

Dynamics of circulation and salt balance in the upper reaches of Periyar estuary

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Abstract. The dynamic characteristics of the upper reaches of Periyar estuary were studied during different seasons of the year and the factors responsible for the changes were assessed. The Eulerian residual currents were directed down the estuary throughout the water column during the monsoon season. During the summer months the residual flow was directed up the estuary. The Stokes drift was considerably small and ranged between 0.003 to 0.280 cm/sec. The small values were due to small frictional effects due to the high fresh water discharge. The classification based on the stratification and circulation parameter showed that this part of the estuary behaved differently from season to season. The estuary was well mixed during June - August, partially stratified by December - January and became highly stratified during February - May. September - November was the transition period. The residual flux of salt was directed down the estuary just after the South-West monsoon period and was low. The main source of salt was through vertical shear in the tidal and residual currents and due to the residual flux through tidal pumping. During the lean months of fresh water flow, *ie.* March - April, the residual flux of salt was directed up the estuary with the major contribution through advection. This is because during this period the Eulerian residual current was generated by the tidal flow while in other periods this was generated by the input due to fresh water discharge into the estuary.

Keywords. Estuarine circulation; Eulerian residual currents; tidal pumping; Stokes drift; salt flux; vertical shear;

1. Introduction

The studies conducted so far have conclusively proved that (Dyer 1973, 78, 80; Hansen and Rattray 1966; Officer 1976) a given estuary may show different characteristics as a function of longitudinal distance along the estuary, seasons of the year or phases of tide. These varying characteristics can be due to any one or the combined effect of factors such as coupling of strong tidal oscillations with residual water circulation generated by the non-linear interaction between the tidal flow and the estuarine topography, density gradient mass input due to fresh water discharge and meteorological forces (Elliot 1976). Thus any estuary may behave in different ways at different times of year and because of the topographic differences one estuary will be distinctly different from the other. With this in view, the upper reaches of the Periyar estuary was studied to understand the dynamic characteristics during different seasons of the year and to assess the factors responsible for the changes.

2. Materials and methods

One of the branches of the perennial river Periyar which gets bifurcated from the main river about 26 km up stream from the barmouth, after flowing through the industrial-complex area in the suburbs of Cochin Corporation and empties into the Cochin backwater system. The other branch empties into the Arabian Sea at Azhikode, about 18 km north of the Cochin barmouth.

The following study pertains to that part of the river, which takes its course through the industrial belt. Two stations were selected as shown in figure 1. Synoptic measurements of current speed and direction, salinity, temperature, etc were made at hourly intervals from these stations for a complete tidal cycle. Every month, the stations were occupied during the spring tide. The data collection was made from August 1982 to August 1983. The sampling was done at 1 m interval from surface to near bottom. The data was interpolated for the non-dimensional depth $\eta = 0.0 (0.1) 0.9$. The data thus obtained was smoothed out by plotting the data for each η value at a constant depth against the time. The curves were smoothed and the data was read out for lunar hourly intervals and used for further computations. Depth and tide averages were computed using the method given by Kjerve 1975. Following the method given in Uncles and Jordan 1979; the parameters mentioned below were computed.

- (i) The non-tidal vertical distribution of salinity and current during the different month $\langle U \rangle_\eta$ and $\langle S \rangle_\eta$;
- (ii) The depth averaged Eulerian residual current or the non-tidal drift $[V_1 = \langle \bar{U} \rangle]$;
- (iii) The residual rate of transport of water resulting from tidal pumping or Stokes drift $[V_2 = \langle \tilde{H} \cdot \tilde{U} \rangle / \langle H \rangle]$;

- (iv) The depth averaged residual fluxes of salt due to
 - (a) the residual transport of water

$$[V_{s,1} = \langle Q \rangle \langle \bar{S} \rangle / \langle H \rangle];$$

- (b) the tidal pumping resulting from the non-zero correlation between \tilde{Q} and \tilde{S}

$$[V_{s,2} = \langle \tilde{Q} \cdot \tilde{S} \rangle / \langle H \rangle]$$

- (c) the vertical shear in the tidal and residual currents $[V_{s,3} = \langle H \cdot U' S' \rangle / \langle H \rangle];$

where \bar{X} represent average over depth $\langle X \rangle$ the tidal average $\langle \bar{X} \rangle$ the depth average of the tidal average $\tilde{X} = X - \langle X \rangle$ and $X' = X - \bar{X}$ (X can be any variable such as salinity S and velocity U , and H the observed depth and $Q = H \cdot \bar{U}$)

An attempt was also made to classify this region of the estuary on the method suggested by Hansen and Rattray 1966.

