

Circulation and Mixing Process in Vasishta - Godavari Estuary, East-Coast of India

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Circulation and Mixing Process in Vasishta - Godavari Estuary, have been studied by using estuarine classification model. Analysis of salinity, salt budget, diffusion coefficients and flushing times based on salinity data of Vasishta-Godavari estuary for different months has been carried out. I-D advection-diffusion model has been adopted for computing diffusion coefficients along the channel axis using input data on tidal average salinity, bathymetry and river discharges. The mean value of diffusion coefficient ranges between 20880 m²/s - 3888 m²/s in the southwest monsoon season (July - September) while for post and pre-monsoon seasons (November- May) the coefficient is between 515 m²/s and zero. The fluctuations in diffusion coefficients reflect the topographic features. The maximum value of flushing time for Vasishta - Godavari is 75.17 tidal cycles during the period of low discharge, while minimum is 0.81 during high river discharge. With the onset of southwest monsoon, the runoff increases considerably and the estuary loses about 90% of salt content during the first 2 months of the season. About 75% of this loss is recovered in the subsequent 3 months when the runoff decreases. The estuarine salt budget shows an increase in salt content gradually from September to January. Model studies based on these observations may be more useful in understanding the basic mechanisms involved in circulation, mixing and flushing aspects of the estuary.

Introduction

The pollutants will be subjected to number of physical, chemical and biological processes in the estuary ultimately resulting in their dilution and dispersion. This process can be mathematically modeled to fulfill the pre-operational evaluation of discharge pollutants by conducting continuous field experiments. The implementation of modeling to describe these processes due to external and internal forces mostly depends on the dimensions of the estuary and environmental conditions. In a well-mixed estuary, the turbulent energy generated by bottom friction is sufficient to mix the mass and momentum efficiently throughout the water column and there exists a reasonable uniformity of horizontal current. So by neglecting vertical component of velocity, a 3-D problem can reduce to a 2-D by depth averaging the governing equations (Rao et.al, 1998). The dynamics of weakly stratified and well-mixed estuaries may be described by integrating the fluid equation over the cross sectional area (Uncles and Redford, 1980; Fried riches and Aubrai, 1988). This leads to reduction of 2D to 1D. The reduction to 1-D problem takes advantage of the following characteristics: larger hydrostatic pressure gradient, a narrow estuary, a small aspect ratio (depth much smaller than the width) and strong mixing between fresh and seawater. In light of the above features, the Coriolis force and lateral pressure gradient terms can be neglected and the problem reduces to a first order approximation (Rao, et.al, 1998).

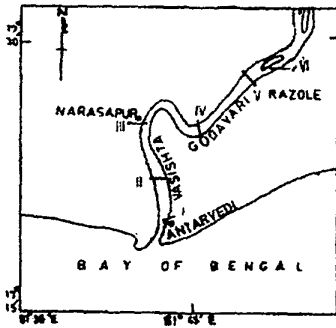


Fig.1: Station location in Godavari estuary

As a case study we have applied 1-D advection-diffusion model to the waters of Vasishtha Godavari estuary to determine the diffusion coefficients, their empirical relations (spatial and temporal) and flushing times (month wise) of effluents to predict the impact assessment.

Vasishtha- a physical description

The Study area (Fig. 1) covers a stretch of 30 km of Vasishtha Godavari and the downstream point is Antarvedi where it debouches in to the Bay of Bengal. The depth of the estuary varies between 4 to 14 m through out 30 km stretch of the estuary and the average depth is 9 m. The width of the channel varies between 600m and 1300m and its average is approximately 900m. Although the width as well as depth variations along the estuary are somewhat irregular, an approximate linear fit could be obtained for the width\depth ratio. The width\depth ratio shows a linear decrease from head to the mouth of the estuary. The mean cross-sectional area varies in three stages. Initially the mean cross-sectional area decreases exponentially from river mouth up to 14km and later linearly increases up to 20km and finally decreases linearly up to the head (30km) of the estuary.

The tides recorded at Kakinada harbour are semi diurnal with a marked diurnal inequality (ITT 2000) and its range is about 1m to 1.5m. The range during spring tide is about 1.5m and that of neap is 0.6m. The rainfall shows marked time variability corresponding to the onset and retrieval of the monsoon (Ranga Rao *et al.* 1988; and Ramasarama 1965). The fresh water discharge is maximum during June to Oct. in southwest monsoon. The rainfall shows marked time variability corresponding to the break and active phase of southwest monsoon. Consequently, the runoff into the estuary can fluctuate from 4200m³/s to negligible during this period. The rainfall is minimum during December to May during which period the runoff is almost negligible in the catchment area (receives < 10 cm of rainfall). The runoff in the river is believed to decrease monotonically from December till the onset of the next southwest monsoon.

