Estuarine turbidity maximum in six tropical minor rivers, central west coast of India

Lina L. Fernandes, V. Purnachandra Rao, Pratima M. Kessarkar and Suja Suresh

ABSTRACT

Understanding patterns of erosion and sedimentation and their driving mechanisms is important for formulating a variety of estuarine management issues (conservation, shoreline protection, navigation, dredging and embanking). Therefore, the present study aims to determine the factors influencing the seasonal distribution and dynamics of suspended particulate matter (SPM) of two meso-(Mandovi and Zuari) and four micro-tidal (Terekhol, Chapora, Sal, and Talpona) river estuaries of Goa, on the central west coast of India. These estuaries exhibited salinity stratification near their mouths during the wet season and well-mixed water columns during the dry season. The SPM concentrations were two times higher in the wet season than in the dry season. Estuarine turbidity maximum (ETM) was a consistent feature in both the seasons at the mouth of the estuaries, except in the estuary of the Sal River. The *in situ* vertical distribution of SPM volume concentration and mean particle size allowed for a better visualization of the ETM formation and distribution. The gravitational circulation as well as flocculation at the salt–freshwater interface during the wet season and the impact of tidal and wind-induced currents at the river mouths during the dry season were primarily responsible for the formation of the ETMs.

Key words | estuary, micro-tidal rivers, suspended sediments, turbidity maxima

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INTRODUCTION

Rivers are the major contributors of particulate material to coastal seas. Presently, rivers transport around 95% of sediment to the ocean (Syvitski 2003) through the suspended load and bed load (Gaillardet *et al.* 2003; Walling 2006). The annual sediment discharge of rivers along the Indian coast is $\sim 1.2 \times 10^{12}$ kg (Chandramohan *et al.* 2001). Most of the rivers in India originate in hilly or mountainous regions and traverse the valleys, plateaus, and plains to meet the sea. Estuaries, being at the interface between the river-derived freshwaters and saline coastal waters, are characterized by significant gradients in both physico-chemical and biological factors, in particular, salinity and suspended sediment concentrations (Schubel & Carter 1984; Kitheka *et al.* 2016). The river transport and estuarine processes, both physical (tides, currents) and chemical (flocculation (Krone 1962), organic coating (Eisma *et al.* 1991)), enhance particle settling near the salt–freshwater interface, thereby influencing the concentration and composition of suspended particulate matter (SPM) (Morris *et al.* 1995). Further, in areas with high SPM containing a significant clay component, the flocculation is reported to occur at varying salinity conditions (Lamb & Parsons 2005; Schieber & Southard 2009) either in stagnant or high energy conditions (Macquaker & Bohacs 2007). As a result, a region of elevated suspended sediment concentration (10 to 100 times) often occurs in estuaries near the landward limit of

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the salt intrusion which is called the estuarine turbidity maximum (ETM) or turbidity maximum zone (TMZ) (Geyer 1993; Shi 2004). Thus, organic and inorganic material from the river and the coastal ocean enters into the ETM region and becomes part of the inter- and intra-tidal cycles of sedimentation and resuspension, either in the main channel of the estuary (Kostaschuk & Luternauer 1989; Kostaschuk & Best 2005) or the intertidal regions of the river (Pearson & Gingras 2006; La Croix & Dashtgard 2014). In recent years, there have been countless investigations worldwide focusing on the characteristics of salinity intrusion and turbidity maxima in estuaries during different seasons (Uncles *et al.* 2006; Vijith & Shetye 2012) and intra-tidal to annual time-scales (Yang *et al.* 2004; Uncles & Stephens 2010). A great number of studies have also focused on the suspended sediment circulation, transport, erosion/resuspension, deposition within the estuarine systems (Allen *et al.* 1980; Hughes *et al.* 1998) and emergent intertidal bedforms (Boersma & Terwindt 1981; Allen *et al.* 1994). The ETM has also been reported in different regions of an estuary (Allen *et al.* 1977; Uncles & Stephens 1993; Mitchell *et al.* 1998, 2003; Schoellhamer 2001; Rao *et al.* 2011; Suja *et al.* 2016).

The ETM affects the functioning of estuarine ecosystems; for example, the ETM region is an important nursery area for larval fish (Dodson *et al.* 1989; Jassby *et al.* 1995), creates a predation refuge for them (Chesney 1989), and holds larvae in optimal salinity or temperature conditions (Strathmann 1982). Therefore, the ETM results in increased zooplankton biomass and production (Simenstad *et al.* 1994; Boynton *et al.* 1997). The rich supply of organic material from both detritus and algae settling on the bed in the ETM region increases the turnover rates (Covi & Kneib 1995; Alongi 1998), which enhances the production of sediment-dwelling invertebrates, including nematodes, copepods, annelids, molluscs, and peracarid crustaceans. For example, in the York River, bivalves (filter and surface deposit feeders) were found to be abundant in the ETM region (Sin *et al.* 1999; Schaffner *et al.* 2001). The role of the ETM in estuarine productivity and its relationship with estuarine-dependent fish have been reported in major estuarine systems such as the Chesapeake Bay (North & Houde 2003; Shoji *et al.* 2005), the St. Lawrence estuary (Sirois & Dodson 2000), the Dollard-Ems estuary (Jager 1998), and the San Francisco Bay estuary (Jassby *et al.* 1995; Bennett *et al.* 2002). Since the large SPM concentration in the ETM affects productivity, water quality, navigation, dredging and embanking, and coastal defense, it is necessary to understand the factors influencing the ETM formation for effective and sustainable use of these environments (Mitchell & Uncles 2013). The exploration of the ETM variability will be helpful in understanding its complexity and diversity and is of considerable significance in strategy-making of engineering management.

STUDY AREA

Regional geology and environmental setting

The pre-Cambrian Dharwar rocks occupy a large area in Goa and consist of schists, metavolcanics, metagreywackes, conglomerates (tilloids), banded ferruginous quartzites associated with phyllite/argillite/limestone, and dolomite intruded by granites, ultrabasic and basic rocks. They are covered by about 30–40 m laterite on the coast that thins to the interior. The major part of the coast is covered with sandy and reddish brown laterite soil.

The rainfall and runoff are highly seasonal in Goa. Two distinct periods (wet and dry seasons) determine the volume and composition (i.e., salinity) of water in these estuaries. The maximum rainfall (~300 cm/yr) occurs during the southwest monsoon (June–September; wet period), and the maximum estimated runoff available for the Mandovi River is $\sim 2{,}190 \times 10^6\ \mathrm{m}^3$ (Shetye *et al.* 2007; Suprit & Shankar 2008). During the dry period (October–May), the rainfall, as well as the river runoff into the sea, are negligible. The mean wind speed varies from 2.72 to 5.44 m/s with the maximum occurring during the wet season. From June to September, the wind blows from the SW while for the remaining period the wind direction is from NE. From November to May, the winds are dominated by the sea breeze. Along the west coast of India, waves are predominantly swells (Kumar *et al.* 2000; Hameed *et al.* 2007) during the wet season with periods ranging between 8 and 10 s (Kumar *et al.* 2000). However, during the dry season, sea breeze plays a major role in controlling the wave characteristics (Aparna *et al.* 2005). The tides are semi-diurnal (i.e., exhibiting two high and two low waters in a tidal day). The tides in the Mandovi and Zuari are meso-tidal with a mean tidal height of ~2.3 m and 1.8 m during the spring and neap tides, respectively (Sundar & Shetye 2005). On the other hand, the tides are micro-tidal in the other rivers with a mean tide height of ~2 m for the spring and ~0.25 m for the neap tide (NIO 1997).

Rivers and their drainage patterns

There are nine minor rivers (catchment area below 2,000 km^2; Rao 1979) draining the Goa region, namely the Terekhol, Chapora, Baga, Mandovi, Zuari, Sal, Talpona, Saleri, and Galgibag (Figure 1). These rivers/estuaries are considered to be drowned river valleys (Ahmad 1972) and are mostly straight with sharp bends. Six rivers are considered for the present study. The Terekhol and Chapora rivers originate in Maharashtra state, while the Mandovi and Zuari rivers originate in Karnataka. The Sal River originates as a small stream in the hilly region of Verna village in south Goa and opens up into the Arabian Sea near the Betul beach. It has a very low shore-line with gentle submarine slope and a narrow mouth, which hinders the transport of domestic wastes into the sea. The Talpona River originates in the dense, mixed jungles of the Sahayadri Hills and drains into the Arabian Sea near the village of Talpona. Rocky outcrops and vertical cliffs are present along the shores from the Terekhol to the Zuari rivers, followed by a long stretch of sandy beach until Betul. At Betul, the shore is mostly of laterite cliff. Further south, rocky shores are

