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# Suspended sediment dynamics on a seasonal scale in the Mandovi and Zuari estuaries, central west coast of India

V. Purnachandra Rao*, R. Shynu, Pratima M. Kessarkar, D. Sundar, G.S. Michael, Tanuja Narvekar, Viegas Blossom, Prakash Mehra

*National Institute of Oceanography, CSIR, Dona Paula 403 004, Goa, India*

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A B S T R A C T

Suspended particulate matter (SPM) collected at regular stations from the Mandovi and Zuari estuaries indicates that the peaks of high SPM coincide with peaks of high rainfall and low salinity and also with peaks of moderate/low rainfall coupled with high salinity during the monsoon. The estuarine turbidity maximum (ETM) is a characteristic feature, it occurs in the channel accompanying spring tide during the monsoon and pre-monsoon, and shifts to the bay on neap tide during post-monsoon. ETM remains at the same position in the Mandovi River, both during the monsoon and pre-monsoon, whereas in Zuari it stretched upstream during monsoon and migrates seaward of the channel during pre-monsoon. The ETM coincides with the freshwater–seawater interface during the monsoon and is formed by the interaction between tidal currents and river flows. The ETM during pre-monsoon is associated with high salinities and is generated by tidal and wind-induced currents. The turbidity maximum on neap tide during post-monsoon may be due to the erosion and resuspension of sediments from the emergent tidal flats and transport of these turbid waters into the bay. Funneling effect of the narrowing bay in the Zuari estuary and associated physical processes effectively enhance the magnitude of the currents and transports sediments to the channel. SPM retention percentage indicates that the estuarine channel is prone to siltation.



## 1. Introduction

Knowledge on the suspended sediment dynamics in the estuarine system has received considerable attention in recent years in response to the fact that the estuaries receive agricultural, industrial and domestic waste runoff from their watersheds; they are impacted by nutrients and pollutants, and siltation in the channels leads to navigational problems (Oslen et al., 1982; Regnier and Wollast, 1993; McKee et al., 2000; Kistner and Pettigrew, 2001; Patchineelam and Kjerfve, 2004; Hossain et al., 2004). Dynamic estuarine processes control the manner in which suspended sediments are distributed and transported. Understanding the suspended sediment movement on a seasonal scale is important for monitoring water quality, fate of pollutants, and for the success of dredging operations. Investigations revealed that the distinctive feature in estuaries is the occurrence of estuarine turbidity maximum (ETM), where the concentrations of suspended particulate matter (SPM) are higher than the SPM concentrations both seaward and landward (Schubel and Kennedy, 1984; Nichols and Biggs, 1985; Dyer, 1988). ETM is important because of its influence on primary productivity, pollutant flushing, fish migration and dredging (Mitchell et al., 1998). ETM may occur in any part of the estuary (Schoelhamer, 2001), but is usually present near the saltwater–freshwater interface, which in turn is determined by the strength of estuarine circulation (Postma, 1967; Festa and Hansen, 1978), or away from the saltwater–freshwater boundary as a result of tidal processes, which resuspend sediment from the bed (Allen et al., 1980; Gelfebaum, 1983; Uncles and Stephens, 1989; Le Bris and Glemarec, 1996; Mitchell et al., 1998, 2003). Freshwater discharge and tidal forcing produce gravitational circulation and salinity stratification within estuaries and can be directly related to the distribution of SPM concentrations and location of the ETM (Geyer, 1993). Seasonal migration of turbidity maximum towards downstream/upstream positions of the estuary was reported (Wellershaus, 1981; Uncles et al., 1994; Mitchell et al., 1998, 2003). A cycle of deposition, bed erosion and resuspension can also contribute to the ETM formation (Uncles et al., 1994; Wolanski et al., 1995). Comparison between estuaries reveals large differences in SPM concentrations due to differences in freshwater discharge, tidal characteristics and sediment sources. Moreover, no two estuaries

* Corresponding author.
*E-mail address:* vprao@nio.org (V. Purnachandra Rao).

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are alike in terms of the parameters responsible for their sediment characteristics (Althausen and Kjerfve, 1992). Studies related to the suspended sediment concentrations on seasonal timescales are somewhat neglected for Indian estuaries. The objectives of this study are: (1) To compare the SPM variability and position of turbidity maximum on a seasonal scale in two adjacent estuaries of the rivers of nearly the same length, sharing similar terrain and rainfall conditions. (2) To identify the processes that influence sediment transport in the Mandovi–Zuari estuarine system.

## 2. Background

The Mandovi and Zuari Rivers are tropical, minor rivers of Goa in the central west coast of India (Fig. 1). They originate in the Western Ghats (mountain ranges) and flow through a narrow coastal plain. The length of the Mandovi and Zuari are ∼50 km each and the average depth is 5 m. The estuarine portion of the rivers has two parts, a channel and a bay through which the channel is connected to the Arabian Sea. The size and morphology of the bays are, however, different (Fig. 1). The Aguada Bay, off Mandovi River, is small and semi-circular in shape, with an area of ∼4.36 $km^2$, a width of 3.33 km at the mouth and 1 km at the joining point of the channel and an average depth of 5 m. The Mormugao Bay, off Zuari River, is relatively large with an area of ∼46.7 $km^2$; it has a length of 10 km and is funnel-shaped with a width of 5 km at the mouth and narrows down to 1 km at the joining point of the channel. A narrow canal, called the Cumbarjua canal, connects these two estuaries. Several tributaries join the Mandovi and Zuari rivers. The estuaries of the rivers are meso-tidal, and the tidal ranges are ∼2.3 and 1.5 m during the spring and neap tides, respectively (Shetye et al., 2007; Manoj and Unnikrishnan, 2009). The tides are of mixed semi-diurnal type (Sundar and Shetye, 2005) and vertical mixing of the water column is mainly due to tidal activity. Both flood and ebb currents are stronger in the Zuari than in the Mandovi estuary (Manoj and Unnikrishnan, 2009). Simulation data show that the magnitude of tidal currents in the downstream regions of the estuaries during the spring and neap tides are ∼0.8 m $s^{-1}$ and 0.4 m $s^{-1}$, while the measured values are 1.0 m $s^{-1}$ and 0.65 m $s^{-1}$, respectively (De Souza, 2000).

