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Suspended sediment dynamics in Krishna estuary, east coast of India

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Distribution and flux of suspended sediments and turbidity in the Krishna estuary were examined. TSM showed an increasing trend from head to mouth. A vertical gradient in TSM, increasing from surface to bottom prevails at all stations in monsoon. Distribution of TSM in tidal cycle shows relatively high load during high tide indicating the dominance of saline water. Turbidity exhibited relatively high values in monsoon and low values in premonsoon and postmonsoon. Horizontal variation of turbidity closely resembles that of TSM with an increasing trend from head (st. 1) to mouth (st. 3) of the estuary. Turbidity maximum, noticed with different intensities in all seasons. This was due to gravitational residual circulation and settling and resuspension processes of the fine sediment. The spatial distribution of turbidity resembles that of TSM in all seasons. Minor deviations observed in the distribution of turbidity from that of TSM were attributed to the differences in nature, particle size and shape of TSM.

[**Keywords:** TSM, turbidity, Krishna estuary, Bay of Bengal]

Introduction

Indian rivers, from about 7% global area, contribute about 6% of the global mass transfer to the ocean across the land ocean boundary[1]. Indian rivers in mountainous terrain carry higher amounts of suspended load while the rivers in plain areas carry dissolved loads predominantly[2]. Indian rivers transport nearly[3,4,5] 1.2×10^{12} kg y^{-1} or 2.873×10^{12} kg y^{-1} of suspended load into the ocean out of 8×10^{12} kg y^{-1} or 16×10^{12} kg y^{-1} of global estimate[6]. The distribution of suspended particulate matter in the coastal waters off Godavari, Krishna and adjoining regions are reported by Madhusudhan Rao[7]. Suspended matter coming from the estuarine areas largely includes inert material (silt, clay, etc.) with little organic matter. Though the studies on the riverine region of the Krishna river have been reported extensively, very few reports are available in the estuarine region[8,9]. Recent studies on the Krishna river indicated that the lower Krishna basin is a closed basin based on (i) a decrease by more than half of the surface water inflow into the lower basin due to water development in the upper basin, (ii) an uncontrolled unisalion development in the lower basin itself, (iii) rapid decrease in ground water due to pumping out to irrigation purposes and (iv) rapid increase of sea water in it[10,11] (Venot *et al.* 2007, 2008). The present study consists the transport and behaviour of TSM in the estuarine region.

Krishna estuary is about 45 km in length and the estuarine system of Krishna river covers an area of about 320 km^2 with all its four distributaries. The tidal portion extends up to 39 km upstream near Penumudi in the river. It is essentially a shallow one with a mean width of 1.2 km and an average depth of 5-7 m. The estuary has a well developed sandy coast that experiences long shore drift, build-up spits and barriers across river mouths creating a coastal lagoon. It is a meso-tidal estuary with a tide range of 2-3 m and strong tidal current of 1.2 m sec^{-1}. Dissolved and particulate loads of the Krishna river are derived from a variety of igneous, metamorphic and sedimentary rocks in their catchment areas. In addition to this, the estuarine system is fringed with extensive mangrove vegetation[9].

Materials and Methods

The water samples were collected from four depths (S, 0.2D, 0.6D and 0.8D) at three stations each with three sub-stations A, B & C (Fig. 1) for two low tides and two high tides where D is depth in meters during premonsoon (May'99), monsoon (Sep'99) and post monsoon (Feb. 2000) seasons. Water samples were collected by using water sampler designed for shallow waters by Ramkumar and Pattabhi Ramayya[12].

Salinity was measured on board the boat using salinometer in a μP Based water analyzer kit (Model: CMK 731) after calibration. Accuracy in the