Materials and methods

Water samples were collected at six stations using insitu T-S bridge, and depth of the stations were measured using a portable echo sounder along the axis

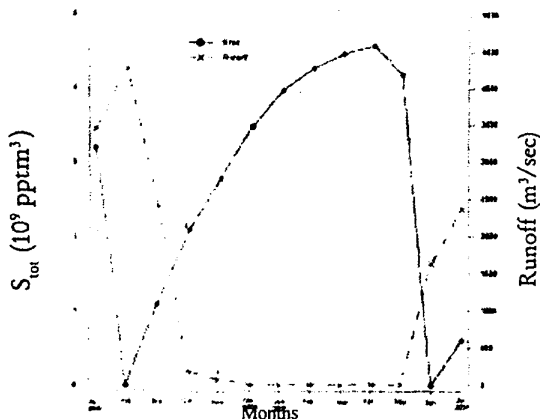


Fig.2: Annual cycle of total salinity (Sept) and monthly runoff

of the estuary during the study period (July 2000-June 2001), (Ramamurthy and Dyer,1969). Fresh water discharge data were taken from Godavari Head works Division Dowleswaram, Andhra Pradesh.

Seasonal salt budget and horizontal diffusion coefficients

From July 2000 to June 2001 the salinity distribution at surface, mid depth, bottom in the Vasishta were recorded during one tidal cycle every month. The tidal - depth -mean salinity describes the annual cycle in the estuary. The axial variations of salinity in the estuary have a wide range in the present study. The mean salinity values obtained from the data have been plotted for each month. These curves give, for each month, salinity S as a continuous function of x , the upstream distance from the mouth of Vasishta. The total salt in the estuary S_{tot} , is given by

$$S_{tot} = \int_x^{\infty} S(x) A(x) dx$$

where, A is the cross-sectional area. The upper limit is the far upstream end of the estuary where salinity S vanishes. Annual cycle of S_{tot} and monthly mean runoff shown in Fig. 2. As seen from the figure, with the onset of active southwest monsoon in August 2000 the river was in heavy floods. Hence, the salinity is zero and estuary loses 100% of salt content. When river runoff decreases in the subsequent 3 months about 80% of this loss is recovered. Total salinity increases continuously from November to May. Again due to flash floods caused by a cyclone in June 2001, the salinity became zero and the increased in the next month, which is an exceptional case. For estimation of the horizontal diffusion coefficient along the channel axis (x), the following equation was adopted

$$\text{(Shetye and Murthy 1987)} \quad \frac{\partial}{\partial t} \int_x^{\infty} S(x) A(x) dx = K A \frac{\partial S}{\partial x} + RS$$

Where K, R, t, A are the axial diffusion coefficient, river runoff, time period and cross sectional areas respectively. Here, assumption has been made that the observation time is much greater than the mixing time (Fischer *et al* 1979). In view of this, one can easily adopt the one-dimensional advection diffusion model. Averages of $\partial S/\partial x, R, S$ are also used as input parameters in the above one-dimensional advection-diffusion model. The above input parameters are seasonally integrated (Ralson and Wilf, 1966) for the monthly period starting from July 2000 to Jan 2001.

A one-dimensional advection-diffusion model study

Regression equations for the spatial (y_{ix}) and temporal (y_{it}) diffusion coefficients have been established by least square method. The computed values of diffusion coefficient (K) for different months show the trend in variation of K with distance from the mouth. It is clearly noticed that there is a marked spatial variation (decrease) in diffusion coefficients in the lowermost 12km of the estuary. However, beyond 12km upstream the diffusion coefficients varied gradually. The variation of coefficients with time (temporal) show that there is a rapid fall in the values of diffusion coefficients from July to September and thereafter remain almost same. It is clearly noticed that the coefficients are sensitive to the river flow.

These equations are given below.

