STUDIES ON THE DYNAMICS AND SUSPENDED SEDIMENT TRANSPORT IN THE AZHIKODE ESTUARY (SOUTH-WEST COAST OF INDIA)

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CERTIFICATE

This is to certify that this thesis bound herewith is an authentic record of the research carried out by Shri.C.Revichandran, M.Sc., under my supervision and guidance in the National Institute of Oceanography, Regional Centre, Cochin, in partial fulfillment of the requirement for the Ph.D. Degree of the Cochin University of Science and Technology and that no part thereof has been previously formed the basis of the award of any degree, diploma or associateship in any University.

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PREFACE

Estuaries are very important even though their area is only a small proportion of the world's surface. Because of their fertile waters, sheltered anchorages and the navigational access they provide to a broad hinterland, estuaries have been the main centres of commerce. Some of the oldest civilizations have flourished in the hinterlands of estuarine environment such as the lower reaches of Indus, Tigris and Euphrates rivers. Estuaries form natural breeding ground for large variety of fishes and shrimps. Of late, some estuaries have been subjected to ruthless rampage, extensive damage and even total destruction as a result of the great pressure of population, industrialisation in the adjacent areas and along the river banks, and urbanisation. Furthermore, man-made changes up-stream, such as the construction of dams, barrages and bunds upset the free flow of water upsetting the ecological balance. Indiscriminate deforestation in the catchment areas, removal of vegetation along the river banks and overgrazing have caused severe soil erosion and heavy siltation of estuaries.

Because of the interaction of so many variables no two estuaries are alike, and difference in the physio-chemical, biological and meteorological conditions that exist in the different regions of our country, makes generalisation somewhat difficult,necessitating detailed studies on each estuary.

This thesis incorporates the results of the studies carried out by the author on some of the dynamical and sedimentological aspects of Azhikode estuary, (South-west coast of India), by conducting synoptic field observations every month for a period of one year on current speed and direction, salinity, tides and suspended sediment concentrations at four cross-sections, between river mouth and 15 Km up-stream. The thesis is presented in 7 chapters.

The first chapter gives, apart from a general introduction, a survey of literature in the relevant fields and a description of the study area in the background of it's geological and climatological setup. The methods of data collection and techniques of data processing have been presented in chapter-2.

Annual distribution of temperature, axial and transverse distribution of salinity and currents are detailed in chapter-3. Variability of residual current and the relation between depth-tide mean salinity with river flow and tidal amplitude are also presented in this chapter.

Chapter-4 deals with the residual fluxes of water and salt and their temporal and spatial variations in the Azhikode estuary at four cross-sections, each comprising of 3 stations. The major physical forcings which influence the transport processes are identified and their relative dominance is discussed. Based on the above results, an attempt has been made to classify the estuary during different months. Flushing time scales and mixing characteristics of the estuary during each month have been presented in chapter-5.

Temporal and spatial variations of suspended sediment concentration have been discussed in chapter-6. Relation between sediment concentration with current speed and tidal amplitude and river flow have also been analysed. An attempt has been made to quantify the annual input of river borne sediment and to suggest possible remedial measures to prevent or reduce the sandbar formation and siltation at the estuarine mouth which are causing havoc to the safe navigation of fishing boats. The salient features emanating from the foregoing discussions are summarised in chapter-7.

CHAPTER - 1

1. INTRODUCTION

An estuary is a partly enclosed coastal body of water that forms where sea water is mixed and diluted by river water (Pritchard 1952). In general the estuarine environment is one that is defined by salinity boundaries rather than the geographical boundaries. Estuaries have long been important to man as harbour sites and centres of commerce. Some of the oldest civilzation have flourished in the hinterlands of estuarine environments such as the the lower reaches of the, Indus, Tigris and Euphrates rivers. As the civilizations developed, it was logical that the sea ports were founded at the seaward point of major river systems. In this way, commerce could move cheaply and relatively safely down the rivers and be loaded on to ships to be moved to other distant ports. The world fishing industry is, to a great extent dependant on the estuarine environments, either directly as areas of fishing or indirectly as regions were the species spend a part of their life cycle.

1.1 Formation of estuaries

The geologic processes that form the estuary are extremely complex and varied, but it is clear that the existence of estuary or estuarine environment is largely dependent on the position of sea level relative to the fresh water discharge. The estuarine brackish water zone is relatively narrow in width and is located at the margin of the continents. If the sea level were lowered, the estuarine zone would migrate sea ward. Such migration has occurred in the past in consequence to several continental glaciations. For each glaciation the primary source of moisture has been the oceans. When sea level fell, the estuarine environment and continental margin was forced to migrate in a seaward direction. Areas of marine water becomes brackish and supported fauna that were typically estuarine rather than marine. During the period of lowered sea level some rivers had become entrenched in the continental shelf and deepened their valleys . These valleys are soon flooded by the rising marine water forming a typical drowned river estuary.

Many forms can be adopted to classify estuary depending on which criteria are used. Topography, river flow and tidal action must be important factors that influence the rate and extent of the mixing of salt and fresh water. By taking topography as the criterion, estuaries can be classified into four major categories namely drowned river valleys, Fjords, Bar-built estuaries and tectonicaly formed estuaries. Drowned river valleys are formed during the Flandrian transgression by flooding of previously incised valleys. Sedimentation has not kept pace with the inundation and the estuarine topography is still very much like that of a river valley. Fjords were formed in areas covered by pleistocene ice sheets. The pressure of the ice cover over deepened and widened the pre-existing river valleys, but left rocks bars or sill in places particularly at the fjord mouth and at the intersection of the fjords. Because of over deepening, the fjords have small width–depth ratio, steep sides and an almost rectangular cross section. A bar-built estuary is formed when a drowned river valley is enclosed from open sea by a bar or barrier. Bar -built estuaries are generally found in tropical areas or in areas with active coastal depositional sediments. Estuaries formed by continental tectonic or movement of the land surface are called tectonicaly formed estuaries.

In most estuaries, there is a certain amount of to and fro motion of the water as the tide flush in and out of the basin. Besides this, there is a net circulation pattern within estuaries that is a function primarily of the mixing of fresh and salt water in this complex area.

Pritchard (1955) and Cameron and Pritchard (1963) have classified estuaries by their stratification and characteristics of their salinity distribution into four categories such as salt wedge type ,fjords, partly mixed and homogeneous. Highly stratified estuaries are found in regions where tidal range is low and river discharge into the estuary is high and the ratio of width to depth is relatively small. Fjords type estuaries are similar to the salt wedge type. As tidal flow increases or river discharge decreases, more mixing takes place between upper and lower waters in an estuary and thus partly mixed estuaries develop. As mixing increases due to tides and wind, the water becomes less stratified and ultimately reaches a point at which its properties from top to bottom are relatively constant at any location within the estuary, This type of estuaries are called well-mixed estuaries or vertically homogeneous estuaries.

1.2 Azhikode estuary

The coastal area of Kerala extending from north to south as a barrier strip of land includes a chain of lagoons and backwaters with connection to the sea at various points. There are nine estuaries and twenty one backwaters in Kerala with Nileswar backwater in the north and Akathurai lake in the south. The Vembanad lake which is the largest backwater in kerala, run almost parallel to the coast covering an area of 205 Km^2 (Fig.1.1) and extends from Alleppy in the south to Munambam in the North. Major inlets connecting vembanad lake to the Arabian sea are Cochin and Azhikode. A third inlet which exists at Thuravoor is seasonal which remain closed except during the monsoon season (Raju et.al, 1979). The Azhikode estuary (Fig.1.2) is formed by part of the Vembanad lake which joins the sea at Munambam. The major tributaries of the Azhikode estuary are Periyar and Chalakkudy rivers. Compared to Cochin estuary Azhikode estuary is shallower, maximum depth at the channel being about 10 m. The width of the estuary near the bar-mouth is

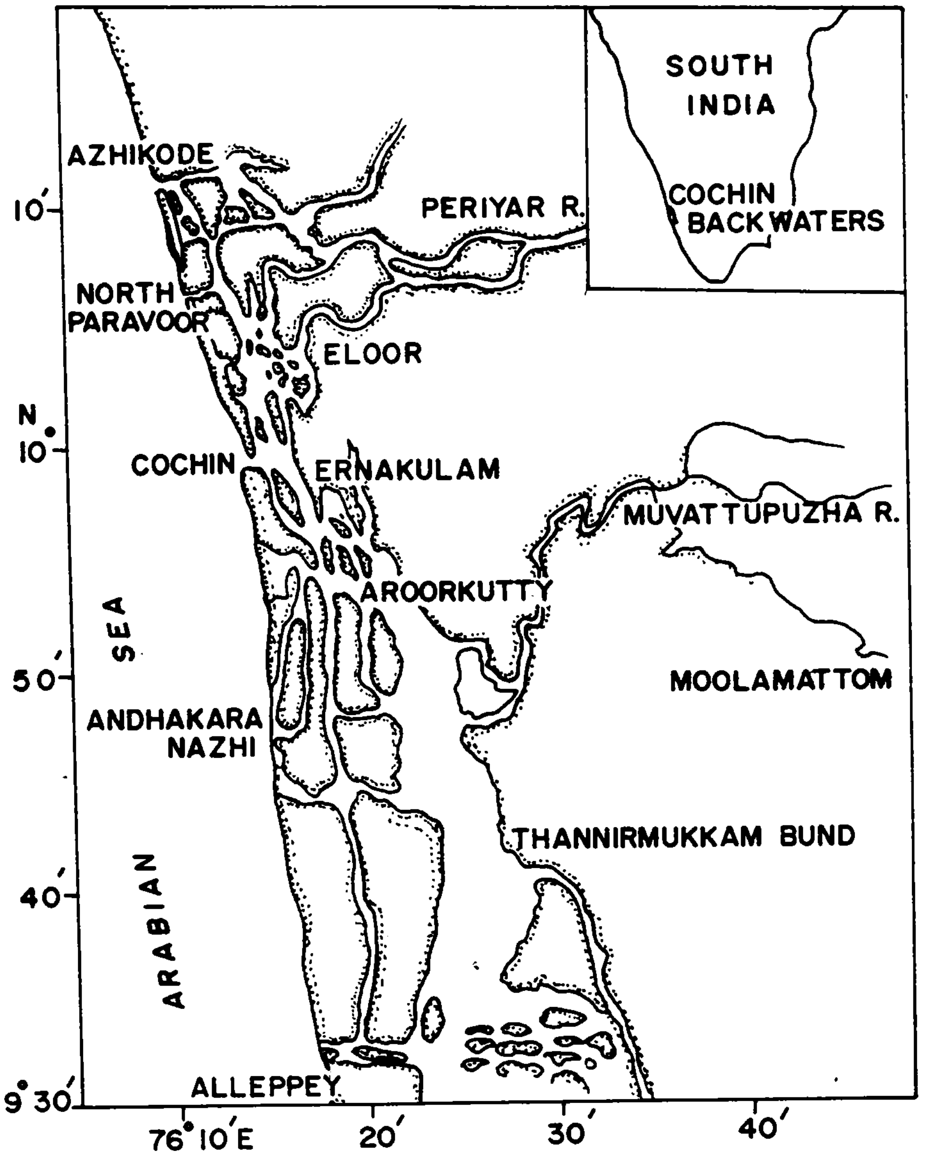


Fig. 1.1. Vembanad Lake system.

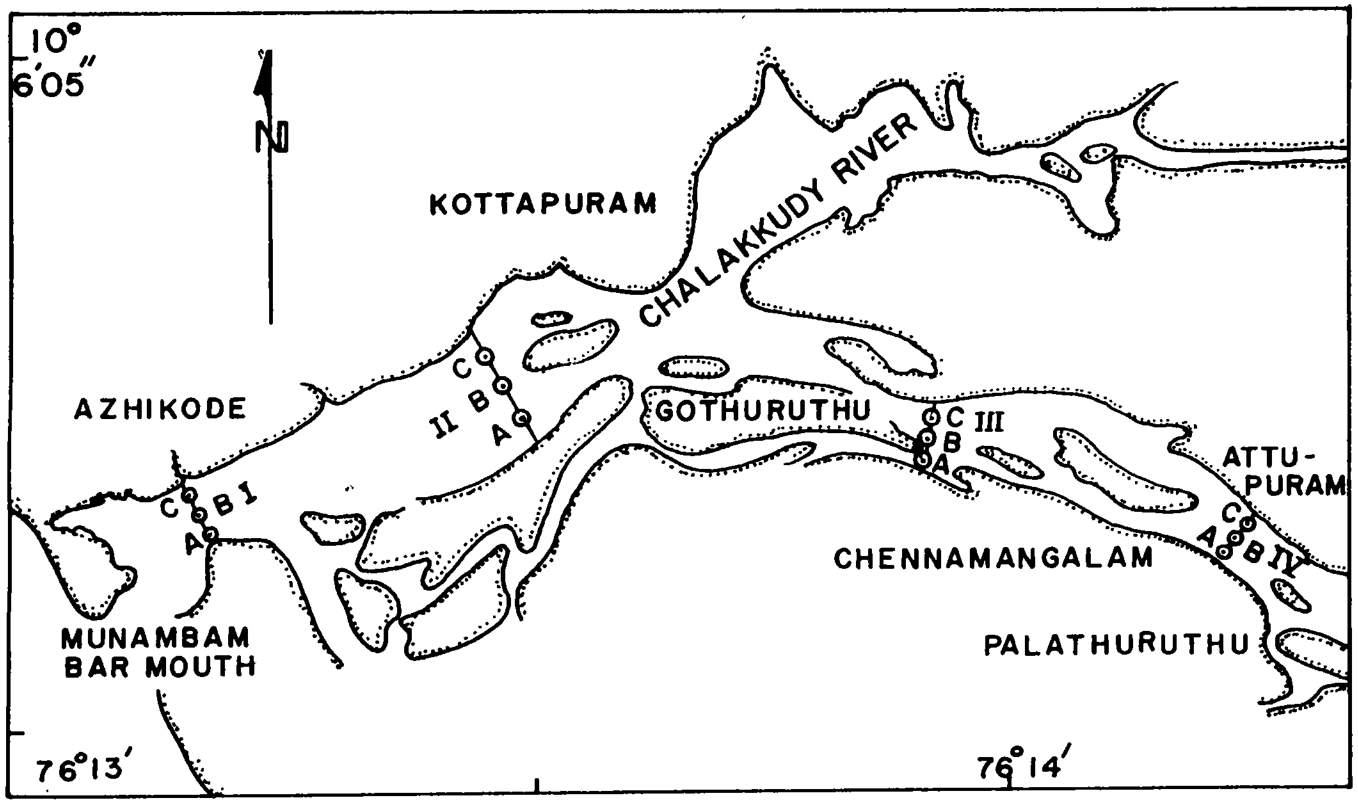


Fig. 1.2. Map of the Azhikode estuary showing the location of sections.

750 m and at the inlet entrance , it is about 250 m. The average depth of the estuary is 3.5 m.

1.3 Munambam fishing harbour

Munambam was the point of entry to the ancient Musori or Kodungallor port in early days. Presently it is a major fishing centre in the state of Kerala; about 400 mechanised boats operate from here. According to the boat owners, the fish catches by Munambam fishermen were worth to the tune of Rs.24 crores a year. The state government earns at least Rs.1 lakh a day as sales tax on diesel sale and the port department earnes about Rs.1.5 lakhs on license account. About 2500 workers, directly connected with the mechanical boats and 2000 workers in the allied fishing industries find employment in Munambam. Sedimentation in the estuarine region and the sand-bar formation at the bar-mouth is a major hindrance to the safe entry of the fishing boats. According to the local people the sand bar formation has caused 79 casualties and destroyed over 70 country crafts .

Sandbar was noticed at Munambam, early in the seventies 1.5 Km across the bay and sand carried by the periyar was deposited on both sides of the land reducing the outlet to a small and shifting channel of shallow depth. Position of the channel changes with the season, direction of the waves and the river flow. Southerly littoral current and the associated littoral transport and the westerly winds favour the formation of sand bar. Sediments eroded due to wave action from the adjacent coastal area are transported by the southerly littoral current. They get deposited across the bar mouth leading to the formation of sand bar. High suspended sediment load and bed load may also be contributing to the formation of sand-bar, but this has not been proved conclusively. To remove the sand banks, dredging work was carried out by state government owned dredger Meena Kerala during 1977. But the sand bars reappeared causing more accidents.

1.4 Rainfall and river input

Tropical humid climate prevails over the study area. On the basis of meteorological and hydrographical conditions four seasons namely Pre-monsoon or hot weather period (March-May), south-west monsoon (June-September), northeast monsoon (October-December) and winter or post-monsoon (January-February). Average annual rain fall in the study area was 310 cm. Intensity of rain fall varies from month to month. Maximum rainfall occurs during the south-west monsoon season.

The freshet depends on the intensity of rain fall in the catchment areas. The discharge normally shows pronounced dry season and wet season signals as well as large inter annual variations. The quantity of fresh water inflow is

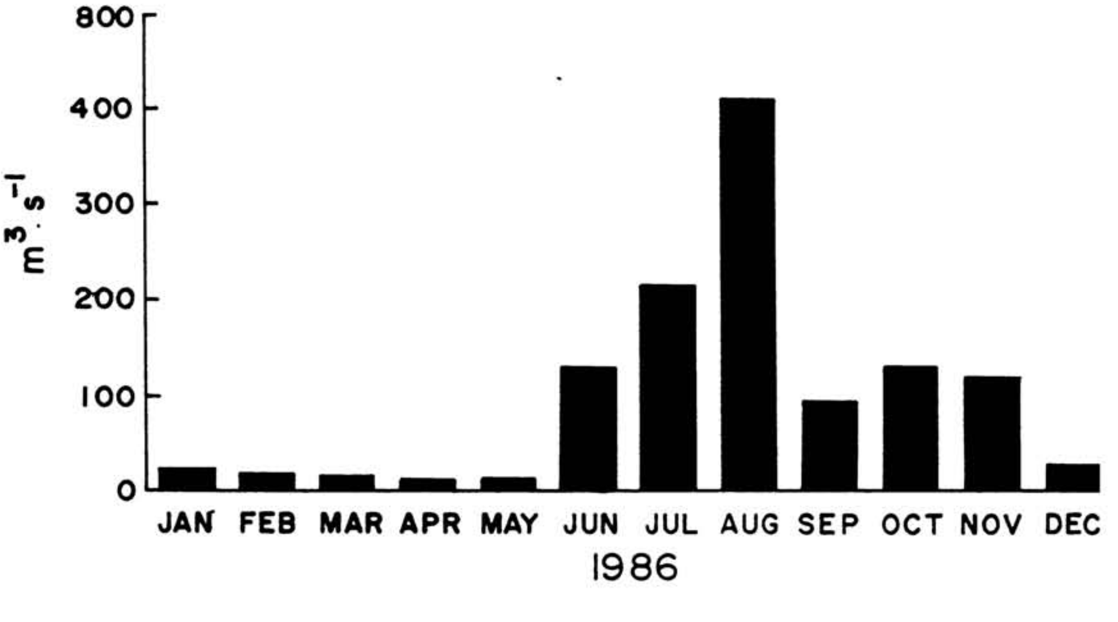


Fig. 1.3. Effective monthly averaged fresh water input to the Azhikode estuary.

important in determining the nature of the estuary. During periods of high discharge, fresh water inflow may force most of the salt out of the estuary. During other seasons, when river discharge is low , the estuary may be more akin to an extension of ocean rather than an estuarine environment. Moderate river discharge may stratify or layer the estuary with the low density brackish water on top and the denser more saline water below. Seventy percent of the fresh water input into the Azhikode estuary is from Periyar river while thirty percent is from Chalakkudy river. Net effective fresh water input into the Azhikode estuary varied between 21 $m^3.s^{-1}$ during January to 12.3 $m^3.s^{-1}$ during April(Fig.1.3). During the wet season (June to September), the water discharge varied between 123 $m^3.s^{-1}$ and 387 $m^3.s^{-1}$.

1.5 Tides

Tides are the continuous and quasi periodic rise and fall of the sea level caused by the attraction of moon and sun. These vertical displacements are accompanied by horizontal displacements of water called tidal currents. Tides in the estuary are due to ocean tide rather than the action of the tide generating forces on the estuarine water. The ebbing and flooding provide much of the energy for the mixing which takes place in the estuaries.

If the estuary is of the correct depth and length, then it is possible for the tidal wave to enter and be reflected from the upstream and return in a time equal to a harmonic of the tidal period. The reflected wave will then interfere with the wave just entering, a standing wave system can thus set up in the estuary. The high and low waters and the time turn of currents will then be simultaneous throughout the estuary. The tidal amplitude and salinity variation will be then 90° out of phase with the current velocity. If the energy of the tidal wave is completely dissipated before reflection then the tidal wave becomes solely progressive in nature. The amplitude of the tide and the magnitude of the tidal currents diminishes towards the head of the estuary and there is a progression in the times of high and low water and turn of the current along the estuary. In this case, the maximum flood current would occur at high water.

Tides in the Azhikode estuary are semi diurnal, with amplitude of 1 m during spring tides and 60 cm during neap tides. Tidal wave reaches approximately 30 Km landward of Munambam. The tidal waves are progressive in nature and at spring tide the high water is delayed as much as 45 minutes between Azhikode and Chennamangalam (See Fig.1.2).

1.6 Literature review

Studies of estuaries over the last twenty five years in small and moderate sized estuaries revealed a two layered tidally averaged circulation pattern. In the early 1950's D.W.Pritchard described the characteristics of estuaries and their classification in a series of papers on partially mixed estuaries (Pritchard 1952,1954,1955,1956) has formed the basis for the analytical and numerical model during the last 30 years. Attempts were made by Bowden (1960,1963) , Bowden and Sheraf El DIn (1966), Bowden and Galligan(1971) and Collar (1978) to describe the two layer flow pattern of estuaries and to evaluate the various terms in the dynamic and kinematic equation describing the estuaries. A classification of estuaries based on the physical character of circulation was proposed by Stommel (1953) and Ketchum (1953). The state of the knowledge on estuarine circulation and the distribution of properties in estuaries up to fairly recent times was admirably presented by Dyer (1973) in his text book.

Scale models were also used to study the circulation and mixing phenomenon by Pritchard (1954), Rattray and Lincoln (1955), Inglis and Allen (1957). Simmon (1960) and Breusers (1981) and has described the principles on which such models are designed.

The analytical model of estuarine circulation developed and described by Rattray and Hansen (1962) , Hansen and Rattray (1965, 1966) and Hansen (1967) was probably the first model to clearly demonstrate the classical two layered estuarine flow pattern. This model was described in a simplified form by Officer (1976). Cameron and Pritchard (1963) reported the three layered circulation pattern observed in tributary estuaries having very little fresh water inflow. An analytical model model for such three layered flow was developed by Hansen and Rattray (1972). Keulegan (1947) described a series of model experiments for salt wedge estuaries and Farmer and Morgan (1953) theoritically analysed the salt wedge flow based on the equation of continuity.

Magnitude of the tidal flushing effects in the estuaries are earlier evaluated by tidal prism method. This method was modified by Ketchum (1951) who applied the modified method to Raritan River Bay. Ketchum (1950) has reported his studies on flushing of tidal estuaries to avoid stream pollution. A further development of the method was described by Preddy and Webler (1963) for non conservative pollutants. Kent (1958) has studied various aspects of diffusion. A review of the works on circulation mixing and pollution distribution has been presented by Ketchum (1953), Kjerfve (1975), Farmer and Osborne (1976) and Smith (1977).

Dyer (1976) described the effects of channel curvature and cross sectional shape on the lateral variations in the velocity field including the occurance of flood channel and ebb channel; that is, when the flood flow is more pronounced in one part of the cross-section of the channel and ebb flow is strong in another part of the cross-section. Nunes(1985) has reported the axial convergence in estuaries.

Barthurst et.al (1977) and Dyer (1977) made investigations on the topographic effects on estuaries. Pickard and Rodgers (1959) and Rattray and Hansen (1962) have reported about the wind effects on estuarine circulation.

The residual circulation and mixing, have however received much less attention . Using a simple theory together with observations on water density, Hamilton (1973) estimated the density driven flow in the mouth of channels. Tee (1976), Ianniello(1977,1981) and Uncles and Jordan (1979,1980) measured residual currents at two stations in the Severn estuary and subsequently predicted and compared the Stokes drift in the estuary . Contribution of transverse and vertical shear to the transport of salt and sediment have been discussed by Allen et.al (1980), Lewis & Lewis (1985) and Uncles et. al. (1985).

Bowden and Sheraf El Din (1966), Dyer (1974), Murray and Siripong (1978), Hughes and Rattray (1980) and Hunkins (1981) have studied vertical distribution of estuarine currents both experimentally and theoritically. Theoritical studies on lateral variation and axial dispersion have been made by Fischer (1972,1976). Observations of the transverse structure of current and salinity have been made for number of estuaries by Hansen (1965), Dyer (1974), Lewis (1979) and

Hughes and Rattray (1980). Wind effects on estuarine circulation and mixing have been studied by Kjerfve (1975), Farmer and Osborne (1976) and Smith (1977) . Zimmerman (1978) discussed about the topographic generation of residual circulation.

In recent years, there has been a rapid development in the representation of estuarine circulation and mixing by models, particularly by numeric models. Festa and Hansen (1978) modeled the steady state gravitational structure in a estuary of uniform geometry, taking vertical viscocity and diffusion coefficients, N_z and K_z, as constant and assuming zero longitudinal velocity at the bottom. Blumerg (1977) modeled real time, or tidal variations in an estuary using realistic bathymetry . Hamilton (1975) modeled the real time variation in an estuary of varying width. Mathematical model for the Salt intrusion in the estuaries has been developed for individual estuaries by Harleman et. al. (1966), Thatcher and Harleman (1972,1981) and Perrels (1981).

There have been a number of investigations on the suspended sediment distribution in estuaries. These include works by Manheine et. al. (1972), Meade (1972), Allen et. al. (1976,1980), Peterson (1975), Bulle et. al. (1975), Postma (1967), Bartholdy (1984), Casting and Allen (1981), Avoine et. al. (1983), Kirkby et. al. (1983), Gelfenbaun (1983). Analyses of the vertical distribution and flux of sediment as a function of semidiurnal tide have been presented by

Schubel (1969,1971, 1978), Hunter and Liss (1979) and Vale and Sundby (1987) and Postma (1961) have reported the suspended sediment transport in the Dutch wadden sea. Larsonneur et. al.(1982) , Uncles et. al. (1985) and Bale et.al (1985) studied the seasonal pattern of sediment movement in a macro-tidal estuary using one dimensional hydrodynamic and sediment balance model. Formation of turbidity maximum and it's migration in response to changing river flow have been studied by Richardson and Zaki (1954), Krank (1973,1981), Allen et. al. (1976,1980) and Festa and Hansen (1978). Studies pertaining to the suspended sediment balance in the estuary have been carried out by Flemming (1970) , Dyer (1978) and Yarbo et. al. (1983). A review of the present knowledge on physical dynamics of the estuarine sediments has been documented by Officer (1981)

1.7 Estuarine studies in India

In India, estuarine studies date back to the second half of this century . Hydrobiological observations of the Hoogly estuary have been made by Dutta et. al. (1954) and Roy (1955). Godavary estuary has been studied in detail by Chandramohan (1963) and Chandramohan and Rao (1972). Work on Mahanadi estuary was carried out by Ray et. al. (1981). Investigations on various physical and biological aspects of Vellar estuary were made by Krishnamoorthy (1961) and Ramamoorthy et. al. (1965). Hydrography, circulation, suspended sediment distribution and other related aspects of Mandovi and Zuari estuarine systems of Goa have been studied by Das et. al. (1975). Physical aspects of the estuaries of Goa region have been reviewed by Rao (1981). Among the estuaries in India, Cochin estuary is the most intensively studied one. Considerable number of studies related to the biological aspects of this estuarine system have been carried out in early 1960's. Distributions of various hydrographic properties in the Cochin estuary have been reported by Ramamritham and Jayaramn (1963), George and Kartha (1963), Quasim and Reddy (1967), Cheriyan (1973), Quasim et. al. (1968, 1969),Sankaranarayanan and Quasim (1969) and Wellerhaus (1974). Sankaranarayanan et. al. (1986) computed the fresh water fraction at different locations and assessed the extent of salt water intrusion in the estuarine system during different seasons of the year. Distribution of current in the estuarine system has been described by Varma et. al. (1981). Stratification and salinity distribution in the Cochin estuary has been reported by Jomon and Kurup (1990). Suspended sediment distribution in the Cochin estuary was investigated by Gopinathan and Quasim (1971), Kurup (1971), Cherian (1973) and Raju et. al. (1979). Some investigations have been made on the physical aspects of Azhikode estuary by Revichandran et. al. (1987) and Abraham Pylee et. al. (1989).

1.8 Scope of the present study

With increasing requirements of water and with increase in the concern about the environment for aesthetic and practical reasons, there will be increasing attention towards problem that must be solved by estuarine studies. The main problem in the estuarine studies is that the river flow, the tidal range and the sediment distribution are continually changing and consequently an estuary never presents a steady state system, it may be trying to reach a balance which it never achieves. Many studies on individual estuaries are available in literature, and variability in estuaries make generalisation a risky undertaking.

Keeping in view the above facts, the present study was undertaken to assess the temporal and spatial variation of the hydrographic parameters, circulation, mixing and suspended sediment distribution in the Azhikode estuary. Knowledge on the dynamics of the Azhikode estuary will be of considerable help in the planning and execution of any developmental programme for the Munambam fishing harbour, whose economic importance and the the inherent problem of sand bar formation have been discussed earlier. The problem of contamination of surface and ground water by intrusion of salinity from the sea is very common in coastal areas. The presence of salinity in estuaries may alter the sedimentation and pollution dispersion characteristics in the estuaries. The upper region of the Azhikode estuary serve portable water for thousands of people. These problem can be tackled only if an adequate understanding is developed on the dynamics of the estuary.

CHAPTER - 2

2. MATERIALS AND METHODS

2.1 Basic considerations in estuarine investigations

For successful implementation of an estuarine investigation, the precise objective must be clearly and unambiguously defined so that the optimum procedure may be derived. The design of an estuarine hydrographic study is critical for its meaningful completion. Variations in measured parameter occur in all three direction as well as in time. Before making any estuarine measurement, it is therefore wise to carefully choose a suitable sampling design. Location of stations, total number of vertical measurements and number of stations per section should be selected with care. These will vary from estuary to estuary. If discharge of fluxes or material is the goal of the study, it is usually necessary to include a minimum of three stations in a cross section. It is important that the shallow regions are adequately represented. In the vertical axis, it is usually required to make measurements at least at five depths between surface and bottom, if the water depth permits. Along the estuary, station separation needs to be large enough to ensure that the difference in mean value between the stations are larger than the sampling error and yet sufficiently close so that the gradients between stations are sufficiently linear. During the operational planning of an investigation, the practical implication of tidal movements must also be born in mind. The actual sequence in which a grid of stations is sampled will depend on a number of factors including navigational considerations. However, if the inter-station distance is of the order of less than the tidal excursion at that vicinity, care must be taken to ensure that sampling at adjacent station is not carried out in a way such that the one effectively samples the same parcel of water.

Whatever be the overall time scale of observations and the frequency of sampling at any position, it must be remembered that sampling in discrete time yields results which are characterised only of those times. Choice of sampling position is determined by the scale of the investigation and the gradient and fluctuation of properties of interest with in the scope of investigation. The position of the individual sampling points and their spacing must be such that one can interpolate credibly between them. Any sharp fluctuation in properties of a scale, axial transverse or depth wise, shorter than the distance between the sampling point will remain undetected or poorly represented.

2.2 The present study

Sampling and monitoring stations were located throughout the Azhikode estuary extending from Munambam to Chennamangalam, nearly the upper limit of the tidal intrusion. Four sections selected for the present study are Azhikode (Section-I), Kottappuram (Section-II), Gothuruthu (Section-III) and Chennamangalam (Section-IV). Average distance between the sections are 3-5 km, greater than or equal to the average tidal excursion. These sections were fixed with the help of prominent land marks. Three stations were established in each section using anchored marker buoys during the observation periods. Care was taken to collect the synoptic data as far as possible. For this purpose, two 30 feet motor boats having access to the selected sampling positions and sufficient manoeurability under adverse weather and tidal conditions and sufficient speed to conform to the time schedule, sufficient space for instruments and equipments were used. Observations were carried out on two consecutive days; that is sections I & II are covered on one day and sections III & IV are covered on the next day. It is assumed that the tide meteorological conditions do not vary on these days. All the stations were occupied once in every month for 13 hour for a period of one year so as to cover one complete semi diurnal tidal cycle. Current and salinity measurements had to abandoned in May, September and December due to instrument failure and operational constraints. However the data collected is deemed to be representative since the over riding influence is the monsoonal cycle and during other months of the season adequate data has been gathered. Procedure adopted and instruments used for measuring various hydrographic parameters are given below.

2.2.1 Current speed and direction

Eulerian current speed and direction were measured by using direct reading current meter designed by N I O, Goa, India. The current meter uses an Aanderaa rotor and magnetic compass to measure speed and direction respectively. The circuitory employs the INTEL 8748 single microcomputer programmed chip to compute and displays the measured parameter on seven segment LED display. Accuracy for velocity $\pm$ 1 $cm.s^{-1}$ and for direction $\pm$ 2.68°.

2.2.2 Temperature and salinity

Temperature, salinity and depth measurements were accomplished by S T D meter (Salinity,Temperature, Depth) designed by Environmental System Engineers, Cochin. The under water unit consists of three sensors for salinity, temperature and depth and are connected to the deck unit by cables in which signals are displayed. The salinity sensor is a platinum conducting cell measuring conductivity changes as a function of salinity of water. The temperature unit make use of a thermistor. The depth sensor consists of stainless steel bellows whose compression due to hydrostatic pressure is converted into electric induction. Accuracy of the instrument for salinity, temperature and depth are $\pm$ 0.1 X 10^{-3}, $\pm$ 0.1 °C and $\pm$ 0.1 m respectively.

