STUDIES ON THE HYDRODYNAMICS OF THE BEYPORE ESTUARY

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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. Anilkumar. N. under my supervision and guidance in the National Institute of Oceanography, Regional Centre, Cochin-18, 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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Introduction

PREFACE

Estuaries constitute a small part of the area and even smaller part of the volume of the total marine hydrosphere. Estuaries are unique water systems; they are the interface between fresh river water and saline coastal water. Situated between the land and sea, they play a dynamic role in mixing, circulation, sediment and water dynamics in the transitional zone. Estuaries have high biological productivity. Pollution problems in estuaries have been aggravated by the concentration of human population along the shores of the estuaries. To preserve the water resources in these systems, where complex interactions of physical, chemical and biological factors occur, studies have to be made in the midst of many conflicting interest.

A gradient of salinity from the freshwaters of the river to the coastal waters at the mouth is the characteristic of estuaries. In well mixed estuaries, the vertical distribution of salinity is uniform but in stratified estuaries the surface waters may be considerably fresher than the waters at the bottom. At any given place within the estuary the salinity can vary widely on several time scales. As the river flow varies seasonally the freshwater moves seaward during high freshwater discharge while the sea water moves landward during periods of low river flow. During dry period the estuary will become saltier while during wet period it becomes fresher. The geographical extent and the magnitude of these changes are largely determined by the unique geomorphology of each estuary. Also all estuaries are characterised by an extremely variable set of environmental conditions which impose unusual stresses on the population that inhibit them.

Chaliyar river is one of the major estuarine system in the middle of the Kerala coast in India. Detailed studies on the distribution of suspended sediment and salinity in the entire estuarine region for the computation of fluxes in the estuary has not been reported so far. The variation of hydrographical features, the stability of the estuary, sediment and water dynamics, flushing characteristics, mixing and circulation, longitudinal coefficient of eddy diffusivity are topics of interest involved in this study. The saline intrusion into tidal streams causes problems to irrigation, industrial and domestic water supply schemes. A thorough knowledge of the suspended sediment distribution is needed for understanding the sedimentation process

This thesis is presented in seven chapters. The first chapter describes the general introduction and gives a clear picture about the classification based on geomorphology, freshwater flow, evaporation, stratification and circulation. The literature review covering the relevant fields of physical aspects, description of the study area and the scope of the work are also included in this chapter.

The method of data collection, processing and analysis are given in chapter-II.

Monthly variation of the distribution of temperature, salinity and currents are described in chapter-III. Apart from these the longitudinal and vertical variation of time averaged values of salinity, the variability of residual currents and residual salinity with non-dimensional depths are presented here. The influence of Chaliyar river discharge, rainfall and wind speed are also detailed in this chapter.

Residual flow of water and salt are presented in chapter-IV. The influence of different forces causing transportation of water and salt are discussed and the classification of the estuary is also done.

In chapter-V computed values of the Richardson's number are used for comparing the stabilising effect of stratification. The flushing time for different months were computed. Based on longitudinal eddy diffusivity mixing processes were discussed.

Discussions about the distribution and transportation of suspended sediments during different months of the period of study are given in chapter-VI. The variation of suspended sediment with tidal amplitude and current speed are also discussed here. The annual sediment input and entrapment in the estuarine system is quantified.

All the discussions in the previous chapters are summarised in chapter-VII.

CHAPTER I

INTRODUCTION

An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater derived from land drainage (Pritchard, 1967). But as per the definition of Ketchum (1951), Pritchard (1954, 1955) and Cameron (1951) the brackish water areas, where the rivers flowing into non tidal seas are also considered as estuaries. The definition states that estuary is a coastal feature and hence limits to some extent the size of the bodies of water under consideration. A free connection must allow essentially the continuous exchange of water between the estuary and the ocean. From the physical point of view, the definition of an estuary should follow certain basic similarities in the distribution of salinity and density, as well as the circulation pattern and the mixing processes. Pritchard (1967), Emery and Stevenson (1957) considered an estuary as a wide mouth of a river, or an arm of the sea, where the tide meet the river currents and the tide is the principal cause of special estuarine condition at the river mouth.

The estuary, where the river flow meets the flood of the tide, is a unique and important part of the aquatic environment. It forms the transition zone between the inland world of freshwater and the sea water lying off shore. As such, it shows some characteristics of both freshwater and marine environment but it also has unique properties of its own. Some of these unique properties are common to all estuaries of the world, others are determined by local conditions so that each estuary has its own individual and special properties (Ketchum, 1983).

In the last few years there has been a considerable increase in the effort on studies of the inshore region, particularly in the United states and Canada. During the first forty years of this century a relatively greater proportion of work by the marine investigators in Europe was directed towards the study of estuaries.

Because of the complexities of shore line processes no definite agreement exists in the field as to even the proper definition of what constitutes an estuary. These complexities result in a number of definite estuarine types, classification of which has not yet reached general acceptance.

1.1 Classification of Estuaries

It may be possible to distinguish lagoons and estuaries by analysing the hydrological feature mainly by the instability of salinity. When the inflow of freshwater in a separated basin develops a stable body of brackish water, it may be considered as a lagoon, if mixing of fresh and marine water is not stable but shows periodic changes the basin may be considered as an estuary (Hubert Caspers, 1967). The regional distribution of estuaries and lagoons corresponds to the regional characteristics of continental shelves and coastal plains. Lagoons occur where continental shelves and coastal plains are wide and nearly flat, where the shelves and coastal plain distribution coincides. There is a long established concept that lagoons are formed by the marine deposition of offshore bars in areas of low relief, and estuaries are drowned valleys cut by streams of glaciers, Emery (1967).

1.1.1 Classification by freshwater inflow and evaporation

Estuaries may be divided into two large groups depending upon the relationship between freshwater inflow and evaporation. Historically the term "estuary" has been applied to coastal indentures in which there is a measurable dilution of sea water by freshwater. Surface salinities are consequently low within the estuary than in the open sea. To this group we will apply the term positive estuaries. Higher precipitation and lower evaporation exist in most estuaries that are positive ones (Dyer, 1979). In brief, a positive estuary is an estuary where the freshwater derived from river discharge and precipitation exceeds evaporation. Estuaries in which evaporation exceeds land drainage plus precipitation are known as negative estuaries (inverse estuaries). There may also exist a group of estuaries in which neither the freshwater inflow nor the evaporation dominates. This class will be termed neutral estuaries.

1.1.2 Classification in terms of Geomorphological Structure

Estuaries have been classified on the basis of geomorphology, and the characteristic type of circulation. These systems are interdependent to large extent and the geomorphology combined with the tidal range and the river flow determine to a large degree the type of salinity distribution and this in turn determines the dominant mechanism influencing the circulation (Ketchum, 1983). From a geomorphological stand point, there are four sub divisions of estuaries: (1) Drowned river valleys (coastal plain estuaries) (2) Fjord type estuaries (3) Bar built estuaries and (4) Estuaries developed by tectonic process.

In these types the action of gravity upon the density difference between sea water and freshwater tends to cause vertical salinity stratification and a characteristic convective flow that has come to be known as "estuarine circulation" or gravitational convection. Geomorphology, freshwater flow and tide are the dominant variables determining the distribution of salinity and circulation within the estuary.

1.1.3 Classification by stratification and circulation

The mixing process in an estuary arise from the combined effects of currents and turbulent diffusion. The circulation in an estuary is largely determined by the interaction of river discharge, the tidal currents and the geometrical configuration of the estuary. The quantitative estimation of the current and salinity distribution are very essential for the present study because they are related to parameters of the estuary and in particular to stratification and circulation.

Estuaries have been classified according to their salinity stratification. The terms commonly applied are salt wedge or highly stratified, partially mixed or moderately stratified and well mixed or vertically homogeneous to express the relative stratification (Stommel and Farmer, 1953; Cameron and Pritchard, 1963).

1.1.3.1 Salt wedge estuary

Salt extends as a wedge into the river and because of the small amount of friction between the freshwater layer above and salt water layer below, the interface slopes slightly down in the upstream direction. The steep density gradient at the interface reduces the turbulence mixing to a very low level.

1.1.3.2 Partially mixed estuaries

Partially mixed estuaries are divided into two types a) two layer flow with entrainment b) Two layer flow with vertical mixing.

a) Two layer flow with entrainment.

The velocity of the seaward flowing upper layer exceeds a certain value, internal waves will produce at the interface and will break at crests resulting in an entrainment of salt water into the upper layer. It is a one way process. The salinity of upper layer increases and its volume also increases as it moves towards the sea resulting in an increase of velocity in the upper layer. There is a slow movement of water towards upstream in the lower layer to compensate the loss by entrainment.

b) Two layer flow with vertical mixing.

In shallow estuaries tidal currents of increasing amplitude, extend through the depth, mixing freshwater downwards and saline water upwards. But there is a surface of no motion, separating seaward upper layer and landward lower layer. Salinity profile shows a continuous increase from surface to bottom, with maximum gradient at the interface.

1.1.3.3 Well mixed or vertically homogeneous estuary.

In this type of estuary tidal currents are very strong and there is no variation in salinity from surface to bottom, but there is a horizontal gradient in salinity. This type of estuaries can be divided into two. a) with lateral variation b) laterally homogeneous.

a) With lateral variation

If width-depth ratio is high coriolis force comes into action and a lower saline water on right side while looking towards the sea and seaward flow on right side of the estuary.

b) Laterally homogeneous

If width-depth ratio is small no appropriate variation in properties across the channel is observed. No lateral or vertical variation occur, and the net flow is uniform across the channel.

1.2 Factors affecting the estuarine system

The main physical factors affecting the estuarine system are tides, salinity, currents, temperature and suspended sediments.

1.2.1 Tides

The tide is the name given to the alternating rise and fall of the sea level with a period of about 12 and a half hours which is the semidiurnal tide and about 25 hours is the diurnal tide. The rise and fall is the most obvious feature to most observers but fundamentally the prime phenomena are horizontal tidal motion; the rise and fall at the coast is simply a consequence of the convergence and divergence occurring there when the tidal currents flow towards or away from the shore.

The highest water of the tide is called the high water and the lowest water is the low water, the rise of the water is designated as flood, the fall as ebb. The difference in height between low water and high water is called the range of the tide. As the successive high waters are as different as the successive low waters , one can distinguish a rise of the water during the flood and fall of the water during the ebb. The arithmetic mean of both is the mean range of the tide. The average interval between two successive high waters or between two successive low waters is 12hrs and 25minutes.

1.2.2 Salinity

Salinity changes and distribution in an estuary is largely affected by the intrusion of sea water and freshwater inflow, in addition to the agricultural and industrial discharges. Most of the physical, chemical and biological processes in the estuary are affected by the intrusion of saline water. Salinity is the most important parameter for stratification and circulation of the estuarine system.

1.2.3 Temperature

The distribution of temperature in an estuary is usually of secondary importance as compared to salinity. It has less important effect on density of water.

1.2.4 Currents

Current measurements are important in estuaries for navigation, for planning the disposal of industrial and domestic wastes, forecasting floods and siltation, for the design and construction of piles and other sub structures, for recreational use of water, and for the development of fisheries.

1.2.5 Suspended sediment

Rivers carry suspended sediment materials in their upper and middle courses, and the source of these materials may be land, sea or the estuary itself. One theory supported by a number of geologists is that the sediments found in the estuaries is from inland.

Fine grained material will move in suspension and will follow the residual water flow, though there may be deposition and re-erosion round about slack water. Suspended sediment in rivers play a vital role in transporting materials from land to sea. Suspended matter brought by the freshwater, after coming in contact with sea water, flocculates and gets deposited. The study about the distribution of suspended sediments can be used for tracing tidal currents and circulation. It also gives information on dispersion of pollutants.

1.3 Study of physical aspects in estuaries

The theoretical description of estuarine circulation and mixing is confined in the three equations of motion plus the continuity equations for mass and salt. Various simplifications and reductions in the defining terms of the equations have to be made to obtain solutions. One such simplification that is often used to reduce the turbulent stress and flux terms to the product of the spatial gradient of velocity or salinity and a coefficient of viscosity (N) or a coefficient of diffusion (K). Conceptually one can object to such simplifications but within limits they have proven useful.

In addition to the internal or turbulent stress terms in the equations of motion there are a number of other possible stress terms. The coastal tides, considered as a driving force at the mouth of the estuary, are important. The tidal motion and resultant tidal mixing are often observable and obvious in estuaries. The wind stress at the ocean surface can also produce observable effects as measured over time sequences longer than a single tidal cycle. Correspondingly there is the bottom frictional stress. When effects within the bottom boundary layer are not of direct interest, this stress can often be approximated as the product of a bottom frictional coefficient and the square of the near-bottom current velocity. The density difference between the freshwater near the estuary head and the more saline brackish water at the estuary mouth is an important longitudinal stress term. This stress is related to the difference in elevation of the water surface from near the estuary head to its mouth and provide the driving forces for the density gradient circulation commonly observed in estuaries. For estuaries which have a substantial lateral extend the coriolis force can also be contributive. In addition there are the inertial terms in the equations of motion related to spatial acceleration changes in the flow dynamics. At places where there are gross changes in the flow geometry, such as at bends or constrictions in an estuary, these terms are of first importance.

For the salt continuity equation there are in addition to the diffusion terms the simple advection, or mass transfer, terms. Appropriate source and sink terms must also be included in the equations of continuity for other observable quantities, as well as the reaction, or decay, terms if the quantity is non-conservative.

1.4 Studies conducted in different estuarine systems.

The form and extent is being constantly altered by erosion and deposition of sediment and drastic effects are caused by a small raising or lowering of sea level (Dyer, 1979). Ketchum (1951) has defined the inner end of the estuary as the cross section above which the volume of water involved in raising the level of water from the low tide to the high tide mark is equal to the volume contributed by the river during one half of a tidal cycle. There is no net exchange of water across this boundary during the flood tide; during the ebb tide there will be a seaward loss of river flow per tidal cycle. This is a dynamic boundary and not a geographical one. It implies that the inner boundary of the estuary moves up and down the stream as the river flow varies. Following maximum flood currents there is a slow deceleration until high water slack which is followed by long period of slow currents and these currents are greatly influenced by both shallow water overtides and density driven currents which opposed the near bed ebb directed tidal flow immediately following high water (Uncles *et. al*, 1991).

The equilibrium condition in estuaries is controlled by four independent factors; the tidal prism, duration of the flood and ebb phases of the tide, the freshwater discharge and sediment transport through the entrance (Gao and Collins, 1994).

In an inlet system which has reached it's equilibrium, it is not the current speed at the entrance which determines the intensity of sediment transport through the entrance but the intensity of sediment supply which controls the current speed, and it is more appropriate to consider current speed as a dependent rather than an independent variable (Gao and Collins, 1994).

Correlations between daily averaged suspended sediment concentrations and river runoff and tidal range during the separate deployments often showed a significant dependence of suspended sediment on these variables (Uncles *et. al*, 1994).

The vertical structure of the water column and the spacial distribution and semidiurnal variability of bacteria were investigated by Painchaud *et. al* (1995). The variation with time of size spectrum of inorganic marine particle samples stored according to three different methods are detailed by Fontolan and Grenni (1995). The study conducted by Leonard *et. al* (1995) identifies the important processes controlling suspended solid transport in the broad expanses of *Funcus roemerianus*. The mechanism that resuspended bottom sediments in old Tampa bay, a shallow, microtidal, subtropical estuary in west central Florida were determined by Schoellhamer (1995).

1.4.1 Studies conducted in Indian estuaries

Krishnamurthy (1961) and Ramamurthy *et. al* (1965) have made studies on the physical and biological aspects of the Vellar estuary. Ramamritham and Jayaraman (1963), George and Kartha (1963), Qasim and Reddy (1967), Qasim *et. al* (1969), Wellershaus (1974) have studied various aspects of the hydrography of the Cochin estuary. Gopinathan and Qasim (1971), Kurup (1971), Cherian (1973), Raju *et. al* (1979) have studied the suspended sediment distribution in the Cochin estuary. Das *et. al* (1972) have studied suspended sediment distribution, circulation pattern and other aspects of the Mandovi and Zuari estuarine systems. Varma *et. al* (1975) studied the variations in temperature, salinity, suspended matter and currents at mouth, middle and upstream regions of

Mandovi estuary in relation to tides at three seasons viz. premonsoon, monsoon and postmonsoon. Seasonal changes in hydrographic conditions of estuarine and coastal waters of the Old Mangalore Port were studied by Reddy *et. al* (1979). The current distribution in the Cochin estuarine system was described by Varma *et. al* (1981). Studies on the *meiofauna* of Netravathi-Gurpur (Mangalore) west coast of India, were done by Venkataswamy Reddy and Hariharan (1985). The freshwater fraction at different location and the salt water intrusion in the Cochin estuarine system was studied by Sankaranarayanan *et. al* (1986). The dynamics of circulation and salt balance in the upper reaches of the Periyar estuarine system was studied by Udayavarma *et. al* (1987). In the Azhikode estuary salt and water budget during the postmonsoon period was studied by Revichandran *et. al* (1987). Computation of longitudinal coefficient of eddy diffusivity and flushing time in the Pavenje river estuary was studied by Devaraju *et. al* (1987). Shoreline stability at Mandovi estuary, Goa was studied by Nayak and Chandramohan (1989). Stratification and salinity distribution in the Cochin estuary was reported by Jomon and Kurup (1990). The dynamics and suspended sediment transport in the Azhikode estuary was studied by Revichandran (1993).

1.4.2 Earlier studies in the Beypore estuary.

Many authors have studied different aspects of the Beypore estuary. The nutrient distribution studies in the estuary was reported by Sarala Devi *et. al* (1983). The exchange of fresh and salt water in the estuary was studied by James and Ramamritham (1983) and on the circulation and mixing by James and Sreedharan (1983). Premchand *et. al* (1987) have studied the hydrography of the Beypore estuary. Relation between dissolved oxygen and salinity and the distribution of salinity was reported by Giridhar Hadnoorker *et. al* (1987). Vertical suspended sediment distribution in the Beypore estuary was studied by Nair *et. al* (1987). The effect of salinity variation on the *flora* and *fauna* was investigated by Nirmala *et. al* (1990). Studies on the nutrient chemistry of Chaliyar river estuary were carried out by Jose (1993).

The above studies are only confined to the estuarine mouth region. There has been no work covering the entire year and also utilising measurements during different phases of the tide. Therefore an attempt has been made in the present study to understand various physical parameters with reference to tidal changes in a systematic manner and also during different months of the year.

1.5 Literature Review

Keulegan (1947) described a series of model experiments for salt wedge estuaries. Two layer flow with entrainment is generally found in fjords and Tulley (1949) has studied the Alberni inlet in British Columbia. Ketchum (1950) has reported his studies based on flushing of tidal estuaries to avoid stream pollution. The earliest attempt to estimate the magnitude of tidal flushing effects was by the tidal prism method. This method was modified by Ketchum (1951) who applied the modified method to Raritan river bay. Ketchum also showed how allowance could be made for complete mixing based on his studies in Alberni inlet, British Columbia and Grand pond, Falmouth. Arons and Stommel (1951) extended Ketchums idea to a mixing length theory.

Ketchum (1950) Pritchard (1952) and Williams (1960) have described the instruments used for determining salinity in-situ by electrical conductivity methods. Two layer flow with vertical mixing has been investigated by Pritchard (1952, 1954) in the James river. Stommel and Farmer (1953) derived the equation for computing the depth of the upper layer at the transitional section for a given discharge and density difference. Farmer and Morgan (1953) theoretically analysed the salt wedge flow based on the equation of motion and continuity. An approach for estimating streamflow into a tidal estuary was presented by Todd (1956). Pickard and Trites (1957) used data on the flow of heat to determine the rate of flow in the upper layer of the estuary.

A theoretical and experimental study of turbulent entrainment was carried out by Ellison and Turner (1959). Taylor's (1954) theoretical treatment of the dispersion of matter in turbulent flow through a pipe was extended by Elder (1959) in open channel and this theory was later applied to tidal estuaries. Simmons (1960) has described the principles on which Scales model are designed and the application of Scaling law and its limitations. Harleman and Ippen's (1960) laboratory studies showed that the intensity of turbulence varied independently of the flow. Dorrestein (1960) has devised a mathematical model for the longitudinal spreading of dissolved or suspended matter along an estuary in a steady state. The classical studies of Postma (1961) on suspended sediment transport in the Dutch Wadden Sea have demonstrated that tides play an important role in sediment transport and trapping in estuaries, which is beyond the effects of variations in river flow and the density driven estuarine circulation. Pickard and Rodgers (1959) and Rattray and Hansen (1962) have reported about the wind effects on circulation. A detailed review of the theories of diffusion and their comparison with observed data has been presented by Okubo(1962). Trites and McGregor (1962) used electromagnetic method for determining the tidal flow.

The analytical model of estuarine circulation developed and described by Rattray and Hansen (1962) and the circulation and mixing processes were considered to be as parts of the same system in a theoretical treatment carried out by them. Cameron and Pritchard (1963) reported the three layered circulation pattern observed in tributary estuaries having very little freshwater inflow. The relative merits of some of the methods for determining pollutant distributions in estuaries have been discussed by Pyatt (1964). Scales model has also been used to study the circulation and mixing phenomena by Pritchard (1954), Inglis and Allen (1957) and Rattray and Lincoln (1965). Bowden *et. al* (1966) has devised a method to compute the distribution and concentration of effluent discharged at a given point in an estuary. Hansen and Rattray (1965, 1966) and Hansen (1967) have developed probably the first model to clearly demonstrate the classical two layered estuarine flow. An analytical model for three layered flow was developed by Hansen and Rattray (1972).

Ranganna (1975) has attempted to estimate freshwater flow into a tidal estuary from salinity data. Hamilton (1975) modelled the real time variation in an estuary of varying width. The analytical model for estuarine circulation was described in a simplified form by Officer (1976). The hydrodynamic effects that occur in estuaries are described in the review articles by Pritchard (1952), Bowden (1962, 1967) and Cameron and Pritchard (1963), the classification system developed by Hansen & Rattray (1966) and the texts by Dyer (1973) and Officer (1976). Barthurst *et. al* (1977) and Dyer (1977) made investigations on the topographic effects in estuaries. Kjerfve (1975), Farmer and Osborne (1976) and Smith (1977) have studied the effects of wind on the physical processes of estuaries like circulation and mixing. Several authors have pointed out that the residual circulation of fine grained sediments in an estuary may not be assumed to be the same as the residual circulation of water (Gibbs, 1977; Kirby and Parker, 1977). Modelling on the steady state gravitational structure in an estuary of uniform geometry was done by Festa and Hansen (1978). Boon (1978) has shown the difficulty in assessing net sediment transport in environments where the net transport is small compared with the flood and ebb transports.

Zimmerman (1978) discussed the topographic generation of residual circulation. Several concepts have been developed about tidal accumulation mechanisms within estuaries, mainly based on ebb and flood current asymmetry (Allen *et. al*, 1980). The movement of the turbidity maximum zone with the river discharge was studied by Richardson and Zaki (1954), Krank (1973, 1981), Allen *et. al* (1976, 1980) and Festa and Hansen (1978). The residual currents and Stokes drift in the Severn estuary were studied by Tee (1976), Ianniello (1977, 1981) and Uncles and Jordan (1979, 1980). Mathematical modelling on salt intrusion in various estuaries has been developed by Harleman *et. al* (1966), Thatcher and Harleman (1972, 1981) and Perrels (1981). The vertical variation of the estuarine currents were studied by Bowden and Sheraf El Din (1966), Dyer (1974), Murray and Siripong (1978), Hughes and Rattray (1980) and Hunkins (1981).

A review of the present knowledge on physical dynamics of the estuarine sediments has been documented by Officer (1981). A review of the works on circulation, mixing and dispersion of pollutants has been presented by James (1982). The suspended sediment concentration field may vary on semi-diurnal, fortnightly and seasonal time scales, and all the three time scales should ideally be included in any consideration of sediment dynamics in estuaries (Gelfenbaum, 1983).

Many studies have investigated the sediment transport through salt and tidal marsh ecosystems (Valiela *et. al*, 1978; Nixon, 1980; Chrzanowski *et. al*, 1982; Heinle and Flemer, 1976; Jordan *et. al*, 1983). Studies pertaining to the suspended sediment balance in the estuary have been carried out by Flemming (1970), Dyer (1978) and Yarbo *et. al* (1983). Salt and sediment transport by the transverse and vertical shear have been discussed by Allen *et. al* (1980), Lewis & Lewis (1983). Postma (1967), Manheine *et. al* (1972), Peterson (1975), Bulle *et. al* (1975), Casting and Allen (1981), Avoine *et. al* (1981), Meade (1982), Kirkby *et. al* (1983), Gelfenbaun (1983), Bartholdy (1984) have studied the distribution pattern of suspended sediment in various estuarine systems. Studies of meso and macro tidal estuaries have shown that when there are large fluctuations in the semidiurnal tidal range and freshwater discharge the suspended sediment concentration field can vary and some times be dominated by the spring - neap tidal cycle (Allen *et. al*, 1980; Casting and Allen, 1981; Avoine *et. al*, 1981; Gelfenbaum, 1983; Millman *et. al*, 1984). Tidal freshwater marshes support a high standing biomass and high rates of primary productivity (Simpson *et. al*, 1983; Odum *et. al*, 1984), so they are important in the sediment budgets of estuaries.

Using one dimensional hydrodynamic and sediment balance model Larsonneur *et. al* (1982), Uncles *et. al* (1985a,b,c) and Bale *et. al* (1985) studied the seasonal pattern of sediment movement in a macro tidal estuary which reveal that suspended sediment dynamics is controlled mainly by tidal processes. Two basic mechanisms involved in sediment dynamics are current velocity fluctuations and tidal wave deformation (Allen *et. al*, 1980; Nichols and Biggs, 1985). The dispersion or accumulation of suspended sediment may vary widely in relation to the stage of infilling and river discharge. The extent and position of the turbidity maxima vary according to different time scales associated with neap-spring semidiurnal tidal cycles and seasonal variations in river inflow (Avoine and Larsonneur, 1987).

Tidal processes and their modifications by freshwater runoff and the effects of intratidal variations in water column stability are described by Hamblin (1989), Sheng and Villaret (1989). A number of papers have been published by several authors on estuarine turbidity maxima phenomena (Festa and Hansen (1978), Allen *et. al* (1980), Officer and Nichols (1980), Officer (1981), Uncles *et. al* (1985a,b,c) Dronkers (1986), Grabemann and Krause (1989), Hamblin (1989), Uncles and Stephens (1989). The relation between the concentration of suspended sediment and the depth averaged values of the tidal currents were studied by West and Sangodoyin (1991). Renshun (1992) has described the transport processes of the suspended sediments through the tidal mudflats. The distribution of the suspended sediment in a partially mixed estuarine system has been described by Althausen and Kjerfve (1992). The axial distribution of salinity and it's variation with the river discharge was described by Garvine *et. al* (1992). Studies pertaining to the nature of the turbidity maximum was carried out by Uncles and Stephens (1993).

