were not monotonic, however, and S_{mean} changed much less from S6 to S7 (Pakhirala), which was located on a branch of the SEG (figure 6). S7 lay ~ 11 km east of S6, but S_{mean} decreased from S6 to S7 by just 0.083 psu (table 2, figure 5b). Similarly, though S_{mean} generally decreased eastward in Sector 2, an eastward increase in S_{mean} was seen in some parts. For example, S_{mean} increased eastward by 0.961 psu from M22 (Purandar) to B23 (Pathankhali), which are separated by ~ 11 km, and by 1.552 psu from B23 to B19 (Gosaba), which were separated by ~ 8 km. Similar differences in S_{mean} were observed between TSLs situated on the opposite banks of an estuary: S_{mean} (25.765 psu) at M14 (Kaikhali, west bank of the Matla) was 0.827 psu lower than that at (26.592 psu) at M15 (Jharkhali Jetty, east bank of the Matla).

3.2 Temporal variation of surface salinity

For several TSLs, the tidal half-cycle from 4–9 AM on 18 March 2011 is incomplete because the LW level occurred about an hour earlier. For this tidal cycle, we designate the first reported data at 4 AM as LW1. Though there are differences in the temporal variation of salinity across the TSLs and even across tidal cycles at some TSLs, a few patterns can still be inferred.

The time series of hourly salinity at the 30 TSLs is plotted in figure 7; the mean range is listed in table 2. At the peak of the dry season and in the absence of precipitation, the major source of salinity variation in the monsoonal estuaries of the SES is the twice-daily incursion of the saline sea water due to the semi-diurnal tidal cycle (Vijith *et al.*, 2009). Therefore, a majority of the TSLs showed a dominance of the semi-diurnal cycle in salinity. This semi-diurnal tide-driven oscillation, which was roughly sinusoidal, is clearly discernible in the salinity curves for 20 (S6, S9, ST13, T10, T11, M15, M16, M22, M26, B19, B20, G12, G18, GH21, H17, R25, R24, R28, R29, and R27) of the 30 TSLs. At these 20 TSLs, the observed salinity increased (decreased) with the rise (fall) in water level, attaining the maximum (minimum) salinity for a tidal cycle at or around the HWL (LWL).

The time taken for salinity to decrease from the maximum to the minimum value was longer than the the time taken for salinity to increase from the minimum to the maximum value. Though the sampling temporal interval for salinity (one hour) is coarser compared to water level (15 minutes), it is possible to infer the nature of tidal asymmetry. The salinity variation also displayed a duration asymmetry, but the type of asymmetry tended to vary between flow-dominance and ebb-dominance at 20 of the 30 TSLs (table 3). Ebb-dominance was seen in the salinity variation at six TSLs and flow-dominance at the other four TSLs. The same asymmetry was seen for both water level and salinity only at eight TSLs: flow-dominance was seen at three TSLs and mixed asymmetry at five TSLs (table 3). Thus, though flow-dominance was striking for water level (22 TSLs), the asymmetry tended to be mixed for salinity.

The observed patterns of salinity variations were complex and different at each of the 10 TSLs that did not show a clear semi-diurnal cycle (figure 7). At two of these 10 TSLs, S7 and B23, there was a semi-diurnal oscillation, but the range was low (table 2, figure 5c). At M4 and M8 too, there was a semi-diurnal oscillation in salinity, but the variation was not smooth, unlike at the 20 TSLs that showed a clear semi-diurnal oscillation; at these two TSLs, the salinity was also out of phase with the tide. Likewise, the semi-diurnal oscillation at B16 was also not smooth. At two other TSLs, both on the Saptamukhi, the semi-diurnal oscillation was evident in some, but not all, tidal cycles. At S5, the westernmost TSL, the salinity was low and showed almost no variation over the first two cycles, but a clear semi-diurnal oscillation was seen in the remaining four cycles. In contrast, at S1, the TSL nearest the seaface, the semi-diurnal oscillation was seen over the first two cycles, but the oscillation went out of phase (with the tide) and the salinity showed a decreasing trend over the remaining four cycles. Furthermore, the range, R_S , was low at S1 (table 2).

It is only at three TSLs (S2, S30, and M3) that the semi-diurnal oscillation was not evident at all (figure 7). At S2, which was located on the east bank of the SEG (figure 6), the only discernible pattern was a sawtooth variation: a slow increase in salinity was followed by a rapid decrease (figure 7). Six cycles were seen in the data, but with shorter oscillations superimposed on the sawtooth variation that had a period around six hours. Likewise, six cycles were seen at S30, but the salinity persisted around the maximum value for most of the cycle; the increase to this maximum and the decrease to the minimum were rapid and the minimum was V-shaped. No clear pattern was discernible at M3, which was located in an east-west channel off the west bank of the Matla (figure 7); the salinity often oscillated at periods shorter than six hours.

Note that eight of the 10 TSLs at which a clear semi-diurnal oscillation was not evident are located in Sector 1 (S1, S2, S5, S7, S30, M3, M4, and M8); only B16 (where the tidal oscillation is seen, but is not smooth) and B23 (where the tidal oscillation has a low range or R_{WL}) on the Bidya are located in Sector 2. Hence, the semi-diurnal oscillation was not as striking at the TSLs closer to the mouth in comparison to those located farther from the seaface. R_S was also higher in Sector 2 (table 2).

One of the most striking discoveries of SEP2011 was the existence of a tidal stand in the SES (C2013). Stands with duration exceeding 75 minutes were seen in the northeastern TSLs on the Bidya, Gomdi, Harinbhanga, and Raimangal (figure 4), but the salinity at these TSLs showed no such persistence around the HWL (figure 7): the salinity varied semi-diurnally even during the tidal stand. Indeed, the highest salinity range, R_S , was observed at R24 (Bagna), where C2013 observed the longest stand. Thus, the tidal stand in the SES is not reflected in the salinity variation.

3.3 Vertical profile of salinity

The CTD salinity time series at all three stations shows a well-mixed profile (figure 8); the temperature, as expected, is also well-mixed (figure not shown), suggesting that the Matla is a well-mixed estuary during the Spring tide. Since only three CTDs were available, the vertical profiles are restricted to the Matla. Nevertheless, since the Kalash TSL was not located on the

main Matla channel, but in an east-west channel off the west bank (figure 6), the well-mixed nature may extend beyond the Matla to the other SES estuaries.

