

## A study on the seasonal dynamics of Beypore estuary, Kerala coast

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Mixing characteristics of the Beypore estuary were determined up to 15 km upstream of Chaliyar river. The study area was divided into four sections (5 km interval) with two transverse stations on either side of each section. The diffusivity values were found to be almost equal in four sections during premonsoon months. In July it was  $9.08 \text{ m}^2/\text{sec}$  at river mouth and zero at the upper reaches of the estuary. In postmonsoon season the diffusivity values decreased upstream. Maximum value of flushing time was computed in March (14.85 tidal cycle) and minimum in July (0.23 tidal cycle). At the river mouth the water flux was directed seaward during the postmonsoon and monsoon season. During the premonsoon period the transport was upstream and the net transport was higher during May. Maximum flux of the suspended sediment was obtained during July ( $1220.97 \text{ mg}/\text{cm}^2/\text{sec}$ ) at the river mouth. Highly negative fluxes were obtained during premonsoon period with the highest negative value occurring during May ( $-381.31 \text{ mg}/\text{cm}^2/\text{sec}$ ) at river mouth. During the study period the annual sediment input and the net sediment transported towards the sea were estimated to be  $8.8 \times 10^4$  and  $5.7 \times 10^4$  tons/year respectively so that the annual entrapment of sediment was  $3.1 \times 10^4$  tons/yr. The logarithmic values of Richardsons number ( $\log R_L$ ) showed large variation at river mouth section of the estuary and at about 10 kms upstream during the postmonsoon period. During the premonsoon period there was no noticeable variation in  $\log R_L$  values at these two places and the estuary was found to be well mixed. During the monsoon period, the stratification was higher and the variation in  $\log R_L$  was high from flood to ebb tide.

[ **Key words:** Beypore estuary, eddy diffusivity, flushing time, flux, sediment budget ]

Estuaries are complex dynamic systems that serve as a transition zone between terrestrial and marine environments. Estuarine processes control the distribution and transportation of suspended sediments. These processes vary in a systematic manner within the tidal cycles (semi-diurnal and diurnal) and weather cycles (seasonal and inter annual cycles)<sup>1,2</sup>. Earlier studies have been conducted to understand the circulation, mixing and salinity distribution in the Beypore estuary<sup>3,4</sup>. But these studies were confined to the river mouth region only. No attempt has been made so far to study the region beyond the tidal influence and also a synoptic data collection. Information on the dynamics of the Beypore estuary-velocity and density fields, river discharges and suspended sediment distribution etc. are not reported so far. The main objectives of the present study are i) to understand the mixing characteristics, ii) the residual fluxes of salt and water, iii) flushing characteristics, iv) the flux of materials and v) the transportation of suspended sediments in the Beypore estuarine system.

### Materials and Methods

In order to study the mixing and suspended sediment distribution in the estuary it has been divided into four sections (5 km interval) up to 15 km

upstream with two transverse stations on each section. A map showing the area of study and the sampling locations are given in Fig. 1. The tides at Beypore estuarine system are of semidiurnal type with a period of 12 hr and 40 minutes. The maximum tidal range obtained during spring tide in the entire period of study was 1.2 m and during neap tide it was 0.80 m. The water level data during the period of study was collected from Minor Port Authorities, Beypore Calicut

Monthly data on current, salinity and suspended sediment were collected for one tidal cycle (13 hrs) from four sections for a period of nearly one year from October 1990 to September 1991. Hourly measurements of current and salinity at 1 m depth interval at each station were made using the Direct Reading Current Meter (accuracy for velocity  $\pm 0.01 \text{ m}/\text{sec}$  and direction  $\pm 2.68^\circ$ ) and STD meter (accuracy  $\pm 0.1 \text{ psu}$ ) respectively. Suspended sediment concentration was measured at the surface, mid depth and bottom (the water samples were filtered through a pre-weighed Millipore filter paper of  $0.45 \mu\text{m}$  pore size and a diameter of 0.047 m). River flow data during the period of study was obtained from the Central Water Commission, Cochin.

