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Estuarine characteristics of lower Krishna river

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Present study consist the spatial and temporal variations of depth, temperature and salinity, currents, flushing times and classification of the Krishna estuary. Temperature exhibited a distinct seasonal variation with higher values in premonsoon (30.0±0.09°C) and monsoon (29.2±0.08°C) seasons compared to that of winter (26.6±0.06°C). Salinity and current pattrns shows distinct seasonal and spatial variations noticed. Changes in hydrodynamic conditions infers that the river mouth as a positive type of estuary. Flushing times varied with seasons and locations due to changes in river discharges and circulation pattern. Considering the two dimensional Hansen and Rattray's stratification and circulation diagram, the estuary has been classified as partially mixed with no stratification type during postmonsoon and stratified during monsoon and premonsoon seasons.

[**Keywords:** Krishna estuary, flushing times, stratification, circulation, salinity, currents]

Introduction

Estuaries are constituents of coastal zone and are highly dynamic with respect to physical, chemical, biological and geological processes. Physical processes in estuaries namely the mixing, circulation and transport control the transfer of materials and hence studies on these processes help understanding the exchange of materials in the estuaries. Krishna estuary, one of the estuaries in the east coast of India has been least studied on physical[1], and biological processes[2-4] though several reports are available on geochemical[5-10] geomorphological[11-14] and geological studies[15-19]. The present study consist the flushing time scales and the classification of Krishna estuary.

Materials and Methods

Seasonal synoptic field observations of vertical profiles of temperature, salinity and currents were made at 9 stations along three cross-sections, 1, 2 and 3 of the estuary (Fig. 1) during premonsoon (May' 99), monsoon (Sep' 9) and postmonsoon (Feb' 2000). Depth profiles along the Krishna estuary channel were measured with the help of Digital Depth Sounder (Hondex, Japan make, 1 cm resolution, 1-79 metres range) for every 250 m along the channel course and every 15 m across the channel. Based on these measurements, three Stations 1, 2 & 3 with three sub-stations (A, B, C) in each station were selected along the main distributary of the Krishna estuary for sampling of water as shown in the Fig. 1. Water sampling was done at surface, 0.20, 0.60 and 0.80 depths. The water sampler designed and described by Ramkum and Pattabhi Ramayya[20] or a horizontal water sampler has been used to collect water sample. Water samples were collected in three months namely May, 1999 (Premonsoon), September, 1999 (monsoon) and February, 2000 (postmonsoon). Sampling was done for every six hours starting with lowest low tide for two complete tidal cycles (Le., four times of sampling from each location). At

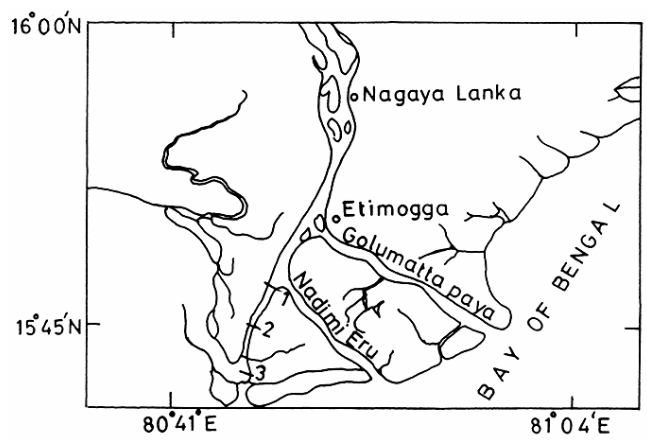

Fig. 1—Krishna estuary station locations

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each of the sampling location, each time, depth (Digital Depth Sounder) and current speed (EMCON make current meter, 0.1 cm sec^{-1} accuracy) were noted . Temperature was measured on board the boat using temperature probe in a J,JP Based water analyzer kit (Mode: CMK 731), the accuracy in the measurement of temperature being +/- 0.1°C in the range -100°C to + 200°C. Sensitive thermometer (0.1°C) was used to calibrate the probe. Salinity was measured on board the boat using salinometer in a µP Based water analyzer kit (Model: CMK 731) after calibration. The accuracy in the measurement of salinity is +/- 0.5 of the range +/- 1 digit. The values from these measurements were verified by standard Grasshoff method[21].