The surface salinity from the CTD measurements compares well with the salinity estimated from the autosal at the three stations (figure 9), providing an independent verification of the quality of salinity analysis. The correlation between the two estimates is high (0.96, 0.88, and 0.73 at Purandar, Kaikhali, and Kalash, respectively) and statistically significant at the 99% level. In retrospect, it would have been good to collect water samples from the CTD boats in addition to the TSL boats at these stations to compare the surface salinity measured by the CTD and the salinity estimated from the water sample, but these additional samples were not collected.

4 Discussion

We begin this concluding section with a brief summary of the results, followed by a discussion of the freshwater source for the SES estuaries and the implications of the observed spatio-temporal variation of salinity for the Sundarbans.

4.1 Summary

The salinity observations during SEP2011 showed that the mean salinity, S_{mean} , over the six tidal cycles decreased upstream (figures 5b,6) and the mean range of salinity over the six tidal cycles, R_S , increased upstream (table 2). In addition to this along-channel variation, S_{mean} varied zonally across the SES. Salinity was lowest in the eastern SES, with the lowest S_{mean} occurring at the TSLs on the Raimangal. The minimum S_{mean} recorded was 18.373 psu at R29 (Sahebkhali). Though higher than at the Raimangal TSLs, S_{mean} was also low (23.873 psu) at S5 (Mahendranagar, table 2), the westernmost TSL located on the SWG, and at ST13 (24.812 psu; Raidighi, table 2), the northernmost TSL on the SEG close to the confluence of the SEG and the Thakuran (figure 6). Salinity tended to be higher in the central part of the SES (figure 6).

At 20 of the 30 TSLs (three on the Saptamukhi, two each on the Thakuran and the Bidya, four on the Matla, three on the Gomdi, one on Harinbhanga, and all the five TSLs on the Raimangal), the salinity exhibited a semi-diurnal variation (figure 7), like the water level (figure 4), with maximum (minimum) salinity tending to occur at or around HW (LW). The temporal variation was more complex at the other 10 TSLs, of which five were located on the Saptamukhi, three on the Matla, and two on the Bidya. Thus, eight of these 10 TSLs were located in Sector 1 in the southwestern part of the SES and only two were located in Sector 2. Two of these 10 TSLs showed a semi-diurnal oscillation, but with a low range (R_S), three TSLs showed a semi-diurnal oscillation that was not smooth and the salinity was out of phase with the water level, and two TSLs (S1 and S5 on the Saptamukhi) showed a semi-diurnal oscillation in some cycles and not in others. At two TSLs (S2 and S30), there was no sinusoidal semi-diurnal oscillation, but the salinity did vary with a period of roughly six hours; in contrast, no clear periodicity was evident at M3, where the salinity tended to vary at periods shorter than six hours.

Though the tidal asymmetry tended to be of the flow-dominant type for water level (22 TSLs), it tended to vary between flow-dominance and ebb-dominance for salinity at 20 of the 30 TSLs (table 3). Even at the TSLs at which a tidal stand exceeding 75 minutes was seen in the water level (C2013; figure 4), the salinity oscillated with a semi-diurnal period (figure 7). Thus, the salinity variation was unaffected by the stand of the tide.

CTD data from three stations on the Matla show that it was well-mixed; it is possible that all the SES estuaries are of the well-mixed type during the Spring tide.

4.1.1 Freshwater sources

The tides are the main agents that carry salt in and out of an estuary and eventually lead to the mixing of salt and various nutrients, sediments, and other particulates within it. In general, the observed large-scale salinity in an estuary is determined by this tidal action, and the dominance, or vice versa, of dilution by freshwater over evaporation. For most estuaries, the main source of freshwater is the runoff from rivers at the head. Other sources are precipitation, which was absent before and during the 72-hour observation period in the SES, and local runoff. In the case of the SES, there is no riverine freshwater discharge to the principal estuaries, with the exception of the Hoogly and the Raimangal.

Therefore, during SEP2011, which was conducted at the peak of the dry season in the SES, the main source of salinity variation in the estuaries is the tide. Evidence of this tidal effect was seen all over the SES, with the salinity oscillating semi-diurnally at 20 TSLs; variation with a period of roughly six hours also seen at nine of the other 10 TSLs (figure 7).

The salinity decreased upstream in all the channels (figures 5b,6, table 2), suggesting that the observed along-channel variation of salinity is due to the preceding summer monsoon, when the inflow of freshwater into the channels would have lowered salinity throughout the SES estuaries. Following the cessation of rains, the ingress of salt from the seaward end owing to the tides is expected to lead to an along-channel gradient in salinity that is typical of monsoonal estuaries (Vijith *et al.*, 2009, 2016). The freshwater received from the Raimangal via its parent river, R. Ichhamati (a tributary of R. Ganga), led to the lowest salinities occurring at the five TSLs on this estuary (figure 6, table 2). Equally intriguing is that the salinity was also low at S5 (figures 5b,6, table 2), the westernmost TSL (figure 6), where the salinity showed almost no variation during the first two cycles and varied semi-diurnally over the last four cycles (figure 7). The possible source of the freshwater that lowers salinity at S5 is R. Hoogly, to which the Saptamukhi is connected via numerous east–west channels.

The Farakka Barrage was constructed to keep Kolkata port functional by diverting a part of the flow in the Ganga into the Bhagirathi — known farther downstream as the Hoogly — at Farakka (figure 1). A treaty, signed in 1996 between India and Bangladesh (Anonymous, 2017), states how the flow is to be divided during the dry season (January–May). During the peak of the dry season in March–April, 35000 cusecs ($\sim 991 \text{ m}^3 \text{ s}^{-1}$) is to be released in alternate 10-day blocks to India (Hooghly) and Bangladesh. The main point is that the Hoogly carries freshwater throughout March each year, but the amount of freshwater varies through the month. The Hoogly and SWG are connected by a complex network of channels, which must be transporting freshwater from the Hoogly to the SWG. An analysis of the salinity variation at S5 is beyond the scope of this paper, but we conjecture that the low, nearly invariant salinity over the first two cycles at S5 is due to an increased supply of freshwater. The later increase in salinity and the switch to a semi-diurnal oscillation suggests a dominance of the tidal circulation and weaker freshwater inflow. It may be just a coincidence that the intermittency in the freshwater diversion into the Hoogly at Farakka is captured in the salinity variation at S5.

