

Mixing and flushing time scales in the Azhikode estuary, southwest coast of India

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Flushing time scales of the Azhikode estuary showed pronounced dry season and wet season signals as well as large inter-annual variation. Cumulative flushing time of the estuary varies from 4.8 tide cycles in April to 1.22 tide cycles in August. Longitudinal eddy diffusion which is a measure of pollution dispersion lies between $2 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$ in January and $42 \times 10^6 \text{ cm}^2 \text{ s}^{-1}$ in August.

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 is produced by the methods which provide estimates of the flushing time of the estuary as a whole or a portion of it. The simplest of the more detailed treatment to know the relevant time scale of mixing and flushing is the steady state one dimensional approach, in which the distribution of properties along the length and breadth of the estuary is considered but only averages are taken over each cross-section.

Azhikode estuary is formed by the part of the Vembanad lake which joins the Arabian Sea at Munambam (Fig. 1). Total length of the estuary is about 20 km and maximum depth at the channel is about 10 m. The width of the estuary near the bar-mouth is 750 m. Tides in the Azhikode estuary are semidiurnal, with amplitude of 1m during spring tides and 60 cm during neap tides. Tidal effects extend to approximately 25 km landward of Azhikode. Tide is progressive in nature and at spring tides the high water is delayed as much as 45 minutes between Azhikode and Chennamangalam (upper most station in the study area). Average annual rainfall in the study area was 310 cm. The present study was carried out to delineate the mixing and circulation pattern in the Azhikode estuary and to estimate the mixing and flushing time scales. Monthly mean fresh water input into the Azhikode estuary varied between $21 \text{ m}^3 \cdot \text{s}^{-1}$ during January to $10 \text{ m}^3 \cdot \text{s}^{-1}$ during April.

During the wet season (June to September), the water discharge varied between $123 \text{ m}^3 \cdot \text{s}^{-1}$ and $387 \text{ m}^3 \cdot \text{s}^{-1}$. Monthly mean freshwater discharge data were obtained from Central Water Commission (CWC) gauging station located at Nileswar 35 km upstream of Ahikode.

Materials and Methods

Sampling and monitoring stations were located throughout the estuary (Fig. 1) from Munambam to Chennamangalam nearly the upper limit of the tidal intrusion. Four sections selected for the present study were Azhikode (Section-I), Kottappuram (Section-II), Gothuruthu (Section-III) and Chennamangalam (Section-IV). Average distance between the sections were 4-5 km which is greater than or equal to the tidal excursion. Synoptic data on the vertical profile of current speed, direction and salinity were collected by

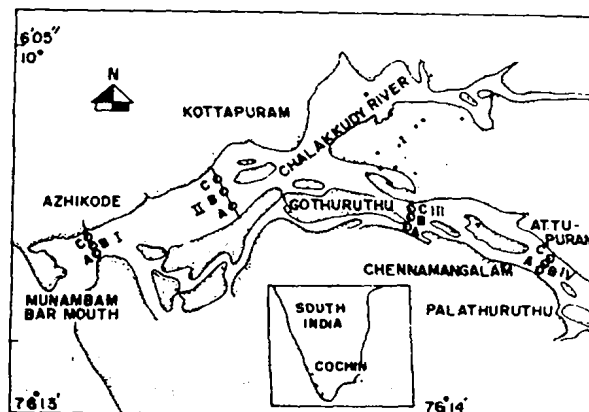


Fig. 1—Location map

engaging two boats and the sections I and II were covered on one day and the sections III and IV were covered on the consecutive day. It was assumed that the tide and meteorological conditions do not vary on these days. All the stations were occupied for a period of 13 hours once in every month during January to December 1986, so as to cover one complete tidal cycle. Currents and salinity measurements have to be abandoned in May, September and December due to operational constraints, such as faulty instruments and non-availability of boats etc., however data collected deemed to be representative, since the overriding influence is the monsoonal cycle and during other months adequate data have been gathered. Sampling procedures and data analysing techniques are discussed in detail in earlier publication¹.

Flushing time is the time required to replace the fresh water in the estuary at a rate equal to the river discharge. In this paper fraction of fresh water method^{2,3} is adopted for computing flushing time. Fresh water fraction (f) in any section of the estuary is given by the equation $f = (S_s - S) / S_s$, where S_s is the salinity of seawater and S is the salinity of the section. If V is the volume of a section of the estuary and R is the river discharge, then flushing time can be calculated by the formula $T = f.V/R$.