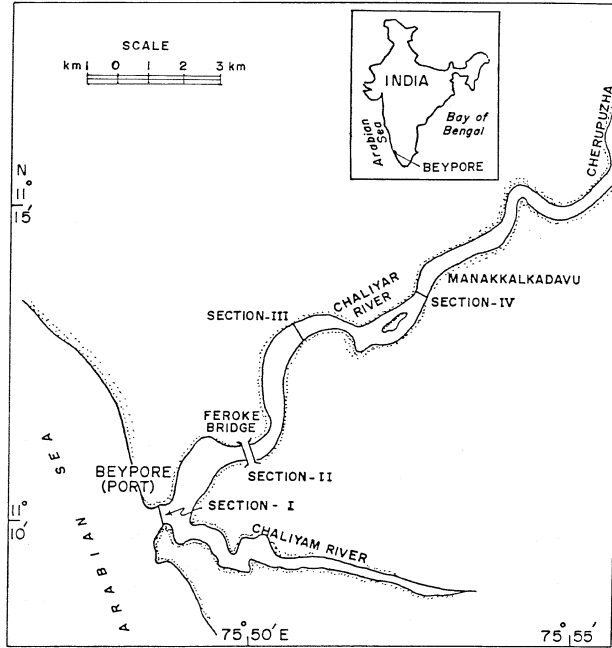


Fig. 1—Observation sections and stations in the estuary.

*Estimation of coefficient of eddy diffusivity*—The longitudinal coefficient of eddy diffusivity ( $K_x$ ) and flushing time were computed<sup>5,6</sup> as following :

$$K_x = Rs/A(\delta s/\delta x) = R(f-1)/A(\delta f/\delta x)$$

where  $K_x$  ( $m^2/sec$ ) is the longitudinal coefficient of eddy diffusivity, ' $f$ ' is the fresh water fraction, ' $R$ ' is the river discharge( $m^3/sec$ ), ' $A$ ' is the mean area of cross section ( $m^2$ ) and  $(\delta f/\delta x)$  is the longitudinal variation of fresh water fraction, and ' $s$ ' is the salinity. The flushing time ( $T$ ) is computed as :

$$T = [\text{Mean}(f) \cdot V] / R$$

where ' $V$ ' is the total volume of the estuarine region, ' $f$ ' is the freshwater fraction and ' $R$ ' is the river discharge.

If  $S$  is the salinity of mixed water and  $S_s$  is the salinity of seawater then the fresh water fraction( $f$ ) is calculated from :

$$f = (S_s - S) / S_s$$

*Estimation of fluxes of salt, water and suspended sediment*—The cross sectional averaged value for all the parameters was taken for the computation of fluxes.  $H$  and  $V$  are the instantaneous depth and current velocity. Then the instantaneous rate of transport of water through a unit width of water column of depth  $H$  is  $Q = HV$ . The residual rate of transport<sup>7-11</sup> per unit width of water column is:

$$\langle Q \rangle = \langle HV \rangle$$

The residual rate of transport of salt is

$$\langle Q_s \rangle = \langle H \rangle [V_{1,s} + V_{2,s} + V_{3,s}]$$

where  $V_{1,s}$ ,  $V_{2,s}$  and  $V_{3,s}$  are the depth averaged residual fluxes of salt (in units of  $10^{-3} g/cm^2/sec$ ) due respectively to the residual transport of water  $\langle Q \rangle$ , the tidal pumping resulting from a non-zero correlation between  $Q$  and  $S$ , and the vertical shear in the tidal and residual currents. Suspended sediment fluxes were calculated from velocity and sediment concentration<sup>12,13</sup>

Material transport through a particular cross section was obtained by multiplying the net fluxes by the mean cross sectional area. The positive sign indicated transport towards the sea and the negative sign indicated transport towards the river.