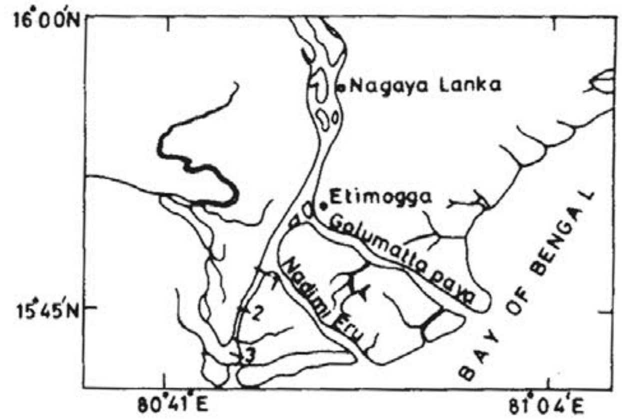

Fig. 1—Krishna estuary station locations

measurement of salinity is +/- 0.5 of the range +/- 1 digit. Values from these measurements were verified by standard Grasshoff's method. Turbidity was determined on board the boat using turbidity meter (Model: CTD-401) calibrated with the formazine standard solution. TSM was determined by filtering an aliquot of sea water (0.25-1 litre) depending on TSM content, through a pre-weighed 0.45 μm Sartorious membrane filter under vacuum, washing the residue with distilled water and weighing it with a sensitive analytical balance to an accuracy of ± 0.1 mg after drying at 60°C.

Distribution of turbidity and TSM are represented in figures 2 and 3 and their ranges and averages at three stations 1, 2 and 3 in May' 99 (premonsoon), September, 99 (monsoon) and February, 2000 (post monsoon) are given in Table 1.

Turbidity (NTU)

Turbidity is a measure of clarity of the water and it is due to suspended particles, turbidity maximum is due maximum concentration of these particles[13] and is expressed in Nephelometric Turbidity Units (NTU). Turbidity in water is caused by the presence of suspended matter such as clay, silt, finely divided organic and inorganic matter, plankton and other microscopic organisms. This is an optical property of the water sample that represents the scattered and absorbed light. Further, it is considered to be reciprocal of transparency of light through the water. This is mainly influenced by the amount of the particulate matter and hence is closely associated with TSM. At the same time attempts to correlate turbidity with the amount of TSM are to some extent impractical because it not only varies with the quantity but also with the size, shape and refractive index of the particles.

The overall turbidity in the Krishna estuarine region varied from 0.1 to 25.7 (5.6 ± 0.9) NTU during premonsoon, from 0.7 to 48.6 (12.6 ± 2.1) NTU during monsoon and from 0.2 to 5.2 (1.2 ± 0.1) NTU during post monsoon (Table 1). Thus it showed low values during post monsoon and high values during monsoon with moderate values during premonsoon indicating its close relationship with TSM and fresh water discharge in the estuarine system (Fig. 2). This might be due to high river discharge with high suspended matter and high tide based currents with intrusion of bottom saline waters during monsoon leading to high suspension of sediment loads in the waters compared to other seasons.

Turbidity showed an increasing trend from station 1 to station 3 during premonsoon and monsoon. During post monsoon season it showed practically no horizontal variation from head to mouth. High turbid nature is found to be occurring at or near the mouth (station 3) of the estuary. Gradual decrease of turbidity towards inland waters signifies the control of marine forces on turbidity in the estuary. Formation of turbidity maximum (TM) was observed in all the seasons albeit with different intensity. Usually, TM in an estuary is considered to be the result of the gravitational residual circulation[14,15] and the settling and resuspension process of the fine sediment[16,17]

The vertical changes in turbidity are significant during premonsoon and monsoon with vertical gradients ranging respectively from 9.5 – 4.8 NTU and from 3.4 – 19.9 NTU at different stations. On the other hand the turbidity does not exhibit any change during post monsoon. This is on par with the prevailing physical conditions such as high river discharge during monsoon, circulation and mixing conditions during premonsoon and reset of estuarine conditions during post monsoon. Further the vertical gradation decreases from head to mouth during premonsoon, it increases initially from station 1 to station 2 and then again decreases to mouth during monsoon and practically no change during post monsoon. Though these variations might be due to the changes found in total suspended matter (TSM), or might be due to the slight differences observed are due to the role of particle size and composition of the TSM as they influence turbidity rather the amount of TSM.