## 3. Materials and methods

Two types of data were collected in the Mandovi and Zuari estuaries: (1) Salinity data and surface waters were collected every day at one station in the mid-channel of the estuaries during monsoon (June–September) 2007 for Mandovi, and during monsoon 2008 for Zuari estuary. This station is referred here as the “regular” station (Fig. 1). (2) Salinity data, surface water, and bottom sediments were also collected fortnightly at five stations along the main channel of the Mandovi estuary (hereafter referred to as “transect” stations) during June–September 2007, using a mechanized boat. Further, from October 2007 to May 2008, two stations were added towards the river-end of the estuary. Similarly, salinity data and surface water were collected during spring and neap tides of every month between June and September 2008 at 7 transect stations in the Zuari estuary and from October 2008 to May 2009 two stations were added towards the river-end of the estuary. Data collection was repeated during January–May 2009 for Mandovi and October 2009–May 2010 for Zuari at the same stations. In case of Mandovi, sampling stations are confined to the main estuarine channel, while in Zuari sampling stations cover both the channel and bay parts (see Fig. 1). Five liters of surface water collected at each station were filtered through 0.4-μm Millipore filter paper. Three filter papers were used for each station, and the

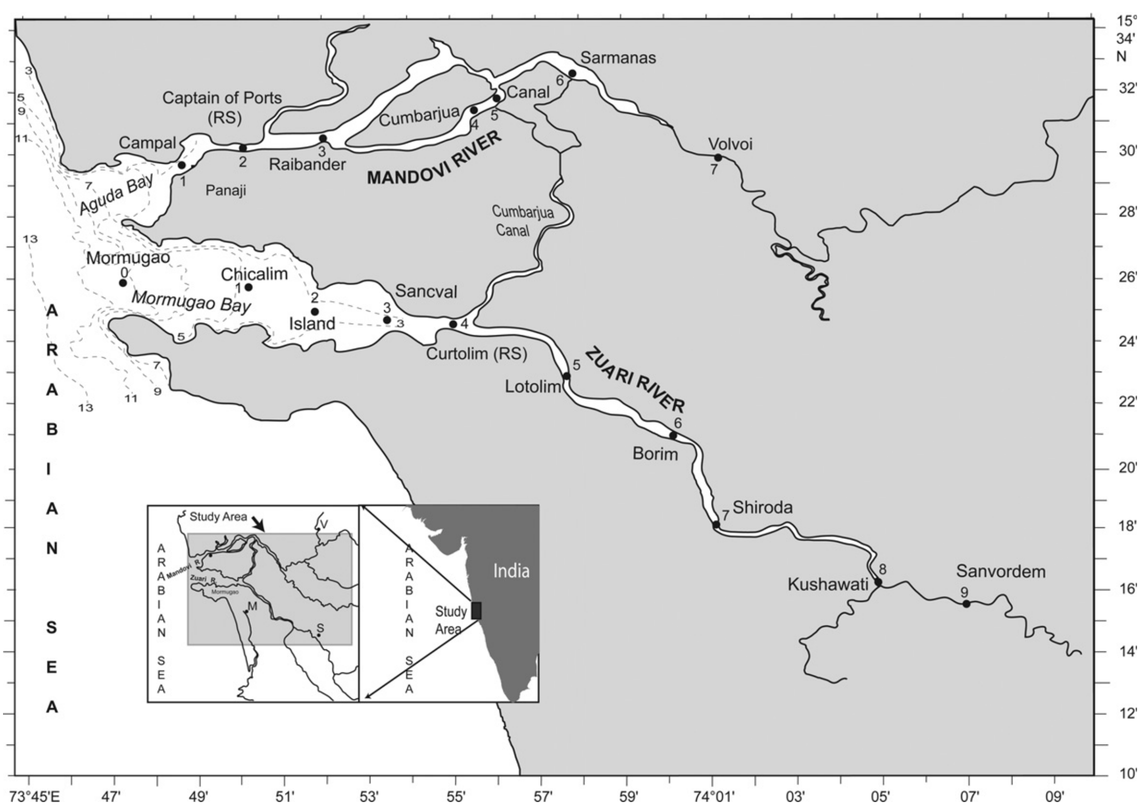


**Fig. 1.** Location of samples in the Mandovi and Zuari River estuaries, central west coast of India. RS – regular station; M and S in the insert figure are rain guage stations, M – Madgaon and S – Sangeam.

suspended particulate matter (SPM) retained on filter papers was dried and weighed. SPM is expressed as milligram per liter.

