Variability in stratification and flushing times of the Gautami–Godavari estuary, India

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In order to examine the influence of forcing (river flow and tides) and anthropogenic activities (dredging and dam regulation) on stratification, a study was conducted over a period of 19 months (June 2008–December 2009) in the Gautami–Godavari estuary (G–GE) during spring and neap tide periods covering entire spectrum of discharge over a distance of 36 km from the mouth. The bathymetry of the estuary was recently changed due to dredging of ∼20 km of the estuary from the mouth for transportation of barges. This significantly changed the mean depth and salinity of the estuary from its earlier state. The variations in the distribution of salinity in the Godavari estuary are driven by river discharge during wet period (June–November) and tides during dry period (December–May). The weak stratification was observed during high discharge (July–August) and no discharge (January–June) periods associated with dominant fresh water and marine water respectively. The strong stratification was developed associated with decrease in discharge during moderate discharge period (October–December). Relatively stronger stratification was noticed during neap than spring tides. The 15 psu isohaline was observed to have migrated ∼2–3 km more towards upper estuary during spring than neap tide suggesting more salt enters during former than latter period. Total salt content was inversely correlated with river discharge and higher salt of about 400×10^6 m^3 psu was observed during spring than neap tide. Flushing times varied between less than a day and more than a month during peak and no discharge periods respectively with lower times during spring than neap tide. The flushing times are controlled by river discharge during high discharge period, tides during dry period and both (river discharge and tides) under moderate discharge period. This study suggests that modification of discharge, either natural due to weak monsoon, or artificial such as dam constructions and re-routing the river flow, may have significant impact on the stratification and biogeochemistry of the Godavari estuary.

1. Introduction

An estuary is a semi-enclosed coastal body of water with a free connection to the open sea, within which the sea water is measurably diluted with freshwater derived from land drainage (Pritchard 1952; Cameron and Pritchard 1963). The vertical stratification of the estuary depends upon the volume of freshwater input and tides (Hansen and Rattray 1966). Jay and Smith (1990) reported that residual circulation changes with river flow, tides, storms and other low-frequency processes that play a significant role in salt estimation.

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The Godavari estuary is the largest monsoonal estuary in India in terms of length and volume of discharge (Sarma *et al.* 2009). The river Godavari originates in the Western Ghats near Nasik city at an altitude of about 1620 m and flows eastwards through Godavari garben and joins the Bay of Bengal at Bhairavapalem (figure 1). The discharge of freshwater from the upstream is mainly controlled by Low Dam at Dowlaiswaram (Rao 1975; Sarma *et al.* 2009). After the dam, this estuary divides into two branches: the northward flowing Gautami–Godavari (G–GE), and the southward flowing Vasistha–Godavari (V–GE). Since the major discharge occurs through G–GE compared to V–GE, most of the earlier studies were carried out in the former branch. This estuary is influenced by Indian Summer Monsoon (ISM; (June–September)). Recently, Vijith *et al.* (2009) found unsteady state in the monsoonal estuaries due to special characteristic of monsoonal runoff. The runoff into monsoonal estuaries is highly seasonal and exceeds the total volume of the estuary during peak discharge period (Vijith *et al.* 2009). Therefore, stratification in the estuary is controlled by river flow during ISM, and horizontal diffusion of salt due to tides during dry period.

Ranga Rao *et al.* (1988) studied G–GE from mouth to ~22 km upstream at monthly intervals (except during March and August) and observed that salinity in the estuary was mainly controlled by discharge during ISM with strong stratification whereas well mixed conditions were found during January. However, they did not collect data during peak discharge period (i.e., August) to examine the stratification in the estuary. Reddy and Ranga Rao (1993) estimated flushing time in G–GE during September (48 h) and December (552 h) and no efforts were made during other periods, especially during peak discharge and no discharge periods. Jyothi *et al.* (2000) measured salinity in the estuary during January, April and November in G–GE and observed increase in salt content by 62% and 32% from November to January and from January to April, respectively. Narasimha Rao (2001) observed that stratification was stronger at low water slacks and weaker at high water slacks. Recently, Shetye *et al.* (2007) noticed weak salinity stratification during spring (~2 psu of salinity difference between surface and bottom) than neap tide (~6 psu) in the Mandovi estuary. Therefore, the magnitude of tidal range has significant impact on strength of mixing and stratification in the estuary.