Richardsons number ( $R_L$ ) is calculated as :

$$R_L = gh(\rho_b - \rho_s) / U^2 \rho_o$$

where  $U$  is the depth mean velocity,  $\rho_o$  is the depth mean density,  $h$ , the water depth and  $(\rho_b - \rho_s)$  is the surface to bottom density difference. Calculation of Richardsons number allows a quantitative estimate of the intensity of mixing at different stages of the tide in a partially mixed estuary. When  $R_L < 2$  the bed generated turbulence is the main mixing process and for  $R_L > 20$ , the water column is stable and bottom turbulence is not effective in mixing<sup>14</sup>

## Results and Discussion

The computed values of longitudinal coefficient of eddy diffusivity are given in Table 1. The diffusivity values were found to be almost equal in four sections during premonsoon (February to May) season. In March it did not show any considerable variation and it has a constant value of  $0.06 m^2/sec$  from lower reaches to 15 km upstream. During April and May also the variation in the diffusivity coefficients were found to be negligible. The low diffusivity values obtained during the premonsoon season shows the estuary was well mixed and influence of fresh water was very low. Diffusivity values showed a predominant variation in the monsoon (June to September) period. It was  $9.08 m^2/sec$  at rivermouth during July when the river discharge was maximum and in the upper reaches of the estuary it was found to be zero due to the domination of fresh water. In postmonsoon (October to January) season the diffusivity values decrease towards upstream and in December it varied between  $0.26$  to  $0.06 m^2/sec$  from the marine end to the river end.

The flushing time was calculated for every month and is given in Table 1. It showed higher values during the premonsoon season and lower values during monsoon. After the postmonsoon season the value increased from January onwards and maximum value was computed in March (14.85 tidal cycles) and which shows that pollutants cannot be flushed out easily from the estuary during this period due to the low river run-off. In monsoon period the river discharge was high and the flushing time required to flush out the materials present in the estuary was very less. In July the value of flushing time was found to be 0.23 tidal cycle. Higher values were not observed during the postmonsoon period. Flushing time computed in October was 1.89 tidal cycle. During November and December the flushing time values were 1.60 and 4.81 tidal cycles respectively.

*Semi-diurnal variation of salinity and Richardsons number during different seasons*

Since  $R_L$  values are high the logarithmic values of  $R_L$  were taken. From the synoptic observations made in the entire study area it was seen that the salinity values were nearly zero at sections III and IV during the postmonsoon and monsoon periods and the intrusion of saline water was predominant at section-III and section-IV only during premonsoon season so the studies on mixing were conducted in section-I and section-II. As shown in Fig. 2 the hourly salinity profiles at section-I and section- II (the averaged value of the two stations in each section) were taken for the graphical representations here. During the postmonsoon season the salinity profile indicates the formation of a higher vertical salinity gradient (23) at section-I during 1200 to 1300 hrs and it reduced to a minimum (4) at 1700 hrs. The value of  $R_L$  (the averaged value of the two stations in each section) showed a similar variation, i.e. maximum when the stratification was high (Fig. 3) and minimum when the stratification was low at both the sections i.e. the  $\log R_L$  values vary between 3.08 and - 0.045 at section-I and between 3.88 and -0.45 at section-II from the maximum stratification period to the minimum stratification period. During ebb tide strong currents (40 cm/sec) lead to increased turbulence and mixing. During the postmonsoon season the river discharge was moderately high (80 m<sup>3</sup>/sec, Table 1) and during high tide also the surface layer was found to be lower in salinity and maximum stratification was found at section-II during high tide. This was reflected in the rapid decrease of  $R_L$  at both sections when the stratification was weak.

Table 1—Longitudinal coefficient of eddy diffusivity and flushing time for different months