1.6 Description of the study area

Chaliyar river, the third largest river in Kerala, flows towards west from Western Ghats and joins the Arabian sea at Beypore. It originates at the Ilambaliri hills in Gudalur taluk of Nilgiri district in Tamil nadu at an elevation of 2066m above the mean sea level. The estuary is situated at 11°05'N latitude and 75°50'E longitude (Fig.1.1). The Chaliyar river is 169kms long with a total drainage area of 2923km^3 out of which 2535km^2 lie in Kerala state and remaining 388km^2 in Tamil Nadu.

The Beypore estuary of the Chaliyar river enters the sea in a south westerly direction and the inlet is situated in a stable region. There is a horse-shoe shaped bar at the entrance and the depths over it varies from 1.5m to 1.9m. The sea bed at Beypore is comparatively flat with 9m contour at a distance of 3.5km from the river mouth (based on the survey conducted by the Port authorities in 1967). The tides at Beypore are of semi-diurnal type with a period of 12hr and 40 minutes and marked salinity intrusion was noticed beyond

15kms upstream. The maximum tidal range obtained during spring tide in the entire period of study was 1.2m and during neap tide it was 0.80m. In spring tide there is a time lag of 1hr for high water between the mouth and upper most section of the estuary. The maximum monsoonal flow occur in June-July where the tidal limit comes down to 5km upstream.

The present study area is from the mouth of the river to 15 km upstream. No detailed study on the dynamics and hydrography of the estuary has been reported so far. For a complete understanding of various physical processes occurring in the estuary, synoptic measurements of current, tidal changes, salinity, temperature distribution and suspended sediment concentration over a tidal cycle is a prerequisite. Therefore the above data has been collected monthly and synoptically for a period of one year. The mixing of freshwater with sea water was quantified for studying the mixing process of the estuary which in turn gives the rate of dilution of pollutants in the estuary. The ecology of tidal stream was determined by the process of exchange of freshwater and salt water.

1.7 Scope of the work

Earlier studies have been conducted to understand the circulation, mixing and salinity distribution in the Beypore estuary. But these studies were confined to the river mouth region only. No attempt has been made so far to conduct an exhaustive survey for studying the region beyond the tidal influence and also a synoptic data collection. An accurate information on the dynamics of the Beypore estuary - velocity and density fields, tidal variations, river discharges and suspended sediment distribution etc were not reported so far.

The main objectives of the present study are 1) to understand the diurnal and seasonal variations in the flow characteristics, ii) the residual fluxes of salt and water iii) flushing characteristics iv) the flux of materials and the transportation of suspended sediments in the Beypore estuarine system.

Due to the river discharge and tidal currents the estuarine system is not a stable one. A detailed study on the dynamics and flushing characteristics was undertaken to understand the fate of any pollutant discharged in the river and estuarine system.

The distribution of suspended matter near the tidal inlets is influenced by the tides and transportation of suspended sediments affected by the circulation and tidal currents. Taking into consideration the importance of suspended sediment distribution a detailed study on the concentration of suspended sediment was also done.

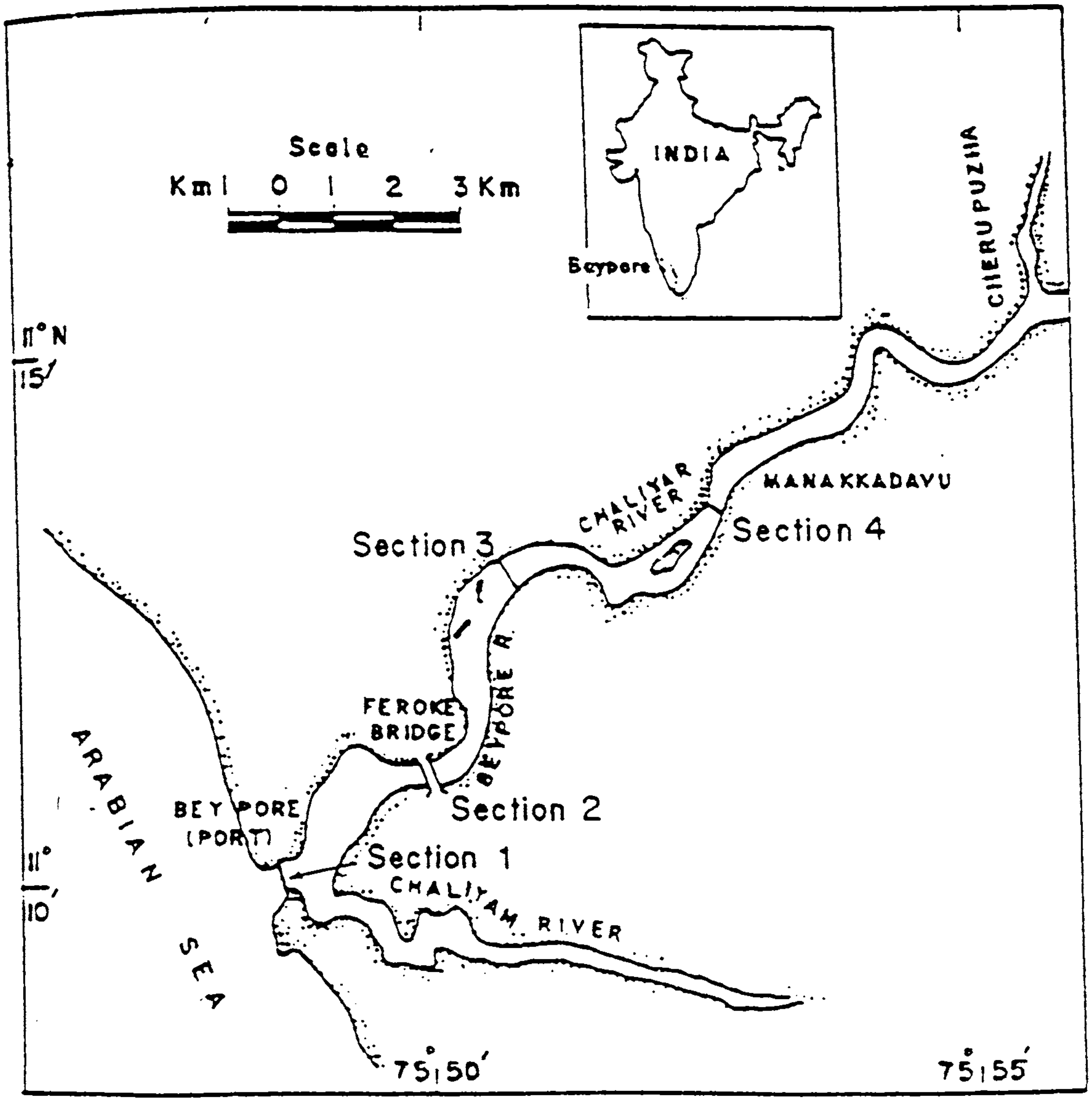


Fig. 1.1. Observation sections in Beypore estuary

CHAPTER II

MATERIALS AND METHODS

Estuaries experience considerable variations diurnaly as well as seasonally in material concentrations, water level and flow characteristics. Before making any estuarine hydrographical study it is wise to choose a suitable sampling design. Therefore care has been taken to choose the sampling locations so as to cover the representative portions of the estuarine system. Sampling positions during these observations were selected with the assumption that the locations for this study are reasonably the representative portions of the estuarine system.

The quantitative measurements help to make a systematic and qualitative study of the dynamics of the estuary and on the various physical processes occurring in the estuarine system. Synoptic tidal observation were made from a small boat anchored at the station locations and recordings were made on the spot and the boat was maneuvered accordingly so that the measurements made were very enlightening. The present investigation is mainly conducted for collecting data on temperature, salinity, circulation, mixing, sedimentation and flux of materials in the Beypore estuary.

In the present investigation detailed study of various physical aspects of the Beypore estuary has been carried out. For this purpose the estuary has been divided into four sections upto 15km upstream with two transverse stations on each section. A map showing the area of study and the sampling locations are given in Fig. 1.1. First section is at the river mouth and the distance between the consecutive sections is 5km. There are two stations along each section located one in middle of the shallow area and other in middle of the deep area. The four cross sections at the observation points are shown in Fig. 2.1.

Section-I: 'Located at the river mouth of the estuary. The mean depth of section-I varies from 2.45m to 2.95m in the entire observation period and the width of the section is about 390m.

Section-II: About 5km away from the mouth of the estuary. The mean depth is found to vary between 2.99m and 3.50m and the width is 294m.

Section-III: The narrowest section among the four sections located 10km upstream of the river mouth. The average depth of the section varies from 4m to 4.54m and having a width of 200m.

Section-IV: The upstream part of the study area and is at a distance of 15km upstream from the mouth of the estuary. The mean depth of the section varies from 2.52m to 3.06m. The width of the section is found to be 243m.

2.1. Procedure of the synoptic field observation.

Monthly physical data were collected from the four sections covering eight stations for a period of one year starting from October 1990 to September 1991. Synoptic observations of salinity, current and suspended sediment were made at each station of the four cross sections. Since the tide in this region is of semi diurnal type the observations were extended to 13 hrs to cover one complete tidal cycle. Hourly observations of salinity and current measurements were taken at each station from surface to bottom at 1m depth interval. Hourly concentration of suspended load were measured at the surface, mid depth and bottom.

2.1.1. Current measurements

Current speed and direction measurements were made using the indigenous rotor current meter (accuracy of the instrument for velocity ± 1 cm/s and direction ± 2.68°, designed by NIO, Goa, India).

2.1.2. Temperature and salinity

The STD meter designed by Environmental System Engineers, Cochin was mainly used for temperature and salinity measurements. Salinity was computed from the conductivity obtained in the platinum conducting cell of the unit. Using a thermistor, temperature is measured. There is a depth sensor unit in the instrument which consists of stainless steel bellow whose compression due to hydrostatic pressure is converted into electric induction. Accuracy of the instrument for salinity, temperature and depth are $\pm 0.1 \times 10^{-3}$, ± 0.1 °C and ± 0.1 m respectively.

2.1.3. Suspended sediment concentrations

Water samples were collected for suspended sediment concentration at hourly intervals from the surface, mid depth and near bottom of the water column. Surface samples were collected using a clean plastic bucket and Niskin sampler was used for the collection of mid and near bottom samples. Sampling was done with the tide at the least possible time to minimise errors. The water samples were filtered through a pre-weighed millipore filter paper of 0.45 micro-meter pore size and a diameter of 47 mm. Filtering was carried out at 25cm Hg vacuum and the volume of the sample filtered varied from 500-1000 ml. After filtration the filters were rinsed with distilled water thrice and dried at 70°C. The initial and final weights were taken upto 2 decimals of a milligram. The difference between final and initial weights gives the concentration of the suspended sediment(mg/l). The filtered samples were used for grain size determination. Percentage of sand, silt and clay portions was determined by sieving through a net of 64 u mesh size and pipette analysis as described by Krumbein and Pettijohn (1938).

2.1.4. Area of cross sections

Sounding across each cross section was taken using an echo sounder. The depth was taken in every 10sec along the cross sections and from which the area of cross section was worked out. The width of each section was measured using a theodolite.

2.1.5 Tide Measurements

Tidal measurements at the mouth of the estuary was obtained from the Minor Port Authorities, Beypore, Calicut.

2.1.6 River discharge

The river discharge data obtained from the Central Water Commission, Hyderabad were used for computing longitudinal coefficient of eddy diffusivity and flushing time.

2.2 Processing the hydrographic data

Only at finite points between the surface and bottom the hydrographic parameters were measured. By interpolating the shape of each vertical profile and then reading the data values at regularly spaced intervals the data analysis can be standardised. The numerical interpolation of the data profile was adopted with most data sets, as they can be analysed quickly on a computer without introducing operational errors.

It is convenient to measure (interpolate) data at fixed fractions of the instantaneous non-dimensional depths, y (y=0 and 1 at the surface and bed respectively). The standard fractional depths were taken to be y = 0.1 (0.2) 0.9. Cubic splines were used for interpolating data for velocity and salinity. The program fit 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 eleven equally spaced non-dimensional depths beginning at the surface and ending at the bottom. Non-dimensional depth is defined by (d(t) - Z)/dt, Z is the distance above the bottom, dt - total water depth at a given station at time t. The standardised instantaneous data profile thus obtained were averaged for computations. For each parameter it is convenient to compute net or time average values for the non-dimensional depths (eleven depths at 0.1 interval including surface and bottom) rather than for fixed distance below the surface or above the bottom.

Extrapolation of data was sometimes necessary to estimate nearbed or nearsurface values. Nearbed values for velocity were estimated by fitting a logarithmic boundary level to the data. Nearsurface values were estimated by assuming a local parabolic profile for velocity. The same technique was used for extrapolating the data for salinity, both for estimating nearsurface and nearbed values.

These methods have the advantage of not amplifying errors or inherent variability in the measured data. When extrapolated values were required for the nearsurface or bed then these were assumed to be equal to those values which were measured closest to the surface or bed. The tidal averages were formed by integrating observed data or derived data at each fraction of the depth over a tidal period of 12.5 hours. The depth averaged values were obtained by integrating the derived data at each hour over the eleven non-dimensional depths. For time averaging of velocity it is sufficient to consider the flow to be parallel to the banks. The flood flow is considered as negative and the ebb flow as positive.

2.3 Estimation of suspended sediment fluxes.

Suspended sediment fluxes were calculated from velocity and sediment concentration as given by Stern et al (1986) with some modifications. Instead of single point observation at the centre by Stern et.al. (1986; 1991), here the sampling was done at two stations in a cross section and at three depths (surface, mid depth and bottom) at each station.

The cross sectional and depth averaged value of the horizontal component of the velocity vector at each section during every sampling hour in the semi-diurnal observation was computed. It has been multiplied by the respective cross sectional and depth averaged value of the suspended sediment concentration for the water column to get the instantaneous flux. The net fluxes were calculated by dividing the algebraic sum of the instantaneous fluxes over a tidal cycle by the number of observations in the tidal cycle. Net fluxes for all the four cross sections were calculated (using a fortran computer program) and presented as flux per cm^2 for a cross sectional area per second.

Material transport through a particular cross section was obtained by multiplying the average of the net fluxes by the mean cross sectional area. Changing Cross sectional area due to changing water level was also taken into account in the calculations. The positive sign indicated transport towards the sea and the negative sign indicated transport towards the river.

The present study aimed at an investigation on the tidal, seasonal and spatial variations of the hydrographic parameters, circulation and mixing of the lower reaches of Chaliyar river. Based on the relative residual salinity structure the circulation pattern is classified. From the observed salinity and velocity values stratification and circulation parameters were worked out. Based on the stratification and circulation, the estuary is classified. By comparing the suspended solids and salt concentrations at the upper reaches where the salinity is low and at the river mouth where salinity is high it is easy to study the mechanism of transport through the estuarine system and its influence on the suspended load concentrations. This will enable to understand the riverine influence on material transport through the estuary and the influence of the estuarine system on water passing through it. The transport can be computed hourly from the velocity, water level and concentration value.

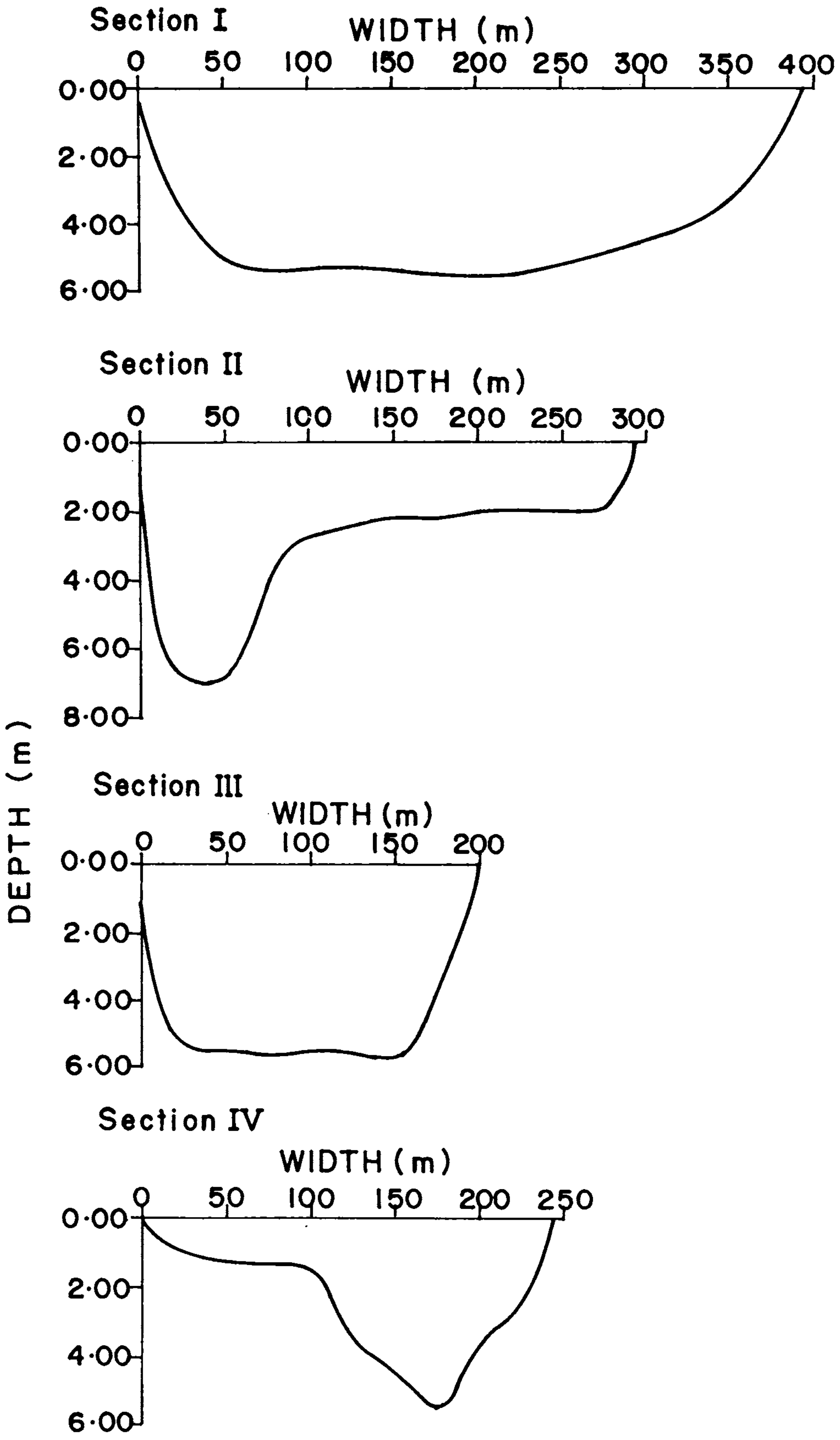


Fig. 2.1. Cross sections at the observation points in the Beypore estuary.

CHAPTER III

GENERAL HYDROGRAPHY

3.1 Temperature distribution

Longitudinal distribution of the cross sectional average values of temperature from October 1990 to September 1991 are shown in Fig. 3.1. In October the temperature was found to be increasing from 30°C to 31.5°C at surface and 29.5°C to 31.3°C at bottom from river mouth to the upper most section of the estuary. Here upto 5km upstream a vertical variation of 0.5°C was obtained and beyond this variation was negligible. During the month of November slightly lower temperature was observed at the upper reaches of the estuary compared to October. It was varying between 29.6°C and 30.8° at surface and 29.6°C to 30.4°C at bottom from section-I to section-IV. No vertical variation was observed in the study area upto 10km from the river mouth and beyond this a slight vertical variation of 0.3°C was noticed during this period of observation. During December the longitudinal variation was from 29°C to 30.8°C at the surface and from 28.8°C to 30.8°C at the bottom from section-I to section-IV. In January temperature varied between 30.8°C and 31°C at the surface and from 30.7°C to 30.8°C at the bottom from lower most section to the upper most section of the estuary. During February the vertical variation was negligible at all the cross sections of the estuary and the temperature was varying from 30.9°C to 32.2°C from river mouth to 15km upstream. Higher values of temperature were obtained during the premonsoon season. During March the isotherms were found to

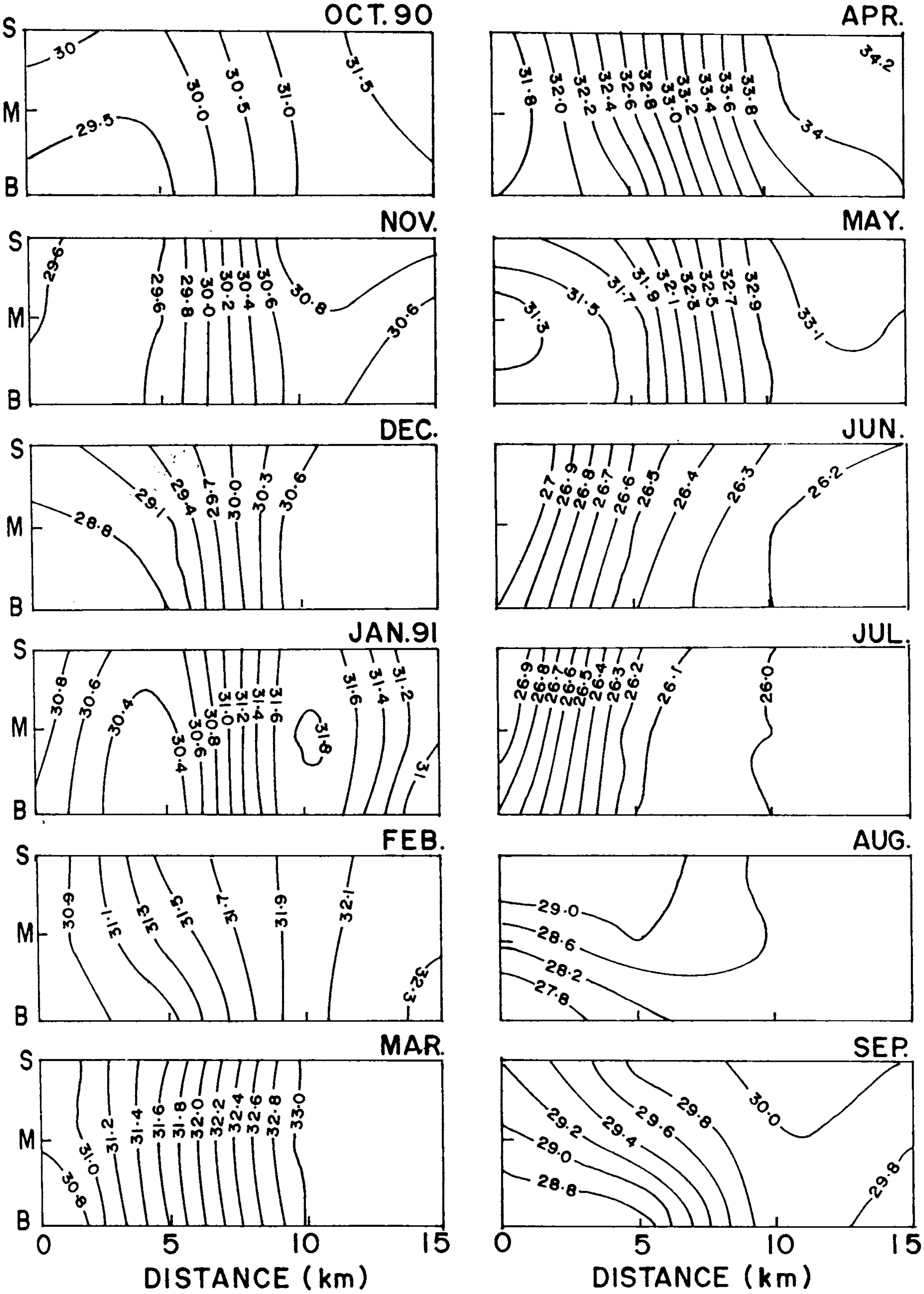


Fig. 3.1. Spatial variations in temperature during each month of observations.

be parallel to each other and the temperature values varied from 30.8°C to 33°C from section-I to section-II. Highest temperature was observed in April. During this period the vertical variation at all the four cross sections were also found to be negligible. At the surface the temperature varied from 31.8°C to 34.2°C and at bottom from 31.8°C to 34°C. During May the vertical variation was more predominant between sections I & II and the isotherms were almost parallel beyond section-II(5km upstream). During the months of June and July higher temperature was observed between the lower sections, I & II. In June the temperature decreased from 27.2°C to 26.2°C at the surface and from 27°C to 26.2°C at the bottom and in July it decreased from 27°C to 26°C at the surface and from 26.8°C to 26°C at the bottom from section-I to section-IV. There was a a general decrease in the surface and bottom temperatures in the months of June and July. This phenomenon was due to the freshwater influence in the upper reaches of the estuary. However at the lower reaches the influence of sea water was evidenced by higher temperatures recorded at the river mouth. Most significant vertical variation in temperature was observed during August. While the temperature of the surface water was 29.4°C, the bottom water registered a lower temperature of 27.4°C. This difference was experienced only upto section-II beyond this the variation was insignificant (28.6°C to 28.2°C). In September the vertical variation was 0.6°C at section-I and 0.2°C at section-IV.

In general higher temperatures were observed at the upstream sections except during June - July. This may be due to the shallow nature of the estuary. The low temperature of water observed in the months of July - September (monsoon season) can be explained due to the precipitation and river runoff.

3.2 Salinity distribution

Of all the characteristics which typify estuaries, perhaps the most distinctive one is salinity. The complete range of salinities from freshwater to sea water is always found where freshwater meets the sea. The classification of the estuary, mixing characteristics and diffusion processes are all highly depended on the salinity distribution pattern. Monthly distribution of salinity at surface, mid-depth and bottom during the flood and ebb tidal phases is presented in Fig. 3.2.a to 3.2.f

October

Stratification was highest at 5km away from the river mouth, the vertical salinity gradient was 25×10^{-3} at the river mouth and 25.6×10^{-3} at section-II during flood tide. Intrusion of seawater extends upto 10 kms upstream. Beyond this the salinity value reduced to zero due to freshwater flow. During this tidal phase at river mouth the surface salinity was greater than 10×10^{-3} and was decreasing longitudinally upto 5×10^{-3} at section-II and reduced to zero after section -III. The predominance of freshwater was beyond 10kms from river mouth. Bottom salinity was high (35 x 10^{-3}) at river mouth and it reduces to 33 x 10^{-3} at section-II and zero beyond 10kms upstream. During ebb tide the surface salinity varied between 5 x 10^{-3} to zero between sections I and III. The bottom salinity values were less than 8 x 10^{-3} at the river mouth and reduced to zero after section-III.