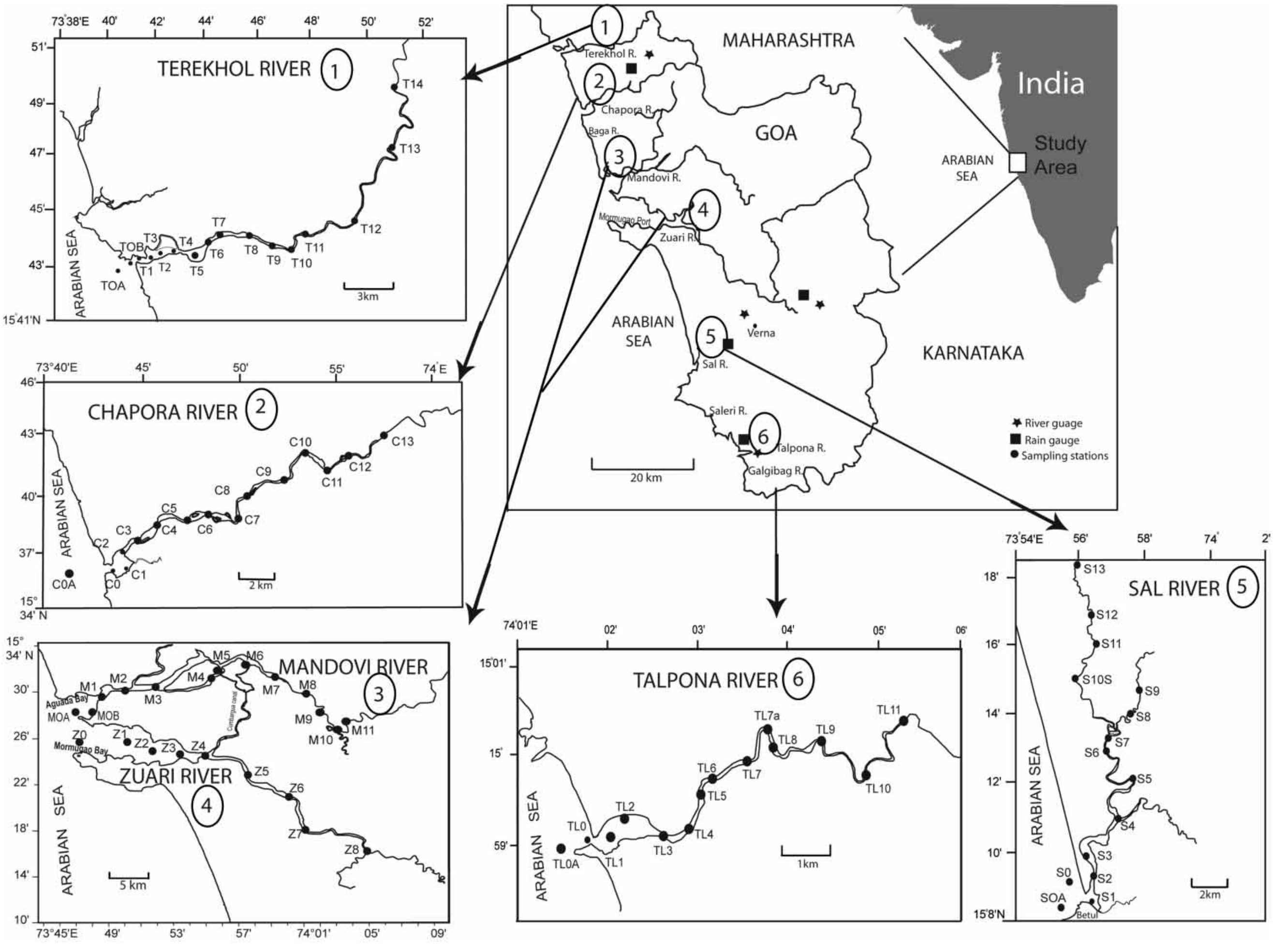

Figure 1 | Map showing the locations of the Terekhol, Chapora, Mandovi, Zuari, Sal, and Talpona rivers on the central west coast of India. The locations of sampling sites in each of the estuary are also shown.

present until the Talpona River. Goan rivers exhibit dendritic drainage (Wagle 1982). The drainage area trends in a NW or NNW and EW direction; the former follows the regional trend of the formations while the latter is structurally controlled by major faults/fractures and master joints (Feio 1956). The Sal River is an exception, as it runs parallel to the coast, due to the west coast fault and finally opens into the sea after touching the rocky exposures (Figure 1). Laterite beds have been reported in the estuaries of the Chapora, Mandovi, and Zuari (Wagle 1991). The distance traversed by each of the rivers varies before meeting the sea and is ~28 km (Terekhol), ~33 km (Chapora), ~75 km (Mandovi), ~142 km (Zuari), ~35 km (Sal), and ~32 km (Talpona) (Table 1; www.goaenvis.nic.in). The width of the estuaries at the river mouths varies from 4.50 to 0.30 km. Wide stretches of tidal flats are seen along the Terekhol, Chapora, Mandovi, and Zuari rivers. In spite of tremendous headward erosion capacity, favorable rainfall and climate for delta formation, no deltas are developed anywhere along the coast due to submergence or strong dispersion of sediments at the river mouths by the waves and the currents (Wagle 1991).

Several investigators have studied the physico-chemical features of the Indian estuaries (Perumal *et al.* 2009; Nedumaran *et al.* 2011) and reported the formation, mechanism, and role of the ETM in these river estuaries (Kessarkar *et al.* 2009, 2010; Rao *et al.* 2011; Priya *et al.* 2015). All the rivers form an integral part of Goan life because of their potability, irrigation facilities, agriculture, fisheries and coastal resources, transport of mining ores, etc. Among the rivers, the Mandovi and Zuari drain ~2,553 km^2, equivalent to 70% of the total geographical area of Goa. Unrestricted sand mining activity is observed at several sites along the rivers, being most conspicuous along the Mandovi, Zuari, Chapora, and Terekhol rivers. Although, the Mandovi and Zuari have been extensively studied with respect to physical (Shetye *et al.* 2007; Sundar *et al.* 2015), biological (Patil & Anil 2015), and geological characteristics of the waters and bed sediments (Kessarkar *et al.* 2010; Shynu *et al.* 2012), much less is known about the four micro-tidal rivers. In the present study, the coexistence of waves, tidal currents, and river discharges, make these coastal systems highly dynamic and complex, so that the interplay of the physical processes and the resulting dynamics need to be explored. Therefore, in this study, we have investigated the SPM concentration in six minor river estuaries of Goa, namely the Terekhol, Chapora, Sal, Talpona, Mandovi, and Zuari rivers during the wet and dry seasons. The purpose of the present study is to determine the factors influencing the SPM distribution and the ETM formation. As fishing is the main occupation for the people in Goa, investigating the ETM holds importance for the region.

Table 1 | Details of the drainage basins of the six rivers studied

Rivers	Basin/ Catchment area (in Goa) in km^2	Surface runoff (MCM)	Width at the river mouth (km)	Total length of the river (km)	Length within the salinity zone (km)
Terekhol	71	164.25	0.45	26	26
Chapora	255	588.35	0.65	32	32
Mandovi	1,580	3,580	3.70	75	36
Zuari	973	2,247	4.50	92	42
Sal	301	694	0.35	40	14
Talpona	233	515	0.30	32	7

METHODS

Water sampling was carried out in the six minor rivers during the flood phase of the spring tide, in both the wet (monsoon) and dry (pre-monsoon) seasons. The details of the date and time of the sampling are given in Table 2.

Table 2 | Details of the date and time of sampling in the six rivers studied

Name of the river	Season	No of stations	Tidal conditions	Date of sampling
Terekhol	Wet	14	Spring flood tide	24/08/2014
	Dry	16	Spring flood tide	09/04/2015
Chapora	Wet	14	Spring flood tide	15/08/2014
	Dry	15	Spring flood tide	08/04/2015
Mandovi	Wet	12	Spring flood tide	12/08/2014
	Dry	13	Spring flood tide	27/05/2015
Zuari	Wet	10	Spring flood tide	11/08/2014
	Dry	10	Spring flood tide	26/05/2015
Sal	Wet	13	Spring flood tide	31/07/2014
	Dry	09	Spring flood tide	07/04/2015
Talpona	Wet	13	Spring flood tide	27/08/2014
	Dry	14	Spring flood tide	10/04/2015

Water samples were collected at 9–16 stations in each of the rivers (Figure 1) at every ~2 km distance from the mouth to the upstream of the rivers by using a hired fishing trawler and/or motorized canoe. Wherever the depth was too shallow for trawler/canoe entry, samples were collected from the closest bridge near the station. During the wet season, offshore stations in almost all the rivers could not be sampled due to rough weather. We could not sample the upstream stations in the River Sal during the dry season because the stations were either dry or had low water levels. The surface waters were collected using a clean plastic bucket. The salinity of the surface water was determined using 8,400 Guild Line Autosal Salinometer, as per the standard procedure. The pH was determined with a pH meter (Eutech Instruments) using standard solutions of pH of 4.0, 7.0, and 9.2. The monthly rainfall and freshwater discharge data for each of the rivers were obtained from the Water Resource Department of Goa.

Suspended particulate matter

For the SPM studies, 1.5 L water samples were filtered from each of the stations through preweighed polycarbonate membrane filters of 47 mm in diameter (pore size 0.4 μm). The SPM retained on the filter papers was dried, weighed, and expressed as milligrams per liter.