2.2.3 Suspended sediment

Water samples were collected from surface, mid-depth and bottom at all stations using conventional water samplers. Samples were then filtered through pre-weighed filter paper of pore size 0.45 µm and diameter of 47mm. Filtering was carried out at 25 cm.Hg vaccum and the volume of filtration varied between 500 - 1000 ml. After filtration the filter were rinsed with distilled water to remove residual salt and dried at 70 °C. The initial and final readings were taken in milligram.

2.2.4 Tide

Since the horizontal and vertical salinity variations occur simultaneously due to tidal fluctuations, it is essential to measure simultaneous and relative water levels throughout the estuary. In the present study tide measurements were made by using simple tide staffs at selected and fixed points near each of the cross-section using graduated during the observation period and data are compared with the predicted tide from the tide table.

2.2.5 Bathymetry

The hydraulics of estuaries is governed by their shape,size and other geometric properties. Due to practical limitations, bathymetry of the entire study area is not taken, however, the cross-sectional information of the estuary are gathered only at the selected sites. Cross-sectional bathymetry were taken using an echo sounder and at times manually by lead sounding.

2.2.6 Computation of cross-sectional area

The cross-sectional area were determined using a planimeter from the drawing of the cross-section. Average low tide volume of the estuary enclosed by various cross-section were derived by multiplying the average cross-sectional are at low tide with distance.

2.2.7 Processing of hydrographic data

After completion of the hydrographic measurements, it is convenient to manipulate the data to make a standard analysis procedure. This was accomplished by a computer programme, which uses current speed, direction, temperature and salinity at various depth as input. The programme fits vertical profiles through each set of data points and gives final output, the values of the two orthogonal horizontal velocity components, temperature and salinity at 11 equally spaced non-dimensional depths, beginning at the surface and ending at the bottom. The non dimensional depth is defined by η = (d(t)-z)/(d(t) where 'z'is the distance above the bottom and 'd(t)' is the total water depth at a given station. In the computer programme, cubic splines were used to interpolate data for velocity and salinity. Data on suspended sediment were 'noisy' throughout the water column when concentration was low. Therefore, linear interpolation was used to define theses data at the standard non-dimensional depths. Near -bed values for velocity were estimated by fitting logarithmic boundary layer to the data. Another programme was used to interpolate these data at the same instances of time at all the stations and to generate 12 lunar hourly distributions of axial and transverse velocity, salinity and suspended sediment. Tide average value of the parameter were formed by integrating the derived data at each fractional depth over a period of 12.42 hours and depth averages were formed by integrating the derived data at each hour over $\eta = 0$ to $\eta = 1$.

CHAPTER-3

3. HYDROLOGY

3.1 Introduction

An important feature of estuarine flow system is its great spatial and temporal (seasonal, semi-diurnal) variation resulting from interaction between tidal oscilation and fresh water flow. The distribution of salinity and temperature governs the dynamic structure of the system. Knowledge of the distribution of temperature and salinity is important as it provides information on the general hydrology of an estuarine system.

3.2 Temperature distribution

The distribution of temperature in an estuary is dependant on the temperature of the incoming river and sea water, the mixing processes and also on the exchange of heat through the surface. In most estuaries, river water is colder than seawater in winter and warmer in summer, due to the greater heat capacity of the sea and its slower response to the heating and cooling processes. The effect of temperature is to increase the density difference between river and sea water in summer and reduce the difference in winter. On the whole, the dynamical effect of temperature changes is smaller than that of salinity in estuaries, unlike in the open sea. In the Azhikode estuary, it is seen that the distribution is controlled mostly by the local weather conditions. Surface temperature of the water chiefly depends on the incoming solar radiation, the estuary being a shallow one, the distribution appeared to be dominated by the diurnal effect rather than tidal effect.

In this chapter, only the annual march of tidal mean temperature is discussed for surface, mid-depth and bottom levels obtained from synoptic surveys. The distribution of temperature is represented by a longitudinal section which follows the central axis of the estuary.

Monthly variation in the tidal mean temperature at the surface, mid-depth and bottom are shown in Fig. 3.1.a,3.1.b & 3.1.c respectively. All observations were made during day time. Distribution pattern of temperature observed at surface, mid-depth and bottom are similar. Surface temperature clearly follows the annual march of atmospheric temperature. Maximum temperature of 31°C is observed upstream of Kottappuram (Section-II) during February-May and the surface temperature decreases from 30 C to 27°C with the onset of southwest monsoon. On an average, river end of the estuary is warmer by 1°C than the sea end and this difference is maintained during all seasons of the year except during the peak monsoon period. Minimum tidal mean temperature of 25°C is observed down-stream of Gothuruthu (Section-III) during July - August. At mid-depth maximum temperature of $>$31°C is observed during February-May at upstream of Kottappuram. Mid-depth water throughout the

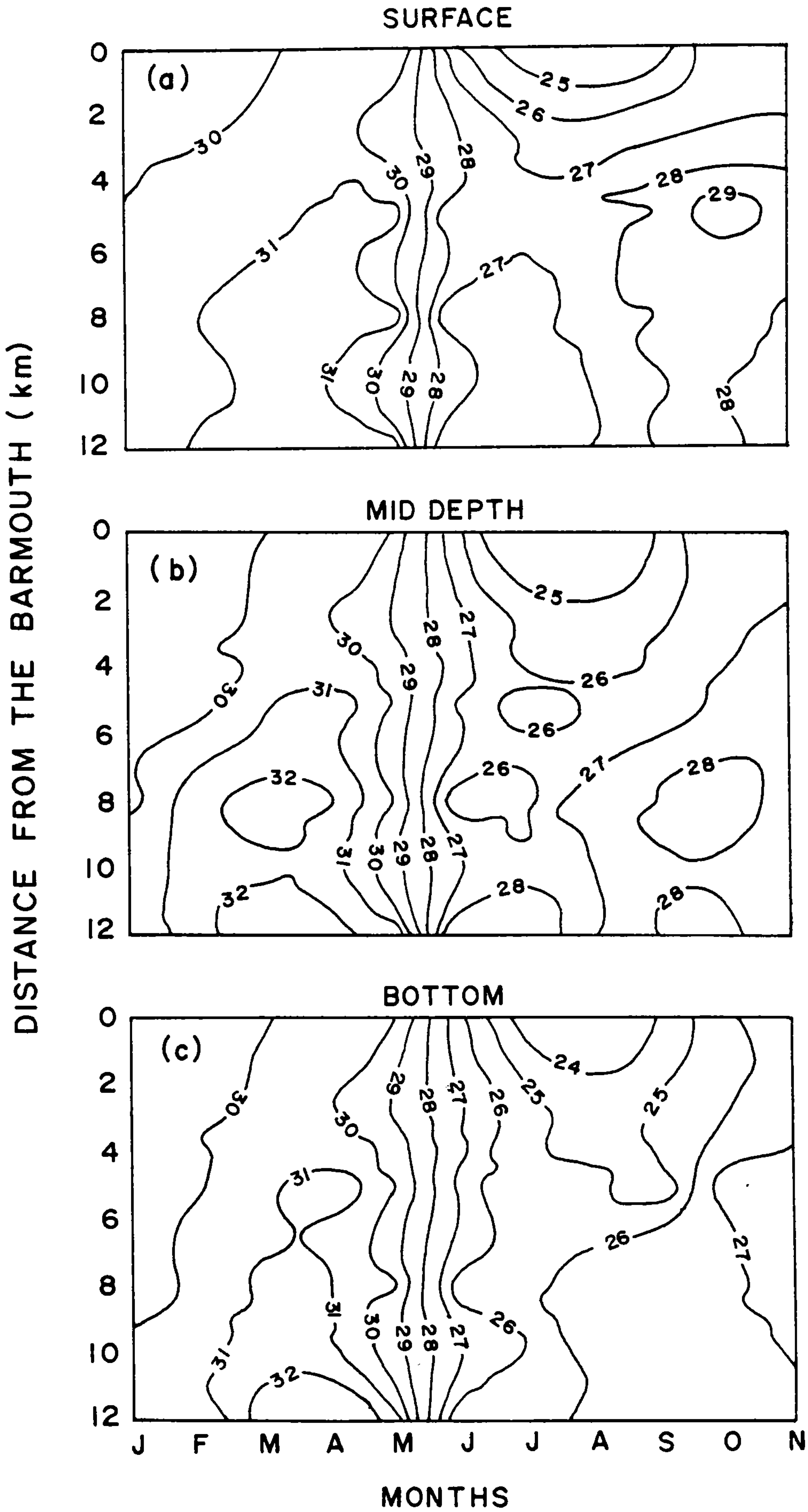


Fig. 3.1. Monthly variations of tidal mean temperature

estuary is 1 °C cooler than surface water during June-November. At the bottom layers, minimum temperature of 24 °C is observed at the seaward end of the estuary, and the maximum temperature of 31 °C is observed at the river end during February-May.

3.3 Salinity distribution (Synoptic)

Information on the distribution pattern of salinity in an estuary is vital as it throws light on the many physical processes taking place in the estuary. Salinity data collected during nine synoptic surveys are presented here to illustrate the difference in salinity distribution in the estuary as a function of ebb tide and flood tide, high and low river discharge. Synoptic surveys carried out during January and February represents the postmonsoon. Pre-monsoon and southwest monsoon seasons are represented by March-April and June-August respectively. Data collected during October and November represents the northeast monsoon condition. Contour plots for salinity are drawn with longitudinal distance from the bar-mouth on the x-axis and non-dimensional depth on the Y-axis, because bathymetric information was gathered only at and in the close vicinity of the selected sites. Cross-sections are represented in figures by S-I, S-II, S-III & S-IV respectively for Azhikode, Kottappuram, Gothuruthu and Chennamangalam respectively.

January

River input into the system during the survey period is 21 $m^3.s^{-1}$ and the maximum diurnal tidal amplitude is 0.64m. Distribution of salinity during ebb tide and flood tide are shown in fig 3.2.a & 3.2.b respectively. During ebb tide salinity intrusion is observed upto and beyond Chennamangalam as evidenced by the 32 X 10 $^{-3}$ isohaline. The estuary is well mixed upto Kottappuram. Longitudinal gradient of 19 X 10 $^{-3}$ is observed between Chennamangalam and Gothuruthu. Possible reason for this sharp longitudinal gradient may be the influx of Chalakkudy river which Joins the estuary upstream of Kottappuram. During flood tide (Fig.3.2.b) , longitudinal and vertical gradients are not as sharp as those observed during ebb tide. Difference in salinity at any point in the estuary between ebb tide and flood tide is $\geq$ 1 X 10 $^{-3}$.

February

Reduction in river discharge (16.41 $m^3.s^{-1}$) and increase in diurnal tidal amplitude (0.67m) results in a comparatively more gentle longitudinal gradient during February than January. However, the distribution pattern of salinity at ebb and flood are similar to those in January. During ebb tide (Fig.3.2.c) , well mixed zone is observed downstream of Kottappuram. Difference in salinity between

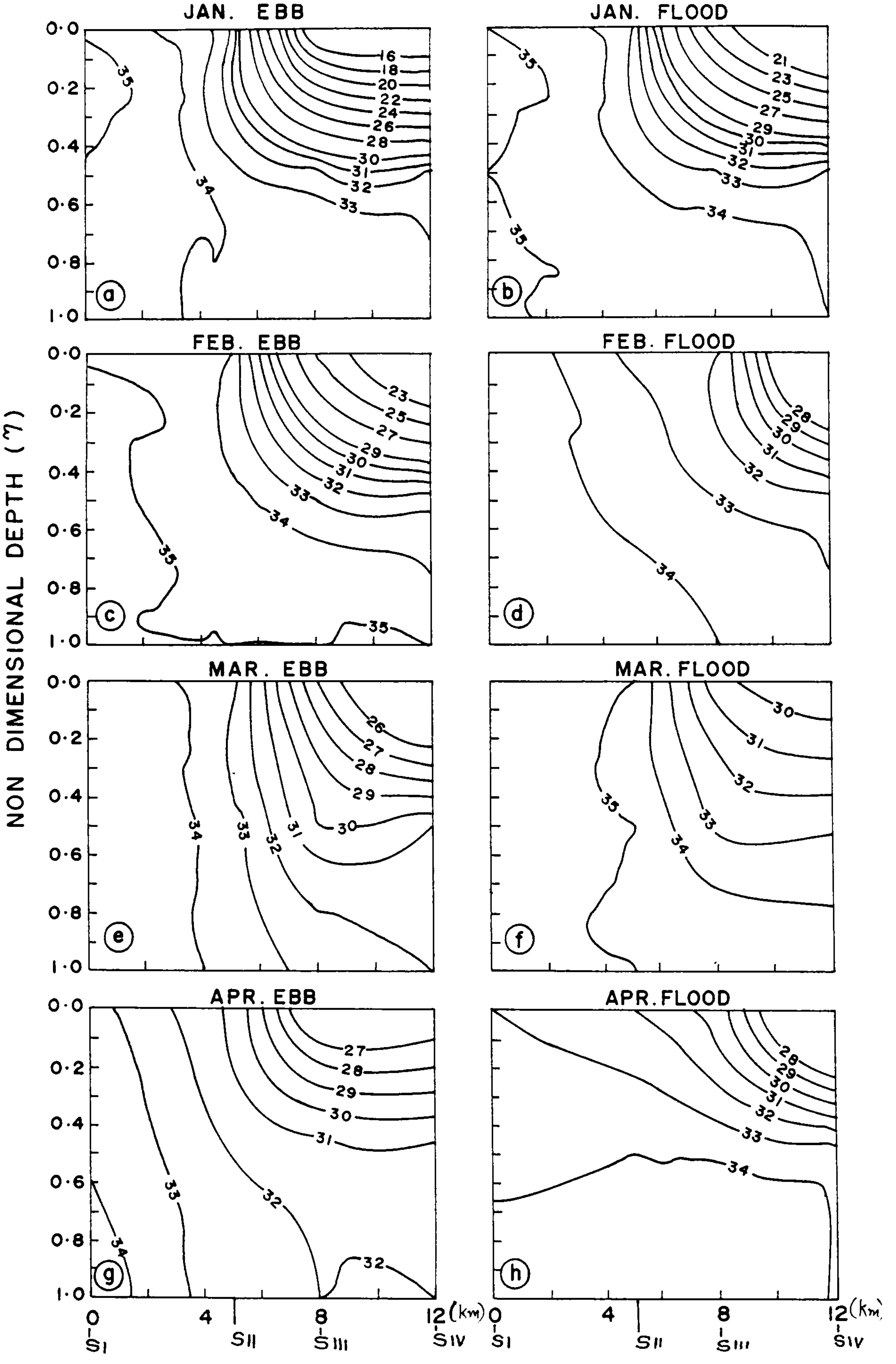


Fig. 3.2. Longitudinal salinity distribution.

river end and sea end is 10 X 10 $^{-3}$ at surface and 1 X 10 $^{-3}$ at the bottom. A sharp halocline with vertical salinity gradient of 12 X 10 $^{-3}$ is observed upstream of Kottappuram. During the flooding phase of the tide (Fig.3.2.d), due to the increased action of the tide, well mixed zone extends even upto Gothuruthu (S-III). At flood tide horizontal gradients are uniformly distributed, but vertical gradients are significant in the surface layer (between η =0.0 and η = 0.5) in the upstream section.

March

Fresh water input into the estuary during this month is 14.56 $m^3.s^{-1}$ and the maximum diurnal tidal amplitude is 0.69m. March and April represents the pre-monsoon season. During these lean periods , tide is the principal factor which controls the transport processes and the distribution of properties in the estuarine system. The ebb tide distribution of salinity is shown in Fig.3.2.e. High saline water penetrates well beyond Chennamangalam. Longitudinal gradient in salinity between Azhikode and Chennamangalam is 9 X 10 $^{-3}$ at the surface and 3 X 10 $^{-3}$ at the bottom. Fig.3.2.f depicts the salinity distribution at flood tide. Increased influence of tide is very much manifested in the distribution pattern, well mixed zone extends further upstream and reaches upto Gothuruthu(S-III) as implied by 35 X 10 $^{-3}$ isohaline. Axial and vertical gradients are weakened and the estuary becomes moderate to well mixed state.

April

Distribution of salinity during ebb and flood are shown in Fig.3.2.g and 3.2.h respectively. The fresh water input to the system is the least in April (10.3 $m^3.s^{-1}$) , while the diurnal amplitude of tide is 0.66m. The well mixed zone extends upto Gothuruthu. Upstream of Gothuruthu, significant vertical gradients are observed in the water column between η=0.0 and η= 0.5 below which homogeneous high saline water is encountered. Horizontal gradients are gentle in the lower reaches while they are very sharp in the upper reaches. At flood-tide isohalines are widely seperated and run almost parallel to the longitudinal axis indicating the absence of axial gradients. Condition of very low freshets and strong tides during flooding phase of the tide results in homogeneous high saline water (> 34 X 10^{-3}) below mid-depth and vertical gradient of 7 X 10^{-3} in salinity in the upper water column. Difference in salinity between ebb and flood tide at any position in the estuary is $\geq$ 2 X 10^{-3}.

June

Influence of increased freshets (123 $m^3.s^{-1}$) is reflected in the distribution properties during June. River flow is the major factor which controls the distribution during this period. Initial response of increased river flow is a rapid reduction of salinity and stratification implying that the increase in adverse barotropic pressure gradient is sufficient for a short period to prevent strong penetration of salinity into the lower estuary (Fig. 3.3.a). Maximum surface salinity at the sea end during ebb tide is 12 X 10^{-3}. Traces of salinity are observed only upto Gothuruthu and upstream of which is completely dominated by fresh water. Flood tide distribution (Fig.3.3.b) pattern is precisely similar to the ebb-tide distribution. Significant variation in salinity (21 X 10^{-3}) is observed between the two phases of the tide at the lower sections and this difference decreases in the upstream direction. Strong axial gradient observed between Kottappuram and Chennamangalam could be attributed to the interaction between the seaward flowing fresh water and the landward flowing seawater. When the river flow increases, shear intensifies and causes entrainment of salt into the surface water (Dyer,1972).

July

July and August are the active period of southwest monsoon. River discharge into the estuary increases from 116 $m^3.s^{-1}$ in June to 204 $m^3.s^{-1}$ in July. Only flood tide distribution (Fig.3.3.c) plot is presented because saline wedge is mixed and advected totally out during ebb tide. At flood tide, salinity intrusion takes the form of a gradient zone with strong longitudinal gradients as indicated by the

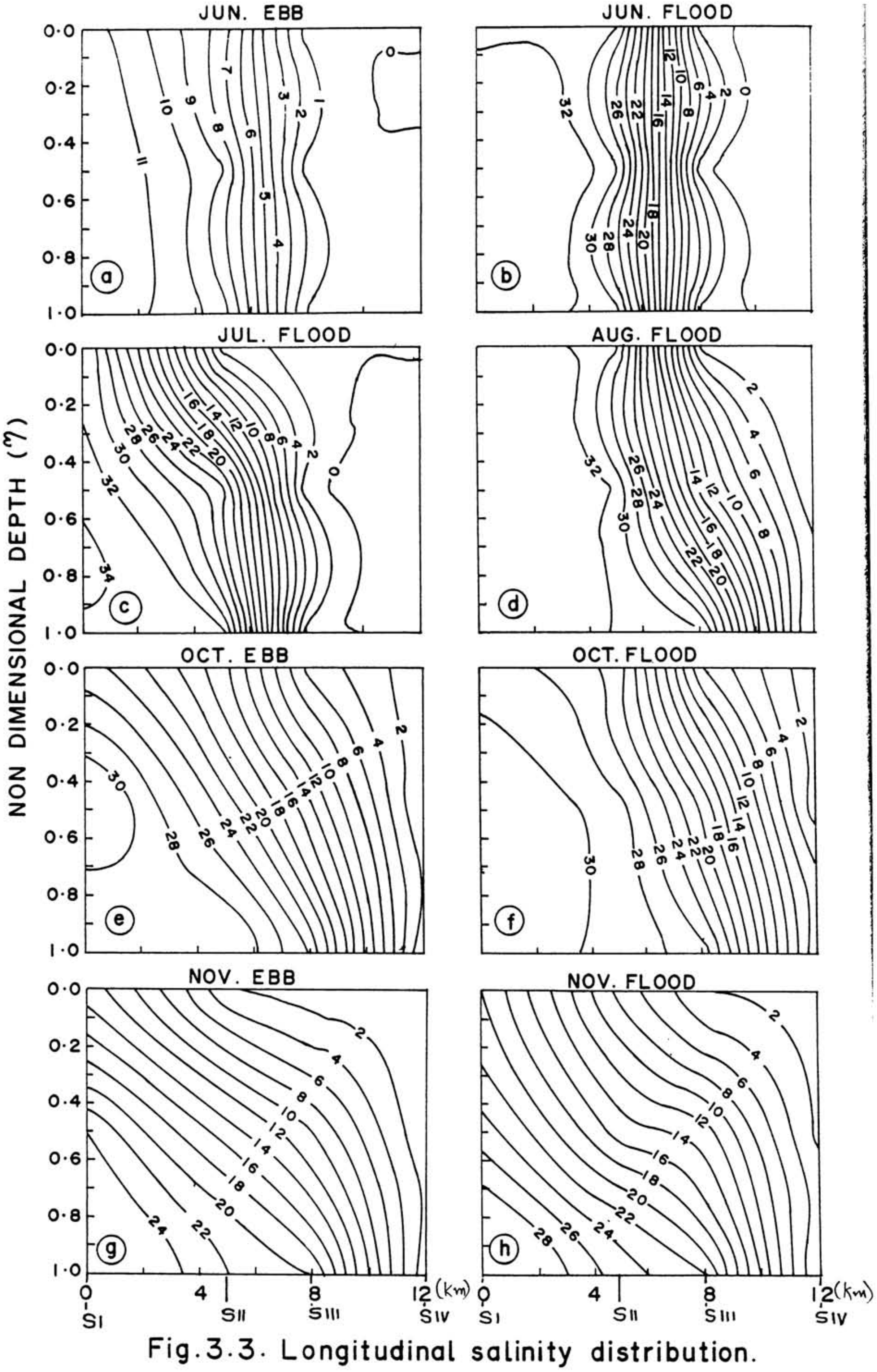


Fig. 3.3. Longitudinal salinity distribution.

32×10^{-3} isohaline which touches the surface at Azhikode and bottom at Kottappuram. Contrary to the observation during earlier periods, longitudinal gradient is higher in the bottom layers between Kottappuram and Gothuruthu, where within a span of 4 km, the salinity gradient reaches as high as 26×10^{-3}.

August

Salinity plots are presented only for flood-tide (Fig.3.3.d), since salinity is $< 1 \times 10^{-3}$ during ebb tide in the entire study area. Maximum freshet into the estuary occured in this month (387 $m^3.s^{-1}$) and the diurnal tidal amplitude is 0.64 cm. Regardless of the increased river discharge, vertical homogeneity is maintained in the lower 5 km reaches of the estuary as indicated by 32×10^{-3} isohaline which touches both surface and bottom at Kottappuram (Section-II). Further upstream, axial salinity gradient increases and reaches as high as 28×10^{-3} between Gothuruthu and Chennamangalam at surface and 22×10^{-3} at bottom.

October

Fresh water into the system is 121.21 $m^3.s^{-1}$ and the maximum diurnal tidal amplitude is 0.36 m. Distribution of the properties during ebb tide and is depicted in Fig.3.3.e. Horizontal gradients are much more uniform in the surface layer than at the bottom. Isohalines are parallel to each other and converges at the bottom. The entire reach is under the influence of salinity intrusion as indicated by 2×10^{-3} isohaline at the upper most section. Because of the smaller tidal amplitude, distribution trend does not vary between ebb and flood. At flood tide (Fig.3.3.f) lower 7 km reach of the estuary is nearly well mixed and further upstream, the orientation of isohaline is similar to that at ebb tide. On an average, difference in extreme values of salinity at any position during high and low tide is 4×10^{-3}

November

November represents the typical northeast monsoon period. Azhikode estuary receives freshets at the rate of 111 $m^3.s^{-1}$ during this period and diurnal amplitude of tide is 0.42 m. At ebb tide (Fig.3.3.g), vertical salinity gradient at Azhikode is 14×10^{-3} and increases in the upstream direction and reaches to 18×10^{-3} at Gothuruthu (Section-III). Axial gradient at the surface between Azhikode and Chennamangalam is 10×10^{-3} and the corresponding gradient at the bottom is 26×10^{-3}. Flood tide distribution (Fig.3.3.h) is similar to the ebb tide distribution, but the vertical salinity gradient at the seaward end is weakened. Intratidal variation in the salinity is observed only in the lower sections as the tidal amplitude is low.

3.4 Transverse variation of salinity and currents

Lateral distribution of salinity and current speed at four cross-sections in the Azhikode estuary are contoured for flood and ebb tide during February and July which represents the dry and rainy seasons respectively.

Azhikode (Section-I)

Fig.3.4.a & b shows the distribution of salinity at ebb and flood respectively during February. Salinity distribution is homogeneous in the entire section during both the phases of the tide with values ranging between 34-35 X 10^{-3}. During ebb tide isotachs (Fig.3.4.c) are vertical indicating lateral variation with faster seaward currents in the southern flank and current speed progressively decreasing towards north. Flood tide distribution (Fig.3.4.d) is characterised by up-estuary currents in the southern and central part of the section and weak seaward currents in the northern side of the section. During July, salinity is $\leq$ 1 X 10^{-3} in the entire cross-section at ebb tide, whereas, at flood high saline water having salinity values between 33 - 35 X 10^{-3} is distributed homogeneously across the section (Fig.3.4.e & f). During ebb tide, currents are directed seaward and are faster in the southern and central parts of the section (Fig.3.4.g). Flood tide distribution (Fig.3.4.h) is characterised by upstream currents from south to central part of the section and

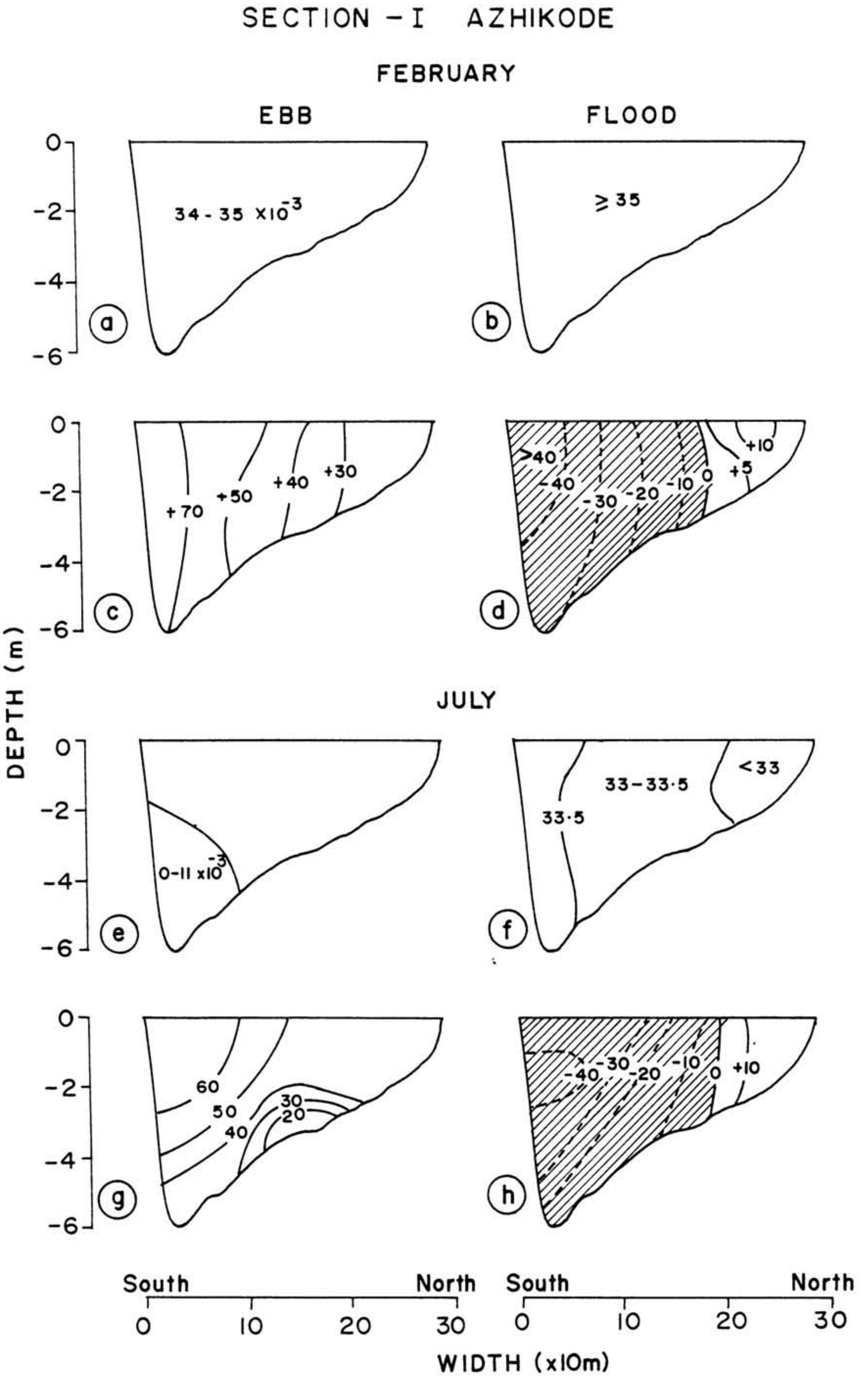


Fig. 3.4. Transverse distribution of current speed and salinity.

downstream currents at the northern side, with negligible vertical gradients.

Kottappuram (Section-II)

Transverse distribution of salinity during February at ebb and flood tides are depicted in Fig.3.5.a & b respectively. Salinity ranges between 33 and 35 X 10^{-3} in the entire section irrespective of the phases of the tide. Isotachs during ebb tide are more or less parallel to the transverse axis (Fig.3.5.c) indicating lateral homogeneous seaward flow with vertical gradient. During flood tide (Fig.3.5.d), up-estuary currents are seen in the entire section with faster currents in the deeper layers, reaching up to 25 $cm.s^{-1}$ at the centre of the stream. During the periods of active southwest monsoon (July), salinity is $\leq$ 1 X 10^{-3} in the entire cross-section during the ebb-tide (Fig.3.5.e) while during flood tide, salinity reaches up to 5 X 10^{-3} at the surface and 30 - 32.5 X 10^{-3} at the bottom (Fig.3.5.f). Current speed contours during ebb tide (Fig.3.5.g) are almost horizontal indicating the absence of transverse gradients whereas a vertical gradient of 10 $cm.s^{-1}$ between surface and bottom persists in the entire cross-section. During flood tide (Fig.3.5.h) even though the general direction of the current is up-estuary, isolated down estuarine flows with speed $\leq$ 5 $cm.s^{-1}$ are noticed near the surface in the central part of the section.

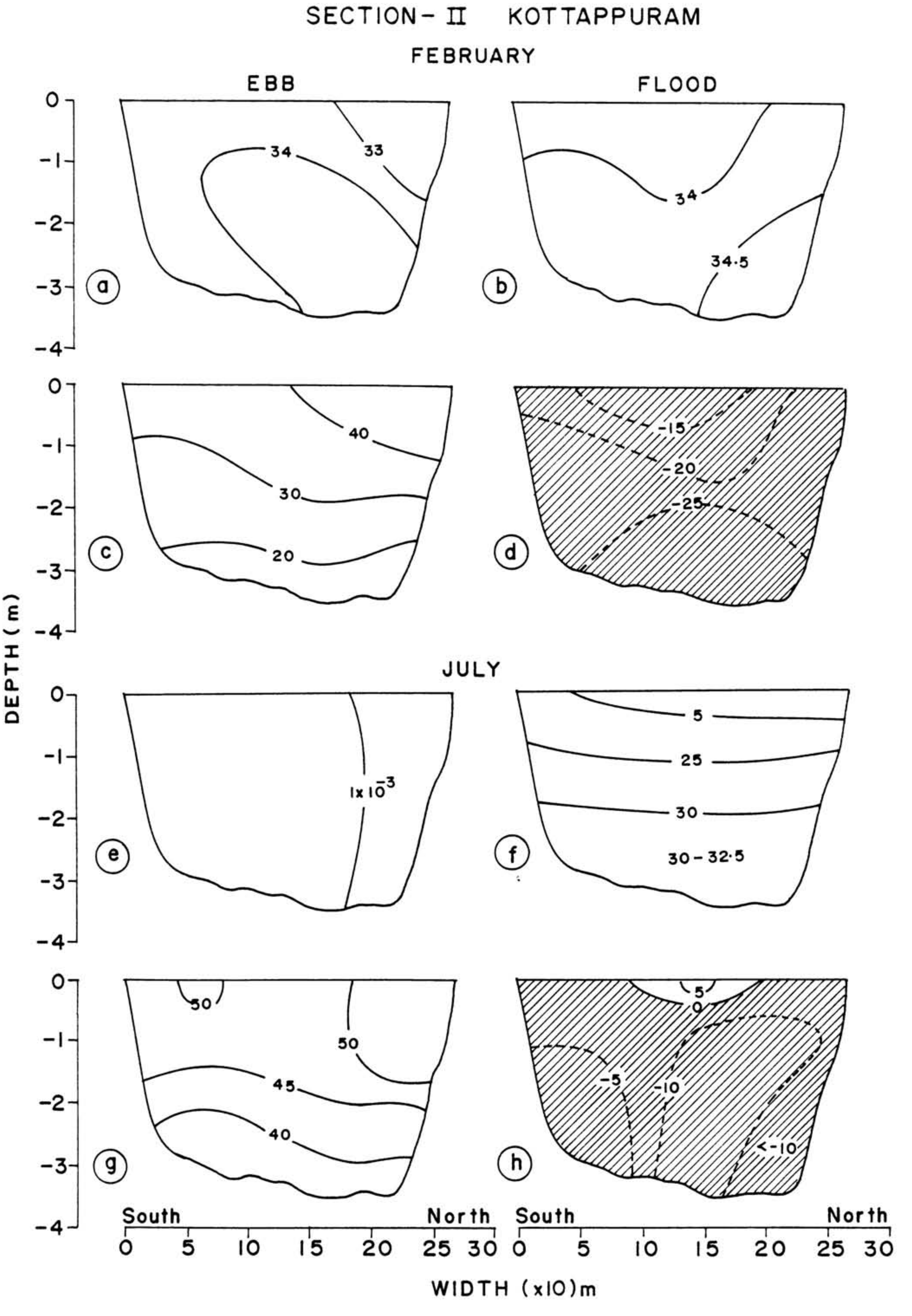


Fig. 3.5. Transverse distribution of current speed and salinity.