| Period/Area | Distance from the mouth (km) | Cross sectional area (m <sup>2</sup> ) | Fresh water fraction | River discharge (m <sup>3</sup> /sec) | Longitudinal eddy diffusivity (m <sup>2</sup> /sec) | Flushing time (tidal cycle) |
|-------------|------------------------------|----------------------------------------|----------------------|---------------------------------------|-----------------------------------------------------|-----------------------------|
| October     |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1138.80                                | 0.49                 |                                       | 0.95                                                |                             |
| II          | 5                            | 1029.00                                | 0.71                 | 71.03                                 | 0.59                                                | 1.89                        |
| III         | 10                           | 906.50                                 | 0.99                 |                                       | 0.02                                                |                             |
| IV          | 15                           | 736.29                                 | 0.99                 |                                       | 0.02                                                |                             |
| November    |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1123.2                                 | 0.40                 |                                       | 1.07                                                |                             |
| II          | 5                            | 1022.00                                | 0.74                 | 80.36                                 | 0.49                                                | 1.60                        |
| III         | 10                           | 903.00                                 | 0.98                 |                                       | 0.04                                                |                             |
| IV          | 15                           | 717.00                                 | 0.99                 |                                       | 0.01                                                |                             |
| December    |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1150.00                                | 0.19                 |                                       | 0.26                                                |                             |
| II          | 5                            | 1038.00                                | 0.39                 | 17.14                                 | 0.23                                                | 4.81                        |
| III         | 10                           | 912.54                                 | 0.64                 |                                       | 0.14                                                |                             |
| IV          | 15                           | 743.58                                 | 0.88                 |                                       | 0.06                                                |                             |
| January     |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1068.60                                | 0.08                 |                                       | 0.17                                                |                             |
| II          | 5                            | 976.08                                 | 0.32                 | 8.51                                  | 0.14                                                | 7.34                        |
| III         | 10                           | 870.33                                 | 0.51                 |                                       | 0.11                                                |                             |
| IV          | 15                           | 692.55                                 | 0.73                 |                                       | 0.08                                                |                             |
| February    |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1097.90                                | 0.06                 |                                       | 0.11                                                |                             |
| II          | 5                            | 937.86                                 | 0.15                 | 3.44                                  | 0.11                                                | 1070                        |
| III         | 10                           | 844.00                                 | 0.33                 |                                       | 0.09                                                |                             |
| IV          | 15                           | 661.00                                 | 0.48                 |                                       | 0.09                                                |                             |
| March       |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1138.80                                | 0.01                 |                                       | 0.06                                                |                             |
| II          | 5                            | 1029.00                                | 0.09                 | 1.60                                  | 0.06                                                | 14.85                       |
| III         | 10                           | 906.50                                 | 0.18                 |                                       | 0.06                                                |                             |
| IV          | 15                           | 736.29                                 | 0.31                 |                                       | 0.06                                                |                             |
| April       |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 939.90                                 | 0.00                 |                                       | 0.10                                                |                             |
| II          | 5                            | 879.06                                 | 0.09                 | 2.19                                  | 0.10                                                | 9.72                        |
| III         | 10                           | 804.00                                 | 0.19                 |                                       | 0.09                                                |                             |
| IV          | 15                           | 612.36                                 | 0.32                 |                                       | 0.09                                                |                             |
| May         |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1033.50                                | 0.00                 |                                       | 0.08                                                |                             |
| II          | 5                            | 949.62                                 | 0.11                 | 1.80                                  | 0.08                                                | 10.85                       |
| III         | 10                           | 852.24                                 | 0.19                 |                                       | 0.07                                                |                             |
| IV          | 15                           | 670.68                                 | 0.33                 |                                       | 0.07                                                |                             |
| June        |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1053.00                                | 0.89                 |                                       | 3.97                                                |                             |
| II          | 5                            | 964.32                                 | 0.97                 | 273.33                                | 0.04                                                | 0.54                        |
| III         | 10                           | 862.29                                 | 1.00                 |                                       | 0.00                                                |                             |
| IV          | 15                           | 682.83                                 | 1.00                 |                                       | 0.00                                                |                             |
| July        |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 1111.50                                | 0.91                 |                                       | 9.08                                                |                             |
| II          | 5                            | 1008.42                                | 1.00                 | 670.00                                | 0.00                                                | 0.23                        |
| III         | 10                           | 892.44                                 | 1.00                 |                                       | 0.00                                                |                             |
| IV          | 15                           | 719.28                                 | 1.00                 |                                       | 0.00                                                |                             |
| August      |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 975.00                                 | 0.80                 |                                       | 5.08                                                |                             |
| II          | 5                            | 905.52                                 | 0.93                 | 329.66                                | 0.57                                                | 0.41                        |
| III         | 10                           | 822.09                                 | 1.00                 |                                       | 0.00                                                |                             |
| IV          | 15                           | 634.23                                 | 1.00                 |                                       | 0.00                                                |                             |
| September   |                              |                                        |                      |                                       |                                                     |                             |
| I           | 0                            | 967.20                                 | 0.48                 |                                       | 1.12                                                |                             |
| II          | 5                            | 899.64                                 | 0.73                 | 73.00                                 | 0.72                                                | 1.54                        |
| III         | 10                           | 818.07                                 | 0.88                 |                                       | 0.09                                                |                             |
| IV          | 15                           | 629.37                                 | 0.99                 |                                       | 0.01                                                |                             |