November

The extent of incursion of saline water was same as that in the month of October that is upto 10kms upstream from the river mouth. During flood tide at the mouth of the estuary surface salinity observed was 24 x 10^{-3}, and there is a sudden decrease to 3 x 10^{-3} at section-II and reduced to zero beyond 10km upstream. But at the bottom the salinity values were reducing from 32 x 10^{-3} to 5 x 10^{-3} from section-I to section-III. During ebb tide higher values of salinity obtained at the bottom was 31 x 10^{-3} at river mouth and reduced to zero at 10km upstream and at surface the salinity decreasing from 7 x 10^{-3} to zero from section-I to section-III. The vertical salinity gradient was also found to be increasing during this month. Higher vertical gradient of salinity during flood tide was observed at section-II, about 25 x 10^{-3}. At river mouth it was only 8 x 10^{-3}. During ebb tide the vertical stratification in salinity was increased from 24 x 10^{-3} to 30 x 10^{-3} from section-I to section-II. The estuary was found to be freshwater dominated beyond the

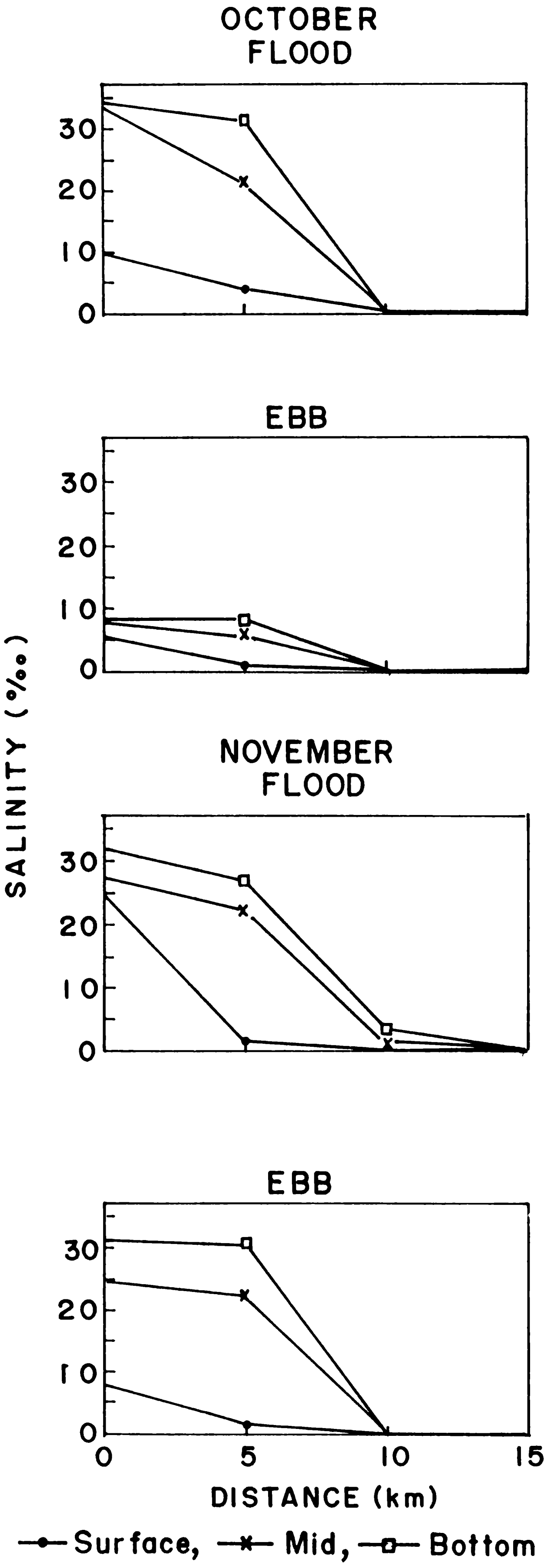


Fig.3.2.a. Longitudinal variation of salinity during flood and ebb tidal phases.

second section.

December

Low river discharge and higher tidal influx was found during December as compared to October and November. Longitudinally the salinity values were found to be reducing from section-I to section-IV. Higher value of surface salinity obtained during flood tide at the mouth of the estuary was greater than 29 x 10^{-3} and it reduced to less than 5 x 10^{-3} at 15kms upstream. The bottom values of salinity were reduced from 34 x 10^{-3} to 11 x 10^{-3} from section-I to section-IV. During ebb tide at lower reaches the surface salinity values were greater than 25 x 10^{-3} and at bottom the salinity was greater than 30 x 10^{-3}. The vertical salinity gradient was small and intrusion of saline water was observed beyond 15kms upstream. The estuary was partially mixed during this month and the stratification was lesser as compared to previous months. The vertical gradient of salinity during flood tide was nearly 5 x 10^{-3} near the river mouth, 15 x 10^{-3} at section-II, 13 x 10^{-3} at section III and 9 x 10^{-3} at section-IV. Almost a similar longitudinal variation in the vertical gradient was observed during ebb tide also.

January

Salinity distribution indicated that the lower reaches of the estuary was well mixed during this month. The stratification was less and the maximum vertical gradient

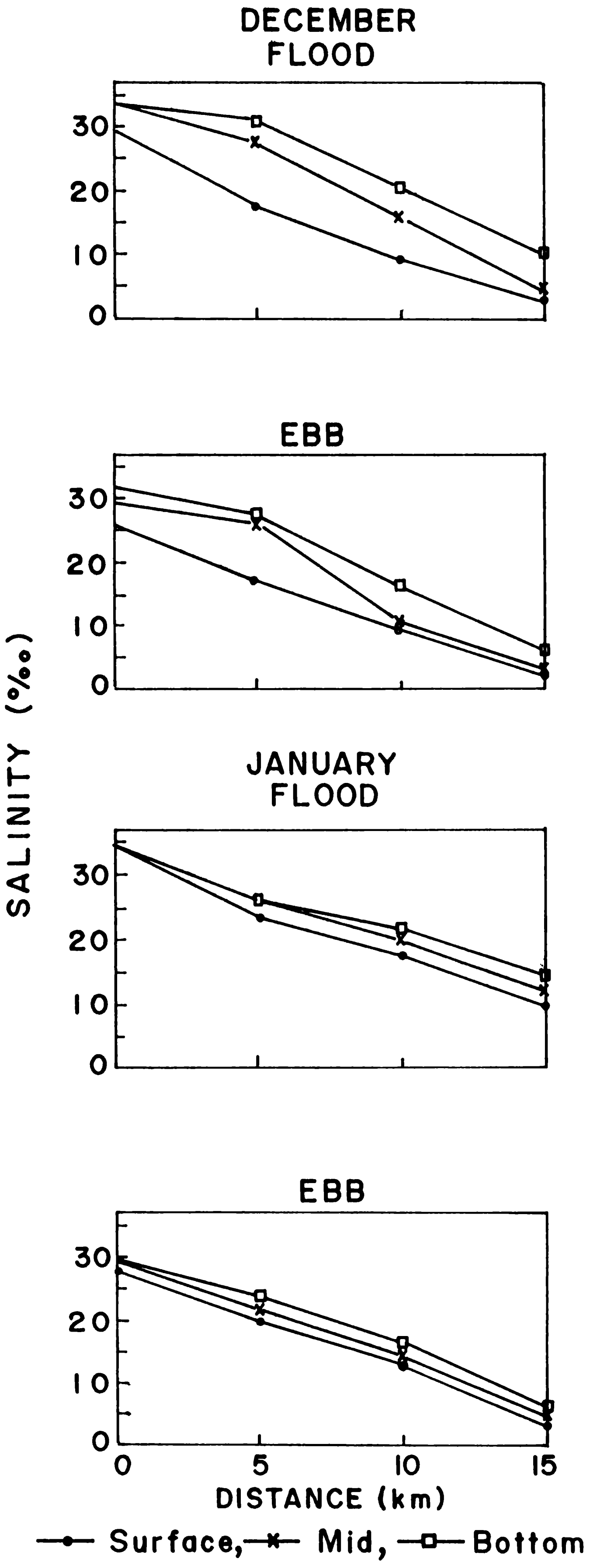


Fig.3.2.b. Longitudinal variation of salinity during flood and ebb tidal phases.

observed was 3 x 10^{-3} between the surface and bottom values through out the estuarine area. During this period of observation low freshwater discharge and high tidal influx was observed comparing with November and December. During flood tide the longitudinal variation of surface salinity was almost linear and reduced from 34 x 10^{-3} to 11 x 10^{-3} from river mouth to the uppermost section and at the bottom salinity value reduced from 35 x 10^{-3} at the river mouth to 16 x 10^{-3} at section-IV. During ebb tide the higher salinity obtained was 30 x 10^{-3} at bottom near the river mouth section which reduces to 8 x 10^{-3} at section-IV. Surface salinity reduces from 27 x 10^{-3} to 5 x 10^{-3} from section-I to section-IV.

February

Higher tidal influence and reduced river discharge resulted in gentle longitudinal salinity gradient during this month. Saline water influx was higher during this month. During flood period the salinity values reduced from 35 x 10^{-3} to 22.5 x 10^{-3} at surface and from 35 x 10^{-3} to 26 x 10^{-3} at bottom from river mouth to section-IV. The difference in salinity values at surface mid-depth and bottom between high tide and low tide was always less than or equal to 5 x 10^{-3} in the lower sections of the study area. In the upper sections the difference in salinity values between the two phases of tide were less than 8 x 10^{-3}. During ebb tide at surface the salinity reduced from 30 x 10^{-3} to 15 x 10^{-3}

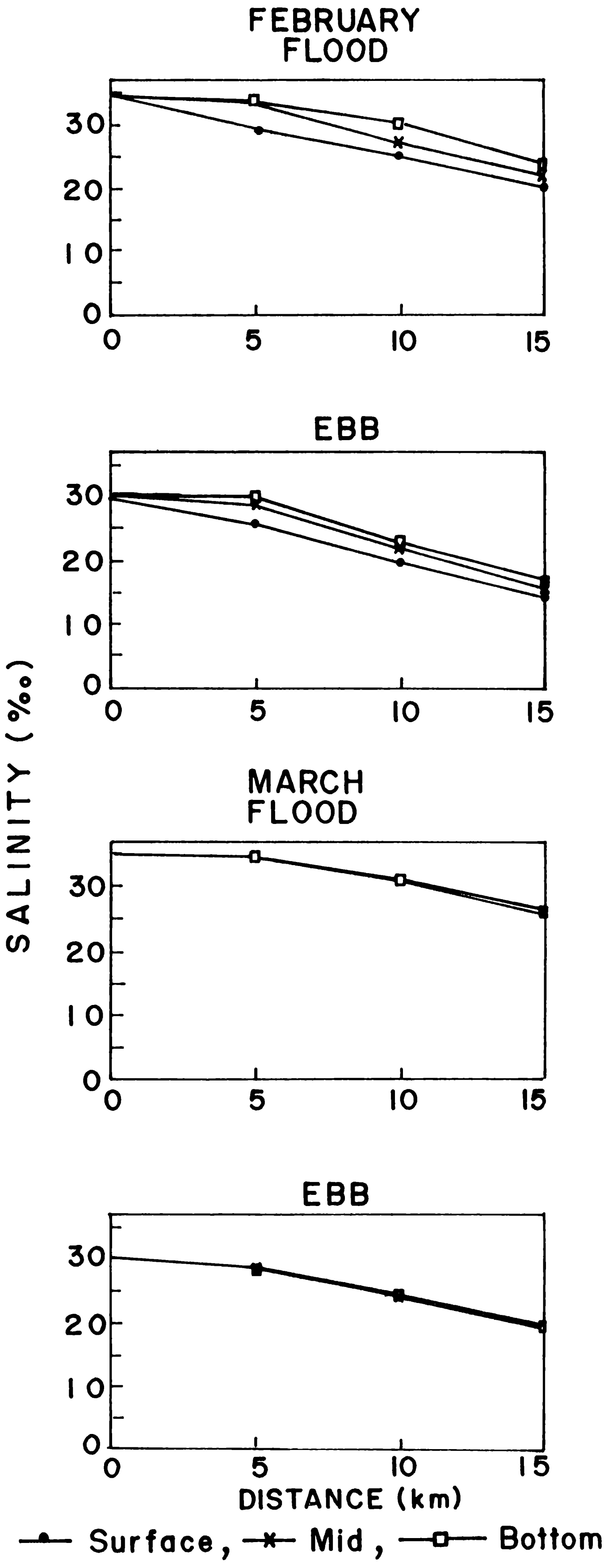


Fig. 3.2.c. Longitudinal variation of salinity during flood and ebb tidal phases.

and at bottom it reduced from 32 x 10^{-3} to 18 x 10^{-3} from section-I to section-IV. In this month the vertical variation from surface to bottom at the four sections was nearly 3 x 10^{-3}.

March

A well mixed estuarine condition was observed due to the predominance of tidal incursion. The distribution and transport process were mainly controlled by the tidal currents. No noticeable change in salinity variation was observed upto section-II. A longitudinal gradient of 10 x 10^{-3} was observed between the river mouth and the uppermost section of the study area during both the phases of tide. The difference in salinity between the two phases of the tide in the entire study area was less than or equal to 5 x 10^{-3}.

During this period a vertically well mixed condition was very much manifested throughout the estuary eventhough longitudinal gradient was observed during both the phases of tide. In brief the estuary was found to be a well mixed one due to the low longitudinal and vertical gradients of salinity.

April

The freshwater inflow into the estuary was very low during this premonsoon month. In the lower reaches of the estuary the salinity values were high. The estuary was vertically homogeneous especially downstream of section-II

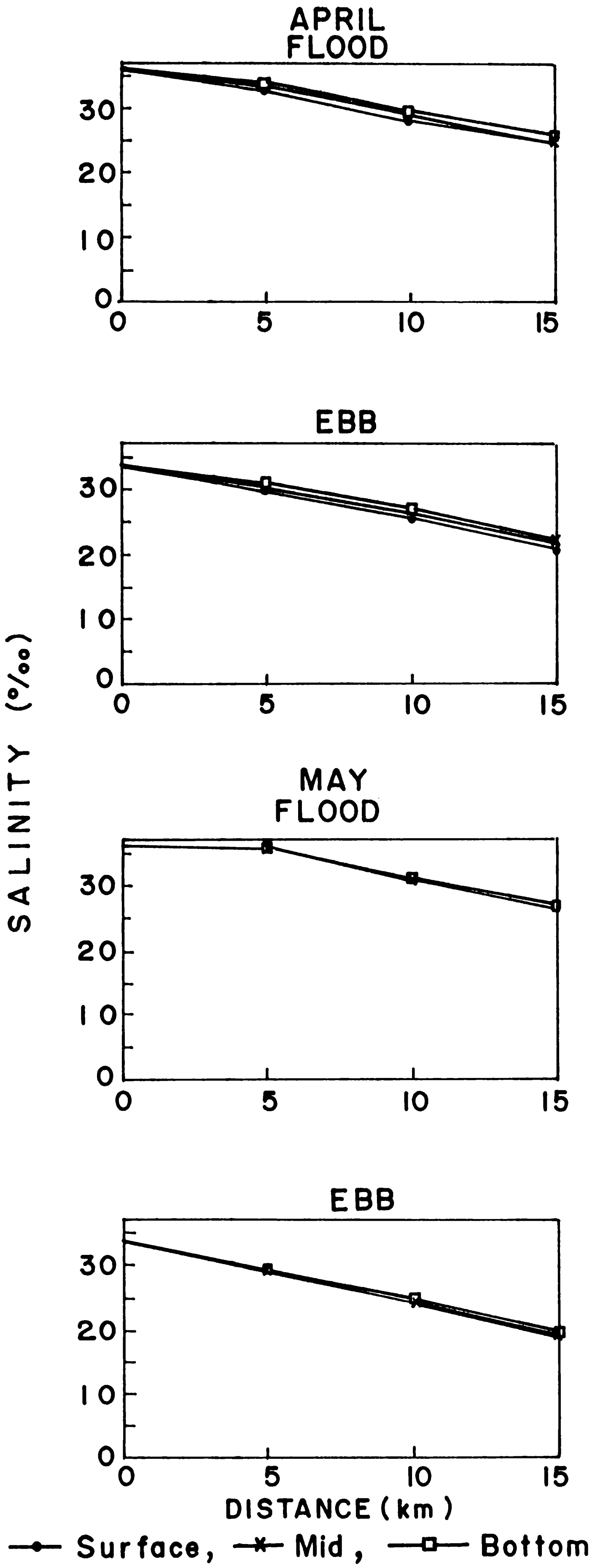


Fig.3.2.d. Longitudinal variation of salinity during flood and ebb tidal phases.

and upstream of this section gentle vertical gradients were observed which showed a weakly stratified condition. Longitudinal gradients (12×10^{-3}, for both the phases of tide) was more predominant than the vertical gradient in the entire study area.

May

High salinity values with very little fluctuations with the tidal changes and a vertically homogeneous water column suggest a well mixed condition during this month. During the flooding phase of the tide the salinity values has no vertical variation at the four sections of the estuary. During flood phase of the tide the horizontal salinity values varied between 35.8×10^{-3} and 26.7×10^{-3} from the lower to the upper section of the estuary and high saline water penetrate well beyond 15km upstream. The longitudinal gradient of salinity during the ebb tidal phase was nearly 14×10^{-3} in the water column between the river mouth and 15kms upstream. The longitudinal variation of salinity was almost linear during ebb tide.

June

A higher stratification at the river mouth section and a sudden sharp longitudinal decrease of the salinity values during the flood tide implies that the influence of increased freshets and the estuary was fully freshwater dominated. A higher bottom salinity of 31×10^{-3} was observed at river mouth during flood tide. During ebb tide the entire estuary

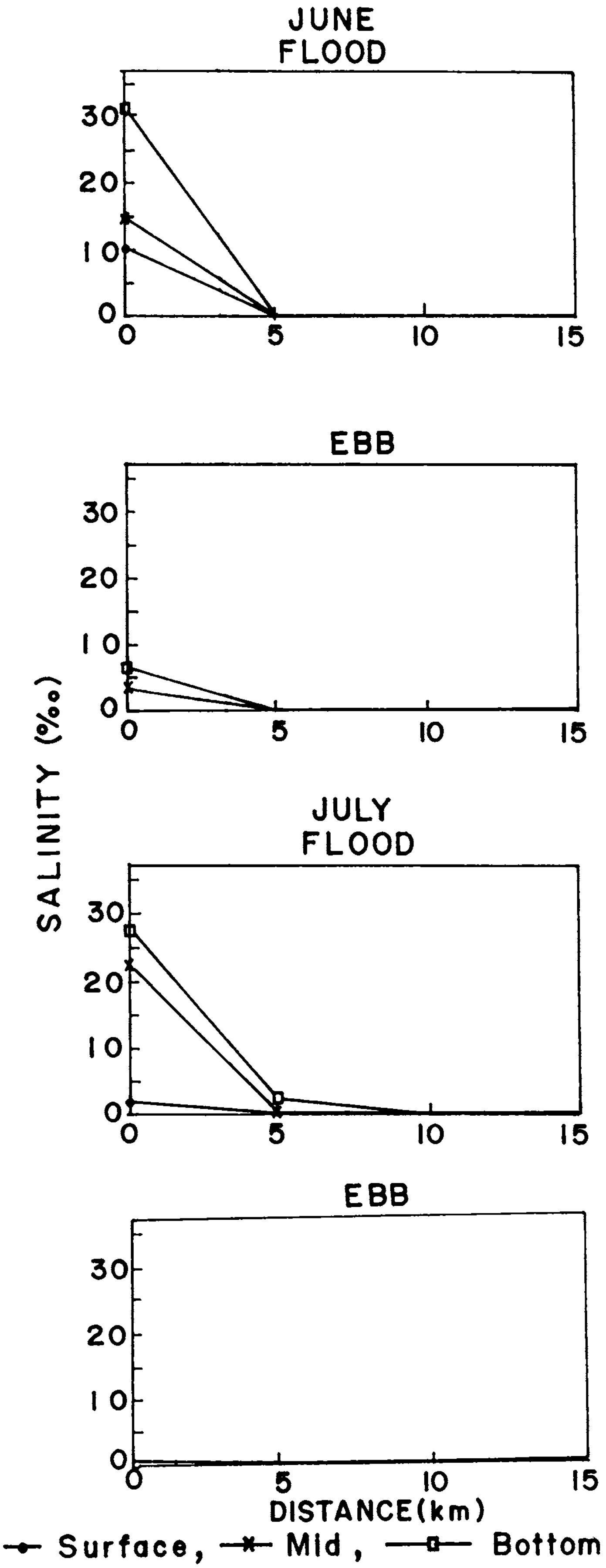


Fig.3.2.e. Longitudinal variations of salinity during flood and ebb tidal phases.

was found to be freshwater dominated. Influence of saline water was not significant even at the mouth of the estuary during the ebb tidal phase. During flood tide a strong longitudinal gradient was observed between the mouth and second section such that the salinity values reduced to zero at 5 kms upstream. The strong penetration of saline water into the lower estuary was prevented by the high river runoff.

July

July represents an active monsoon month and large quantities of freshwater enter into the estuary results in low saline water at the surface and dense saline water at the bottom during flood tide. The entire water column of the estuary exhibits nearly freshwater conditions during ebb tide. During this southwest monsoon period, the upstream section beyond section-II were completely devoid of saline water. At the mouth of the estuary, a higher stratification of 26×10^{-3} was observed during the flooding phase of the tide and the vertical gradient reduced 3×10^{-3} at section-II and was nearly zero further upstream of section-III.

August

A high stratified condition was observed during the flood tide in the lower reaches of the estuary, upto 5kms upstream. At the river mouth of the estuary, the stratification was maximum (26×10^{-3}), and at section-II it

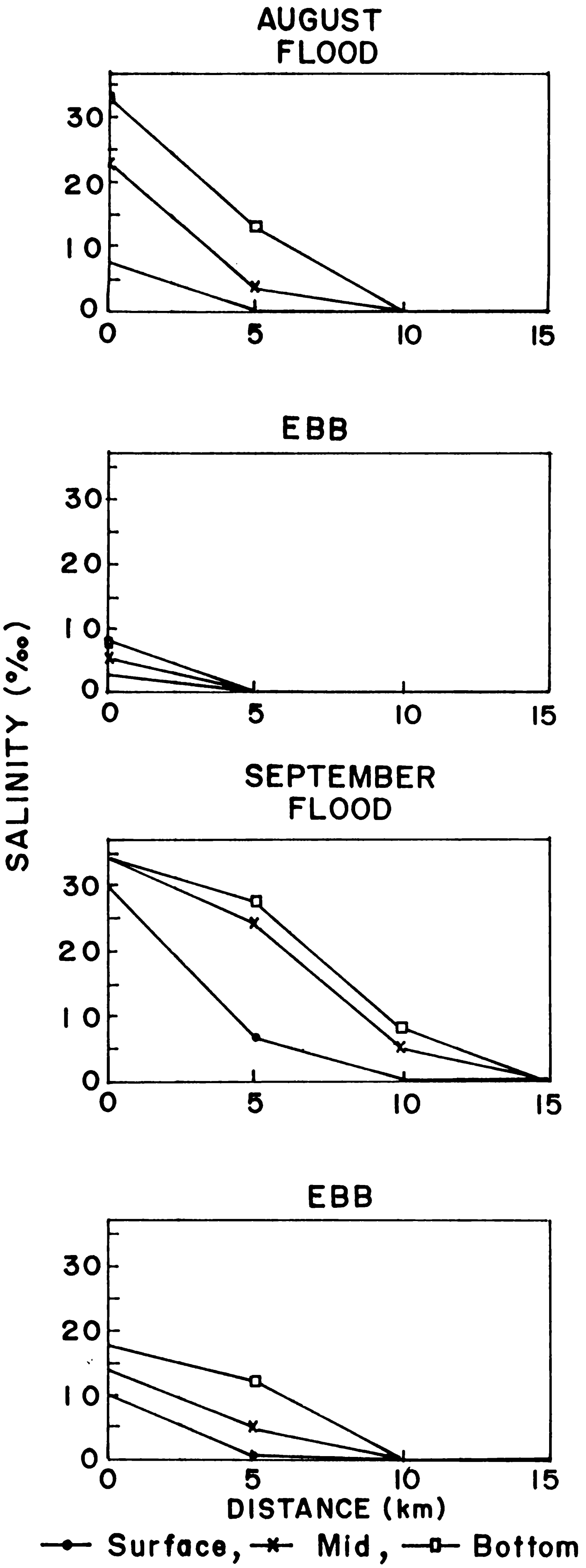


Fig.3.2.f. Longitudinal variation of salinity during flood and ebb tidal phases.

was 14 x 10^{-3} during flood tide. The salinity values reduced due to the higher influence of freshets. At ebb tide there was no marked change in salinity values in the upstream sections and which reduced to zero beyond 5kms upstream, where the estuary was freshwater dominated.

September

The horizontal gradient is much more sharp in the bottom layer where the salinity values varied between 34 x 10^{-3} and zero from the lowermost to the uppermost sections, during the flood tide. The vertical gradient was most significant at section-II (greater than 21 x 10^{-3}) and the stratification reduced well beyond section-III, due to the dominance of freshwater. At the ebb tidal phase the salinity variations were noticeable upto 8km upstream and the higher stratification obtained was greater than 12 x 10^{-3} at section-II.

3.3 Seasonal and longitudinal variation of tidal mean salinity during flood and ebb tidal phases.

Fig. 3.3 shows the time averaged values of salinity against the distance from the river mouth during both flood and ebb tides. Higher stratification upto 10km upstream was found during the postmonsoon period. The influx of saline water was most predominant even in the upstream sections during the premonsoon period and isohalines were parallel to each other which showed no stratification in the four sections and the water was well mixed. During the monsoon

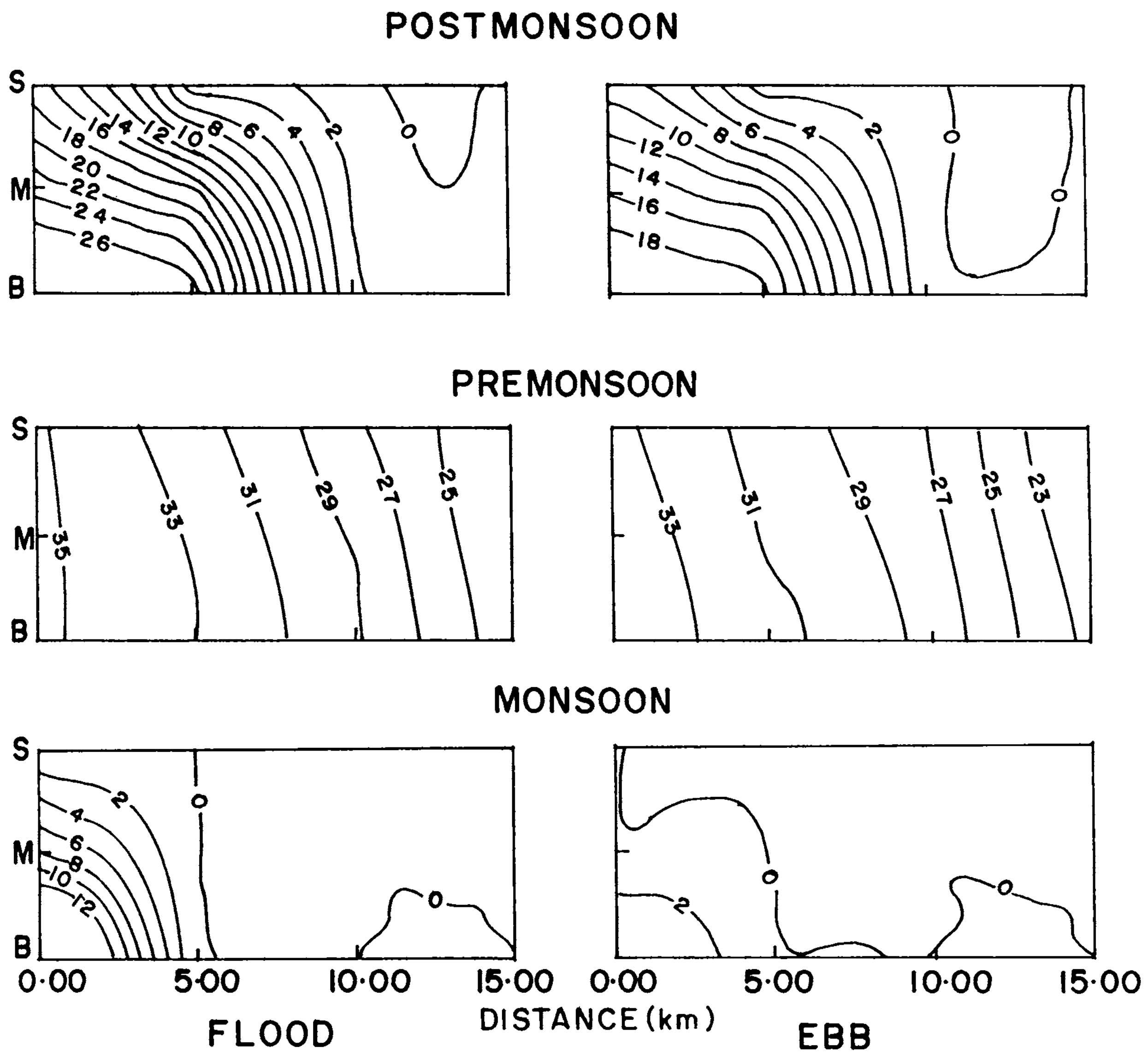


Fig. 3.3. Seasonal variation of tidal mean salinity along the estuary.

season the entire estuarine area was freshwater dominated and the salinity intrusion was only upto 5km upstream and the estuary was well stratified at the mouth section and the stratification was most significant at the river mouth during flood tide. The upper reaches of the estuary was river dominated and no saline water intrusion was observed.