Tidal variation

Turbidity showed the lowest value during post monsoon and highest during monsoon with moderate

Table 1—Distribution of total suspended matter and turbidity in the Krishna Estuary

STATION	TSM ($mg.dm^{-3}$)		TURBIDITY (NTU)	
	Range	Average	Range	Average
		PREMONSOON		
STATION –1	16.3 – 64.0	32.3	0.1 – 25.7	4.3
STATION – 2	13.8 – 57.7	33.4	0.5 – 22.6	5.3
STATION - 3	16.9 – 84.5	49.3	0.9 – 22.2	7.4
AVERAGE		38.3		5.6
		MONSOON		
STATION – 1	6.5 – 44.6	18.3	0.7 – 6.5	3.4
STATION – 2	10.0 – 151.8	12.3	1.6 – 43.5	11.5
STATION - 3	7.4 – 166.8	58.4	1.6 – 48.6	23.0
AVERAGE		40.3		12.6
		POSTMONSOON		
STATION – 1	16.5 – 55.3	34.9	0.5 – 1.6	1.1
STATION – 2	21.1 – 100.6	34.9	0.2 – 1.4	0.9
STATION - 3	11.6 – 99.9	48.7	0.5 – 5.2	1.5
AVERAGE		39.3		1.2

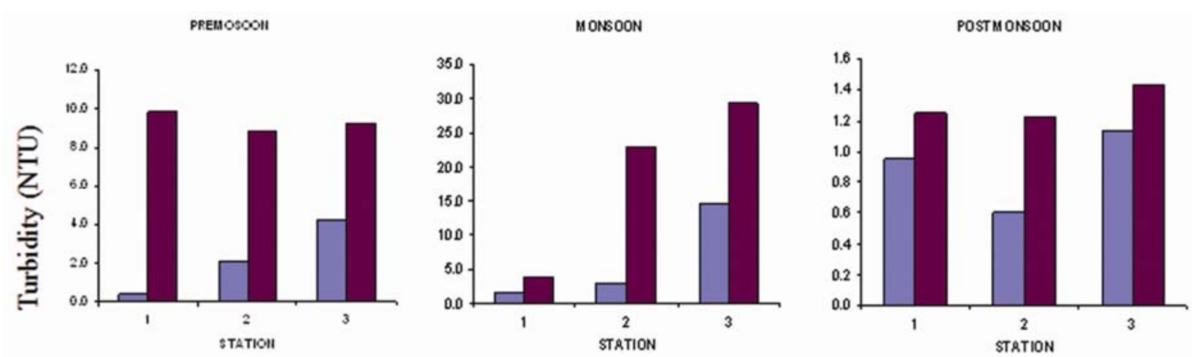

Fig. 2—Distribution of turbidity (NTU) in Krishna estuary. ■ – Surface, ■ – Bottom

values during premonsoon during both the tides. In all the seasons the low tide values are lower compared to those of high tide indicating dominance of marine conditions.

During premonsoon and monsoon seasons the turbidity increased from station 1 to station 3 during both high tide and low tide periods. But in post monsoon, station 2 showed slightly lower values than the station 1 during both the tides. It is also noted that during low tides, a strong wind, directed towards offshore occurs which creates sustained waves in the estuarine waters. Since, the estuary is shallow (about 2m), the higher wave height (1–1.5m) results in resuspension of bottom sediments. Schoellhamer[18] stated that bottom sediments of estuary could be suspended by tidal currents, and waves and wave-current interaction. Turbidity showed significant positive correlation with salinity in premonsoon indicating their association with dominant marine conditions and lack of linear relationship, in other seasons (monsoon and postmonsoon) (Fig. 4).

Total suspended matter (Tsm)

Total suspended matter in the Krishna estuarine region varied from 13.8 to 84.5 (38.3 ± 2.6) $mg.dm^{-3}$ during premonsoon, from 6.5 to 166.8(40.3 ± 6.0) $mg.dm^{-3}$ during monsoon and from 11.6 to 100.6 (39.3 ± 2.8) $mg.dm^{-3}$ during post monsoon seasons (Table 1).

Relatively high TSM values during monsoon might be due to high river run off with high suspended load and due to littoral currents that carry high suspended sediments into the river in this season. Intermediate values in postmonsoon may be attributed to relatively low river flow with low TSM and reset of estuarine conditions. Low values in premonsoon might be due to low river discharge with low suspended load. Ramesh and Subramanian[19] noted that the concentration of TSM in Krishna river seems to be in the proportion of 2:1 with respect to the wet and dry seasons particularly at Vijayawada but this is not found in the present study of the Krishna estuary which might be due to the existing hydrodynamic conditions in different seasons. This type of general seasonal distribution has been reported by several workers in the Godavari estuary[20,21].