The studies carried out so far in the G–GE have not covered entire river discharge spectrum, impact of spring and neap tides on stratification, salt intrusion to the upstream estuary and flushing
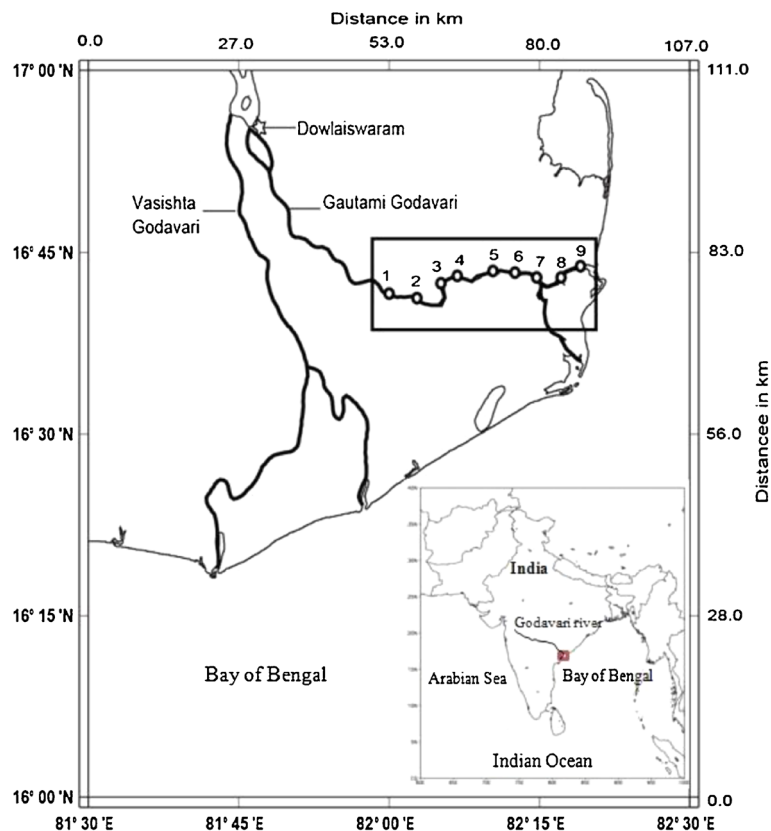

Figure 1. Study area along with the station locations (1– 9).

time. In addition to this, earlier studies carried out about two decades ago and recent changes, such as bathymetry and monsoonal intensity, might have modified physical processes in the G–GE. In order to examine these, a systematic study extending over 19 months, was carried out to understand the influence of river discharge and tides on stratification, intrusion of salt, salt budget and flushing time in the G–GE. The data collection and methodology adopted is explained in section 2, while results are given in section 3. Finally, the conclusions and the intra and inter-annual variability in river discharge, variations in stratification, salt intrusion and flushing times of the estuary with reference to recent variability in bathymetry and tides are discussed in section 4.

2. Data and methodology

2.1 *Study area*

Godavari estuary is characterized by many islands and creeks that significantly influence flow of water (Narasimha Rao 2001). The tides in the estuary are semi-diurnal with spring and neap tides in the ranges of 1.0–1.5 and 0.27–0.7 m, respectively. The average depth and width of the estuary is 8 and 1200 m, respectively, which were ∼12 and 1000 m during 1990 (Reddy and Ranga Rao 1993).

Coarse sand from the upstream river (Kotipalli) is being dredged for domestic purposes, as it is widely used in the civil engineering sector. This led to increase in depth from 6 m during 1990 (Ranga Rao *et al.* 1988) to ∼11 m during study period. On the other hand, dredging was carried out from mouth to middle of the estuary (up to station 6, Yanam) (figure 2a) in 2007 for transportation of barges. Such activities led to increase in the depth of mid-estuary in recent years to 21 m from that of earlier (∼10 m). At the mouth, the estuary was widened and shallowed (7 m) compared to that two decades earlier. The width to depth ratio increased from mouth to upstream during 1990, whereas it decreased during 2008 due to dredging (Sridevi 2013). Since the estuarine bathymetry changed during last 20 years due to anthropogenic activities, it is hypothesized that stratification of the estuary might have been modified in the recent years.

2.2 *Data*

Bathymetry data of the estuary was collected during June 2008 from mouth to upstream, over a stretch of 36 km, at 500×50 m grid spacing using Differential Global Positioning System (DGPS; Ceeducer, Australia). The DGPS is a satellite-based
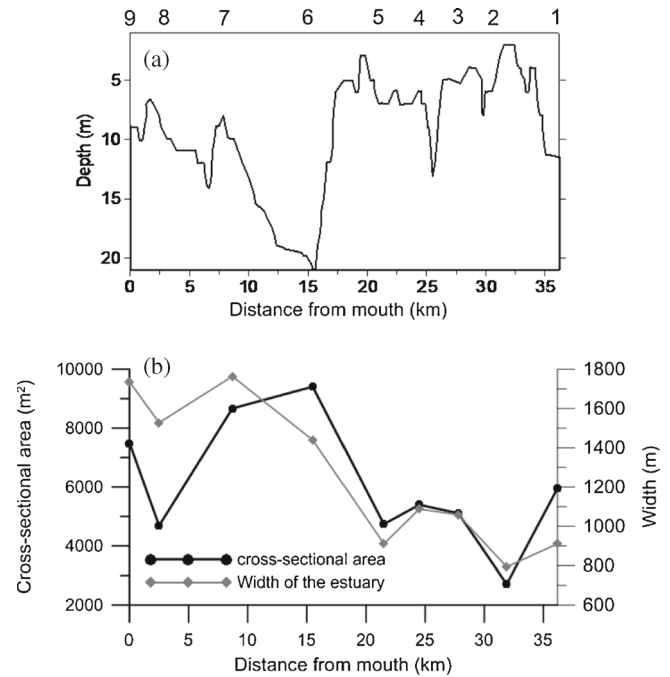

Figure 2. Variability of (**a**) along channel depth and (**b**) cross-sectional area at transect locations in the Gautami–Godavari estuary. The numbers on the top indicate station numbers. The distance was calculated from the mouth of the estuary (Bhairavapalem) to the upstream.

navigation surveying system with the accuracy of ± 1 m and 1 cm for geographical position and depth values respectively. The depth measurements were made by transmitting the acoustic pulse at 200 kHz frequency through the water media. The received acoustic pulse was processed with the principle of sound velocity in the water and the processed output was digitally recorded as depth value. The cross-sectional area at each station was computed using spline interpolation technique (Ralston and Wilf 1966). The cross-sectional area increased from mouth to 16 km towards the head of the estuary except at station 8 (figure 2b). Further upstream of station 6, it decreased until station 2 and then again increased at station 1 (head of the estuary) (figure 2b).