3. Results

Fresh water inputs, the position along the axis of the estuary and tidal range determine the physical behaviour of an estuary. In the present study, the sections 1 and 2 are located about 11 km and 21 km upstream from the barmouth (figure 1). The tidally averaged depths at these stations are 3 m and 4 m respectively. The tidal range at spring tide is around 0.8 m. The residual currents and the tidally averaged salinity distribution are

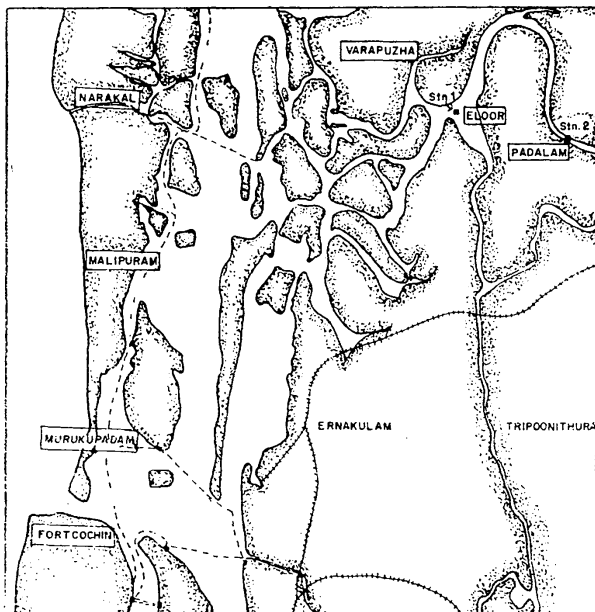


Fig. 1 Location map

presented in figure 2. $\langle U \rangle$ was directed down the estuary throughout the water column at both the stations except during March – May. Down the estuary transport was observed during the period of South-West and North-East monsoon having heavy influx of fresh water discharge (table 1). Also the slope generated by the Stokes drift which was directed upstream during these months could add to the generation of $\langle U \rangle$ down estuary (Uncles and Jordan 1980). The bottom to surface velocity gradient $\frac{d\langle U \rangle}{dz}$ was very small. Seasonally averaged vertical current profiles are depicted in figure 3. The profile for the monsoon season resembles exactly the computed current profile of Prandle (1985) for fresh

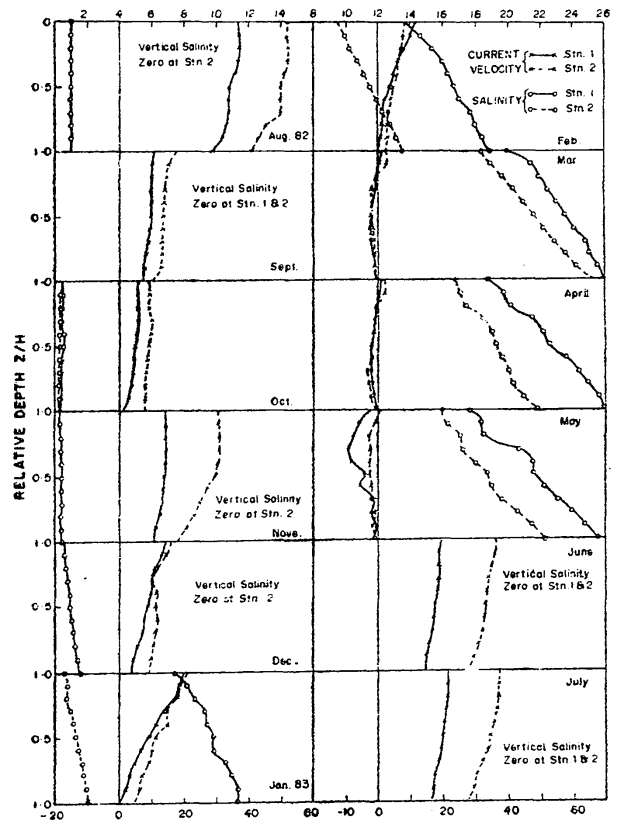


Fig. 2 Vertical salinity and Eulerian residual currents during different months.

