

## Studies on mixing of the waters of different salinity gradients using Richardsons number and the suspended sediment distribution in the Beypore estuary, south west coast of India

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The study was conducted up to 15 km upstream in the Beypore estuary of the Chaliyar river in Calicut. The study area was divided into four sections (5 km interval) with two transverse stations on either side of each section. The logarithmic values of Richardsons number ( $\log R_L$ ) shows high variation at river mouth section of the estuary (section-I) and at about 10 km upstream (section-II) during the postmonsoon period. During the premonsoon period there was no noticeable variation in  $\log R_L$  values at section-I and section- II 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. The lower part of the estuary is a turbidity maximum zone, especially during premonsoon season. During the postmonsoon period the concentration of suspended matter was not high compared to premonsoon and monsoon period. There was a high surface value during ebb tide in monsoon period.

Estuaries are complex dynamic systems that serve as a transition zone between terrestrial and marine environments. Dynamic estuarine processes control the distribution and transportation of suspended sediments. Estuarine processes vary in a systematic manner within the tidal cycles (semi-diurnal, diurnal) and weather cycles (seasonal and inter annual cycles)<sup>1,2</sup>.

The hydrography of the Beypore estuary<sup>3</sup>, exchange of fresh and salt water in the estuary<sup>4</sup> and also on the circulation and mixing<sup>5</sup> have been reported earlier. Relation between dissolved oxygen and salinity and the distribution of salinity too were reported<sup>6</sup>. Vertical suspended sediment distribution in the Beypore estuary was studied earlier<sup>7</sup>. The main objective of this study is to understand the mixing processes and the distribution pattern of the suspended sediment in the estuary.

### Materials and Methods

Chaliyar river, the third largest river in Kerala, flows towards west from Western Ghats and joins the Arabian Sea at Beypore (Fig. 1). The Beypore estuary of the Chaliyar river joins the sea in a south westerly direction and the inlet is situated in a stable region.

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.

Synoptic observations of current, salinity and suspended sediment were made every month for one tidal cycle from

four sections with two stations within each section for a period of one year starting from October 1990 to September 1991 (October to January is coming under postmonsoon, February to May is coming under premonsoon and June to September is coming under monsoon season). Since the tide in this region is of semi-diurnal type the observations were extended to 13 hour to cover one complete

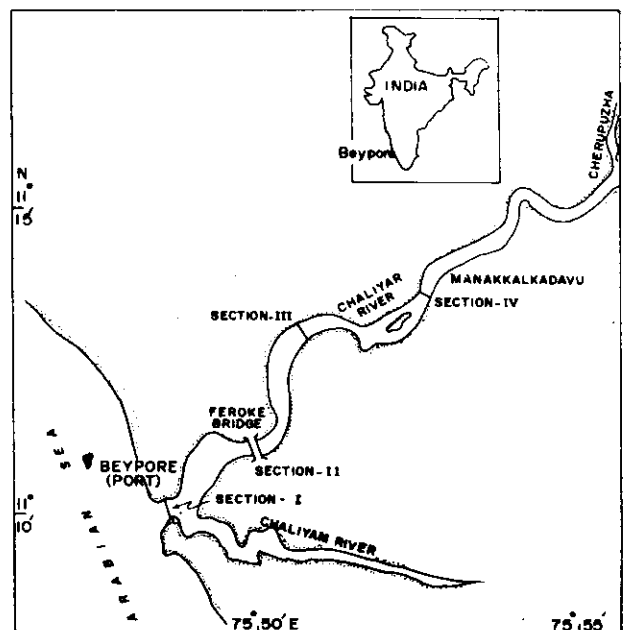


Fig. 1—Observation sections and stations in the estuary.

tidal cycle. The hourly current measurements at 1m depth interval at each station were made using the Direct Reading Current Meter (accuracy for speed is  $\pm 1$  cm/s and direction  $\pm 2.68^\circ$ ) designed by National Institute of Oceanography, Goa. Hourly observations of salinity were taken (the STD meter designed by Environmental System Engineers, Cochin was mainly used for salinity measurements, accuracy  $\pm 0.1$ ) at each station from surface to bottom at 1m interval. Hourly concentrations of suspended load were 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 47 mm. After filtration the filters were rinsed with distilled water thrice and dried at  $70^\circ\text{C}$ . The difference between final and initial weights gives the concentration of the suspended sediment(mg/l).