In situ salinity, SPM, and mean particle size measurements

A portable SBE 19 SEACAT CTD profiler (Sea-Bird Electronics, Inc., USA) was used to obtain the vertical profiles of salinity. For *in situ* SPM and particle size distribution, the instrument LISST-25X (Sequoia, USA) was utilized. This instrument applies a laser diffraction device which allows the measurement of SPM properties such as Sauter mean diameter (SMD) and particle volume concentration (PVC). The LISST-25X gives SMD, which is the mean of particle size and the size distribution is in the range of 2.5–500 μm. Due to potential problems reported with measuring estuarine aggregates with the LISST (McCave *et al.* 1995; Mikkelsen & Pejrup 2000), the SMD values reported here should not be taken as precise measurements but rather as an index for comparing the size distribution. The volume concentration is comparable to the SPM concentration and has units in μL/L. The CTD and LISST instruments were lowered over the side of the boat at 10-minute intervals. For the CTD, the deploy lasted for about 3–5 minutes and the readings were taken every second, while for the LISST around 40 readings were taken per minute. The depths obtained from the LISST are taken tentatively corresponding to the water depth of the rivers and have +0.5 m variation.

RESULTS

The details of the river basins are given in Table 1.

Salinity and pH

The locations of the freshwater/seawater boundary in the estuaries are strongly dependent on the seasonal freshwater discharge. The monthly freshwater input into the estuary and rainfall in the different regions during the wet period varied in the range of 8.23–82.46 $m^3 s^{-1}$ and 11.54–39.20 cm in the Chapora River, 3.23–11.34 $m^3 s^{-1}$ and 8.26–31.72 cm in the Sal River, 13.88–113.47 $m^3 s^{-1}$ and 10.43–36.2 cm in the Talpona River, and 6.02–58.48 $m^3 s^{-1}$ and 15.45–48.50 cm in the Zuari River, respectively. On the other hand, during the dry season, no river discharge was observed in the Zuari River while low river discharge was seen in the Chapora and Talpona (<8 $m^3 s^{-1}$) rivers. The rainfall and river discharge data for the Terekhol River are not available. Since the Chapora and Terekhol rivers are adjacent to each other with similar river lengths, we presume that the discharge and rainfall in the Terekhol River is the same as that of the Chapora River. The river discharge and rainfall in the Mandovi River ranged from 30 to 133 $m^3 s^{-1}$ and 35 to 145 cm during the wet season with low discharge during the dry season (Ibrampurkar 2012). Overall, abundant freshwater discharge occurred during the wet season (June–September), with low or negligible discharge during the rest of the year (dry season) in all the rivers (Figure 2). A higher longitudinal surface salinity difference (0–25) was seen in the meso-tidal estuaries as compared to the micro-tidal estuaries (0–8) during the wet season, while during the dry season the longitudinal surface salinity

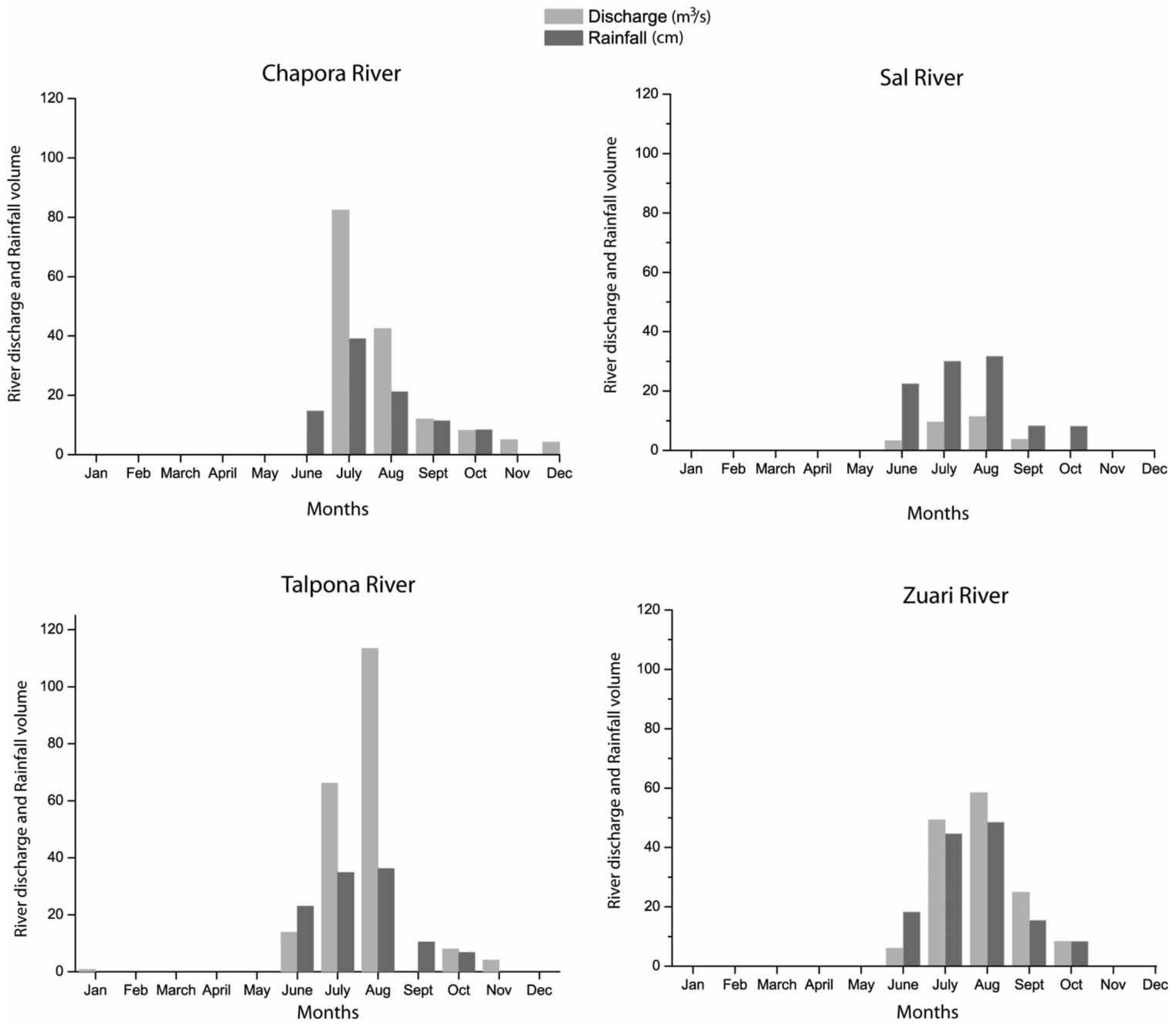

Figure 2 | Histograms depicting the monthly rainfall (cm) and river discharge (m^3/s) measured at gauging stations in the Chapora, Zuari, Sal, and Talpona rivers.

range was higher but similar in all the rivers (0–33) (Table 3). In both the seasons, the surface salinity increased gradually from the freshwater-dominated to the marine water-dominated stations of all the rivers (Figure 3(a)). During the wet season, the marine water-dominated stations showed high surface salinity (15–25) in all the rivers, with saline waters intruding for some distance only in the estuaries of the Terekhol (3.5 km) and Chapora (4 km), while low salinity (<5) waters were prevalent along the entire estuarine stretch of the other rivers (Mandovi, Zuari, Sal, Talpona) (Figure 3(a)). The salinity contours showed that the estuaries were stratified near the mouth region, with seawater intrusion into the rivers through the bottom waters (Figure 3(b)). The bottom salinities were in the range of about 0.04–32.75 in the Mandovi River, 0.02–35.42 in the Zuari River, 0.07–32 in the Terekhol River, 0.03–25.83 in the Chapora River, and 0.03–34.20 in the Talpona River. The average bottom water salinity was observed to be higher than the respective surface water salinity in both the seasons. In the wet season, under high freshwater discharge,

Table 3 | Distribution of salinity, pH, and suspended particulate matter (SPM) concentrations in different rivers studied