## 4. Results

### *4.1. Variations of SPM at the regular stations of Mandovi and Zuari estuaries*

Fig. 2A and B depicts the variations of SPM and surface water salinity at the regular stations (RS; Fig. 1) of the Mandovi and Zuari estuaries and rainfall measured by rain gauge at two stations in their drainage basin during monsoon 2007 and monsoon 2008, respectively. The concentrations of SPM during the monsoon vary significantly and range from ∼3 mg/l to 158 mg/l in Mandovi, and ∼2 mg/l to 90 mg/l in the Zuari estuary. Peaks of high SPM concentrations occur more frequently in the Zuari than in the Mandovi estuary. Active spells of high rainfall vary from 50 mm/day to 225 mm/day in the Mandovi River basin, and from 70 mm/day to 200 mm/day in the Zuari River basin. Although the peaks of high SPM correspond with that of high rainfall in both the estuaries (‘a’ in Fig. 2A–B), the correlation between rainfall and SPM is weak (‘*r*’ varies from 0.2 to 0.4 by using data from different rain gauge stations). During the initial phase of the monsoon, surface waters maintain high salinity for a longer time in the Mandovi (31–35‰; until 17th June 2007) than in the Zuari estuary (29–33‰; until 6th June 2008). Thereafter, the salinity values fall sharply in both the estuaries with increase in rainfall (‘a’ in Fig. 2A–B). Excursions of high saline water into the estuary during weak spells of rainfall within the monsoon are characteristic of both estuaries. However, the frequency of these incursions is greater in the Mandovi estuary (Fig. 2A). Peaks of high SPM coinciding with high salinity and low rainfall (see ‘b’ in Fig. 2A–B) at the beginning of the monsoon and peaks of high SPM corresponding with low rainfall and moderate/low salinity (see ‘c’ in Fig. 2A–B) are common in both the profiles. The peaks of moderate SPM in Zuari also correspond well with peaks of high tide, and low SPM with troughs of low tide (Fig. 2B).

### *4.2. Variations of SPM at the transect stations of Mandovi and Zuari estuaries*

SPM and salinity data were collected at each station fortnightly in the Mandovi and during spring and neap tides in Zuari estuaries.

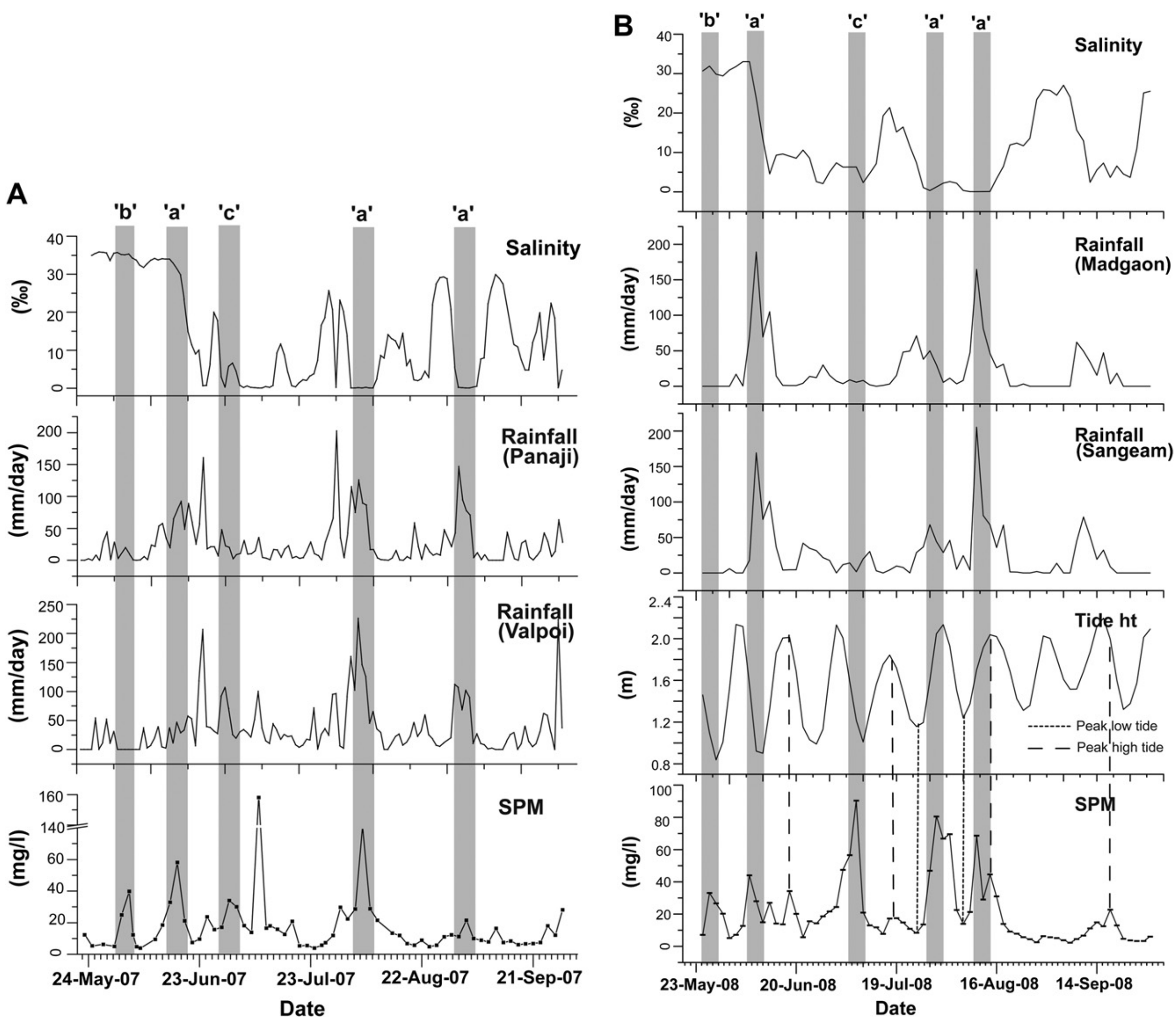


**Fig. 2.** Variations in suspended particulate matter (SPM), salinity and rainfall at the regular station (RS) of the Mandovi (A) and Zuari (B) estuaries. Bands marked are peaks of high SPM coinciding with heavy rainfall and low salinity as ‘a’, with moderate/low rainfall and high salinity as ‘b’, and with low rainfall and moderate salinity as ‘c’.