Results and Discussion

Fresh water fraction is computed for all the sections of the estuary during varying river discharge and are presented in Table 1. For computation of flushing time estuary is divided into three compartments such as segment-I between Azhikode and Kottappuram, segment-II between Kottappuram and Gothuruthu and segment-III between Gothuruthu and Chennamangalam. Mean value of the freshwater fraction is taken for the freshwater volume in each segment. Computed value of flushing time and cumulative flushing time are given in Table 2. Owing to the large volume in segment-I than the other segments flushing time was higher in this segment during the study period. Cumulative flushing time of the estuary during post and premonsoon ranged between 3.47 tide cycles in March to 4.30 tide cycles in April. With the high

river discharge associated with the southwest monsoon flushing time of the estuary decreases and reaches the minimum value of 1.22 tide cycle during August when the river discharge was $387 \text{ m}^3 \cdot \text{s}^{-1}$. This means if a pollutant is introduced upstream of Chennamangalam it will take 1.22 tide cycles to flush completely out of the estuary during August whereas the same would require 4.22 tide cycle in April for a river discharge of $10.3 \text{ m}^3 \cdot \text{s}^{-1}$. Flushing time (T) is related to river discharge (R) in Fig. 2. It is observed that flushing times decreases rapidly with increasing river flow and for higher river flow the decrease is slow. This agrees with the results of Ketchum⁴ obtained for Bostan harbour. Linear regression equations were fitted for freshwater fraction on the longitudinal distance from the bar-mouth for various river discharges and the equations obtained are given below, where X is the longitudinal distance from the bar mouth in km.

January

$$f = 0.0568.X + 0.4300 \text{ (for } R = 21.00 \text{ m}^3 \cdot \text{s}^{-1}) \quad \dots (1)$$

Table 1—Freshwater fraction at different cross-section in the Azhikode estuary

Months	Azhikode	Kottappuram	Gothuruthu	Chennamangalam
JAN	0.050	0.128	0.403	0.690
FEB	0.030	0.090	0.340	0.414
MAR	0.037	0.084	0.226	0.304
APR	0.086	0.121	0.179	0.234
JUN	0.296	0.536	0.804	0.943
JUL	0.337	0.675	0.782	0.957
AUG	0.343	0.649	0.714	0.907
OCT	0.404	0.640	0.746	0.795
NOV	0.629	0.763	0.792	0.856

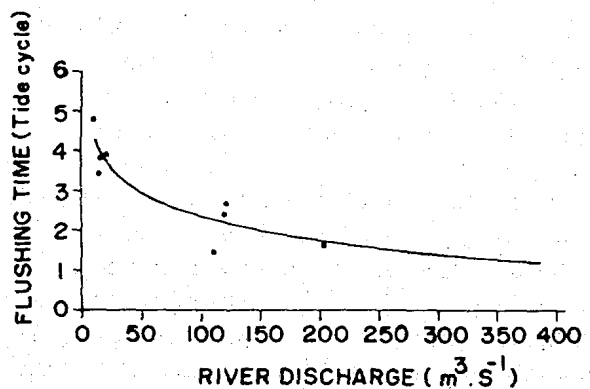


Fig. 2—Flushing time of Azhikode estuary versus fresh water discharge

Table 2—Flushing time of the Azhikode estuary

Segment	Mean fresh water fraction	Volumex10 ⁶ V	Fresh waterx10 ⁶ F	Flushing time (Tide cycles) F/R	Cumulative flushing time (Tide cycles)
January (R = 1.01x10 ⁶ .m ³ /tide cycle)					
Segment -I	0.076	17.82	1.36	1.35	1.35
Segment-II	0.266	2.50	0.67	0.66	2.01
Segment-III	0.547	3.50	1.91	1.89	3.90
February (R = 0.78x10 ⁶ .m ³ /tide cycle)					
Segment -I	0.060	17.30	1.04	1.33	1.33
Segment-II	0.215	2.50	0.57	0.73	2.06
Segment -III	0.377	3.73	1.40	1.79	3.85
March (R = 0.69x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.060	17.94	1.07	1.55	1.55
Segment-II	0.155	2.67	0.41	0.59	2.14
Segment-III	0.265	3.48	0.92	1.33	3.47
April (R = 0.62x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.104	13.96	1.76	2.83	2.83
Segment-II	0.150	2.67	0.57	0.73	3.56
Segment-III	0.207	3.74	0.77	1.24	4.80
June (R = 5.80x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.416	17.80	7.40	1.28	1.28
Segment-II	0.670	2.71	1.82	0.81	2.09
Segment-III	0.874	3.93	3.26	0.56	2.65
July (R = 9.49x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.506	17.43	8.20	0.86	0.86
Segment-II	0.729	2.68	1.95	0.20	1.06
Segment-III	0.870	3.75	3.26	0.56	1.62
August (R = 18.83x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.496	16.96	8.41	0.86	0.86
Segment-II	0.729	2.68	1.95	0.20	1.06
Segment-III	0.810	3.78	3.06	0.16	1.22
October (R = 5.77x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.522	13.33	8.52	1.47	1.47
Segment-II	0.693	2.74	1.90	0.32	1.89
Segment-III	0.770	3.73	2.87	0.49	2.38
November (R = 5.29x10 ⁶ .m ³ /tide cycle)					
Segment-I	0.696	16.38	11.40	1.47	1.47
Segment-II	0.778	2.72	2.12	0.40	1.87
Segment-III	0.824	3.74	3.08	0.55	1.42