Gothuruthu (Section-III)

Lateral distribution of salinity for ebb tide and flood tide are contoured in Fig.3.6.a & b respectively. Isohalines are parallel to the transverse axis and are widely separated during both ebb tide and flood tide. Difference between ebb and flood tide is that the 35×10^{-3} isohaline located at 3m during ebb tide is shifted upward to occupy 2 - 2.5 m depth during ebb tide. Isotachs during ebb tide (Fig.3.6.c) are parallel to the transverse axis in the bottom layers while, in the surface lateral gradients in current speed are noticed. During flood tide (Fig.3.6.d) up-estuary currents at the central part is sandwiched between downstream currents both at the southern and northern flanks. During the period of active river discharge (July), salinity in the section is $\leq 2 \times 10^{-3}$ irrespective of the stages of the tide (Fig.3.6.e & f). During ebb-tide (Fig.3.6.g) the flow is seaward with speed decreasing from > 40 $cm.s^{-1}$ on the southern flank to < 30 $cm.s^{-1}$ on the northern flank. The flood tide distribution shows (Fig.3.6.h) a well defined vertical gradient at the central portion and this gradient decreases towards either side.

Chennamangalam (Section-IV)

Cross-sectional distribution of salinity and current during February for ebb tide and flood tide are shown in Fig.3.7.a & b respectively. Isohalines are parallel to the

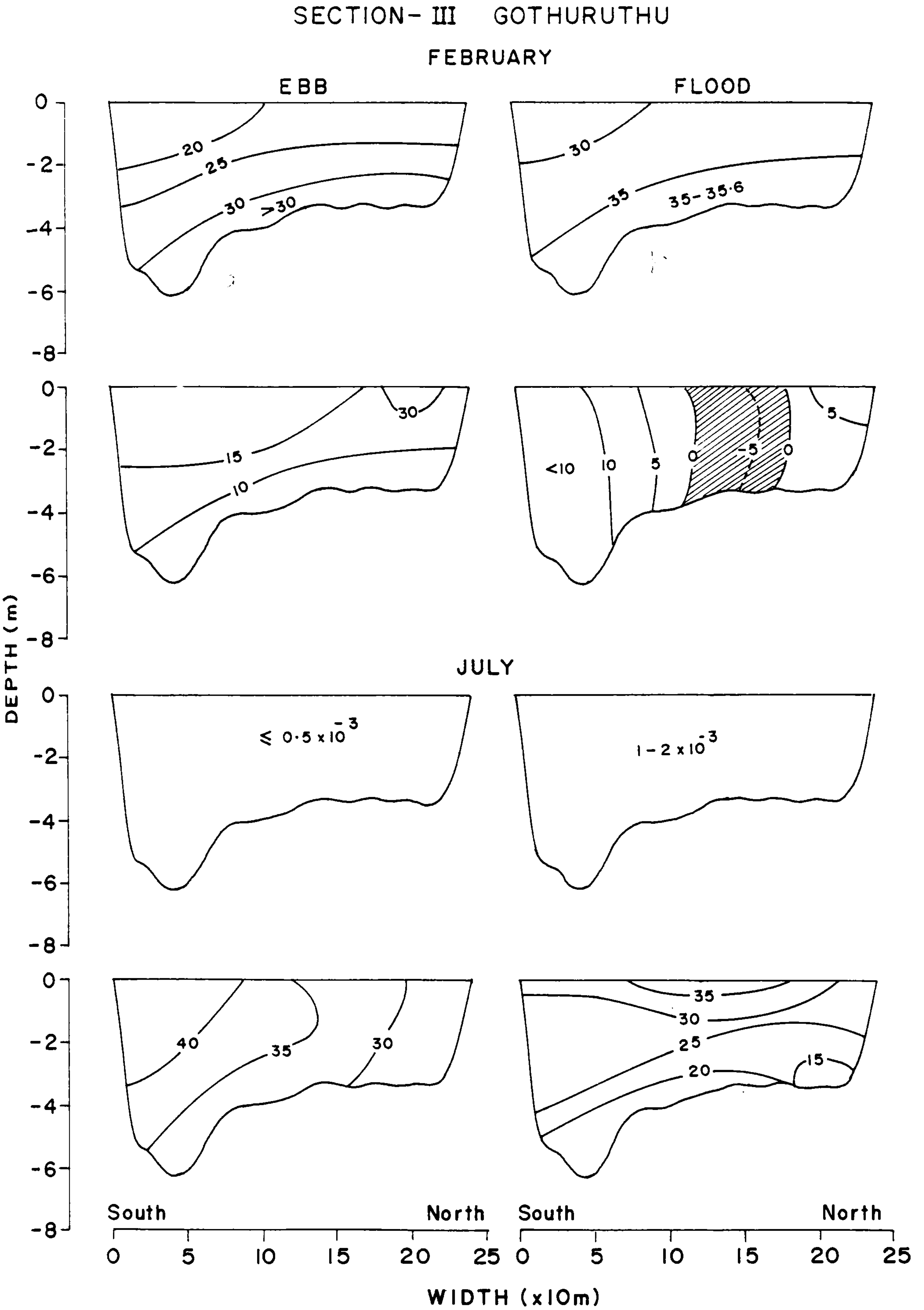


Fig. 3.6. Transverse distribution of current speed and salinity.

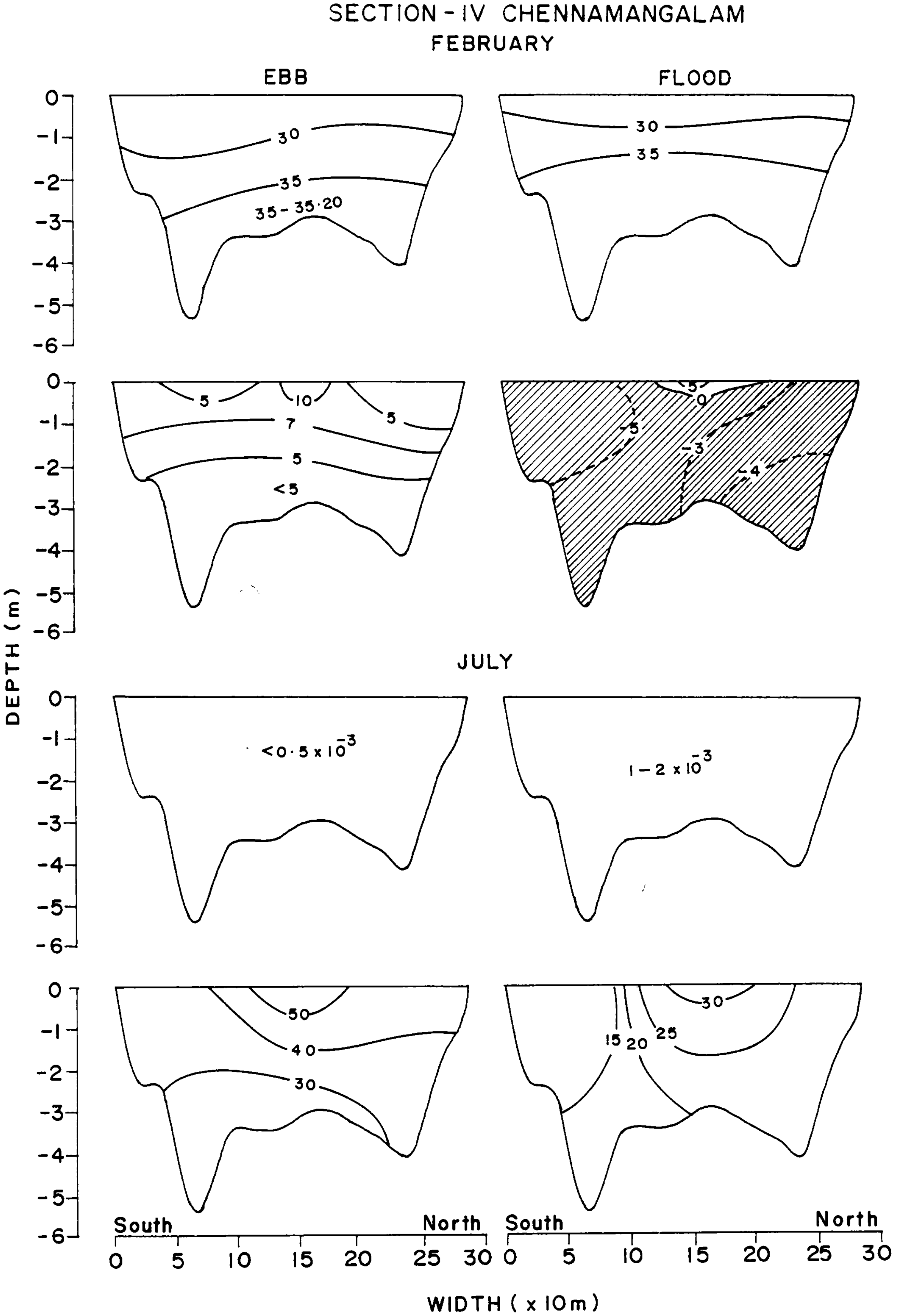


Fig. 3.7. Transverse distribution of current speed and salinity.

transverse axis during both the phases of the tide, with salinity ranging between < 30 to 35 X 10^{-3} . Orientation of the isotachs during ebb-tide (Fig.3.7.c) are parallel to the transverse axis indicating lateral homogeneity of current speed in the layers and gradients in the column. During flood tide (Fig.3.7.d), the current direction is up-stream in the entire cross-section except in the surface layer along the central part of the stream. During July, the section is completely fresh water dominated (Fig.3.7.e & f) regardless of the stages of the tide. At ebb tide (Fig.3.7.g) the cross-section is entirely dominated by seaward current with maximum speed of 50 $cm.s^{-1}$ at the surface along the central part. The isotachs are closely spaced at the central part of the section indicating a sharp vertical gradient which decreases towards either flank. During flood tide (Fig.3.7.h) also, the flow is seaward in the entire section though the speeds have considerably reduced. Lateral gradients in current speeds are significant in the central and northern portion of the cross-section.

3.5. Tidal mean salinity and current profile

Tidal mean salinity and current velocity profiles are presented for each cross-section during January, April, July and October representing the Post-monsoon, pre-monsoon, Southwest monsoon and Northeast monsoon respectively.

Azhikode (Section-I)

Tidal mean current and salinity profiles are plotted against non-dimensional depth in Fig.3.8a & b respectively. During January mean currents are seaward in the entire water column varying between a minimum of 10 $cm.s^{-1}$ at η =0.9 and a maximum of 22 $cm.s^{-1}$ at surface. The lowest seaward mean current of magnitude less than 5 $cm.s^{-1}$ are encountered during April. Residual current is directed up-estuary between η = 0.35 and 0.70. During the active period of southwest monsoon (July), seaward currents are observed in the entire water column, residual current speed varies from 25 $cm.s^{-1}$ at surface to 8 $cm.s^{-1}$ at the bottom (η =0.90). Maximum velocity gradient is observed between η = 0.20 to η = 0.50. The observed residual currents are higher in October. During this period current velocity increases from 31 $cm.s^{-1}$ at the surface to 35 $cm.s^{-1}$ at η = 0.20 and thereafter it decreases with depth and reaches the minimum value of 11 $cm.s^{-1}$ at η = 0.90. During both the pre monsoon and post monsoon seasons,the salinity profiles are vertical with values exceeding 30 X 10^{-3} . <S> shows the lowest value during July varying to a minimum of 12 X 10^{-3} at surface to a maximum of 23 X 10^{-3} at the bottom. During October tidal mean salinity shows gradient up to η = 0.4 afterwards <S> increases gradually. The vertical variations during this month is from 21 X 10^{-3} at surface to 31 X10^{-3} at bottom.

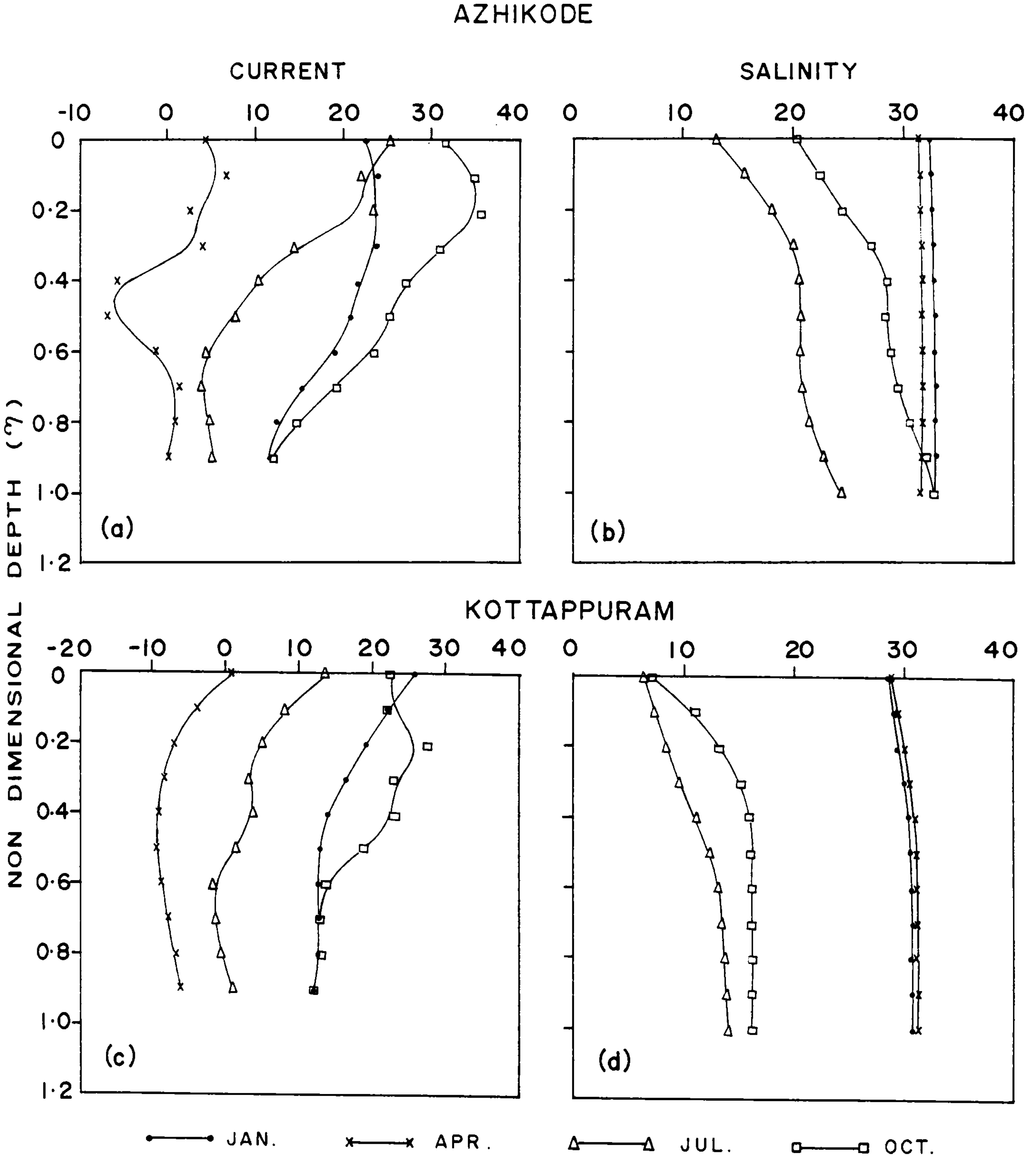


Fig. 3.8. Tidal mean current and salinity profile

Kottappuram (Section- II)

Fig.3.8.c shows the residual current profiles at Kottappuram. In January residual current is directed seaward in the entire water column. Current speed decreases from 25 $cm.s^{-1}$ at surface to 13 $cm.s^{-1}$ at η =0.90. Mean current is landward throughout the water column during April, whereas during July seaward current is observed between η= 0.50 and η= 0.60 and below which up-estuary current is seen up to η= 0.85. As observed at Azhikode, residual currents have maximum values between η = 0.1 and η= 0.60. Fig.3.8.d shows the residual salinity profiles at Kottappuram. During post monsoon and pre monsoon periods <S> profiles are nearly parallel to the depth axis with values exceeding 30 X 10^{-3} below η= 0.20. Lowest values of <S>, varying between 7 X 10^{-3} at the surface to 13 X 10^{-3} at the bottom are encountered in July. During October a well marked gradient in <S> is observed between η = 0.0 to η= 0.40 overlying a layer without appreciable vertical variation in residual salinity.

Gothuruthu (Section - III)

Residual current profiles at Gothuruthu are presented in Fig.3.9.a. During January, the profiles show the typical two layer flow, with seaward current between η = 0 and η =0.50 and up-estuary below η = 0.50. Lowest residual currents are observed in April, with seaward current between surface and

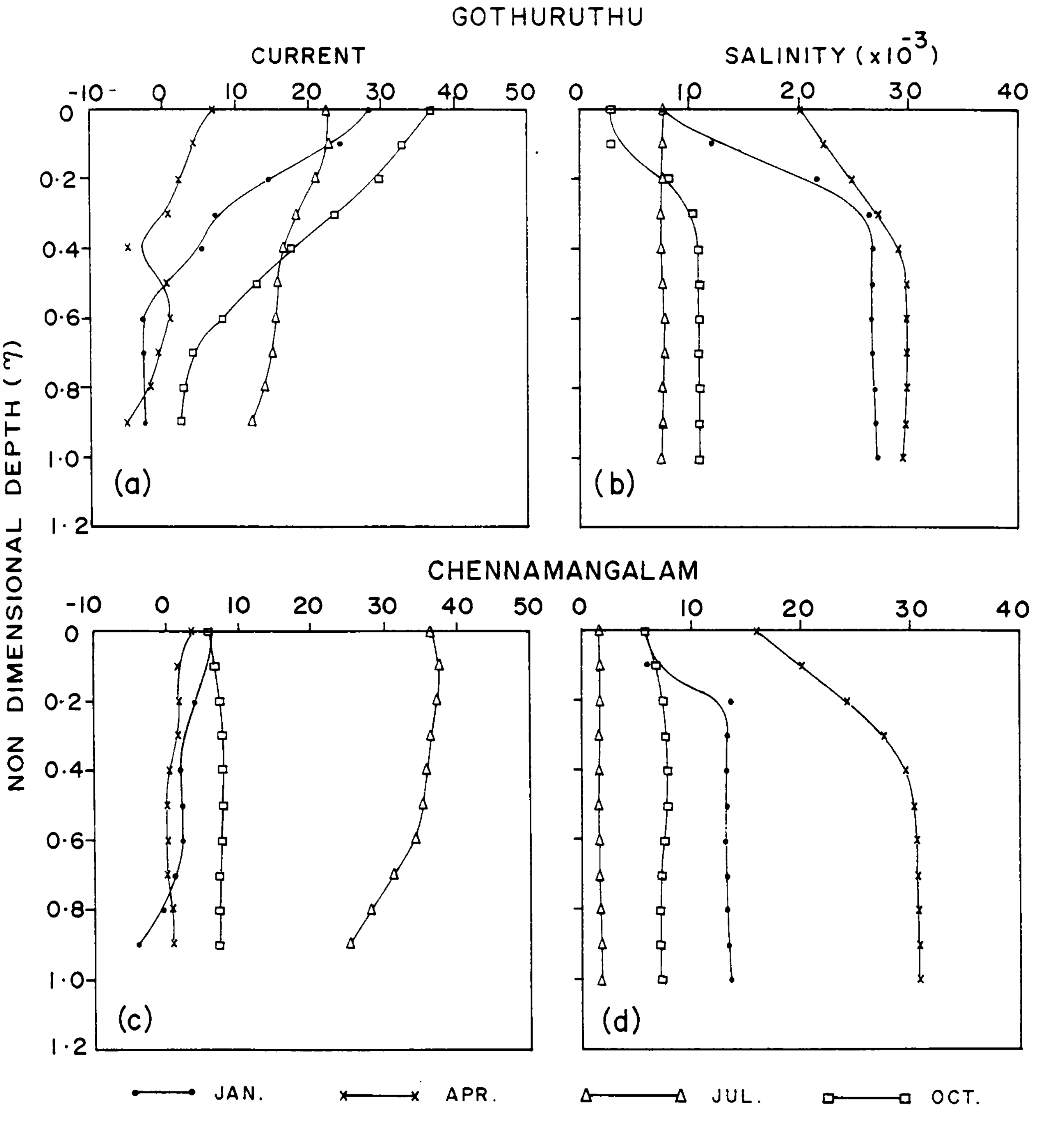


Fig. 3.9. Tidal mean current and salinity profiles.

$\eta = 0.30$ and upstream flow between η = 0.30 and η = 0.50. Between η = 0.50 and η = 0.70, the residual flow is seaward below which up-estuary current increases with depth and attains the maximum speed of 5 $cm.s^{-1}$ at η = 0.90. During July, the residual currents are towards the sea in the entire water column with magnitude decreasing from 22 $cm.s^{-1}$ at surface to 12 $cm.s^{-1}$ near the bottom. Residual surface currents are faster in October with velocity decreasing sharply from 38 $cm.s^{-1}$ at surface to 13 $cm.s^{-1}$ at η = 0.50, below which the velocity decreases gradually to 4 $cm.s^{-1}$ at η=0.90. Fig.3.9.b. shows the residual salinity profiles. The salinity profiles during January and April distinctly vary from those for July and October by the presence of a sharp halocline between η = 0 and η = 0.30 and higher magnitude. During July <S> values are low with magnitude < 10 X 10 $^{-3}$ in the entire water column. In October <S> increases very rapidly from 3 X 10 $^{-3}$ at surface to 10 X 10 $^{-3}$ at η = 0.30 and below that there is no appreciable variation in <S>.

Chennamangalam (Section-IV)

Fig.3.9.c shows the vertical residual current profiles at Chennamangalam. During January the residual current is towards the sea between surface and η = 0.75 and below that the residual current is directed up-estuary. Current profiles during April is similar to that in January. Fastest

currents are observed in July with magnitude varying between 38 $cm.s^{-1}$ at surface and 25 $cm.s^{-1}$ near the bottom. During October, the current profiles are parallel to the depth axis with magnitude < 10 $cm.s^{-1}$ in the entire water column. Fig.3.9.d illustrate the residual salinity profiles for different seasons. Salinity profiles for January show a well defined gradient between surface (16×10^{-3}) and η = 0.40 (30×10^{-3}), below which the residual salinity does not show any variation with depth. During April, the residual salinity profiles are characterised by high values and a sharp gradient between surface and η = 0.40. Below η = 0.40, the profile is parallel to the depth axis. During July <S> profile is parallel to the depth axis with magnitude < 2×10^{-3} in the entire water column. During October <S> values are higher than those in July and varied from 5×10^{-3} at surface to 8×10^{-3} near the bottom.

3.6. Depth-tide mean salinity distribution

Linear regression lines fitted for depth-tide averaged salinity on longitudinal distance for the various periods are shown in Fig.3.10. Slope of the fitted line depends upon the river input into the estuary, thus the maximum slope (axial gradient) is observed in June and the minimum gradient in April. Regression equations of the fitted lines are given below

January (Post monsoon)

$\langle \bar{S} \rangle = 33.63 - 1.15 \cdot (X)$ for river flow = 21 $cm.s^{-1}$

April (Pre monsoon)

$\langle \bar{S} \rangle = 32.37 - 0.44 \cdot (X)$ for river flow = 10.3 $cm.s^{-1}$

June (Southwest monsoon)

$\langle \bar{S} \rangle = 22.09 - 1.78 \cdot (X)$ for river flow = 123 $cm.s^{-1}$

October (Northeast monsoon)

$\langle \bar{S} \rangle = 20.42 - 1.20 \cdot (X)$ for river flow = 121.21 $cm.s^{-1}$

3.7. Predictive linear regression model

Multiple regression equations are fitted for depth-tide averaged salinity $\langle S \rangle$ on tidal amplitude (T) and river discharge (R). The following are the equations obtained for various cross-sections in the estuary.

Azhikode (Section-I)

$\langle \bar{S} \rangle = 11.96 - 0.033(R) + 29.19\ (T), F(2,6,5\%) = 3.90$

Kottappuram (Section -II)

$\langle \bar{S} \rangle = 05.19 - 0.060(R) + 35.45(T), F(2,6,5\%) = 4.46$

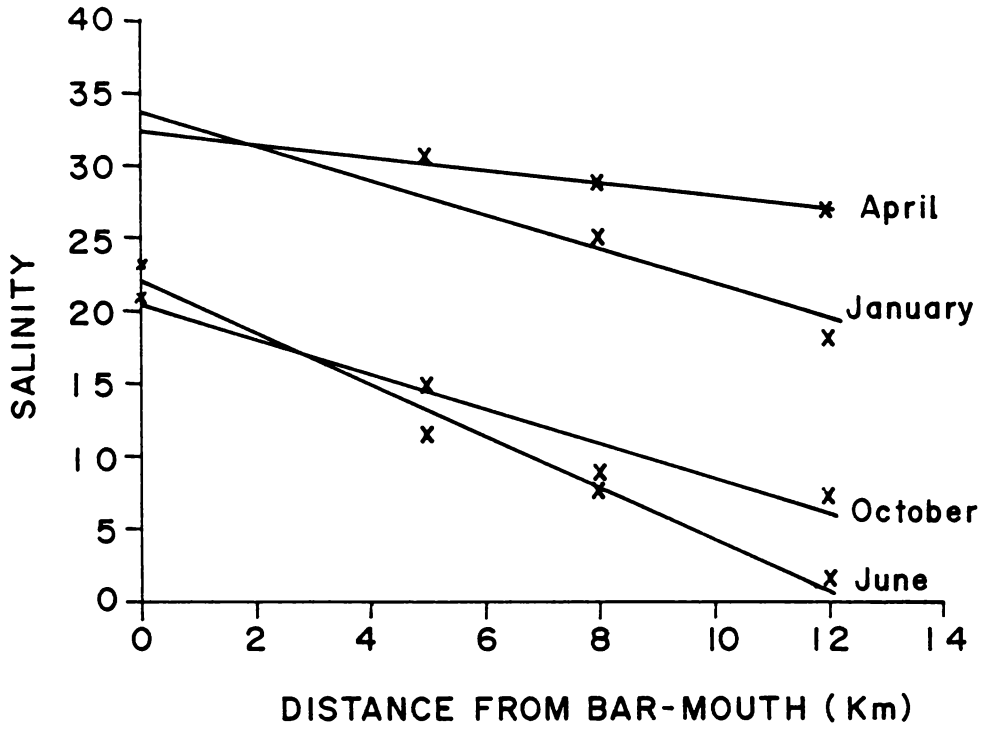


Fig. 3.10. Axial distribution of tide depth averaged salinity during different months.

Gothuruthu (Section -III)

$\langle\overline{S}\rangle$ = -1.92 - 0.053(R) + 37.76(T),F(2,6,5%)=6.04

Chennamangalam (Section- IV)

$\langle\overline{S}\rangle$ = -1.99 - 0.059(R) + 31.38 (T),F(2,6,5%)=4.18

where T is in cm and R is in m^3.sec.

Relative importance of these parameters are tested and the the results obtained are suumarised below

	Azhikode	Kottappuram	Gothuruthu	Chennamangalam
R	0.5762	0.7028	0.7147	0.7271
T	0.6736	0.6627	0.5609	0.5202

Thus from the above table it is seen that the lower most section (Azhikode) tidal amplitude is the major factor which controls the salinity distribution whereas in the other section river discharge is the principal agent which controls the mean salinity distribution. Relative importance of tidal amplitude generally decreases in the upstream direction.

CHAPTER-4

4. RESIDUAL FLUXES OF SALT AND WATER

4.1 Introduction

The circulation of water within an estuary is charactarised by strong tidal oscillations on which are superimposed residual water circulation which may be generated by non-linear interaction between the tidal flow and estuarine topography, density gradients,wind stress and mass input due to fresh water discharge into the estuary.

The depth integrated residual transport of water at a position in the estuary is the result of flows due to the depth averaged eulerian residual current together with the tidal pumping of water associated with possible non-zero correlation between the tidal oscilation in water depth and velocity. Tidal pumping will occur if the tide is of the partially progressive type. (Dyer,1974; Kjerfve, 1975; Hunter, 1972; Tee, 1976) . The long term cross-sectionally averaged residual transport of water is determined by the fresh water input into the estuary.

In this chapter transverse, axial and vertical structure of the residual transport of water and salt are investigated for the lower reaches of the Azhikode estuary. Residual fluxes are interpreted in terms of the various dispersion mechanisms and the results are used to estimate their relative importance of residual flow, tidal pumping and vertical shear in the axial and transverse dispersion of salt. The physics of these various dispersion mechanisms are as follows. Considering the salt transport, the salinity and axial velocity at any point on a cross-section can be represented as the sum of a cross-sectional average and a deviation there from. The integral over the Section area of the product of the velocity and salinity deviation yields the instantaneous rate of salt transport due to shear dispersion. The velocity and salinity deviation will result from inhomogenities through the water column and across the width . The shear dispersion associated with spatial variation through the water column and across the width are known as vertical and transverse dispersion respectively. As the number of observations along the cross section is less, only vertical shear transport is computed and discussed in this study. Tidal pumping arises in the following way. Water entering the estuary on the flood mixes with fresh water in the upper reaches of the estuary. The mixing may be due to small scale turbulence or breaking of internal waves. An amount of this mixed water leaves on the ebb flow. Because the flood and ebb flows are roughly equal (the difference being due to fresh water input) and the ebb water is fresher than the flood water, this leads to down-estuary pumping of salt.

4.2 Definition and variables

Residual fluxes of water and salt through a water column can each be separated into their various components. These components result from distinct physical processes. Bowden & Sharaf El Din, 1966; Fischer, 1972; Dyer, 1974; Lewis, 1979 and Uncles & Jordan, 1979 have derived theoretically the analytical description of these variables. The axial (x) component of motion along the estuary is considered here, with H, U and Q the instantaneous depth, current and rate of transport per unit width $Q = \langle H.U \rangle$ respectively. Residual rate of transport per unit width of water column is

$$\langle Q \rangle = \langle H.\overline{U} \rangle = h (\overline{u_E} + \overline{u_S}) = h.\overline{u_L} \quad \text{-------} \quad (1)$$

in which diamond bracket denote a tidal average, and the overbar a depth average,

$$h = \langle H \rangle \quad \text{-------------} \quad (2)$$

$$\overline{u_E} = \langle \overline{U} \rangle \quad \text{-------------} \quad (3)$$

$$\overline{u_S} = \langle \tilde{H}.\tilde{U} \rangle / h \quad \text{-------------} \quad (4)$$

with

$$\tilde{U} = U - \langle \overline{U} \rangle \text{ and } \tilde{H} = H - \langle H \rangle \quad \text{-------------} \quad (5)$$

and $$\overline{u_L} = \langle Q \rangle / h \quad \text{--------------} \quad (6)$$

If $\langle A \rangle$ is the tidally averaged area of cross -section and $\langle Q_F \rangle$ the tidally averaged rate of input of fresh water volume up-estuary of this section and then

$$\overline{u_F} = \langle Q_F \rangle / \langle A \rangle \quad \text{---------------} \quad (7)$$

The residual transport of salt per unit width of column is (in X 10 $^{-3}$.cm.s^{-1})

$$F = F_L + F_{TP} + F_V \quad \text{---------------} \quad (8)$$

where F_L is due to the residual flow of water u_L, and F_{TP} and F_V are due to tidal pumping and vertical shear respectively. If S denote the instantaneous salinity and s = < S > then

$$F = \langle H.\overline{U.S} \rangle / h \quad \text{----------------} \quad (9)$$

$$F_L = \overline{u}_L . \overline{s} \quad \text{----------------} \quad (10)$$

$$F_{TP} = \langle \widetilde{Q} . \widetilde{S} \rangle / h \quad \text{----------------} \quad (11)$$

$$F_V = \langle H . \overline{U' . S'} \rangle / h \quad \text{--------------} \quad (12)$$

where

$$S' = S - \overline{S} \text{ and } U' = U - \overline{U} \quad \text{-----------} \quad (13)$$

One dimensional depth averaged Eulerian, Stokes and Langrangian residual currents in the Severn estuary has been estimated in Uncles & Jordan (1980). Similar studies have been reported by Van De Kreeke (1978) and Ianniello (1981).

4.3 Axial Distribution of residual fluxes

A summary of the residual current during different periods of observation for different stations are given in Table- 4.1 to 4.11. To discuss the axial distribution these data for the stations lying along the central axis of the estuary are considered and are plotted on the same distance scale as for the salinity distribution in chapter-3.

January :- Observed currents during this period are shown in

Fig 4. 1.a. Eulerian residual current varies from 15 $cm.s^{-1}$ near the barmouth to 3 $cm.s^{-1}$ at Section- IV. Stokes drift (u_S)is directed up-stream at all Sections with very small magnitude ranging between 0.2 $cm.s^{-1}$ and 0.9 $cm.s^{-1}$. Fresh water induced residual current (u_F) varies from 1.56 $cm.s^{-1}$ at the barmouth to 2.54 $cm.s^{-1}$ at Section-III. Langrangian residual current (u_L) follows the direction of u_E.

February:- Fresh water induced residual current (u_F) varies from 1.21 $cm.s^{-1}$ near the barmouth to 2.02 $cm.s^{-1}$ at Section-II (Fig.4.1.b). Eulerian residual current (u_E) decreases from 14.63 $cm.s^{-1}$ at Section-I to 1.2 $cm.s^{-1}$ at Section-IV. Except at Section-I, Stokes drift is directed up-estuary.