Horizontal variation

TSM recorded a uniform longitudinal gradation in the estuary from head (station1, 6.5 - 44.6, ave18.3 ± 2.7 mg.dm^{-3}) to station 2 (10.0 - 151.8, ave 44.2 ± 12.30 mg.dm^{-3}) and to mouth (station 3, 7.4 - 166.8, ave 58.4±10.9 mg.dm^{-3}) during monsoon. During premonsoon, it showed an increasing trend from head to mouth of the estuary with very little change between station 1 (range16.3 - 64.0, 32.3 ± 4.0 mg.dm^{-3}), and station 2 (13.8 - 57.7, 33.4±3.7 mg.dm^{-3}) and very high content at station 3 (16.9 - 84.5, 49.3 ± 4.7 mg.dm^{-3}). During postmonsoon season TSM followed a similar increasing trend as in premonsoon i.e., from station 1 (16.5 to 55.3, 34.9 ± 2.9 mg.dm^{-3}), and station 2 (21.1 to 100.6, 34.9 ± 4.8mg.dm^{-3}) to station 3 (11.6 to 99.9, 48.7 ± 5.9mg.dm^{-3}). Thus there is a general increasing trend from station 1 to 3 during the three seasons contrary to general trend of decrease from head to mouth. Another pertinent feature of this horizontal distribution is the presence of very low TSM at station 1 and very high values at stations 2 and 3 in monsoon, in spite of high river discharge with high suspended load. Further, strong opposite tidal currents with high sediment load[22,23] in flood dominated conditions near confluence result in the high TSM in the lower reaches of the estuary. This is also supported by the shallow nature of the estuary due to sedimentation during this season. The slope of the bottom decreases rapidly from Vijayawada leading to settling of the suspended matter in the upper reaches of the Krishna estuary before entering the estuary leading lower amounts of TSM in the station 1.

TSM exhibited a decreasing trend from monsoon to premonsoon. It showed an increasing trend from station 1 to station 3 contrary to the general trend of decreasing order from head to mouth. Another pertinent feature of the horizontal variation of TSM is its low values at station 1 particularly in monsoon. This might be due to high sedimentation in the upper estuary due to strong opposite ebb and flood currents with high sediment load and flood dominated conditions in the estuary.

Significant increase in TSM from surface to bottom in three seasons is noticed (Fig. 3) with high vertical gradient in monsoon and premonsoon seasons while it is low in post monsoon. This is mainly because of prevailing currents, intrusion of saline waters and resuspension of bottom sediments.

Vertical gradient in TSM, increasing from surface to bottom particularly significant at all stations in monsoon also lends support to its horizontal variations. The regular increasing trend with depth might be due to seaward fresh water flow with low TSM and upward flow of saline waters with equal or more suspended load, settling of surface fluvial material to the bottom or resuspension of recent sediments into overlying waters.

TSM exhibited significant trend (Fig. 4) during a tidal cycle with high values in high tide and low values in low tide periods. Also tidal variation is significant in bottom compared to surface waters. Practically no change in TSM during tidal cycle at stations 1 and 2 in all seasons. At the mouth of the estuary (station 3), the tidal impact on TSM is

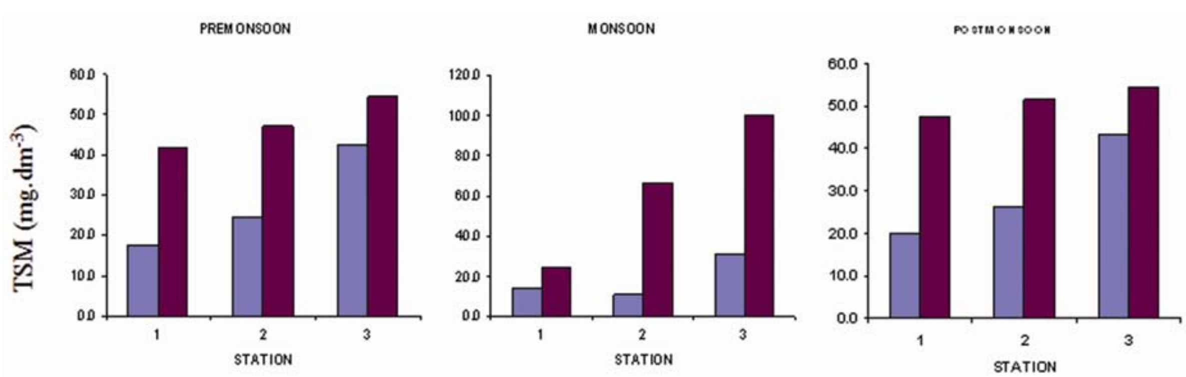

Fig. 3—Distribution of TSM (mg.dm^{-3}) in Krishna estuary. ■ – Surface, ■ – Bottom