Since the intensity of monsoon and trade winds exhibit significant seasonal changes in tropical regions, seasonal variations in SPM concentrations were thought to represent the most important variations that occurred in the estuary. Seasonal variations of mean SPM and salinity (average for four months) were calculated at each station of the Mandovi (Fig. 3A) and Zuari estuaries (Fig. 3B–C). The concentrations of mean SPM in the main channel of Mandovi estuary are low at the river-end stations and increase gradually seaward and are highest at sea-end stations of the estuary, both during the monsoon and pre-monsoon. The mean salinity, however, varies from 0 to 8‰ at 5 stations covering a distance of 19 km during the monsoon, and 10–34‰ at 7 stations covering a distance of 35 km during the pre-monsoon. The concentrations of SPM are consistently low (<7 mg/l) at all stations, despite salinity variation from 2.5 to 32‰ at 7 stations during the post-monsoon.

Fig. 3B and C illustrates the seasonal concentrations of mean SPM and salinity along transect stations of the Zuari estuary during the spring and neap tides, respectively. In Zuari, stations 0–3 represent the bay part and stations 4–9 represent the channel part of the estuary (see Fig. 1). On spring tide SPM is high and nearly equal (av. 19 mg/l) at all stations in the channel, but decreases gradually seaward from 17 mg/l to 8 mg/l in bay stations during the monsoon. On the other hand, the mean salinity varies from 0 to 8‰ in channel stations and increases seaward from 10 to 31‰ in bay stations. During the post-monsoon, the mean SPM is much lower (3–10 mg/l) with relatively high values (8–10 mg/l) at stations 2–5, close to the junction of the bay and estuary channel. The mean salinity increases steeply from 1 to 31‰ from river-end to sea-end stations in the channel, and marginally from 32 to 35‰ in bay part of the estuary. During the pre-monsoon, the mean SPM