March :- Observed residual currents are depicted in Fig.4.1.c. u_F varies from 1.08 $cm.s^{-1}$ at Section-I to 1.4 $cm.s^{-1}$ at the up-stream section. Direction of u_E is up-estuary in the lower most two sections, with values 8.6 $cm.s^{-1}$ at Section-I to 1.6 $cm.s^{-1}$ at Section-II. In the section lying on the river end of the estuary u_E is directed down-stream.

April:- Fresh water induced residual current (u_F) is lowest in this period, and the values range between 0.76 $cm.s^{-1}$ to 1.38 $cm.s^{-1}$ (Fig.4.2.a). Eulerian residual current (u_E) is up-estuary at Section-I where tidal action is predominant and at all other sections u_E is directed up-stream. Stokes

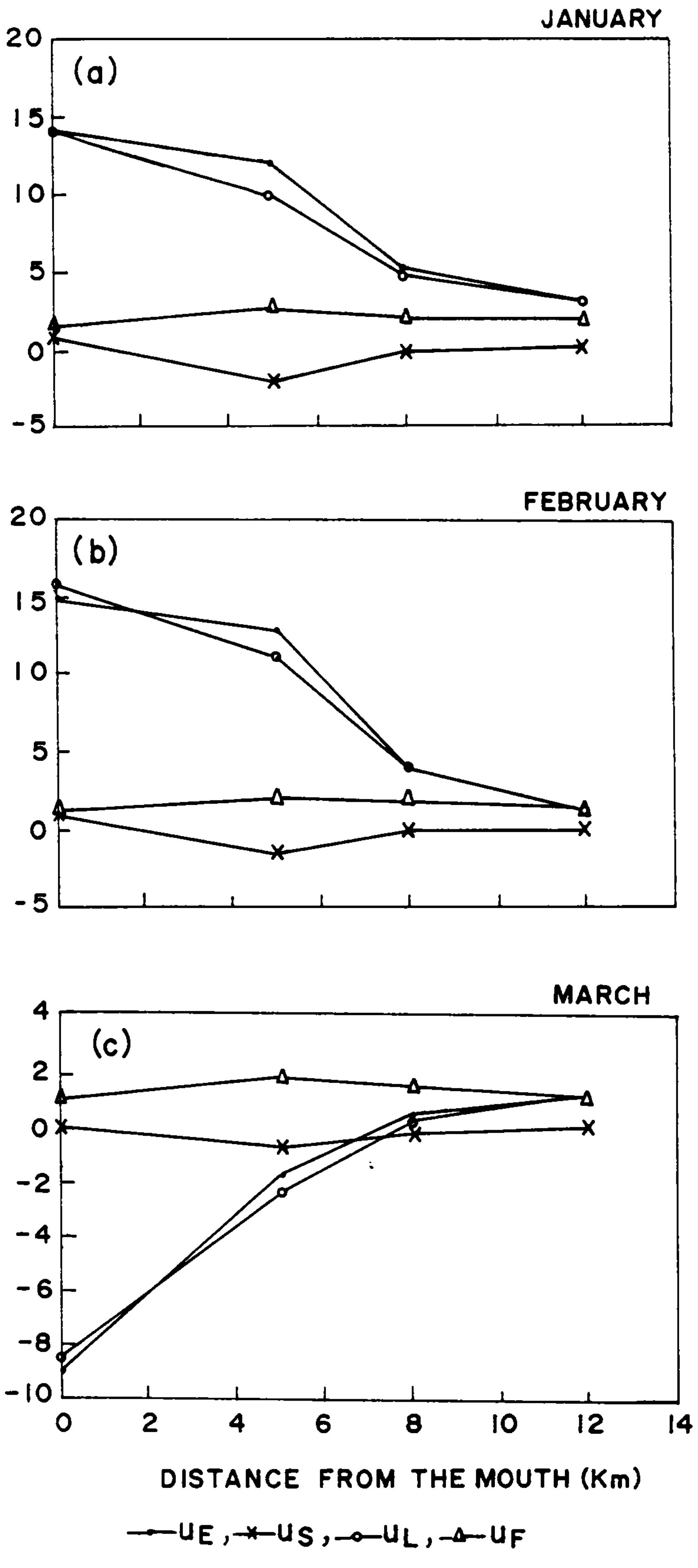


Fig. 4.1. Longitudinal distribution of Eulerian residual current (u_E) Stokes drift (u_S) Langrangian residual current (u_L) and Fresh water induced residual current (u_F).

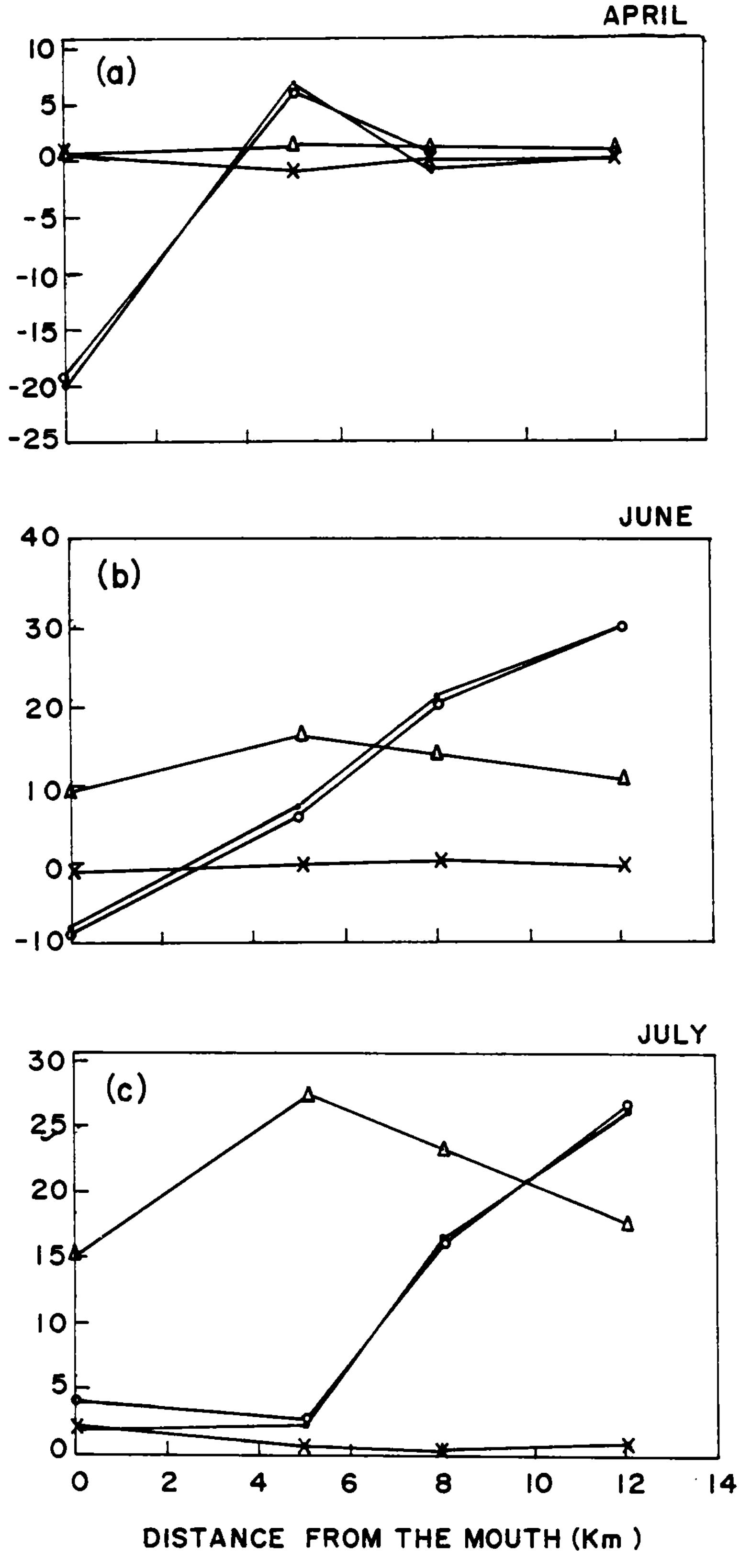


Fig. 4.2. Longitudinal distribution of Eulerian residual current (u_E) Stokes drift (u_S) Langrangian residual current (u_L) and Fresh water induced residual current (u_F).

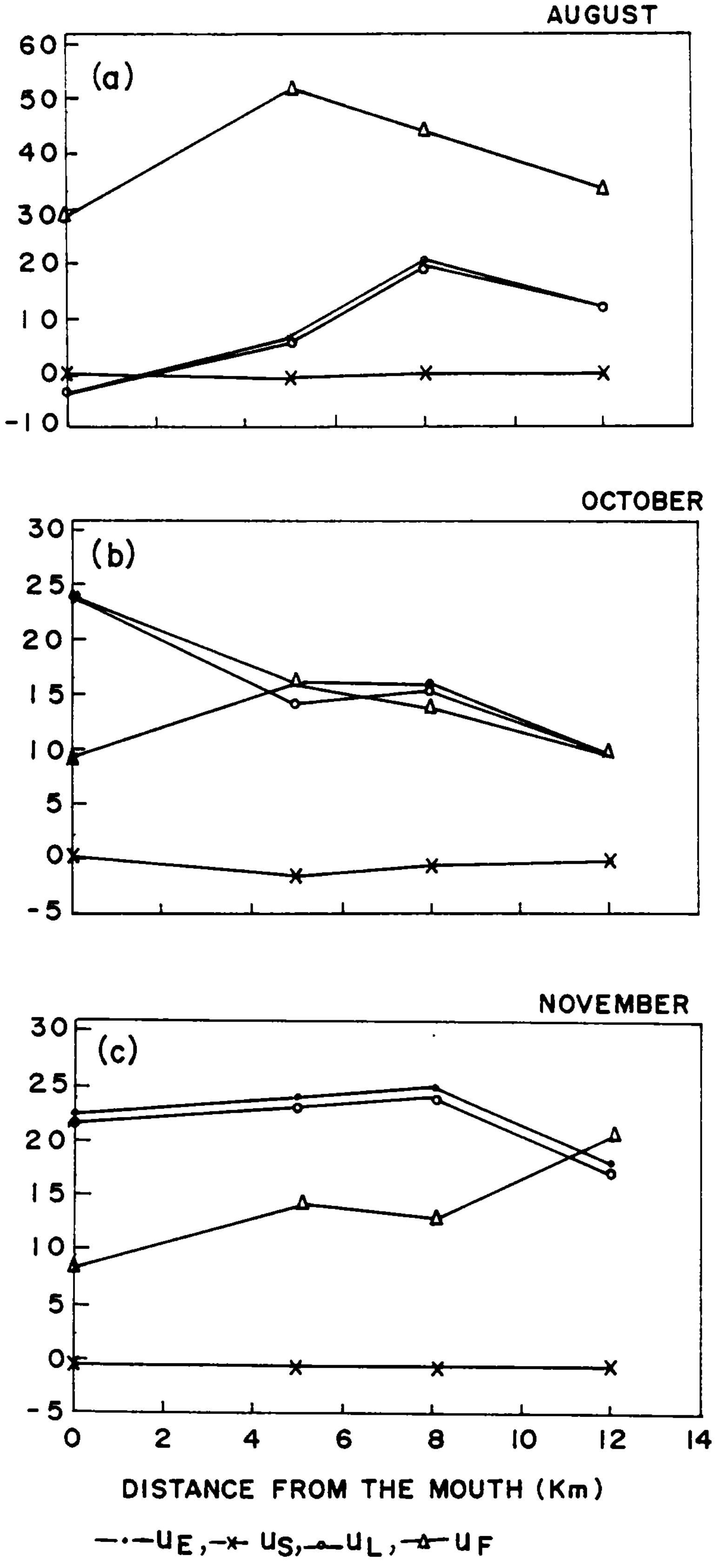


Fig.4.3. Longitudinal distribution of Eulerian residual current (u_E) Stokes drift (u_S) Langrangian residual current (u_L) and Fresh water induced residual current (u_F).

drift (u_s) is towards the river at all sections other than Section-I.

June:- Eventhough the river discharge into the estuary is higher during this period, up-estuary directed residual currents are observed in the lower two sections. Fresh water induced current at Section-I is 10.75 $cm.s^{-1}$(Fig.4.2.b). Tidal pumping (u_s) registered only very low values compared with u_E and u_F .

July:- Unlike in June, the residual current in July is towards the sea in the entire sections during July. Axial variation of u_F is negligible and the values range between 15.20 $cm.s^{-1}$ to 17.8 $cm.s^{-1}$ (Fig.4.2.c). Magnitude of u_E increases towards the river end. Minimum value of 1.89 $cm.s^{-1}$ is observed at Section-I and the maximum value of 26 $cm.s^{-1}$ is observed at Section-IV. Stokes drift values are very low and are mostly seaward.

August:- Maximum river discharge into the system occurred in this period and it is very much reflected on the magnitude of u_F . Maximum value of 52 $cm.s^{-1}$ (Fig.4.3.a)is observed at Section -II. Up-estuary eulerian residual current of 5 $cm.s^{-1}$ is observed at Section -I.

October:- Fig.4.3.b, illustrate the axial distribution of the residual current in this month. u_F varied between 9 $cm.s^{-1}$ to 9.5 $cm.s^{-1}$ between Section-I and Section-IV. u_E

is towards the sea at all the cross-section with higher magnitude at Section-1 (24 $cm.s^{-1}$) . (u_s) recorded only very low positive values within the range 1.6 - 0 $cm.s^{-1}$.

November:- Observed currents are presented in Fig. 4.3.c, Stokes drift is less than 1 $cm.s^{-1}$ at all sections and is up -estuary. Maximum value of river induced current of 24 $cm.s^{-1}$ is observed at Section - IV. Eulerian residual current (u_E) is down-stream in the entire study area. Strength of u_E is maximum at Section -III.

4.4 Annual variation of Residual current and Stokes drift

Section-I (Azhikode):- Residual current and Stokes drift computed for station-A and station-B are presented in Fig.4.4.a and 4.4.b respectively. As station-C is very shallow having depth < 2 m during most of the observation time and the chosen interpolation programme is not applicable and hence the residual currents are not computed for station-C. At station-A residual current is down estuary from January to February and up-estuary from March to June. Direction of this component changes towards the sea from July and acquire the maximum value of 24 $cm.s^{-1}$ in October. Annual march of residual current at station - B is similar to that of station-A in direction and differed only in the magnitude. It is observed that seaward currents are faster at station-B.

Stokes drift at Section -I registered only very small

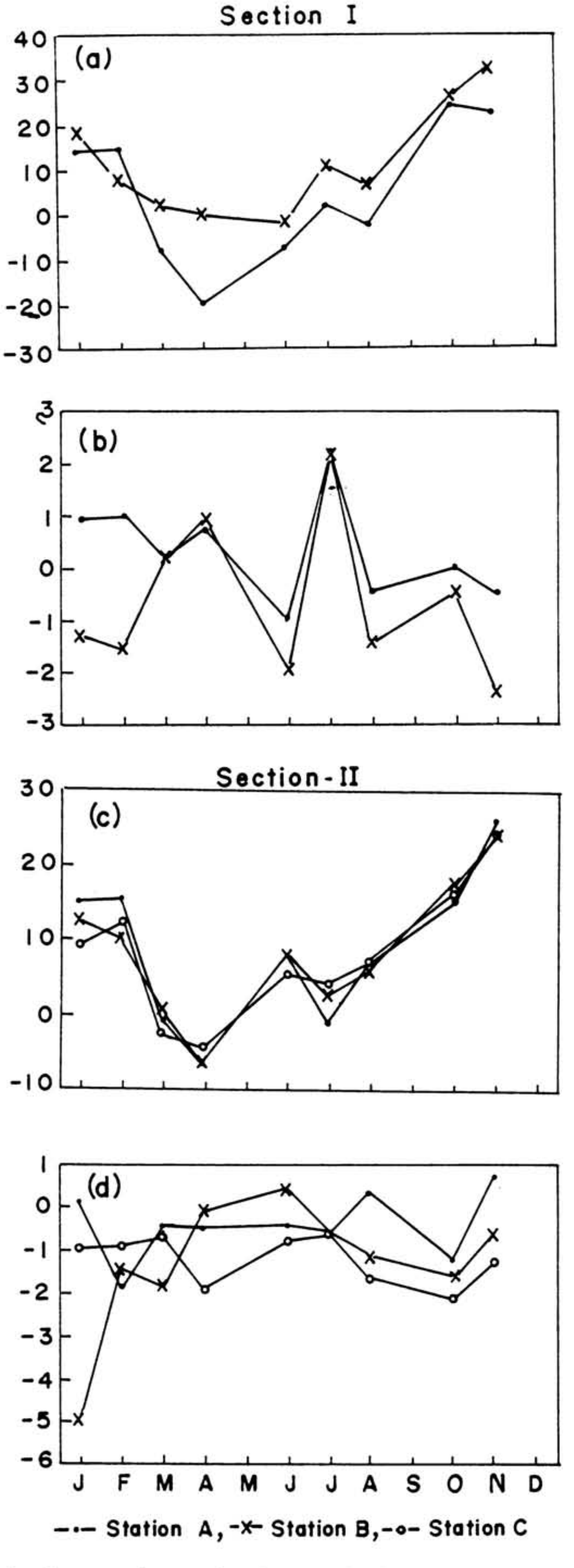


Fig. 4.4. Annual variation of Eulerian residual current (a,c) and Stokes drift (b,d)

values. Direction of the Stokes drift is irregular. Higher values are observed in July at both stations. In more than 60 % of the observations Stokes drift is found up-estuary.

Section - II (Kottappuram)

Annual distribution of residual currents and Stokes drift at different stations along Section - II are presented in fig 4.4.c and fig 4.4.d respectively. Distribution trend of residual currents are identical for the three stations. Most often residual currents are down-estuary and land ward current occurred only in March to May. Maximum residual current (28 $cm.s^{-1}$) is observed during October-November. Trend of distribution of Stokes drift did not show any consistent pattern. Over 95 % of the observation period,Stokes drift is directed up-estuary with maximum values of $5 cm.s^{-1}$ at station-A for the month of January.

Section - III (Gothuruthu)

Direction of the residual currents is seaward (Fig 4. 5.a) during all the observation period with the exception of April. Strength of the current is < 10 $cm.s^{-1}$ from January to April. From May onwards,there is a rapid increase in the strength and which reaches as high as 28 $cm.s^{-1}$ in June. Subsequently, the current speed decreases through July - August and then again increases and reaches the highest value in November. Annual distribution patterns are similar

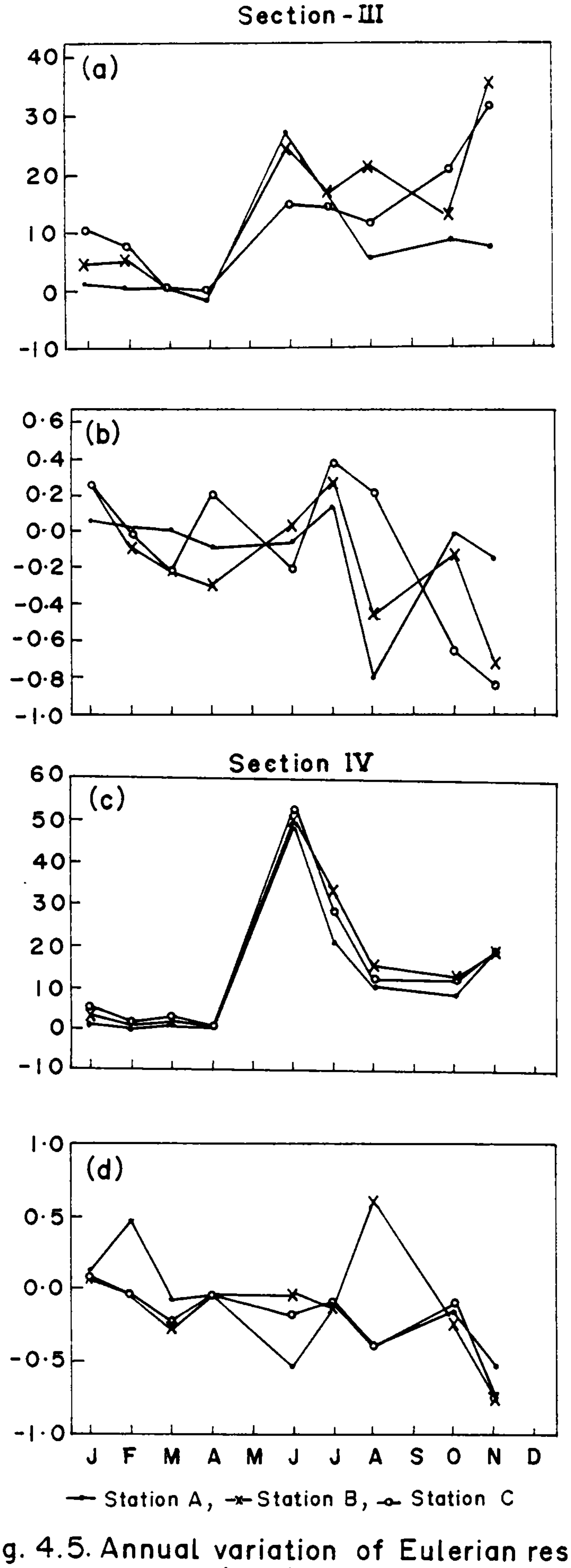


Fig. 4.5. Annual variation of Eulerian residual current (a,c) and Stokes drift (b,d)

for all the stations. Distribution trends of Stokes drift (Fig 4.5.b) are irregular. Magnitude of this component ranged between -0.9 to + 0.5 $cm.s^{-1}$. Only in July, seaward Stokes drift is observed at all the stations. During other seasons intra-sectional variation is observed both in direction and magnitude.

Section -IV (Chennamangalam)

Fig 4.5.c shows the annual distribution of residual current at different stations along Section - IV. Trend of distribution is identical for all the stations, there is not much variation in magnitude and direction between the stations. As this section is situated near the river end of the estuary, observed currents are higher when compared to other sections. Current speed $\leq$ 5 $cm.s^{-1}$ is observed in January to April, and with the onset of monsoon, current speed increases very rapidly and reaches to the tune of 50 $cm.s^{-1}$ in June and then decreases to 10 $cm.s^{-1}$ in August. Contrary to all other sections, residual currents are seaward at all the stations throughout the observation period. As discussed for other stations, Stokes drift distribution curve (Fig.4. 5.d) did not show any set pattern either with time or with stations. Yearly variation in Stokes drift ranged between - 0.8 $cm.s^{-1}$ to 0.7 $cm.s^{-1}$.

4.5 Axial dispersion of salt

Residual fluxes of salt per unit width of water column, given by equation (8), are presented for each station in Tables 4.1 to 4.11. Results are used to estimate the relative importance of residual discharge of water, tidal pumping and vertical shear to the axial dispersion of salt. This type of observations are of significance as they contribute to the knowledge of the magnitudes of mechanism affecting the salt and water budgets.

(Section-I) Azhikode

At station-A, Residual rate of transport of salt due to the residual discharge of water is down-estuary (Fig.4.6.a) during January to February. Salt transport by tidal pumping F_{TP} and F_V are very small, therefore the major component which controls the transport process is the residual water discharge. Net transport is up-estuary from March to August and down-estuary during January, February, October and November. At station-B (Fig.4.6.b) net salt transport is up-stream during April to August. At the periods of high fresh water discharge (June - August), it is observed that the the salt transport by the tidal pumping (F_{TP}) dominates over F_L . Transport by the shear processes are very low and are directed up-estuary throughout the observation period.

SECTION- I

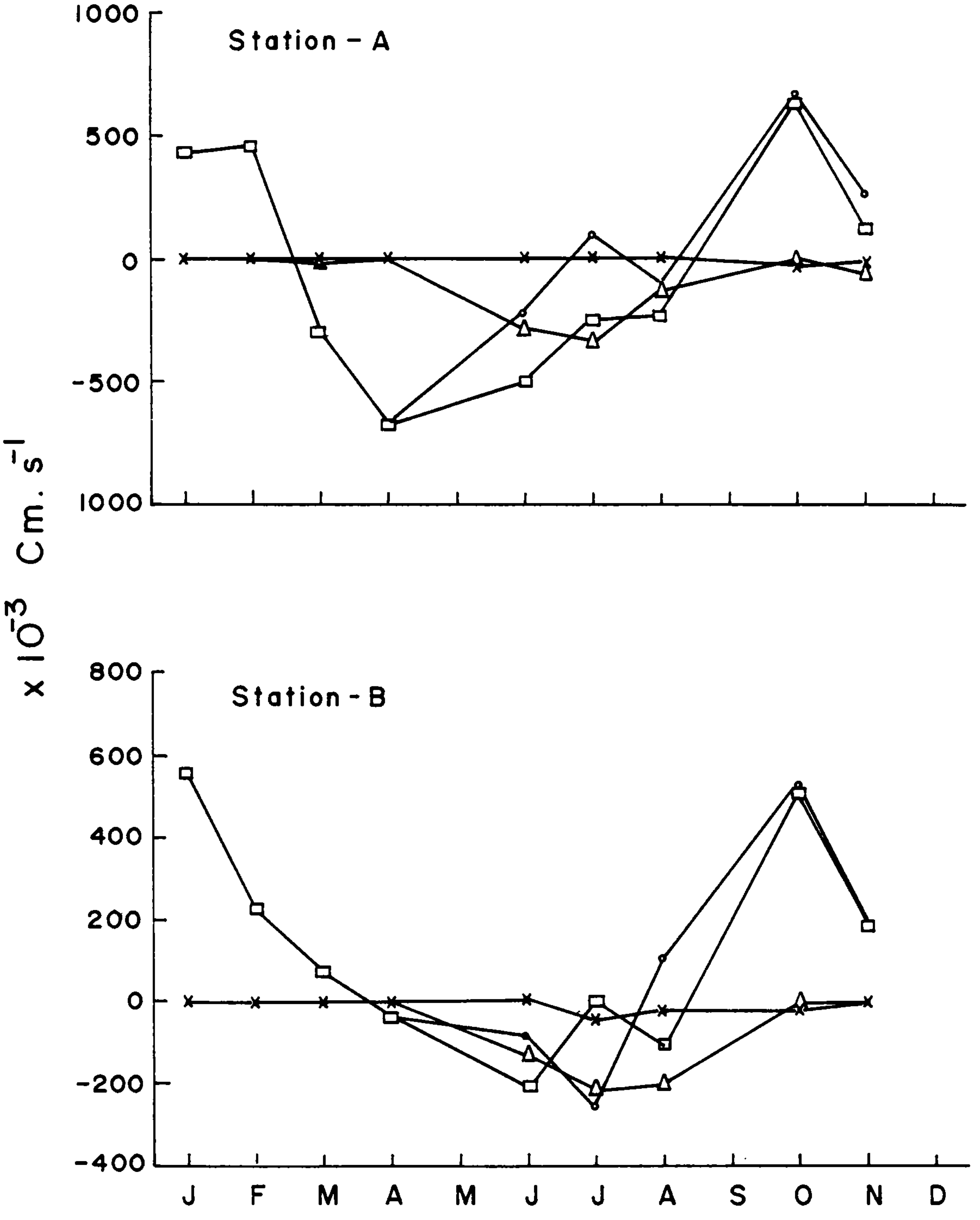


Fig. 4.6. Observed residual transport of salt due to residual flow of water (F_L), tidal pumping (F_{TP}), vertical shear (F_V) and their sum (F)

Section -II (Kottappuram)

At station-A (Fig.4.7.a) residual transport of water is the dominant mechanism for the residual transport of salt. Tidal pumping appears to be of secondary importance in the salt balance of the estuary. At station-B, (Fig.4.7.b) general direction of the salt transport is dictated by the residual flow of water during the entire observation period. Net transport is directed seaward in most of the observations but for a very weak up-estuary transport in March and April. Residual rate of transport of salt due to residual flow of water is directed down-estuary during January-February and May-November. During March- April (F_L) is up-stream. Generally,the tidal pumping of salt (F_{TP})is directed up-estuary. Thus tidal pumping is such that fresher water is mixed with more saline water (derived from down - estuary) on the flood and partly removed on the ebb. Contribution from the shear transport is very small to be compared with F_L,F_{TP} and are directed up-estuary. At station-C, net transport of salt is up-stream in March and April. Salt transport by the tidal pumping is very high in January and February. During the monsoon period, shear processes become the second important mechanism in the salt transport processes.

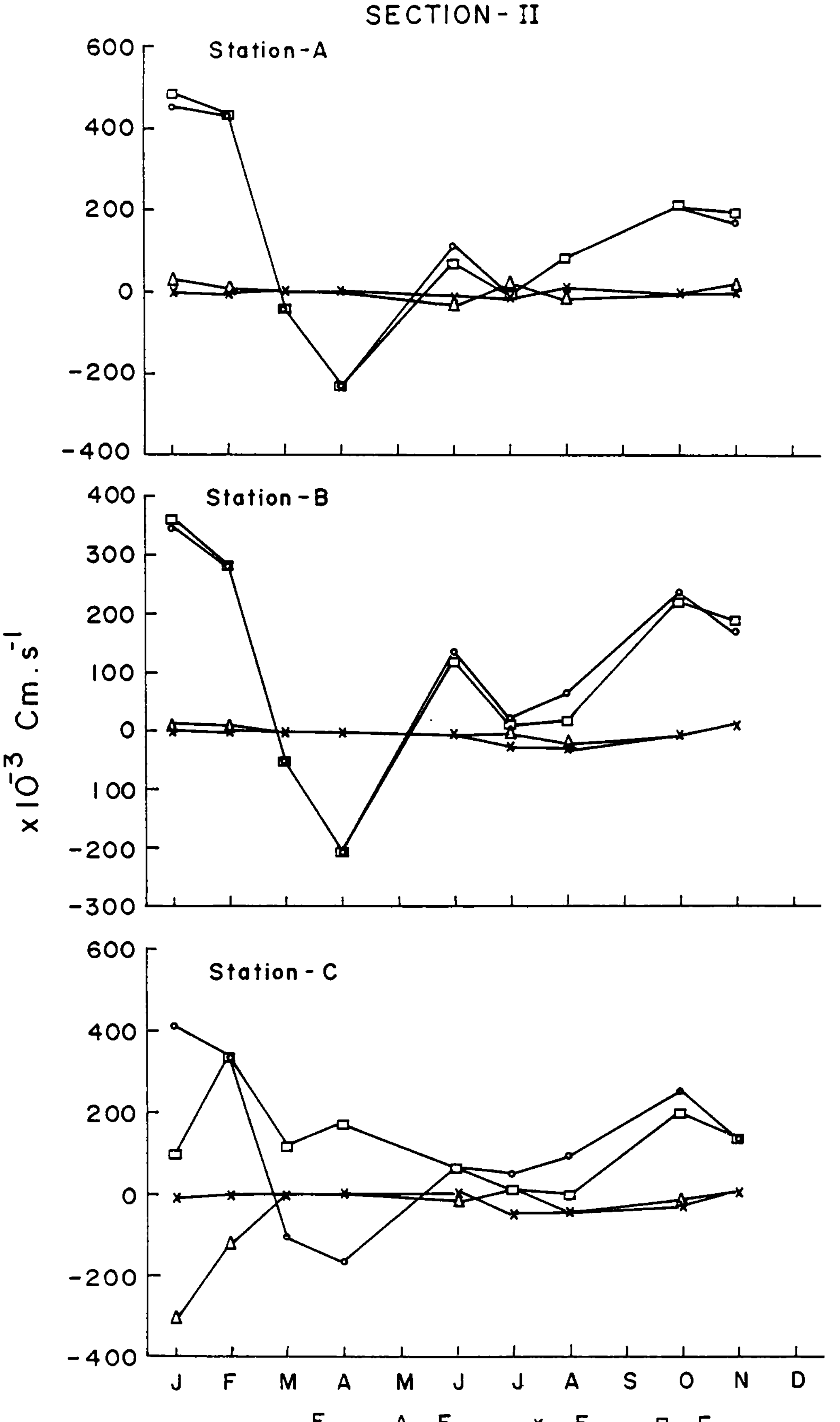


Fig. 4.7. Observed residual transport of salt due to residual flow of water(F_L), tidal pumping (F_{TP}), vertical shear (F_V) and their sum (F).

Section - III (Gothuruthu)

Observed values of salt transport at station A,B & C are plotted in Fig 4.8.~~a,4.8.b and 4.8.c respectively~~. At station-A it is noticed that most often salt transport by the shear processes (F_V) dominates over F_{TP}. F_L is directed down-stream in the entire cross-section in all the months except in April. F_V is directed up-estuary at all stations barring a very weak down-estuary transport at the periods of high fresh water discharge. This process is diffusive and are either comparable or much larger than F_{TP}, thus emphasizing the importance of shear processes in the upstream sections. Net down stream transport of salt is observed during almost all the observation period ~~the~~. With the exception of February and March, net salt transport is downstream. Similar distribution trend is observed at station-B. At station-C , dominance of eulerian residual current is observed throughout the year. Vertical shear transport appears to have dominated over the tidal pumping and takes the second position in controlling the salt transport processes.