3.4 Residual mean currents and salinity

The residual mean values of current and salinity are presented in Fig. 3.4.1 to 3.4.4 (positive values represent the seaward currents and negative values represent the upstream currents). The tidal mean values of current and salinity were taken along the x-axis. The non-dimensional depth was taken along the y-axis.

Section I

In this section, during the postmonsoon season the currents were seaward in the entire depth of the water column, decreasing from 28cm/s at surface to 8.5cm/s at bottom (Fig.3.4.1). Higher vertical gradient in current velocity was observed during this period. The residual mean currents varied between -6.3cm/s to -6.1cm/s from surface to bottom and were upstream in direction in the entire water column during the premonsoon period. In the monsoon season, the higher values of residual mean currents were observed and in the entire depth the current velocity was varying from 50cm/s to 24cm/s from surface to bottom and were seaward in direction in the entire water column.

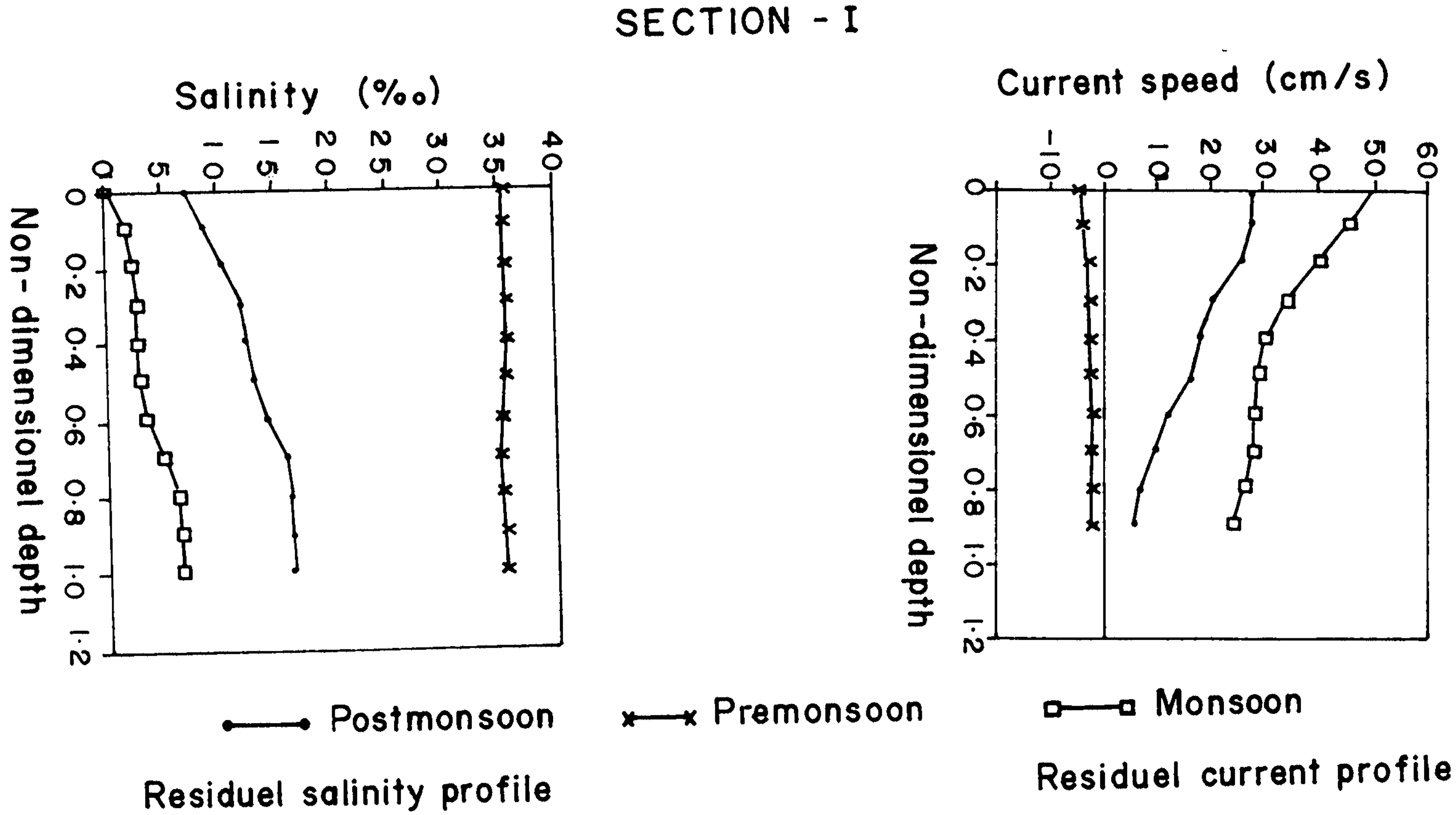


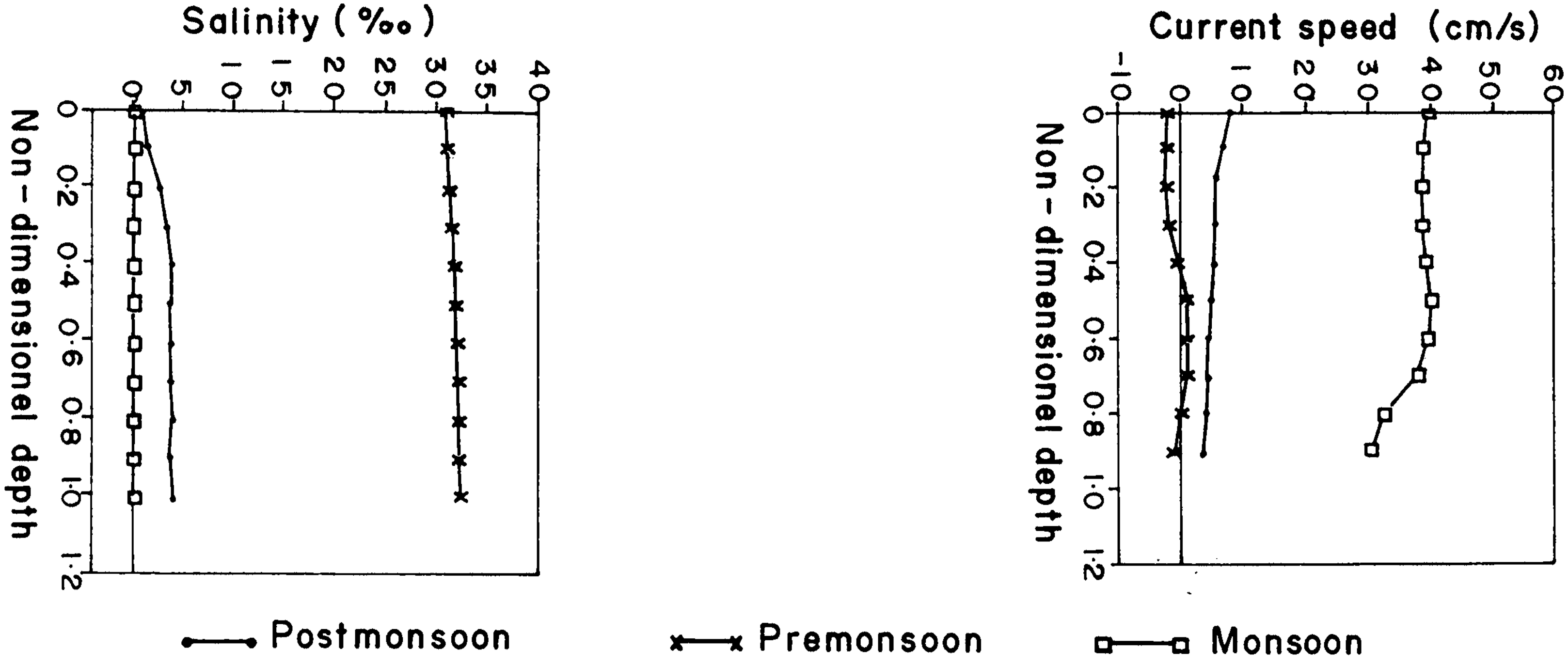
Fig. 3.4.1. Seasonal variation of residual current and salinity profile against the non-dimensional depth.

During postmonsoon period the residual mean salinity varied between 7×10^{-3} to 16.61×10^{-3} from surface to bottom. During this period there is a predominant increase in salinity with depth upto $y = 0.4 (12.09 \times 10^{-3})$ and there after it increased gradually uto $y = 0.9$ (16.61×10^{-3}), where 'y' represents the non- dimensional depth. A very sharp vertical profile was observed during premonsoon season. Higher values for residual salinity ($\langle s \rangle$) was observed during this season (greater than 35×10^{-3}) in the entire water column. The lowest value for $\langle s \rangle$ profile was observed during the monsoon season varying from zero to 6.7×10^{-3} from surface to bottom.

Section II

The residual current and salinity profile for section II are presented in Fig.3.4.2. During postmonsoon the current velocities varied between 8.3cm/s and 3.5cm/s. At surface the residual current showed a higher value of 8.3cm/s. As depth increases the current velocity decreases and reaches a lower value of 3.5cm/s at $y = 0.9$. In the entire water column the direction of residual current was always seaward. In the premonsoon season the current velocities were upstream in direction at surface (-2.03cm/s) and reverses in direction at $y = 0.6$ (1.1cm/s) and at bottom it was directed upstream (-1.05cm/s). The mean residual currents were up estuary in direction and were higher in magnitude during monsoon in the entire water column and varied between 40cm/s at surface to

SECTION - II



Residuel salinity profile

Residuel current profile

Fig. 3.4.2. Seasonal variation of residuel current and salinity profile against the non-dimensionel depth.

33cm/s at $y = 0.9$

In postmonsoon the residual mean salinity varied from 1.14×10^{-3} at $y = 0$ to 4×10^{-3} at $y = 0.9$, not much variation was observed in the salinity profile. In the premonsoon season the residual mean salinity profile was linear and the mean salinity values were greater than 30×10^{-3} in the entire water column. During monsoon the mean salinity values were almost zero from surface to bottom.

Section III

Residual current profiles at section-III are presented in Fig.3.4.3. The profile showed that the flow was towards sea from surface to bottom and the residual current speed varied from 3.75cm/s at surface to 6.5cm/s at $y = 0.7$. From $y = 0.7$ it decreases to 5.34cm/s at bottom. During premonsoon also there is a dissimilarity in residual current profile as shown in Fig. 3.4.3. At the surface (-3.57cm/s) the current velocity was directed towards upstream and from $y = 0.2$(1.66cm/s) to $y = 0.3$(1.11cm/s) the flow was towards the sea and below $y = 0.3$ the profile showed an upstream current upto $y = 0.9$(-5.78cm/s). In monsoon the residual currents were towards the sea in the entire water column and it decreased from 39cm/s at $y = 0$ to 26 cm/s $y = 0.9$.

The residual salinity profiles during postmonsoon and monsoon showed that the salinity values were negligibly small at all non-dimensional depth. During premonsoon $\langle s \rangle$ profile

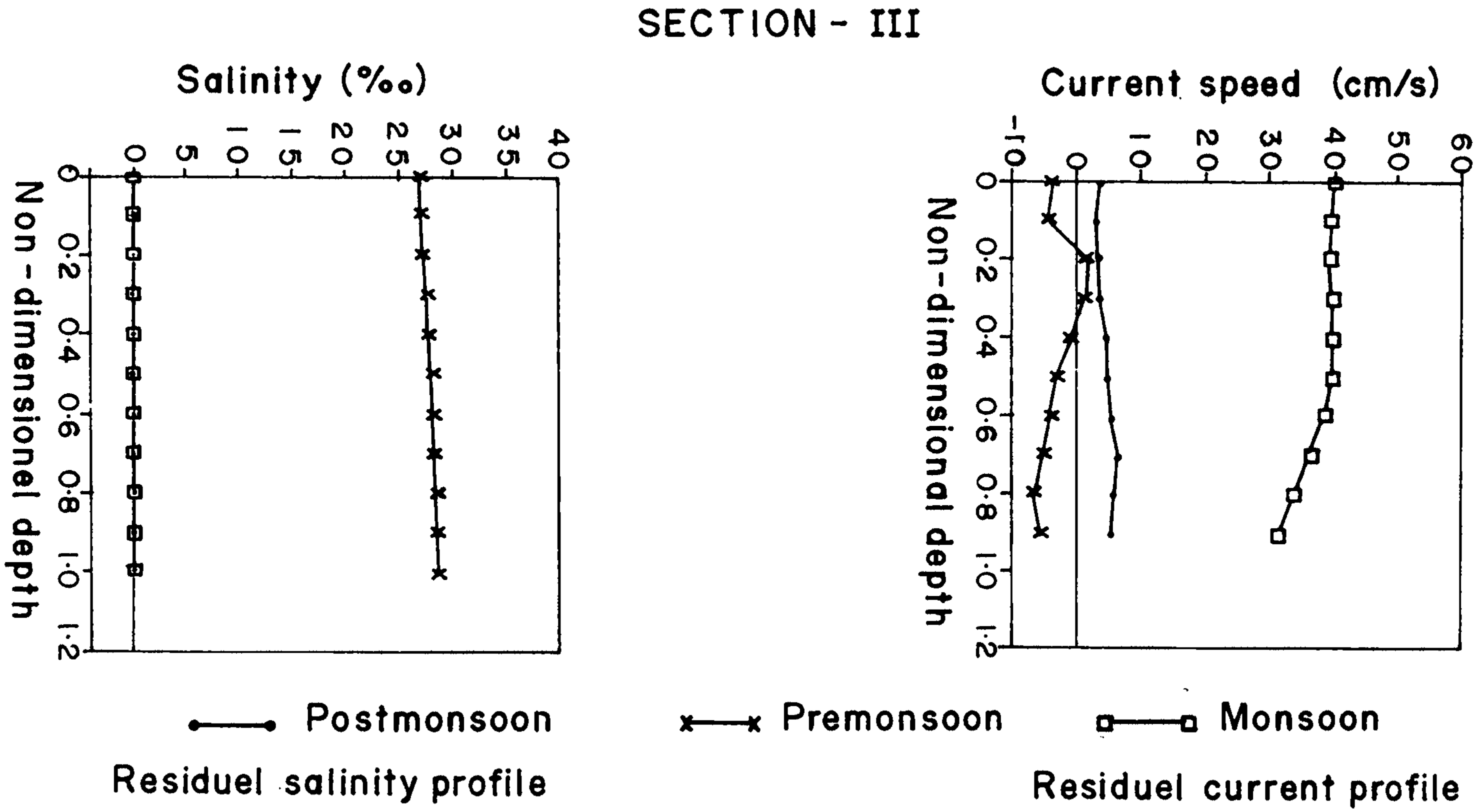


Fig. 3.4.3. Seasonal variation of residuel current and salinity profile against the non-dimensionel depth.

did not show much vertical variation in the residual mean salinity values and from y = 0 to y = 0.9 it varied between 26.76×10^{-3} to 28.45×10^{-3}.

Section IV

The residual current and salinity profile for the fourth section during all the seasons are shown in Fig.3.4.4. In postmonsoon the current velocity was seaward at all depths and there was not much vertical variation in the entire water column. During this period the residual current increases from 7.21cm/s at surface to 8.57cm/s at y = 0.5 and decreases .to 6.1cm/s at bottom. During the premonsoon season, from surface to bottom, the direction of the residual current velocity was towards upstream and the residual current speed varied between -2.86cm/s to -1.53cm/s from surface to y = 0.3 and there after it increases to -7.08cm/s at bottom. The maximum current velocity in this section was observed during monsoon, during this period in the entire water column the flow was towards the sea and the current velocity decreased from 36cm/s at y = 0 to 25cm/s at y = 0.9.

During postmonsoon and monsoon the <s> profile showed the mean salinity values were almost zero at all depths. During the premonsoon period the residual salinity profile was almost parallel to the x-axis and the <s> profile varied between 21.7×10^{-3} at y = 0 to 22.5×10^{-3} at y = 0.9, which shows that the vertical variation was less than 1×10^{-3}.

SECTION - IV

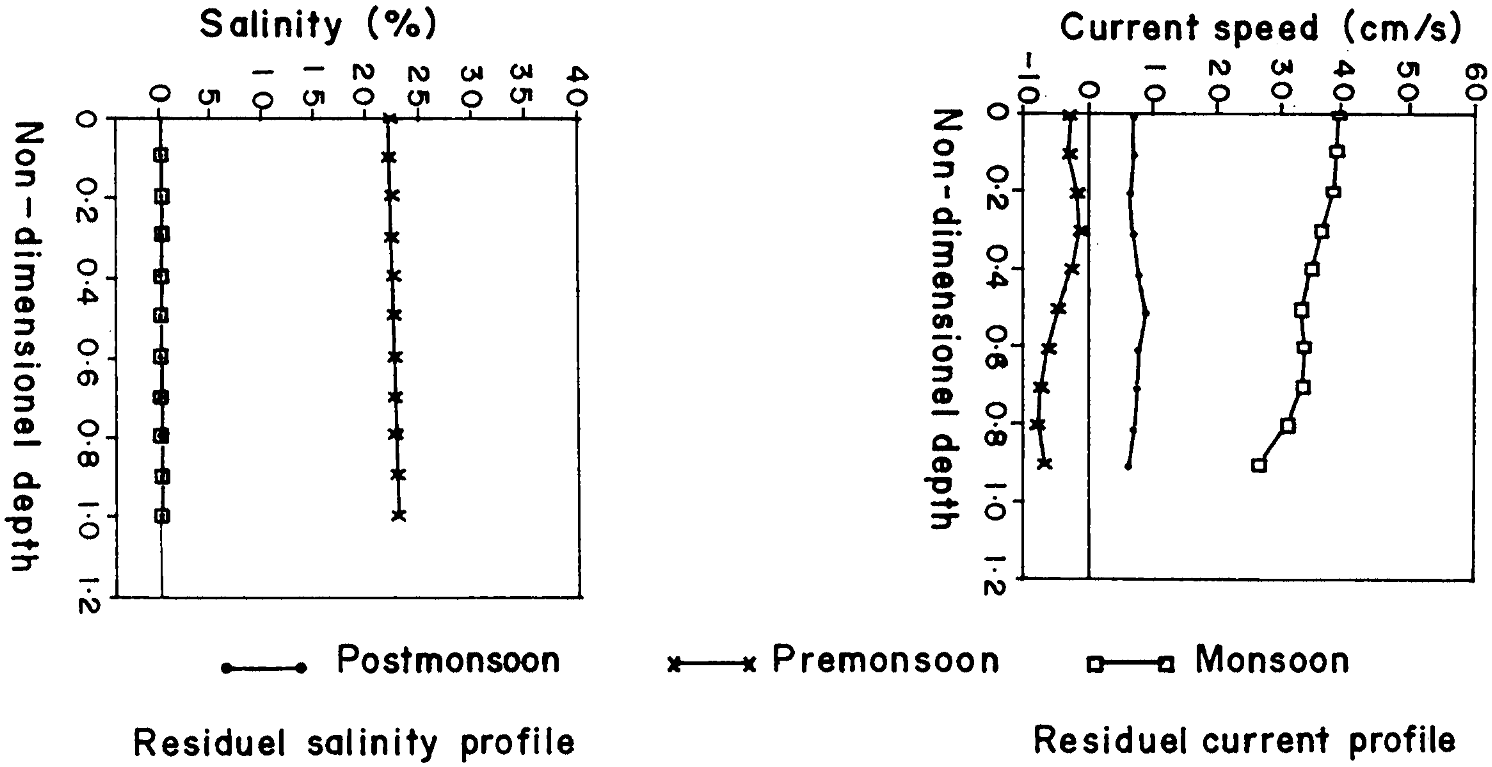


Fig. 3.4.4. Seasonal variation of residuel current and salinity profile against the non-dimensionel depth.

3.5 Monthly variation of River discharge, Rainfall and Mean wind speed.

In Fig. 3.5.1 monthly river discharge through Chaliyar river is shown. Moderately high river discharge was observed during the post monsoon period. The river discharge values showed a minimum during the premonsoon season. Monthly average value of the river discharge during March, April and May were $1.69m^3/s$ and $2.19m^3/s$, $1.80m^3/s$ respectively. High river run-off was observed during the monsoon season. The maximum river discharge was observed during July ($670m^3/s$).

Monthly variation of the rainfall and mean wind speed are shown in Fig. 3.5.2. About 75% of the rainfall was received during the southwest monsoon season that too during the months June to August. Usually heavy showers occurred with the onset of the south west monsoon towards the end of May. The rain fall in the first month of monsoon amounts to above 20% of the annual rainfall. The rainfall in July was heavy and thereafter it decreases with the advance of the season (Anonymous, 1986).

From Fig. 3.5.2 winds were generally moderate with some strengthening during the period of February to May. It decreased from 8.8km/hr to 8.1km/hr from October to November and it increased to 12.6km/hr in April and again it decreased to 8.7km/hr in September. In the southwest monsoon months winds blow mainly from west or northwest (Anonymous, 1986).

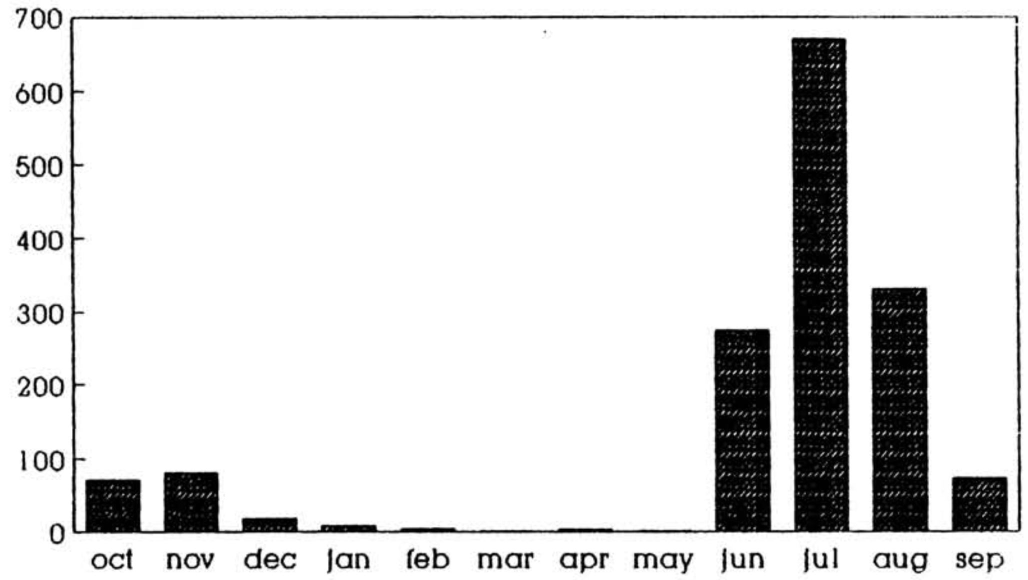


Fig. 3.4. 2. Annual variation of river discharge($\times 10^3 m^3/S$)

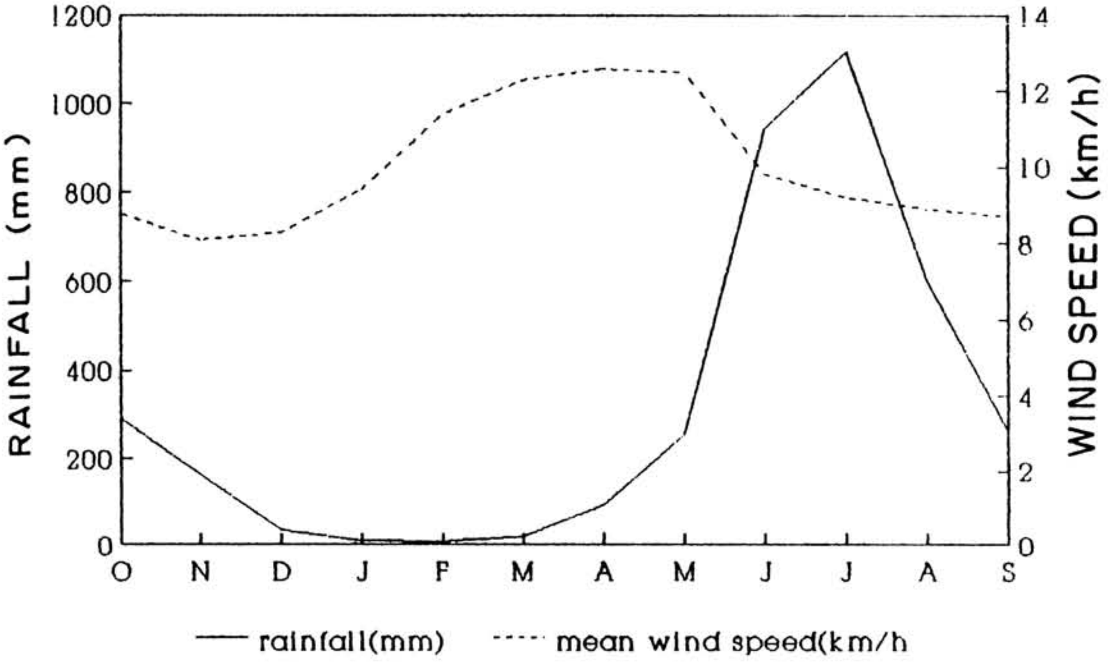


Fig. 3.4.3. Annual variation of rainfall and mean wind speed.