water mode of circulation. $\langle U \rangle$ was always greater at station 2 during this season. After the cessation of the North-East monsoon the influence of the tidal forcing in the circulation pattern was evident from the vertical profiles of $\langle U \rangle$ for periods from January–May. The average vertical profile of January – February showed a transition from the fresh water mode of circulation to the tidal mode. By March – May the tidal mode of circulation gets completely established. The depth integrated Eulerian residual current, would in general,

Table 1: Results of Study

Months	$V_1 = \langle \bar{U} \rangle$	$V_2 = \frac{\langle \bar{H}\bar{V} \rangle}{\langle \bar{H} \rangle}$ (cm/sec.)	$V_{s,1}$	$V_{s,2}$	$V_{s,3}$	$\langle Q_s \rangle^j$	Fresh water flux (cusecs)
<i>Eloor</i>							
August	33.95	0.003	0.00	0.00	0.00	0.00	1444.50
September	8.49	0.048	0.00	0.00	0.00	0.00	251.40
October	3.61	-0.176	1.91	-0.11	-0.005	6.06	183.50
November	12.67	-0.059	9.55	-1.78	-0.151	39.07	240.70
December	8.49	-0.270	7.94	-0.22	-0.678	20.65	38.32
January	8.56	-0.216	91.43	-5.73	-7.457	228.03	22.18
February	3.12	-0.156	80.43	-2.87	-5.428	202.04	20.27
March	-0.80	-0.104	-21.31	-1.59	-2.030	-85.81	23.42
April	-0.66	0.062	-18.45	-1.23	2.205	-68.00	17.56
May	-3.05	-0.232	-85.61	-1.18	2.150	-323.40	32.18
June	13.80	-0.140	0.00	0.00	0.00	0.00	506.07
July	18.61	-0.204	0.00	0.00	0.00	0.00	1536.18
August	25.93	-0.222	0.00	0.00	0.00	0.00	1992.12
<i>Paihalam</i>							
August	47.66	-0.113	0.00	0.00	0.00	0.00	1444.50
September	12.85	-0.102	0.00	0.00	0.00	0.00	251.40
October	8.19	-0.207	1.37	-0.105	-0.005	3.78	183.50
November	26.20	-0.227	0.65	-0.023	-0.002	2.20	240.70
December	9.63	0.212	0.24	-0.015	-0.002	0.77	38.32
January	10.86	-0.205	15.15	-4.690	-2.317	30.16	22.18
February	3.40	-0.168	10.34	-1.248	-2.168	29.50	20.27
March	-0.34	-0.132	-18.50	-1.048	-1.926	-63.48	23.42
April	-0.80	0.040	-15.35	-0.812	1.825	-45.00	17.56
May	-1.57	0.138	-68.61	-0.926	2.001	-208.32	32.18
June	16.78	-0.186	0.00	0.00	0.00	0.00	506.07
July	29.23	-0.232	0.00	0.00	0.00	0.00	1536.18
August	38.02	-0.280	0.00	0.00	0.00	0.00	1992.12

Unit of f in 10^{-3} g cm $^{-1}$ sec $^{-1}$; j in 10^{-3} g sec $^{-1}$

contain a component which would attempt to compensate the tidal pumping. If the depth averaged Eulerian residual currents $V_1 = \langle U \rangle$ for different periods of observation (figure 4) are compared it would be seen that V_1 changes from season to season. Uncles and Jordan(1979) have observed that the difference could be attributed to the increasing or decreasing tidal range if

V_1 were generated only by the non-linearities in the tidal flow. However, in the present study it had been observed that the Eulerian residual current was mostly generated by the mass input due to fresh water discharges into the estuary. Generation due to the tidal flow was restricted to only one or two months just before the South-West monsoon season.