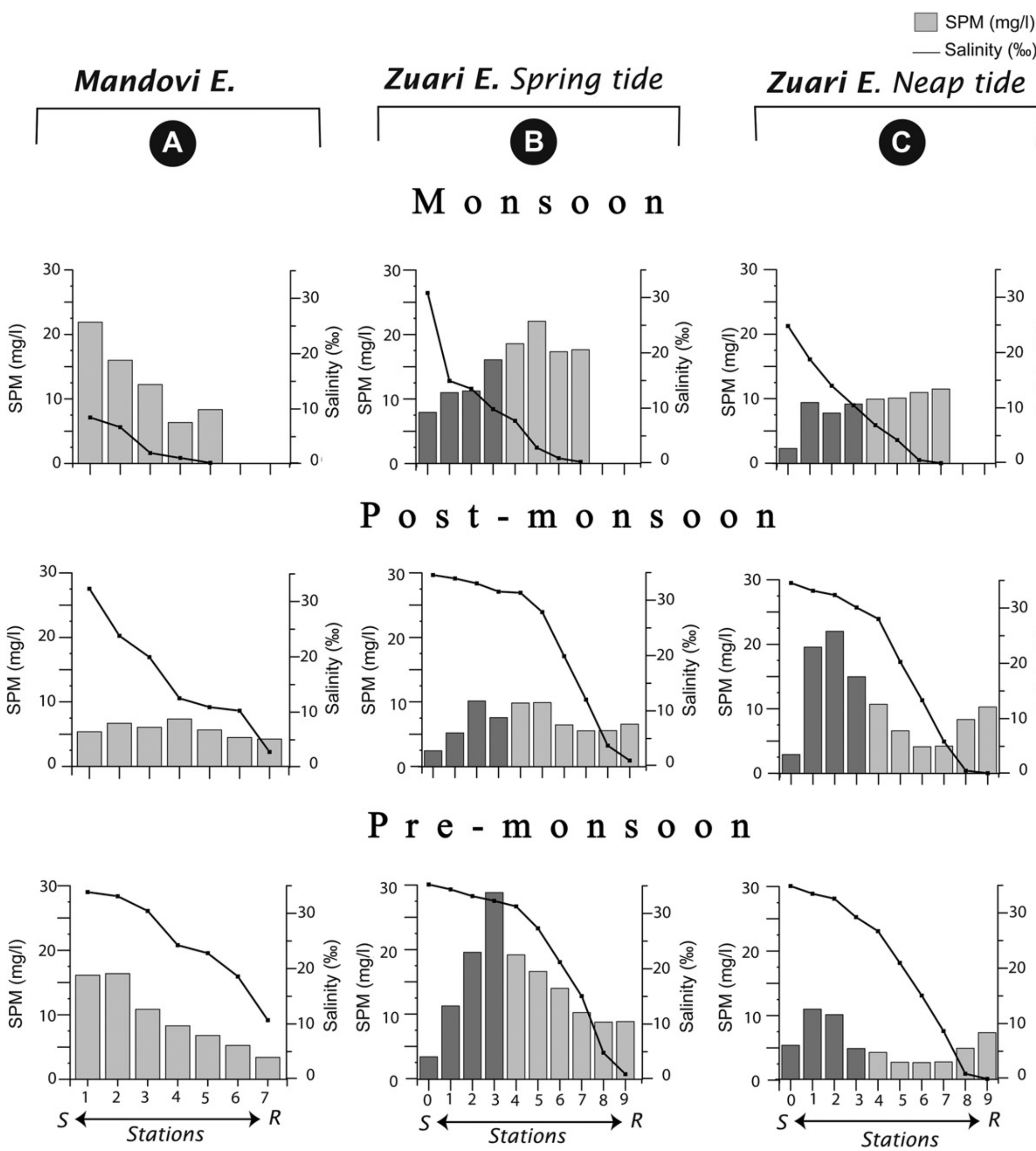


**Fig. 3.** Seasonal mean SPM concentrations and salinity (average of four months) from river-end (R) to sea-end stations (S) of the estuarine channel in Mandovi River (A), in channel and bay stations of Zuari River on spring (B) and neap tides (C). Dark grey histograms represent bay stations and light grey histograms represent channel stations in Zuari River.

concentrations again increase gradually from river-end (9 mg/l) to sea-end stations (19 mg/l) of the channel with the highest values (30 mg/l) at station 3, close to the junction of bay and channel, and then decreases seaward gradually in the bay. The mean salinity variations are nearly the same as those during post-monsoon, except that the slope of the salinity curve is gentler in pre-monsoon than post-monsoon (Fig. 3B). The mean SPM and salinity variations during neap tide (Fig. 3C) are as follows: SPM concentrations are high (12 mg/l) at the river-end stations and decrease marginally towards sea-end stations of the channel and the bay during the monsoon. The mean salinity varies from 0 to 25‰ from river-end station of the main channel to the bay-end station of the estuary. The mean SPM concentrations in channel stations are much lower during the post- and pre-monsoons than in monsoon, but highest SPM (19–22 mg/l; av. 20 mg/l) occurs at stations 1 and 2 of the bay (Fig. 3C). Salinity variations during the neap tide are the same as those during the spring tide.

## 5. Discussion

### 5.1. Controls on SPM concentrations at the regular station (RS)

SPM concentrations in estuaries, in general, are controlled by several factors, including river discharge, salinity and turbidity in the water column. Rainfall during the SW monsoon shows high variability, both on seasonal and sub-seasonal timescales (Shetye et al., 2007). Moreover, active periods of heavy rainfall within the monsoon period are interrupted by drier 'break' periods, during which saline waters intrude into the estuaries. The SPM, salinity and rainfall data collected at the regular stations of Mandovi and Zuari estuaries are for monsoon 2007 and 2008, respectively. Therefore, the variations in peak SPM concentrations in the Mandovi (158 mg/l) and Zuari (90 mg/l) rivers (Fig. 2A–B) at the RS are controlled by the duration and intensity of heavy spells of high rainfall in 2007 and 2008 and by the influence of intruded saline waters. Peaks of high SPM coinciding with high rainfall and low salinity in both profiles ('a' in Fig. 2A–B) indicate that the SPM brought by rivers to the estuary during heavy monsoon rains is a controlling factor. Peaks of high SPM coinciding with high salinity and low/medium rainfall ('b' in Fig. 2A–B), and weak correlation of SPM with rainfall ($r = 0.2$ to 0.4), however, indicate that the SPM is also affected by other factors, such as turbidity caused either by processes at the interface of saltwater with freshwater, or resuspension of bottom sediments. The coincidence of high SPM and high salinity at the beginning of the monsoon suggests that resuspension, at times, controlled the SPM concentrations. The RS in the Mandovi is 6.3 km away from the mouth of the estuary and is located within the main channel and is somewhat protected from physico-chemical processes occurring in the bay. While in Zuari the RS is 10 km away from the mouth of the estuary and is located at the end of the main channel and beginning of the conical- or funnel-shaped bay and is directly affected by the processes in the bay. Greater number of the peaks of moderate SPM in the Zuari than in Mandovi estuary and, peaks of high SPM corresponding to that of high tide and vice versa (see Fig. 2B) suggest that the RS in the Zuari is affected by enhanced tidal currents in the bay (see below), which keep pushing the resuspended sediments from the bay to the estuary channel, leading to the events of moderate SPM. Moreover, enhanced tidal currents favour strong vertical mixing in the water column that may be responsible for relatively lesser number of excursions of high saline waters during weak spells of rainfall in the Zuari (Fig. 2B), compared to that in Mandovi (Fig. 2A). More number of peaks of high saline waters in Mandovi estuary also cause rapid settling of SPM. The SPM at the RS in both Mandovi and Zuari estuaries is influenced by river discharge, resuspension of bottom sediments and salinity excursions.