CHAPTER IV

RESIDUAL FLUXES OF WATER AND SALT

The components of residual fluxes of water and salt are theoretically derived by Bowden and Sharaf El Din (1966), Fischer (1972), Dyer (1974) Lewis, (1979) and Uncles and Jordan(1979). H and V are the instantaneous depth and current velocity. Then the instantaneous rate of transport of water through a unit width of water column of depth H is $Q = H\bar{V}$. The residual rate of transport per unit width of water column is

$$\begin{aligned} \langle Q \rangle &= \langle H\bar{V} \rangle = \langle H \rangle (\langle \bar{V} \rangle + \langle \tilde{H}\tilde{V} \rangle / \langle H \rangle) \\ &= h (V_1 + V_2) \\ &= hV_L \qquad \text{-------------} \qquad (4.1) \end{aligned}$$

The diamond bracket denote a tidal average, and the overbar denotes the depth average.

$V_1 = \langle \bar{V} \rangle$

$V_2 = \langle \tilde{H}\tilde{V} \rangle / \langle H \rangle$

$h = \langle H \rangle$

$\tilde{V} = \bar{V} - \langle \bar{V} \rangle$

$\tilde{H} = H - \langle H \rangle$

$V' = V - \bar{V}$

$S' = S - \bar{S}$

$V_L = \langle Q \rangle / h$

V_1 is the depth averaged Eulerian residual current or non tidal drift (Dyer, 1974), V_2 is a measure of the residual rate of transport of water resulting from tidal pumping, which is referred here as the Stokes drift (Hunter, 1972; Tee, 1976).

The instantaneous rate of transport of salt per unit width through a water column is denoted by Q_s.

$$Q_s = HVS \quad \text{---------------------} \quad (4.2)$$

The residual rate of transport of salt is

$$\langle Q_s \rangle = \langle H \rangle \left[V_{s,1} + V_{s,2} + V_{s,3} \right] \quad \text{----------} \quad (4.3)$$

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

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

$$V_{s,3} = \langle H \overline{V'S'} \rangle / \langle H \rangle$$

$V_{s,1}$, $V_{s,2}$ and $V_{s,3}$ are the depth averaged residual fluxes of salt (in units of $10^{-3} gcm^{-2} S^{-1}$) due respectively to the residual transport of water $\langle Q \rangle$ the tidal pumping resulting from a non-zero correlation between Q and S, and the vertical shear in the tidal and residual currents.

4.1 Annual variation of Eulerian residual current and Stokes drift

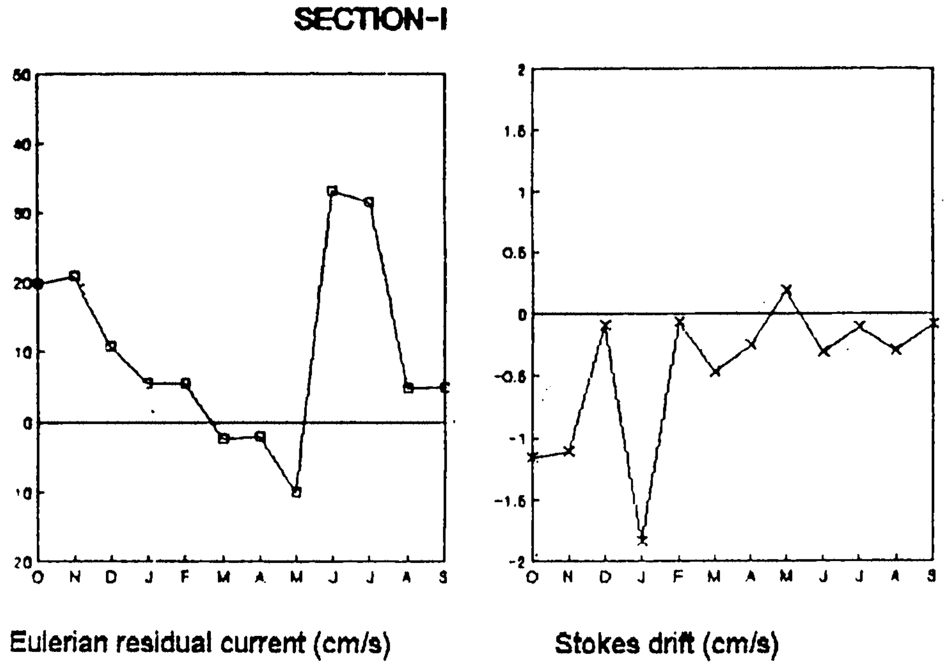
Section - I

The annual variation of Eulerian residual current and Stokes drift are shown in Fig. 4.1.1 and Table 4.1. The direction of the current was down the estuary from October to February. During this period the current velocity reduced from 19.75cm/s to nearly 5.5cm/s. In the premonsoon months the Eulerian residual current changed its direction towards upstream. During this period the residual current speed showed a variation from -2.4cm/s in March to higher value of -10cm/s in May (negative values shows the upstream direction). During monsoon months the Eulerian residual current direction was down estuary and the current velocity varying from a maximum of 33.15cm/s in June to 4.89cm/s in September.

From October to December the Stokes drift varied between -1.16cm/s and -0.10cm/s and during January and February it was -1.84cm/s and -0.07cm/s respectively. In the premonsoon period the variation was between -0.47cm/s and 0.18cm/s(from March to May). From June to September it varied between -0.31cm/s and -0.09cm/s. In most of the periods of observation the Stocks drift was predominantly in the upstream direction.

Section - II.

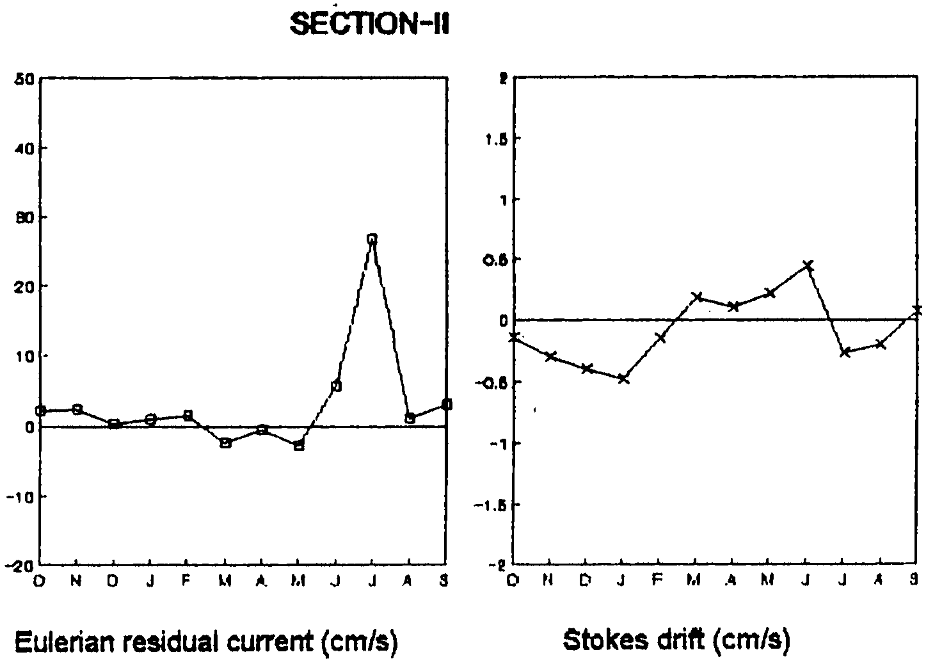
Fig. 4.1.2 and Table 4.2 shows the residual current distribution pattern at this section. During the postmonsoon and monsoon months it's direction was downstream. From October to December the residual current velocity varied between 2.15cm/s and 0.35cm/s and it increases to 1.46cm/s in February and was directed down the estuary. The current direction was towards upstream in the premonsoon season (from March to May) and the higher value in this direction was observed during May (-2.75cm/s). The higher values in the downstream direction was observed during the monsoon season



Eulerian residual current (cm/s)

Stokes drift (cm/s)

Fig. 4.1.1



Eulerian residual current (cm/s)

Stokes drift (cm/s)

Fig. 4.1.2

Fig. 4.1.1
&
Fig. 4.1.2 Annual variation of Eulerian residual current and Stokes drift

and the maximum value (26.69cm/s) was obtained during July.

In this section the annual variation of the Stokes drift was not consistent. During postmonsoon season the Stokes drift was in the upstream direction. From October to January it varied between -0.14cm/s and -0.48cm/s and during February it was -0.15cm/s. In the premonsoon months the direction was downstream and in magnitude it varied from 0.18cm/s to 0.1cm/s from March to April. During May and June it was 0.20cm/s and 0.44cm/s respectively. From July to September the Stokes drift varied from -0.27cm/s to 0.07cm/s and there is a reversal in direction during the monsoon months.

Section - III

As shown in Fig. 4.1.3 and Table 4.3 residual current velocity was directed downstream during postmonsoon period and the residual current speed varied between 6.68cm/s and 15.5cm/s from October to November and between 10.44cm/s and 2.71cm/s from December to February. During the premonsoon period (March to May) the residual current varied between -2.52cm/s and -5.41cm/s and the current direction was upstream. During the monsoon season the residual current was downstream in direction and showed a variation 39.69cm/s in June to 5.25cm/s in September.

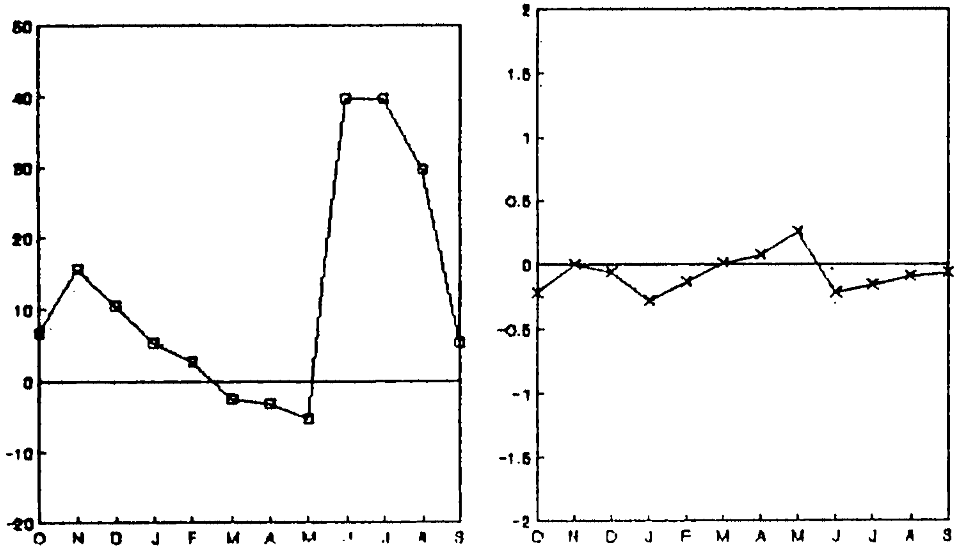
As in the previous sections, in this section also the Stokes drift was found to be upstream in most of the period of observation. In the postmonsoon season it was directed upstream and from October to November the Stokes drift was varying between -0.23cm/s and -0.01cm/s. It was increasing from -0.06cm/s to -0.23cm/s from December to January and decreased to -0.14cm/s in February. From March to May the variation was from 0.01cm/s to 0.25cm/s in the downstream direction. Again it reverses it's direction during the monsoon period and varied between -0.22cm/s to -0.07cm/s from June to September.

Section IV

The residual current was seaward from October to February (varied between 7.12cm/s and 3.06cm/s) and June to September (varied between 36.84cm/s to 3.36cm/s) as given in Fig. 4.1.4 and Table 4.4. The maximum value of the residual current in the downstream direction (38.72cm/s) was during July. From March to May the residual current velocity varied from -3.22cm/s to -4.53cm/s and the current reverses in direction(flows towards upstream). From May the magnitude of the current values increases sharply and reaches a maximum during July and decreases through September.

In this section also the Stokes drift was not consistent. It was varying between -0.53cm/s and -0.31cm/s from October to February. In the premonsoon period it was varying between -0.72cm/s and -0.1cm/s. From June to September the Stokes drift was varying between 0.26cm/s and -0.01cm/s. In majority of the observation period it was directed upstream.

SECTION-III

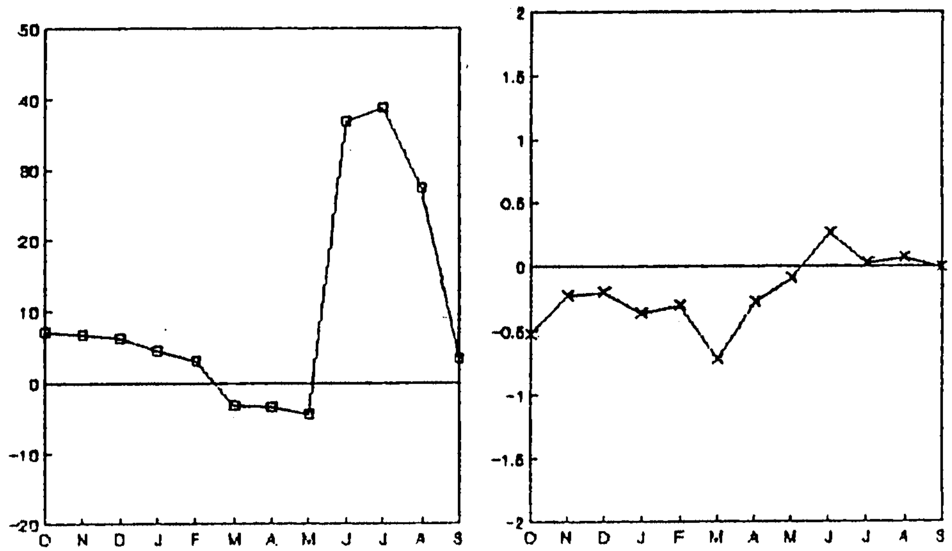


Eulerian residual current (cm/s)

Stokes drift (cm/s)

Fig. 4.1.3

SECTION-IV



Eulerian residual current (cm/s)

Stokes drift (cm/s)

Fig. 4.1.4

Fig. 4.1.3
&
Fig. 4.1.4
Annual variation of Eulerian residual current and Stokes drift

4.2 The fluxes of salt

The residual transport of salt through an estuary is the result of fluxes arising from the residual flow of water, tidal pumping and vertical shear.

Section-I

The salt transport at the section is shown in Fig. 4.2.1 and Table 4.1. In the entire observation period the residual flow of salt was mainly controlled by the residual flow of water. In postmonsoon and monsoon season flux was seaward in direction. During the premonsoon period the transport was upstream and the net transport was higher during May.

Comparing with the salt flux due to the residual flow of water, the flux of salt due to tidal pumping and vertical shear were not much significant. In general during most of the months in the entire observation period the salt transport due to tidal pumping and vertical shear were directed upstream.

Section II

The salt transport at the section is shown in Fig. 4.2.2 and Table 4.2. The influence of residual water transport was more predominant in the residual flow of salt in the entire observation period at this section. The net transport and salt transport due to residual water flow showed almost a similar pattern in this cross section. The salt flux due to

SECTION - I

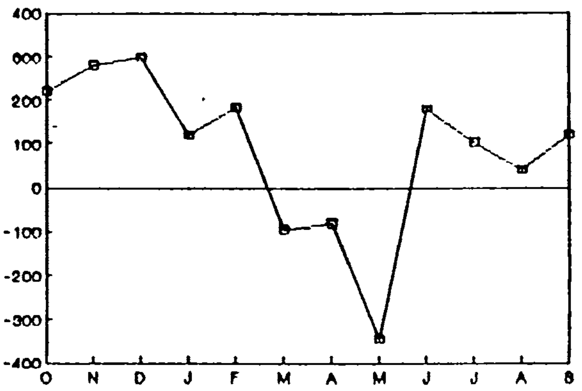


Fig. 4.2.1a

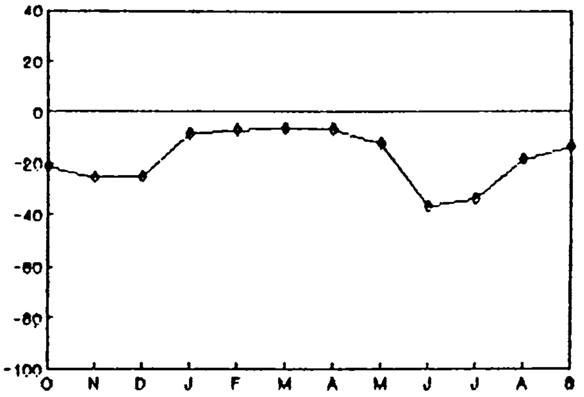


Fig. 4.2.1b

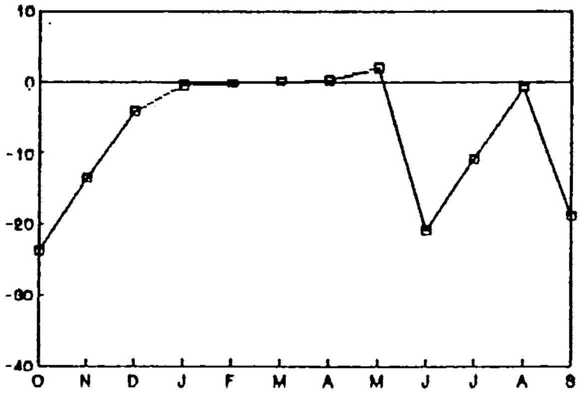


Fig. 4.2.1c

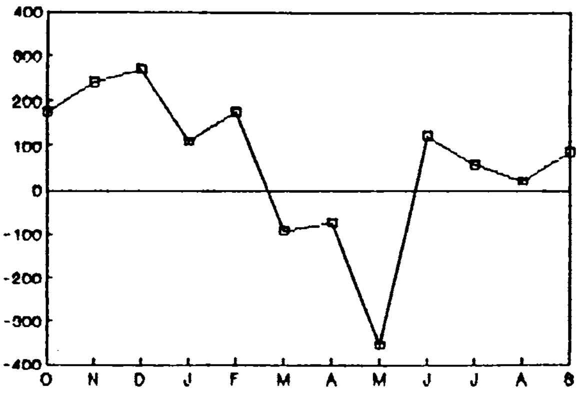


Fig.4.2.1d

Fig. 4.2.1 Annual variation of residual flux of salt due to 1) Residual Flow of Water (Fig.4.2.1a) 2) Tidal pumbing (Fig. 4.2.1b) 3) Vertical Shear (Fig. 4.2.1c). Fig.4.2.1d Sum of the above three fluxes.

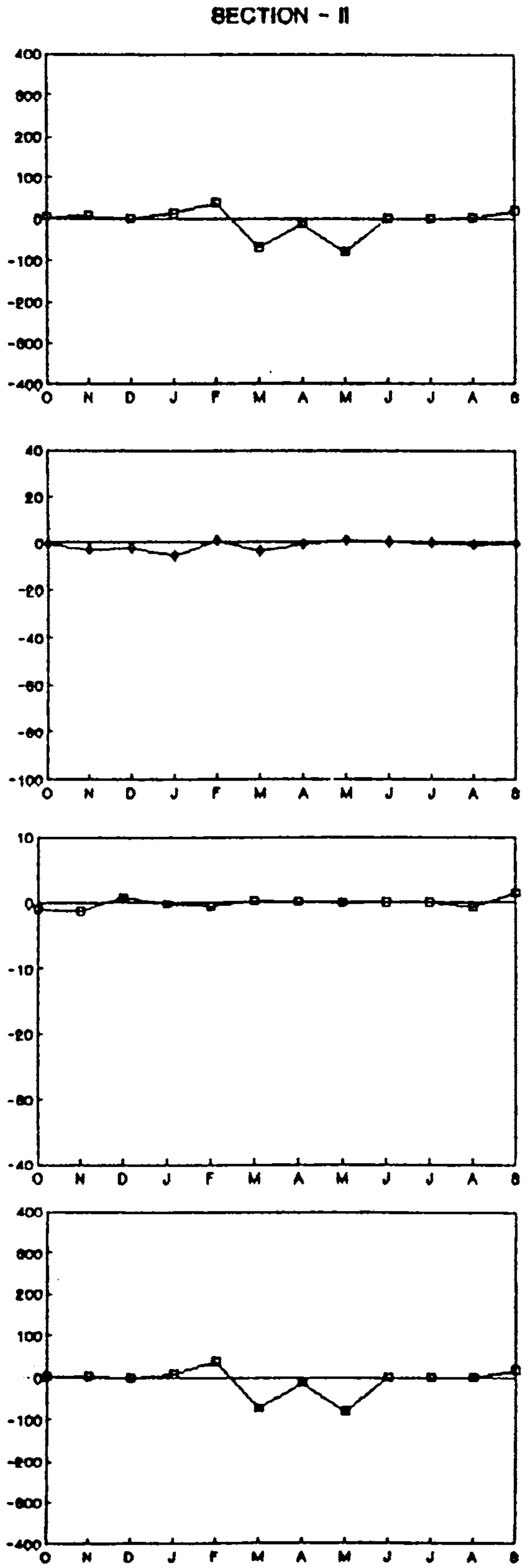


Fig. 4.2.2 Annual variation of residual flux of salt due to 1) Residual Flow of Water (Fig.4.2.2a) 2) Tidal pumbing (Fig. 4.2.2b) 3) Vertical Shear (Fig. 4.2.2c). Fig.4.2.2d Sum of the above three fluxes.

residual water transport was directed downstream in the entire cross section except during the premonsoon season.

The residual salt transport due to tidal pumping and vertical shear were very small in magnitude and directed towards upstream in most of the periods of observation. During the monsoon months influx of saline water was very less and the residual salt transport due to various physical processes were very small compared to other seasons. So the net salt transport was not predominant. However there was a small net salt transport upstream from March to May.

Section III

From Fig. 4.2.3 and Table 4.3 it can be observed that there was a resemblance in the salt transport due to residual flow of water and net salt transport. The net salt flux was directed towards downstream during the postmonsoon period. The upstream flux of salt was observed during the premonsoon season. During the monsoon period no flux of salt was observed due to the dominance of river water.

The salt transport due to tidal pumping was upstream during most of the observation period, with exception during the monsoon months due to the dominance of freshwater. The salt flux due to vertical shear was upstream in the entire cross section during all the periods of observation except the monsoon period (zero due to the dominance of freshwater). This process is diffusive and emphasize the importance of shear processes for the flux of salt in the upsteam sections.

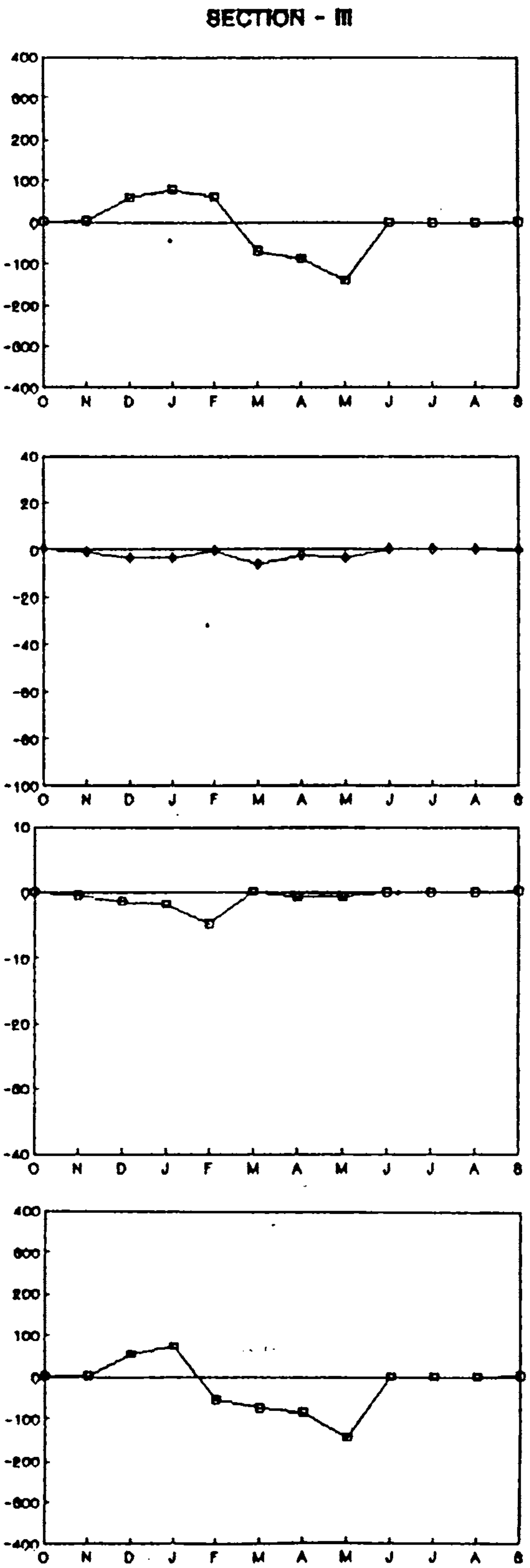


Fig. 4.2.3a

Fig. 4.2.3b

Fig. 4.2.3c

Fig.4.2.3d

Fig. 4.2.3 Annual variation of residual flux of salt due to 1) Residual Flow of Water (Fig.4.2.3a) 2) Tidal pumbing (Fig. 4.2.3b) 3) Vertical Shear (Fig. 4.2.3c). Fig.4.2.3d Sum of the above three fluxes.

SECTION - IV

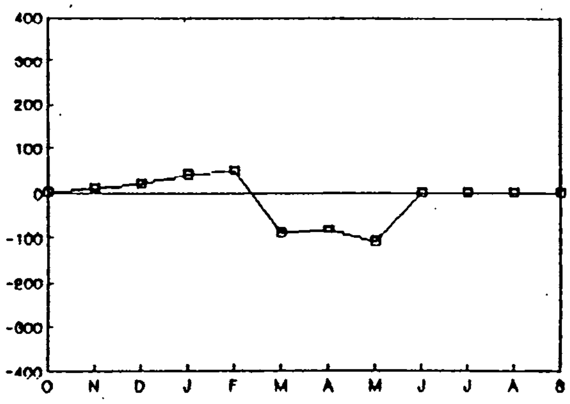


Fig. 4.2.4a

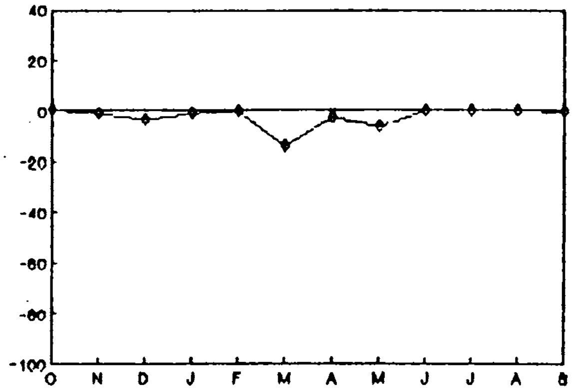


Fig. 4.2.4b

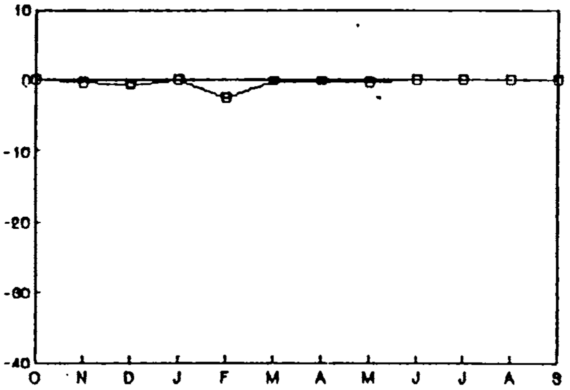


Fig. 4.2.4c

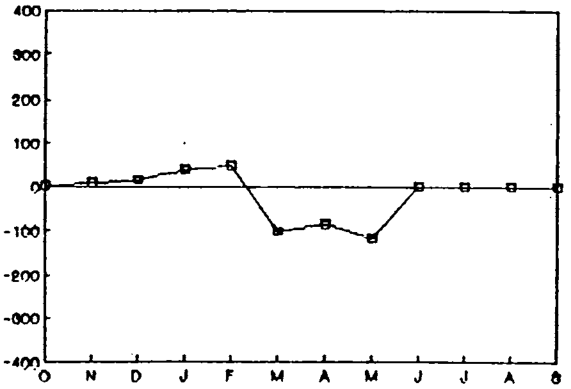


Fig.4.2.4d

Fig. 4.2.4 Annual variation of residual flux of salt due to 1) Residual Flow of Water (Fig.4.2.4a) 2) Tidal pumbing (Fig. 4.2.4b) 3) Vertical Shear (Fig. 4.2.4c). Fig.4.2.4d Sum of the above three fluxes.