			SPM (mg/L)			Salinity			pH		
Tidal range	**Goa rivers**	**Seasons**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**	**Min**	**Max**	**Avg**
Meso-tidal	Mandovi	Wet season	4.037	25.66	8.83	0.03	6.35	1.14	6.96	7.4	7.18
		Dry season	1.25	16.29	4.66	7.80	34.09	25.35	7.48	7.92	7.77
	Zuari	Wet season	4.06	31.58	16.65	0.03	8.04	2.515	6.98	7.64	7.32
		Dry season	2.29	12.73	7.70	0.16	34.67	22.35	7.32	7.92	7.73
Micro-tidal	Terekhol	Wet season	3.95	21.90	7.06	0.04	23.75	4.99	7.01	8.04	7.74
		Dry season	2.23	11.67	6.47	13.11	31.46	27.20	7.39	7.94	7.80
	Chapora	Wet season	3.24	12.84	6.25	0.04	26.35	6.93	7.12	8.28	7.63
		Dry season	1.52	11.08	6.17	0.08	28.30	12.91	7.45	8.05	7.78
	Sal	Wet season	0.05	23.27	15.45	0.05	6.75	0.59	3.52	7.10	6.59
		Dry season	5.21	11.28	8.73	5.91	30.55	20.31	7.52	8.08	7.84
	Talpona	Wet season	2.21	8.74	5.53	0.03	2.86	0.30	6.72	7.50	7.12
		Dry season	1.42	13.81	7.01	0.09	33.53	26.63	7.61	8.09	7.80

the salt–freshwater boundary based on the bottom salinity in the meso-tidal rivers was located at 4 km in the Mandovi River and 15 km in the Zuari River from the estuary mouths (Figure 3(b)). In the micro-tidal rivers, the saline bottom-water intrusion occurred up to 10 km in the Terekhol River and 5 km in the Chapora River, while in the remaining two rivers high salinity bottom waters occurred only at stations near the estuary mouth (Figure 3(b)). During the dry season, under low freshwater discharge conditions (Figure 2), the surface saline waters intruded for ~30 km in the Terekhol, ~15 km in the Chapora, ~40 km in the Mandovi, ~34 km in the Zuari, ~14 km in the Sal, and ~7 km in the Talpona estuaries (Figure 3(a)). The salinity contours showed well mixed estuarine conditions with high saline waters (30) reaching 14 km upstream in the Terekhol River, while in the Chapora, Mandovi, and Zuari rivers the salinity decreased from the estuary mouth (35) towards the upstream (<5), with high saline waters seen at a distance of 3 km, 10 km, and 15 km in the Chapora, Mandovi, and Zuari rivers, respectively, from the estuary mouths (Figure 3(b) (E–H)). The surface water pH ranged from 6.70 to 8.28 during the wet season and from 7.39 to 8.09 for the dry season (Table 3). The pH values were more towards the alkaline side in the Terekhol and Chapora rivers (7–8) as compared to the other rivers (6.7–7.5) in the wet season. However, all the rivers exhibited a similar pH range (7.4–8.1) during the dry season (Figure 3(a)).

Suspended particulate matter

The SPM showed large spatial variations along the transect of the estuaries (Figure 4, Table 3). The lowest average surface SPM concentration was observed in the Talpona River (5.53 mg/L) during the wet period and in the Mandovi River (4.66 mg/L) during the dry period. On the other hand, the highest average surface SPM concentrations were seen in the Zuari (16.65 mg/L) and Sal (8.74 mg/L) rivers during the wet and dry periods, respectively. Further, during the wet period, the average surface SPM concentrations of the Zuari and Sal rivers (15–16 mg/L) were twice that of the other rivers (6–7 mg/L). Almost all the rivers exhibited an average surface SPM concentration of ~6–8 mg/L during the dry season. The average surface SPM concentrations in the estuaries of the Terekhol and Chapora rivers were similar during both the seasons, whereas in the estuaries of the Mandovi, Zuari, and Sal, the average concentrations of surface SPM in the wet season were twice than that of the dry season. The average surface SPM concentration in the Talpona River during the wet season was lower than that in the dry season. In general, the surface SPM concentrations decreased rapidly and linearly with the decreasing salinity (Figure 3(a)). All the rivers except for the Talpona showed higher average surface SPM concentrations during the wet season as compared to the dry season. The ETMs were located near the estuary mouths of almost all the rivers during the wet season.

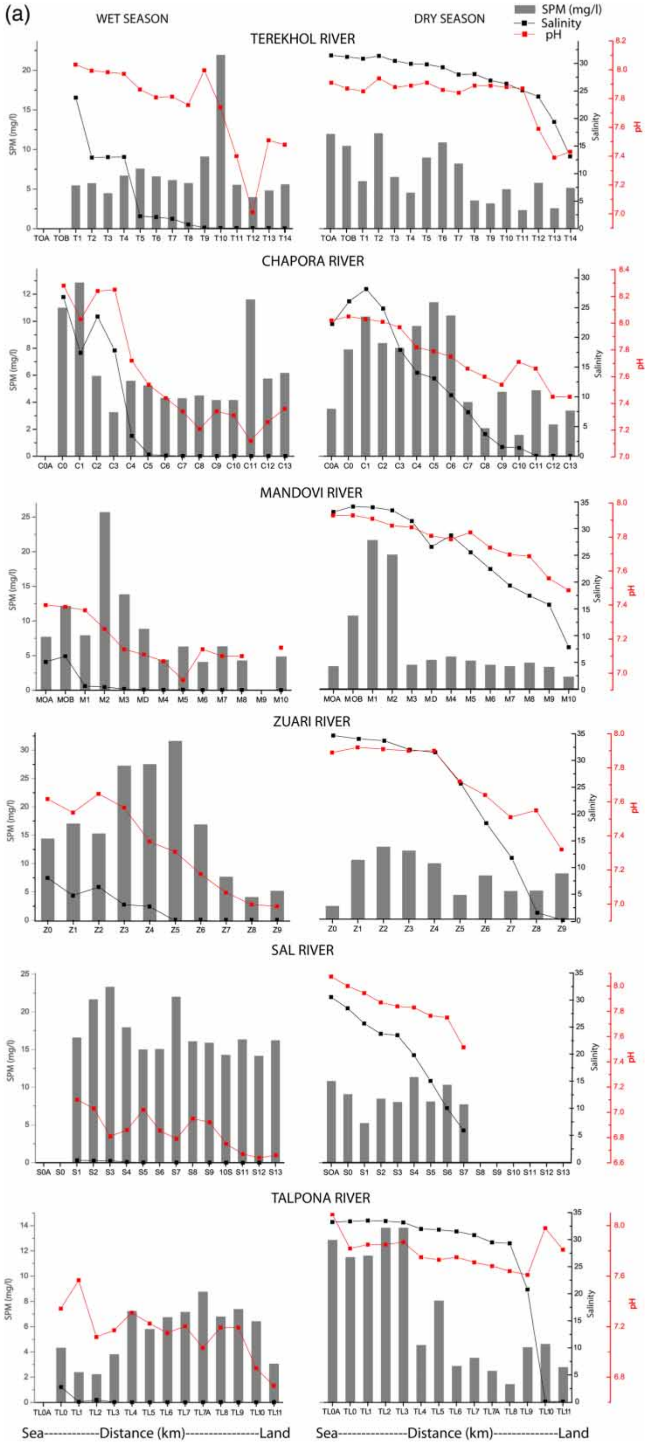

Figure 3 | (a) Seasonal surface distributions of SPM, salinity and pH in the Terekhol, Chapora, Mandovi, Zuari, Sal, and Talpona rivers and (b) seasonal vertical distributions of salinity in the Terekhol, Chapora, Mandovi, and Zuari rivers.

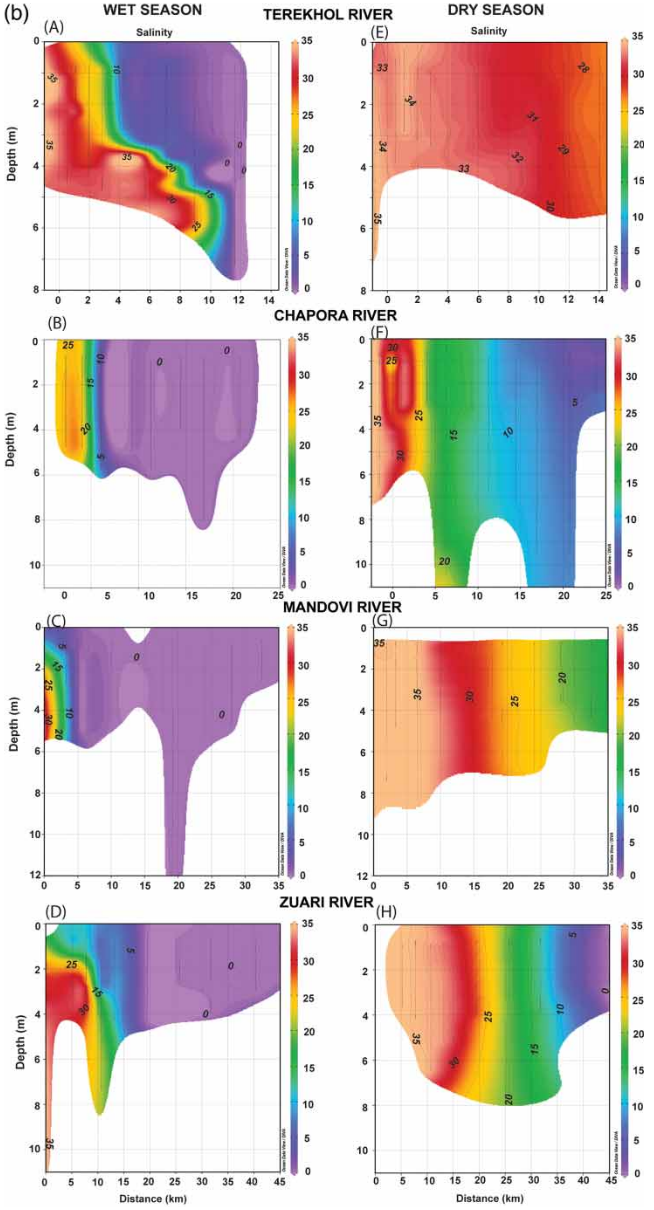

Figure 3 | Continued.