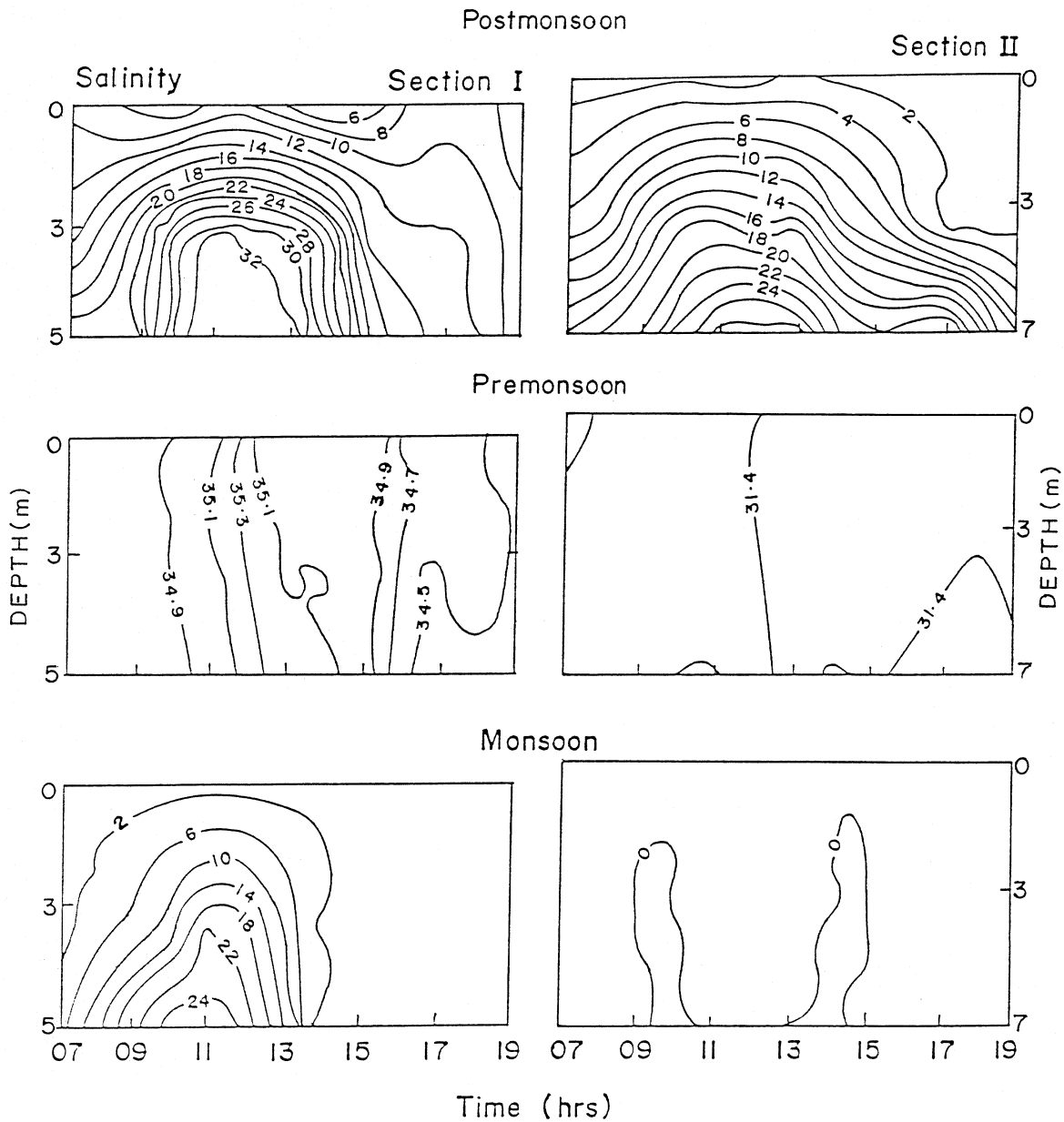


Fig. 2— Semi-diurnal and seasonal variation of salinity at Section -I and Section-II