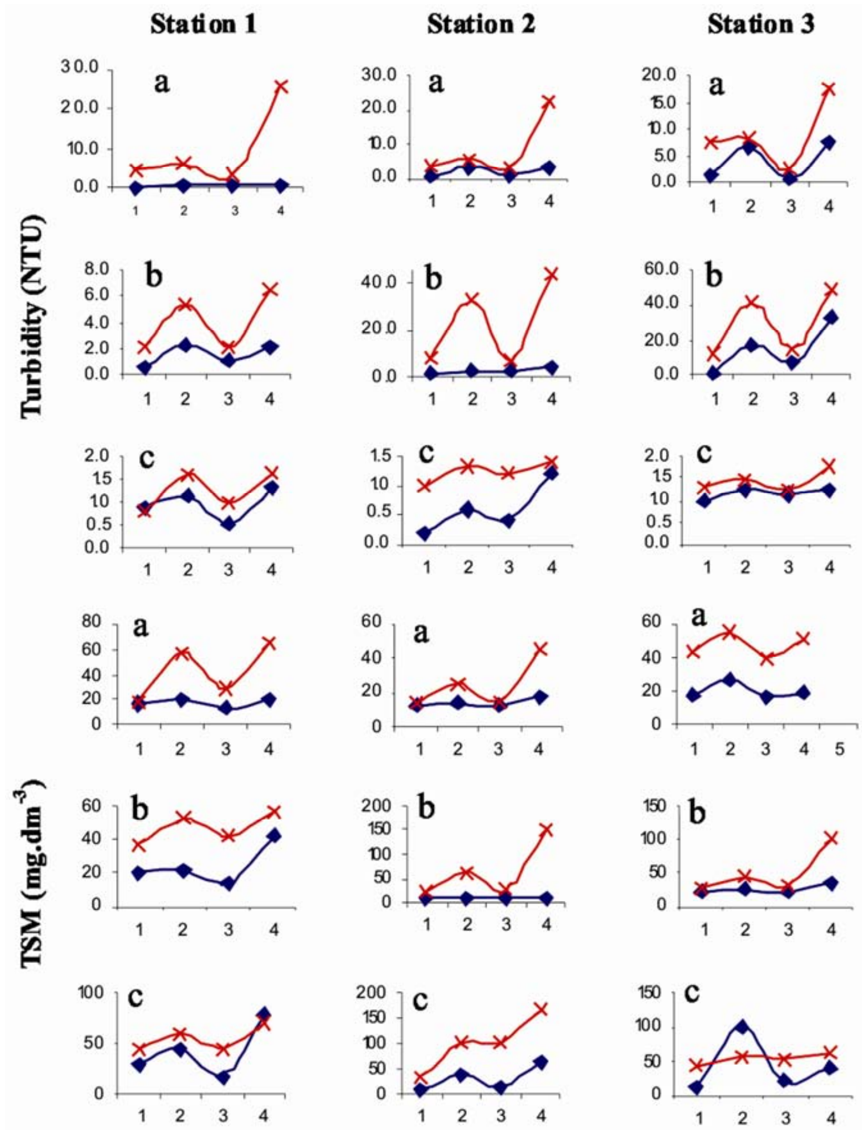

Fig. 4—Tidal variations of turbidity (NTU),TSM (mg.dm^{-3}) in Krishna estuary a-Premonsoon, b-Monsoon, c-Postmonsoon 1&3-Low tide, 2&4-High tide. --♦-- Surface, –x—Bottom

predominant, as expected, in entire water column during three seasons. Further, the vertical gradation is predominant during high tide periods compared to that during low tide periods. These observations indicate the dominance of intrusion of sea water during flood tide and the prevailing littoral currents causing flocculation of fine sediment during fresh-saline water mixing in the estuary that results in settling of the suspended sediments and re-suspension of finer particles from estuarine channel bed.