Vertical profiles of temperature and salinity were collected at 9 stations from June 2008 to December 2009 during spring and neap tide periods along the channel using conductivity, temperature and depth profiler (CTD; SBE19 plus Seacat profiler, Sea Bird Electronics, USA). The accuracy of temperature and conductivity were 0.005°C and 0.0005, respectively, and salinity was obtained from conductivity. A mechanized boat was used to cover about 36 km upstream from the mouth.

Daily river discharge data was obtained from dam authorities at Dowlaiswaram (figure 1). Water elevation was measured at an interval of 10 min by a tide gauge, designed by Marine Instrument Division, National Institute of Oceanography, Goa,

installed at station 6. Stratification was estimated as the difference between salinity at surface and bottom, following Haas (1977).

2.3 *Total salt content*

The total salt content of the estuary was computed by considering salinity (S) as a continuous function of distance (km) from mouth to upstream. Then S_{tot} is given by the following equation (Jyothi *et al.* 2000:

$$S_{tot} = \int\limits_0^L S(x)A(x)dx \qquad (1)$$

where $A(x)$ is the cross-sectional area of the estuary at x. The upper limit L denotes length of the estuary and it is 36 km for the present study. Salt content between two successive stations was computed by a cubic spline integration method (Ralston and Wilf 1966) using salinity and cross-sectional area; the salt content was integrated along the length of the entire estuary to get total salt content.

2.4 *Computation of flushing time (T)*

Flushing time (T) can be defined as the average time taken by a parcel of freshwater to pass through the estuary (Bowden 1980) or the time required to renew existing volume of water in an estuary (Monsen *et al.* 2002). This T can be estimated following two methods, namely, freshwater fraction method (Dyer 1973; Huang 2007) and tidal prism method (Monsen *et al.* 2002).

2.4.1 *Freshwater fraction method*

The fraction of the freshwater (f) at a particular location is given by:

$$f = \frac{(S_0 - S)}{S_0},$$

where S_0 represents mean oceanic salinity. For the present case, S_0 is taken as mean observed salinity of 33 psu. S is the depth averaged salinity at a particular location. Flushing time given by freshwater fraction method is:

$$T = \frac{F}{Q} = \frac{\int \frac{fd(V)}{Vol}}{Q}, \qquad (2)$$

where F is the volume of the freshwater present in the estuary and Q is the rate of river discharge. V is the volume of the estuary. This method accounts for the influence of river discharge, salinity intrusion and gravitational circulation (Sheldon and Alber 2006). This method, however, is not valid during negligible or no discharge period.

2.4.2 *Tidal prism method*

Tides dominate the estuarine circulation during no discharge period (Monsen *et al.* 2002) and hence flushing times were estimated using tidal prism method when discharge was negligible. Flushing time given by tidal prism method is:

$$T = \frac{VT_{tidal}}{(1 - b)P}, \qquad (3)$$

where T_{tidal} is tidal period, b is return flow factor and P is the tidal prism (Monsen *et al.* 2002). Based on the high resolution shallow seismic survey, the volume of the estuary was precisely computed as 2.77×10^8 m^3 (volume between upstream and mouth). Semi-diurnal period (T_{tidal}) is predominant in the Godavari estuary (0.53 days; 12.42 h). P is the tidal prism in m^3 and it is approximately the product of surface area of the estuary and tidal range. Vijith *et al.* (2009) considered b as 0.5 in the Mandovi estuary. It means that about 50% of the water that goes out of the estuary during ebb tide returns to the estuary during consecutive flood tide. Hence, the flushing time derived from the tidal prism method may be either under- or over-estimated according to Luketina (1998). Tidal prism method was adopted for zero and low discharge (i.e., on 8 June and 26 October 2009) periods.

3. Results

3.1 *Intra- and inter-annual variations in river discharge*

The rate of daily river discharge in the Godavari estuary varied from 0 to 11015 m^3 s^{-1} during 2008. The onset of monsoon occurs during June, but the peak in river discharge was observed during July (3216 m^3 s^{-1}). The discharge decreased by the end of August 2008 and peaked again during the first week of September and decreased rapidly from October to December to the negligible rates with the withdrawal of the ISM.

In contrast, pulsed nature of discharge was observed during 2009 due to breaks in monsoonal rainfall. Significant discharge was observed during July and virtually stopped by the middle of August for about 2 weeks and then increased sharply by the end of August. By the end of September, discharge decreased to minimum and stopped completely by December. The total annual river runoff in 2008 (180 m^{3}d^{-1}) was more than double to that of 2009 (68 m^{3}d^{-1}). Peak discharge was more than three times higher during 2008 (>11000 m^3 s^{-1}) than 2009 (~3000 m^3 s^{-1}). The number of days and daily discharge exceeded the volume of the estuary (2.77×10^8 m^3). It was 25 (~6×4) in 2008 and was

only 4 in 2009. As a result, the estuary was flushed ∼6 times more during 2008 than 2009.