Section - IV (Chennamangalam)

At station-A (Fig 4.9.~~a~~) residual rate of transport of salt is down-estuary during majority of the observation period. In January and February, net transport is up-estuary because the up-estuary shear processes dominated the

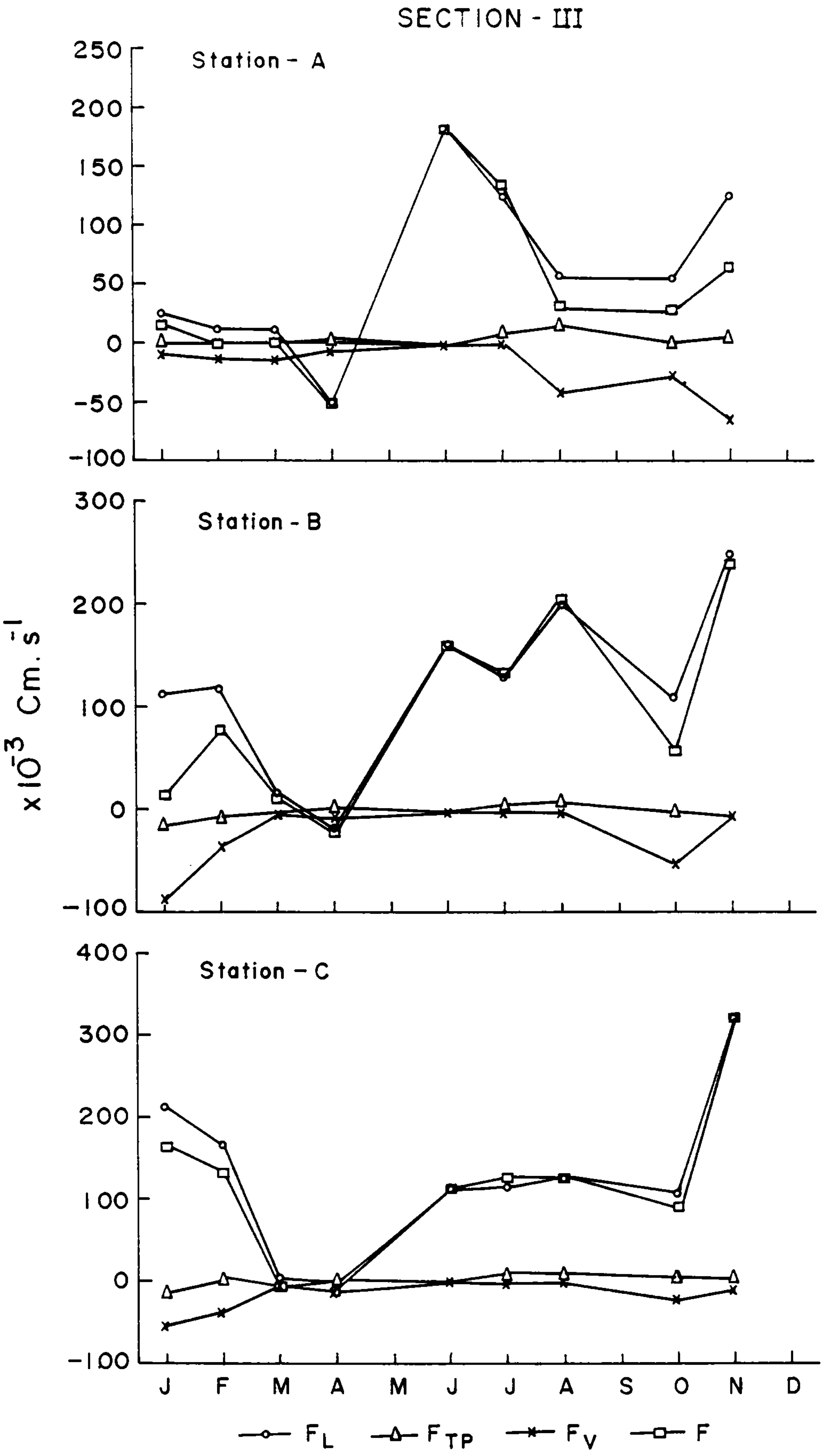


Fig. 4.8. Observed residual transport of salt due to residual flow of water (F_L), tidal pumping (F_{TP}), vertical shear (F_V) and their sum (F).

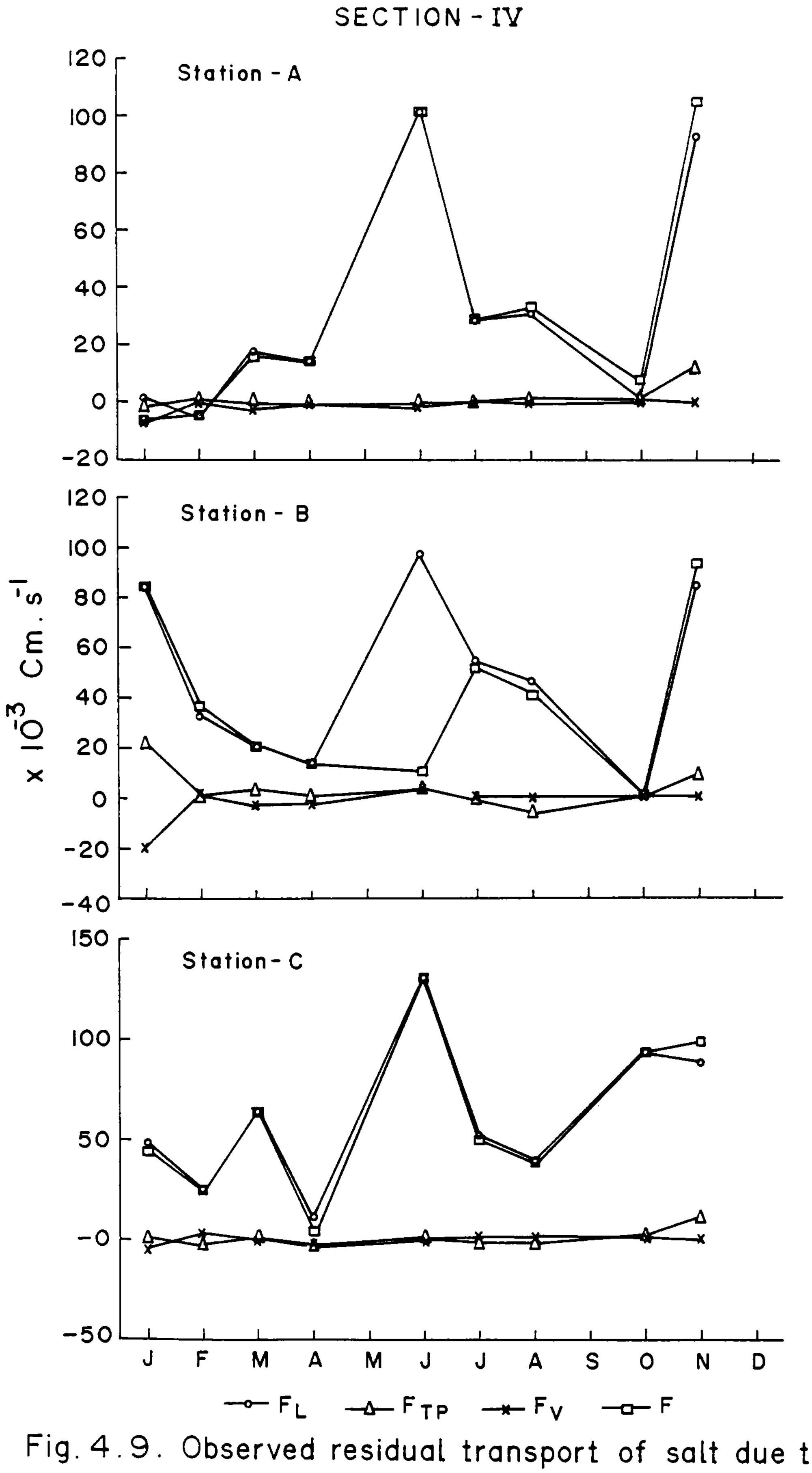


Fig. 4.9. Observed residual transport of salt due to residual flow of water (F_L), tidal pumping (F_{TP}), vertical shear (F_V) and their sum (F)

F_{TP} and F_L .At station-B (Fig 4.9.b) net salt transport is towards the sea with high values in January and November. F_{TP} is directed down - estuary and F_V is generally directed up-estuary. Distribution trend is similar at station-C , but varied in magnitude (Fig.4.9.c).

4.6 Lateral distribution of water and salt fluxes

Transverse structure of the residual transport of water and salt is investigated at three cross-section of the estuary under varying dilution intensities. Lateral distribution is not presented for Section-I because station-C at this section is very shallow and as such it is not possible to apply the interpolation technique and computer programme to the data.

Fig 4.10.b shows the water transport at Section -II in May., Stokes drift (U_S) is very small and up-estuary in the entire cross-section. Eulerian residual current is towards the sea in the entire cross section. At Gothuruthu, residual current is up-stream in the southern flank and down estuary in the comparatively shallower northern flank. Stokes drift is very small and is up-estuary in the entire cross-section. At the Section-IV (Chennamangalam) eulerian residual flow has a simple river like form with fastest speeds in the deeper southern flank. Tidal pumping is up-estuary in the entire cross -section. Lateral profiles of salt transport at

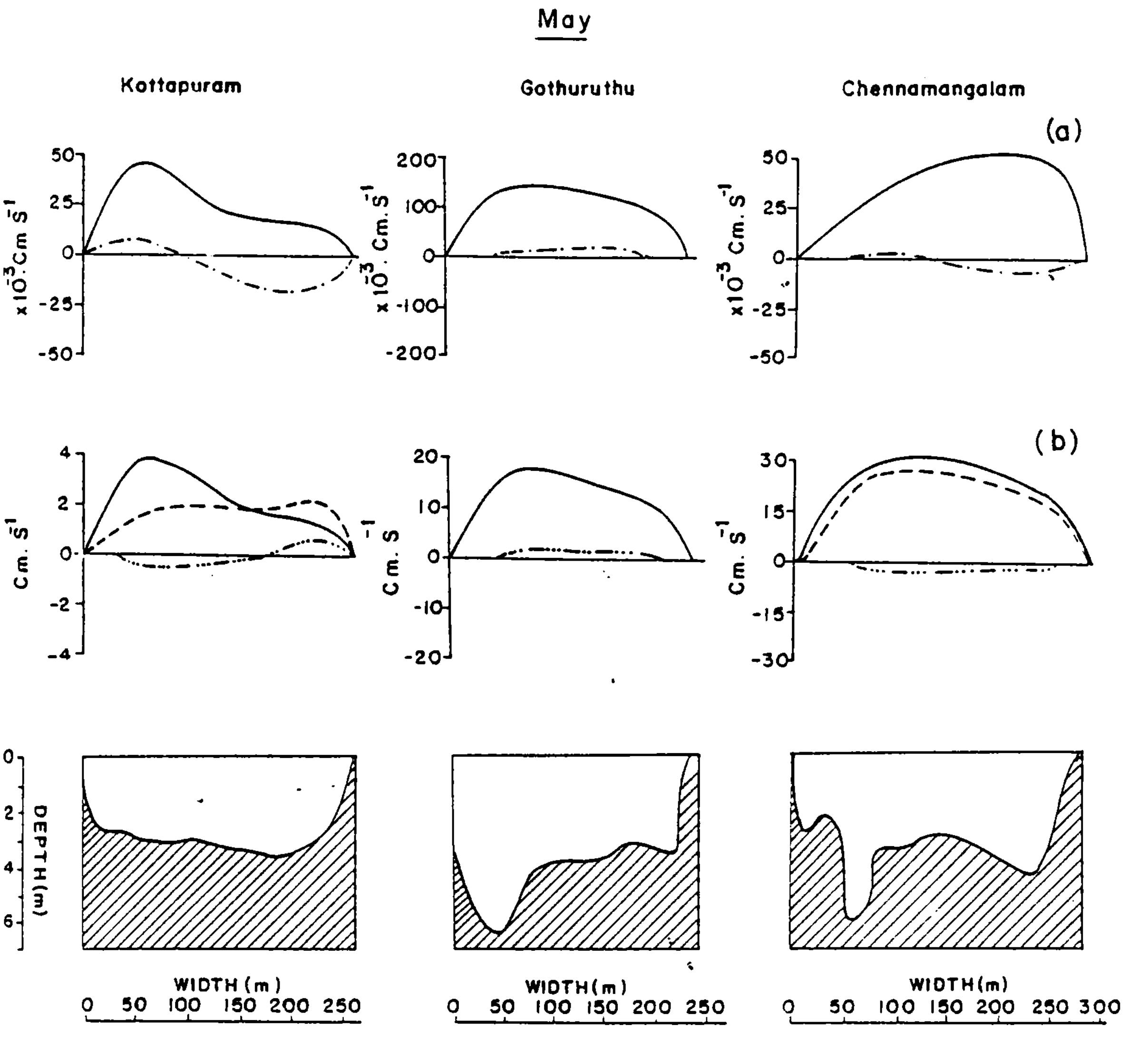


Fig.4.10.a.Lateral profiles of depth averaged residual salt transport per unit width of water column (10^{-3}.cm.s^{-1}) due to Advection(——); Tidal pumping (-·-·-) at different cross sections.

b. Residual water transport per unit width of water column (cm.s^{-1}) due to Eulerian residual current (——); Stokes drift (—····-) and theie sum (---)

various sections are presented in Fig.4.10.a. The advective transport of salt is down-estuary and are uniformly distributed at all sections. Salt transport by tidal pumping (F_{TP}) is towards the river and the strength is very small. At Gothuruthu the pattern of advective transport of salt (F_L) is very similar to that of residual flow of water (Fig.4.10,a & 4.10.b) This may be due to the relative insignificance of transverse variation in salinity when compared with sectionally averaged values. Thus, the advective transport is directed up-estuary in the deeper southern flank and down estuary in the central and northern flank. At Chennamangalam advective transport of salt is similar to that of residual flow of water. Essential difference between Section-III and IV is in the direction of the tidal pumping. Though the Stokes drift is towards the sea, the salt transport associated with the tidal pumping (F_{TP}) is up-estuary.

Lateral profiles of residual rate of salt transport in July are presented in Fig.4.11.a for different cross-sections. At Kottappuram residual transport of water is down -stream with faster currents in the southern flank. Stokes drift is up-estuary in the southern and central flank of the estuary and is down estuary in the northern side. At Gothuruthu and Chennamangalam, both advective transport of water and tidal pumping are down-estuary.

The lateral profile of advective transport of salt (F_L)

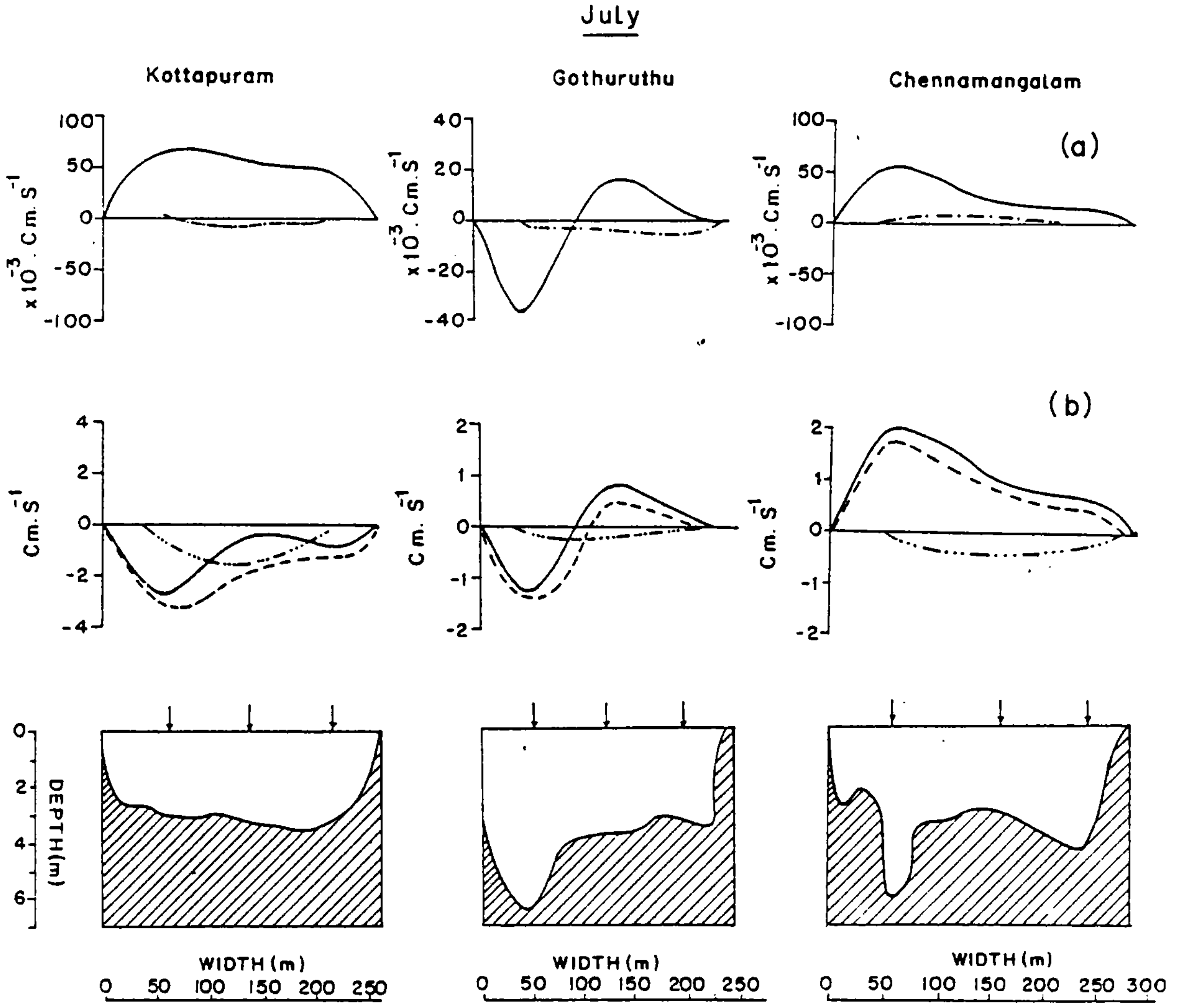


Fig.4.11 .a.Lateral profiles of depth averaged residual salt transport per unit width of water column (10^{-3}.cm.s^{-1}) due to Advection(—); Tidal pumping (-·-·-) at different cross sections.

b. Residual water transport per unit width of water column (cm.s^{-1}) due to Eulerian residual current (—); Stokes drift (-·····-) and theie sum (---)

and u_E are very much similar . F_{TP} exhibited an inverse relation with the u_s. At Gothuruthu, profile of u_E and F_L are similar with largest values at the deeper southern side. At the fourth section (Chennamangalam), advective transport is higher at the central section. Stokes drift is up-stream in the entire cross-section. Salt transport associated with the tidal pumping is down-estuary near the southern and central region and up-estuary pumping is observed at the northern flank. In general lateral variation in the transport processes is negligible when the estuary is narrow and is not comparable with axial variation

4.7 Estuarine Classification

Estuarine classification has been studied experimentally for many years (eg. Pritchard;1954, Bowden;1964, Bowden & Gilligan; 1971, Collar; 1978, Lewis, 1981; Lewis & Lewis; 1983) and a review of much of the earlier works are given by Dyer(1973) and Officer(1976).

A quantitative means of classifying and comparing estuaries and one which requires measurement of salinity and velocity only has been developed by Hansen & Rattray (1966). They related estuarine type to it's position on the stratification circulation diagram, constructed by using two dimensionless parameters, a stratification parameter and a circulation parameter. Stratification parameter is defined as the ratio of the difference between bed and surface tidally averaged salinity (δs) = s(1) - s(0) to the mean depth averaged, tide averaged salinity s. The circulation parameter is defined as u_E (0)/ u_E , where $u_E(0)$ is the residual current at the surface and u_E is defined in equation (3). Hansen and Rattray assumes a steady state condition and uniformity over cross - section.

For the purpose of this study only sectional mean values are taken. Data on salinity stratification and circulation parameters during the observation period are plotted in Hansen & Rattray diagram for Section- I,II,III & IV in Fig.4.12.a, 4.12.b,4.12.c & 4.12.d respectively.

Azhikode:- From January to March, section falls under well mixed type to partly mixed type and at periods of high fresh water discharge this section corresponds to type 2b in the classification scheme. From October - November this part is in transitional or well mixed.

Kottappuram:- From the classification diagram for this section (Fig. 4.12.b) it appears that the section is well mixed to partly mixed during the pre-monsoon season, implies that both advection and diffusion contribute to the up - estuary salt flux. At periods of high fresh water discharge section falls under well mixed type.

Gothuruthu:- From (Fig.4.12.c) it is observed that during the most of the observation period this part of the estuary

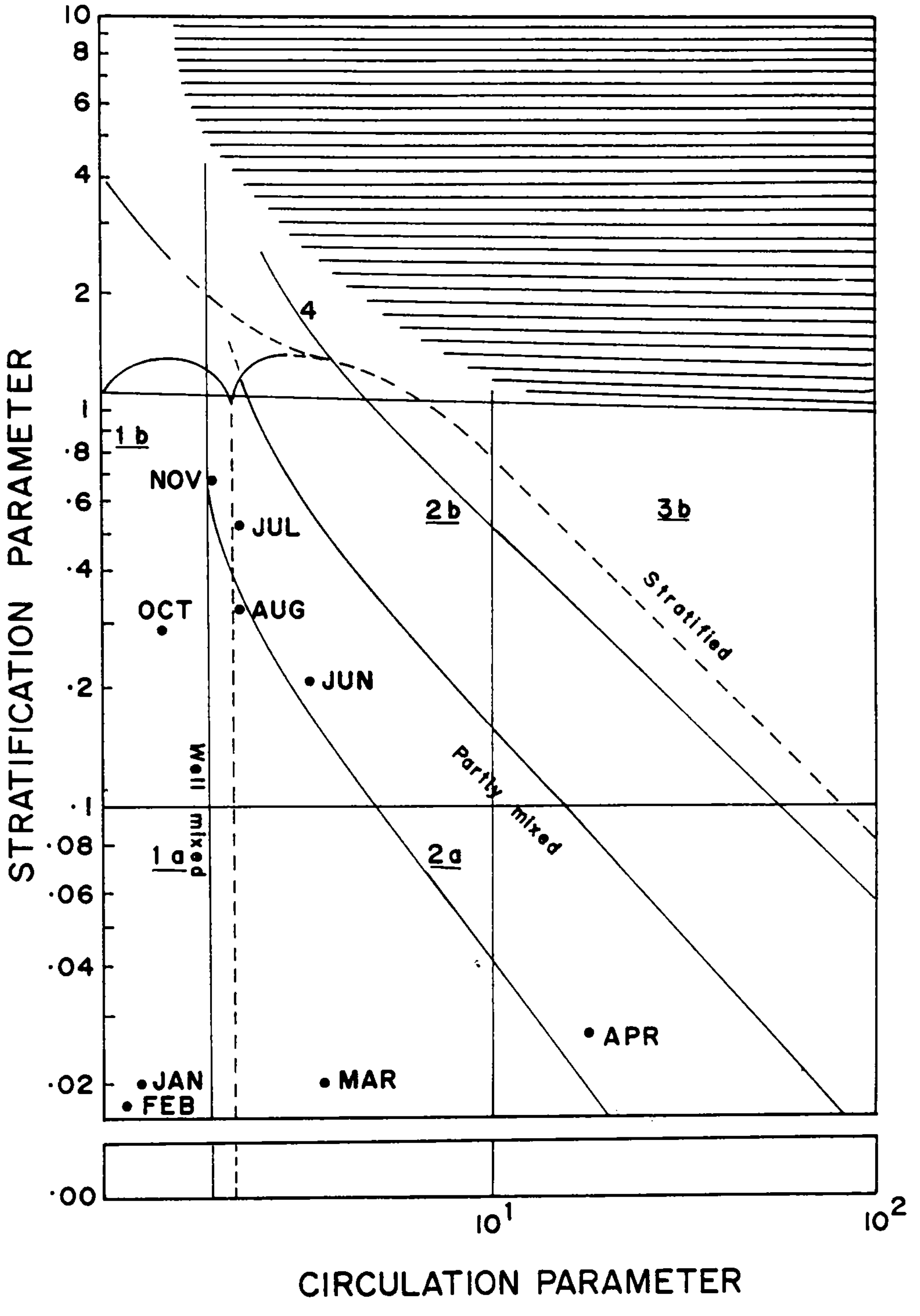


Fig. 4.12.a. Hansen & Rettray estuary classification diagram for section I

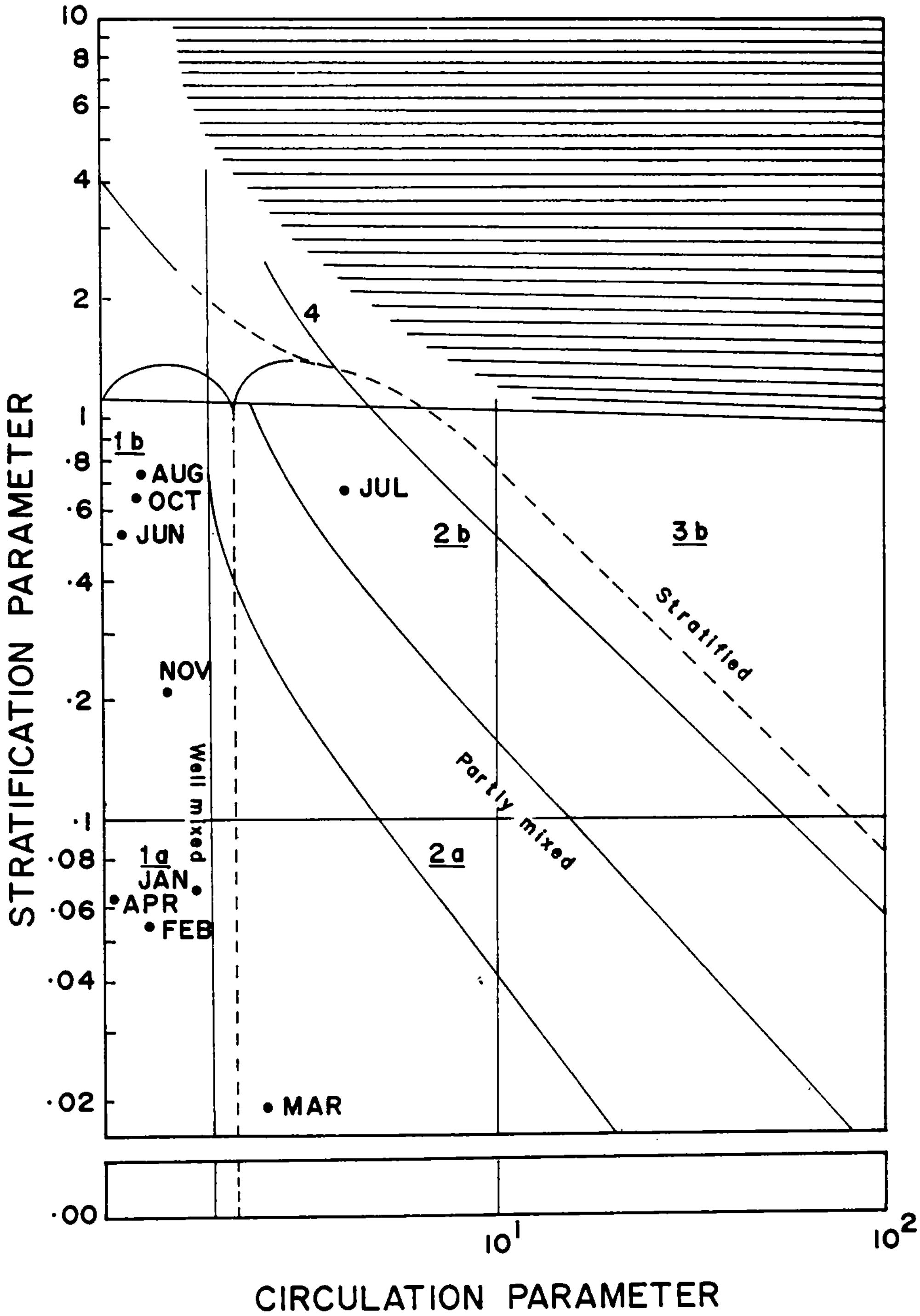


Fig. 4.12. b. Hansen & Rettray estuary classification diagram for section II

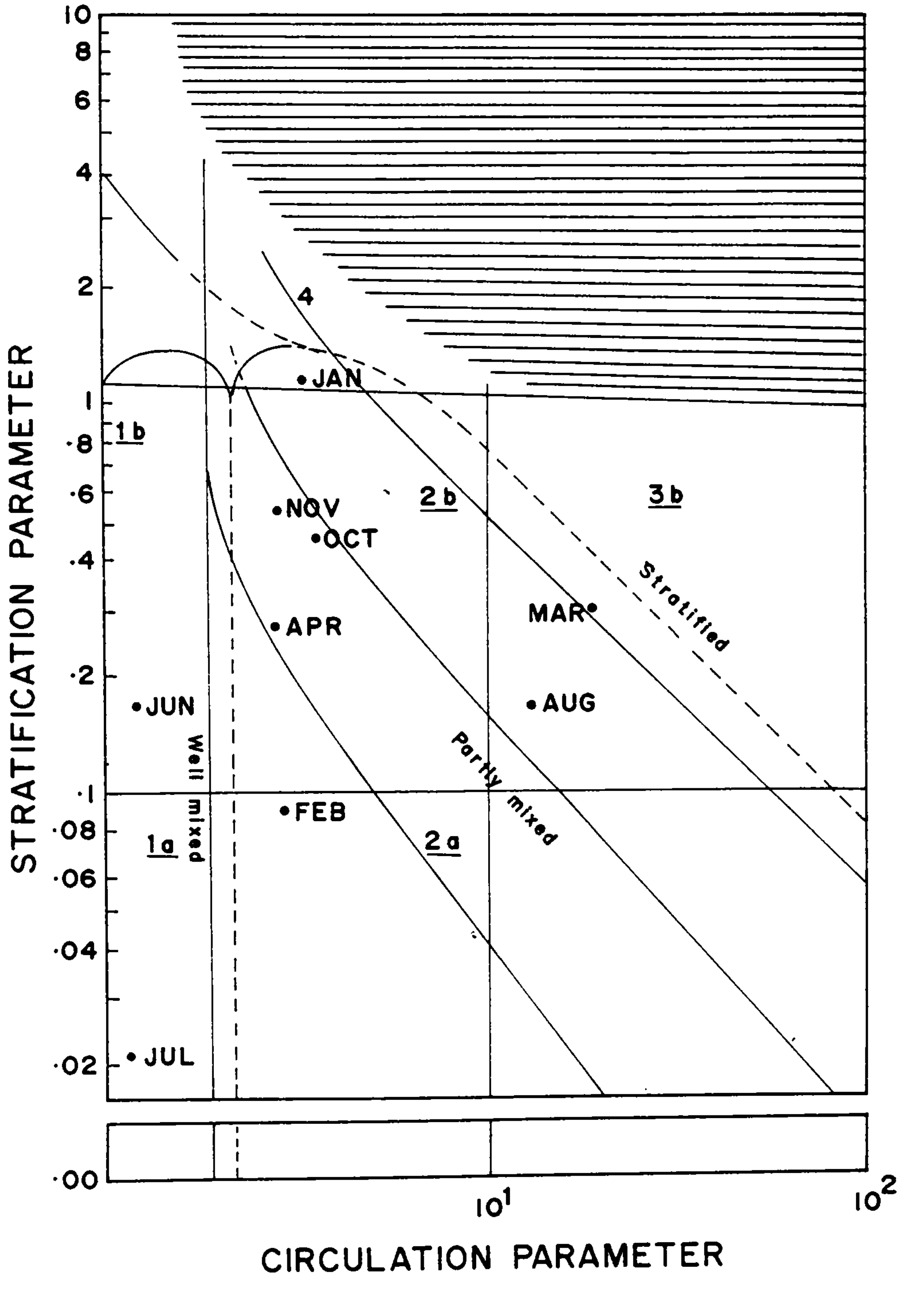


Fig. 4.12.c. Hansen & Rettray estuary classification diagram for section III

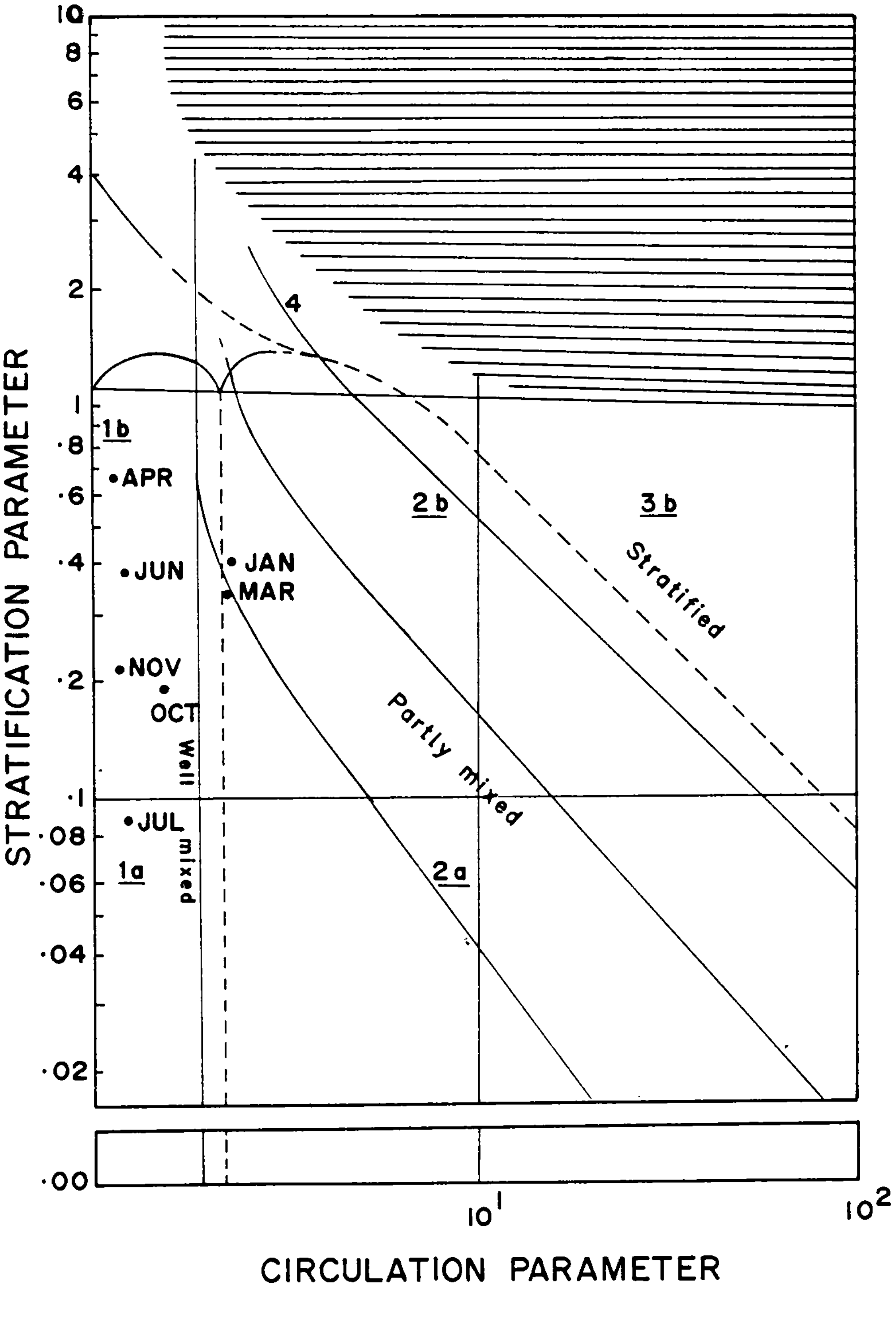


Fig. 4.12.d. Hansen & Rettray estuary classification diagram for section IV

falls under type 2b, in which the estuary is partly mixed. Only during June and July Section falls under the well mixed type.