During the premonsoon period river discharge into the estuarine system was very low and tidal influx was higher compared to other seasons. The  $\log R_L$  varies between 0.38 and -0.206 at section-I and between 0.38 and -0.106 at section-II. Due to the higher influence of saline water, both the sections were found to be weakly stratified, so that  $\log R_L$  did not show a higher value in the entire tidal observation. Strong inflow in the lower layer of the water column may cause considerable bed generated turbulence at both the sections I and II, this might be the reflection of the lower values of  $R_L$  during this period of study.

During the monsoon period at section-I higher stratification values were observed due to the high freshwater flow from the upper reaches of the estuary and the logarithmic value of the Richardson's number showed a significant variation between 2.377 and -0.82 from high tide to low tide because of the salinity intrusion which was predominant only during the flood tide and high vertical gradient in salinity was observed. At section-II the intrusion of saline water was very less and the Richardson's number did not show any significant variation. Maximum river discharge ( $670 \text{ m}^3/\text{sec}$ ) was observed during the

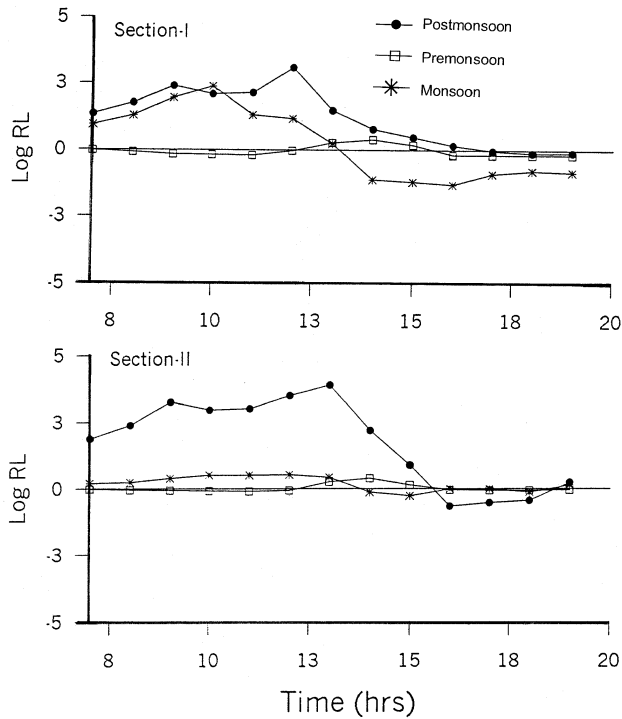


Fig. 3—Semi-diurnal and seasonal variation of  $\log R_L$  at Section-I and Section-II

monsoon season. Hourly salinity profile showed the maximum salinity gradient (24) at 1100 hrs was significant at section-I. Just an hour prior to this time Richardson's number reached the maximum (2.52) confirming the high stratified condition. During ebb tide the seaward flow due to freshwater discharge increases and the influx of saline water was very less. Therefore surface to bottom density difference ( $\rho_b - \rho_s$ ) becomes negligibly small and the depth mean velocity reached maximum and the corresponding value of  $R_L$  reduced to a minimum value. A noticeable variation in the computed values of  $R_L$  were found during the monsoon period.

#### Monthly variation of salt fluxes

The salt transport at sections I-IV are shown in Fig. 4. In the entire observation period the residual flow of salt was mainly controlled by the residual flow of water. In postmonsoon months flux was seaward in direction at sections I-IV and during monsoon it was found to be nearly zero except at section-I (Fig. 4d). During the premonsoon period the transport was upstream and was higher during May. Comparing with the salt flux due to the residual flow of water (Fig. 4a), the flux of salt due to tidal pumping (Fig. 4b), and vertical shear (Fig. 4c), were insignifi-