Results and Discussions

Depth

Cross-sectional profiles of tidal mean depths at stations 1, 2 & 3 along the main branch of Krishna river estuary (for May, September and February representing premonsoon, monsoon and postmonsoon conditions) are presented in Fig. 2. In premonsoon, water depths gradually decreased as one goes downstream i.e. from station 1 to station 3. Maximum depths of 5.7 m at station 1 Band 3.2 m at station 3B were noticed. The shallow depths at station 3 are attributed to sediment deposition associated with the formation of sand bar at the confluence.

There are considerable seasonal variation in depth though the measurements were done in identical tidal range. Greater depths was noticed in premonsoon (May) compared to that of monsoon (September) and postmonsoon (February) seasons. This may be due to possible occurrence of high sea level in the month of May along the coast[22]. The deepening of depth also may be due to erosion of bottom sediments caused by prevailing strong tidal currents under low upland fresh water discharge[1]. Huge quantities of sediments from the river discharge settle to the bottom at the time of high tide when the currents attain low speed. Further, the flood current transports sediments into the river due to northerly littoral currents during monsoon and postmonsoon months. This type of sediment transportation deposits silt at the bottom and decreases the depth.

In premonsoon, the sub-station B in all the three cross-sections (1, 2 & 3) occupied greater depths, indicating the menace of a deeper channel running along the middle portion of the estuary. However, in monsoon and postmonsoon, sub-station A in all the three cross-sections occupied greater depths indicating the shift in deeper channel now running along the left bank of the estuary. The seasonal migration of deeper portion and the deepening of the estuary may be due to seasonal variation in sediment transport into the estuary associated with tidal circulation patterns and interaction of fresh water discharge from landward and tidal propagation from seaward directions.

Depth variations over a tidal cycle at stations 1 J 2 and 3 for premonsoon, monsoon and postmonsoon are shown in Fig. 3. These variations (at all stations in all three seasons) are in synchronous with the variation of tidal phase Le. the depth increased during rising tide and decreased during falling tide. However, in premonsoon the variations of depth at sub-stations 1 A and 2A have not *n* synchronous with tidal phase. This may be due to development of some sort of secondary circulation at these stations i.e. occurrence

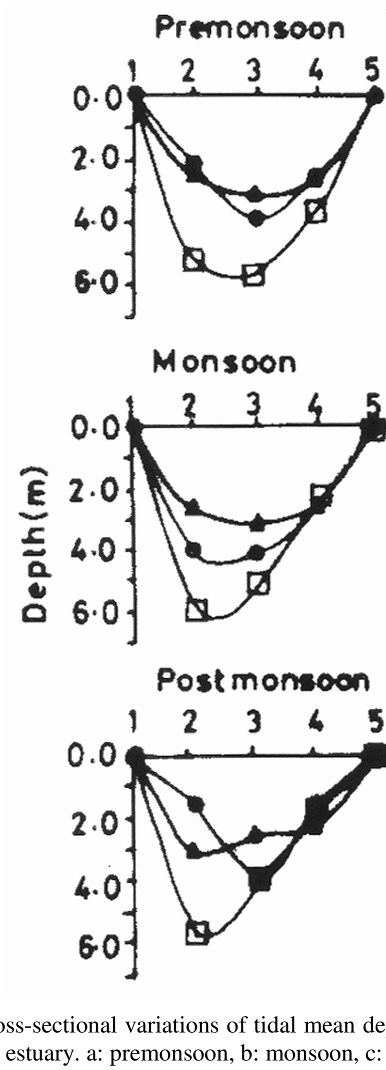

Fig. 2—Cross-sectional variations of tidal mean depths (m) along the Krishna estuary. a: premonsoon, b: monsoon, c: postmonsoon