The gradient Richardson's number is defined as

$$R_g = -(gd\rho/dz)/\rho(du/dz)^2 \quad \dots (1)$$

where  $\rho$  = water density,  $u$  = velocity at height  $z$  above bed and  $g$  = acceleration due to gravity.  $R_g$  is a dimensionless number which essentially compares the stabilising effect of density stratification ( $d\rho/dz$ ), to the current shear which leads to mixing ( $du/dz$ ). There is a theoretical critical value of  $R_g = 0.25$ , below which turbulent mixing of the water column may occur, although values up to 1 are sometimes used for this limit<sup>8</sup>. For  $R_g > 0.25$ , the stratification should be sufficient to inhibit vertical mixing.

In practice, it is difficult to measure the required variables at Eq. (1) at sufficiently closed and spaced depth intervals. When the mixing is due mainly to be generated turbulence, the layer Richardson's number ( $R_L$ ) would be more suitable for use as a simplified mixing criteria for partially mixed estuaries<sup>9</sup>.  $R_L$  is calculated as

$$R_L = gh(\rho_b - \rho_s)/U^2\rho_0 \quad \dots (2)$$

where  $U$  = the depth mean velocity,  $\rho_0$  = the depth mean

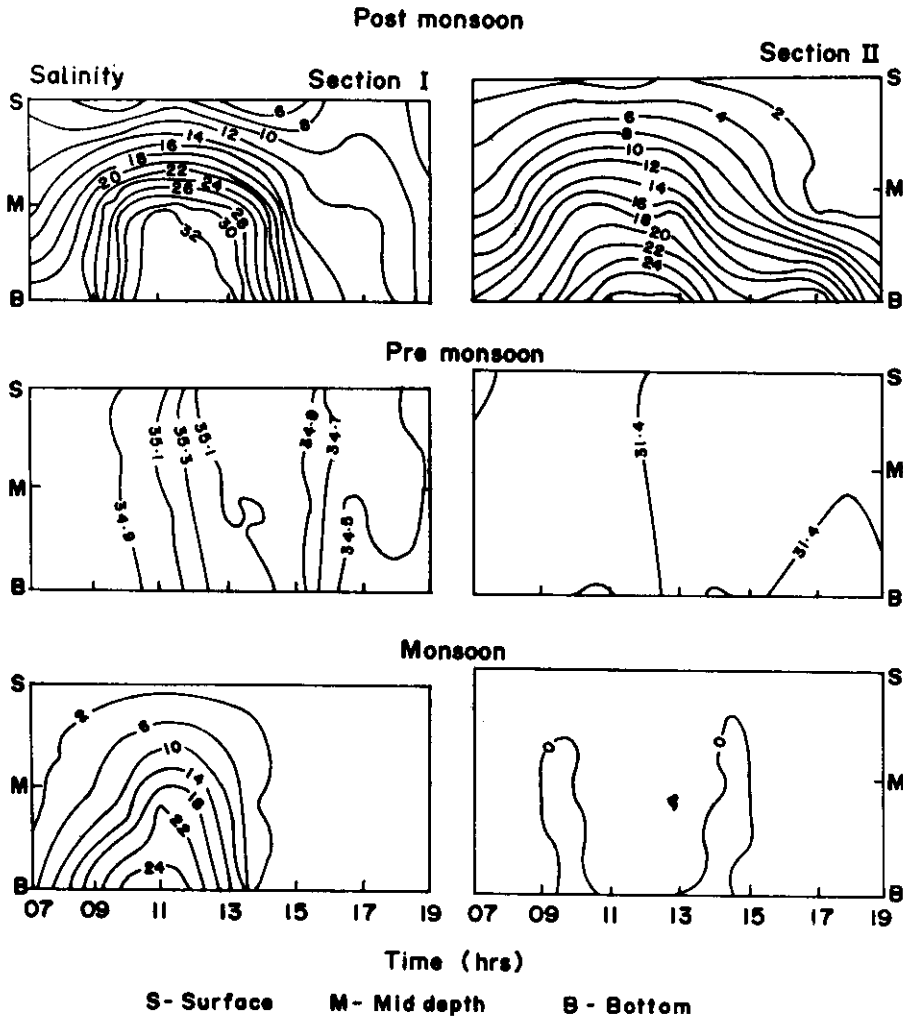


Fig. 2—Semi-diurnal and seasonal variation of salinity at Sections- I and II

density,  $h$ , the water depth and  $(\rho_b - \rho_s)$  = the surface to bottom density difference. Calculation of  $R_L$  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>9</sup>.

### Results and Discussion

#### *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/s) lead to increased turbulence and mixing. During the postmonsoon season the river discharge was moderately high (80m<sup>3</sup>/s, Fig. 4) 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.

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  $\log R_L$

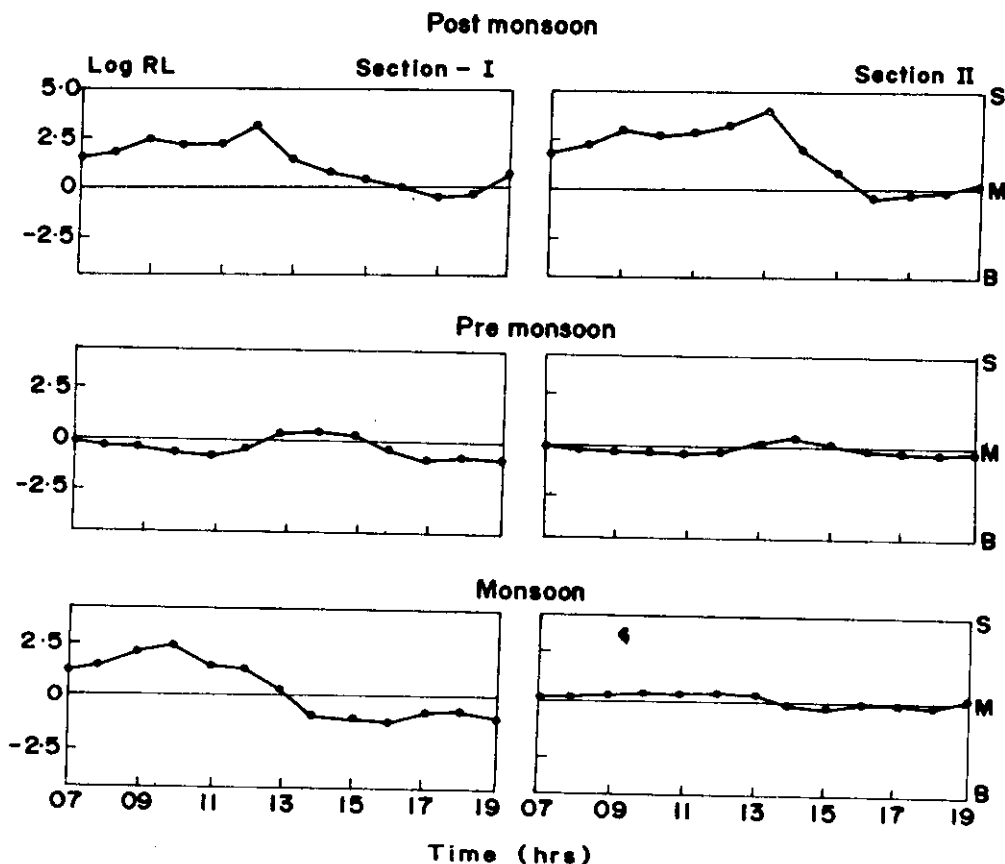


Fig. 3—Semi-diurnal and seasonal variation of  $\log R_L$  at Sections - I and II