3.2 *Spatial and temporal variability in stratification*

3.2.1 *Influence of river flow*

The discharge initiated the development of stratification and disappeared with insignificant horizontal and vertical variations in salinity, when river flow is greater than or equal to the volume of the estuary. For instance, the volume of freshwater discharge recorded at the head of the estuary on 19 August, 2008 (2.58×10^8 m^3 day^{-1}) (figure 3d) was just about the volume of the estuary ($>2.77 \times 10^8$ m^3) that led to filling of the entire estuary with freshwater, with no stratification (figure 4b). Saline water intrudes into the estuary with the decrease of discharge (87×10^6 m^3 day^{-1}; figure 4c) and a horizontal as well as vertical salinity gradient develops. Due to intrusion of saline water at the bottom, high vertical salinity difference was noticed in the middle (6 psu) and lower estuaries (5 psu) in October (figure 4c). During this time, the orientation of isohalines indicated the turning of the estuary from a salt wedge to a partially mixed type estuary (figure 4c). On further decrease of discharge, estuary turned from a partially mixed type to a well mixed type (figure 4d) and this resulted in low vertical salinity difference (figure 4d) due to dominance of salt water in the entire estuary and termination of freshwater input from upstream end.

Discharge also influenced the amount of salt present in the estuary. For instance, the intrusion of saline water, represented as the distance between the mouth and location of 2 psu isohaline, into estuary was up to ∼24 km (station 4) from the mouth on 31st October 2008 when the discharge was 100 m^{3}s^{-1} (figure 4c). On the other hand, 2 psu isohaline was noticed beyond 36 km (study region) from the mouth during no discharge period with weak salinity gradient between surface and bottom suggesting estuary is of well-mixed type (figure 4d).

The salinity difference between surface and bottom was variable along the estuary due to changes in bathymetric structure. For example, the vertical salinity difference was higher (15 psu) on 20 June 2008 at station 6, where the water column was the deepest (21 m), and this difference was ∼2 and 0 psu at the mouth of the estuary where depth of the water column was ∼6 m and at the upstream where the water column depth was ∼11 m (figure 4a). The orientation of isohalines clearly indicates that salinity distribution in the middle of the estuary was sandwiched between tidal effect from mouth and discharge from the upstream.

3.2.2 *Influence of tides*

Semi-diurnal tides were predominant with a tidal range of 1.0–1.5 m during spring and 0.3–0.7 m during neap tide (table 1). Tides played a significant role in penetration of salt into the estuary during moderate and negligible discharge periods. For example, 33 psu of salinity was noticed at the mouth of the estuary during 8 June 2009 (spring tide) and it was 30 psu during 16 June 2009 (neap tide) (figure 5d) at the same location. The difference of 3 psu salinity between spring and neap tides suggests that more salt water intruded into the estuary during the former than the latter period. On the other hand, the difference in salinity at the mouth/head of the estuary was less (∼1 psu) during negligible discharge period when the tide changed from spring to neap (figure 5a and b). During October 2009, the decrease of discharge from 252 to 2 m^3 s^{-1} (table 1) from spring to neap tide, resulted in higher salinities at the bottom during the neap tide (17 psu) than the spring tide (13 psu) in the middle of the estuary (figure 5g and h). So, it is difficult to capture the difference in salinity between spring and neap tides during discharge period as freshwater discharge dominates on salinity variations over the tidal effect. For instance, high salinity intrusion was noticed during neap tide on 27 August 2008 compared to spring tide (19 August 2008) when the river discharge was 2989.9 and 1474.7 m^3 s^{-1} respectively, suggesting that magnitude of discharge dominates more than tides on salt intrusion (figure 5e and f).

In order to examine the monthly variability in salinity stratification during spring and neap tide at upper (station 1; figure 3a), middle (station 6; figure 3b) and lower estuary (station 9; figure 3c), the salinity difference between surface and bottom was plotted with reference to discharge in figure 3. From this figure, it is observed that the variability in stratification was noticed from August 2008 to June 2009 between spring and neap tide and it was higher during the former period than in the latter period. Furthermore, the highest stratification was noticed at station 6 (middle estuary) in the entire estuary due to deep water column. In order to further examine the variations in salinity intrusion during spring and neap tides, the location of 15 psu isohaline from the mouth of the estuary was examined during the period of observation (figure 3d). The 15 psu isoline was observed relatively more towards upstream by 2–3 km during spring than neap tide in dry period. Before the onset of ISM (during April 2009), 15 psu isohaline reached up to 36 km from the mouth and it decreased to ∼18 km during moderate discharge (120 m^3 s^{-1}) and disappeared during August to October (figure 3d). The 15 psu isohaline appeared at 6 km from