However, in the Sal River, no distinct region of high surface SPM was observed. From the vertical SPM profiles obtained from the LISST instrument during the wet season, the particle volume concentration (PVC) was in the range of 7.32–3,110 μL/L in the Terekhol River, 42.13–2,176 μL/L in the Chapora River, and 39.36–1,156 μL/L in the Talpona River (Figures 5–7). The SMD values varied from 9.36 to 337 μm,

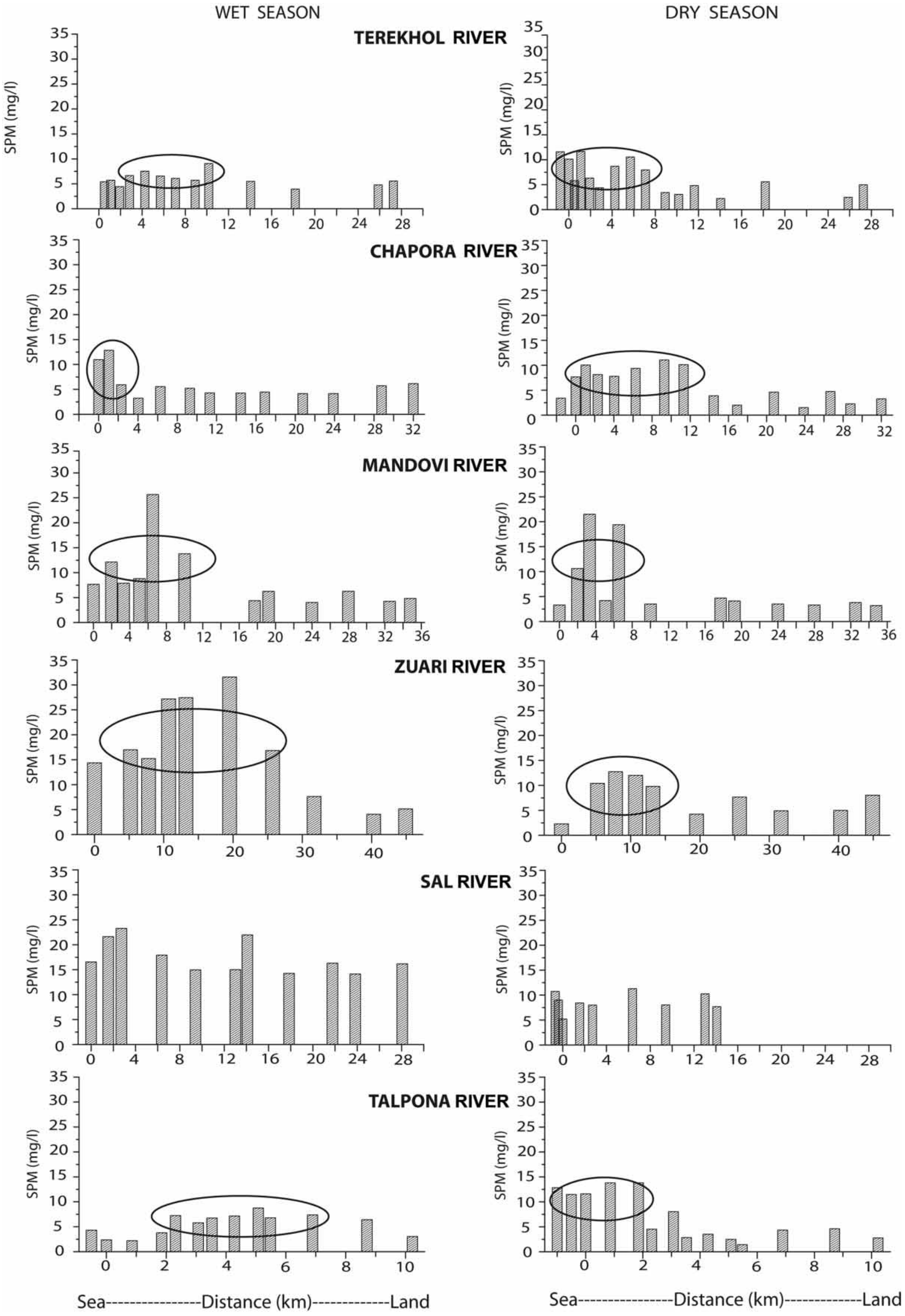

Figure 4 | Location of the ETMs in the Terekhol, Chapora, Mandovi, Zuari, Sal, and Talpona rivers with distance from the estuary mouth.

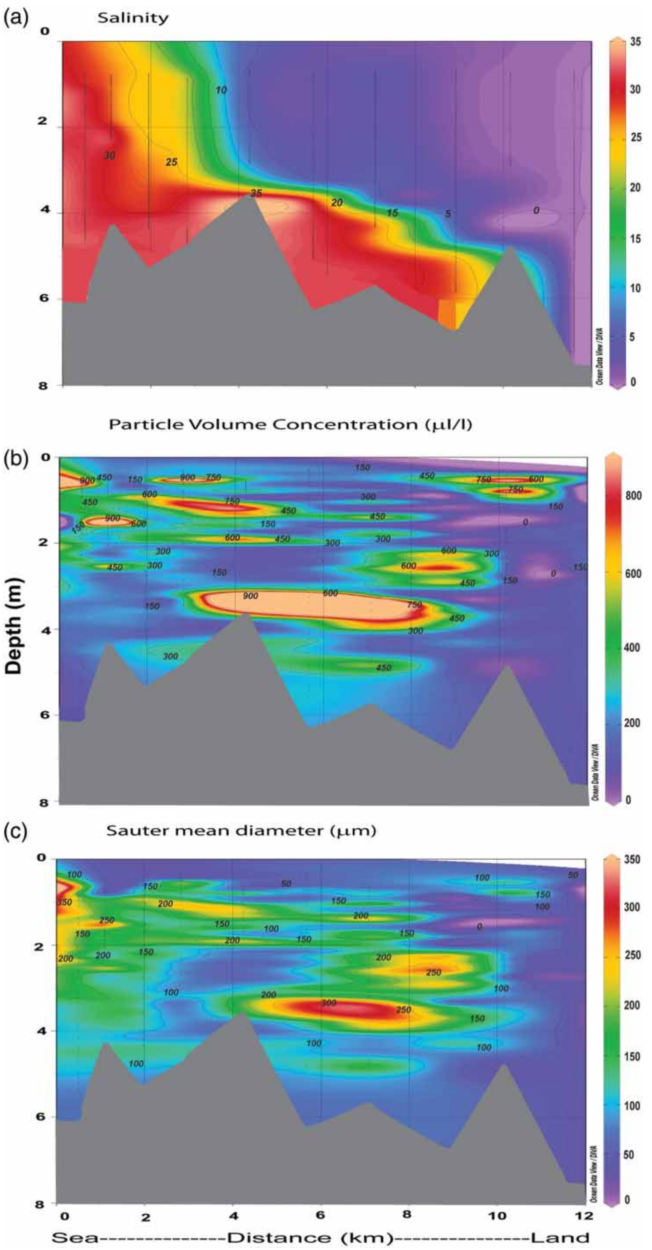

Figure 5 | Vertical distribution of (a) salinity, (b) volume concentration, and (c) SMD with distance from the estuary mouth in the Terekhol River during the wet season.

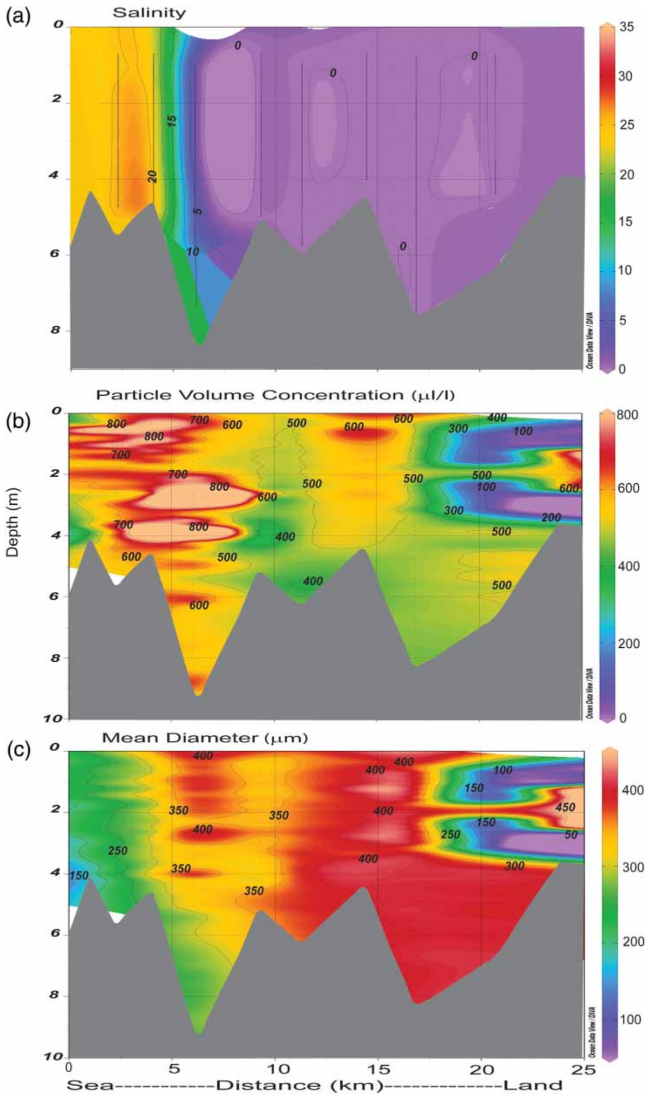

Figure 6 | Vertical distribution of (a) salinity, (b) volume concentration, and (c) SMD with distance from the estuary mouth in the Chapora River during the wet season.