Curiously, as noted earlier, the behaviour at S1, which is nearest the seafloor, is in contrast to that at S5. At S1, there was a semi-diurnal oscillation during all six cycles, but the salinity showed a decreasing trend after the first two cycles. Since the salinity tends to be lower in the northeastern Bay of Bengal or the coastal regime off Bangladesh in comparison to the salinity in the northwestern bay or the coastal regime off the Sundarbans (see figure 19 of Chatterjee *et al.*, 2012), advection of the fresher water from the east may lead to the decrease in salinity at S1. We note, however, that a similar decrease in salinity should then occur at M3, which lies east of S1, but salinity tends to increase instead at M3 over the last four cycles (figures 7,8). Another possible cause of this decreasing trend may be the inflow from the Hoogly, which can occur via the Bay of Bengal in addition to the possibility of being driven via the SWG. The complex geometry of the SES estuaries will play role in determining local salinity variations by the process of tidal trapping (Medeiros and Kjerfve, 2005) observed in other estuarine systems.

What makes it difficult to draw inferences for the Saptamukhi is the multiplicity of lateral freshwater sources, unlike the more direct and common source at the head of the Raimangal. Mapping the salinity variation in the southwestern SES is a challenge.

4.1.2 Implications for the Sundarbans

In the introduction, we noted the importance of salinity in determining the availability of potable water for domestic and agricultural uses, fishery, and the mangroves.

The absence of a direct freshwater source at the head in six of the seven estuaries (Raimangal being the exception) suggests that salinity can be expected to be low only in the northeastern SES (Sector 2) during the dry season. Therefore, ingress of saline water is more likely in the southwestern SES (Sector 1). An implication is that it will be more difficult to tap potable water in the southwestern SES. The migration of the *Hilsa* and the restriction of the *Sundari* tree, which require fresher water, to the eastern part of the SES is also likely to be driven by the higher salinity in the western SES.

Therefore, from the viewpoint of salinity and freshwater, the eastern SES is more conducive to human habitation than the western SES, with the region around the Hoogly being the exception. The northern part of the eastern SES, Sector 2, is inhabited, but the southern part constitutes the reserved forest. Yet, as noted by C2013, the northeastern SES (Sector 2) is more prone to the effect of the storms and the surges, with the long tidal stand during HW increasing the probability of the surge coinciding with the high tide. Thus, both inhabited parts of the Sundarbans suffer from significant disadvantages. The advantage of lower surge levels in Sector 1 is compensated by the poorer availability of potable water and the advantage of better availability of potable water in Sector 2 is compensated by the higher propensity for damage from surges. In both regions, the disadvantages are due to natural causes: natural, geological changes over a few centuries have led to the higher salinity in Sector 1 and the geometry of the SES to the amplification of the higher harmonics, and therefore a more damaging surge, in Sector 2.

Thus, life in the Sundarbans has been (Abúl-Fazl-Allami, 1589–1598; Bandopadhyay, 1936) — and is (Ghosh, 2004; Bhattacharyya, 2011) — a constant struggle against the forces of nature. Any attempt at mitigating the hardships in the region will have to counter the problems posed by the natural obstacles provided by saline water and the surges due to storms. Whether human ingenuity can overcome these significant obstacles to improve the quality of life in the Sundarbans remains to be seen. It is clear, however, that future research will have to build on the results of SEP2011 to provide the baseline information and improve predictive capabilities in a terrain that presents a significant observational and modelling challenge if the natural obstacles are to be overcome.

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Author statement

The specific contribution of each author is as listed below.

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- V. Vijith: Analysis and interpretation of the data, preparation of the figures, and writing of the manuscript.
- G. K. Sen: PI of the project and planning the SEP, overall supervision and logistic coordination during SEP2011 in Sector 2.
- D. Sundar: Planning the SEP and the methodology to be followed, overall supervision and logistic coordination during SEP2011 in Sectors 1 and 2.
- G. S. Michael: Planning the SEP and the methodology to be followed, overall supervision and logistic coordination during SEP2011 in Sectors 1 and 2.
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- P. Sanyal: Planning the SEP and the methodology to be followed, and overall supervision and logistic coordination during SEP2011 in Sector 1.
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Reference and description	Location	Period	Salinity
Chugh (1961): Monthly-mean data from R. Hooghly (Kolkata)	Diamond Harbour	Mar 1953–1959	15.70
	Garden Reach	Jul 1958–1959 Mar 1953–1959	10.80 4.30
Gole and Vaidyaraman (1967): Daily-mean data from R. Hooghly	Sagar Island	12 Jul 1964	22.00
		14 Jul 1964	20.40
	Diamond Harbour	7 Jul 1964	17.61
		12 Jul 1964	14.40
		13 Jul 1964	13.20
		14 Jul 1964	11.25
	Falta	7 Jul 1964	12.35
		12 Jul 1964	12.50
		13 Jul 1964	3.90
	Royapur	14 Jul 1964	2.70
		7 Jul 1964	7.11
		12 Jul 1964	3.20
	Garden Reach	13 Jul 1964	2.40
		14 Jul 1964	1.70
		7 Jul 1964	0.42
		12 Jul 1964	0.50
Haldia	13 Jul 1964	0.49	
	14 Jul 1964	0.47	
	7 Jul 1964	33.30	
	1 Sep 1964	0.06	
Rao (1969): Fortnightly sampling from 30 sampling stations over four years in the Hooghly Estuary consisting of the Hooghly, Roopnarayan, and Matla. The entire Hooghly was divided into three zones: Zone 1 (upper freshwater zone), Zone 2 (middle brackish-water zone), and Zone 3 (lower seaward or marine zone).	Hooghly Zone 1	Mar 1962	0.00
	Hooghly Zone 2	to	0.10–12.68
	Hooghly Zone 3	Feb 1966	4.32–29.77
	Roopnarayan Zone 4		0.00–5.72
	Matla Zone V		10.72–30.41
Bhunia and Choudhury (1981): Fortnightly samples during ebb tide from six stations on the Mooriganga Creek (6 km long).	Sagar Island (all six stations)	Nov-1976 to Oct-1977	0.50–18.50
		Jul–Oct	0.50–2.10
		Nov–Jun	10.50–18.50
Nandy <i>et al.</i> (1983): Fortnightly sampling with the same zonation as Rao (1969). Maximum salinity values during 1960–1961 (pre-Farakka) and 1976–1977 (post-Farakka, in parentheses) reported for six stations. Shows impact of the Farakka Barrage on salinity.	Barrackpore (Z 1)	1960–1961	0.20 (0.00)
	Geonkhali (Z 2)	(1976–1977)	20.20 (0.98)
	Uluberia (Z 2)		12.00 (0.12)
	Kakdwip (Z 3)		32.80 (18.00)
	Kolaghat (Z 4)		6.50 (0.41)
Canning (Z 5)		28.00 (28.40)	
Sadhuram <i>et al.</i> (2005): Measurements during ebb (E) and flood (F) tides at eight stations on the Haldia channel of the Hooghly.	Average over all eight stations	May 1998 (E)	4.50–6.00
		May 1998 (F)	7.00–13.00
		Nov 1998 (E)	0.20–1.20
		Nov 1998 (F)	1.80–2.40
Mitra <i>et al.</i> (2011): Average of salinity measurements at 12 stations between Sagar Island and Diamond Harbour on the Hooghly at high tide and low tide during 20–25 April 2008.	Average over 12 stations	Low tide	1.39–20.43
		High tide	2.48–22.08