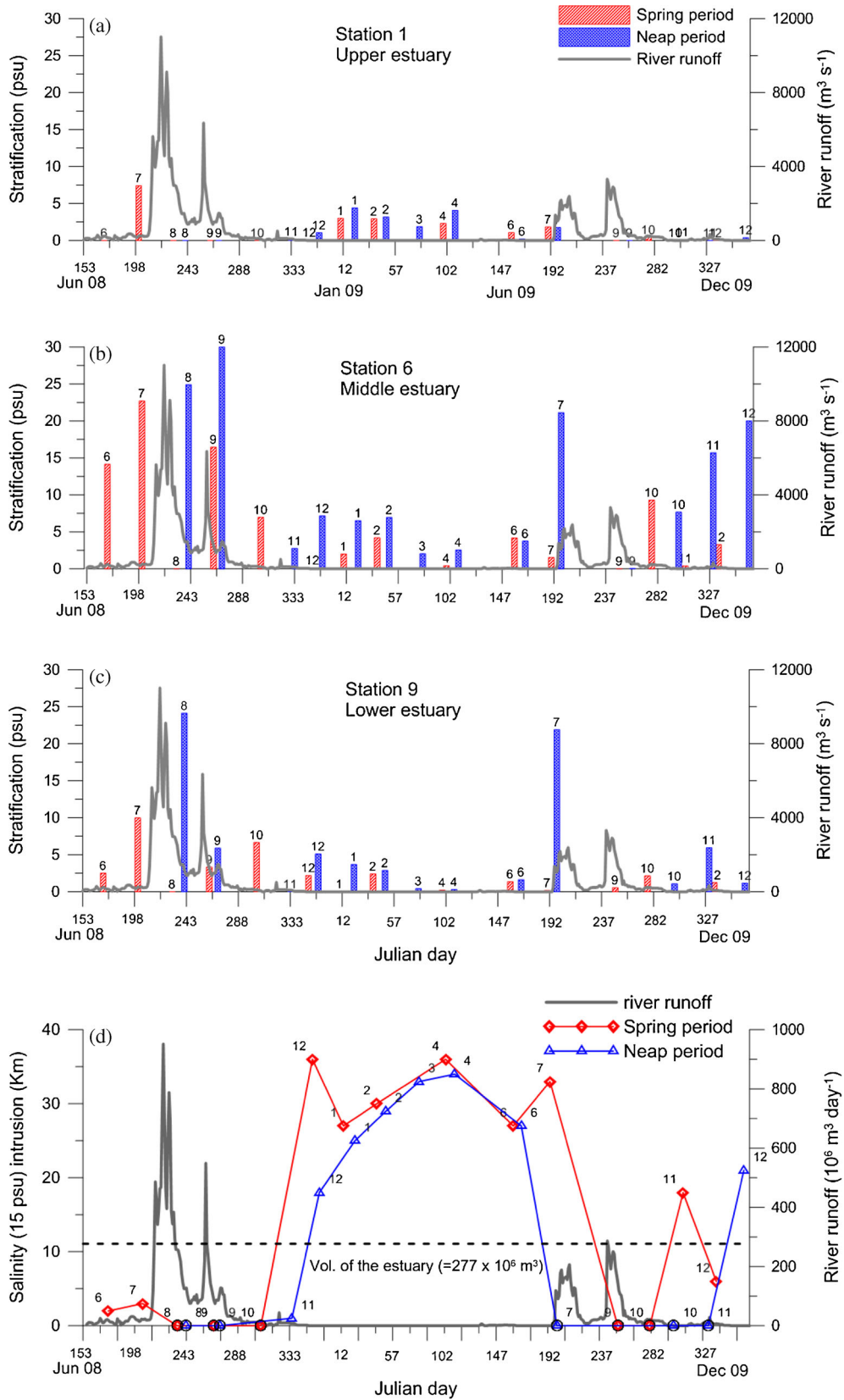Figure 3. Vertical spring–neap stratification of (**a**) upper (station 1), (**b**) middle (station 6), (**c**) lower (station 9) estuary and (**d**) intrusion of 15 psu salinity contour during spring and neap tides in the Godavari estuary on the left axis and river discharge on the right axis during the observational period. [Stratification was estimated as the difference between the top and bottom layer salinity; numbers on the top of each bar indicate the month in a year.]
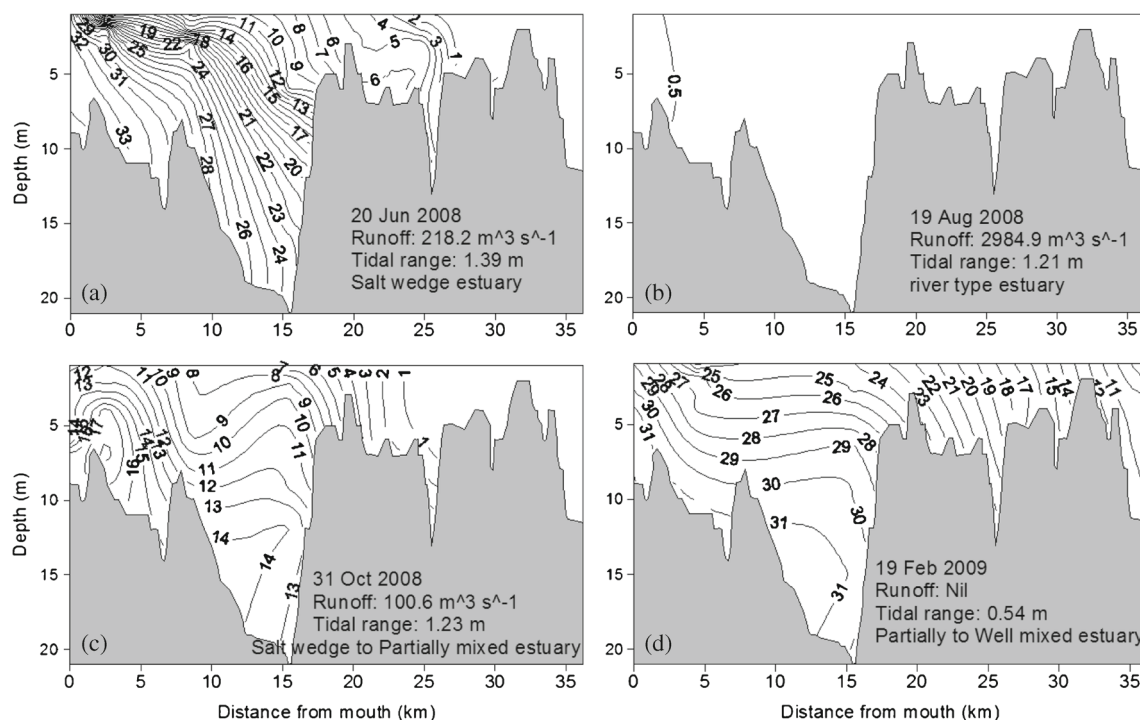
Figure 4. Along-channel sections of salinity in the Godavari estuary during (**a**) 20 June, 2008, (**b**) 19 August, 2008, (**c**) 31 October, 2008 and (**d**) 19 February, 2009.