Section IV

At this section (Fig. 4.2.4 and Table 4.4) the net salt flux was down the estuary form October to February, the salt transport due to residual flow of water was also downstream during this period. During the premonsoon season the flow pattern was towards upstream and the net salt transport was also in the same direction. During the above two seasons the salt flux due to tidal pumping and vertical shear were towards upstream. During monsoon season the upstream sections were fully dominated by the freshwater flow and no transport of residual salt was observed in the upper reaches of the estuary.

In general the net transport of salt was mainly depended on the magnitude of the slat flux due to residual flow of water at all the four sections. The salt transport due to tidal pumping and vertical shear were predominant only in the lower reaches of the estuary, but there also the dominance of salt flux due to residual flow of water was much more effective.

4.3 Estuarine classification

The action of gravity upon the density difference between seawater and freshwater tends to cause vertical salinity stratification and a characteristic convective flow that has come to known as `estuarine circulation' or gravitational convection. Estuaries, traditionally have been classified according to their geomorphology and their salinity stratification (Hansen and Rattray, 1966). To express the relative salinity stratification the estuaries are classified as salt wedge or highly stratified, and well mixed or vertically homogeneous (Stommel and Farmer, 1952; Camerone and Pritchard, 1963).

The classification diagrams, are depicted in the diagrams developed by Hanson and Rattray (1966). They related estuarine type to its position on the stratification circulation diagram, constructed by using two dimensionless parameters, stratification parameter and circulation parameter. The circulation parameter is the ratio of the net surface current to mean freshwater velocity through the section (U_s/U_f) and the stratification parameter is the ratio of the top to bottom salinity difference to the mean salinity over the section, d_s/S_0.

In the stratification circulation diagram the type 1 represents the net flow is seaward at all depths and the flux of salt towards upstream is affected by diffusion. Type 1_a is the well mixed estuary in which the salinity stratification is negligibly small, while in 1_b there is appreciable stratification. For type 2 the net flow reverses and both advection and diffusion contribute importantly to salt flux. Type 3, 99% of the upstream salt transfer is primarily advective. Type 3_a characterises of small stratification. In type 3_b estuaries, the lower layer is so deep that in effect the salinity gradient and circulation do not extent to the bottom. Type 4, the salt wedge estuaries, the stratification is greater.

Section-I

From September to December there was appreciable stratification and during this period the section falls under type 1_b. During the premonsoon season the estuary was well mixed to partially mixed. During the monsoon season the section was slightly stratified.

Section-II

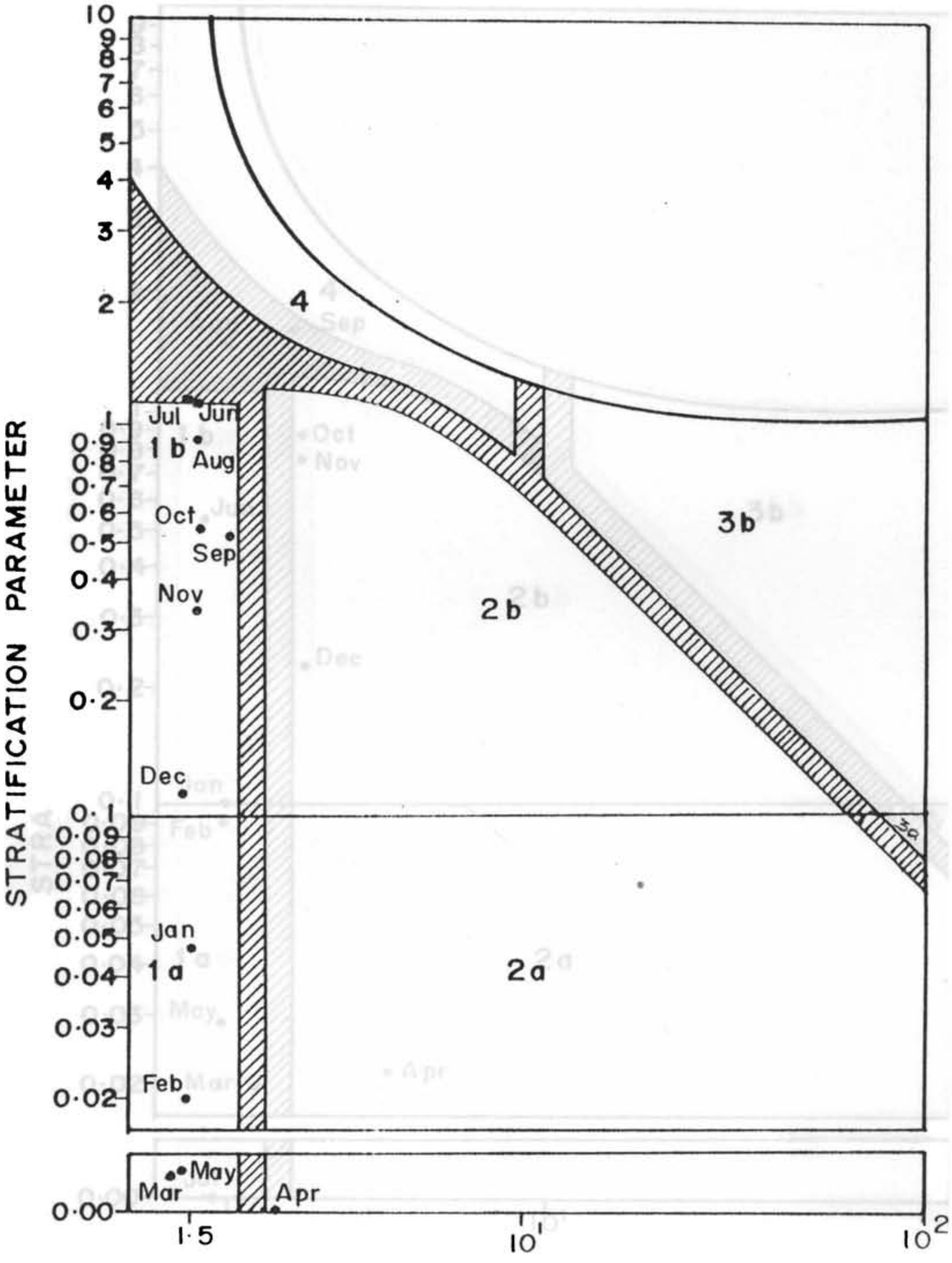
During the postmonsoon period the estuary was partially mixed type and during the premonsoon and monsoon periods the section falls under well mixed type to partially mixed type.

Section-III

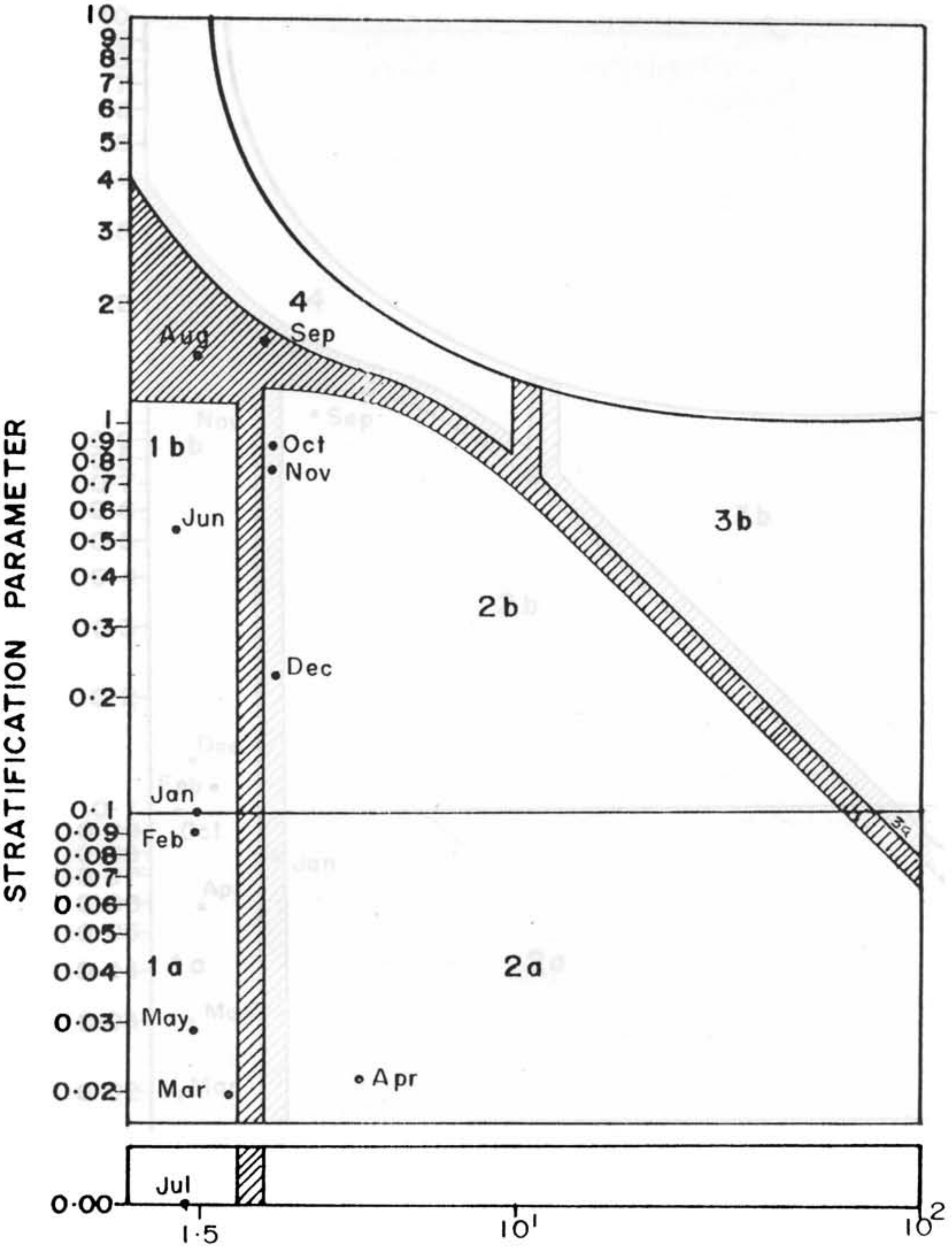
The section was coming under type 1_a that is well mixed type during the monsoon and premonsoon period. During the postmonsoon period the section falls under slightly stratified to laterally homogeneous well mixed type.

Section- IV

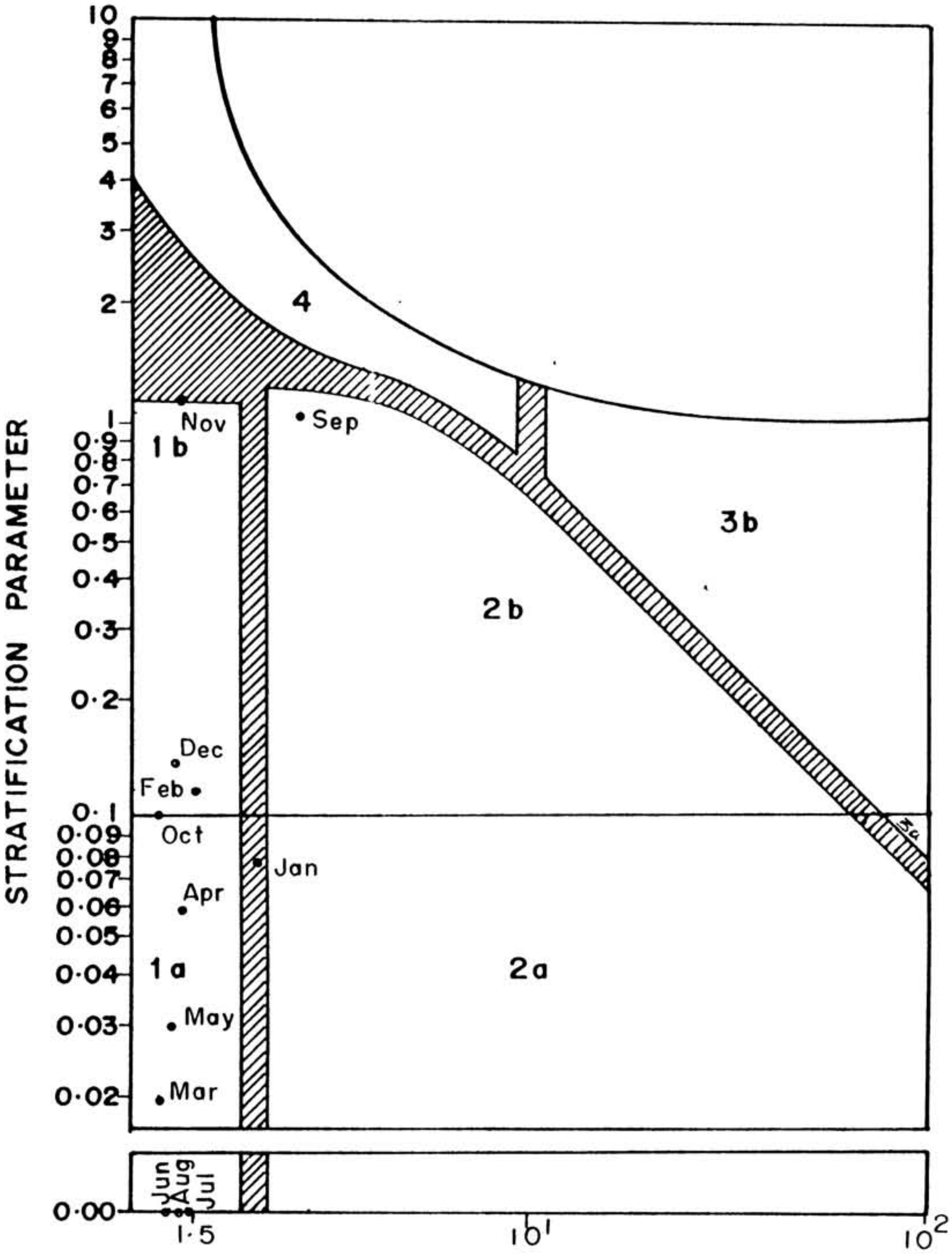
During periods of low river discharge and high river



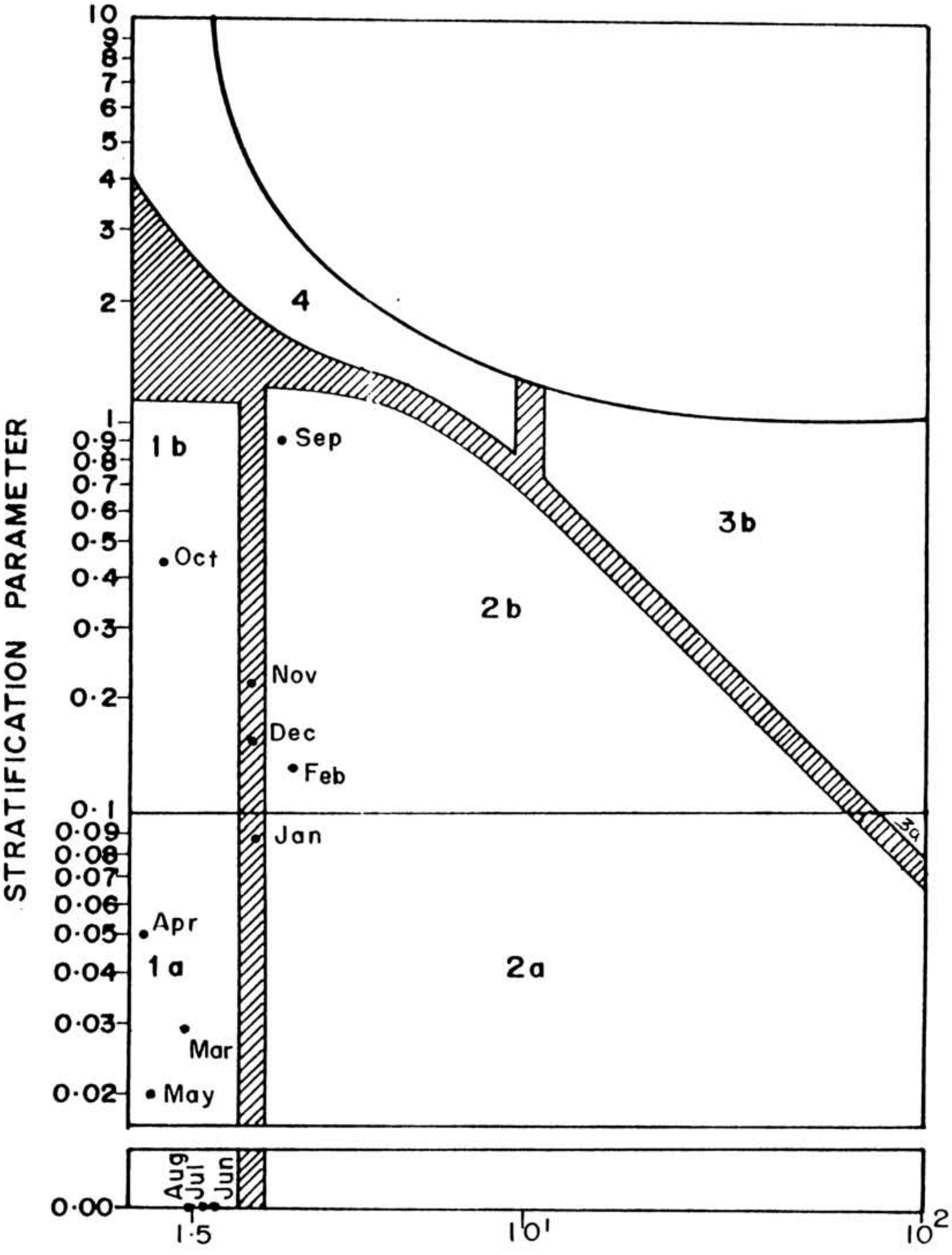
Stratification circulation diagram showing classification of Estuary section. I



Stratification circulation diagram showing classification of Estuary section. II.



Stratification circulation diagram showing classification of Estuary section. III.



Stratification circulation diagram showing classification of Estuary section. IV.

discharge the section was well mixed type. During the postmonsoon period that is the period of moderate river discharge the section was slightly stratified.

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

Section-I

Months	V_1	V_2	V_L	$\langle Q\rangle$	$V_{s,1}$	$V_{s,2}$	$V_{s,3}$	$\langle Q_s\rangle$
	$cm\ s^{-1}$			$cm^2\ s^{-1}$	$x\ 10^{-3}\ cm\ s^{-1}$			
OCT	19.75	-1.16	18.59	8449.16	218.83	-21.3	-23.83	173.70
NOV	20.81	-1.11	19.70	9073.57	279.43	-25.56	-13.66	240.17
DEC	10.72	0.10	10.62	5105.46	297.05	-25.10	-4.13	267.82
JAN	5.50	-1.84	3.65	1746.82	117.94	-8.47	-0.45	109.02
FEB	5.51	-0.07	5.44	2150.81	181.54	-6.98	-0.25	174.31
MAR	-2.40	-0.47	-2.87	-1494.79	-98.14	-6.43	0.05	-91.76
APR	-2.03	-0.26	-2.29	-959.68	-80.39	-6.65	0.25	-73.99
MAY	-10.00	0.18	-9.82	-3540.20	-346.31	-12.10	2.02	-356.39
JUN	33.15	-0.31	32.84	15635.78	177.95	-36.45	-21.11	120.39
JUL	31.50	-0.11	31.39	14775.24	101.24	-33.74	-10.82	56.68
AUG	4.76	-0.30	4.46	1720.72	38.65	-18.31	-0.83	19.51
SEP	4.89	-0.09	4.80	1882.14	118.36	-13.60	-19.03	85.73

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

Section - II

Months	V_1	V_2	V_L	$\langle Q\rangle$	$V_{s,1}$	$V_{s,2}$	$V_{s,3}$	$\langle Q_s\rangle$
	$cm\ s^{-1}$			$cm^2\ s^{-1}$	$\times 10^{-3}\ cm\ s^{-1}$			
OCT	2.15	-0.14	2.01	977.12	5.25	-0.77	-2.26	2.22
NOV	2.40	-0.30	2.10	958.15	7.13	-3.12	-3.55	-0.45
DEC	0.35	-0.40	-0.05	-25.78	-0.45	-2.25	0.79	-1.91
JAN	1.05	-0.48	0.57	268.17	12.84	-5.45	0.19	-7.58
FEB	1.46	-0.15	1.31	630.53	37.89	0.70	-0.56	38.03
MAR	-2.40	0.18	-2.22	-1083.60	-69.93	-3.60	0.25	-73.28
APR	-0.55	0.10	-0.45	-212.71	-14.05	-0.79	0.07	-14.77
MAY	-2.75	0.20	-2.52	-1098.01	-79.38	-0.93	-0.22	-81.99
JUN	5.70	0.44	6.14	2962.53	0.31	0.12	0.01	0.44
JUL	26.69	-0.27	26.42	12748.57	0.02	-0.01	0.01	0.02
AUG	1.16	-0.20	0.96	664.67	1.48	-0.87	-0.71	-0.10
SEP	3.08	0.07	3.15	1367.88	17.28	-0.55	-3.90	12.83

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

Section - III

Months	V_1	V_2	V_L	$<Q>$	$V_{s,1}$	$V_{s,2}$	$V_{s,3}$	$<Q_s>$
	$cm\ s^{-1}$			$cm^2\ s^{-1}$	$x\ 10^{-3}\ cm\ s^{-1}$			
OCT	6.68	-0.23	6.45	3155.99	1.85	0.51	-0.05	2.32
NOV	15.50	-0.01	15.49	7431.02	2.72	-1.03	-0.38	1.31
DEC	10.44	-0.06	10.38	5211.80	57.77	-3.27	-1.32	53.18
JAN	5.27	-0.23	5.04	2646.10	78.52	-3.15	-1.73	73.64
FEB	2.71	-0.14	2.58	1259.27	60.37	-0.48	-4.63	-55.26
MAR	-2.52	0.01	-2.51	-1240.54	-69.26	-6.04	0.12	-75.36
APR	-3.26	0.07	-3.19	-1540.81	-88.35	-2.10	-0.72	-85.53
MAY	-5.41	0.25	-5.16	-2413.44	-141.46	-3.26	-0.66	-145.38
JUN	39.69	-0.22	39.47	19335.56	0.00	0.00	0.00	0.00
JUL	39.77	-0.16	39.61	19336.81	0.00	0.00	0.00	0.00
AUG	29.64	-0.11	29.53	113874.08	0.00	0.00	0.00	0.00
SEP	5.25	-0.07	5.18	2433.72	1.55	-0.24	0.21	1.52

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

Section - IV

Months	V_1	V_2	V_L	$\langle Q \rangle$	$V_{s,1}$	$V_{s,2}$	$V_{s,3}$	$\langle Q_s \rangle$
	$cm\ s^{-1}$			$cm^2\ s^{-1}$	$\times 10^{-3}\ cm\ s^{-1}$			
OCT	7.12	-0.53	6.59	1960.00	1.55	0.35	-0.02	1.88
NOV	6.76	-0.23	6.53	1843.68	9.69	-1.03	-0.29	8.37
DEC	6.22	-0.21	6.01	1643.97	19.02	-3.22	-0.80	15.00
JAN	4.53	-0.36	4.17	1046.75	40.34	-1.12	-0.05	39.17
FEB	3.06	-0.31	2.75	669.93	49.08	-0.07	-2.55	46.46
MAR	-3.22	-0.72	-3.94	-1063.41	-88.91	-13.90	-0.21	-103.02
APR	-3.42	-0.28	-3.70	-957.34	-82.25	-2.47	-0.23	-84.95
MAY	-4.53	-0.10	-4.63	-1709.63	-109.69	-6.24	-0.28	-116.21
JUN	36.84	0.26	37.10	10461.46	0.00	0.00	0.00	0.00
JUL	38.72	0.02	38.74	10923.91	0.00	0.00	0.00	0.00
AUG	27.37	0.06	27.43	7062.45	0.00	0.00	0.00	0.00
SEP	3.36	-0.01	3.35	862.52	0.08	-0.24	0.00	-0.16

CHAPTER V

EDDY DIFFUSIVITY, FLUSHING TIME, AND STUDIES ON MIXING BY RICHARDSON'S NUMBER

Introduction

The cause of pollution in an estuary is mainly due to the effluent discharge. In the Chaliyar river estuary some studies on salinity intrusion (James and Sreedharan 1983) circulation and mixing (James and Ramanadhan 1983) was conducted based on the data collected by Harbour Engineering Department. To understand the annual variation of longitudinal coefficient of eddy diffusivity and flushing characteristics a detailed study was conducted with the sufficient data collected from the Beypore estuary during October 1990 - September 1991.

Near the mouth of the estuary the freshwater fraction is relatively low as the salt water is slightly diluted. Enough of the mixture must escape on each tide to remove a volume of freshwater equivalent to the river flow. The escaping volume can thus be an order or more greater than the river flow and it is this volume that is available for the dilution and removal of pollutants. Estuaries are better in diluting and removing pollutants than the tributary river.

If a consistent rate of discharge of a conservative non decaying pollutant is made into an estuary, the tidal mixing will distribute it both upstream and downstream. The maximum concentration will be in the vicinity of the discharge point. 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 made on knowledge of the distribution of freshwater in the estuary.

5.1 Coefficient of eddy diffusivity, freshwater fraction and flushing time.

Let the cross sectional average concentration at the outfall after steady state condition have been achieved be C_0 then $C_0 = (P / R) f_0$ where P is the rate of supply of the pollutant, R is the river discharge and f_0 is the cross sectional fractional freshwater concentration.

Downstream of the outfall, the pollutant must pass through a cross section at the same rate as it is discharged at the outfall. Upstream of the outfall the quantity of pollutant carried upstream with the saline water will balance that carried downstream by the mean flow. Downstream it will have the same form as the salinity distribution and upstream the inverse of salinity distribution.