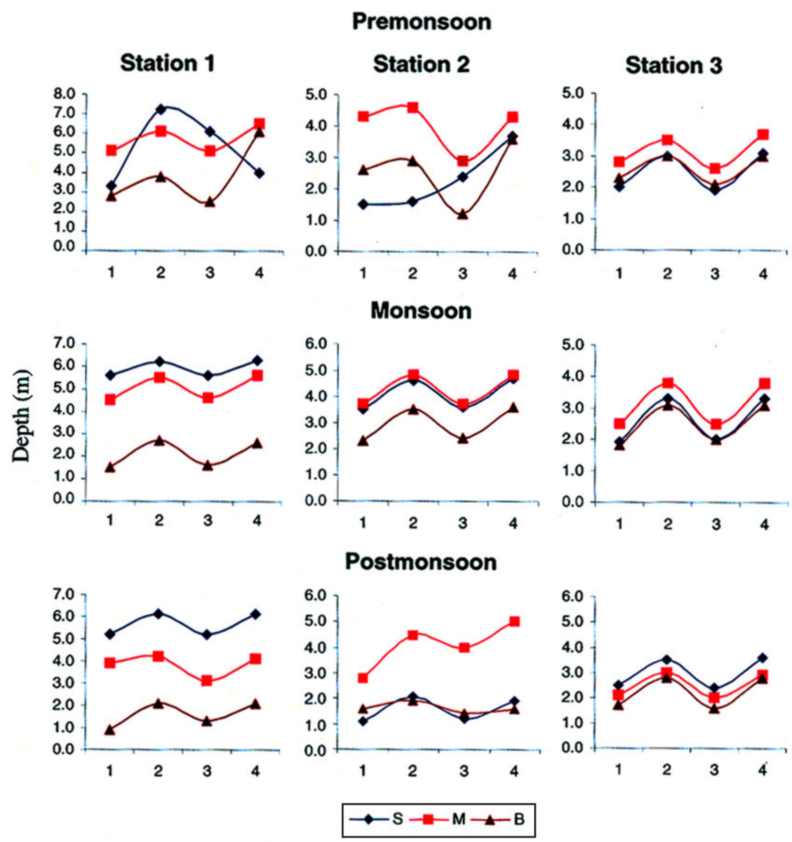

Fig. 3—Tidal variation of depth in the Krishna estuary at different sections during three seasons. 1 & 3 - low tide, 2 & 4 - high tide

of possible seaward flow along the left bank between stations 1A and 2A (Fig. 3).

Krishna Rao *et al.*[15] while studying mineralogical and geochemical aspects of Krishna estuary observed that it was a shallow one with a mean depth of 5.6 m. Higher depths during May and at the middle sub-station (8) compared to monsoon (September) and winter (February) months might be due to the erosion of bottom sediments by prevailing currents as explained by Ramanadham and Varadarajulu[1]. Further during this period (May) the flood and ebb currents are oscillatory when unconsolidated sediments are transported to and fro along with the currents. Strong currents are able to erode the unconsolidated bottom and transport the sediment to the sea. During monsoon and winter months huge quantities of sediments brought by the river discharge settle to the bottom at the time of high tide when the currents attain low speed. These variations in bottom topography indicate the characteristics of a bar-built estuary with low depths (2.Q-3.4 m) at the confluence (station 3) and with increasing depth upstream.

Temperature

The overall temperature in the Krishna estuarine region decreased (Fig. 4) from May (30.0 ± 0.09°C), to September (29.2 ± 0.08°C) and to February (26.6 ± 0.06°C). These seasonal changes in temperature due to seasonal variation are relatively low in the Krishna estuary (~4°C) compared to other tropical estuaries (8°C). Rivers are usually cooler than the coastal waters in winter and warmer in summer. A slight fall in temperature (0.3-0.5°C) has been noticed from the mouth upstream along the estuarine system throughout the year. This may be because of warmer coastal atmospheric temperature and comparatively cooler conditions at inland regions. In addition, the presence of anthropogenic agrochemical constituents and the influence of ionic strength from the head to mouth may result in the increase of heat retention capacity of the estuarine waters.

Salinity

Salinity in the lower reaches of the Krishna estuary exhibited a marked decrease of ~14.0 from May