Chennamangalam:- Fig.4.12.d shows the Hansen & Rattray classification diagram of this section. When the fresh water discharge into the estuary is minimum, the section falls under partly mixed type and at periods of higher discharge, the section corresponds to 1a in the classification scheme, which is the laterally homogeneous well mixed type.

Table.4.1. Axial components of the residual fluxes of water and salt.

SECTION-I

STATION-A

Months	U_E	U_S	U_L	$\langle Q\rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	14.09	.90	14.99	9677	438.00	8.60	0.80	447.42
FEB	14.63	0.96	15.50	10377	468.00	-5.69	3.22	465.51
MAR	-8.09	0.15	-8.44	-7306	-284.00	-11.00	2.10	-293.00
APR	-20.03	0.72	-19.31	-18888	-665.00	-9.60	-0.53	-676.00
JUN	-7.71	-1.01	-8.72	-7639	-215.00	-283.00	2.60	-496.00
JUL	1.89	2.20	4.09	3144	95.16	-329.00	-4.51	-239.00
AUG	-3.01	-0.48	-3.50	-2557	-94.00	-127.00	-1.15	-222.00
OCT	23.86	0.00	23.86	14320	664.00	-2.32	-30.54	632.00
NOV	22.07	-0.49	21.58	8365	262.54	-48.87	-20.23	124.00

Table.4.2. Axial components of the residual fluxes of water and salt.

SECTION-I

STATION-B

Months	U_E	U_S	U_L	$\langle Q \rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	18.03	-1.3	16.73	3554	553.00	4.13	-0.14	559.00
FEB	8.04	-1.60	6.98	2260	235.00	-10.00	-1.40	223.00
MAR	2.09	0.12	2.15	312	72.29	-1.82	-0.84	69.00
APR	-0.19	.89	0.70	-279	-33.00	-2.80	-1.68	-37.00
JUN	-1.82	-2.0	-3.82	-912	-85.00	-129.00	6.08	-208.00
JUL	10.84	2.01	12.85	3798	256.18	-216.00	-39.64	00.21
AUG	6.10	-1.48	4.62	1332	106.25	-198.56	-18.11	-110.00
OCT	25.86	-0.49	25.40	9439	529.00	-1.02	-17.42	510.00
NOV	31.94	-2.40	29.54	8701	190.00	-4.03	-6.45	180.00

Table.4.3. Axial components of the residual fluxes of water and salt.

SECTION -II

STATION -A

Months	U_E	U_S	U_L	⟨Q⟩	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	14.75	0.14	14.88	2558	454.00	28.79	-0.22	485.00
FEB	15.36	-1.88	13.48	2437	427.00	10.40	-5.98	433.00
MAR	-0.94	-0.44	-1.38	-337	-44.37	2.02	0.04	-42.00
APR	-7.02	-0.47	-7.49	-1524	-230.00	3.17	-0.39	-227.00
JUN	7.48	-0.4	7.08	1719	115.00	-32.93	-11.83	71.00
JUL	-1.11	-0.65	-1.72	-371	-14.16	24.42	-15.25	-4.90
AUG	6.78	0.39	7.17	1580	88.20	-9.40	10.88	89.00
OCT	15.46	-1.17	14.29	3306	212.00	0.14	-1.44	211.00
NOV	26.11	0.76	25.30	566	166.00	23.00	0.46	191.00

Table.4.4. Axial components of the residual fluxes of water and salt.

SECTION-II

STATION-B

Months	U_E	U_S	U_L	$\langle Q \rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$\times 10^{-3}.cm.s^{-1}$			
JAN	12.03	-5.00	7.03	3007	349.00	12.30	0.16	363.00
FEB	10.09	-1.40	8.69	2456	276.00	9.50	-1.40	284.00
MAR	0.31	-1.79	-1.49	-429	-47.72	-1.57	-2.65	-52.00
APR	-6.70	-0.05	-6.75	-1752	-207.00	0.99	-0.55	-207.44
JUN	8.04	0.50	8.54	2273	138.00	-10.30	-7.27	120.82
JUL	2.54	-0.49	2.05	547	23.32	-4.72	-28.77	10.16
AUG	5.87	-1.11	4.76	1359	65.33	-18.48	-30.04	16.85
OCT	17.65	-1.65	16.00	4253	237.00	-7.11	-8.48	222.00
NOV	24.42	-0.58	24.36	6947	166.00	14.27	7.78	189.00

Table.4.5. Axial components of the residual fluxes of water and salt.

SECTION-II

STATION-C

Months	U_E	U_S	U_L	<Q>	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	9.00	-0.92	8.09	1780	411.00	-303.00	-11.80	96.28
FEB	12.01	-0.84	11.17	2569	345.00	-120.00	-0.30	332.00
MAR	-2.68	-0.63	-3.31	-888	-106.00	-2.20	-1.90	-110.54
APR	-4.46	-1.87	-6.33	-1410	-172.00	2.67	-0.40	-170.00
JUN	5.42	-0.72	4.70	1209	71.55	-15.81	5.37	61.00
JUL	4.04	-0.52	3.52	869	48.65	10.48	-52.57	6.56
AUG	7.27	-1.59	5.68	1516	89.77	-47.44	-48.16	-6.30
OCT	16.25	-2.05	14.20	3693	247.00	-19.60	-31.20	195.00
NOV	24.23	-1.22	23.01	5466	128.25	2.70	1.90	133.00

Table.4.6. Axial components of the residual fluxes of water and salt.

SECTION-III

STATION-A

Months	U_E	U_S	U_L	⟨Q⟩	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	1.17	0.05	1.22	619	25.42	-0.23	-8.84	14.80
FEB	0.52	0.02	0.54	305	11.81	1.18	-14.52	-1.50
MAR	0.53	0.01	0.54	305	11.81	1.18	-14.52	-1.50
APR	-1.64	-0.09	-1.73	-1010	-49.81	3.19	-4.76	-52.18
JUN	27.06	-0.06	27.12	16219	186.00	-2.44	-1.31	182.00
JUL	16.28	0.14	16.42	9379	124.00	8.26	0.41	133.00
AUG	5.25	-0.81	4.44	2446	56.28	15.44	-41.53	30.20
OCT	8.31	-.01	8.29	4787	55.74	0.13	-28.00	27.00
NOV	7.41	-0.15	7.26	4321	126.00	3.60	-65.00	63.95

Table.4.7. Axial components of the residual fluxes of water and salt.

SECTION-III

STATION-B

Months	U_E	U_S	U_L	<Q>	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	4.58	0.24	4.80	1616	113.00	-14.22	-86.14	13.52
FEB	5.22	-0.09	5.13	1672	118.00	-6.74	-34.65	76.80
MAR	0.85	-0.22	-0.63	235	15.91	-3.11	-3.37	9.40
APR	-0.33	-0.30	-0.63	-173	-17.35	2.52	-8.57	-23.40
JUN	24.44	0.02	24.64	8090	162.00	-1.53	-0.93	160.10
JUL	16.34	0.27	16.61	4844	127.00	4.44	0.31	132.90
AUG	21.25	-0.46	20.79	6136	199.00	8.05	-1.28	206.00
OCT	12.53	-0.13	12.40	4305	109.00	-2.12	-51.00	56.72
NOV	34.94	-0.73	34.22	9508	249.00	-5.55	-6.07	238.00

Table.4.8. Axial components of the residual fluxes of water and salt.

SECTION-III

STATION-C

Months	U_E	U_S	U_L	$\langle Q \rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	10.43	0.24	10.67	2724	214.00	-14.31	-51.52	165.00
FEB	7.71	-0.03	7.69	1759	167.00	1.71	-36.83	133.00
MAR	0.37	-0.23	0.14	37	2.99	-5.28	-7.10	-9.30
APR	-0.29	0.20	0.08	-16	-1.93	1.84	-12.71	-10.40
JUN	14.83	-0.22	14.61	3956	111.00	1.41	-0.42	112.90
JUL	14.33	0.37	13.90	3687	115.00	10.12	-0.77	125.00
AUG	11.30	0.21	11.51	2695	126.00	7.90	0.26	126.44
OCT	20.64	-0.66	19.98	4641	107.00	4.23	-21.65	89.90
NOV	31.26	-0.84	30.42	7609	324.00	3.87	-11.31	319.00

Table.4.9. Axial components of the residual fluxes of water and salt.

SECTION-IV

STATION-A

Months	U_E	U_S	U_L	$\langle Q \rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	0.85	0.12	0.09	67	1.58	-0.91	-7.20	-6.50
FEB	-0.41	0.46	-0.37	-151	-5.43	1.40	-0.20	-4.20
MAR	0.71	-0.08	0.63	239	17.72	0.21	-1.80	16.12
APR	0.53	-0.02	0.51	205	14.17	0.38	-0.41	14.15
JUN	49.07	-0.54	45.53	18920	102.00	0.51	-1.06	101.45
JUL	21.04	-0.12	20.92	8420	28.18	0.58	-0.05	28.80
AUG	10.58	-0.39	10.19	2860	30.94	1.89	0.28	33.18
OCT	8.85	-0.17	8.68	3434	2.98	1.47	1.45	7.80
NOV	18.58	-0.54	18.04	6810	92.79	12.57	0.10	105.00

Table.4.10. Axial components of the residual fluxes of water and salt.

SECTION-IV

STATION-B

Months	U_E	U_S	U_L	<Q>	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	2.44	0.07	2.38	801	83.42	21.61	-20.10	85.02
FEB	1.25	-0.03	1.22	377	33.58	2.05	1.0	36.71
MAR	0.98	-0.27	0.71	201	21.40	2.81	-3.15	21.05
APR	0.60	-0.06	0.54	163	14.46	0.83	-1.95	13.37
JUN	48.60	-0.05	48.55	14662	97.60	2.54	2.81	10.30
JUL	32.61	-0.14	32.47	9821	54.01	-1.04	-0.40	51.62
AUG	14.87	0.60	14.27	3996	46.48	-5.74	-0.07	40.80
OCT	12.29	-0.24	12.05	3575	0.00	0.00	0.00	0.00
NOV	17.44	-0.73	16.71	4668	84.23	9.04	-0.60	92.85

Table.4.11. Axial components of the residual fluxes of water and salt.

SECTION-IV

STATION-C

Months	U_E	U_S	U_L	$\langle Q \rangle$	F_L	F_{TP}	F_V	F
	$cm.s^{-1}$			$cm^2.s^{-1}$	$X\ 10^{-3}.cm.s^{-1}$			
JAN	4.59	0.09	4.68	1504	48.08	0.78	-4.59	44.00
FEB	1.20	-0.03	4.68	360	24.50	-2.36	1.30	23.50
MAR	2.35	-0.21	2.14	605	63.91	1.00	-0.76	64.20
APR	0.48	-0.05	0.43	129	10.44	-3.69	-2.70	3.90
JUN	52.36	-0.19	52.17	15752	130.00	0.94	-0.65	131.00
JUL	28.61	-0.09	28.52	8618	53.17	-2.47	-0.24	50.47
AUG	11.82	-0.38	11.44	3719	40.60	-2.25	0.42	38.41
OCT	11.67	-0.09	11.58	3445	91.60	2.42	0.61	94.00
NOV	18.57	-0.76	17.81	4965	87.89	11.98	-0.20	99.00

CHAPTER - 5

5. MIXING AND FLUSHING TIME SCALES

5.1 Introduction

In estuarine environments the mixing and flushing of sea water and fresh water are activated by tidal currents and fresh water discharge. An overall view of the mixing properties of an estuary is provided by the methods which provide as estimate of the flushing time of the estuary as a whole or major division of it. The water and their dissolved and particulate constituents are redistributed and to quantify the ratio of the processes one has to know the relevant time scale of mixing and flushing.

The simplest of the more detailed treatment is the steady state one dimensional approach, in which the distribution of properties along the length of the estuary is considered but only averages are taken over each cross-section. More attention has been given, up to the present to longitudinal dispersion and its representation by one dimensional model formulation.

A two dimensional treatment involving averaging in either the vertical or transverse direction, is the next advance in complexity. In relatively shallow estuaries, lateral averaging can be used to eliminate the transverse variation but the vertical current shear and salinity stratification is represented. In this way vertical and longitudinal dispersion of a pollutant, released at a certain depth in a given cross-section may be studied. In broad estuaries,especially where there is considerable transverse variation in depth, the lateral variation in current and salinity may be more significant than those in the vertical. In this case a vertically averaged two-dimensional representation, taking into account the lateral variations of properties may be more appropriate. In some estuaries, the vertical and lateral variation appear to be of comparable significance for mixing purposes and a complete three dimensional treatment is thus desirable.

5.2 Definition of mixing time scales

In literature a lot of names of time scale with respect to mixing and flushing of natural basins are in use such as "residence time", "flushing time", "transit time", "turnover time" and "age". Rigorous definition of these parameters have been give By Bolin & Rohde (1973).

Consider a natural basin and suppose that it makes sense to regard the mass of the water in the basin to be made up by a large number of elementary (water) parcels which hold their identity as long as they reside in the basin. If mass exchange with the atmosphere is neglected, then in the case of Azhikode estuary, any parcel originates either from barmouth or from the river end. The parcel can be distinguished by means of a label (α, i) which designates the i^{th} parcel that originates from the entrance with a

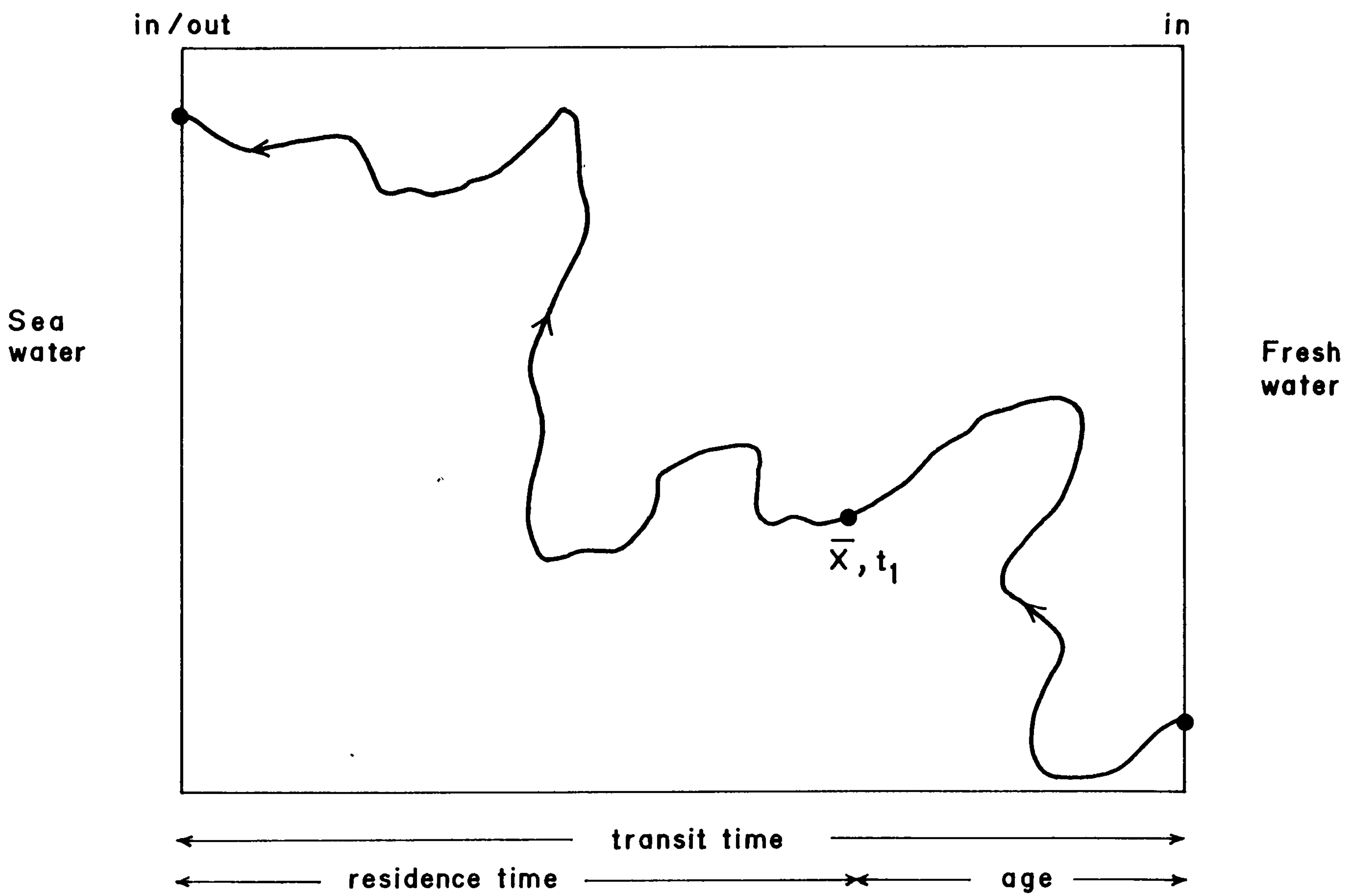


Fig. 5.1. Example illustrating the definition of time scale.(after, Zimmerman, 1976)

positionα. After having entered the basin, the exchange processes assure that the parcel leaves the basin after a certain interval of time. The coordinate describing the successive position of the parcel in the basin are called its trajoctories which in general is a complicated function of time. A two dimensional example of its path is shown in Fig.5.1.a. Residence time (T_r) can be defined as the average time interval a parcel of water or dissolved constituent needs to cover its path through the estuary since its arrival at the point or compartment for which the residence time is calculated. When the time interval is calculated for the total pathway from inlet to outlet, the associated time scale is called transit time. Transit time of fresh water equals the flushing time. Turn over time (T_e) is defined as the time interval needed to decrease the volume of water or mass of dissolved constituent that is present at t=0 to a fraction e^{-1}. Mean age (T_a) has the definition of the time that water parcel located in a certain compartment are present in the estuary since arrival from the source.

5.3 Flushing time

Flushing time is the time required to replace the existing fresh water in the estuary at a rate equal to the river discharge. If the total discharge is designated as R and the total volume of the estuary as Q, then the flushing time T= Q/R. There are number of methods available for computing the flushing time.

5.3.1 Tidal prism method

In this method, the water entering on the flood tide is assumed to become fully mixed with the water inside and the volume of the sea water and river water introduced equals the volume of the tidal prism, the volume between high and low tide marks. On the ebb tide the same volume of fresh water is removed and the fresh water content of it must equal the increment of the river flow. If V is the low tide volume and P the inter tidal volume (the tidal prism) then flushing time in tidal cycle is

$$T = \frac{V + P}{P}$$

5.3.2 Modified tidal prism method

Ketchum(1951) modified the tidal prism approach by dividing the estuary into segments, the lengths of which are determined by the excursion of a water particle during the tide. The innermost section is that above which the Intertidal volume P_0 is supplied by the river flow R. Thus P_0 = R. The low tide volume of this innermost segment is V_0. The limit of the next segment is placed so that $V_1 = V_0 + R$ and so on. Each segment contain at high tide the volume of water contained the volume of water contained in the next seaward segment at low tide. If the mixing is complete at high tide then the portion of water removed on the ebb tide is the ratio between the local inter tidal volume and the high tide volume. Thus an exchange ratio can be defined for any segment n as $r_n = P_n/(P_n + V_n)$. The flushing time in tidal cycles will be $\langle 1/r_n)$. Provided the river flow is constant, each segment receives R volume of river water per tidal cycle. The amount of river water removed on the ebb will be r_nR and the amount remaining will be $(1-r_n)R$. As this process would have already been going on for many tidal cycles, there will be contribution from the river flow at these times, both to the water removed and to that remaining. This can be summarized as follows.

Age in tidal cycle	River water removed	River water remaining
1	r_nR	$(1-r_n)R$
2	$r_n(1-r_n)R$	$(1-r_n)^2R$
3	$r_n(1-r_n)^2R$	$(1-r_n)^3R$
m	$r_n(1-r_n)^{m-1}R$	$(1-r_n)^mR$

The total volume of river water Q_n accumulated in the segment n will be the sum of the last column, plus the volume of river water which has not yet been removed.

$$Q_n = R(1+(1-r_n)+(1-r_n)^2........(1-r_n)^m)$$

This is a geometrical progression whose sum is:

$$\frac{R}{r_n}[1-(1-R_n)^{m+1}]$$

When m is large , $(1-r_n)^{m+1}$ approaches zero and when r_n is less than unity, so that

$$Q_n = R/r_n \quad \text{and} \quad r_n = Q_n/R$$

Similarly the amount of water removed is:

$$R(r_n + r_n(1-r_n) + r_n(1-r_n)^2 \ldots\ldots\ldots r_n(1-r_n)^{m-1}) = R$$

Consequently we can calculate the flushing time $(1/r_n)$ for any section. This is a useful method of calculating the flushing time and the salinity distribution as it only information knowledge on the river flow,tidal range and estuarine topography.

5.3.3 Fraction of fresh water method

Assuming the estuarine water to be a simple mixture of sea water and river water and knowing the salinity, the fraction of fresh water can be calculated. Total flow across the section in the estuary is

$$Q = Q_f.Q_s \qquad \text{-------------- (1)}$$

where, Q_f is the quantity of fresh water, and Q_s is the quantity of saline water

then $$Q = A_fV + A_sV \qquad \text{--------------- (2)}$$

$$Q = A_v\ (A_f + A_s) \qquad \text{--------------- (3)}$$

where A_f and A_s are the areas occupied by fresh and sea water respectively. If f is the fraction of fresh water contained in the section, then

$$f = A_f/A = Q_f/Q \qquad \text{---------------- (4)}$$

and $$Q_f = Q \times f = AV_f \qquad \text{---------------- (5)}$$

If S is the salinity of mixed water, S_s is the salinity of sea water and S_f is the salinity of fresh water, then for a volume of unit width at section

$$A_S = A_s S_s + A_f S_f \qquad \text{-----------------} \quad (6)$$

$$A_S = (A - A_f) S_s + A_f S_f \qquad \text{-----------------} \quad (7)$$

Therefore

$$f = A_f / A \quad = (S_s - S)/(S_s - S_f) \text{ ----------} \quad (8)$$

As S_f is very small compared to S_s it is neglected and

$$f = (S_s - S)/S_s \qquad \text{----------------} \quad (9)$$

In the Azhikode estuary, fraction of fresh water method is adopted for computing flushing time. Fresh water fraction is computed for all sections during varying river discharges and the values are given in Table 5.1. Fresh water fraction is maximum at Chennamangalam during July (0.957) and is minimum at Azhikode during February (0.030).

For computation of flushing time, the study area is divided into three compartments (Segments). 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 fresh water fraction is taken for computation of fresh water volume in each segment. Computed values of the flushing time and cumulative flushing time are given in Table.5.2. Owing to the large volume of segment-I, flushing time is always higher for this segment than the other segments. Cumulative flushing time of the estuary during post and premonsoon

Table 5.1. Fresh water fraction at different cross-sections in the Azhikode estuary during different months.

Months	Azhikode I	Kottappuram II	Gothuruthu III	Chennamangalam IV
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

Tab 5.2. Flushing time of Azhikode estuary during different months.

Azkd- Azhikode, Ktprm- Kottappuram, Gtrh- Gothuruthu, Chmglm- Chennamanglam

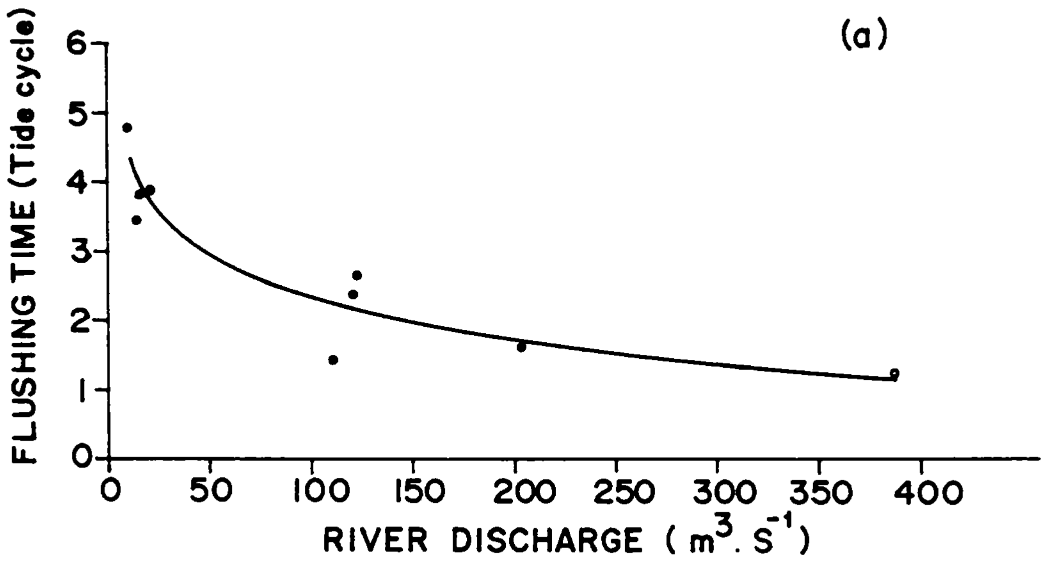
Segment	Mean fresh water fraction	Volume X 10^6 V	Fresh water X 10^6 F	Flushing time (tide cycle) F/R	Cumulative flushing time (tide cycle)
January (R = 1.01 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.076	17.82	1.36	1.35	1.35
Ktprm- Gtrh	0.266	2.50	0.67	0.66	2.01
Gtrh-Chmglm	0.547	3.50	1.91	1.89	3.90
February (R = 0.78 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.060	17.30	1.04	1.33	1.33
Ktprm- Gtrh	0.215	2.50	0.57	0.73	2.06
Gtrh-Chmglm	0.377	3.73	1.40	1.79	3.85
March (R = 0.69 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.060	17.94	1.07	1.55	1.55
Ktprm- Gtrh	0.155	2.67	0.41	0.59	2.14
Gtrh-Chmglm	0.265	3.48	0.92	1.33	3.47

Table.5.2. Continued

Segment	Mean fresh water fraction	Volume X 10^6 V	Fresh water X 10^6 F	Flushing time (tide cycle) F/R	Cumulative flushing time (tide cycle)
April (R = 0.62 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.104	16.97	1.76	2.83	2.83
Ktprm- Gtrh	0.150	2.67	0.57	0.73	3.56
Gtrh-Chmglm	0.207	3.74	0.77	1.24	4.80
June (R = 5.80 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.416	17.80	7.40	1.28	1.28
Ktprm- Gtrh	0.670	2.71	1.82	0.81	2.09
Gtrh-Chmglm	0.874	3.93	3.26	0.56	2.65
July (R = 9.49 X $10^6 . m^3$/tide cycle)					
Azhkd-Ktprm	0.506	17.43	8.20	0.86	0.86
Ktprm- Gtrh	0.729	2.68	1.95	0.20	1.06
Gtrh-Chmglm	0.870	3.75	3.26	0.56	1.62

Table5.2.Continued

Segment	Mean fresh water fraction	Volume X 10^6 V	Fresh water X 10^6 F	Flushing time (tide cycle) F/R	Cumulative flushing time (tide cycle)
August (R = 18.83 X $10^6.m^3$/tide cycle)					
Azhkd-Ktprm	0.496	16.96	8.41	0.86	0.86
Ktprm- Gtrh	0.729	2.68	1.95	0.20	1.06
Gtrh-Chmglm	0.810	3.78	3.06	0.16	1.22
October R = 5.77 X $10^6.m^3$/tide cycle)					
Azhkd-Ktprm	0.522	13.33	8.52	1.47	1.47
Ktprm- Gtrh	0.693	2.74	1.90	0.32	1.89
Gtrh-Chmglm	0.770	3.73	2.87	0.49	2.38
November R = 5.29 X $10^6.m^3$/tide cycle)					
Azhkd-Ktprm	0.696	16.38	11.40	1.47	1.47
Ktprm- Gtrh	0.778	2.72	2.12	0.40	1.87
Gtrh-Chmglm	0.824	3.74	3.08	0.55	1.42



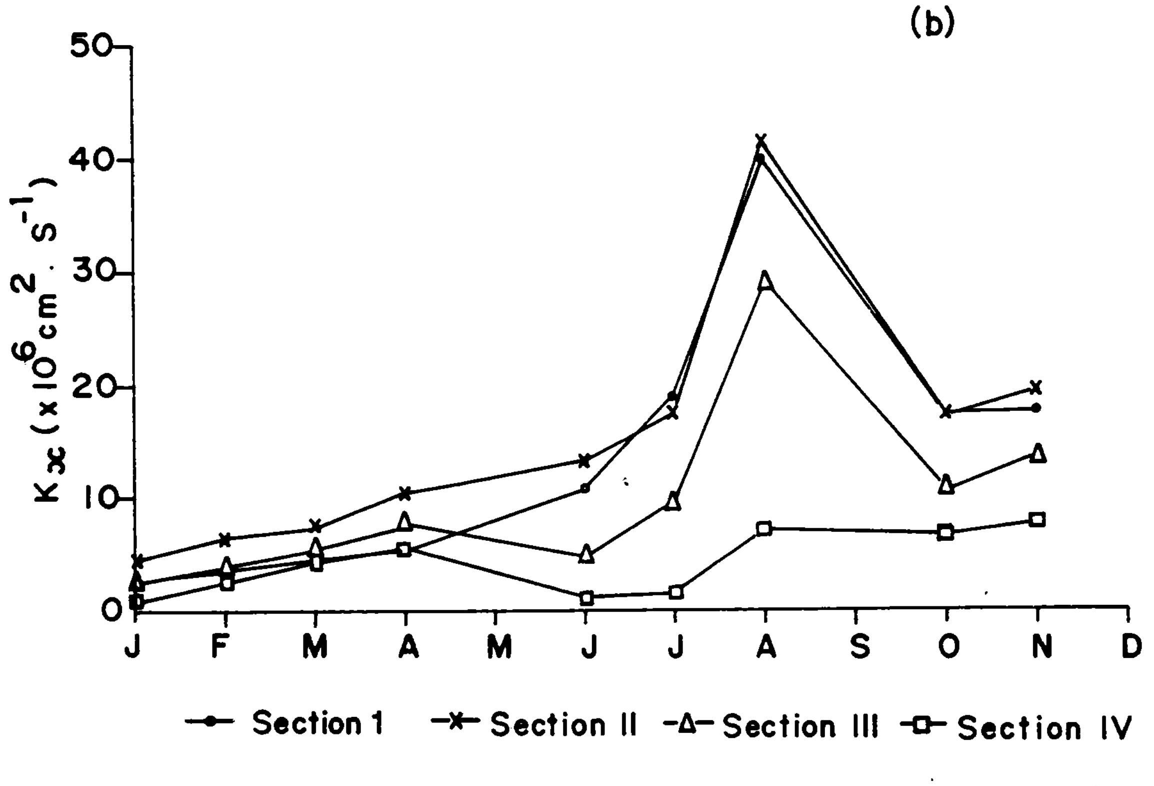


Fig. 5.2.(a) Flushing time of Azhikode estuary versus fresh water discharge. (Curves fitted by eye)

(b) Annual distribution of horizontal eddy difusivity.

seasons range between 3.47 tide cycles in March to 4.80 tide cycles in April. With the high river discharge associated with the southwest monsoon flushing time of the estuary decreases and reaches to a minimum value of 1.22 tide cycle during August when the river discharge is 387 $m^3.s^{-1}$. This means if a pollutant is introduced upstream of Chennamangalam (section -IV) , it requires 1.22 tide cycle to flush it completely out of the estuary during August, where as the same will require in April (R= 10.3 $m^3.s^{-1}$) in 4.8 tide cycles. Since in the all the above calculations fresh water is treated as pollutant and consequently the previously defined turn over time is the flushing time and the transit time is the cumulative flushing time. Flushing time (T) is related to the river discharge (R) in Fig.5.2.a. It is seen that flushing times decreases rapidly with with increasing river flow and for higher higher river flow the decrease is slow. This agrees with the results of Ketchum,(1952) obtained for Bostan Inner harbour. Helder,(1982) has shown that when residence time and turnover time are plotted against the river discharge it showed a similar relationship as the flushing time.

Linear regression equations are fitted for fresh water fraction on the longitudinal axis for various periods. The following are the equations obtained for various periods.