Table 1: Reported salinity measurements in the Hooghly and the Matla. More recently, measurements have been carried out at Hasnabad on the Ichhamati (Ghosh and Satpathy, 2019), but it is not included in this table because the details of sampling are not available. Likewise, the sampling details are not available in Mitra *et al.* (2009), who report annual mean salinity from 1980–2007, with breaks in between, from two stations, one each in the western (1980–2007) and eastern (1980–1995 and 1995–2007) sectors of the Sundarbans.

TSL	Name	Dist.	Lon.	Lat.	R_{WL}	S_{mean} (SD)	R_S
S1	Indrapur	8.0	88.413	21.651	4.62	28.015 (0.238)	0.483
S2	Dhanchi	14.0	88.433	21.704	4.32	27.787 (0.102)	0.485
M3	Kalash	15.0	88.587	21.702	4.83	28.350 (0.105)	0.598
S7	Pakhirala	28.5	88.441	21.796	5.14	27.585 (0.078)	0.337
S30	Shibganj	29.5	88.378	21.764	4.90	27.162 (0.115)	1.485
T11	Kishorimohanpur	32.0	88.523	21.858	4.93	27.483 (0.033)	0.890
M8	Dhulibhasani	33.0	88.557	21.802	5.36	27.735 (0.177)	2.162
M4	Bonnie Camp	35.0	88.622	21.830	4.93	27.566 (0.104)	1.107
S6	Ramganga	35.5	88.370	21.796	5.15	27.668 (0.141)	0.908
T10	Damkal	39.0	88.461	21.897	5.61	27.127 (0.234)	1.082
S5	Mahendranagar	43.0	88.311	21.784	5.14	23.873 (0.238)	2.178
S9	Purbadwarakapur	48.0	88.444	21.906	5.37	27.177 (0.087)	0.632
B16	Jharkhali Bali	54.5	88.697	22.051	5.71	26.507 (0.339)	0.660
M14	Kaikhali	56.0	88.614	22.022	5.54	25.765 (0.133)	0.898
M15	Jharkhali Jetty	61.0	88.682	22.019	5.53	26.592 (0.130)	1.342
M15	Durgaduani	64.0	88.777	22.120	6.04	26.908 (0.092)	0.500
ST13	Raidighi	65.0	88.447	21.994	5.58	24.812 (0.538)	2.657
G18	Pakhiralay	69.0	88.823	22.129	5.08	26.610 (0.120)	1.150
H17	Lahiripur	71.0	88.896	22.092	5.21	26.073 (0.146)	1.185
B19	Gosaba	75.0	88.797	22.165	6.01	26.240 (0.301)	1.395
R25	Kalitala	79.5	89.017	22.208	5.21	22.137 (0.352)	1.542
B20	Rangabelia	80.0	88.831	22.164	5.82	26.067 (0.332)	0.870
M22	Purandar	83.0	88.655	22.207	6.34	23.727 (0.256)	0.938
B23	Pathankhali	83.5	88.748	22.207	5.90	24.688 (0.288)	0.517
R24	Bagna	87.0	88.958	22.192	4.97	22.597 (0.483)	5.208
GH21	Melmelia	95.0	88.887	22.164	5.53	25.683 (0.071)	1.343
M26	Canning	98.5	88.681	22.286	6.73	23.522 (0.341)	0.905
R28	Shitalia	101.0	88.912	22.310	5.33	19.735 (0.306)	2.495
R29	Sahebkhali	108.0	88.957	22.362	5.08	18.373 (0.633)	4.365
R27	Dhamakhali	109.5	88.876	22.356	5.47	18.778 (0.417)	2.618

Table 2: The mean for the range of water level (R_{WL} , m), salinity (psu), and range of salinity (psu) at the 30 TSLs. The TSLs are listed in order of distance (km) from the seaface, defined as the mouth of the Matla (latitude: 21.6025°N). The mean implies averages over the six tidal cycles that occurred during the 72-hour observation period from 4 AM on 18 March to 4 AM on 21 March 2011; all times are in IST. The columns are as follows. C1 lists the station or TSL number, C2 the station name, C3 the distance from the seaface, C4 the longitude (°E), C5 the latitude (°N), C6 the mean of the range of water level (R_{WL}), C7 the mean salinity (S_{mean}), and C8 the mean of the range of salinity (R_S). The standard deviation of salinity is listed in parentheses in C7.

Name	Flow-dominant			Ebb-dominant			Mixed		
	Both	WL	Sal.	Both	WL	Sal.	Both	WL	Sal.
Indrapur							S1		
Dhanchi							S2		
Kalash		M3							M3
Pakhirala		S7							S7
Shibganj							S30		
Kishorimohanpur		T11							T11
Dhulibhasani	M8								
Bonnie Camp			M4					M4	
Ramganga		S6							S6
Damkal		T10							T10
Mahendranagar		S5							S5
Purbadwarkapur		S9							S9
Jharkhali Bali		B16							B16
Kaikhali		M14				M14			
Jharkhali Jetty		M15				M15			
Durgaduani		G12				G12			
Raidighi		ST13				ST13			
Pakhiralay	G18								
Lahiripur							H17		
Gosaba		B19							B19
Kalitala							R25		
Rangabelia		B20							B20
Purandar		M22				M22			
Pathankhali		B23							B23
Bagna						R24		R24	
Melmelia		GH21							GH21
Canning		M26							M26
Shitalia		—				—			R28
Sahebkhali		R29							R29
Dhamakhali	R27								
TOTAL	3	19	1	0	0	6	5	2	15