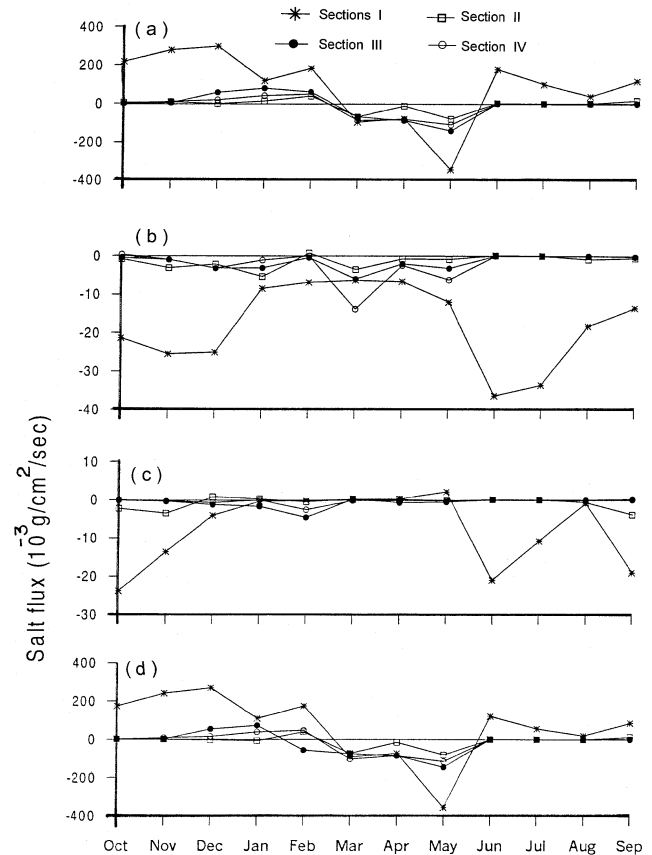


Fig. 4—Annual variation of residual fluxes of salt ( $10^{-3} \text{g/cm}^2/\text{sec}$ ) at Sections I-IV due to a) residual flow of water, b) tidal pumping, c) vertical shear, d) sum of the above three fluxes

cant except during monsoon months, during monsoon both these terms were found to be significant at sections I and nearly zero at sections II, III and IV. Salt flux due to vertical shear is diffusive and emphasises the importance of shear processes for the flux of salt in the upstream sections. In general the net transport of salt was mainly depended on the magnitude of the salt flux due to residual flow of water at all the four sections. The salt transport due to tidal pumping and vertical shear were predominant only in the lower reaches of the estuary, but there also the dominance of salt flux due to residual flow of water was much more effective.

#### Sediment budget

The net flux of suspended sediment ( $\text{mg/cm}^2/\text{sec}$ ) through four cross sections in the estuary are represented in Fig. 5. Generally the net flux increases from head to mouth of the estuary. Owing to the high river discharge and associated seaward current large positive fluxes (towards the sea) are observed. The