Present values of TSM (6.5-166.8 mg.dm^{-3}) in the estuarine region (Table 2) are higher than those reported by Krishna Rao *et al*,[9] (0.3-52.5 mg.dm^{-3}), Sarin *et al*[8] (0.3-50.8 mg.dm^{-3}) and Madhusudan Rao[7] (2 mg.dm^{-3}) in the estuary. The data reported by them are of one time observation and are confined to a particular season. Ramesh and Subramanian 1986[24] while studying the chemical composition of river sediments of the Indian sub continent, reported the TSM of the major rivers and observed that the TSM for the Krishna was 130 mg.dm^{-3} average at Vijayawada which is at a distance of about 60 km from the mouth of the main estuary. This value is much higher than the present (Table 1) values. Further, while analyzing the discharge data of the Krishna River collected over a long period, they observed that the maximum to minimum range of TSM varied annually by a factor of three in upstream

Table 2—Total suspended matter ($mg.dm^{-3}$) in major Indian river, estuarine systems

Name of the River	TSM ($mg.dm^{-3}$) At river mouth[1]	TSM ($mg.dm^{-3}$) In the estuary	References
Hooghly	564 (Calcutta)	100 – 300	Chatterjee, 1987[30].
Mahanadi	268	3.6 – 13.5	Borole, *et al.*, 1979[31].
		0.6-596	Ray, *et al.*, 1984[32].
Godavari	2,000 (M)	0.89-7.97	Rajendran, *et al.*, 1982[33].
	26 (May'77)	(Coastal off Godavari)	
	22.1 - 88.4[33]	122	Subramanian, 1979[1]
		1.5-21.1	Sarin, *et al*, 1985[8].
		(May-June. 81)	
		4.2-7.9	Somayajulu, *et al.*, 1993[34].
		200-370 (M)	Reddy, *et al.*, 1994[20].
		8-38 (PRM)	
		16.1 - 113	Padmavathi,1998[35].
Krishna	130 (Vijayawada)	6.5-166.8	Present work
	600 Aug. 77(Vijayawada)	1.1-50.8 (FW)	Sarin, *et al.*,1985[8].
	5.5 (May. 78)	0.3-13.5 (EW)	
		0.3-52.5 (EW)	Krishnarao, *et al*,1988a[9].
		0.75-2.89	Rajendran, *et al.*,1982[33].
		(Coastal off Krishna)	Subramanian, 1979[1].
Cauvery	220(Mysore) July.77	2.0-690	Ramanathan, *et al.*,1988[36].
	2 (May)	13-742 (UR)	Ramanathan, *et al.*,1993[37].
	10.6 (Tiruchy)	26-692 (LR)	
	94	13-692	Ramanathan, *et al.*,1996[38].
Cochin back waters		3-253 (S)	Sarala Devi, 1989[39].
		24.8-257 (B)	
Mahi		56-197.6 (S)	Bhosle, *et al.*, 1985[40].
		1164	
Narmada	353	26.7-6720	Borole, *et al.*, 1982[41].
	3144	20-4060 (NM)	Borole, 1980[42].
Tapi	333	19.7-691	Borole, *et al.*, 1982[41].
	88		
Damanganga		52-91 (FW)	Zingde, *et al.*, 1980b[43].
		3-277	

M-Monsoon, FW-Fresh water, EW-Estuarine water, UR-Upper reaches, LR-Lower reaches, S-Surface, B-Bottom, NM-Nonmonsoon

and by a factor of seven in downstream. Downstream decrease in suspended sediment concentrations had been reported for a number of rivers[1,25]. Further, Ramesh and Subramanian[19], showed a linear relationship between runoff and sediment transport. At Vijayawada they observed a 100-fold increase in sediment transport for two-fold increase of river run off at low flows (5000-10000 $x10^6 m^3.y^{-1}$). Conversely, at high flow in the range 10,000 – 1,00,000 $\times$ 10^6 $m^3.y^{-1}$, only a two to three-fold increase in sediment transport occurs.