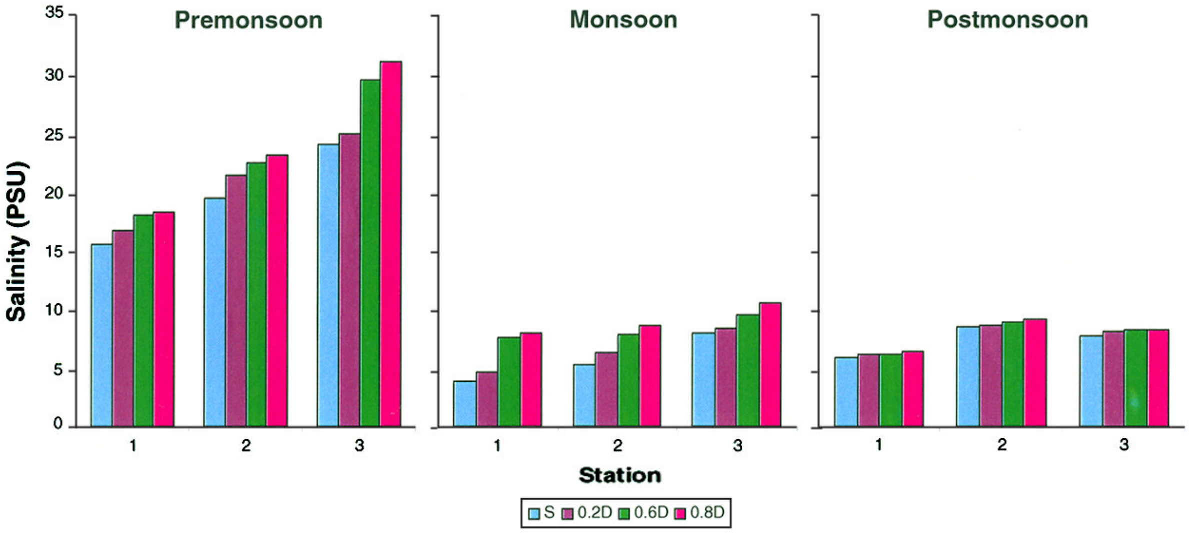

Fig. 4—Distribution of salinity (PSU) in the Krishna estuary. a - premonsoon, b - monsoon, c - postmonsoon

(13.3 - 33.2, 22.0 ± 0.8) to September, (2.6 - 12.4,7.3 ± 0.3) and then a light increase of 0.4 to February (4.1 - 13.4 7.7 ± 0.4). Further, the overall salinity recorded a wide variation from 2.6 in monsoon to 33.0 in pre-monsoon. Such seasonal variations in salinity of tropical Indian estuaries[23] are common because of monsoon and drought! summer conditions representing two extreme situations affecting estuarine environments in dramatically opposite directions[24]. During summer, salinity attains its maximum values within the entire estuary dominated by neritic waters while in rainy season, the whole estuary is dominated by fluvial waters of very low salinity.

Salinity increases in a normal trend from head to mouth of the estuary in all the seasons indicating positive nature of the estuary which represents the dilution of seawater by fresh water because of the dominance of precipitation and runoff over evaporation. Ramanadham and Varadarajulu[1] reported higher values of salinity in the range of 35.5 to 35.9 in the upstream in May 1971 compared to those of the mouth (35.0) with a difference of 0.4 in Krishna estuary and opined that decreasing salinity from head to mouth need not be taken into consideration to classify the estuary as negative.

Salinity values increased from surface to bottom at all the stations during the three seasons. Invariably bottom water was more saline than surface water and the differences were highly pronounced at station 1 (Fig. 4) with a significant variation in vertical gradation (2.7-7.0). The vertical gradients in May increase from station 1 (2.7) to station 3 (7.0) due to very low river discharges and partial stratification of bottom waters. During monsoon, though there is a vertical increase in salinity in all the stations, the gradients decrease from station 1 (4.1) to station 3 (2.6). In postmonsoon, the salinity clearly shows that the vertical variation of salinity is very low with decreasing trend from head to mouth.

Currents and circulation

Synoptic pictures of tidal mean currents for surface, mid-depth and bottom levels for premonsoon, monsoon and postmonsoon are shown in Fig. 5. In premonsoon, most of the surface flow was directed seaward in the left portion of the channel. However, at mid-depth and bottom, most of the flow directed landward in the right portion. In Monsoon season, the seaward flow was almost negligible; the landward flow dominated the entire estuary from surface to bottom except close to right bank at mid-depth and bottom levels. In postmonsoon also, the landward flow dominates from surface to bottom except at upstream end. Tidal mean currents over a cross-section at stations 1, 2 and 3 for premonsoon, monsoon and postmonsoon are shown in Fig. 6.

