Diurnal variation in salinity and currents in Vasishta Godavary estuary, east coast of India

Y V Ramana, V Ranga Rao & B S R Reddy
Department of Meteorology and Oceanography, Andhra University, Waltair 530 003, India
Received 30 March 1988; revised 28 November 1988

Distribution of salinities and currents in Vasishta branch of Godavari estuarine system, in relation to the fresh water discharge and tides has been studied in 3 representative months. In July, when the river discharge is very high, the estuary exhibits some characteristics of a salt wedge type. In September, when the river discharge is usually smaller compared to that during July, the estuary tends to become a partly mixed type while during February (river discharge being minimum) the estuary becomes a well mixed type. These features are well reflected in the hourly (for 12 h) observations of salinities and currents at the 3 selected stations and in the stratification—circulation diagram. Longitudinal exchange coefficients show a decreasing trend with decrease in the fresh water discharge and with the increase in the distance from the mouth upstream.

In an earlier study, variations in salinity, current and temperature in the Gautami branch of the Godavari estuarine system, east coast of India have been investigated. The present paper pertains to diurnal variations (12 h) of salinities and currents in the Vasishta branch of Godavari estuarine system. Current and salinity distribution within the estuary in relation to tide and fresh water discharge is discussed.

Materials and Methods

The study area (Fig. 1) is the lower most 25 km of the Vasishta Godavari branch, which opens into the Bay of Bengal at Antarvedi. The tidal influence, in general, is observed up to 25 km upstream from the mouth of the estuary with the tidal range of 1.5 m at the mouth of the estuary. The estuary has an average width of 500 m and depth of 10 m. The fresh water discharge is maximum during June to October because of southwest monsoon and is minimum during January to May.

Hourly observations (0600 to 1800 hrs, IST) of salinity and current over a full tidal cycle were made at each of the 3 stations (Fig. 1). The stations were fixed along the axis of the channel, where greater depths were encountered. July and September 1986 and February 1987 were selected for observations corresponding to different fresh water discharge conditions. Salinities and currents were measured at 2 m depth intervals from surface to 1 m above the bottom to obtain vertical profiles. The time of occurrence of high water and low water at each station and estuarine depths was studied.

Results and Discussion

Hourly observations of salinities and currents—July: During this month, the river discharge was very high (about 2,35,000 cusecs) into the estuary. For st 1 (Fig. 2a), salinity curves at the surface and intermediate depths coincided
Figs 2 and 3 – Salinity and velocity variations over a tidal cycle on (2) 21-23 July 1986 and (3) 21-23 September 1986 at st 1(a), st 2(b) and st 3(c)
with the zero axis since the estuary at this station was filled with fresh water both at surface and intermediate levels. Even at the bottom layers, the estuary was filled with fresh water at the time of low tide. Salinity at the bottom gradually increased during the flood period reaching a maximum of $14.8 \times 10^{-3}$ around the time of high water and decreased to zero during the succeeding ebb period. Ebb current dominated throughout the tidal cycle at the surface and at the intermediate levels (Fig. 2a). Weak flood currents were however, noticed at the bottom during flood period. At the surface as well as at the intermediate levels, the ebb currents were maximum at the mid ebb period (about 3 h after high water) while the currents were minimum around the mid flood period (about 3 h after low water). Maximum currents ($128 \text{ cm sec}^{-1}$) were observed at the surface during this month. The flood regime was noticed only at the bottom layers; the maximum flood current velocities being $10 \text{ cm sec}^{-1}$. Near the bottom, the change in the direction of the current from ebb to flood occurred around the time of low water and the change from flood to ebb took place 30 min after the occurrence of high water. These conditions clearly showed that the seawater penetrated into the estuary in the form of a thin saline wedge across the mouth.

At st 2 (Fig. 2b) the estuary was completely filled with fresh water from surface to bottom during the entire tidal cycle. Hence, only the distribution of currents is shown in Fig. 2b, along with the tide phase diagram. The flood regime was totally absent at all depths during the entire tidal cycle. This clearly showed the dominance of ebb flow at this station as a consequence of very high discharge into the river. At the surface, maximum current velocity ($135 \text{ cm sec}^{-1}$) was observed during mid ebb period while minimum ($68 \text{ cm sec}^{-1}$) was at the mid flood period. More or less similar variations in currents were observed at the intermediate depth during the tidal cycle. Even at the bottom, the currents were flowing towards the sea (ebb) during the entire tidal cycle, but the velocities were very small ($10$ to $30 \text{ cm sec}^{-1}$).