Though no significant seasonal variation was observed in TSM, turbidity exhibited relatively high values in monsoon and low values in premonsoon. This is in agreement with river discharges. Horizontal variation of turbidity closely resembles that of TSM with an increasing trend from station 1 to mouth of the estuary. Turbidity maximum, noticed with different intensities in all seasons was believed to be the result of the gravitational residual circulation and settling and resuspension processes of the fine sediment. Further, in general, the turbidity resembles TSM in vertical and horizontal variations. Minor deviations observed in the distribution of turbidity from that of TSM were attributed to the differences in nature, particle size and shape of TSM.

Interrelationships

Variations of TSM and turbidity with salinity in the estuarine region during the three seasons are shown in Figure 5. Total suspended matter and turbidity showed significant positive correlation with salinity in all seasons indicating their association with dominant

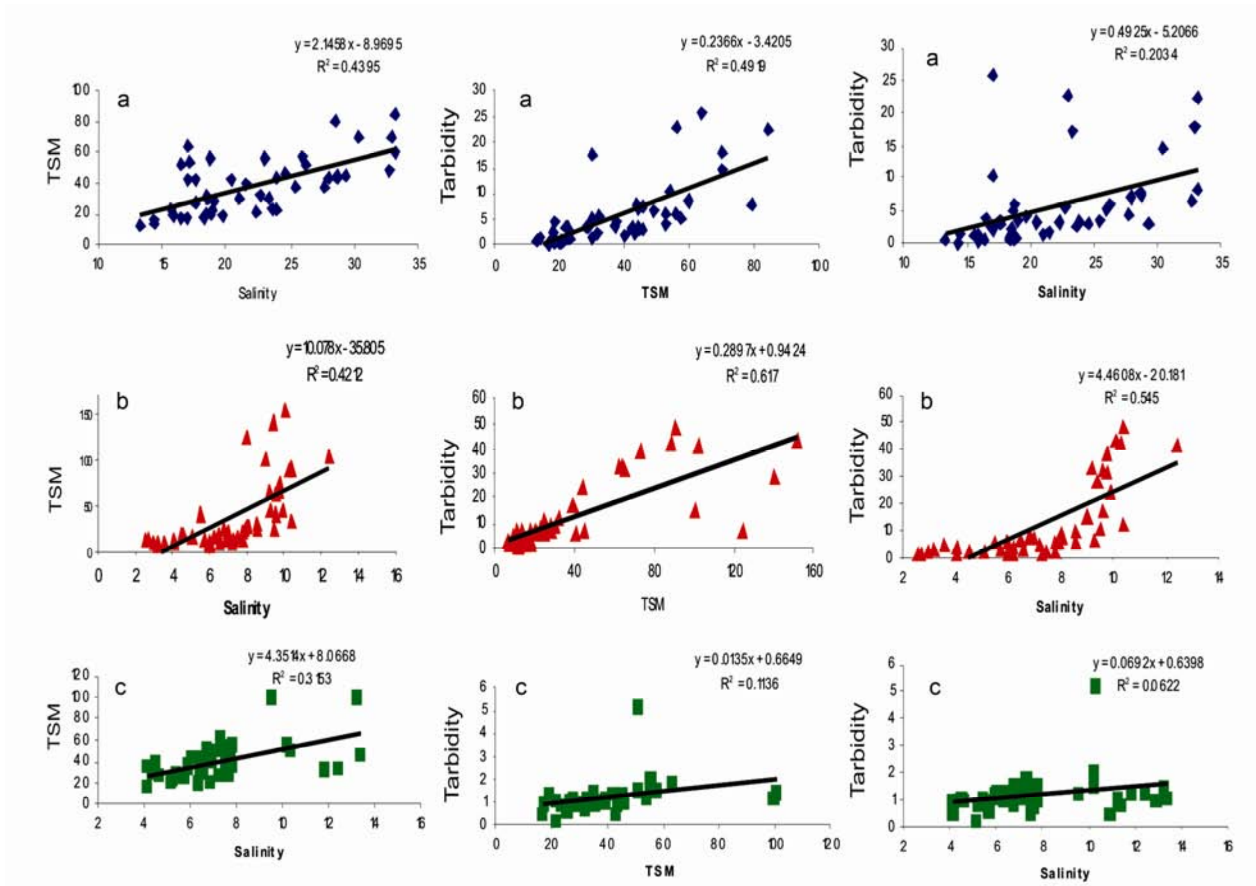

Fig. 5—Relationship between Salinity and TSM (mg.dm^{-3}) and Turbidity (NTU). a-Premonsoon, b-Monsoon, c-Postmonsoon

marine conditions. This is contrary to the general trend of decrease of TSM with salinity indicating the dominance of marine processes over fluvial action. However Sarin *et al*[8] reported an inverse relationship though not significant for Krishna estuary between salinity and TSM and a direct relationship for Godavari. The sediment transport of Krishna river into the Bay of Bengal through the estuary is influenced by several factors.