### 5.2. Controls on SPM distribution and ETM formation at transect stations

#### 5.2.1. During the monsoon

The estuaries of the Mandovi and Zuari Rivers receive maximum sediment discharge because of heavy rainfall (av. 2500 mm/yr) that occurs only during the monsoon. Shetye et al. (2007) and Vijith et al. (2009) reported the total runoff in these rivers is an order of magnitude larger than the estuarine volume during the monsoon. Increase in SPM concentrations from river-end to sea-end stations of the estuary and highest concentrations at the sea-end station of the main channel, both in Mandovi (Fig. 3A) and (during spring tide) Zuari estuaries (Fig. 3B), during the monsoon indicate high SPM concentrations are due to estuarine turbidity maximum (ETM). As salinity in the channel ranges from 0‰ to 8‰, this ETM may be considered as 'traditional ETM' occurring at the freshwater–seawater interface, reported by several others from different estuaries (Schubel, 1968; Festa and Hansen, 1978; Allen et al., 1980; Uncles et al., 1994; Grabemann et al., 1997; Chen et al., 2005; McManus, 2005). Mixing between the freshwater and seawater provokes turbulence, which is generated by currents arising from river flow, tides, or both (Allen et al., 1980). The tidal range during the spring tide is 2.3 m. Strong, westerly to south-westerly winds with a speed of 4–7 m $s^{-1}$ occurring during the monsoon (Shetye et al., 2007) tend to strengthen the currents towards the estuary head. De Souza (2000) reported tidal currents of 1 m $s^{-1}$ during the spring tide. In other words, the intense river flow during the monsoon is counteracted by the strong tidal and wind-induced currents transported from the bay. In such conditions, high SPM would accumulate either at the head of salt intrusion, or in the upper estuary depending on the strength of the estuarine circulation relative to that of tidal transport. Although the zone of ETM with an average SPM of 19 mg/l occurs at sea-end stations of the main channel in both estuaries (Fig. 3A–B), it is found to stretch to ∼21 km during the spring tide of the Zuari and ∼10 km in the Mandovi estuary. This elongated zone of ETM in Zuari indicates greater volume of water with intensified currents were probably pumped into the converging main channel, causing turbulence and keeping particles in suspension and extending ETM upstream. In other words, the greater size and funnel-shaped bay off Zuari and, the small size and circular bay off Mandovi and associated physical processes are responsible for the extended and narrow zones of ETM, respectively. Althausen and Kjerfve (1992) also reported elongated turbidity maximum zone (TMZ) in a partially mixed estuary, Charleston harbor, USA and suggested that elongated TMZ does not necessarily indicate active formation of the TMZ but rather the upstream advection of the previous low tide TMZ. Elongated ETM in Zuari further suggests that the strength of tidal and wind-induced currents is greater than the currents arising from river flows and, suspended sediment in the ETM is a mixture of dominant marine or resuspended sediment transported from the bay, and river SPM. Distinct TMZ could not be seen in the Zuari estuary during the neap tide, but high concentrations of SPM are found upstream of the main channel which are observed to decrease seaward (Fig. 3C). The average SPM retention percentage at each station for different seasons (average for 4 spring and neap tides of 4 months) was calculated using a modified formula of Adame et al. (2010).

$$\text{SPM retention\%} = ((\text{SPM spring} - \text{SPM neap})/(\text{SPM spring})) \times 100.$$

The plot in Fig. 4 shows higher SPM (34–50%) was retained in the estuary channel than in the bay (16–38%) of Zuari after the monsoon and was available to accumulate in the respective regions during the post-monsoon. The increase in retention percentage of SPM from mouth to the constriction of the bay (Fig. 4A) suggests suspended matter may also have been drawn from offshore into the bay.

*5.2.2. During the post-monsoon*

During the post-monsoon river discharge is negligible (Shetye et al., 2007) and saltwater intrudes progressively into the estuarine channel (Fig. 3). The low SPM concentrations in both the estuaries may be due to the absence of estuarine circulation and saltwater intrusion, which suppress turbulence and effectively remove fine suspended sediments from the channel. Relatively high SPM at stations close to the constriction of the funnel-shaped bay in Zuari (Fig. 3B) may suggest the influence of (spring) tidal currents in resuspending sediments. Turbidity maximum, however, occurs at stations 1–3 in the bay part of Zuari estuary on neap tide. Repeated observations during the post-monsoon 2009–10 confirm the consistency of turbidity maximum in two consequent years. The exact mechanism of its formation is unknown. As northeasterly (seaward directed) winds with a speed of 1.8–2.6 m $s^{-1}$ prevail during the post-monsoon (Shetye et al., 2007), it may partly be due to wind-activity generated waves which resuspend fine sediment from the marginal tidal flats and transport seaward during neap tide. The water depths at stations 1–3 are shallower than those of adjacent stations on either side. Moreover, both flood and ebb tides are strong in Zuari estuary (Manoj and Unnikrishnan, 2009). The combined affect of wind-generated and ebb currents at neap tide and their interaction with shallow bottom may have also eroded and resuspended sediments from the shallow bathymetry, leading to the formation of ETM locally. The SPM retention percentage (Fig. 4) shows negative high values in the bay, most probably due to higher SPM during the neap than in spring tide. As the SPM is least at the sea-end station (0) of the bay, the resuspended sediment may be settling largely within the bay.