Spatial

$Y_{1x}(x) = -260562 + 110598x - 12012x^2 + 499.85x^3 - 7.15x^4$	(July - Aug)
$Y_{2x}(x) = 42241 - 8207.2x + 677.02x^2 - 25.57x^3 + 0.36x^4$	(Aug - Sept)
$Y_{3x}(x) = 20573 - 2929.15x + 179.07x^2 - 5.27x^3 + 0.062x^4$	(Sept - Oct)
$Y_{4x}(x) = 1840 - 143.6x + 3.05x^2$	(Oct - Nov)
$Y_{5x}(x) = -494 + 289.38x - 32.12x^2 + 1.34x^3 - 0.02x^4$	(Nov - Dec)
$Y_{6x}(x) = 0.08 - 0.04x + 0.01x^2$	(Dec - Jan)

Temporal

$Y_{1t}(t) = 27102 - 908.99t + 36.74t^2 - 0.64t^3 + 0.01t^4$	(st. I - II)
$Y_{2t}(t) = 167475 - 9810.65t + 224.49t^2 - 2.44t^3 + 0.01t^4$	(st. II - III)
$Y_{3t}(t) = 15197 - 823.0t + 21.21t^2 - 0.26t^3$	(st. III - IV)
$Y_{4t}(t) = 18350 - 1158.53t + 29.28t^2 - 0.34t^3$	(st. IV - V)
$Y_{5t}(t) = 20897 - 1126.96t + 29.62t^2 - 0.34t^3$	(st. V - VI)

These equations would be found more useful to compute concentration of pollutants along the axis of the estuary and to compute flushing times. Thus the studies will be helpful to study the Impact Assessment for any point along the channel axis. The mean diffusion coefficients are found to be maximum during July - August and minimum during November-December and this may be attributed to the river runoff conditions.

Replacement time(T)

Replacement time which indicates the time required for the effluent for complete mixing in the water body under consideration have been established

(Fischer *et al* 1979) from the following formulae.

$$T = 0.4 L^2 / K(x)$$

Where, L is the length of the channel, $K(x)$ is the horizontal diffusion coefficient.

Based on the data, the computed parameters $K(x)$ and L , the replacement time in the study area are found to be wide variations. From the results during monsoon season (July –August) the fresh water discharge is maximum which will washout most of pollutants into the sea less than one tidal cycle. During the negligible discharge during post monsoon season (Dec–Jan.) it is about 75 tidal cycles (Table.1). Overall flushing times of estuary increases with decreasing upland river discharge. Similar types of observations were also observed in the case of Gautami (Reddy and Ranga Rao, 1993, Jyothi *et al* 2000) and Vellar (Dyer and Ramamurty, 1969) estuaries.

Results

The Vasishta Godavari estuary is a salt wedge estuary during periods of high river discharge conditions (July-August). But during the periods of other river discharge conditions the estuary is partially mixed estuary from high to low salinity stratification depending upon the discharge rates (September to November). During the dry season (December to May) the estuary is well - mixed and experiences a temporal increase in salinity.

An overall picture of the rates of mixing the estuary can be given in terms of flushing or replacement time. The maximum flushing time of the estuary is 75.165 tidal cycles during the periods of low river discharge conditions (November to December) while minimum flushing time is 0.806 tidal cycles during the period of high river discharge (July to August). It is clear that the average time required for the river water to move through the estuary decreased with increasing river discharge.

The mixing in the estuary is also studied by the concept of longitudinal diffusion coefficient (1-D Advection-diffusion model). Values of these coefficients are generally larger for higher river discharge condition. The average value of diffusion coefficient is maximum of about 20880 m²/s during July to August and minimum of about 166 m²/s during November to December and thereafter decreases to zero during pre-monsoon season January to May are observed. The fluctuations in diffusion coefficients are also found to be dependent on the bottom topography.

With the onset of active southwest monsoon, the runoff increases considerably and the estuary loses about 90% of salt content during the first 2 months of the season. About 75% of this loss is recovered in the subsequent 3 months when the runoff decreases. The estuarine salt budget shows an increase in salt content gradually from September to January. Total salinity increases continuously from November to May.

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Table.1 Flushing times in the Vasishta Estuary for different months
(1. July -Aug, 2. Aug-Sept, 3.Sept-Oct, 4. Oct-Nov, 5. Nov-Dec)

Estuary Segments	Distance (Km)	Diffusion coefficient $K(x) m^2/sec$					Flushing time(t) Tidal cycles				
		1	2	3	4	5	1	2	3	4	5
II-I	4	19800	18700	11400	1320	230	0.007	0.008	0.012	0.108	0.62
III-I	11	63200	5100	3910	622	302	0.017	0.213	0.277	1.743	3.59
IV-I	17	6810	2710	1800	265	117	0.380	0.956	1.438	9.772	22.13
V-I	22	6490	110	1170	192	94	0.668	3.907	3.706	22.588	46.08
VI-I	27	8100	1498	1160	174	87	0.806	4.360	5.631	37.541	75.16