Table 3: Nature of tidal asymmetry for water level (WL) and salinity (Sal.). The TSLs are ordered upstream from the seafloor as in table 2. The asymmetry is of two types, flow-dominant and ebb-dominant, but some stations show a mixed asymmetry behaviour, with flow-dominance in some tidal cycles and ebb-dominance in others. Accordingly, there are three classifications of the asymmetry: flow-dominant, ebb-dominant, or mixed. For each class, there are three columns because water level and salinity do not necessarily show the same asymmetry. A TSL can be listed in at most two columns; it will figure in only one column if the same asymmetry is seen for both water level and salinity. Only at eight TSLs do we see both water level and salinity showing the same asymmetry: flow-dominance is seen at three TSLs (Column 2) and mixed asymmetry at five TSLs (Column 8). In general, flow-dominance is striking for water level (19 TSLs, Column 3) and the asymmetry tends to be mixed for salinity (15 TSLs, Column 10). No TSL shows ebb-dominance for water level and therefore none is listed in Columns 5 and 6. Only one TSL, M4 or Bonnie Camp, shows flow-dominance for salinity (Column 4) and mixed behaviour for water level (Column 9). The WL asymmetry was not determined for Shitalia (R28, C2013) owing to data gaps.

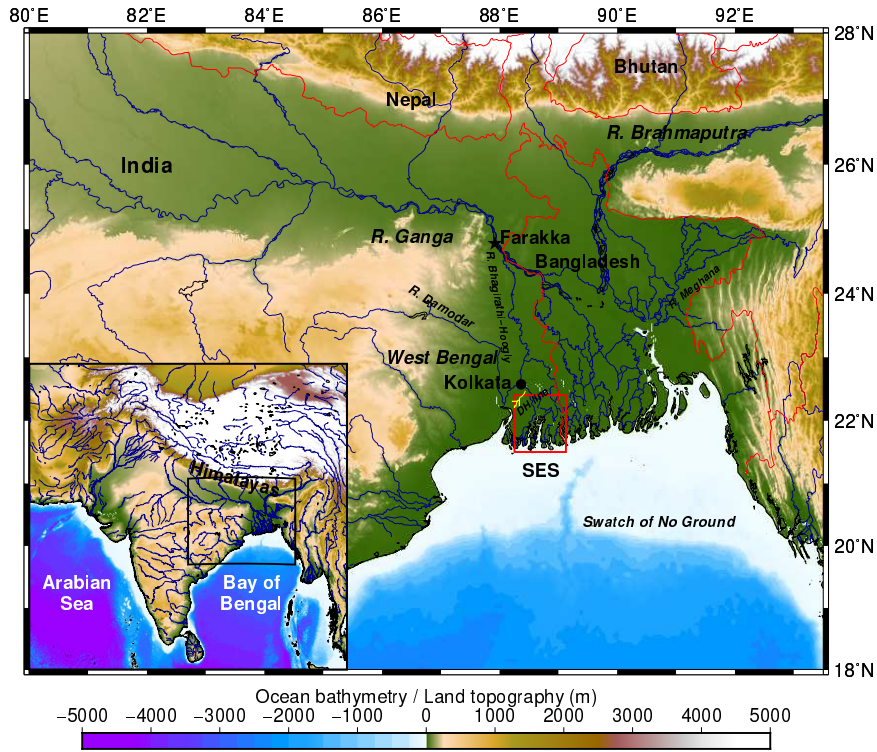


Figure 1: The physical setting of the Ganga-Brahmaputra river system and the delta system. The inset shows topographic and bathymetric details of the entire Indian subcontinent (the black rectangle marks the region plotted) with the major rivers (in blue), the Himalayas, the Arabian Sea and the Bay of Bengal. Topography and bathymetry data are from ETOPO1 (Amante and Eakins, 2009); the colour scale for both maps is at the bottom of the figure. In the larger map, only the ocean bathymetry is plotted to scale, with only a three-step grayscale shading being used to indicate the land topography. The Farakka Barrage is located on the Ganga just upstream of the international border (red curve) between India and Bangladesh. Note the ‘Swatch of No Ground’ in the Bay of Bengal. The region marked by the red box consists of the South and North 24 Parganas districts in West Bengal within which the Sundarbans Estuarine System (SES, excluding R. Hoogly) is located; this red box marks the domain of the map in figures 2 and 6.