It has been very well established[26] that though the basin geology and river discharge exert a major control over sediment load in tropical river basins particularly in the Krishna river, the total suspended load does not reach down to Vijayawada due to the settlement of the most of the sediment load in the upstream major dams and diversion of channels constructed at Srisailam and Vijayawada. These dams act as sediment traps resulting in very low suspended transport down to Vijayawada. A downstream decrease in sediment concentration has been reported for a number of world rivers[27,28].

The maximum elevation in the river basin at Vijayawada is about 19 m above mean sea level from where the plain slope varies gently on an average of 0.0002 (i.e. 20 cm/km) towards the sea. This gentle slope further reduces the current flow leading to high settling velocities and to the deposition of the suspended sediment in the river before it reaches the estuary[9].

The concentration of suspended matter at any location is affected by two common processes, namely advection and diffusion[20]. In the advective transport the suspended material is transported horizontally along the estuarine stretch. In the diffusive transport sediment is transported from zone of higher concentration to the zone of lower concentration. Wave action and tidal currents are mainly responsible for turbulent diffusive transport[20].

Circulation of water within estuary is governed by strong tidal oscillations on which residual water circulations may be generated by non-linear interactions between the tidal flow and bottom topography of the estuary, density gradients, wind stress and the mass input due to fresh water discharge[28].

Residual gravitational circulation with enhanced settling velocities as a result of flocculation is the main process in the longitudinal transport of fine-grained sediments in estuaries. In this theory it is thought that the dispersed fine sediment in the fresh water flocculates when it arrives in the mixing zone of the estuaries[26]. The large aggregates will settle down faster to the lower part of the water column because of their high settling velocities.

Maximum tide ranges[23] observed near the Krishna river confluence are about 1.14 m and these can not significantly influence the circulation in the Nizampatnam bay, since the shoreline of Nizampatnam bay is more a straight coast and tidal currents are only periodically oscillating currents without significantly alerting the direction and magnitude of the mean currents. However during short spells of periods less than one tidal cycle, tidal currents counteract weakening resultant flow of wave and wind induced currents enabling rapid siltation of the suspended sediments in the shallow waters which led to the formation of extensive banks.

Geomorphological and progradation conditions

Among the deltas of the rivers Mahanadi, Godavari, Krishna and Cauvery on the east coast, the Krishna delta is conspicuous in that it not only protrudes out of the coast, much more than the others but also extends due to south unlike others which extend east or southwest[29].

Progradation of the Krishna delta took place in five stages that had been activated by repeated uplift and subsidence of land. The most striking features in the Krishna delta front are the growth of big sandy spits. They are growing on both sides of all the three distributaries. A majority of these show hooked nature indicating successive additions at the tips of the spits, these being the result of the new material transported and deposited in that form due to refraction of waves.

Origin and growth of coastal depositional features like spits and bars especially at the confluences of the river involve a variety of dynamic forces which are the result of cumulative action of both fluvial and marine processes. The fluvial action lies in the river discharge bringing in the sediments to the sea, and the marine action rests in the nature of currents, tides and energy and direction of approach of waves to rework the sediments.

As a result of these features the sediment load carried down to Vijayawada and the suspended matter carried by marine processes help leading to a co linear relationship between the salinity and suspended matter. This is supported by the fact that the depth of the estuary decreases from station 1 (5-6m) to station 2 (4-5m) and to station3 (3-4m) indicating the dominance of marine processes in TSM transport to the estuary. Very little fluvial TSM carried by the river water down to Vijayawada is retained in the upper reaches of the estuary. Under these circumstances it is very difficult to quantify the sediment transport to the Bay of Bengal.

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