At st 3 (Fig. 2c), salinity was zero throughout the tidal cycle at all levels since the river was completely filled with fresh water from surface to bottom. Hence, the current variations only are shown in the figure along with the tide levels. The currents were fairly strong at all levels and the tidal influence was almost absent at this station.

On the whole, salinity and current variations in July reflect the following features. Excessive fresh water discharge into the river caused the predominance of ebb current at all stations. Current velocities were maximum at surface and decreased towards the bottom. The effect of tide was noticed only at st 1, where seawaters entered the estuary, making the waters somewhat saline at the bottom layers. At st 2 and 3 since they are away from the mouth, seawater was not encountered at any level.

September: The river discharge during this month was slightly less (about 37,500 cusecs) into the estuary. At st 1 saline waters mixed with the river water to varying degree at all levels from surface to bottom (Fig. 3a). An increase of salinity from surface to bottom was generally noticed. At the surface, salinity gradually increased during flood period reaching a maximum of $13 \times 10^{-3}$ around high water time and decreased to zero around the mid ebb period. At intermediate level, maximum salinity of $20 \times 10^{-3}$ was observed 30 min after the occurrence of high water, which decreased to $12 \times 10^{-3}$ during ebb period. At the bottom layers variations in salinity were generally less (maximum $22 \times 10^{-3}$ at high water time and $14 \times 10^{-3}$ around low water time). Salinities at all depths were greater than those observed in July. Current distribution at st 1 showed that the flood regime was also well developed during this month but was still not as dominant as the ebb regime. The flood regime persisted for a longer time at the bottom, compared to the ebb regime. Compared to July, ebb current velocities during this month were generally low at the 3 levels but the flood currents at the bottom were slightly high. These observations indicated partially mixed conditions in the estuary at this station during September.

At st 2 (Fig. 3b), the estuary was filled with fresh water near the surface during all phases of tide. Seawater reached this station through the subsurface layers. At intermediate level, salinity increased during flood tide from zero and attained a maximum of $14.8 \times 10^{-3}$ at the time of high water. Thereafter, salinity decreased rather sharply and attained zero value at about 3 h after the occurrence of high water. At the bottom, salinity started increasing at about 1 h before the occurrence of low water, reached a maximum value of $19.8 \times 10^{-3}$ at 30 min after the occurrence of high water and again decreased gradually during ebb period. The flow at the surface was always directed towards sea over the entire tidal cycle. The ebb current velocities were greater compared to the flood velocities. At the bottom layers, there was a clear domination of the flood regime over...
the ebb regime; the flood current persisted for about 7 h, while the ebb current lasted for the rest of the period in the tidal cycle. At the bottom maximum current observed during both ebb and flood was 26 cm sec⁻¹.

At st 3 (Fig. 3c), the estuary was completely occupied with fresh water throughout the tidal cycle. The flow at all levels was directed towards the sea.

Salinity and current variations during September reveal the following features: At st 1, seawater entered the estuary during the flood period and mixed with the river waters bringing about hourly variations in salinity with the tide at all levels. At st 2, saline waters were encountered only at subsurface layers while at surface it was filled with fresh water. This is due to the predominant effect of ebb regime at the surface due to fresh water discharge. At st 3, fresh water discharge was clearly seen and the tidal influence was negligible. The ebb regime dominated from top to bottom at this station. Similar features were reported earlier in Mandovi⁴ and Zuari³ estuaries.

February: The river discharge was negligible during this month and no fresh water was discharged into the estuary. Salinity and current variations with tide were clearly reflected during this month (Fig. 4). Salinity variations at intermediate and bottom levels were more or less similar at st 1 (Fig. 4a). Salinity difference between surface and bottom was very small compared to that during September. The surface to bottom salinity difference was minimum at the mid flood period when the flood currents were fairly strong. But this difference was somewhat high at both high water time and low water time. The same feature was also observed in the narrows of the Mersey estuary⁴. During this month the salinities at all levels were very high compared to those observed in July and September. The currents at all levels at st 1 appeared to be controlled totally by the tide (Fig. 4a) and the current variations were almost in phase with the tide. Maximum ebb currents (46 cm sec⁻¹) were observed at the intermediate level. The flood currents both at the surface and at the bottom were relatively weak. Similar observations were made earlier in Gautami Godavari¹,² estuary.