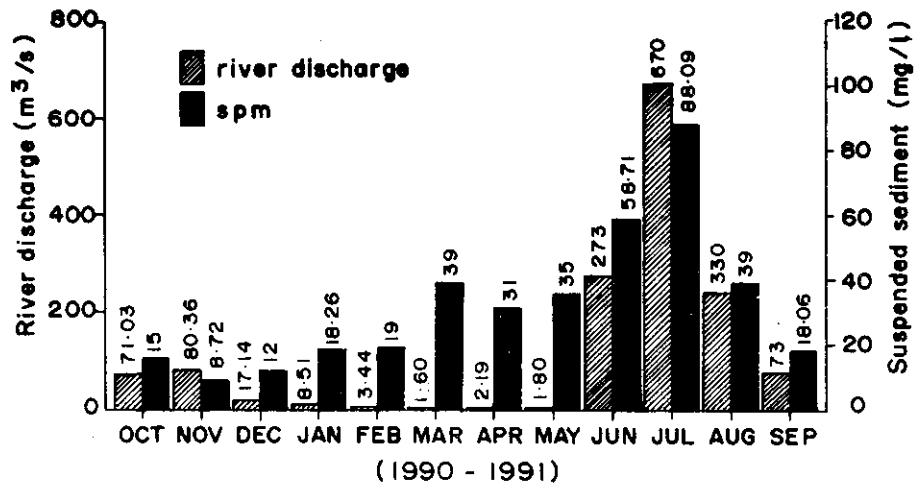


Fig. 4—Annual variation of river discharge (m<sup>3</sup>/s) and suspended sediment concentration (mg/cm<sup>2</sup>/s)

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 m<sup>3</sup>/s) was observed during the 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.

#### Annual variation of river flow and suspended sediment concentration

River flow data during the period of study was obtained from the Central Water Commission. The monthly variation of the river discharge and depth averaged sediment concentration at the upper most section is given in Fig. 4.

Both the river flow and depth averaged value of the suspended sediment concentration at the uppermost section showed pronounced seasonal variation. During the premonsoon and postmonsoon seasons the flow varied between 1.6 m<sup>3</sup>/s to 80.36 m<sup>3</sup>/s but during July (monsoon) the flow had reached 670 m<sup>3</sup>/s. The suspended sediment concentration pattern was similar to the variation of the river flow especially during the monsoon season (Fig. 4). The minimum value of the suspended matter was obtained in the postmonsoon season that is during the moderate river flow period. During this season the depth mean value of the suspended matter concentration varied from 9 mg/l to 18 mg/l. During the premonsoon period the influence of the tidal current was very high and the suspended matter in the lower reaches was high in concentration due to the silt and clay material present at sections I and II. These materials were carried even to the upper reaches by the strong tidal currents. During these low river flow periods the depth averaged value of the suspended matter varied from 19 to 39 mg/l. The depth averaged value of the suspended matter was 58 mg/l in June and 88 mg/l in July and it was the maximum value obtained in the entire period of observations. In August and September it was 38 mg/l and 18 mg/l respectively. The Turbidity Maximum Zone (TMZ) is a distinct factor in the Beypore estuary. It is characterised by the maximum suspended load concentration. The lower part of the estuary is having more turbidity maximum zone, especially during premonsoon season.

#### Longitudinal distribution of suspended sediment concentration during flood and ebb tides

The concentration of suspended sediment in flood and ebb tide during all seasons were used to isolate the effect of tide on the suspended sediment distributions, which are presented in Fig. 5.