Premonsoon: At all the three cross-sections (stations 1, 2 & 3) the landward flow occupied the right portion while the seaward flow occupied the left portion of the channel. The seaward flow was directed mostly in surface layers and land ward flow mostly in deeper layers. Higher strengths (10-18 cm.sec^{-1}) of landward flow in deeper levels and higher strengths

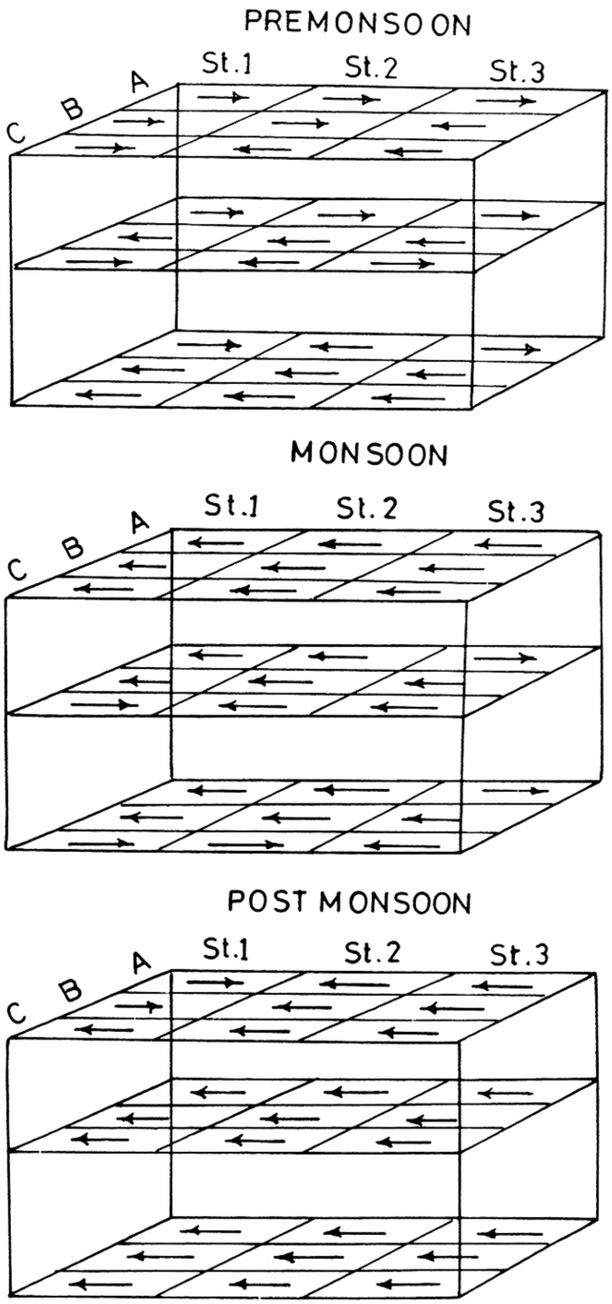

Fig. 5—Synoptic diagram of tidal mean currents in Krishna estuary during three seasons

(20-23 cm.sec^{-1}) of seaward flow in surface levels was noticed.

Monsoon: At all stations, the landward flow occupied the middle portion of the channel while the seaward flow occupied the boundary regions (i.e. close to left and right banks). Further, the landward flow was dominant over the seaward flow at all the three stations (landward strengths of 28-45 cm.sec^{-1} and seaward strengths of 7-11 cm.sec^{-1}.

Postmonsoon: The seaward flow is noticed only in the surface levels at upstream end i.e. close to left bank at station 1 while at other stations the landward flow occupied from surface to bottom. In this season also, the landward flow is overwhelmingly dominant over the seaward flow at all stations. This is evident from higher strengths (77 cm.sec^{-1} at station 3 & 37 cm.sec^{-1} at station 1) of landward flow and higher strengths (7 cm.sec^{-1}) of seaward flow.

On the whole a reversal type of circulation (seaward flow along left bank and landward flow along right bank) is noticed in May (premonsoon), and a dominant landward flow in September (monsoon) and December (postmonsoon) were noticed in the study region.