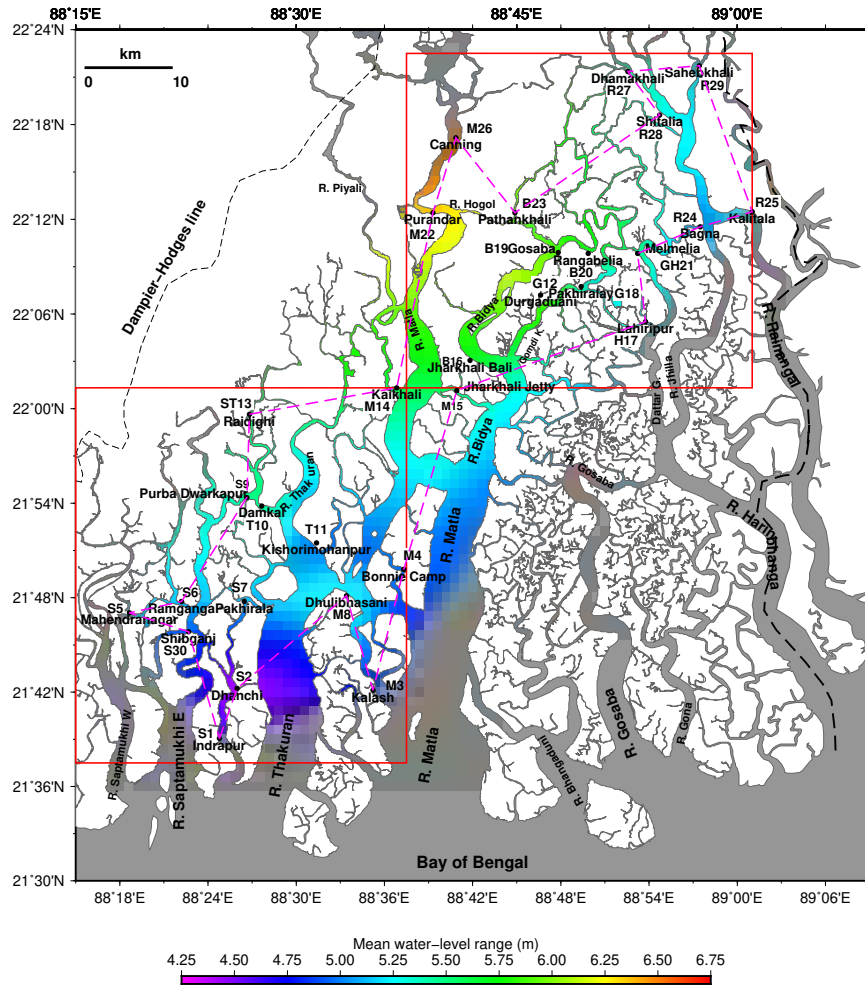


Figure 2: The Sundarbans Estuarine System (SES) and the spatial variation of the mean range of water level, R_{WL} (m), in the SES. The red border marks the area covered during SEP2011. It consists of Sector 1 in the southwestern part and Sector 2 in the northeastern part. The names and numbers of the observation stations or TSLs (table 2) are shown. The thin dashed curve marks the Dampier-Hodges Line and the thick dashed curve marks the Indo-Bangladesh border. The water level was contoured by triangulation using GMT (Generic Mapping Tools; Wessel and Smith, 1991; Wessel *et al.*, 2013). The magenta polygon marks the boundary of the region within which the values are interpolated; outside this polygon, the values are extrapolated.



Figure 3: Photographs related to the collection of water samples during SEP2011. Top left panel: Water surface temperature being read at M26 (Canning). Top right panel: Water sample being collected and stored in a PET bottle at Canning. Bottom left panel: At M8 (Dhulibhasani), the water receded to such a level that while the fixed observation platform, or the mechanised boat, remained on the dry bank, the tide pole still remained immersed in the water. This photograph shows the observer going to collect the water sample from near the tidepole. This situation occurred at several TSLs during low tide. Bottom right panel: Packaging of the salinity sample bottles with station name labels for identification. The packages shown in this photograph are from T11 (Kishorimohanpur) and M15 (Jharkhali Jetty).

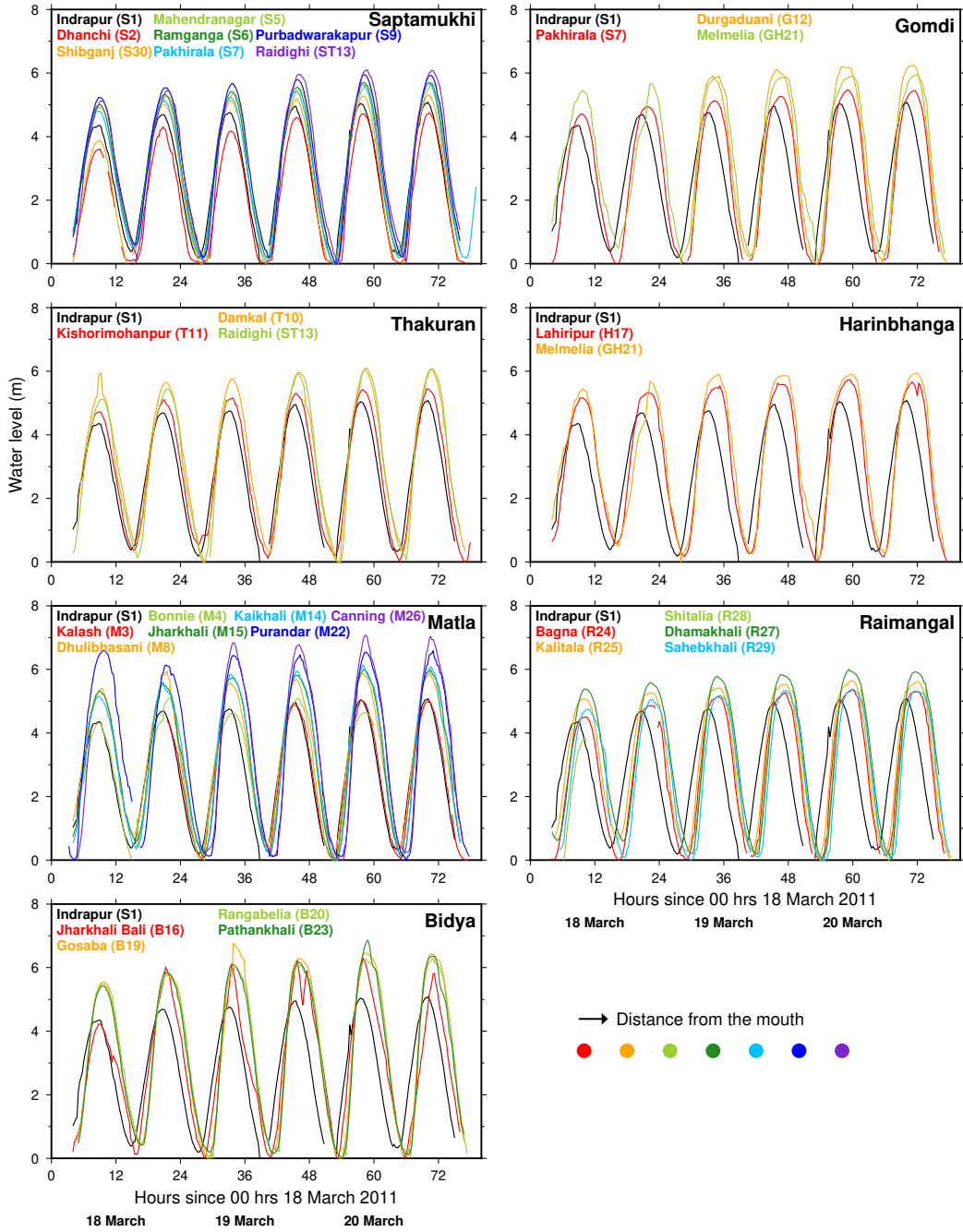


Figure 4: Temporal variation of water level (m) at the TSLs in the SES. A separate panel is used for each estuary. The water level for Indrapur is plotted in each panel and the colours used are mapped to increasing distance from the seafloor. (Adapted from Chatterjee *et al.* (2013).)