The suspended sediment concentration was always higher at high tide than at low tide. From Fig. 5 it can be seen that during the postmonsoon and premonsoon seasons higher concentration of suspended matter was observed during flood tide. But in the monsoon season the entire study area was found to be highly turbid with higher suspended matter at both the tidal phases. In postmonsoon suspended matter concentration ranged from 16 mg/l to 44 mg/l from surface to bottom at river mouth during flood tide. During ebb tide it ranged from 12 mg/l to 16 mg/l from surface to bottom. During premonsoon higher values of suspended sediment (32 - 70 mg/l from surface to bottom) were observed at section-I due to the high influx of saline water during flood tide which cause the resuspension of bottom sediment. Comparing with the postmonsoon season the suspended sediment concentration during the premonsoon season is higher even at the upper reaches of the estuary. This phenomenon may be mainly due to the higher influx of saline water, the resuspended material from the bottom being carried to the upper reaches by the strong tidal currents. The surface to bottom variation during ebb

tide was negligible compared to that in flood tide during this season. During monsoon a maximum value of 120 mg/l was obtained at bottom of the river mouth section and 65 mg/l at surface during flood tide and during ebb tide a surface related maximum value of 110 mg/l was obtained. This surface related maxima may be due to the transportation of sediment from upper regions of the estuary. Though the distribution shows a two layer transport process during this period of high river discharge, the seaward transport greatly exceeds the upstream transport of the suspended matter.

Mixing processes and suspended sediment distributions of the Beypore estuary was dominated by the tidal currents during the premonsoon period and by the freshwater flow during the other seasons. River sediment input was higher during the monsoon season due to high river discharge. During the postmonsoon period the suspended particulate matter concentrations was less compared to the other seasons. A similarity in the suspended sediment distribution could be found in the studies conducted in Azhikode estuary<sup>10</sup>.

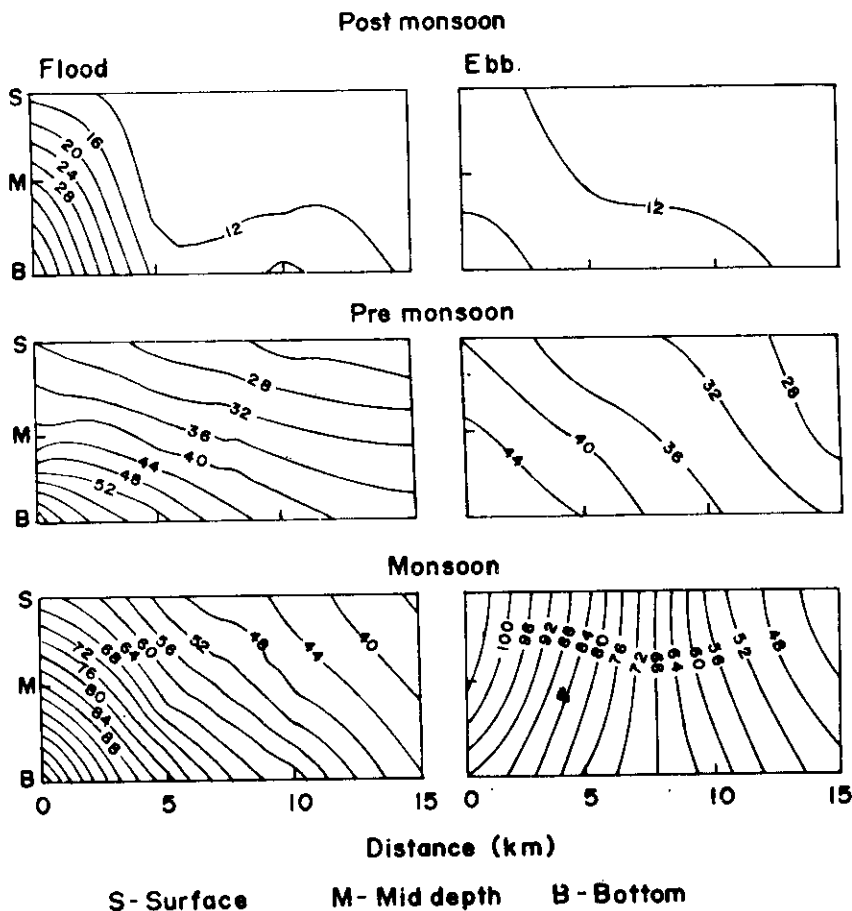


Fig. 5—Seasonal variation of the suspended sediment concentration (mg/l) during flood and ebb tides.

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