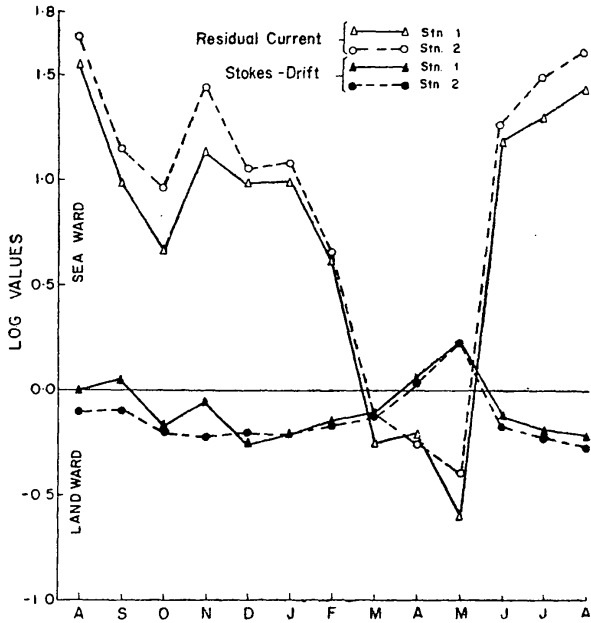


Fig. 3 Tidal and Depth averaged Eulerian residual current and Stokes drift

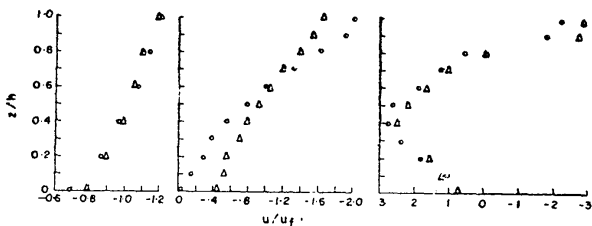


Fig. 4 Seasonally averaged current profiles at Eloor- and Pathalam —

The Stokes drift presented in figure 4, was considerably small at both the stations and ranged between 0.003 and 0.280 cm/sec. It was directed up the estuary during the period October-March and was directed down-estuary during April-May. Thus it could be seen that during the fresh water mode of circulation existing during South-West and North-East monsoons there was an up the estuary Stokes drift. The small values of the Stokes drift is due to small frictional effects, due to high flow of fresh water discharge (Uncles and Jordan 1980).

During the South-West monsoon period from June to November the salinity (figure 2) was less than 0.5×10^{-3} at station 1 and no salinity was observed at station 2. After the cessation of monsoon there was sudden picking up of salinity at station 1 and a gradual picking up at station 2. This period extended upto the month of May. However, during the pre-monsoon months (March - May), the vertical salinity gradient

was very great. From the observed salinity distribution the water column during the South-West monsoon period could also be described as well mixed type. From December onwards stratification took place at both the stations and the water column changed from partially stratified (surface to bottom salinity difference $> 3 \times 10^{-3}$) to highly stratified (surface to bottom salinity difference $> 3 \times 10^{-3}$). There was no halocline noticed in the salinity structure. This was due to the appreciable tidal movements up and down the estuary and the friction on the estuarine bed, creating a velocity shear and turbulence, which mixed the salt water upwards into the fresh water and the fresh water downwards (Dyer 1980).

The residual flux of salt is given in table 1. It could be seen that during June-September there was practically no flux of salt up the estuary or down the estuary. From October to February the residual flux of salt is down the estuary and March - May the residual flux is directed up the estuary which maintained the longitudinal as well as the vertical salinity gradient during the period. The different modes of salt fluxes are also presented in table 1. During October - February the salt flux due to tidal pumping and vertical shear was the main mode of transportation of salt upstream, even though the value remained low. After that, during March - May the residual flow of water and tidal pumping was the main mode of transportation of water.