Salinity and velocity variations at sts 2 and 3 (Fig. 4b and c) exhibit more or less the same features as those observed at st 1. But the salinity values showed a decreasing trend as one moves from st 1 to st 3. Change in the direction of currents took place at all levels, a feature that was not existed for st 2 during July and September.

At st 3, maximum salinities were 10.8 x 10⁻³ and 11.4 x 10⁻³, respectively at surface and bottom. Maximum ebb current velocity of 46 cm sec⁻¹ and a maximum flood current of 36 cm sec⁻¹ were observed at the surface. At the bottom, currents were generally weak due to the effect of bottom friction.

In February, the effect of tide was noticed even at st 3 situated about 25 km, upstream from the mouth of the estuary. Well mixed conditions were encountered at all stations and the surface to bottom salinity difference was quite small. Strong flood currents were encountered at intermediate

Fig. 4 - Salinity and velocity variations over a tidal cycle on 18-20 Feb. 1987 at st 1 (a), st 2 (b) and st 3 (c)
level while strong ebb currents were observed in surface layers. The effect of bottom friction in reducing the current velocities at the bottom is clearly seen.

Classification of estuary using stratification-circulation diagram—Based on measurements of salinity and current velocity, the Vasishta Godavari estuary has been classified into different types using the method developed by Hansen and Ratray. Two dimensionless parameters to characterise estuaries—(i) a stratification parameter $\delta s/s_0$, ratio of surface to bottom difference in salinity ($\delta s$) divided by mean cross-sectional salinity ($s_0$) and (ii) a circulation parameter $(U_s/U_r)$, ratio of net surface current ($U_s$) to mean cross-sectional velocity ($U_r$)—have been used. The values of the above parameters have been evaluated for different months at the 3 stations and located in the stratification-circulation diagram (Fig. 5).

In July, st 1 fell in type 4, representing salt wedge type with intense stratification. Sts 2 and 3 were completely filled with fresh water at all levels and hence did not appear in the stratification-circulation diagram. In September, st 1 fell in type 2b (partly mixed type with considerable stratification). St 2 fell in between type 4 and type 2b indicating that the estuary at this station was tending towards partly mixed type from the salt wedge type. St 3 was completely occupied with fresh water and hence did not appear on the diagram. In February, all 3 stations fell in type 1a, representing well mixed conditions.

Flushing rates and longitudinal exchange coefficients of the estuary were also calculated for the 3 representative months based on all the data collected.

The flushing rate, which represents the rate at which the total volume of the water in the estuary is exchanged, was calculated using a simple relation:

$$\text{Flushing rate} = \frac{R}{\bar{f}}$$

where $R$ = river run off flow and $\bar{f}$ = average fraction of fresh water in the estuary. Fresh water fraction ($f$) at a given location is given by:

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

where $S_0$ = normal ocean salinity of the coastal waters into which the estuary empties and $s$ = salinity at that particular location.

The flushing rates, estimated from the observed data were 5611, 1234 and 87 m$^3$ sec$^{-1}$ respectively for July, September and February. The effect of river discharge is thus clearly reflected in the flushing rate values for different months.

Longitudinal exchange coefficients which are also very important in understanding the characteristics of an estuary were calculated. The exchange coefficient was very large at st 1 during July when the fresh water discharge is very high (Table 1). The coefficient decreased with the decrease in river discharge and was minimum in February. The exchange coefficients showed a decreasing trend from the mouth upstream. Similar features have been reported earlier from Yaquina, TaylO and Potomac estuaries.

Acknowledgement

The authors (Y V R & V R R) express their sincere gratitude to the CSIR, New Delhi for the award of research fellowships during the period of this study.

References

RAMANA et al.: DIURNAL VARIATION IN SALINITY & CURRENTS

7 Officer C B, Physical Oceanography of estuaries, (John Wiley & Sons, USA) 1976, 158.