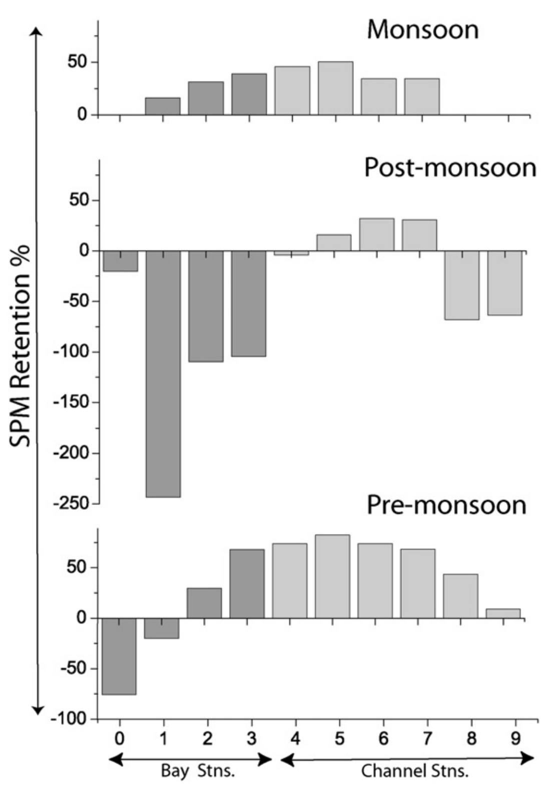


**Fig. 4.** SPM retention percentage at each station of Zuari estuary after each season. This is calculated based on the modified formula of Adame et al. (2010). Dark grey histograms represent bay stations and light grey histograms represent channel stations.

*5.2.3. During the pre-monsoon*

During the pre-monsoon the river discharge is negligible in both rivers and saline waters intrude ~45 km upstream (Shetye et al., 2007). The NW and SW winds blow at speeds of 3.2–3.7 m $s^{-1}$ and the winds are dominated by sea breezes (Neetu et al., 2006). The distribution of SPM in the main channel of the Mandovi River during the pre-monsoon replicates that of monsoon (Fig. 3A), despite negligible river discharge in the former and abundant river discharge in the latter season. Here the SPM concentrations increase from river-end to sea-end stations of the estuary channel and ETM remains at the same position, both during monsoon and pre-monsoon. While in Zuari ETM occurs in the channel on spring tide, stretched upstream during monsoon, but migrates seaward of the channel and close to the constriction of the bay during pre-monsoon (Fig. 3B). This seasonal migration of ETM is in contrast with the medium and high tidal range estuaries, wherein turbidity maximum migrates landward in response to the decrease of freshwater flow (Grabemann and Krause, 1989; Wolanski et al., 1995, 1996). In the absence of estuarine circulation during the pre-monsoon, tidal and wind-induced currents may be responsible for ETM formation in Mandovi and Zuari estuaries. Moderate correlation of SPM concentrations with wind speed in channel stations of Mandovi ($r = 0.53$; Fig. 5A) and Zuari ($r = 0.58$; Fig. 5B) rivers suggests that the wind-induced waves/currents could be a factor (Kessarkar et al., 2009, 2010). Strong correlation of SPM concentrations with wind speed at bay stations in Zuari ($r = 0.77$; Fig. 5B) also argues in favour of the influence of wind in ETM formation. Several investigators (Weir and McManus, 1987; Schoelhamer, 1995; Wolanski et al., 1995; McManus, 2005; Verney et al., 2007; Talke and Stacey, 2008; Uncles and Stephens, 2010) suggested that wind is an important mechanism in generating turbidity maximum. The concentrations of SPM in the zone of ETM are higher in the Zuari (av. 22 mg/l) than in the Mandovi (av. 16 mg/l). As the size and geometry of the bays off Mandovi and Zuari Rivers are different (see Fig. 1), the energy and effectiveness of the physical processes operating in these bays in resuspending and transporting sediments would be different. For example, the funneling effect in the bay of Zuari may have greater impact on the erosion and resuspension of material. As winds are directed towards the narrower parts of the bay, the magnitude of the effect of winds is expected to be higher in the funnel-shaped Zuari bay than in the circular-shaped Mandovi bay. Stronger winds not only generate waves but also reinforce the currents and carry SPM closer to the head (Talke and Stacey, 2008). Moreover, the funneling effect of the water in the narrowing bays increases the tidal range, with the maximum height close to the constriction of the conical-end and stem part of the funnel. The sharp increase in SPM concentrations from station 0 (at the mouth) to station 3 (at the constriction; see Fig. 3) on spring tide and, strong correlation ($r = 0.9$) of SPM concentrations with tide height in bay stations (Fig. 5D) suggest the greater influence of tide in resuspending sediments in funnel-shaped bays leading to high SPM and ETM close to the constriction. The influence of the funneling effect and tidal currents in resuspending sediments, ETM formation and sediment transport were reported in macrotidal estuaries (Postma, 1967; Nichols and Poor, 1967; Allen and Castaing, 1973; Collins, 1983; Wells, 1995; Wolanski et al., 1995; Sanford et al., 2001; Uncles et al., 2002; Scully and Friedrichs, 2007; Manning et al.,