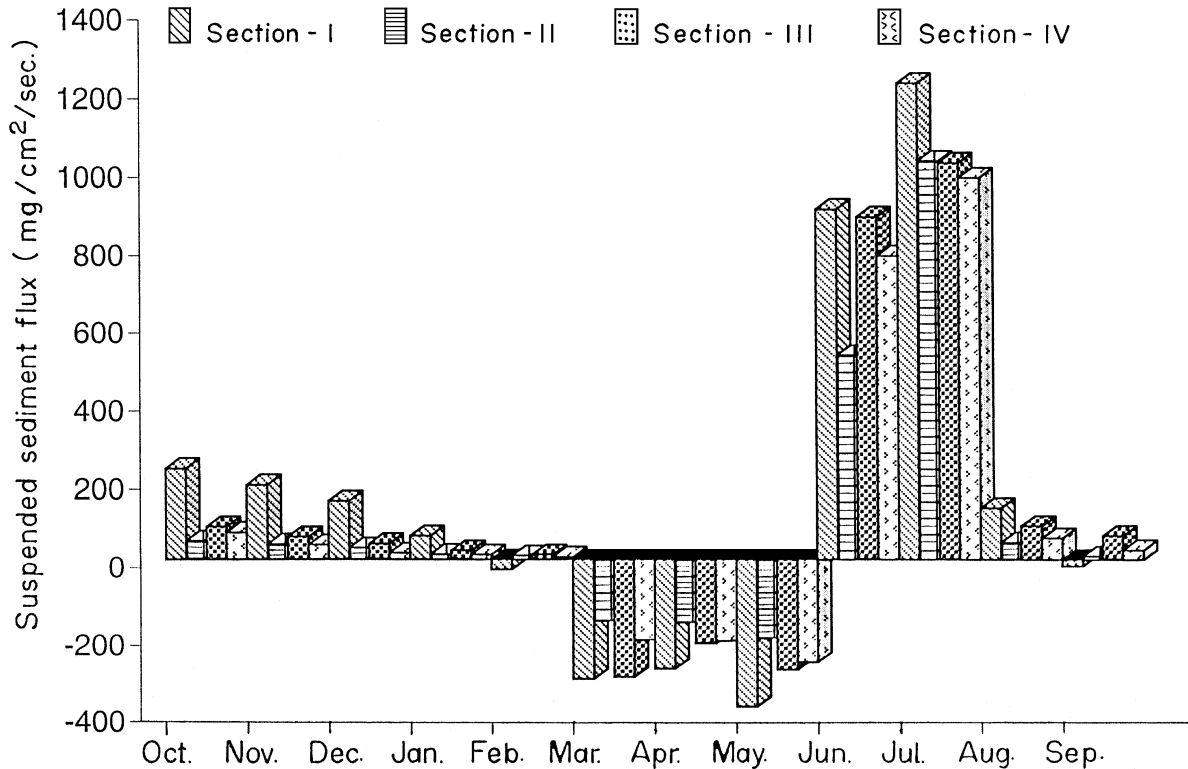


Fig. 5—Annual variation of suspended sediment flux ( $\text{mg}/\text{cm}^2/\text{sec}$ )

maximum flux of the suspended sediment is obtained during July ( $1220.97 \text{ mg}/\text{cm}^2/\text{sec}$ ) at the lower most section of the estuary. During the postmonsoon season fluxes are positive but lesser in value comparing with the monsoon season. Sediment fluxes are upstream during premonsoon period with a maximum value in May ( $-381.31 \text{ mg}/\text{cm}^2/\text{sec}$ ) at river mouth.

Suspended solid concentrations and transports are high during peak monsoon period. For computation of the river input of suspended sediment, river discharge data and mean suspended sediment concentration during ebb tide at the upper most section (nearly the upper limit of the tidal influence) are used. The annual sediment input estimated during the study period was  $8.8 \times 10^4$  tons/yr. The net sediment transported towards the sea was estimated to be  $5.7 \times 10^4$  tons/yr. The annual entrapment of sediment in the estuary was obtained by taking the difference between the total river input and net seaward transport. As a result the estuary is a sink for the suspended sediment. The annual entrapment of the sediment in Beypore estuary was calculated to be  $3.1 \times 10^4$  tons/yr.

The longitudinal coefficient of eddy diffusivity was almost equal at the four sections during the premonsoon period, which shows less influence of fresh

water and well mixed condition of the estuary. The predominant variation in the longitudinal coefficient eddy diffusivity was obtained during July at section-I. Semidiurnal variation in Richardson's number at section I and II shows a highly mixed condition during premonsoon period and a highly stratified condition during monsoon and postmonsoon period. The Richardson's number essentially compares the stabilising effect of density stratification to current shear which leads to mixing.

A detailed study on the flushing characteristics of the Beypore estuary was undertaken to understand the fate of pollutants in the river and estuarine area. Liquid wastes from The Mavoor Gwalior rayons factory and fishing harbour are released into the Chaliyar river which pollutes the river. From the flushing time computed for different months it can be suggested that a pollutant introduced in the Beypore estuary will not be flushed out easily during the premonsoon season because the buoyancy of the incoming fresh water was insufficient to overcome the mixing due to strong tidal currents. But during the monsoon months domestic and industrial wastes discharged into the estuarine system will be flushed out easily due to high river run-off. The annual entrapment of the sediment was  $3.1 \times 10^4$  tons/yr as a result the estuary is a sink

$3.1 \times 10^4$  tons/yr as a result the estuary is a sink for the suspended sediment.

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