Flushing time scales

In estuarine environments the flushing and mixing of seawater and fresh water are mainly activated by tidal currents and fresh water discharge. An overall view of the mixing properties of an estuary can be assessed based on the methods which provide estimates of the flushing time of an estuary as a whole or a portion of it. The relevant time scales of mixing and flushing can be obtained by using the steady state one-dimensional approach in which the distribution of properties along the length and breadth of the estuary is considered taking only averages over each cross section.

Flushing time is the time required to replace the fresh water in the estuary at a rate equal to the river discharge which can be computed by fraction of fresh water method[25-27]. In this simplest method of estimation of flushing time, fresh water is used as a tracer and it is assumed that it is being removed by flushing at the same rate as it is being added by river discharge. The flushing time 'T' is given by

$$T = F/R \qquad 1.1$$

where R is the rate of influx of fresh water, and F is the total volume of fresh water accumulated in the estuary. If S is the salinity at any point within the estuary, and S_o is the salinity of the undiluted sea water which is available for mixing, then the fraction of fresh water content at that point is given by

$$f = \frac{S_o - S}{S_o} \qquad 1.2$$

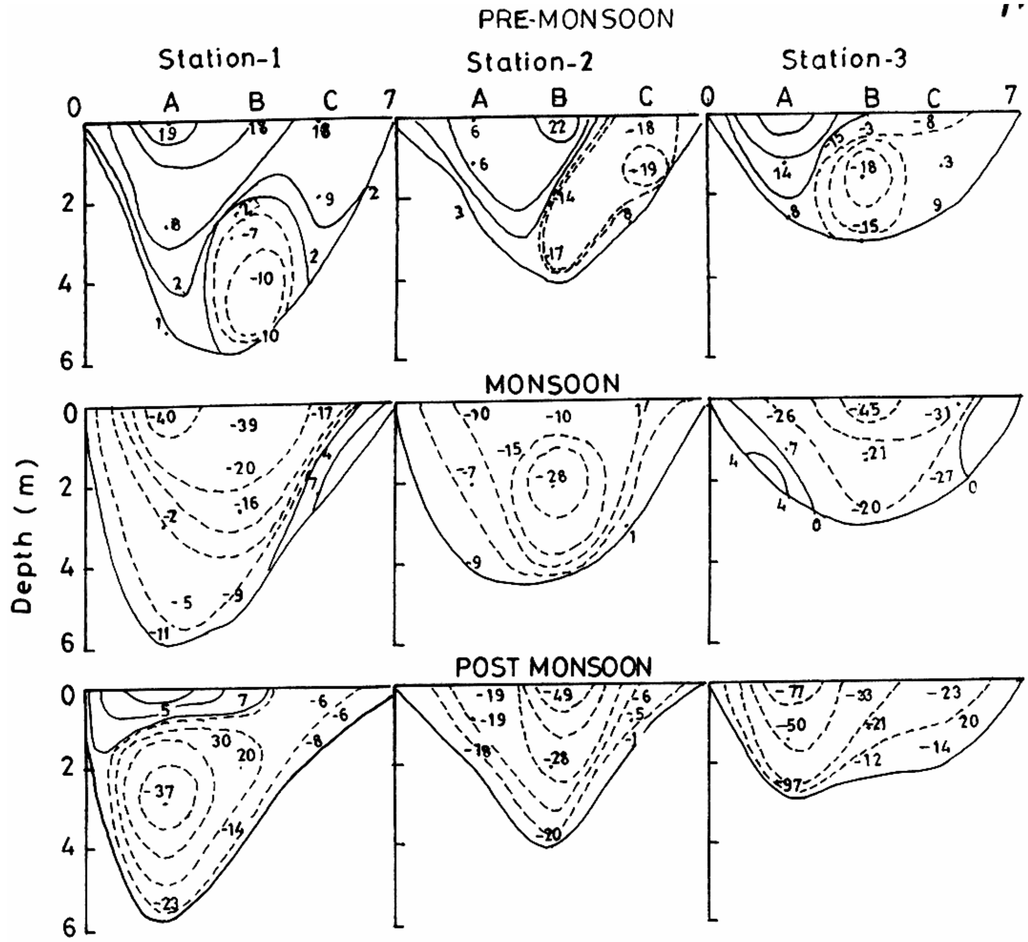

Fig. 6—Cross-sectional circulation in Krishna estuary

To determine F, the estuary is divided into a suitable number of elements of volume σV and the appropriate value of 'f assigned to each element. The total fresh water content is given by

$$F = \Sigma f\delta V \qquad 1.3$$

where the summation is carried out over the total volume V.