January

$f = 0.0568.X + 0.043$ (for $R = 21\ m^3.sec^{-1}$) --- (10)

February

$f = 0.0349.X + 0.006$ (for $R = 16.41 m^3.sec^{-1}$) --- (11)

March

$f = 0.0235.X + 0.016$ (for $R = 14.56\ m^3.sec^{-1}$) --- (12)

April

$f = 0.0126.X + 0.076$ (for $R = 10.3\ m^3.sec^{-1}$) --- (13)

June

$f = 0.0561.X + 0.293$ (for $R = 123\ m^3.sec^{-1}$) --- (14)

July

$f = 0.0510.X + 0.368$ (for $R = 204\ m^3.sec^{-1}$) --- (15)

August

$f = 0.0460.X + 0.367$ (for $R = 387\ m^3.sec^{-1}$) --- (16)

October

$f = 0.0332.X + 0.438$ (for $R = 121\ m^3.sec^{-1}$) --- (17)

November

$f = 0.0185.X + 0.644$ (for $R = 111\ m^3.sec^{-1}$) --- (18)

5.4. Pollution dispersion prediction and computation of longitudinal eddy diffusivity.

There are a number of methods available to compute the processes of circulation and mixing in different types of estuaries. If a constant rate discharge of a conservative non decaying pollutant is made into an estuary, the tidal mixing will distribute it both upstream and downstream. If the pollutant acts in the same way as fresh or salt water, the pollution distribution will be directly related to the salinity distribution; once a steady state have been achieved, prediction can thus be based on the knowledge of the fresh water in the estuary. Ketchum (1952) has developed a fractional fresh water method for predicting concentration of a pollutant. Let the cross-sectional average concentration at the outfall after steady state condition have been achieved be C_o.

Then the $C_o = (P/R).f_o$, where P is the rate of supply of pollutant carried upstream with the saline water , R is the river discharge and f_o is the cross-sectional fresh water concentration.

An alternative method of calculation of distribution of pollutant is by use of the one dimensional diffusion equation (Stommel, 1953a). The advantage of Stommel's theory 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 fresh water. The net seaward flux of pollutant through any section X is

$$F(x) = R_c - A.K_x. dc/dx \qquad \text{-----------------} \quad (19)$$

where R is the river discharge and C is the concentration of pollutant and A the cross-sectional area of the section under consideration. Down stream of the source, the net flux must be constant and equal to the input. Upstream, it will be zero. Provided the diffusion coefficient for the pollutant can be assumed to be the same as that for salt, we can determine K_x by putting F(x) equal to the river flow and the fraction f for C. Thus

$$K_x = R(1-F)/A(df/dx) \quad \text{--------------------} \quad (20)$$

The values of K_x calculated this way are put into equation (19) and the equation is written in a finite difference method and solved by successive approximation. Longitudinal eddy diffusivity (K_x) is calculated for four cross-sections in the Azhikode estuary is computed using equation (20) and the results are given in Table.5.3. Equations (10) to (18) are used to determine df/dx for the corresponding periods. Annual distribution of horizontal eddy diffusivity at various cross-section are shown in Fig.5.2.b. At section-I (Azhikode) eddy diffusivity varied between 2 X 10^6 in January to 40 X 10^6 $cm^2.s^{-1}$ in August. At Kottappuram K_x ranged between 4.39 to 41.20 X10^6 $cm^2.s^{-1}$. At Gothuruthu K_x values varied between a minimum of 2.70 X 10^6 $cm^2.s^{-1}$ in January to a maximum of 28.96 X 10^6 $cm^2.s^{-2}$ in August. Similar trend is observed at section-IV varies within the range 0.98 to 7.04 X $10^6.cm^2.s^{-1}$. Vertical eddy diffusivity (K_z) in the Azhikode estuary during post monsoon season has earlier been computed by Revichandran et.al (1987). According to them, vertical diffusivity decreases in the upstream direction. When K_z values were plotted against non-dimensional depth for Section-I and Section -III, at

Table 5.3. Longitudinal eddy diffusivity (in $cm^2.s^{-2} \times 10^6$) at different cross- sections in the Azhikode estuary during different months.

Months	Azhikode I	Kottappuram II	Gothuruthu III	Chennamangalam IV
JAN	2.59	4.29	2.70	0.98
FEB	3.44	6.33	3.83	2.50
MAR	4.13	7.37	5.45	4.29
APR	5.26	10.49	7.71	5.30
JUN	10.70	13.22	4.88	1.07
JUL	18.80	17.41	9.89	1.45
AUG	39.80	41.21	28.96	7.04
OCT	17.40	17.20	10.41	6.56
NOV	17.80	19.42	13.66	7.69

Section-I K_z was found to increases with depth and reaches the maximum value of 16.41 $cm^2.s^{-1}$ at $\eta = 0.5$ and thereafter decreases with depth whereas at section-III K_z exhibited two maximum values at and $\eta = 0.3$ and $\eta = 0.8$, similar results observed in James estuary (Lauff,1967) have been attributed to the strong vertical mixing above and below the halocline and a region of relatively high stability in the vicinity of the halocline.

CHAPTER - 6

6. SUSPENDED SEDIMENT TRANSPORT

6.1. Introduction

The history of an estuarine system, after it has been established as a geomorphological entity, is largely determined by its sediment supply and sediment movement. Sediment movement occurs as the mobile bed tries to readjust its shape or texture inorder to resist the forces causing movement. In this way sand grain move to form a flat bed to cause ripples, ripples move to create sand banks and erosion and deposition alter sand banks. Many of the world major cities have grown to their present size because they are centered around a large navigable river or estuary. Failure to preserve adequate navigational channels often caused a city to decline or even abandon altogether its importance.

The prime source of sediment is obviously the land. Globally, about 12 Km^3 or 18 X 10^9 tons of chiefly fine grained sediment are carried from the land to the sea every year, mainly by rivers (Kuenen, 1950; Holeman, 1968). A small quantity is transported through the atmosphere. The Asian rivers carry more than of 75 percent of the world sediment discharge and the two third of that is carried by the Howey-Ho (yellow) rivers and the Ganges/ Bramhaputra (Dyer,1986).

To estimate the influence of this transport on the estuarine development or any other engineering problems associated with tidal environment, one must know, first of all, how much of the total amount is retained in near shore areas. There are three possible main regions of deposition, the estuaries, the continental shelf and deep sea. The main mechanism responsible for near shore sediment accumulation are (1) Wave transport which acts mainly on coarse material such as sand, shell remains and pebbles, (2) Tidal transport which acts on fine grained sand and silt and (3) estuarine circulation which acts of silt and mud. Combined they act on the whole grain size spectrum, except on grains of micron sizes which practically behave like dissolved material.

Although the over all value for total suspended load carried by rivers to the sea mentioned above may not be far from truth, accurate data on individual estuaries are not available. A long series of measurements closely spaced in time is necessary to arrive at a realistic input. Abnormal high river run-off may transport more material into an estuary in a few days than normal run-off in years.

This chapter is an attempt to identify the possible source and types of sediment which contribute to tidal shoaling problems in the Azhikode estuary, as well as the various sediment transport processes at work in the tidal environment and the factors on which they depend.

6.2. Properties of near shore and estuarine bed sediment

In the mouth and adjoining nearshore regions sediment pattern is more heterogeneous and patchy. Sediments near the mouth of the estuary are in general of finer fractions with a high percentage of silt and clay. Silt content of the bed material changes steadily from 60-70 percent near the mouth to 80-90 percent at the up-stream section. Typical grain size of the material in the estuary is 8 to 9.6 ∅ and the water content of the bed sediment is 70 percent by weight in the areas of high silt content. In the main channel, bottom material is of fine grained sea borne sand .Near-shore sediments are characterised by coarse to fine grained sand, which is a typical feature of the high energy environment, where finer grains are winnowed away in suspension and the coarser sand and gravels are deposited.

6.3. Sediment dynamics within the estuary

Tides play a significant role in controlling the sedimentological processes, especially in the estuaries. In the Azhikode estuary, though the maximum tidal amplitude is only 1m, signatures of bottom resuspension and localised sediment maximum zone are observed. In the sediment concentration maximum zone, concentration of suspended sediment is greater than in either the landward or seaward source of water and is often called as turbidity maxima. Magnitude of the sediment concentration in this zone depend upon the river and ocean source. Postma (1967) and Schubel (1968,1969,1971) have described that the suspended particles traversing seaward in the upper portion of the water column in the middle to lower reaches of an estuary, where the gravitational circulation is well developed, sink and are carried back landward in the lower portion of the water column to produce suspended sediment maxima. So far a logical connection between estuarine circulation and formation of turbidity maxima has not been rigorously demonstrated. Formation of turbidity maxima in the Azhikode estuary is controlled by a combination of gravitational circulation and tides. A schematic evolution of the turbidity maxima in the Azhikode estuary is shown in Fig.6.1. On every semi diurnal tidal cycle, large quantities of material are suspended during peak current periods and settle at slack waters of the flood and ebb tide. Tidal suspension varies with tidal range; large scale erosion and suspension occur during spring tides, whilst on neap tide, when the currents are weaker, turbidity maximum may not be as conspicuous as those during spring tide.

The concentration of the turbidity maximum vary from one estuary to other. Typical values for the various estuaries are Thames, 300-800 $mg.l^{-1}$; James, 50-200 $mg.l^{-1}$; St.Lawrance, 10-40 $mg.l^{-1}$, Gironde, 100-1000 $mg.l^{-1}$ and Seine estuary > 1000 $mg.l^{-1}$. Typical concentration of the turbidity maxima in the Azhikode estuary lies between 40-50 $mg.l^{-1}$.

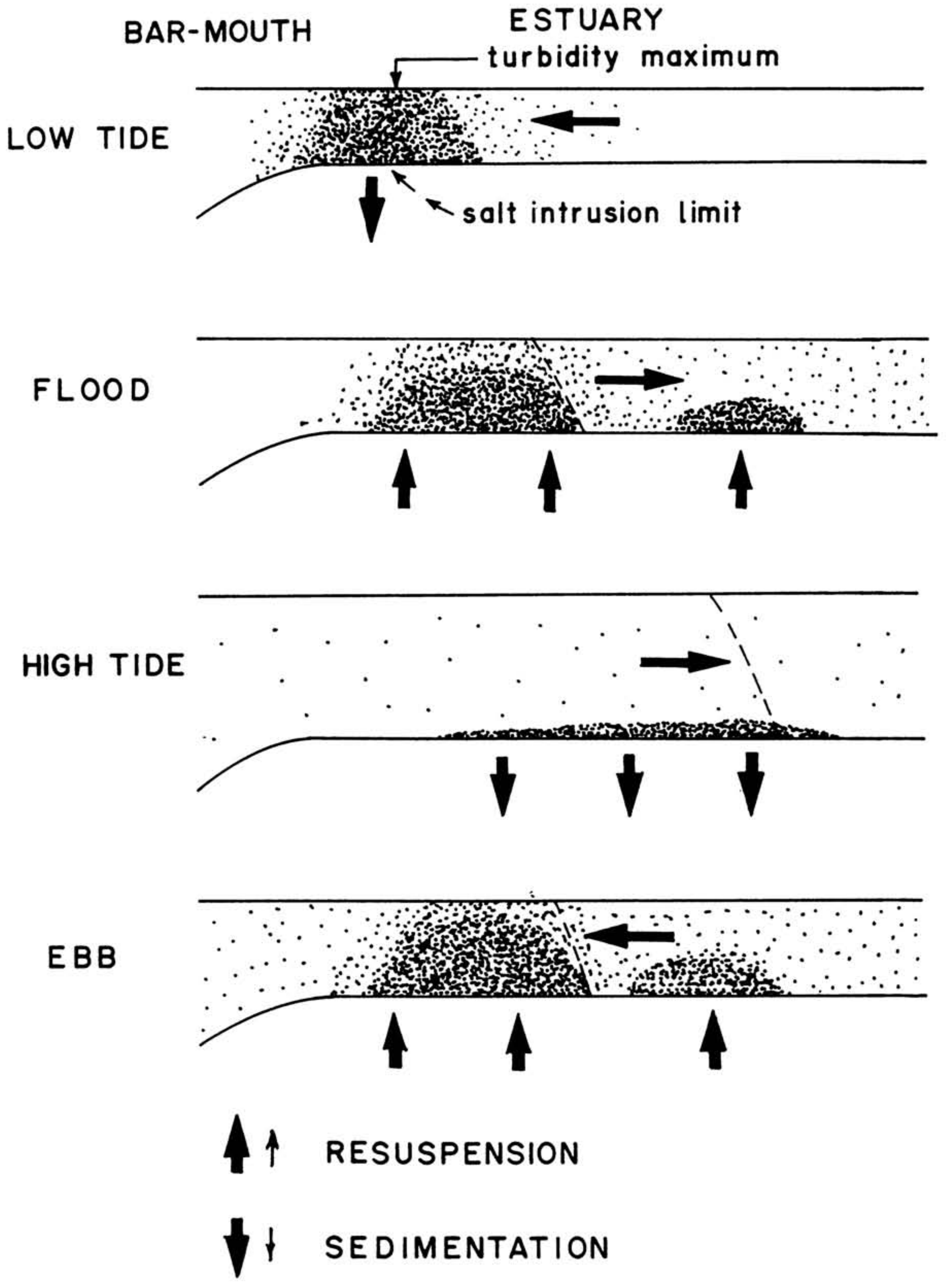


Fig.6.1. Schematic evolution of the turbidity maximum along the Azhikode estuary

Whilst the development of turbidity maxima as a sediment trap for suspended sediments is mainly controlled by tidal forces, its location in the estuary also varies seasonally with river discharge (Fig.6.2). During the periods of low river discharge, turbidity maximum is observed at a distance of 9 Km up-stream from the bar-mouth, while during the period of intermediate river flow, the turbid zone migrates down-stream and is located at 6 Km up-stream from the river-mouth. During the period of peak river discharge sediment concentration is greater than 40 $mg.l^{-1}$ in entire region between river-mouth and 5 Km up-stream, probably due to the low salinity in this period, flocculation and the associated settling of sediments is not taking place and the available sediments are always kept in suspension.

6.4. Semidiurnal fluctuation of suspended sediment

The fluctuation of suspended sediments on semidiurnal time scales in estuaries is well documented particularly in Europe, where river discharge is relatively small, compared to tidally initiated flow; eg. Thames, Severn, Siene (Inglis & Allen, 1957; Kirby & Parker, 1977; Avoine et.al., 1981). But quantitative documentation of tidal-phase control of sediment concentration fluctuation in large river basin are scarce. Available data in literature suggest that tidal phase control of sediment can occur in microtidal estuaries if the difference between spring and neap tidal

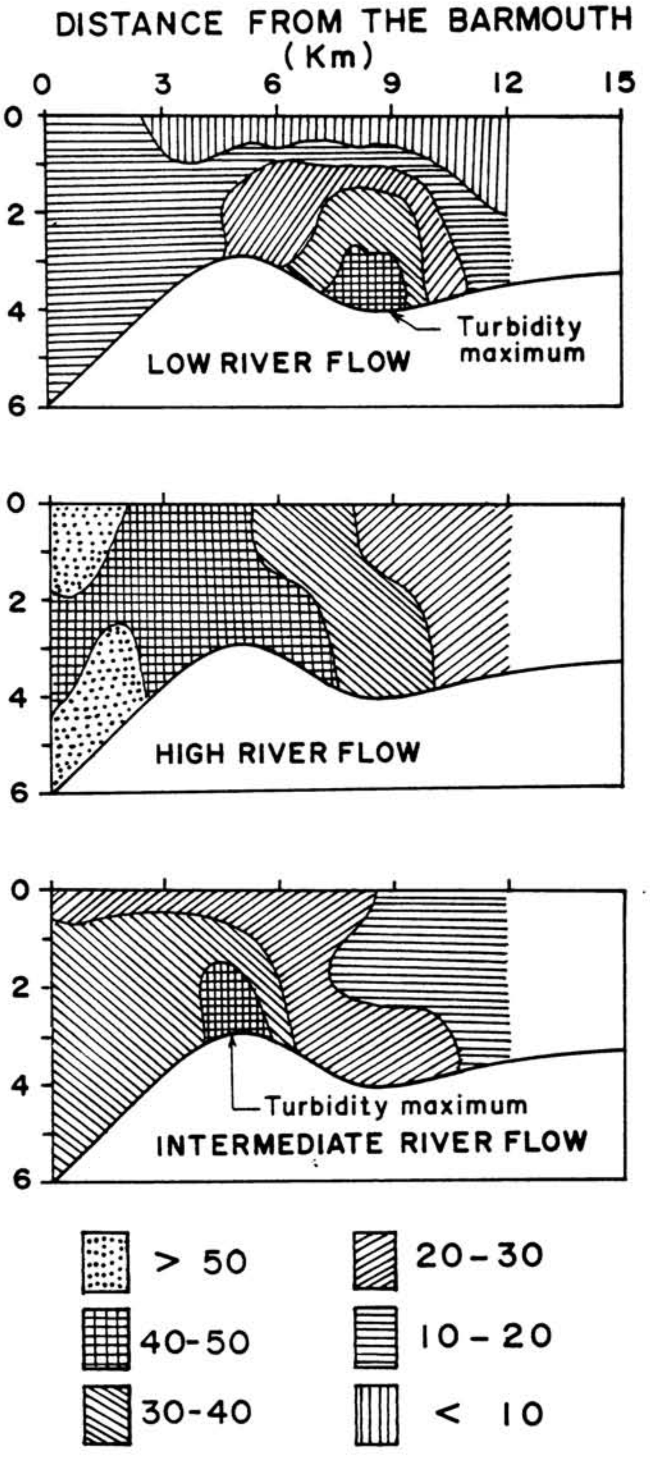


Fig.6.2. Longitudinal sections of the turbidity maximum in the Azhikode estuary at Low river flow, high river flow and intermediate river flow.

range is sufficiently great compared to mean estuarine depth. In the Azhikode estuary, difference between spring and neap tidal ranges is very small compared to the depth and the tidal-phase control is insignificant and only the sediment fluctuation in the semidiurnal time scale is significant.

To investigate the semidiurnal fluctuation of suspended sediment concentration, two lower most stations which lie along the central axis of the estuary are selected and the variations during April (a period of low river discharge) and July (a period of high river discharge) are discussed.

Suspended sediment concentration are contoured with depth and time in Figs. 6.3.a,6.4.a,6.5.a & 6.6.a. Contour plots of salinity are available in Fig.6.3.b,6.4.b,6.5.b & 6.6.b. Current speed plots directly comparable with sediment contours are presented in Fig.6.3.c,6.4.c,6.5.c & 6.6.c. Concurrent plots of mean tidal current velocity are displayed in Fig.6.3.d,6.4.d,6.5.d & 6.6.d.

Azhikode:- During April sediment concentration in the water column varied between 10 $mg.l^{-1}$ at ebb-tide and 55 $mg.l^{-1}$ at flood-tide (Fig.6.3.a). Most prominent feature of the sediment concentration is the occurrence of a concentration maxima at the bottom, which coincides with the time of peak mean flood current velocity (Fig.6.3.a&6.3.d). This maximum appears to be related to the bottom related processes and

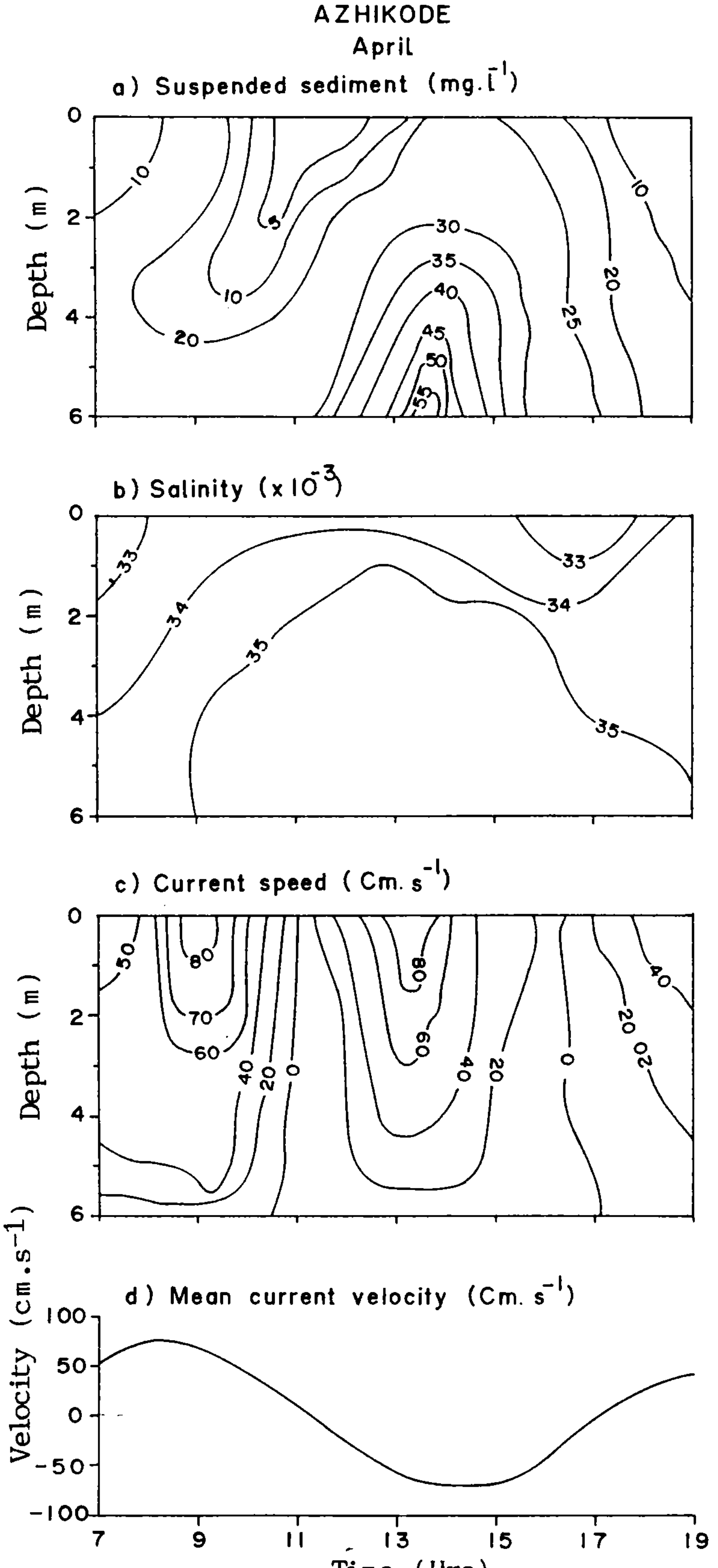


Fig. 6.3. Suspended sediment concentration (a), Salinity (b), Current speed (c), Contoured with depth and time and the mean current velocity (d).

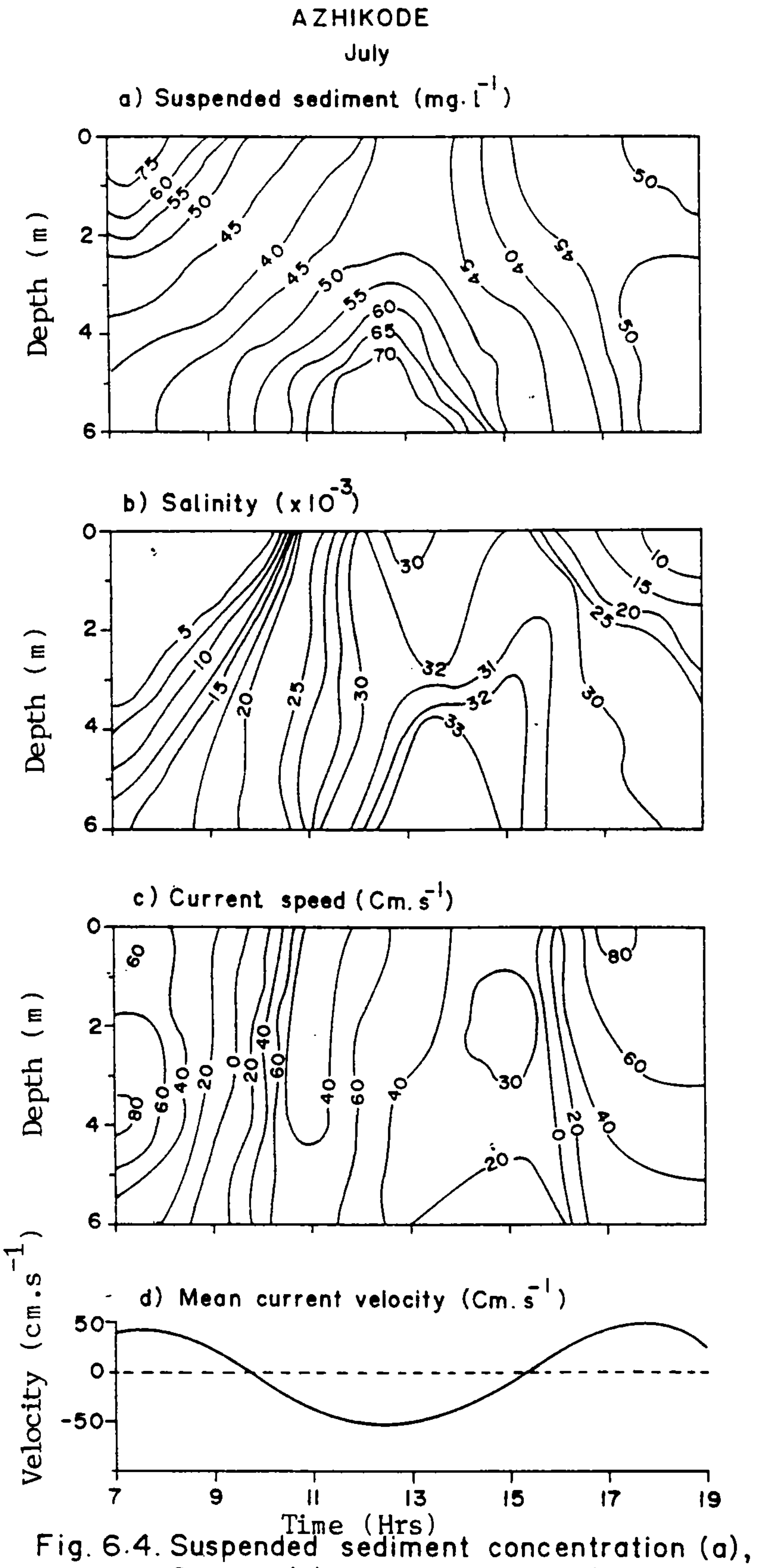


Fig. 6.4. Suspended sediment concentration (a), Salinity (b), Current speed (c), Contoured with dept and time and the mean current velocity (d)

immediate source of this is the tidal resuspension of surficial bed sediments. The vertical extent of this maxima is bounded by 35×10^{-3} isohaline (Fig.6.3.b). It could be seen from the pattern of distribution, that there is a net landward transport in the bottom layers and the landward transport dominates the seaward transport. During July, a surface related maxima is clearly observed when the mean current velocity is seaward (Fig.6.4.a & 6.4.d) in addition to the occurrence of a bottom sediment concentration maxima during flood-tide. This surface related maxima may not be the sediment resuspension, but may be due to the transportation of sediment from upper region of the estuary. This surface sediment concentration maxima during high river discharge is a common phenomenon in estuaries which flow over large inter tidal mudflats. Though the distribution pattern shows a two layer transport processes, during this period of high river discharge seaward transport greatly exceeds the land ward transport.

Kottappuram:- During April, sediment concentration is homogeneously distributed throughout the water column at ebb-tide. A bottom related concentration maxima is observed at the beginning of the flood-tide(Fig.6.5.a & Fig.6.5.d). and the sediment profiles are parallel to depth axis when the mean seaward current velocity reaches the peak value. The lower sediment concentration observed in this station

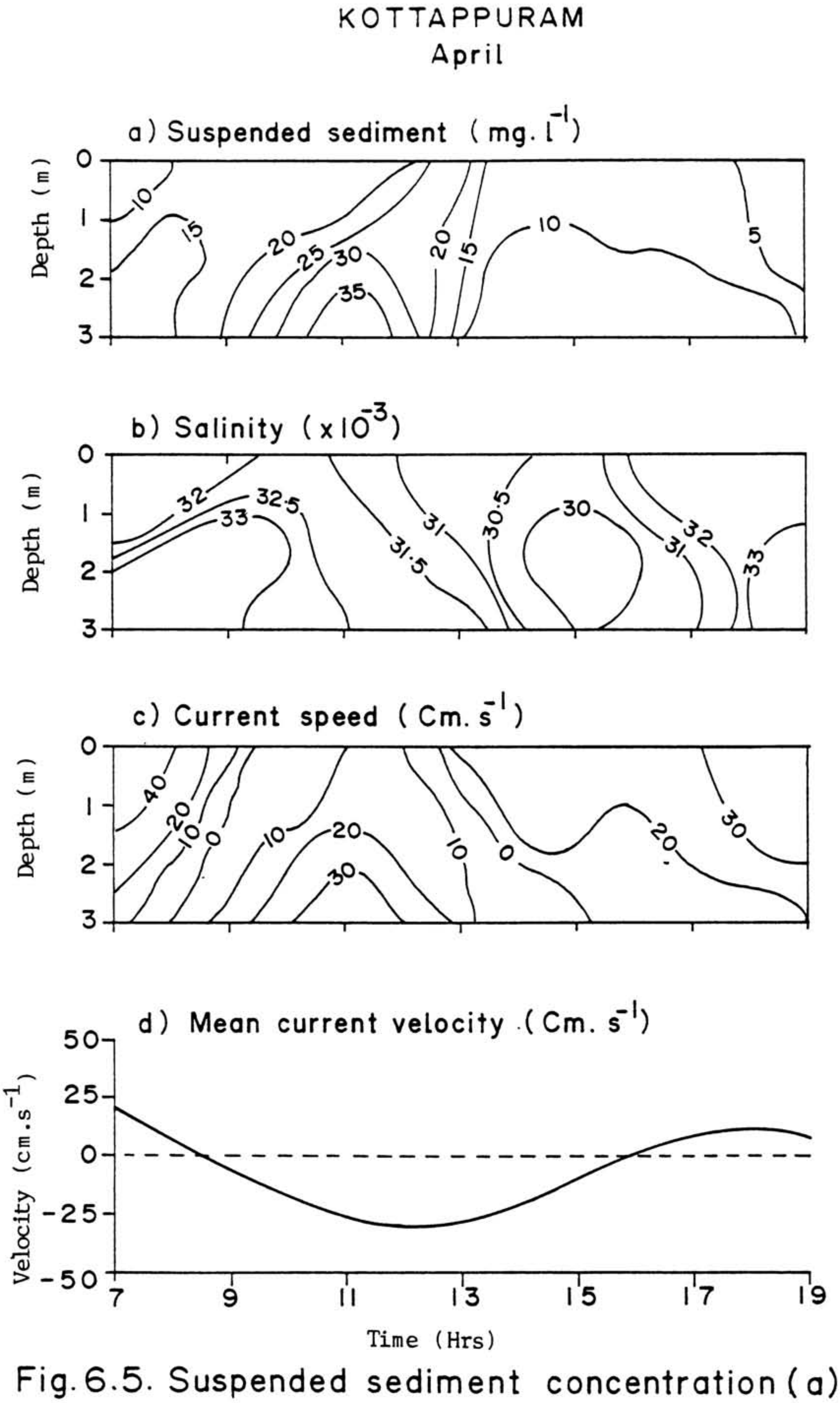


Fig. 6.5. Suspended sediment concentration (a), Salinity (b), Current speed (c), Contoured with depth and time and the mean current velocity (d).

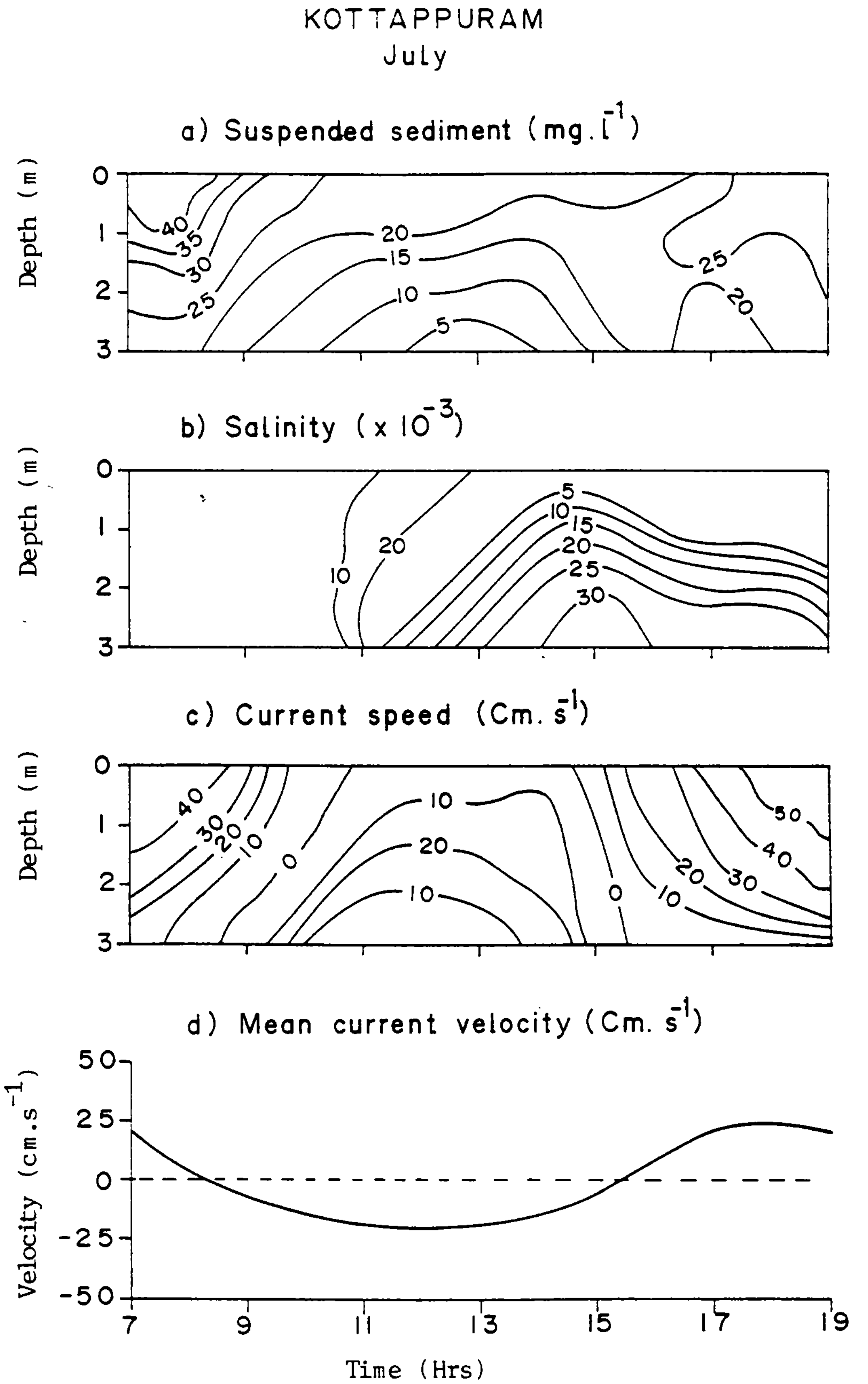


Fig.6.6. Suspended sediment concentration(a), Salinity (b), Current speed (c), Contoured with depth and time and the mean current velocity (d).

may be due to the non availability of the easily eroded bed material or the decreased velocity of the mean current. During July, no bottom related sediment concentration maxima is observed, whilst the upstream source of sediment carried by the strong fresh water is apparent (Fig.6.6.a,6.6.c & 6.6.d). Surface concentration varied between 40 $mg.l^{-1}$ at ebb-tide to 20 $mg.l^{-1}$ at flood tide. Sediment concentration decreases with depth and obviously the net transport is towards the sea irrespective of the phase of the tide.