5.1.1. Theory and Assumptions

The turbulent transport are usually expressed in terms of empirical exchange coefficient for momentum and mass because the physical processes are hidden in these coefficients. They have to be determined for each specific estuary for the circumstances considered. For the application in estuarine studies the turbulent stresses and mass transports can be expressed in terms of concentration of any substance of interest. To compute the coefficient of eddy diffusivity the concentration of freshwater is taken as the substance of interest.

Stommel's theory of tidal mixing was the basic theory adopted for the computation of coefficient of eddy diffusivity and flushing time

The assumptions of the theory are

i) The vertical and horizontal changes in salinity are insignificant across the estuary than along the river.

ii) The estuarine conditions should be same at all tidal cycles.

5.1.2 Computation of Longitudinal coefficient of Eddy diffusivity and Flushing time.

Considering the vertically averaged values of longitudinal velocity and salinity over a tidal cycle and over a cross section normal to the flow, the volume and salt continuity relations are

$$Av_x = R$$

and

$$v_x s - K_x (ds/dx) = 0$$

Where A is the cross sectional area normal to the flow and R is the total river runoff, for convenience, v_x and s represent tidal mean value of the depth averaged values of velocity ($\langle v_x \rangle$) and salinity ($\langle s \rangle$) and K_x is a longitudinal diffusion coefficient as defined by this averaging process. The K_x coefficient is considered as an effective longitudinal dispersion coefficient rather than a simple eddy diffusion coefficient. For a well mixed estuary K_x is indeed simply the tidal diffusion coefficient; for a stratified estuary it includes both the tidal diffusion and circulation effects.

$$K_x = Rs/A(ds/dx)$$

Thus K_x may be calculated for any position in an estuary if the river flow, cross sectional area, and salinity are known.

Considering a conservative pollutant outfall along an estuary whose rate of supply to the estuary is W, a constant and c, the concentration of the pollutant, the pollutant continuity relations are

$$W = Rc - K_x A(dc/dx),$$

in a downestuary direction, and

$$0 = Rc - K_x A(dc/dx)$$

in an upestuary direction.

Considering the freshwater discharge as the rate of supply of pollutant into the estuary,

$$K_x = R(1-f)/A(df/dx)$$

where 'f' is the freshwater fraction.

If S is the salinity of mixed water, S_s and S_f be the salinities of sea water and freshwater, A, A_f and A_s are the area occupied by the mixed water, area occupied by freshwater and area occupied by the sea water respectively then for volume of unit width,

$$AS = A_s S_s + A_f S_f$$

$$AS = (A-A_f)S_s + A_f S_f$$

$$A(S_s-S) = A_f(S_s-S_f);$$

$$f = A_f/A = (S_s-S)/(S_s-S_f)$$

Since S_f is negligible compared to S_s

$$f = (S_s-S)/S_s \qquad \text{-------------} \quad (5.3)$$

Flushing time has been calculated from the volume of freshwater accumulated in the region and river discharge. Flushing time 'T' is the average time required for water to move through a portion of the estuary and is given by W_t/R; W_t is the total volume of water accumulated in the region and R is the river discharge.

then $T = W_t/R$

where

$$W_t = \text{Mean}(f).V, \text{ ie } \quad T = (\text{Mean}(f).V)/R \qquad \text{------} \quad (5.4)$$

'V' is the total volume of the estuarine region.

5.1.3. Annual variation of longitudinal coefficient of eddy diffusivity and Flushing time.

The computed values of longitudinal coefficient of eddy diffusivity are given in Table 5.1a - 5.1c. The diffusivity values were found to be almost equal in four sections during premonsoon season. In March it did not show any considerable variation and it has a constant value of $0.06m^2$/sec from lower reaches to 15kms upstream. During April and May also the variation in the diffusivity coefficients were found to be negligible. The low diffusivity values obtained during the premonsoon season shows the estuary was well mixed and influence of freshwater was very low. Diffusivity values showed a predominant variation in the monsoon period. It was $9.08m^2$/sec at river mouth during July when the river discharge was maximum and in the upper reaches of the estuary it was found to be zero due to the domination of freshwater. In postmonsoon season the diffusivity values decreases towards upstream and in December it varied between $0.26m^2$/sec to $0.06m^2$/sec from the marine end to the river end.

The flushing time was calculated for every month and is given in Table 5.2. It showed higher values during the premonsoon season and lower values during monsoon. After the postmonsoon season the value increased from January onwards and maximum value was computed in March (14.85 tidal cycles) and which shows that pollutants cannot be flushed out easily from the estuary during this period due to the low river runoff. In monsoon period the river discharge was high and the flushing time required to flush out the materials present in the estuary was very less. In July the value of flushing time was found to be 0.23 tidal cycle. Higher values were not observed during the postmonsoon period. 1.89 tidal cycle was the flushing time computed in October. During November and December the flushing time values were 1.60 and 4.81 tidal cycles respectively.

5.2. Mixing processes and Circulation patterns

During the premonsoon period, it was found that the state of the water column, whether mixed or stratified, was closely linked to the tidal cycle. This is an agreement with observations made by Hass (1977) in the James, York and Rappahanock Rivers. Tidal currents introduce momentum to the water column which may lead to turbulent mixing. The degree of mixing depends on the strength of the currents. The degree of stratification depends on the magnitude of freshwater flow with its associated input of buoyancy. The structure of the water column will then be governed by the interaction between the stabilizing influence of the buoyancy input on one hand and the turbulence associated with the tidal currents on the other hand. These ideas are discussed in greater detail by Nunes *et al* (1989).

During the period of higher influx of saline water, the water column was well mixed at high water and showed only small vertical salinity gradient at low water. Here the buoyancy of the incoming freshwater was insufficient to overcome the mixing due to strong tidal currents.

During the low and moderate river flow periods the water column was well stratified and the salinity gradient was high and especially at high water there is sufficient buoyancy in the incoming freshwater to overcome the mixing due to tidal currents.

5.2.1. Richardsons number

The gradient Richardsons number is defined as

$$R_g = \frac{-g d\rho/dz}{\rho(du/dz)^2} \qquad \text{---------------} \qquad (5.5)$$

Where ρ is the water density, u is the velocity at height z above bed and g is the acceleration due to gravity. R_g is a dimensionless number which essentially compares the stabilizing effect of density stratification ($d\rho/dz$), to the current shear which leads to mixing (du/dz). There is a theoretical critical value of $R_g = 0.25$, below which turbulent mixing of the water column may occur, although values utpo 1 are sometimes used for this limit (Pond & Pickard, 1983). For $R_g > 0.25$, the stratification should be sufficient to inhibit vertical mixing.

In practice, it is difficult to measure the required variables in eqn. 5.5 at sufficiently closed and spaced depth intervals. Hence Dyer and New (1986) suggests that when the mixing is due mainly to bed generated turbulence, the layer Richardsons number (R_L) would be more suitable for use as a simplified mixing criteria for partially mixed estuaries. The definition is

$$R_L = \frac{gh\ (\rho_b - \rho_s)}{U^2\ \rho_o} \qquad \text{--------} \qquad (5.6)$$

Where U is the depth mean velocity, ρ_o the depth mean density, h the water depth and $(\rho_b - \rho_s)$ the surface to bottom density difference. Calculation of R_L allows a quantitative estimate to be made of the intensity of mixing at different stages of the tide in a partially mixed estuary. The observations made by Dyer and New (1986) indicate that when $R_L < 2$ the bed generated turbulence is the main mixing process. For $R_L > 20$, the water column is stable and bottom turbulence is not effective in mixing.

Postmonsoon

The $\log R_L$ values vary from 3.08 to - 0.045 at section-I and from 3.88 to -0.45 at section-II respectively from the maximum stratification period to the minimum stratification period. During ebb tide strong currents lead to increased turbulence and mixing. At both the sections the bottom generated turbulence would have been greater due to the high value of seaward velocity and the outflowing layer was in direct contact with the bed. During the postmonsoon season the river discharge was moderately high and during high tide also the surface layer was found to be lower in salinity and maximum stratification was found at section-II during high tide. As shown in Fig. 5.1 the hourly salinity profiles taken at section-I and section-II over this period indicate the formation of a higher vertical salinity gradient at 1200 to 13hrs and it reduced to a minimum at 1700hrs. The computed value of R_L showed a similar variation, ie maximum when the stratification was stabilized (Fig. 5.2.1 & 5.2.2) and minimum when the the lower layer of the water column caused considerable bed generated turbulence at both the sections. This was reflected in the rapid decrease of R_L at both sections when the stratification was weak.

Premonsoon

During the premonsoon period river discharge into the estuarine system was very low and tidal influx was higher comparing with other seasons. LogR_L vary from 0.38 to -0.206 at section-I and from 0.38 to -0.106 at section-II. The maximum intensity of mixing was observed during this period. Due to the higher influence of saline water, both the sections were found to be weakly stratified, so that the computed value of R_L did not show a higher value in the entire tidal observation. Strong inflow in the lower layer of the water column caused considerable bed generated turbulence at both the sections, I & II. This was reflected in the lower values of R_L during this period of study.

Monsoon

At the river mouth section of the estuary higher stratification values were observed due to the high freshwater flow from the upper reaches of the estuary and the logarithmic value of the Richardsons number shows a significant variation from 2.377 to -0.82 from high tide to low tide because the salinity intrusion was predominant only during the high tidal phase and high vertical gradient in salinity was observed during this period. At section-II the

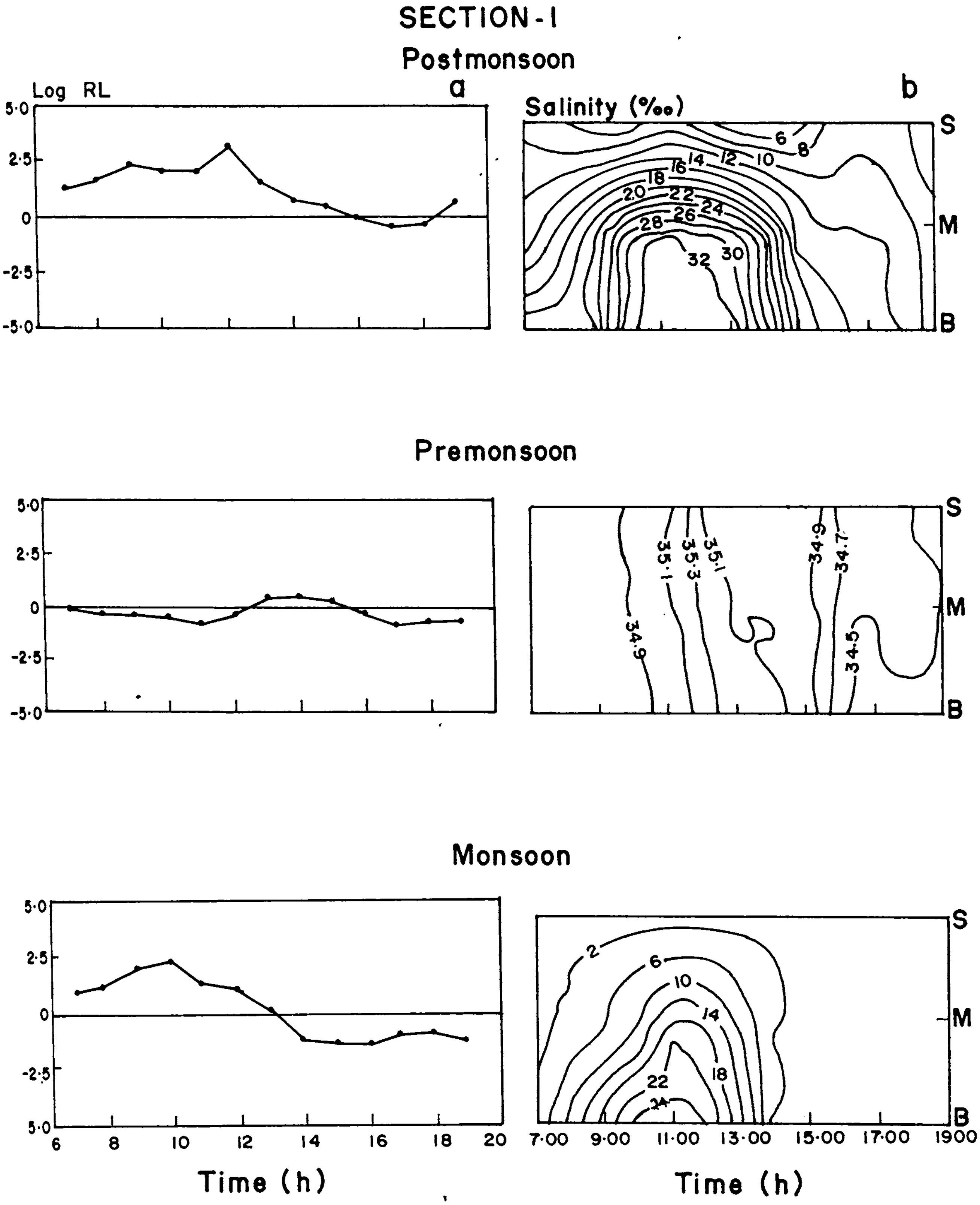


Fig.5.2.1. Semidiurnal and seasonal variation of Log RL(a) and Salinity. (b)

SECTION-II

Postmonsoon

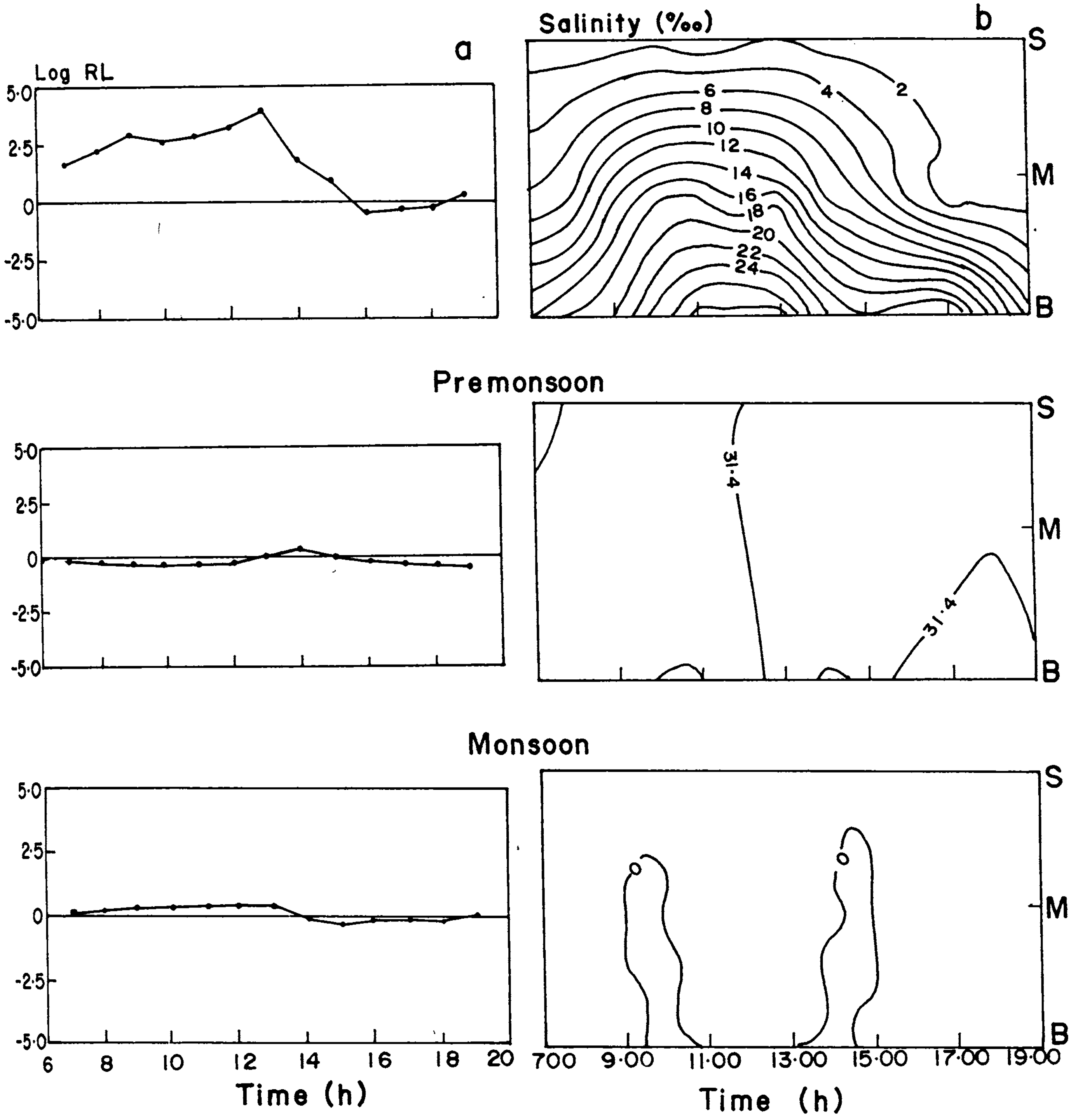


Fig. 5.2.2. Semidiurnal and seasonal variation of Log RL(a) and Salinity. (b)

intrusion of saline water was very less and the Richardsons number did not show any significant variation. Maximum freshwater discharge was observed during the monsoon season. Hourly salinity profile showed the maximum salinity gradient at 1100hrs was significant at section-I. Just an hour prior to this time Richardson number reached the maximum, confirming the high stratified condition. As the seaward flow due to freshwater discharge increases the influx of saline water was very less and surface to bottom density difference (ρ_b - ρ_s) becomes negligibly small and the depth mean velocity reached maximum and the corresponding value of R_L reduced to a minimum value. A noticeable variation in the computed values of R_L were found during this period study.

5.3 Surface salinity distribution modelling

The longitudinal variation of surface salinity of the Beypore estuary is given in Fig. 5.3 and the surface salinity distribution is given in Fig. 5.4. The estuary is considered to be laterally homogeneous and while drawing the longitudinal distribution of salinity an equation is obtained for the months in which salinity intrusion was obtained upto the upper most section of the estuary. The equations for the surface salinity distribution are

December

$Y = -1.4862X + 24.309$

January

$Y = -1.4198X + 29.95$

February

$Y = -1.0418X + 32.69$

March

$y = -0.7668X + 34.63$

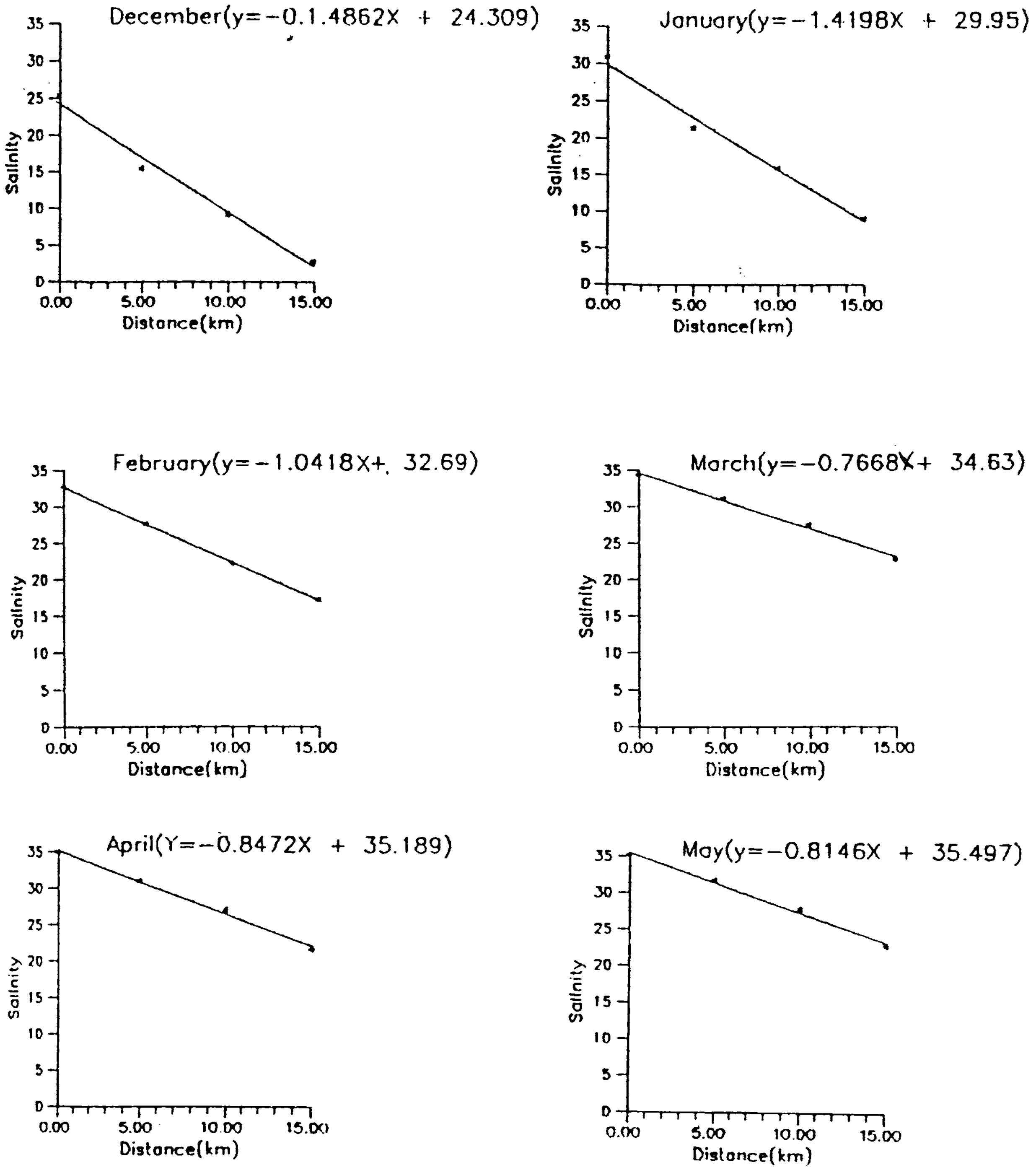
April

$y = -0.8742X + 35.19$

May

$y = -0.8146X + 35.497$

Using the above equations the salinity may be obtained at any position in the estuary. The salinity values at every 2×10^{-3} interval is plotted in the graph. During December the surface salinity varying from 22×10^{-3} to 4×10^{-3} from 1.55km to 13.66km. The variation was from 28×10^{-3} at 1.37km to 10×10^{-3} at 14.05km in January and from 32×10^{-3} at 0.66km to 18×10^{-3} at 14.10km in February. During the peak period of the premonsoon season (March, April and May) the intrusion of salinity was maximum and the surface salinity values varied between 34×10^{-3} at 0.82km to 24×10^{-3} at 13.86km in March, 34×10^{-3} at 1.36km to 24×10^{-3} at 12.80km in April and 34×10^{-3} at 1.84km to 24×10^{-3} at 14.11km in May.


December(y=-0.1.4862X + 24.309)

January(y=-1.4198X + 29.95)

February(y=-1.0418X+. 32.69)

March(y=-0.7668X+ 34.63)

April(Y=-0.8472X + 35.189)

May(y=-0.8146X + 35.497)

Fig. 5.3 Longitudinal variation of surface salinity

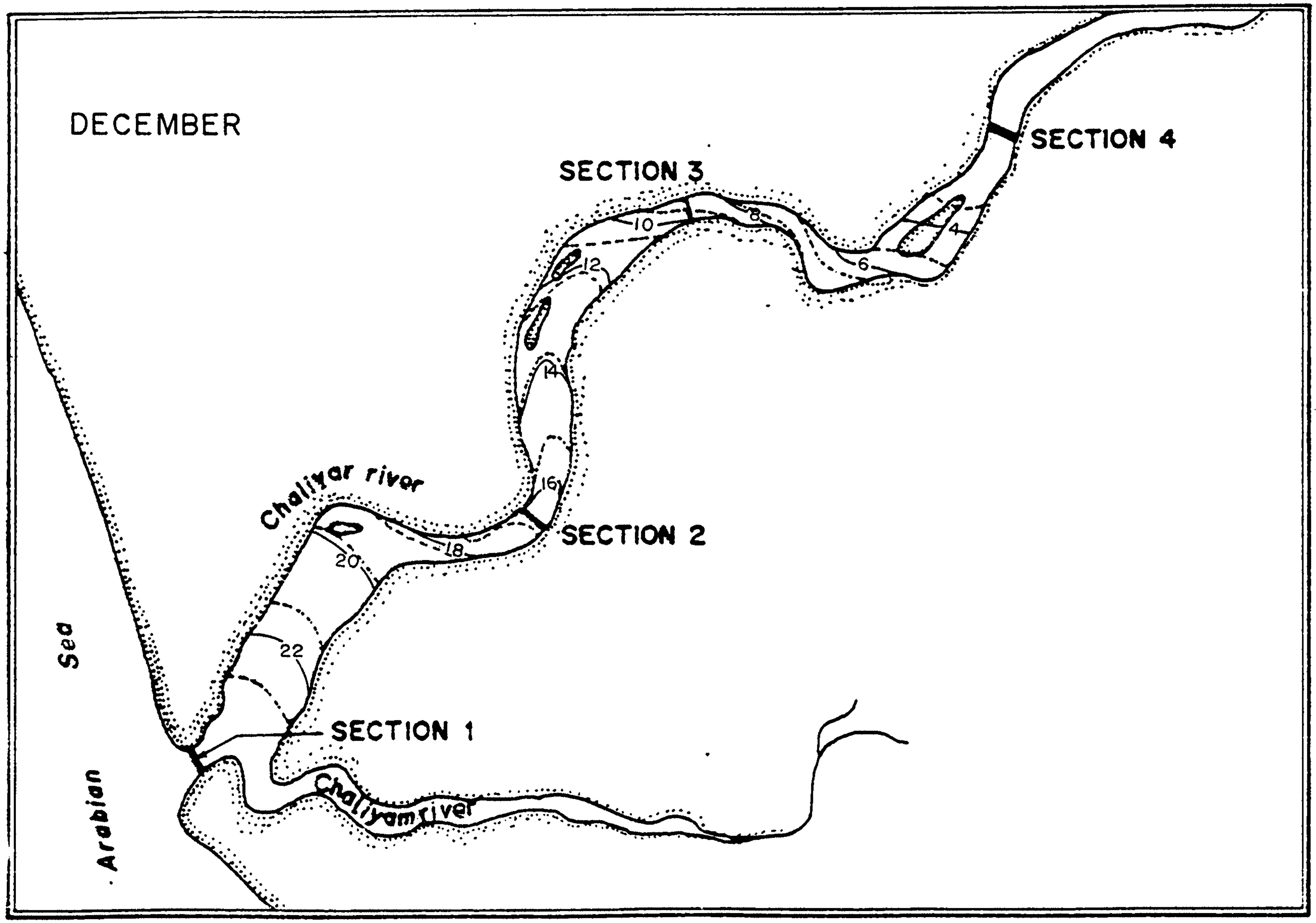


Fig. 5.4. Surface salinity distribution in the Beypore estuary.