The flushing times and relevant data of segment salinity, fresh water fraction (f) in terms of salinity (S) calculated for three seasons using the formula 1.2, and river discharge are incorporated in the Table 1 and Fig. 7. The freshwater fraction, 'f' increases towards the head of the estuary in all the seasons and high values were observed during monsoon with high river discharge compared to premonsoon with low river discharge. The increased river flow causes both a downstream movement of the salinity intrusion and a more rapid circulation of water. Thus increased river discharge is accompanied by a more rapid exchange

Table 1—Flushing times in Krishna estuary

Estuary Segment	S	F	V	F×V	R	T
PREMONSOON						
1-2	19.35	0.447	9.306	4.161	0.93	4.47
2-3	24.45	0.301	11.473	3.458	0.93	3.71
3-M	30.5	0.129	9.594	1.233	0.93	1.33
Total						9.51
MONSOON						
1-2	6.5	0.814	8.295	6.755	8.82	0.77
2-3	8.05	0.770	14.553	11.206	8.82	1.27
3-M	10.05	0.713	9.594	6.839	8.82	0.78
Total						2.82
POSTMONSOON						
1-2	7.5	0.786	7.018	5.514	0.53	10.41
2-3	8.4	0.760	9.240	7.022	0.53	13.25
3-M	10.75	0.693	8.904	6.169	0.53	11.64
Total						35.30

S-Segment Salinity, f-Fresh water fraction, V-Segment volume ($m^3 \times 10^6$) R-River discharge ($m^3 \times 10^6$ per tidal cycle), T-Flushing time (tidal cycles)

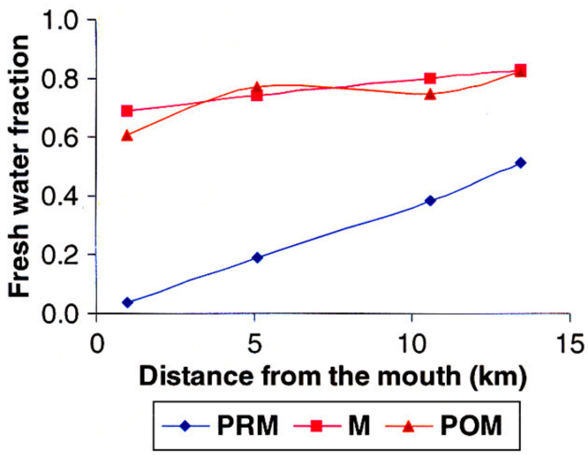

Fig. 7—Distribution of fresh water fraction during different seasons. PRM -Premonsoon, M - Monsoon, POM - Postmonsoon

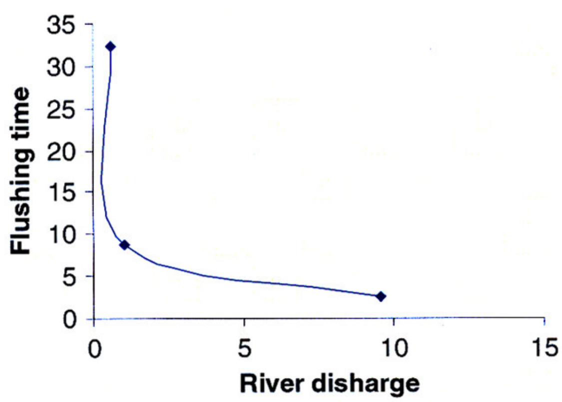

Fig. 8—Variation of flushing time (tidal cycles) with river discharge ($\times 10^6 m^3$/tidal cycles)

of freshwater with the sea, the volume of freshwater accumulated in the estuary increasing to a lesser extent than does the discharge[28] Low 'f' values during premonsoon are an indication of low river discharge and dominant upward seawater movement.

Variation of flushing time scales with river discharges in different seasons is shown in Fig. 8 which indicates an inverse relationship. The total flushing time showed an increasing trend from 2.82 in monsoon to 9.51 in premonsoon and to 35.30 tidal cycles in postmonsoon. Lower flushing time scales in monsoon in spite of partial mixing conditions may be due to very large fresh water discharge leading to easy flushing out in the estuary. High flushing time scales during postmonsoon and premonsoon may be due to low river discharges, tide dominant currents and/or prevailing stratification conditions in the estuary.