The residual flux of salt per unit width of water column is $\langle Q_s \rangle = \langle H \rangle \cdot (V_{s,1} + V_{s,2} + V_{s,3})$

The values obtained are presented in table 1. It could be seen that from October to February the residual flux of salt was directed down the estuary. At the same time it was observed that there was a retention of salt in the water column. During the steady state conditions, there should not be any salt present in the water column if $V_{s,1}$ was compensated for by $V_{s,2} + V_{s,3}$. Hence the tidal pumping and vertical shear together should be greater than that required to balance the down the estuary advection of salt due to residual flow. Because this excess of upstream flux of salt occurred at these cross sections, it was unlikely to have been a consequence of unsteady conditions but was probably due to variations along the cross section. Fisher (1972) had shown that cross an estuary circulation producing a transverse shear would have definite contribution to the cross sectionally averaged salt flux. Hence, an analysis of a few observations along estuarine cross sections were necessary for asserting the relative importance of the different mechanisms of salt transport.

Based on the stratification and circulation parameter (the former is the ratio of the surface to bottom salinity difference δs to the mean vertical salinity $\langle \bar{S} \rangle$ and the latter the ratio of the mean surface velocity U_s to the depth averaged residual flow $\langle \bar{V} \rangle$ through the section) a classification of the estuary was attempted and presented in figure 5. The points only represented the conditions at one point in the estuary at the time of observation. The distribution of points showed the changing type of the estuary from month to month.

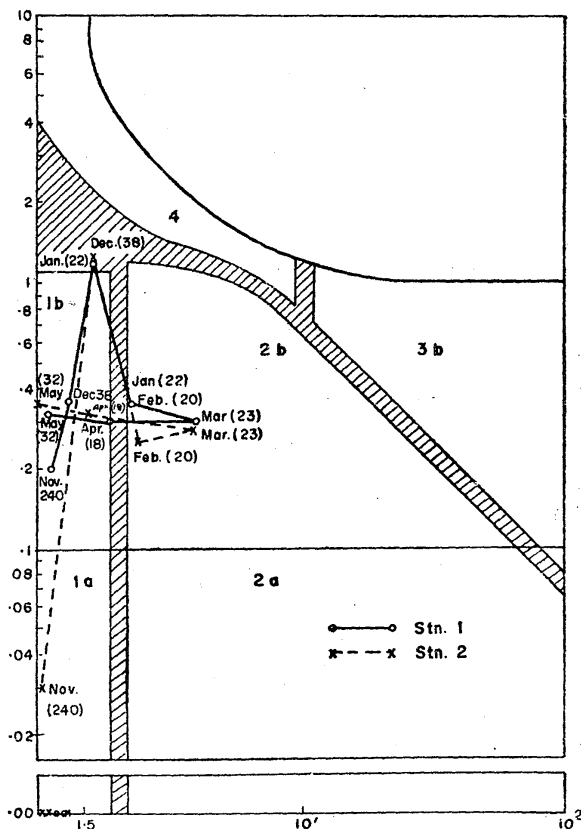


Fig. 5 Estuarine classification (Hansen & Rattray)

At the two stations studied, the estuary behaved like a well mixed estuary during the period June-August with 'zero' stratification number. The circulation parameter varied from 1 to 1.3 responding to the river flow. While station 2 remained well mixed with very low stratification number in November station 1 was appreciably stratified. By December-January increase in stratification was noticed at both the stations with the stratification and circulation parameter becoming high because of the reduction in fresh water flow. During the

months of February - May while the circulation parameter first showed an increase and then a decrease, the stratification parameter ranged between 0.28 to 0.35. This represented a highly stratified condition with very little river flow (both advection and diffusion contributing to the salt flux).

4. Discussions

In the shallow upper reaches of the estuary, the Eulerian residual currents were directed down the estuary under conditions of medium to high run off. These currents were primarily due to fresh water flows and compensation currents and the slopes generated by the Stokes drift even though the Stokes drift was small.

The residual flux of salt was directed down the estuary and was low just after the South-West monsoon period. The main source of salt was through vertical shear in the tidal and residual currents and due to the residual flux through tidal pumping. During the lean months of fresh water flow *ie*, March-April the residual flux of salt was directed up the estuary with the major contribution through advection. This is because during the period the Eulerian residual currents were generated by the tidal flow while in the other periods this was generated by the input due to fresh water discharge into the estuary.

The classification based on the stratification and circulation parameter showed that this part of the estuary behaved differently from season to season. The estuary was well mixed during June-August, partially stratified by December - January and highly stratified during February - May. September - November was the transition period.

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