Segment -I (Azhikode -Kottappuram), Segment-II (Kottappuram -Gothuruthu), Segment -III (Gothuruthu-Chennmanglam)

February
 $f=0.0349.X+0.006(\text{for } R=16.41\text{m}^3.\text{s}^{-1}) \dots(2)$

March
 $f=0.0126.X+0.016(\text{for } R=0.076\text{m}^3.\text{s}^{-1}) \dots(3)$

April
 $f=0.0126.X+0.076(\text{for } R=10\text{m}^3.\text{s}^{-1}) \dots(4)$

June
 $f=0.0510.X+0.293(\text{for } R=123\text{m}^3.\text{s}^{-1}) \dots(5)$

July
 $f=0.0510.X+0.368(\text{for } R=204\text{m}^3.\text{s}^{-1}) \dots(6)$

August
 $f=0.0460.X+0.367(\text{for } R=387\text{m}^3.\text{s}^{-1}) \dots(7)$

October
 $f=0.0332.X+0.438(\text{for } R=121\text{m}^3.\text{s}^{-1}) \dots(8)$

November
 $f=0.0185.X+0.644(\text{for } R=111\text{m}^3.\text{s}^{-1}) \dots(9)$

One dimensional diffusion equation of Stommel⁵ is used for calculating distribution of pollutant in this paper. The advantage of Stommels method of mixing in vertically homogeneous estuary is that it does not call for assumption on the physical nature of the longitudinal diffusivity, which is deduced from the distribution of freshwater. The net seaward flux of pollutant through any section X is:

$F(X)=R_c-A.K_x.dC/dx \dots(10)$

where R is the river discharge and C is the concentration of pollutant and A is the cross -

sectional area of the section under consideration. Downstream of the source, the net flux must be constant and equal to the input. Upstream, it will be zero. Provided the diffusion coefficients for the pollutant can be assumed to be the same as that for salt, we can determine the K_x by putting $F(X)$ equal to the river flow and the fraction f for C. Thus

$$K_x = R(1-F)/A df/dx \quad \dots (11)$$

The values of K_x thus calculated are put into equation (10) and equation is written in finite difference method and solved by successive approximation. Longitudinal eddy diffusivity (K_x) is calculated for four cross-section in the Azhikode estuary (Table 3) using equation (11). Equations (1) to (9) were used to determine the df/dx for the corresponding period. At section-I, eddy diffusivity varied from $2 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ in January to $40 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ in August. At Kottappuram K_x ranged between $4.39 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ to $41.20 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$. At Gothuruthu K_x values varied between a minimum of $2.70 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ in January to a maximum of $28.96 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ in August. Similar trend was observed at Section IV, it varied within the range $0.98 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$ to $7.04 \times 10^6 \text{ cm}^2 \cdot \text{s}^{-1}$. Values of longitudinal eddy diffusivity obtained in the Azhikode estuary are comparable with the results obtained for the Beypore estuary⁶ where the K_x value varied between 6.0 and $90 \text{ cm} \times \text{cm}^2 \cdot \text{s}^{-1}$ near the bar-mouth. Vertical eddy diffusivity K_z in the Azhikode estuary during post monsoon season has earlier been computed¹. Computed values showed a decreasing tendency in the upstream direction. When K_z values were plotted against non-dimensional depth (η) for section-I and section-III, at section-I K_z was found to increase with the depth and reaches the maximum value

Table 3—Longitudinal eddy diffusivity ($\text{cm}^2 \cdot \text{s}^{-1} \times 10^6$) at various cross-sections

Months	Azhikode	Kottappuram	Gothuruthu	Chennamangalam
	I	II	III	IV
January	2.59	4.29	2.70	0.98
February	3.44	6.33	3.83	2.50
March	4.13	7.37	5.45	4.29
April	5.26	10.49	7.71	5.30
June	10.70	13.22	4.88	1.07
July	18.80	17.41	9.89	1.45
August	39.80	41.20	28.96	7.04
October	17.40	17.20	10.41	6.56
November	17.80	19.42	13.66	7.69

($\eta=0.50$ and thereafter decreases with depth whereas at section-III, K_z exhibited two maxima at $\eta=0.3$ and ($\eta=0.8$ due to strong vertical mixing above and below the halocline and a region of relatively high stability in the vicinity of the halocline.

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