Table 1. *Distribution of total salt content and flushing times of the Gautami–Godavari estuary.*

Sl. no.	Date	Tidal range (m)	River discharge (m³ s⁻¹)	Freshwater volume (10⁶ m³)	Total salt content (10⁶ m³ psu)	Flushing time (days)
1	20 Jun 2008 (S)	1.39**	218.2	144.0	2410.2	7.63
2	20 Jul 2008 (S)	1.30*	244.3	155.6	2005.3	7.37
3	19 Aug 2008 (S)	1.21**	2984.9	212.1	25.4	0.82
4	27 Aug 2008 (N)	0.57**	1474.7	202.4	364.4	1.59
5	20 Sep 2008 (S)	1.24*	1001.1	208.9	136.0	2.42
6	25 Sep 2008 (N)	0.72**	1232.6	188.6	849.7	1.77
7	31 Oct 2008 (S)	1.23*	100.6	173.3	1383.1	19.94
8	27 Nov 2008 (N)	0.98**	90.9	189.2	685.7	24.01
9	15 Dec 2008 (S)	1.21**	0.0	121.1	3214.9	8.6 ± 4.6
10	21 Dec 2008 (N)	0.74*	0.0	131.4	2853.2	14.1 ± 7.6
11	11 Jan 2009 (S)	1.31**	0.0	104.9	3781.9	8.0 ± 4.3
12	21 Jan 2009 (N)	0.69*	0.0	114.9	3429.6	15.1 ± 8.2
13	09 Feb 2009 (S)	1.03**	0.0	87.8	4379.6	10.1 ± 5.5
14	19 Feb 2009 (N)	0.54**	0.0	89.3	4327.5	19.3 ± 10.6
15	18 Mar 2009 (N)	0.53**	0.0	75.3	4819.1	19.7 ± 10.7
16	10 Apr 2009 (S)	1.34**	0.0	58.4	5408.6	7.8 ± 4.2
17	18 Apr 2009 (N)	0.41*	0.0	69.0	5039.1	25.4 ± 13.8
18	08 Jun 2009 (S)	1.10**	20.2	155.6	2005.3	9.5 ± 5.1
19	16 Jun 2009 (N)	0.70*	0.0	96.0	4309.4	14.9 ± 8.1
20	10 Jul 2009 (S)	1.19**	0.0	69.8	5010.8	8.8 ± 4.7
21	16 Jul 2009 (N)	0.57*	1288.8	170.7	1476.2	1.53
22	07 Sep 2009 (S)	1.35**	1717.5	212.3	17.6	1.43
23	05 Oct 2009 (S)	1.32**	251.9	184.9	981.3	8.49
24	26 Oct 2009 (N)	0.27*	2.3	165.6	1655.9	38.6 ± 20.9
25	25 Nov 2009 (N)	0.50*	120.3	188.6	849.6	18.14
26	02 Dec 2009 (S)	1.28**	79.3	163.8	1715.5	24.0
27	26 Dec 2009 (N)	0.81*	0.0	128.3	2959.0	12.9 ± 7.0

Note. S: Spring; N: Neap period; ∗∗: ebb and ∗: flood tide.

the mouth during December 2009 during spring tide, whereas it was found at 21 km during neap tide (figure 3d) due to discharge of freshwater (79.3 $m^3 s^{-1}$) during the former period.