6.5. Residual fluxes of suspended sediment

Residual fluxes of suspended sediment at four cross-sections in the Azhikode estuary are analysed to identify the dominant physical processes which controls the sediment transport and its variation with the river flow.

The residual transport of suspended sediment per unit width of water column (in $mg.l^{-1}.cm.s^{-1}$) is given by

$$G = G_L + G_{TP} + G_V \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Subsripts have the same meaning as those for salt flux equation (8) in Chapter-4, If P denotes the instantaneous suspended sediment concentration and p = <P> then G replacing F

$$G = \langle H.\overline{U.P}\rangle/h \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

$$G_L = \overline{u_L}.\ \overline{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots (3)$$

$$G_{TP} = \langle\ \tilde{Q}.\tilde{P}\rangle/h \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$G_V = \langle H \overline{U'P'} \rangle / h \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$p' = P - \bar{P} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

During April (Fig.6.7.a) the flux of suspended sediment transport due to tidal pumping is up-stream at all stations, owing to the low river discharge sediment transport by the residual flow of water (G_L) being very small. Sediment transport by vertical shear is insignificant and it does not exhibit any longitudinal variation. During July, (Fig.6.7.b) sediment transport by the seaward residual flow of water far exceeds G_{TP} and G_V; however, tidal pumping is up-estuary in the lower two sections probably due to the strong tides and associated erosion stress and existence of plentiful supply of bed sediments. Transport associated with the vertical shear is insignificant as the sediment concentration is homogeneously distributed in the entire water column. During November (Fig.6.7.c), sediment transport again appears to be dominated by the seaward residual flow of water, whilst the tidal pumping in the lower two section is up-estuary. Vertical shear contribution to the sediment transport processes is negligible and it is down estuary in the upper two sections. In conclusion, in microtidal estuaries like Azhikode, seaward residual flow of water determines the direction and magnitude of the net sediment transport, except for the period of very low river flows during which tidal pumping (G_{TP}) takes the leading role.

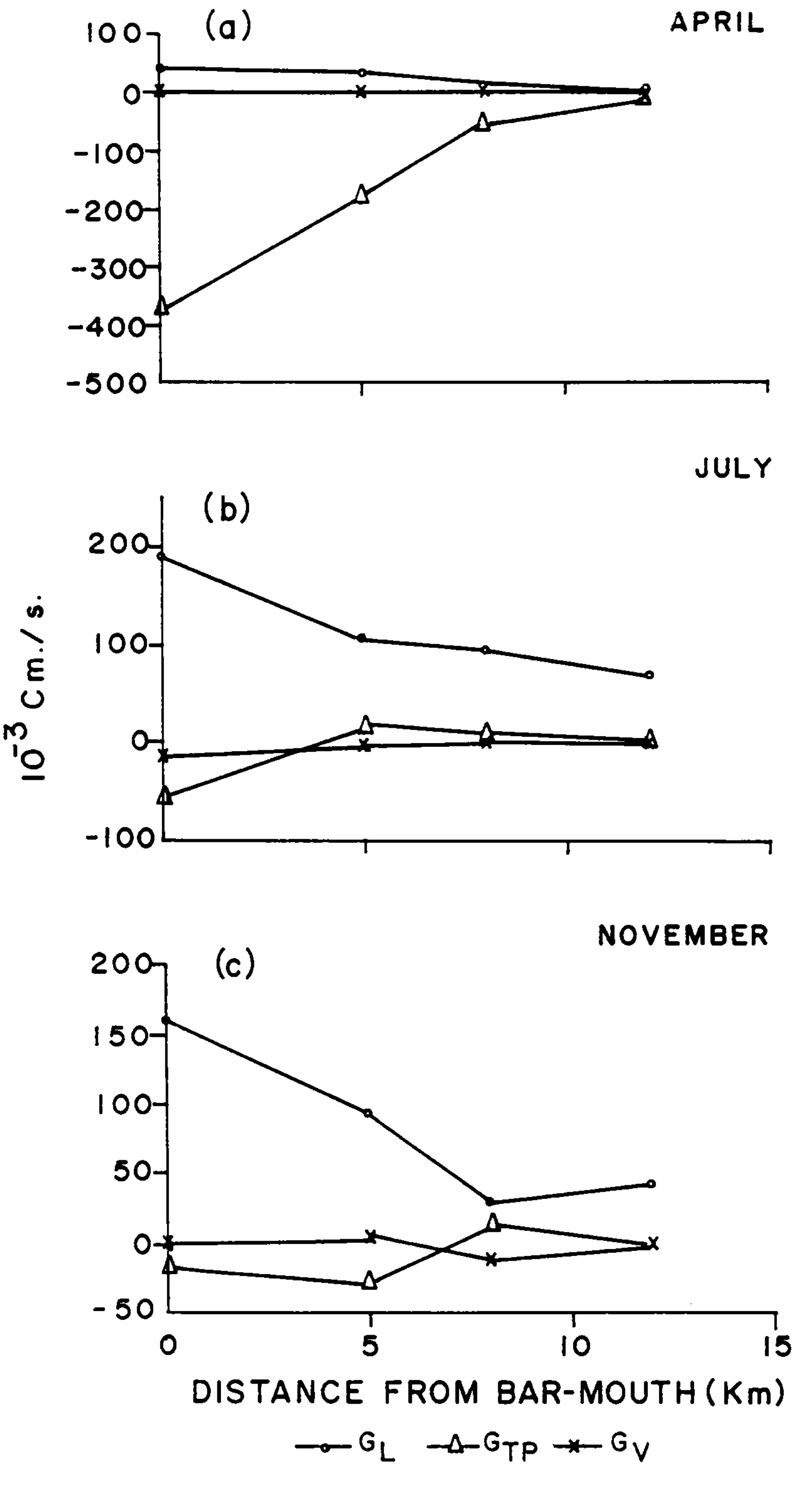


Fig. 6.7. Observed depth-averaged values of the suspended sediment fluxes due to eulerian residual flow of water (G_L) tidal pumping (G_{TP}) and vertical shear (G_V).

6.6. River input

The amount of sediment eroded from a drainage basin, the sediment yield, depends on the geology, the topography and the climate. However, the yield does not usually equals the amount of sediment discharged into the estuary because a great deal is deposited in the lower reaches of the river.

For computation of the river input of suspended sediment, river discharge data and mean suspended sediment concentration during ebb-tide at Chennamangalam (nearly the upper limit of the tidal influence) are used and are presented in Fig.6.8. During the observation period river discharge and suspended sediment varies between 10.3 -387 $m^3.sec^{-1}$ and 5-88 $mg.l^{-1}$ respectively. The annual sediment input into the estuary during the study period, based on the data from Fig.6.8. is estimated to be 5 X 10^4 tons, out of which approximately 50 percent of the input occurred during June-August.

6.7.Sediment budget

The rate of transport of sediment at the four cross-section during the observation period are given in Table.6.1. The computed values of transport calculated above may contain unknown errors caused by sampling of continuously varying quantities, obviously a single bottle sample is not an accurate estimate of the mean concentration over an hour. Sediment transport is towards the sea

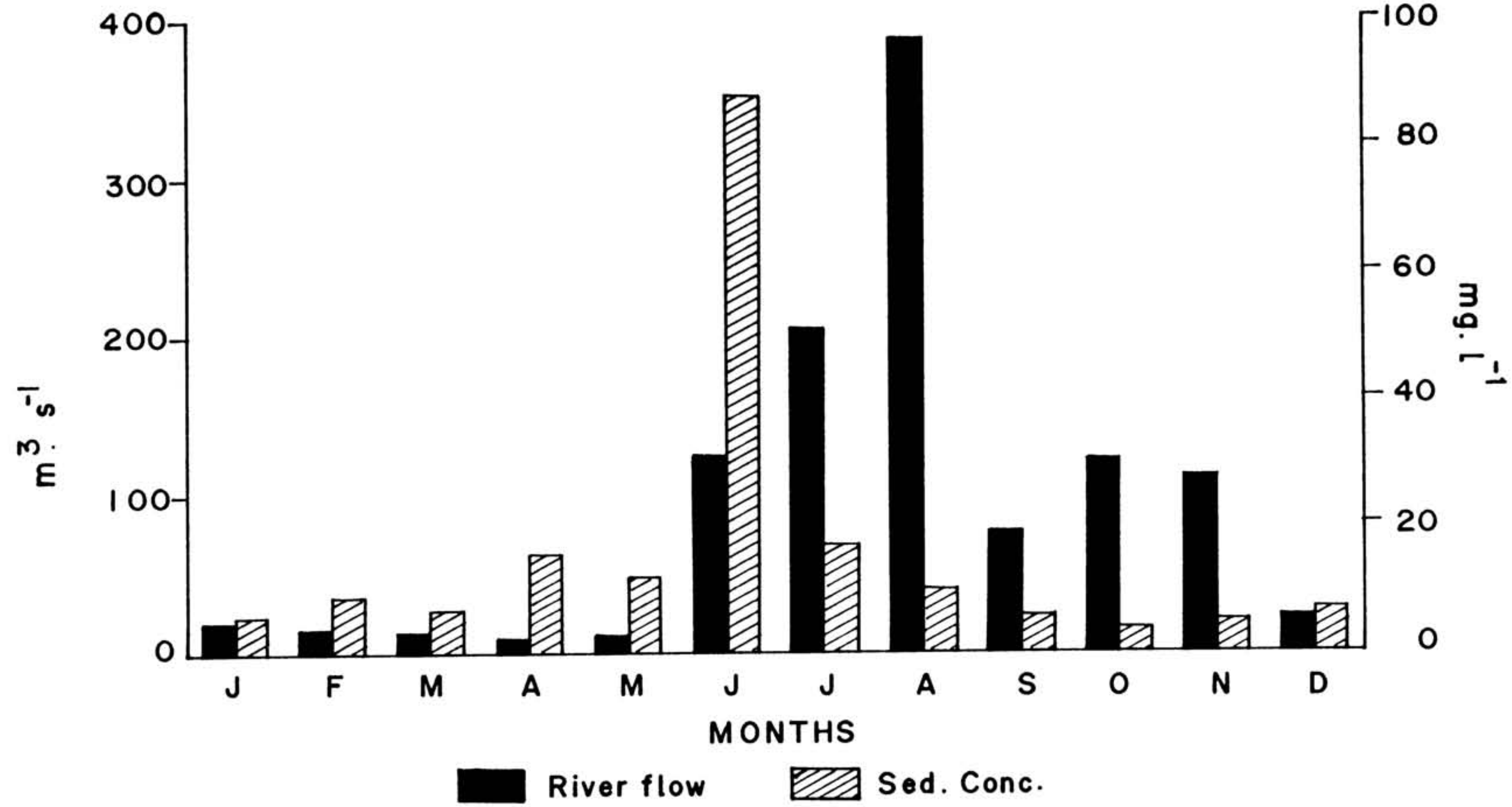


Fig. 6.8. Monthly observations of river flow and suspended sediment concentration during January to December 1986.

Table.6.1. Observed rate of transport of suspended sediment (in $Kg.m^{-1}.s^{-1}$)at various cross-sections during different months.

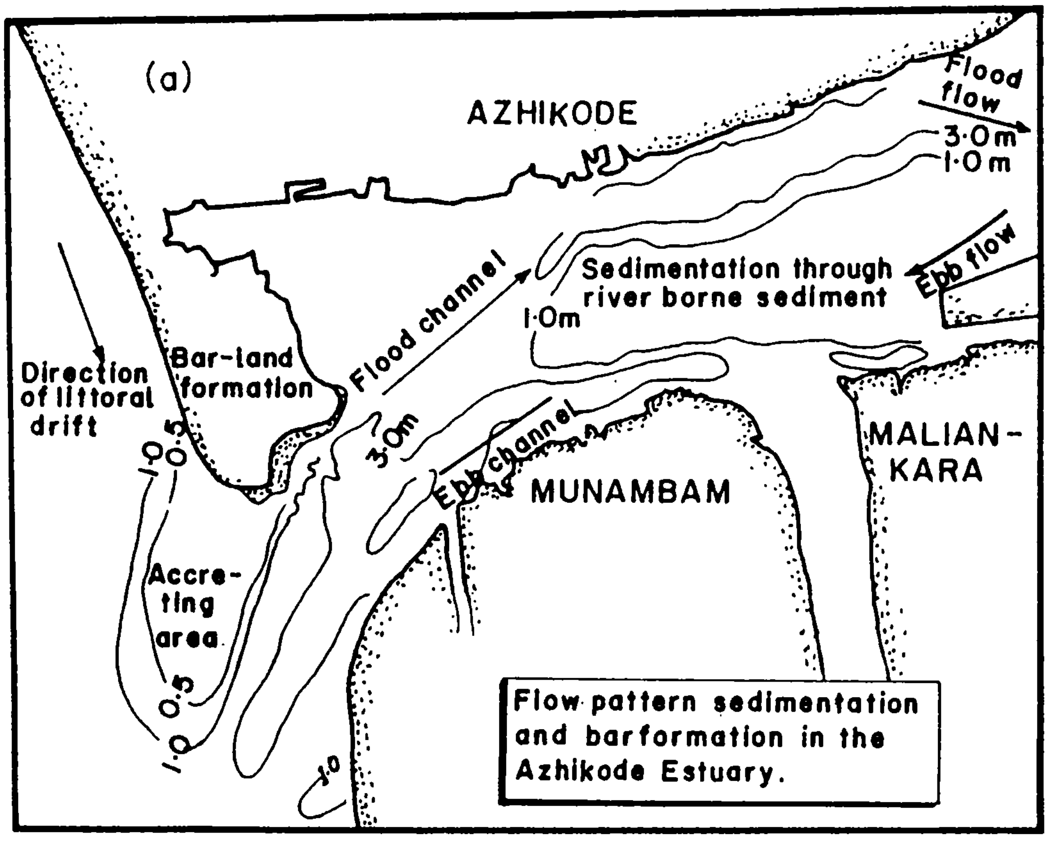
	Section-I	Section-II	Section-III	Section-IV
JAN	130.00	76.10	73.87	41.44
FEB	120.00	54.52	55.29	25.57
MAR	241.00	72.14	64.80	19.00
APR	-540.00	-329.31	-121.76	-304.00
MAY	-	-	-	-
JUN	4754.00	4090.00	4017.00	4405.00
JUL	500.00	364.21	103.86	90.52
AUG	688.00	215.87	104.57	158.20
SEP	-	-	-	-
OCT	632.00	558.00	563.00	214.25
NOV	512.00	434.28	410.21	186.58
DEC	-	-	-	-

throughout the observation except during for the month of April. Rate of transport increases in the down-stream direction probably due to the tidal resuspension and consequent upward movement of the resuspended sediment. During the period of high river flow, rate of transport is nearly equal at all cross-sections, which implies that during this time, river discharge is the major source of suspended sediment. Inspite of the fact that some data are not available, based on the data from Table.6.1, attempt has been made to calculate a tentative sediment budget for the Azhikode estuary. Net seaward escape of sediment load is estimated to be 1.5×10^{4} tons/ year. Comparing this with the total river input (5×10^{4} tons/year), annual entrapment of sediment in the estuary is 3.5×10^{4} tons, - the estuary acts as a sink for the suspended sediment. If this entraped sediment is uniformly deposited in the harbour area ($1.km^2$), it would provide a blanket of fresh sediment of an average thickness of 34 mm assuming density of the sediment as $1020 \ Kg.m^{-3}$ (Mc.Dowel & Connor,1977). The amount of sediment involved in annual sedimentation and erosion cycles in the Azhikode estuary is considerable as shown by the following calculation. Adopting 13 $mg.l^{-1}$ and 100 $mg.l^{-1}$ as the average concentration during low river flow (March) and high river flow (June) respectively and $23.15 \times 10^{6} \ m^3$ as the average volume of the estuary, the mass of suspended matter varies between $3.13 - 24.15 \times 10^{2}$ tons between March and June.

6.8. Sedimentation and sandbar formation at Munambam harbour

The munambam fishery harbour and adjacent regions are shown in FIg.6.9. The deposition of beach material offshore or across the mouth of the inlets or embayments, in such a way to form barrier extending above the normal level of highest tide and partly or wholly enclosing the lagoons, is a widely distributed phenomenon which has received attention in recent years.

The history of sandbar formations, and the menace caused by it have been is detailed in Chapter-1. To discuss the processes behind the formation of sandbar, an understanding of pattern of longshore drifting, waves is of great importance. Wave height in the region varies between 1.5m during June to 0.45m during October. Littoral current is southward during June-September with speed in the range of 20-30 $cm.s^{-1}$. Weak northerly current is observed during October. Annual net littoral drift is southward and is estimated to be $6 \times 10^6 m^3$, out of this $2.5 \times 10^6 m^3$ is transported during June-August (Sajeev,Unpublished). This large southerly drift during the monsoon months and the high rate of seaward escape of suspended sediment (Table.6.1) accounts for the sudden growth of vertical and horizontal extent of the sandbar. So it is to be believed that the southerly littoral drift and bed load transport by waves favours the formation of sandbar. As the water flows over the mudflats on the northern side of the entrance, flow



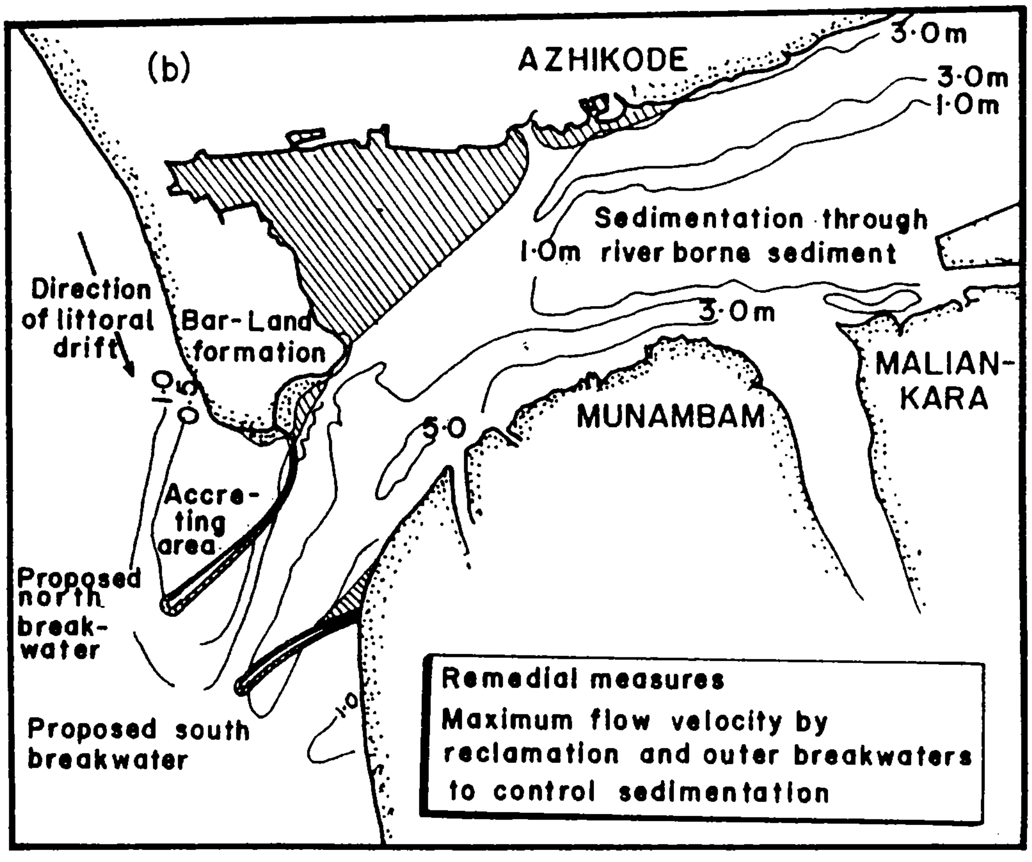


Fig. 6.9.(a) Existing hydrosedimentological set-up.

(b) Suggested remedial measures to prevent shoaling and sandbar formation.

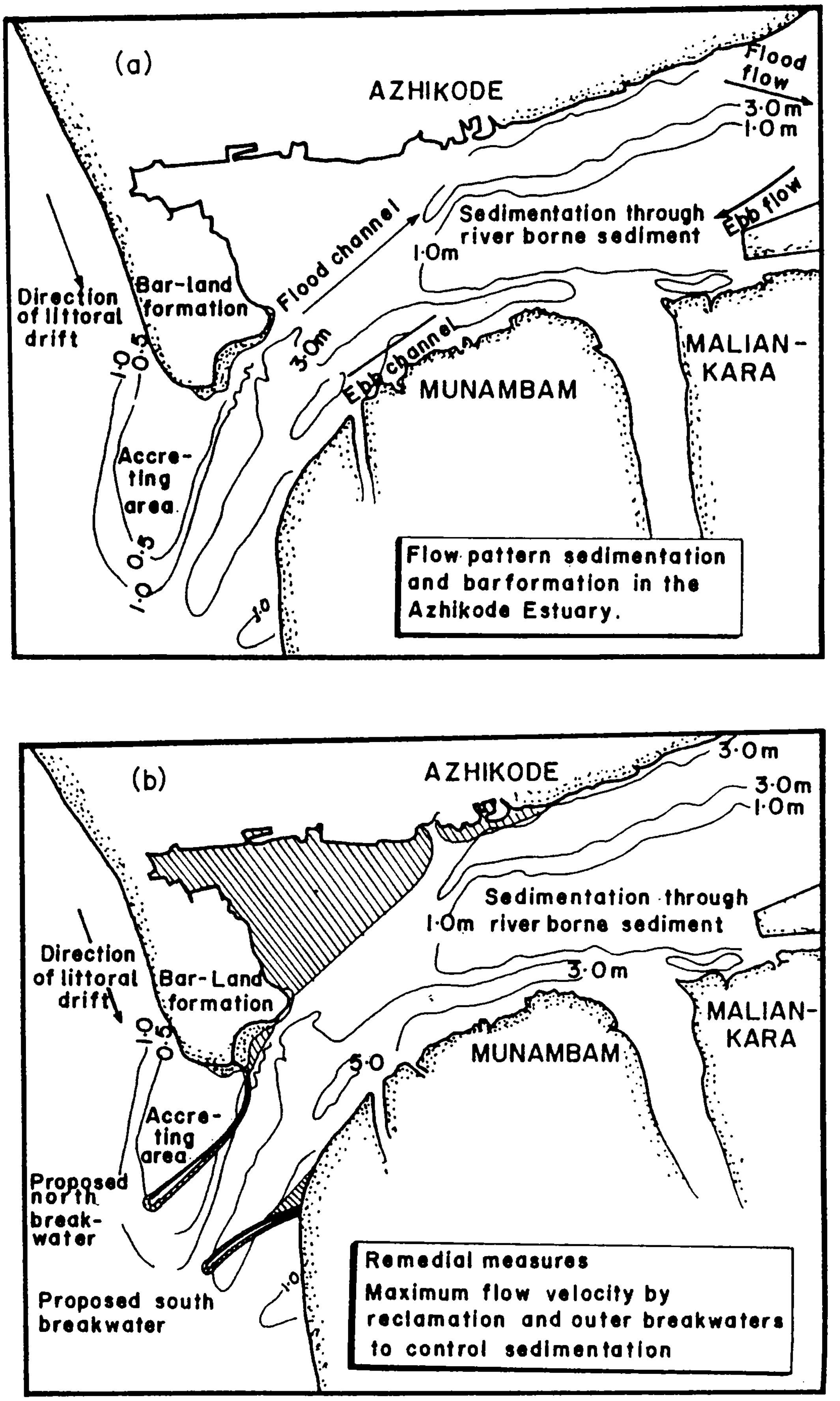


Fig. 6.9 (a) Existing hydrosedimentological set-up.

(b) Suggested remedial measures to prevent shoaling and sandbar formation.

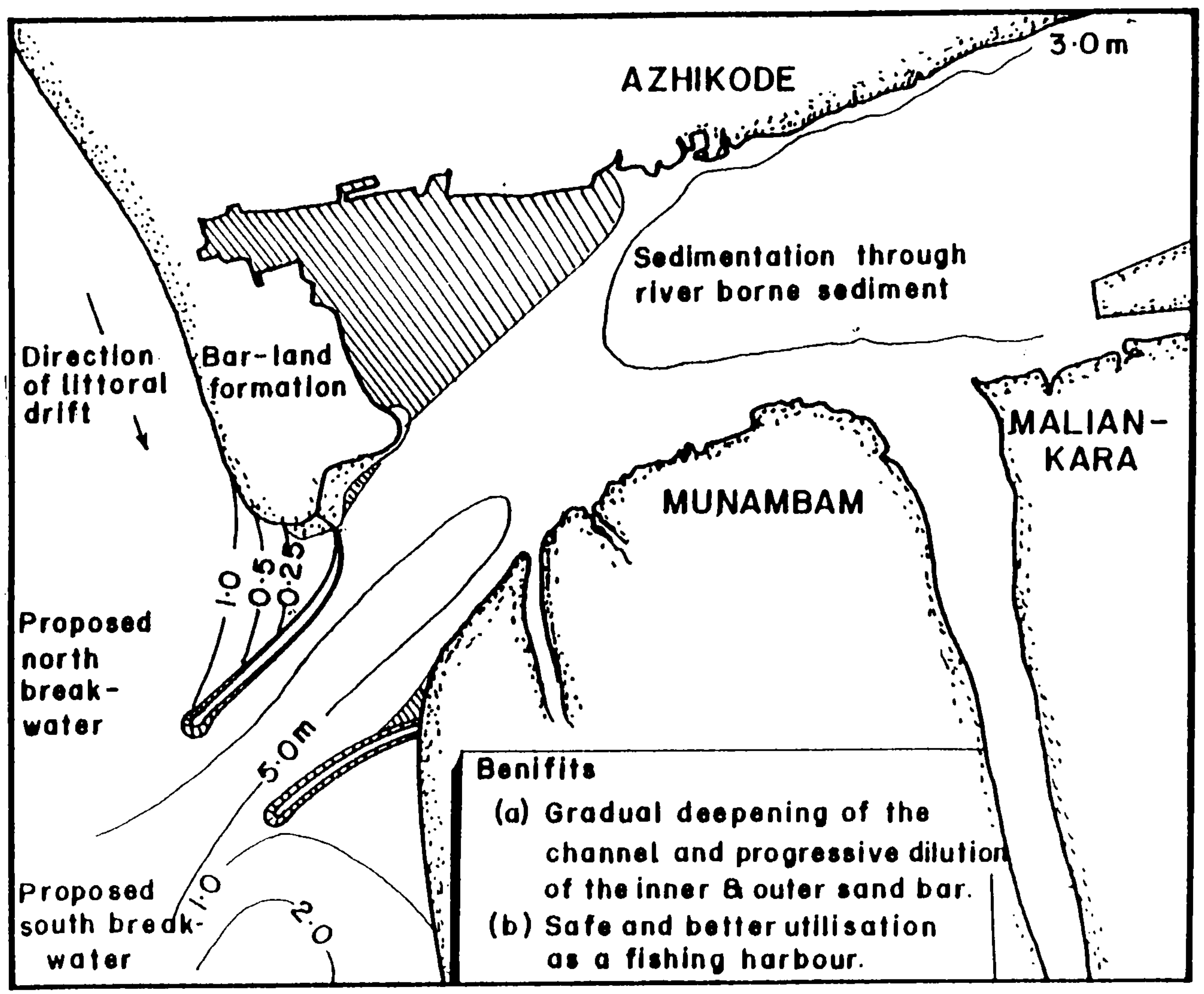


Fig.6.10. Conceptual picture showing possible benifits of suggested remedial measures.

velocity is considerably reduced facilitating enhanced settling of sediment and the consequent shoaling.

Based on the data collected ,the information available from other source and also from the experience gained while studying similar embayments, it is suggested that if the sandbar formed is dredged out and the dredged material is used to reclaim the mudflats area shown in shaded portion in Fig.6.9.b, it will be possible to channelise the river flow to attains the sufficient flow velocity to flush sediment out of the harbour region and thereby prevent shoaling. Construction of two shore connected breakwaters as shown in Fig.6.9.b, will trap the southerly and northerly littoral drift and prevent the formation of sandbar. The orientation nature and length of the breakwaters to be constructed can be decided only after physical modeling. Fig.6.10 is a conceptual picture showing the benefits obtained, such as gradual deepening of the channel and progressive removal of the sandbar on the implementation of the preventive measures suggested.

7. SUMMARY

The hydrodynamics and sediment transport processes in the Azhikode estuary are elucidated from a detailed study, which includes monthly synoptic tidal observation of current speed, current direction, salinity, suspended sediment concentration and tides at selected four cross-sections of the estuary, located between Azhikode and Chennamangalam. Major physical forcings which governs the water, salt and suspended sediment transport processes are identified and their relative dominance is discussed. This study also highlights on the causative factors for the shoaling at the entrance channel and sandbar formation across the mouth.

Tides in the Azhikode estuary are semidiurnal with maximum amplitude of 1 m during spring tides and 60 cm during neap tides. Tidal fluctuations are experienced up to 30 Km from the barmouth during the periods of low fresh water discharge. In the Azhikode estuary it is seen that the distribution of temperature is controlled by local weather conditions. Surface temperature of the water chiefly depends on the incoming solar radiation and so the diurnal effects dominate over the tidal effect. Maximum surface temperature of 31°C is observed during April at Kottappuram and the minimum value of 25°C is observed between Kottappuram and Gothuruthu during July. On an average river end of the estuary is warmer than sea end by 1°C and this difference is maintained throughout the year.

From the synoptic surveys carried out, it is observed that the entire reach is influenced by saline intrusion during post and pre-monsoon and salinity intrusion is limited to the lower 5 Km reaches during the southwest monsoon. Length of salinity intrusion varies with the river discharge. Lateral variation in salinity is insignificant compared to axial variation, but lateral variation in current speed and directions are observed at the lower sections especially during flood-tide. Tidal mean currents shows a clockwise rotation with depth during the period of low river discharge and seaward flow is observed throughout the water column at all sections under high river discharge condition. Tidal mean salinity profiles exhibit a well defined gradient zone between surface and mid depth, when the river discharge is low, and as the river flow increases, the gradient zone is destroyed and profiles become parallel to the depth axis. From the predictive linear regression model, it could be seen that the tidal amplitude is relatively important in the mean salinity distribution only at section-I, and at all other sections river discharge is more important.

Different regions of the estuary falls under varying classification depending upon the river discharge, lower part of the estuary is well mixed during low river flows and partly mixed during high river flow, whereas the upper part of the estuary is partly mixed to well mixed under low to medium river runoff period and well mixed during high river discharge.

Residual transport of water is towards the sea throughout the observation period at all sections except the lowest section, where up-estuary eulerian residual currents are observed during March-April. Land ward Stokes drift is an important component of the residual transport of water in the Azhikode estuary, its magnitude decreases in the up-stream direction. Salt transport by the residual flow of water far exceeds that due to Stokes drift and vertical shear. On a few occasions, at section-I, salt transport by the Stokes drift exceeds that due to residual flow of water. Magnitude of salt transport due to vertical shear increases with the vertical salinity gradient and is directed up-estuary throughout the observation period.

Flushing time of the estuary varies with the river discharge. Cumulative flushing time of the estuary varies from 4.8 tide cycles in April to 1.22 tide cycles in August. Longitudinal eddy diffusivity, which is a measure of pollution dispersion lies between 2 X 10^6 in $cm^2.s^{-1}$ in January to 42 X $10^6.cm^2.s^{-1}$ in August.

Bed sediments in the Azhikode estuary mainly consist of clay and silt and at the entrance channel sediments are characterised by coarse to fine grained sand. Signature of turbidity maximum zones are observed in the Azhikode estuary, position of which change with the river discharge. Typical sediment concentration in the turbidity maximum zone is 40 $mg.l^{-1}$. Remarkable feature of the semidiurnal fluctuation of the sediment concentration is that the occurrence of concentration maximum zone near the bottom due to the tidal resuspension of surficial bed sediment during flood-tide and a surface maxima during ebb-tide owing to the down-stream transport of suspended sediment from the upper stations.

In microtidal estuaries like Azhikode, sediment transport associated with the residual flow of water determines the direction and magnitude of the sediment transport, except during the periods of very low freshets, when the tidal pumping dominates.

Annual river input of suspended sediment in the estuary is estimated to be 5×10^4 tons out of which only 1.5×10^4 is escaped to the sea and the remaining is trapped near the barmouth region resulting in the shoaling of the harbour region. Large southerly drift in the adjacent coastal region and the seaward escape of sediment account for the sandbar formation across the river-mouth. Based on the study and from the historical data available, some remedial measures are suggested to prevent sandbar formation across the mouth and to reduce shoaling at the harbour entrance.

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