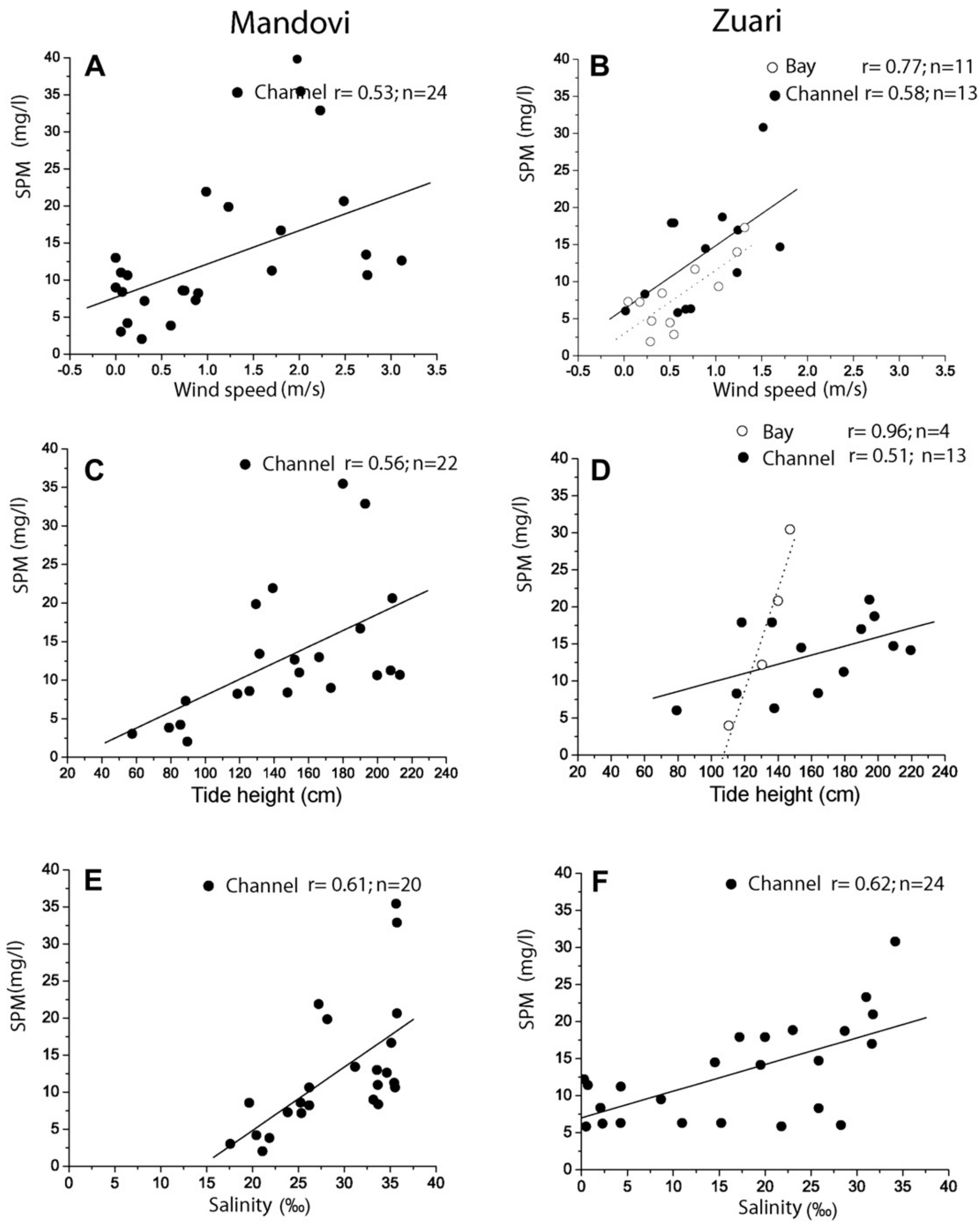


**Fig. 5.** Scatter plots of Wind speed vs. SPM (A–B), tide height vs. SPM (C–D) and salinity vs. SPM (E–F) in Mandovi and Zuari estuaries during the pre-monsoon. A, C and E represent plots for Mandovi and B, D and F represent plots for Zuari estuaries.

2010). Moderate correlation of SPM concentrations with tide height in channel stations of both rivers (Fig. 5C–D) also supports the above argument.

The plot of SPM concentrations vs. salinity at all stations in the main channel of both estuaries during the pre-monsoon (Fig. 5E–F) shows high SPM is a seaward deposit and SPM concentrations decrease with decrease in salinity towards the river-end stations. Moreover, moderate correlation exists between the SPM and salinity (Fig. 5E–F). As river discharge is negligible in both rivers during pre-monsoon, the SPM-laden waters from the bays are eventually pumped into the channel by waves and tidal currents and concentrations of SPM decrease gradually upstream. In other words, the source sediments for SPM are either marine or resuspended sediment from the bay. The maximum SPM concentration during February–May is up to 35 mg/l (Fig. 3A–B). As high SPM during this period is largely due to resuspension of bottom sediment, particle sizes in resuspended sediments must be larger and could have settled faster. Therefore, the impact of sediment by horizontal diffusive transport can only be seen in stations that are closer to the deposit, in spite of saline water incursion 45 km from their mouth (Shetye et al., 2007). The SPM retention percentage during the pre-monsoon (Fig. 4) shows that the channel becomes the major depositional centre (40–80% of SPM) compared to the bay part.

## 6. Conclusion

The estuarine turbidity maximum (ETM) is a characteristic feature of both Mandovi and Zuari. ETM occurs seaward of the channel in Mandovi River and remains at the same position, despite abundant freshwater discharge during monsoon and negligible discharge during pre-monsoon. While in Zuari ETM is stretched upstream of the channel during monsoon, and migrates seaward of the channel and close to the bay during pre-monsoon. ETM shifts to the bay of Zuari on neap tide during post-monsoon. The SPM retention percentage is higher in the channel than in the bay of Zuari during monsoon. It appears that the size and geometry of the bays off the rivers and strength of tidal and wind-induced currents played a major role in erosion, resuspension and transportation of sediments and concentrations of SPM in the turbidity maximum. The SPM-laden waters from the bay are eventually pushed into the channel and the channel becomes the major depositional centre.

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