3.3 *Flushing times and salt budget*

With the onset of ISM, the total salt content of the whole estuary decreased during wet period and increased during dry period. The lowest salt content ($25 \times 10^6 m^3$ psu) was noticed in the estuary during peak discharge period (19 August, 2008) which is <0.5% of the salt content estimated during dry period ($5409 \times 10^6 m^3$ psu on 10 April, 2009). The total salt content increased with the decrease in the discharge and displayed strong inverse correlation ($r^2 = 0.64$; $n = 27$; $p < 0.001$) (figure 6). It was further noticed that $\sim 400 \times 10^6 m^3$ psu more salt was added to the estuary during spring than neap tide in dry period.
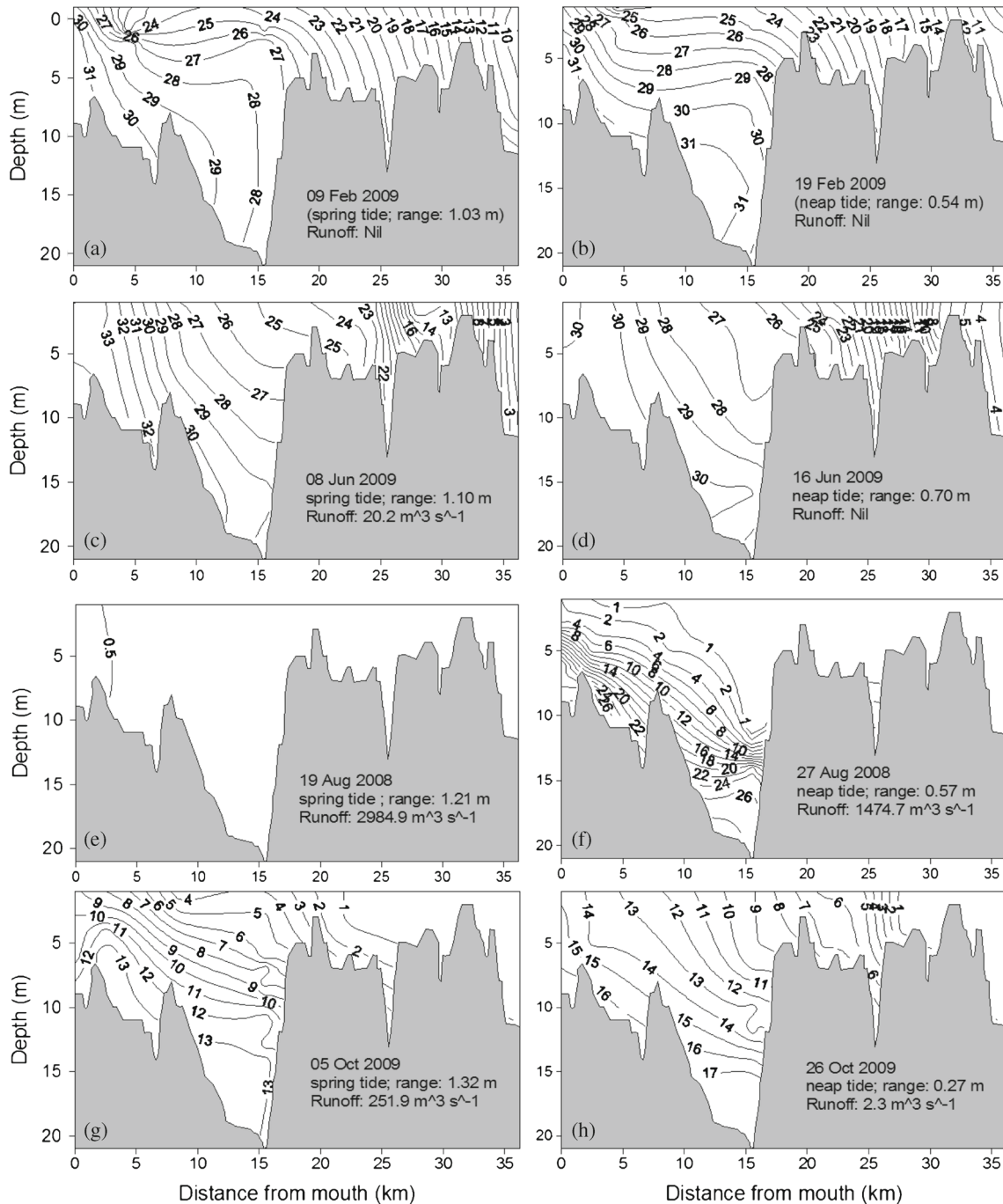

Figure 5. Along-channel sections of salinity in the Godavari estuary during spring tide (**a**, **c**, **e** and **g**) and neap tide (**b**, **d**, **f** and **h**) during February, June, August and October.
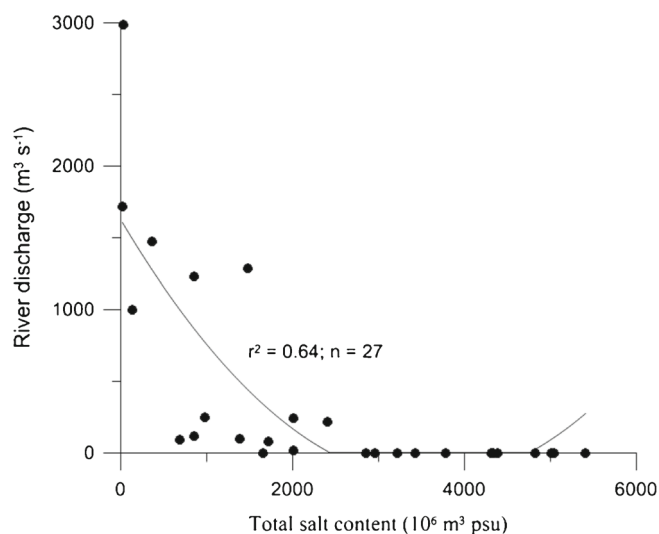
Figure 6. Correlation between river discharge and salt content in the Godavari estuary during the observation period.

Flushing times varied from less than a day to more than a month. To examine possible variations in flushing time through tidal prism method, it was computed at variable b values ranging from 0.2 to 0.8 and results are presented with mean and standard deviation in table 1. During peak discharge period (19 August, 2008), less than a day was sufficient to completely replace the water in the estuary with freshwater. Due to high discharge rates, the estuary was flushed several times more in 2008 than in 2009. With the decrease of discharge rates, flushing times increased and reached to more than a month (38.6 ± 20.9 days; for b is 0.2 to 0.8) at the lowest tidal range of 0.27 m (26 October, 2009; table 1). Relatively higher flushing rates, higher by ~6 days, were estimated during neap tide than spring tide.