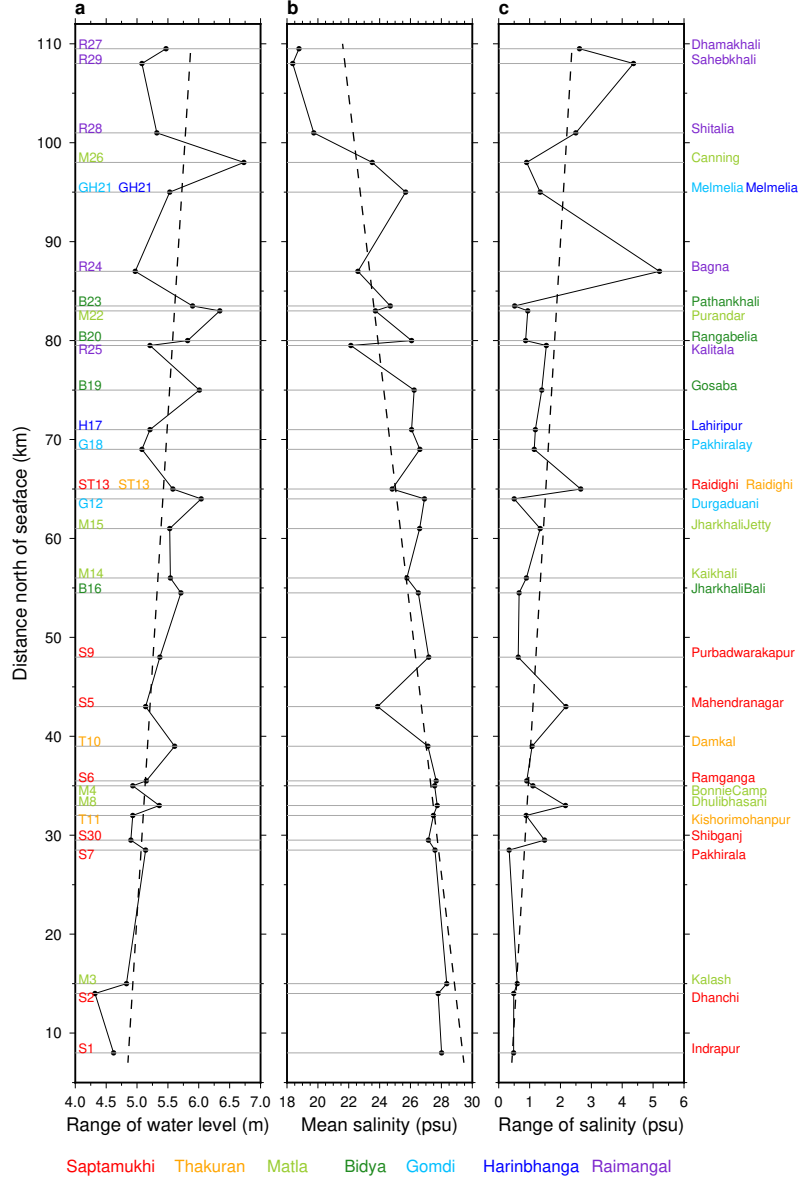


Figure 5: Along-channel variation of (a) the range of water level, R_{WL} (metres), (b) the mean salinity, S_{mean} (psu), over the six tidal cycles, and (c) the mean of the salinity range, R_S (psu), averaged over the six tidal cycles. The ordinate is the distance (km) from the seaface, which is taken to be the mouth of the Matla ($21.603^\circ N$); the station number (name) is labelled on the left (right). Fitting a line to the three curves yields the following relations: $y = 0.0099x + 4.7842$ with $r = 0.57$ for R_{WL} , $y = -0.0763x + 29.9900$ with $r = 0.81$ for S_{mean} , and $y = 0.0190x + 0.2918$ with $r = 0.49$ for R_S .