65.57 to 447 µm, and 10.52 to 255 µm in the Terekhol, Chapora, and Talpona rivers, respectively. The vertical profiles of PVC in these three rivers show zones of high SPM (>800 µL/L in the Terekhol and Chapora rivers, >500 µL/L in the Talpona River) near the estuary mouth indicating the ETM regions (Figures 5–7). The high PVC correspond with the upper limit of salt intrusion exhibiting higher SMD values (>350 µm in the Terekhol River, >450 µm in the Chapora River, and >200 µm in the Talpona River). Interestingly, the ETMs seen in the upstream regions of the Terekhol (at 0.5 m depth, between 10 and 12 km distance, Figure 5(b)) and the Talpona (whole water column beyond the distance of 5 km from the estuary mouth, Figure 7(b)) rivers coincides with lower SMD values (Figures 5(c) and 7(c)). Further, at the upstream region of the Talpona River (stations TL7 and TL8, >4 km), a vertical particle size gradient does not exist in the freshwater section where the high PVC is nearly uniform through the whole water column.

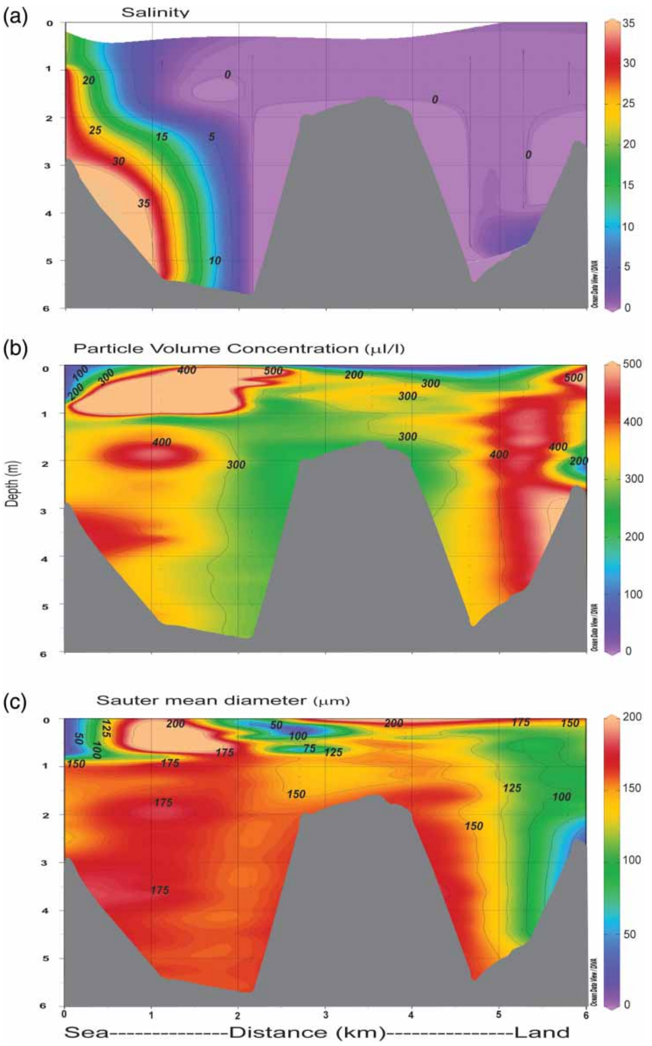

Figure 7 | Vertical distribution of (a) salinity, (b) volume concentration, and (c) SMD with distance from the estuary mouth in the Talpona River during the wet season.

In the surface SPM profile of the dry season, similar observations are seen as those observed during the wet season with the ETMs occurring close to the estuary mouth in almost all the rivers except for the Sal River, wherein a uniform surface SPM distribution was observed along the length of the river. The surface SPM concentrations were low up-estuary with respect to the ETMs in all the rivers, in both the seasons as a function of decreasing salinity. The magnitude and spatial variation of the ETMs changed during the two seasons. The longitudinal shifts in the ETMs' position varied from ~7 to 9 km in the Terekhol River, ~2.5 to 14 km in the Chapora River, ~10 to 4.5 km in the Mandovi River, ~26 to 8 km in the Zuari River, and ~5.5 to 3.5 km in the Talpona River from the wet to the dry season. The corresponding variations in the average surface SPM concentrations in the ETMs for the micro-tidal rivers were 6.93 to 8.56 mg/L in the Terekhol River, 9.91 to 8.45 mg/L in the Chapora River, and 7.11 to 12.71 mg/L in the Talpona River, while in the meso-tidal rivers it varied from 12.65 to 17.10 mg/L in the Mandovi River and 21.37 to 11.24 mg/L in the Zuari River from the wet to the dry season. For most of the rivers in the wet season, except for the Chapora River, the surface salinity and SPM were inversely related, i.e., low SPM at high salinity was observed. However, the surface SPM and salinity showed a good correlation with higher surface SPM values associated with high salinity, especially near the estuary mouths during the dry season. In general, the surface salinity and pH were found to be low during the wet season and high during the dry season (Figure 3(a)), and vice versa for the SPM concentration (high during the wet season and low during the dry season). The surface SPM concentrations were lower at the upstream stations of the estuaries throughout the study.

Sediment texture

The mouth regions of all the rivers were found to be sandy while the offshore stations were clayey. Roy (2008) reported that the sediments near the Terekhol river mouth were made up of medium to coarse sand. In the Chapora and Sal, the rivers were sandy throughout their lengths with the sediment texture fining upstream. In the Talpona River, the sediment was sandy on either end of the river and with muddy sediments at the center (stations TL7 and TL8). Clay was dominant around the mouth regions of the Mandovi and Zuari estuaries and sand dominated at the upstream region (about 20 km upstream from the estuary mouth).

DISCUSSION

Effect of freshwater discharge on the seasonal salinity distribution

Geomorphology, freshwater flow, and tides are the dominant variables determining the distributions of salinity and circulation within an estuary (Schubel & Carter 1984; Uncles & Stephens 1993; Schoellhamer 2001). To express the relative salinity stratification, estuaries have been classified into highly stratified or salt wedge, moderately stratified or partially mixed, and vertically homogeneous or well-mixed (Cameron & Pritchard 1963). The abundant freshwater flow during the wet season (June to September), flushed by the rivers resulted in low salinity values in most of the estuaries. The forces of high fresh water efflux in the rivers can restrict the influence of tides to the lower reaches of the estuary through enhanced tidal friction (Godin 1985; Savenije 2005; Sassi & Hoitink 2013). Among the micro-tidal rivers, the Chapora and Talpona rivers show strong stratification near the estuary mouth while in the Terekhol River the freshwater dominates the upper strata of the water column and high saline water penetrates through the bottom, resulting in stratification and formation of a salt wedge. Alfacs Bay, a small micro-tidal estuary, was reported to remain stratified throughout the year with stratification mainly driven by salinity differences in the water column (Llebot *et al.* 2014). The type of stratification varies in Mandovi and Zuari estuaries. Shetye & Murty (1987) measured the salinity distribution in the Zuari estuary, at monthly intervals for a year, and reported that the estuary was vertically well mixed during the dry season due to the tides, and moderately stratified during the wet season due to the runoff, which drove advective transport out of the estuary. On the other hand, Vijith *et al.* (2016) reported a salt-wedge type of estuarine circulation near the mouth of the Mandovi estuary during the wet period. The circulation, with a distinct upstream flow near the bottom and a downstream flow at the surface, was found to be restricted up to 10 km from the estuary mouth. In the River Sal, salinity stratification is not seen. In this river, as the seawater moves upstream, the influence of the tide decreases due to the high freshwater flow. Further inland, the river channel becomes narrower and shallower, favoring greater turbulence and mixing of the water column, resulting in less scope to develop vertical salinity gradients. During the wet season in all the rivers, the lower tidal effect at the upstream coupled with the riverine water dominance may have given rise to low pH upstream, increasing towards the sea. However, the extension of the saline water is not found to be linearly related to the river discharge, which may be due to the irregular bed topography of the rivers (Figures 5–7). In the Terekhol River, the greater intrusion of saline water (Figure 3(b) (A)) indicates that either the discharge was probably low during the wet season or it has a greater depth. Since the freshwater discharge is similar in the Chapora and Terekhol rivers, the first possibility is ruled out. Extensive sand mining along the Terekhol River, as compared to the Chapora River, might have increased the depth of the water column and hence led to significant marine water input.