4. Summary and discussion

The source of freshwater in the Godavari river is monsoonal precipitation over the Indian subcontinent during ISM. Therefore, the magnitude of discharge to the Godavari estuary is dependent on the intensity of ISM (Acharyya *et al.* 2012). In addition to this, several dams constructed over the Godavari river also control the freshwater discharge. Water is released from the dam, whenever the volume of water in the dam exceeds its capacity. Therefore, the river discharge into the estuary was rather controlled by not only precipitation but also by the dam authorities. The total annual discharge and peak discharge days in 2009 were much smaller than that in 2008 due to weaker monsoon over Indian subcontinent (www.imd.gov.in/doc/warm2009.pdf) during former than latter (Preethi *et al.* 2011). The intra- and inter-annual

variations in river discharge have significant impact on stratification of the estuary (figure 3).

Stratification slowly developed in July due to initiation of discharge. When the discharge reached its peak, it exceeded volume of the estuary ($>2.77 \times 10^8$ m^3) and the entire estuary was filled with freshwater and turned into a river with no vertical and horizontal salinity gradient. Such conditions usually occurred in August. Though peak ISM occurs in July in the west coast, there will be a time lag of about one month for peak discharge in the east coast rivers as it needs to fill the entire basin before it discharges to the estuary. Once the monsoon withdrew, discharge decreased ($<1.73 \times 10^8$ m^3 d^{-1}) and stratification developed both horizontally and vertically. During this period, the estuary turned to a partially mixed type and then gradually to a well mixed estuary during dry period (January–May) (figure 4) associated with termination of discharge. The asymmetry in salinity was noticed between the spring and neap tides (figures 3 and 5). The spatial and temporal variations in the stratification of the estuary were influenced by river discharge and tides during wet period, whereas tides alone governed during dry period.

The magnitude of the mixing and strength of the stratification during discharge or non-discharge conditions is determined by rate of change of water level, which varies for flood/ebb or spring/neap tide periods. During peak discharge period, spring–neap stratification variability was overwhelmed by variability in discharge. With the onset and withdrawal of the monsoon, stratification developed in the estuary with low saline water at the upper level and saline water at the bottom. High variability in stratification from spring to neap tide was observed in middle estuary where deep water column led to trapping of high saline water at the bottom. The salt water intruded up to 2–3 km more towards upper estuary during spring tide compared to neap tide during dry period due to high tidal amplitude during former than latter. The difference of mean salinities between spring and neap tides was ~2 psu up to 15 km from the mouth, then increased to ~5 psu between 15 and 30 km and decreased to 2 psu further upstream (>30 km). Shetye *et al.* (2007) reported that ~2 and 6 psu of vertical salinity difference was noticed during February in the Mandovi estuary. The position of 15 psu contour depended more on the discharge than tide during discharge period. After the withdrawal of monsoon, stratification increased (figure 4) and 15 psu isohaline intruded further upstream. The spring to neap salinity variability was large in the middle to upstream of the estuary, whereas it was similar to that of variations observed between ebb and flood tide at the mouth of the estuary (Acharyya 2012).

On an average, the estuary was saltier by $\sim$9% during spring than that of neap tide during entire study period (table 1). As the discharge began, the total salt in the estuary decreased during first week of June 2009, while salt content almost doubled in the second week as the discharge decreased to almost zero. In addition to tides, the lulls and peaks in the discharge influenced the total salt content in the estuary. It has been observed that $\sim$15% of more salt was noticed in April 2009 compared to April 1996 (Jyothi *et al.* 2000) and this decrease can be attributed to some amount of discharge that occurred during the latter period ($\sim$20 $m^3 \ s^{-1}$), while it was negligible during the former period.

Significant modification in bathymetry during recent years due to dredging activities in the estuary (section 2.2; figure 2b) increased salt intrusion to upstream estuary. In order to examine the recent changes, we had compared the salinity data collected during no discharge period of February 1987 (Ranga Rao 1991) with the data collected during February 2009 (figure 5a and b). It was noticed that salinity at the middle estuary region (station no. 6 in the present study) was 24 and 20 psu during high and low tides, respectively during February 1987 (Ranga Rao 1991) and the same was increased to 28 and 27 psu, respectively during ebb period of spring and neap tides in February 2009 (figure 5a and b). This suggests that recent change in bathymetry has resulted in an increase in salt content of the estuary and upstream region has become more salty during recent years. Reddy and Ranga Rao (1993) estimated a flushing time of $\sim$25 days during December when the average monthly discharge was 40 $m^3 \ s^{-1}$, while it was $\sim$16 days when monthly average discharge was 18 $m^3 \ s^{-1}$ during December 2009. Even though monthly discharge during December 2009 was less than earlier, lower flushing times during former period suggest the intrusion of more saline water during recent years due to dredging of the estuary.

In summary, this study suggests that intra-annual variations in the salinity of the estuary were related to monsoonal precipitation pattern in the watershed. Strong stratification was observed in the estuary associating with initial and withdrawal phase of discharge, while the entire estuary filled with freshwater with weak stratification during peak discharge period. Salt water intruded by 2–3 km further upstream during spring than neap tide resulting in $\sim$9% more saltier water during former than latter period. Modification in bathymetry of estuary during recent years enhanced salt content in the estuary and it may have significant impact on concentrations of nutrients and plankton biomass which may in turn influence food web structure. More integrated studies are required to examine how food web structure is changed in the Godavari estuary in recent years due to anthropogenic interventions.

Acknowledgements

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