Classification of Krishna estuary

Hansen and Rattray[9] proposed a two parameter stratification-circulation diagram considering the two dimensionless parameters namely stratification parameter, $\delta S/S_o$, (where δS is the difference in salinity between surface and bottom and S_o is the depth mean salinity, both averaged over a tidal cycle) as the ordinate and the circulation parameter U_s/U_f, (where U_s is the surface velocity averaged over a tidal cycle and U_f is the discharge velocity that is the rate of river discharge divided by the cross-sectional area) as abscissa. Based on the observations of salinity and currents made in the Krishna estuary and considering river discharge data, the values of $\delta S/S_o$ and U_s/U_f were calculated and presented in Table 2. The Hansen

Table 2—Classification of Krishna estuary

Station	ΔS (PSU)	S_o (PSU)	Us ($cm.sec^{-1}$)	U_f ($cm.sec^{-1}$)	$\delta S/S_o$	U_s/U_f
			PREMONSOON			
1	2.8	17.1	13.3	2	0.16	6.7
2	3.7	21.6	3.3	3	0.17	1.1
3	7.1	27.3	4.0	3	0.26	1.3
			MONSOON			
1	4.2	6.0	32.0	21	0.70	1.5
2	3.4	7.0	10.7	23	0.49	0.5
3	2.6	9.1	34.3	33	0.29	1.0
			POSTMONSOON			
1	0.4	6.2	2.0	2	0.06	1.0
2	0.6	8.8	25.3	2	0.07	12.7
3	0.4	8.0	44.3	2	0.05	22.2

ΔS – difference in salinity between surface and bottom, S_O – depth mean salinity, both averaged over a tidal cycle, U_S – surface velocity averaged over a tidal cycle, U_f – discharge velocity, $\delta S/S_o$ – stratification parameter, U_s/U_f – circulation parameter

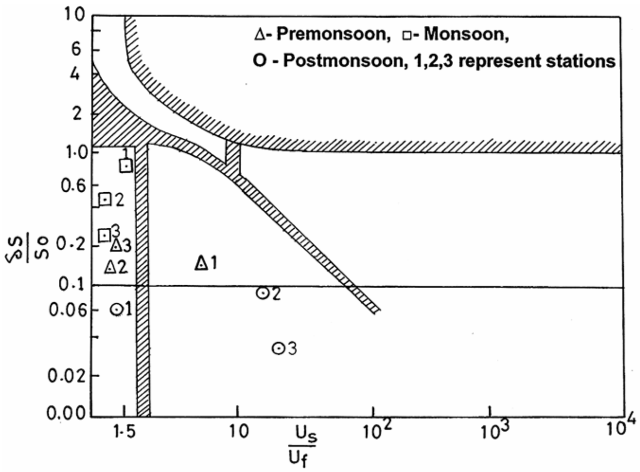

Fig. 9—Classification diagram for Krishna estuary

and Rattray's stratification-circulation diagram constructed for the Krishna estuary is given in the Fig. 9. Plotting the points (Us/Uf, $\delta S/S_o$) for different stations during three seasons. The values of stratification parameters $\delta S/S_o$) are very low in the entire estuary during postmonsoon with $\delta S/S_o < 0.1$ indicating 'a' type sub-division with very little stratification. On the other hand, high values ($\delta S/S_o > 0.1$) during premonsoon and monsoon seasons in the entire estuary indicate 'b' type sub-division with appreciable stratification. Low values of circulation parameter ($U_s/U_f < 2$) in the entire estuary during monsoon and at stations 2 and 3 during premonsoon indicate type 1 estuary with well mixed conditions. On the other hand, station 1 during premonsoon and stations 2 and 3 during postmonsoon recorded U_s/U_f values in the range 2-10 and 10-100 respectively indicating type 2 estuary with reversal of net flow at depth and contribution of both advection and diffusion to the upstream salt flux. Thus, Krishna estuary exhibited different types of estuarine conditions at different stations during different seasons as noted in the Fig. 1. Based on this the Krishna estuary can be considered as partially mixed type with no stratification during postmonsoon and stratified during monsoon and premonsoon seasons.

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