During the dry season, the intrusion of marine water (tidal activity) with reduced freshwater input in all the rivers produced a well-mixed water column with no significant stratification in any of the rivers. Shetye *et al.* (2007) reported well-mixed water column stratification during the flood and ebb phases of the tide and weakly stratified during slack water periods in the Mandovi River during the dry season. The correlation between the pH and salinity in the dry season ($r^2 = 0.88_{\text{Terekhol}}$, 0.94_{Chapora}, 0.58_{Mandovi}, 0.35_{Zuari}, 0.95_{Sal} at $p < 0.005$), indicates a greater influence of coastal seawater along the estuarine regions. The surface salinity was high at most of the upstream stations (>10) and the entire estuarine system had a tidal influence with saline water intruding for a considerable distance upstream from the estuary mouth for most of the rivers except for the Chapora River, probably due to a number of small streams discharging into it. In the Terekhol and Zuari rivers, the saline waters observed at 10 and 15 km from the estuary mouths during the wet season moved progressively upstream, resulting in high salinity mixed water columns in the upstream region. Therefore, the amount of freshwater discharge during both the seasons primarily controlled the extent of seawater intrusion into the rivers in the present study.

Processes governing the formation of ETM in the different rivers

The concentration of SPM in an estuary is a function of the geology of the catchment area, river discharge, tidal phase, spring-neap tide, seasons (wet and dry), density gradient, and wind (Chen *et al.* 2005). In the present study, the concentration of the SPM varied with seasonal changes in the river discharge. Therefore, to explain the distribution and dynamics of SPM, it is important to understand the estuarine processes governing the system seasonally.

Wet season

Factors controlling the SPM concentrations of the rivers

The differences in bathymetry, freshwater discharge, tidal characteristics, and type and availability of sediment make each estuary different in their SPM characteristics (Althausen & Kjerfve 1992; Mitchell *et al.* 2003). The meso-tidal rivers exhibit high SPM as compared to the micro-tidal rivers in the wet season, which may be due to their larger drainage basin, greater freshwater runoff (Mandovi ~3,580 million cubic meters (mcm); Zuari ~2,247 mcm), and larger tidal range (>2 m). The SPM concentrations tend to be greater in the estuaries with high tidal range. The high SPM during the wet season may be due to two factors: (1) the higher river flow might have brought a large amount of sediment from the upstream into the estuary; (2) the higher river flow possibly eroded the solid river bank, generating fresh sediment that deposited and settled in the estuary (Syvitski *et al.* 2000; Uncles *et al.* 2002). Another significant factor is the differences in the geological setting of the region. For example, the basic rocks of the Goa region are green schist and gneiss and are largely covered by thick laterites (Mascarenhas & Kalavampara 2009). However, the laterite thickness varies, being thicker along the Mandovi and Zuari rivers as compared to the other rivers of Goa, resulting in the release of more material during weathering. Therefore, the effect of high freshwater flow during the wet season was felt much more in the Mandovi and Zuari rivers where the easily erodible and abundant sediments were flushed downstream quite rapidly and easily. The mouth regions of these estuaries are reported to have high clay contents with increasing concentrations of sand upstream (Dessai *et al.* 2009). In the Talpona River, the SPM was significantly low as compared to the other micro-tidal rivers. ETMs have not been reported in most micro-tidal rivers with small freshwater flows, due to the low tidal range (Schettini & Toldo 2006; Schettini *et al.* 2006). Further, the geology of the catchment area is composed of granite, meta-basalt, and gneisses and profusely intruded by mafic dykes suggesting that the upstream region and local bed material is highly resistant to erosion. Such conditions are unfavorable for the formation of a strong ETM.

Effect of salt wedge on the SPM distribution

Estuarine circulation has been reported to affect the occurrence of an ETM in an estuary (Mitchell *et al.* 1998; Wai *et al.* 2004; Chernetsky *et al.* 2010). In some cases, the water column stratification has been identified as the main driver for the estuarine circulation (Camp & Delgado 1987; Llebot *et al.* 2014). Rao *et al.* (2011) reported that the occurrence of ETMs in the Mandovi and Zuari estuaries was due to the interaction of salt–freshwater during the wet season along with the activity of tidal currents coupled with strong westerly to south westerly winds. These currents were reported to move towards the estuary head, causing the resuspension of bottom sediments, thus contributing to the high SPM. Our results corroborate these findings. In general, three processes, the residual gravitational circulation, tidal velocity asymmetry, and tidal mixing asymmetry (Postma 1967; Festa & Hansen 1978) are responsible for explaining the ETM at the salt–freshwater interface. Of the three, the residual gravitational circulation is reported to dominate in micro-tidal/meso-tidal estuaries or where topographic depth profiles show major changes (Schubel & Carter 1984; Wolanski *et al.* 1995). The residual gravitational circulation produced by baroclinic, density-driven pressure gradient forces the near-bottom horizontal velocity upstream where it meets the freshwater flow going downstream. The strong and abundant river flow, during the wet season in the present study, resulted in more scouring near the up-stream boundary, wherein the suspended and bed-load were transported and deposited within the accumulation region near the salt-wedge (Geyer 1993) as it moved seaward. The presence of an ETM close to the estuarine mouths in almost all the rivers during the wet season may be due to the process of flocculation at the salt–freshwater interface. In the Terekhol, Chapora, and Talpona rivers, the salt–freshwater interface occurs near the estuary mouth (Figure 3(a) and 3(b)), and the ETMs occur in the low salinity range (<2). In many estuarine systems, the region corresponding to salinity of 5, is an important zone as it marks the zone of most likely and significant flocculation (Dyer 1986). Similar situations are reported in the micro-tidal Coomera River and the Winyah Bay estuary, where the ETM was observed at the salt–freshwater interface or landward at low salinity range (<6) due to gravitational circulation (Uncles & Stephens 1993). Kranck (1981) observed that the increase in settling rates due to flocculation at the limit of salt intrusion could produce a TMZ. Although the ETMs are typically located at low salinities, they may occur even at much greater salinities due to tidal processes that resuspend the bed sediments (Le Bris & Glemarec 1996) like that in the Chapora River. In the Chapora River, the ETM extends from the low salinity (<5) to high salinity region (17–26) near the estuary mouth. Further, the vertical profiles of the SMD exhibit larger grain size (>350 μm in the Terekhol, 450 μm in the Chapora, and 200 μm in the Talpona rivers) corresponding to the ETM regions near the estuary mouth of the three rivers, which attests to the flocculation process occurring near the salt–freshwater interface. Voluminous flocs are reported to occur during the flood or ebb current when high SPMs result in an increased particle collision frequency (Chen *et al.* 1994; Manning *et al.* 2006). Maximum floc sizes of up to 600–800 μm have been observed in the meso-tidal Elbe estuary TMZ (Chen *et al.* 1994; Dyer 1996).

Qasim & Sengupta (1981) and Shetye *et al.* (2007) reported strong winds (4–7 ms^{-1}), tidal currents (~2.5 ms^{-1}) and heavy swells with intensified wave activity during the SW monsoon caused mixing of the water column in the Mandovi and Zuari rivers. Zhong & Li (2006) used a three-dimensional hydrodynamic model to demonstrate that the wind energy input in an estuary with low tides was of the same order of magnitude as the tidal energy. During the wet season, large volumes of sediments brought by the river flow get deposited within the channel bed and, consequently, greater volumes of sediments are available for resuspension. Therefore, in addition to the flocculation, the presence of strong winds caused sediment resuspension near the estuary mouth and contributed to the formation of an ETM. The larger mean grain size (SMD) observed in the ETM region also support this possibility as based on grain size analysis, sediment size near the estuary mouth in all the rivers was found to be dominated by the size 0.1–1 mm (NIO 1997). Thus, from the vertical PVC and SMD profiles, it is clearly seen that the ETM near the estuary mouth in the Terekhol, Chapora, and Talpona rivers corresponds to the highest mean grain size reflecting flocculation as well as the contribution of resuspended sediments at the estuary mouth. The second ETM seen at the upstream regions of the Terekhol (station T10) and the Chapora (station C11) rivers (Figures 5(b) and 6(b)) with a higher mean grain size (Figures 5(c) and 6(c)) may be due to the presence of small rivulets which discharge turbid waters into the main channel of the rivers. On the other hand, the second ETM seen in the upstream of the Talpona River (stations TL7 and TL8, Figure 7(b)) is probably due to the river meandering effect coupled with the high depth (>5 m). The curvatures of the meanders are reported to generate complex three-dimensional flows with upwelling along the inner bank and downwelling along the outer bank (Dermuren & Rodi 1986; Wolanski 2007). During the dry season, the tidal limit is seen up to 7 km (station TL9). The sediment was found to be muddy in this section of the river. According to Dalrymple & Choi (2007), the region of tidal maximum (region having maximum tidal current speeds) corresponds to the muddiest portion of the estuaries which lie at or near the location of the bed convergence. In the Talpona River, the possible mechanism of the second ETM formation at the upstream is likely the local deposition–resuspension process. During the wet season, the freshwater carrying land runoff flows with greater velocity at the upstream end of the river eroding material along the river banks. The river water flows with greater force towards the sea, but once it comes near the river bend (station TL8), it encounters greater depth and its energy decreases. This meandering zone is reported to represent the site of the lowest hydraulic energy (Dalrymple *et al.* 1992) and results in deposition of coarser sediments at the base of the bend while the finer sediments move on seawards. The river flow resuspends the previously deposited sediments (during the dry season) in these deeper sections (mostly muddy) and narrower part of the river. This is clearly seen from the vertical SMD profile (Figure 7(c)), where the smaller mean grain size (75–100 μm) beyond 5 km distance from the estuary mouth corresponds to the ETM region indicating resuspension of previously deposited sediments. A cycle of local deposition, bed storage, and resuspension is reported to contribute to the formation of ETMs (Hamblin 1989; Wolanski *et al.* 1995). It is, therefore, not surprising that the resulting ETM pattern in the Talpona River bears little resemblance to the salinity distributions as it results from local resuspension with topography playing a major role (Kineke & Geyer 1995).