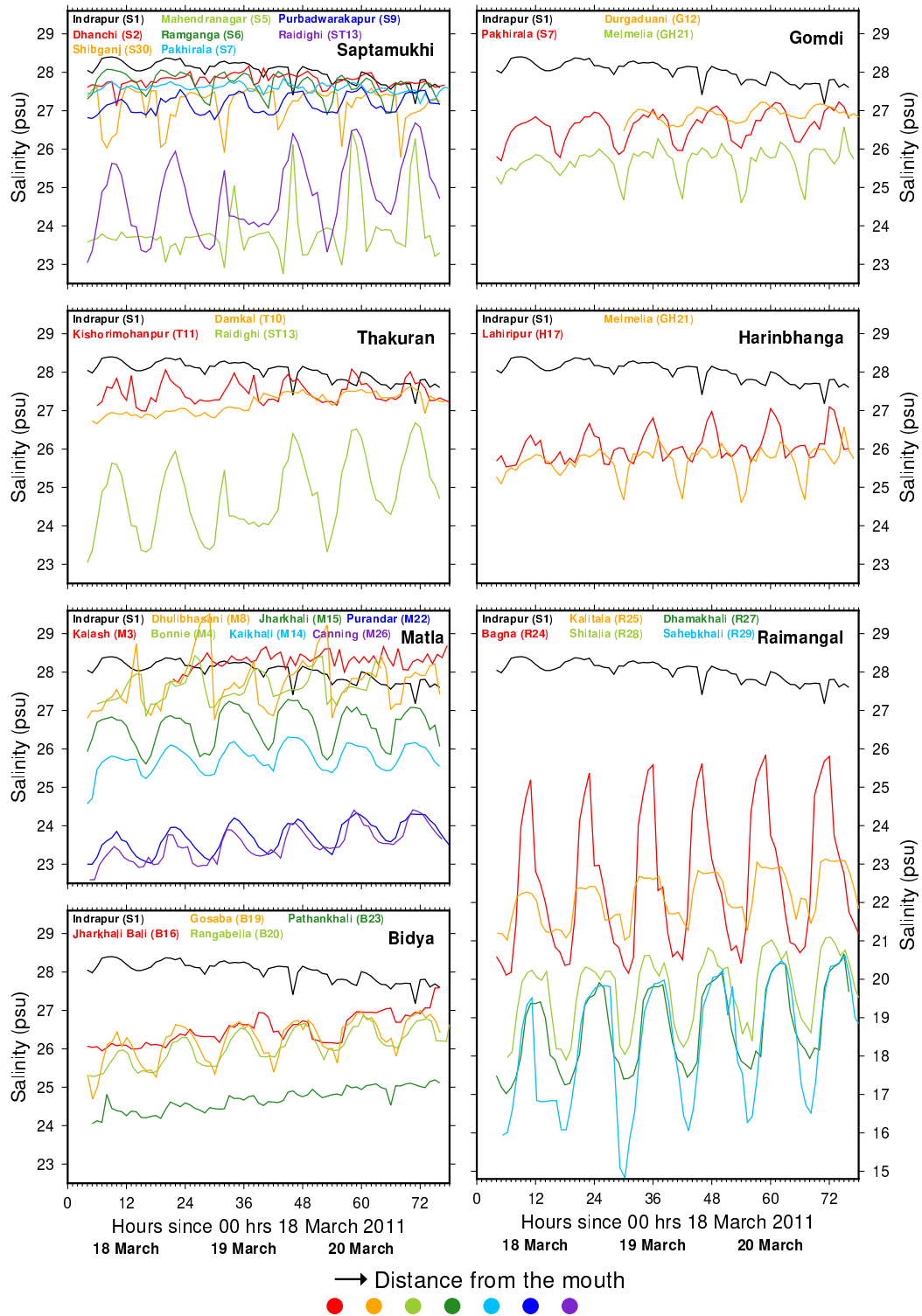


Figure 7: Temporal variation of salinity (psu) at the TSLs in the SES. A separate panel is used for each estuary. The salinity for Indrapur is plotted in each panel and the colours used are mapped to increasing distance from the seafloor. Note the need for a greater range of the ordinate for the Raimangal.

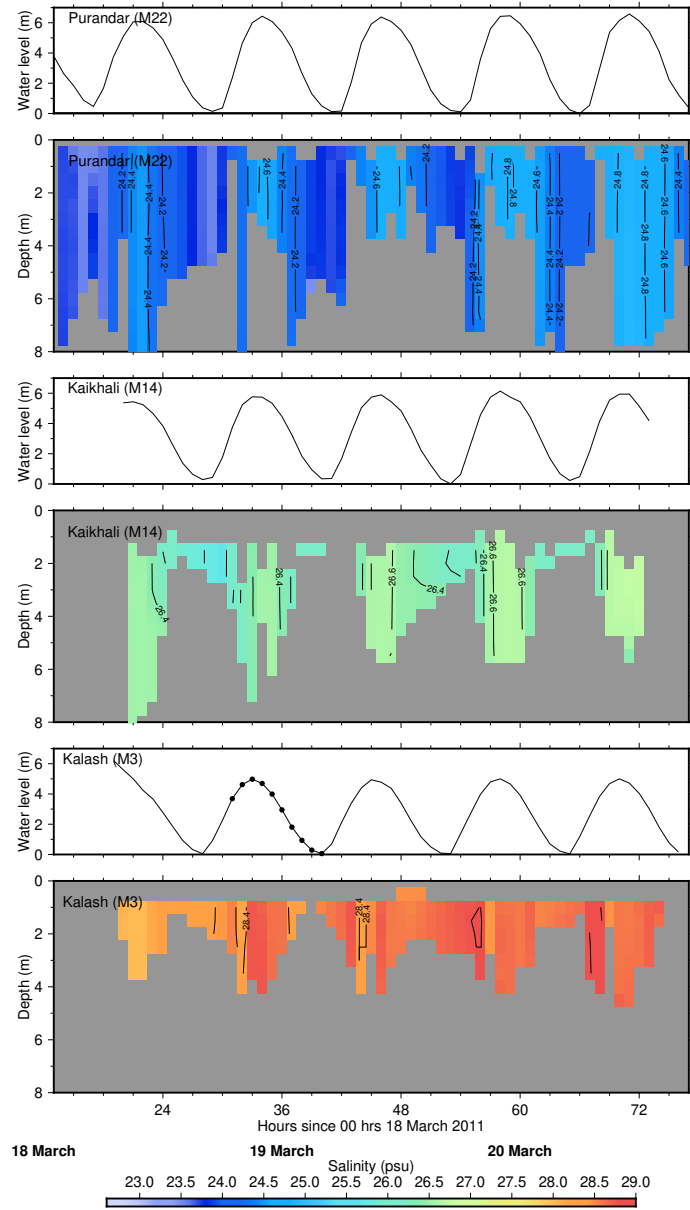


Figure 8: Water level (odd panels, m) and the vertical profile of salinity (even panels, psu) at Purandar, Kaikhali, and Kalash on the Matla; the ordinate range (depth, m) and the colour scale for salinity have been kept the same for all panels in spite of the different ranges of water level and salinity at the three locations. The common depth range leads to more grey shading at Kalash and Kaikhali, where the range of water level is lower than at Purandar. The grey shading indicates absence of data due the range of water level being lower than the range of the ordinate or non-availability of data (as seen at Kaikhali and Kalash at the beginning and end of the 72-hour observation period). The missing water-level data at Kalash were filled using harmonic analysis and a dotted curve is for this part of the time series.

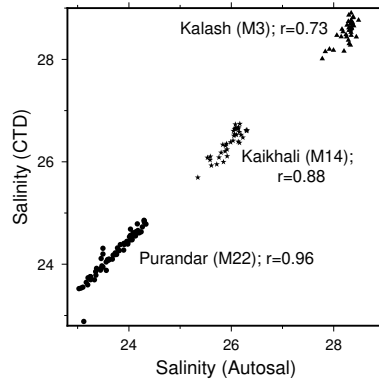


Figure 9: Scatter plot showing the correlation between the surface salinity measured by the CTD and the salinity estimated using the autosal from the water samples collected at Purandar, Kaikhali, Kalash. At Kalash, the salinity samples for autosal analysis were collected 30 minutes before the CTD casts. Therefore, autosal-derived salinity data were linearly interpolated to the time grid of CTD measurements for this scatter plot. The correlations (r) between the CTD and autosal salinity for Purandar, Kaikhali, and Kalash are 0.96, 0.88, and 0.73, respectively, and all correlations are significant at the 99% level.

Research highlights

- Comprehensive description of salinity variability in the Sundarbans Estuarine System (SES)
- Semi-diurnal variation seen at a majority of the stations and the estuaries are well-mixed
- Mean salinity decreases upstream and is lower in the eastern and western SES
- The upstream decrease is due to the preceding monsoon and the tidal ingress of salt
- Direct (indirect) inflow from the Ganga (Hoogly) lowers salinity in the eastern (western) SES