An exception to the normal occurrence of the ETM is seen in the Sal River. The Sal is a very shallow river flowing through a flat plain, with a tidal impact extending up to 20 km from the mouth to upstream during the non-monsoon season. Further, compared to the other rivers, which flow from east to west, the river flow in the Sal River is parallel to the coast. Thus, the magnitude of the tidal flow is reduced considerably due to a change in its course as it enters the river mouth (Figure 1). The river being shallow, the water is well mixed throughout the river length with a similar distribution of SPM throughout the river, leading to the absence of a prominent ETM in both the seasons.

Dry season

The low SPM in all the estuaries during the dry season can be attributed to the low or negligible freshwater discharge while the strong tidal influence favored the ETM and its intensity. During the dry season with the low/no river discharge, the zone of high SPM was located at the estuary mouth in almost all the rivers (Figure 4), indicating a marine source of sediments to the estuary, as was observed by Patchineelam & Kjerfve (2004) for the micro-tidal Winyah Bay estuary, and Levisan & Van Dolah (1997) for the Charleston Harbor estuary. The daily cycle of sea conditions near the Goa coast is influenced by sea breeze (Neetu *et al.* 2006), wherein Aparna *et al.* (2005) reported the prominence of sea-breeze/land-breeze systems during the dry season. Cherian *et al.* (1974) and De Sousa *et al.* (1981) reported the re-suspension of bottom sediment due to strong wave action during the dry period resulted in high SPM near the mouth. Despite the low river discharge, the average surface SPM concentrations are similar in the Terekhol and Chapora rivers in both the seasons. This may be due to resuspension of the bottom sediments. A study carried out by NIO (2011) in the Terekhol River during the dry season reported that the ebb currents were stronger (0.57 m/s) than the flood currents (0.47 m/s). Similarly, in the Chapora River, the surface elevation at the river mouth increased up to 2.20 m during the spring tide of the dry season and the current showed a maximum speed of 0.38 m/s. The currents were found to be stronger within the estuary and along the river than the open sea area. The river flow in both the rivers is predominantly driven by the tides with reversal of currents between the ebb and flood. Also, the extraction of large amounts of sand (sand mining) in both the rivers has caused major modifications (deepening) which might have favored the suspension of sediments in the water column. The increased depth due to sand mining in both the rivers decreases the friction acting upon the incoming floodwater, causing entry of more marine water further landward from the estuary mouth producing a hypersynchronous system. This must have led to an increase in the tidal range and upstream flow and also transport of the SPM. Near the mouth of the Chapora estuary, a ferry terminal (operating year round) is present which must probably be contributing to the sediment resuspension. In the Terekhol River, although the saline water intrudes for a considerable distance upstream, high SPM is not seen upstream. This may be because high saline waters can suppress turbulence and cause rapid settling of SPM. Suppression of turbulence by salinity stratification has been reported to increase settling and trapping of fine sediment, being a more effective trapping mechanism than gravitational circulation (Hamblin 1989; Geyer 1993). In the Mandovi River, the occurrence of the ETM at the same position during both the seasons (near the estuary mouth) was attributed to the tidal and wind-induced currents (Rao *et al.* 2011). In the Sal River, the shallow depth caused turbulence and bottom friction, producing a well-mixed water column with a meager increase in salinity at the upstream end and no distinct ETM. In the Talpona River, the ETM present near the estuary mouth might be primarily due to the marine input and resuspension from the tidal action. Even at depths as shallow as 2 m, tidal currents have been reported to dominate suspension in the micro-tidal York River (Boon 1996).

Factors controlling the ETM length and magnitude

The zone of the ETM expands/stretches in most of the rivers during one of the seasons. Turbidity maxima are usually highly mobile, with the extent and position varying according to different time scales associated with neap-spring semidiurnal tidal cycles, quantity of available sediment supply, seasonal variations in river inflow, winds playing an important role in the horizontal distribution of the SPM (Avoine & Larsonneur 1987; Doxaran *et al.* 2009). In the case of the Terekhol and Chapora rivers, the ETMs are elongated with higher SPM concentration in the dry season than in the wet season. The estuary mouths of the Terekhol (450 m) and Chapora (650 m) are narrow and widen for some distance before narrowing again. Strong winds (speeds of 3.2–3.7 m/s) and sea breezes (Aparna *et al.* 2005) dominate during the dry season. The interface between the saline and freshwater occurs at some distance from the mouth in the Chapora River, creating flocculation which further contributes to the SPM. Elongated zones of ETM in the Mandovi and Zuari rivers may be related to the greater size and geometry (funnel shape) of the bay at the river mouths (Rao *et al.* 2011). In a similar study, the lateral variation of the ETM was reported to be due to the topographical control that resulted in restricted gravitational circulation and enhanced particle trapping (Ganju & Schoellhamer 2009). In the case of the Talpona River, the length occupied by the ETM is greater (5.5 km) but has lower SPM concentrations (average 7.11 mg/L) during the wet period, while during the dry season the ETM has higher SPM concentrations (average 12.71 mg/L) but over a shorter length (3.5 km). This observation indicates that the SPM concentrations are diluted when the zone of ETM is longer. Here, the river topography plays a major role in determining the ETM length.

The present study is on ETM, which has a wide range of applications, a few of which are listed below:

1. The ETM, which is a consistent feature at the mouth of the estuary in both seasons, help us to determine the extent to which materials are transported from the land to sea, which is critical for understanding sedimentary sinks of a wide range of particles (carbon, nutrients, trace elements) (Brunskill 2009). This knowledge is also important for the assessment of coastal pollution (Milliman & Syvitski 1992; Bilotta & Brazier 2008) and must be taken into account during effluent and pollutant discharge in seas and rivers.
2. Tropical minor river estuaries, such as the ones studied here, receive almost negligible river runoff but exhibit high surface productivity during the non-monsoon months (Ram *et al.* 2003). Our study shows that the ETM formation during non-monsoon months is largely due to the re-suspension of bottom sediments in the estuaries. This implies that the re-suspended material may have supplied required nutrients, etc., and thus be a factor for productivity in the estuaries during the non-monsoon months.
3. The SPM concentrations show significant seasonal variations along the transect in the estuaries and also in the zone of the ETMs and depend on several factors including the topography, geometry at the river mouth, and the rock types in the catchment area. This signature of ETM can be used to develop adequate soil and water conservation strategies, sediment transport modeling, and propose effective, sustainable solutions to sediment management problems (Vercruysse *et al.* 2017).
4. Numerous micro-/meso-tidal river estuaries are present along the west coast of India, with no knowledge on their ETM magnitude and locations. Similar type of studies in different estuaries will add to the SPM database (Vanmaercke *et al.* 2011) and provide a more definitive assessment of the current trends in the land–ocean sediment transfer by these rivers.

CONCLUSION

The distribution of SPM and ETM was investigated in six minor rivers with meso- and micro-tidal characteristics, along the west coast of India. The high freshwater discharge during the wet season dampened the tidal currents and aided in salinity-based stratification. Higher SPM was seen during the wet season as compared to the dry season in almost all the rivers. The meso-tidal rivers showed higher SPM concentration as compared to the micro-tidal rivers due to their large drainage basins, higher tidal ranges and erodible rock types. The mechanisms for the formation of ETMs near the estuary mouth in all the rivers were different during both the seasons. During the wet season, gravitational circulation and flocculation at the salt–freshwater interface were responsible for the formation of two ETMs in most of the micro-tidal rivers. However, in the Talpona River, the ETM near the estuary mouth was due to flocculation at the salt–freshwater interface while the second ETM seen at the upstream was because of the increased depth together with the meandering effect of the river which caused deposition of the sediment. On the other hand, in the dry season, the strong winds and tidal currents caused well-mixed water columns producing ETMs near the estuary mouths. The Sal River showed no distinct ETM during both the seasons due to its shallow depth. The zone of ETM covered greater lengths during the wet season than in the dry season. The variations observed in the SPM, both between the different estuaries and within the same estuary at different times, may also be common in other meso-/micro-tidal rivers around the world. This knowledge is important and must be taken into account during effluent and pollutant discharge in seas and rivers as pollutants are associated with the SPM and the estuary will fuction as a concentrator of materials, besides acting as a filter of river-borne materials. This will lead to far-reaching ecological consequences.

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