······ Distance at 1 km interval., —— Salinity (‰)

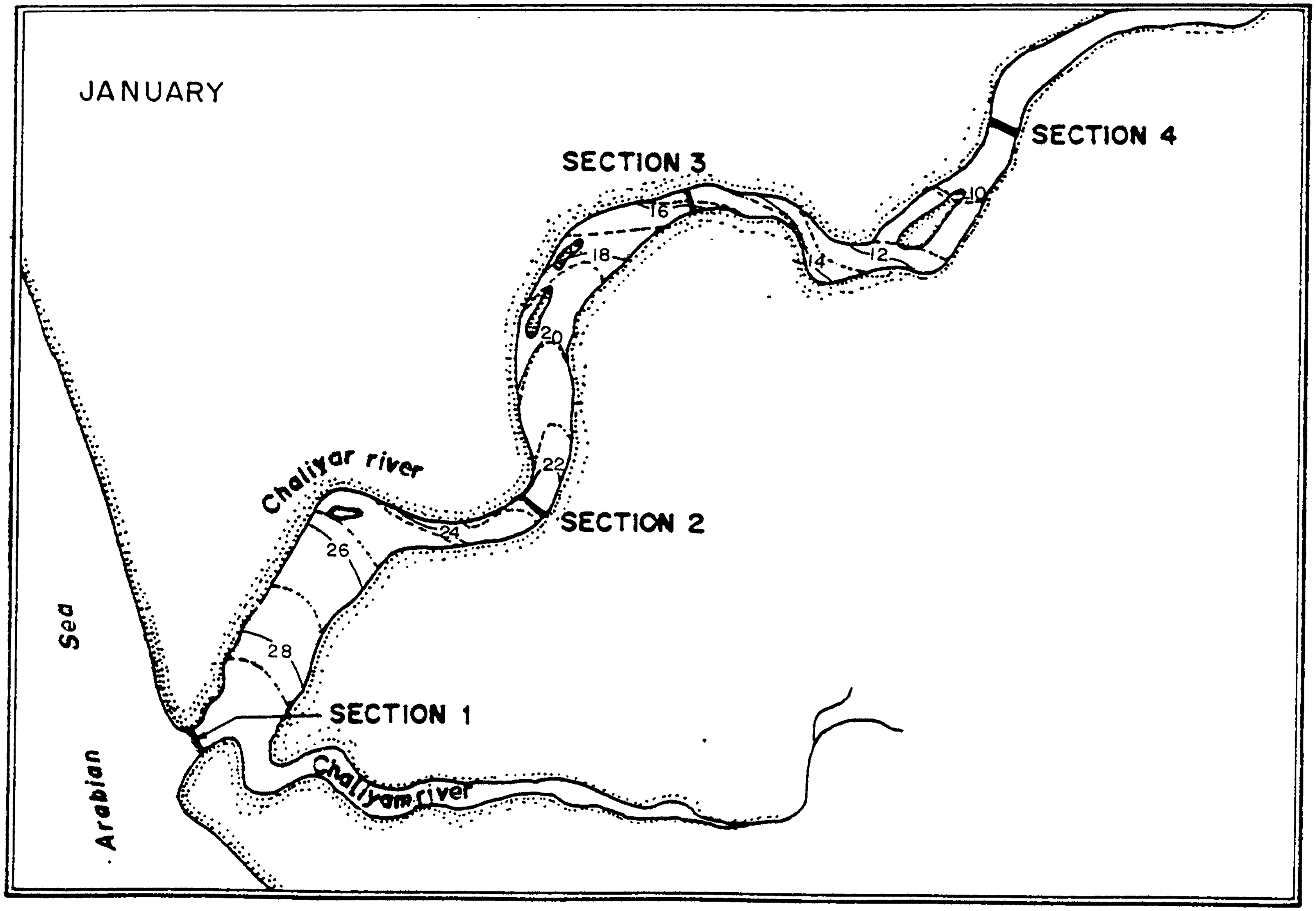


Fig. 5.4. Surface salinity distribution in the Beypore estuary.

······ Distance at 1 km interval., —— Salinity (‰)

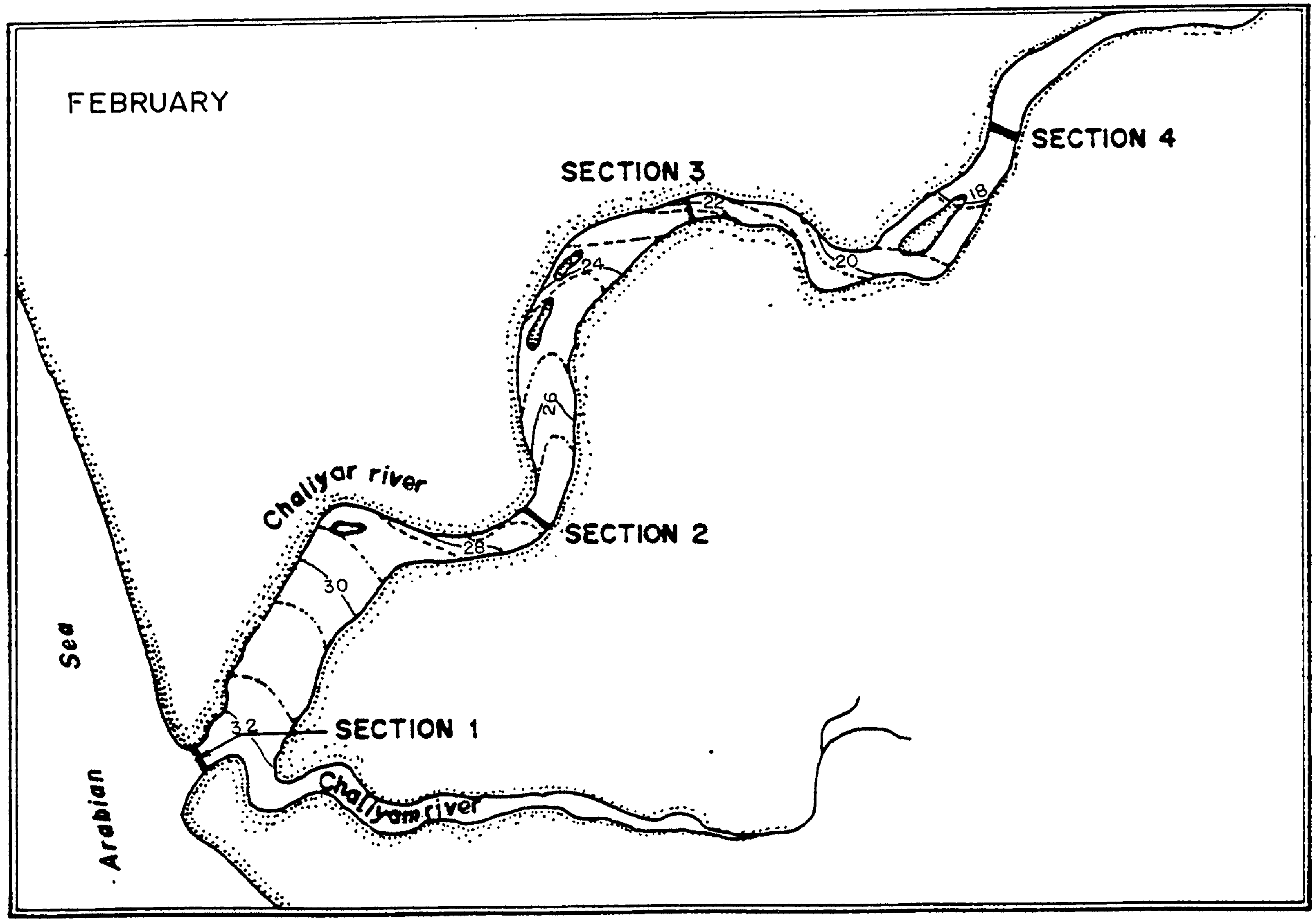


Fig. 5.4. Surface salinity distribution in the Beypore estuary.

...... Distance at 1 km interval., —— Salinity (‰)

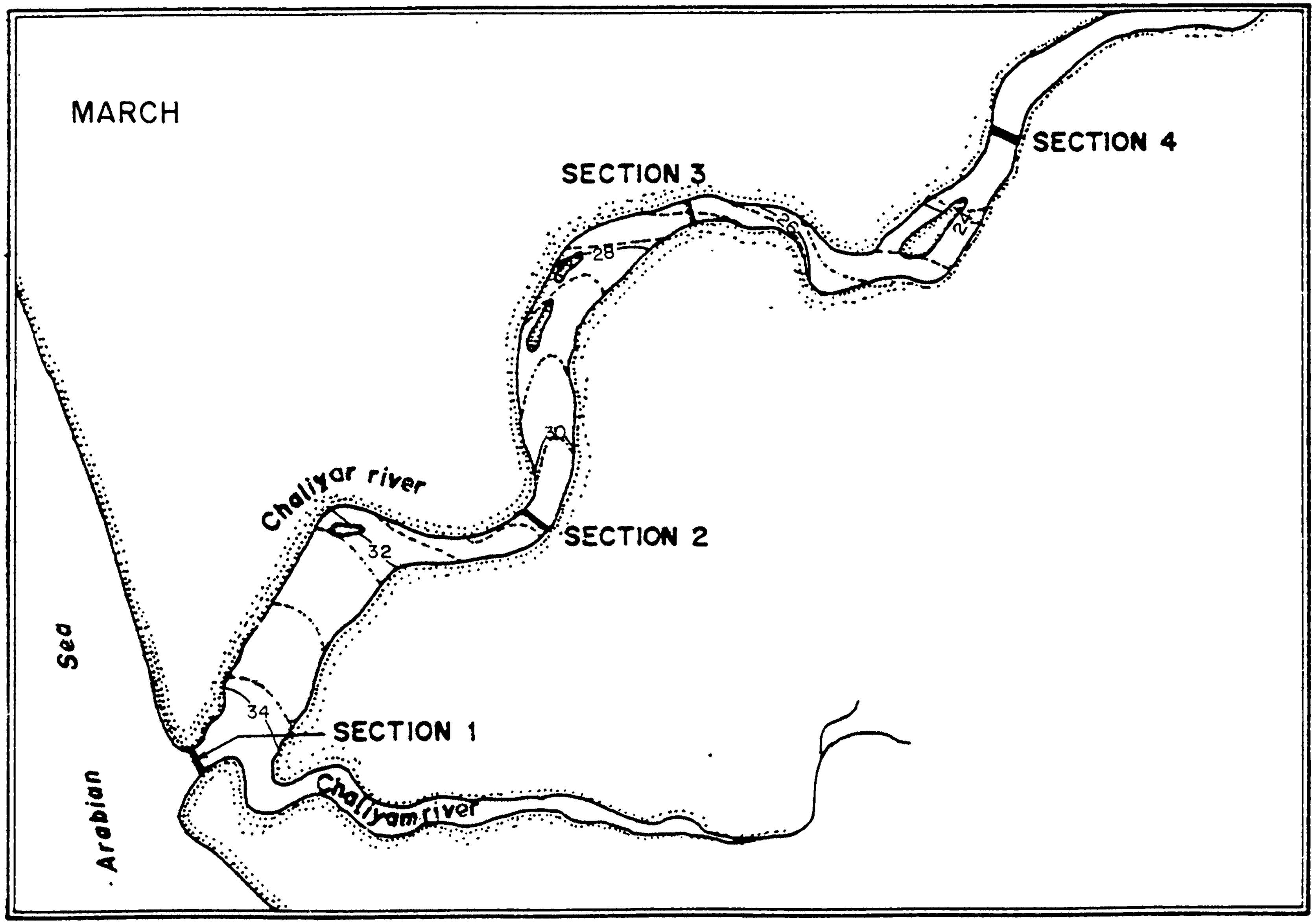


Fig. 5.4. Surface salinity distribution in the Beypore estuary.
······ Distance at 1 km interval., —— Salinity (‰)

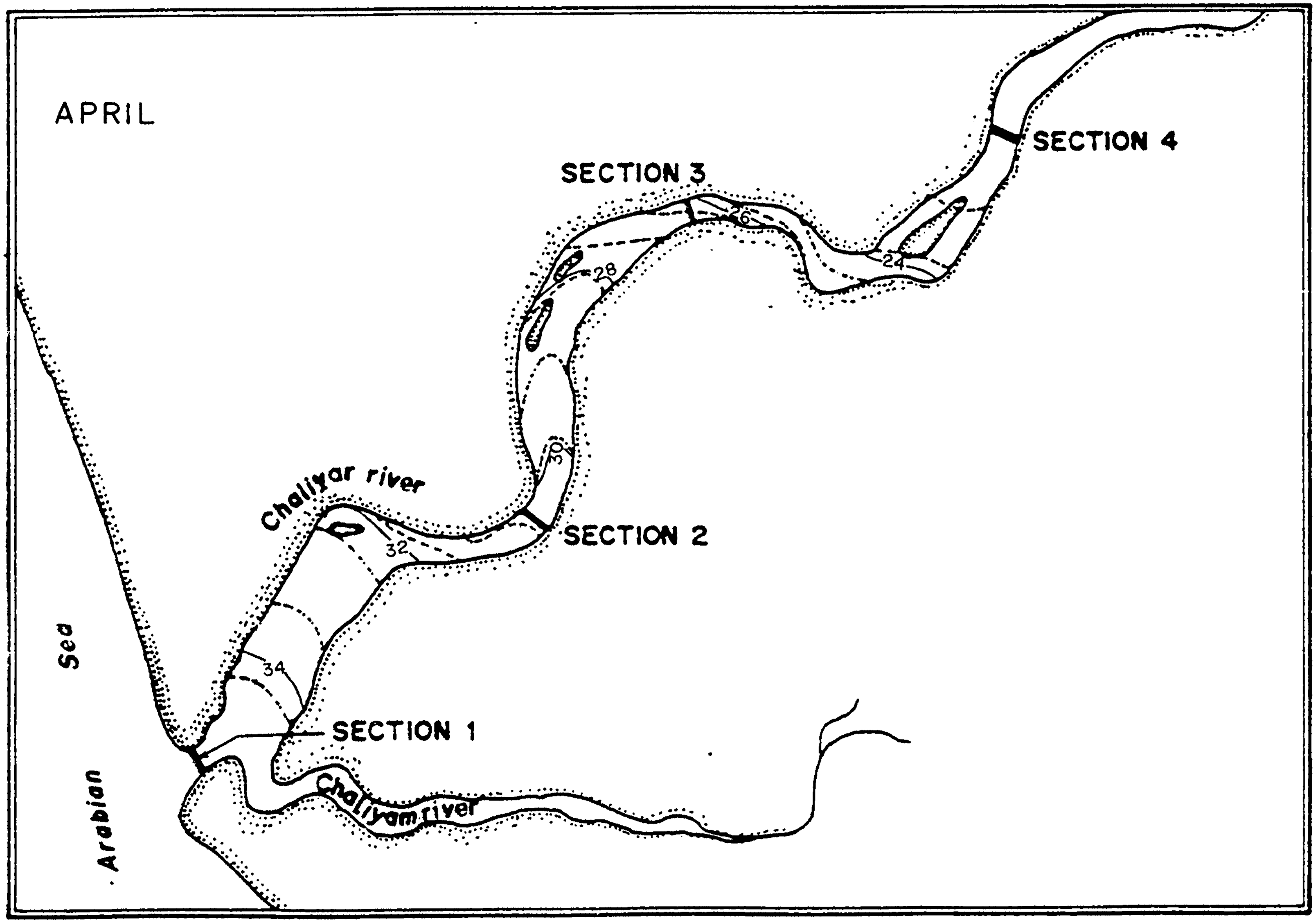


Fig. 5.4. Surface salinity distribution in the Beypore estuary.

······ Distance at 1 km interval., —— Salinity (‰)

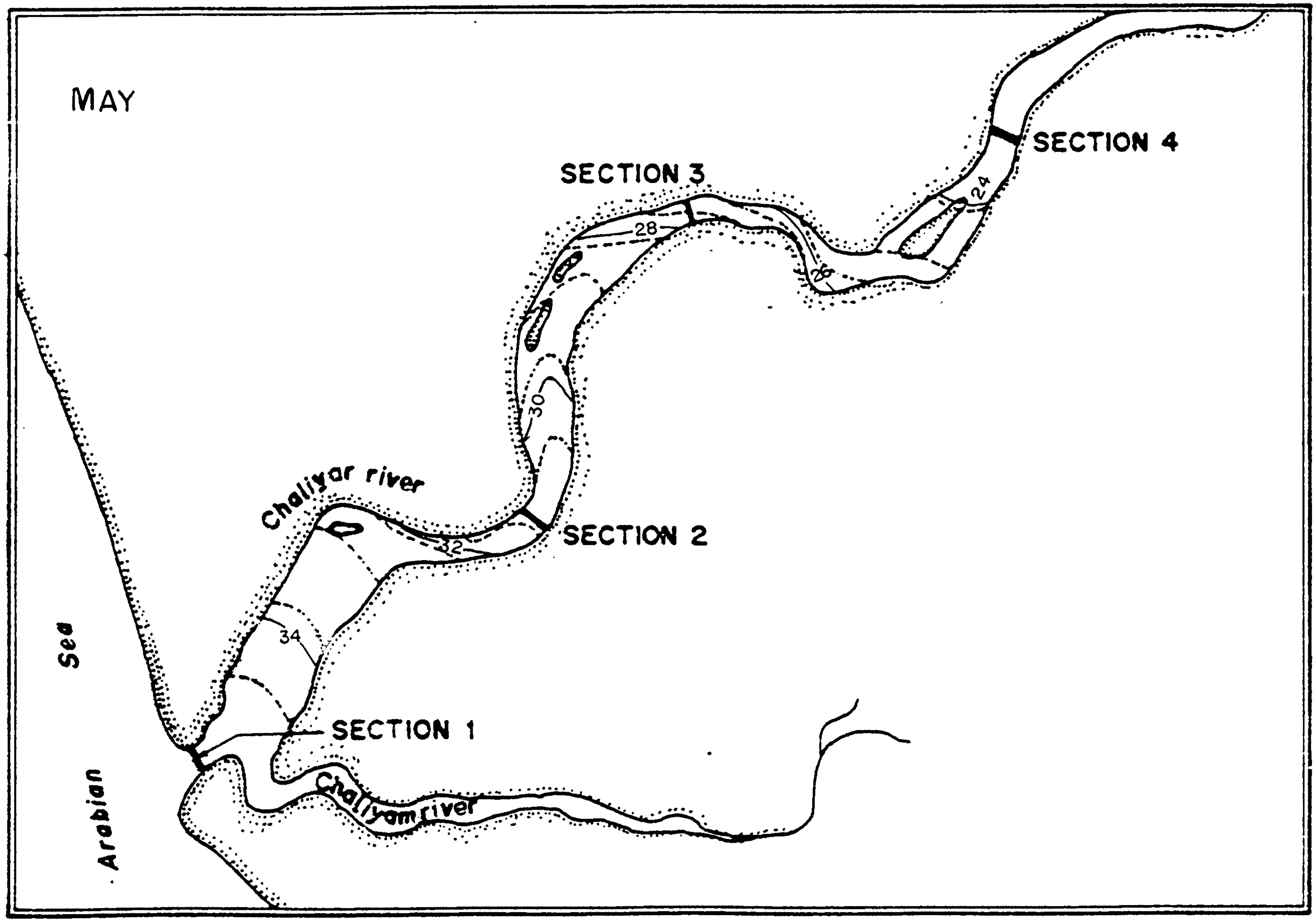


Fig. 5.4. Surface salinity distribution in the Beypore estuary.

······ Distance at 1 km interval., —— Salinity (‰)

Table 5.1a Longitudinal coefficient of eddy diffussivity for different months.

Section	Distance from the mouth. (km)	Cross-sectional area. (m^2)	Fresh water fraction.	River discharge (m^3/s)	Longitudinal eddy diffusivity (m^2/s)
October					
I	0.5	1138.80	0.49	71.03	0.95
II	5.0	1029.00	0.71		0.59
III	10.0	906.50	0.99		0.02
IV	15.0	736.29	0.99		0.02
November					
I	0.5	1123.20	0.40	80.36	1.07
II	5.0	1022.00	0.74		0.49
III	10.0	903.00	0.98		0.04
IV	15.0	717.00	0.99		0.01
December					
I	0.5	1150.00	0.19	17.14	0.26
II	5.0	1038.00	0.39		0.23
III	10.0	912.54	0.64		0.14
IV	15.0	743.58	0.88		0.06
January					
I	0.5	1068.60	0.08	8.51	0.17
II	5.0	976.08	0.32		0.14
III	10.0	870.33	0.51		0.11
IV	15.0	692.55	0.73		0.08

Table 5.1b Longitudinal coefficient of eddy diffussivity for different months

Section	Distance from the mouth. (km)	Cross-sectional area. (m^2)	Fresh water fraction.	River discharge (m^3/s)	Longitudinal eddy diffusivity (m^2/s)
February					
I	0.5	1017.90	0.06		0.11
II	5.0	937.86	0.15	3.44	0.11
III	10.0	844.00	0.33		0.09
IV	15.0	661.00	0.48		0.09
March					
I	0.5	1138.80	0.01		0.06
II	5.0	1029.00	0.09	1.60	0.06
III	10.0	906.50	0.18		0.06
IV	15.0	736.29	0.31		0.06
April					
I	0.5	939.90	0.00		0.10
II	5.0	879.06	0.09	2.19	0.10
III	10.0	804.00	0.19		0.09
IV	15.0	612.36	0.32		0.09
May					
I	0.5	1033.50	0.00		0.08
II	5.0	949.62	0.11	1.80	0.08
III	10.0	852.24	0.19		0.07
IV	15.0	670.68	0.33		0.07

Table 5.1c Longitudinal coefficient of eddy diffussivity for different months

Section	Distance from the mouth. (km)	Cross-sectional area. (m^2)	Fresh water fraction.	River discharge (m^3/s)	Longitudinal eddy diffusivity (m^2/s)
June					
I	0.5	1053.00	0.89		3.97
II	5.0	964.32	0.97	273.33	0.04
III	10.0	862.29	1.00		0.00
IV	15.0	682.83	1.00		0.00
July					
I	0.5	1111.50	0.91		9.08
II	5.0	1008.42	1.00	670.00	0.00
III	10.0	892.44	1.00		0.00
IV	15.0	719.28	1.00		0.00
August					
I	0.5	975.00	0.80		5.08
II	5.0	905.52	0.93	329.66	0.57
III	10.0	822.09	1.00		0.00
IV	15.0	634.23	1.00		0.00
September					
I	0.5	967.20	0.48		1.12
II	5.0	899.64	0.73	73.00	0.72
III	10.0	818.07	0.88		0.09
IV	15.0	629.37	0.99		0.01

Table 5.2 Flushing time for different months

Months	Flushing Time (Tidal cycles)
October	1.89
November	1.60
December	4.81
January	7.34
February	10.70
March	14.85
April	9.72
May	10.85
June	0.54
July	0.23
August	0.41
September	1.54

CHAPTER VI

DISTRIBUTION AND FLUX OF SUSPENDED SEDIMENT

Introduction

Estuaries are complex dynamic systems that serve as a transition zone between terrestrial and marine environments. Dynamic estuarine processes control the distribution and transportation of suspended sediments. Estuarine processes vary in a systematic manner within tidal cycles (semi-diurnal, diurnal), weather cycles(seasonal and inter annual cycles) (Dyer, 1986; Kjerfve and Magill, 1990). The variability of freshwater discharge at the upstream boundary has a major control on sediment concentration and transport (Scubel and Pritchard, 1986; Sharp et al., 1986; Williams, 1989) together with tidal forcing at the down stream boundary (Uncles, 1983; Aubrey, 1986; Abraham, 1988). The freshwater discharge and tidal forcing produce density gradient circulation and salinity stratification within the estuaries and can be directly related to the distribution of total suspended sediment concentration.

The suspended sediments in rivers play a vital role in transporting material from land to sea. Sand, silt, clay, debris from agricultural fields and inorganic matter from weathering of rocks etc. constitute the suspended matter in the rivers and are contributed substantially by the tributaries and bank erosion during the downstream flow towards the sea (Nair *et al.*, 1987). Particulate matter generated by biological productivity may also be important in the formation of suspended sediments in the lower portion of estuaries (Biggs, 1970). Infrequent catastrophic storms augment normal riverine sediment load (Schubel, 1974). The suspended matter of the freshwater after coming into contact with sea water flocculates and creates zones of turbidity maxima (Nair *et al.* 1987). Primary production is inhibited by the turbidity and sedimentation destroys spawning grounds of fishes. High concentrations are detrimental to river fish also. The distribution pattern of the suspended solids would reveal the information on pollutant concentration and dispersion. Sedimentation in the harbours and bays is a problem for navigation at several places along the west coast of India. An understanding of the sources and sinks of suspended sediment is very important for the sediment management of the estuaries.

The turbidity maximum zone occurs the downstream from the interface between fresh and saline waters in most coastal plane estuaries. It is a region of high total suspended sediment concentration as compared to the other parts of the estuary. The mechanisms responsible for the formation of this zone are the estuarine circulation (Dyer, 1986) flocculation deflocculation and total resuspension (Festa and Hansen, 1978).

To explain the distribution and dynamics of total suspended sediment in an estuary it is imperative to understand the governing processes of the estuarine system. Comprehensive estuarine studies have been conducted on the

Chesapeake Bay (Biggs, 1970; Blumberg, 1977; Officer, 1980; Scubal and Pritchard, 1986), Delavare Bay (Sharp *et al.*, 1986), Sanfransisco Bay (Conomos and Peterson, 1976). Comparisons between estuaries reveal large differences in total suspended sediment characteristics due to different freshwater discharge, tidal characteristics and sediment sources.

If the tidal current is strong and turbulent, considerable amount of suspended matter is set into motion. The turbulent motion of tidal current may carry even coarse sand to the surface especially when tide is at a maximum. The suspended matter is divided into two, Sand and Silt. The boundary between these two fractions is 50 μ, sand behaves in a different manner with silt in the tidal currents. Silt contains fine grained sand, clay mineral and particulate organic matter. Critical erosion velocity is the minimum current velocity at which sediment of a particular size begins to move. The movement stops at a flow velocity called the lowest transportation velocity. Critical erosion velocity depend on current velocity indirectly. The important factors are the attractive force acting on the bottom, the roughness of the bottom and turbulence etc.. Critical erosion velocity increases with increasing grain size. The deposition velocity is slightly smaller and is usually about two third of the erosion velocity. Fine grained suspended matter reacts with an inertia to the change of current velocity. When current velocity reduces to zero during turn of tidal phase the suspended matter is not at its minimum value because there is time lag between the deposition of suspended load and slackening of current velocity.

Particles settling in slackening current are not deposited vertically below the place where they start to drop out, they require time to reach the bottom and are carried to some distance before they come to rest, which is known as settling lag. Scor lag is the difference between transport velocity and erosion velocity. In settling lag the distance covered by the particles depends on (1) the settling velocity of the particle, (2) the current velocity in the period of sinking and (3) depth of the water.

In estuaries with weaker tidal influence stratification is maintained over the whole tidal cycle and the salt wedge is a predominant feature, water movement in this wedge is very slow. In such cases the wedge may be filled up with sediments so that the bar is formed. In the lower reaches of many rivers where the estuarine circulation is developed the concentration of suspended matter attains value considerably higher than those in the river water and the sea. It is usually located near the end of salt wedge.

Particles carried downstream sink to lower water layer and with residual water movement it goes upstream and by mixing it comes to the surface and again takes downstream, by repeating the process the particle is gradually carried to the sea. In a saltwedge estuary, the stratified region, acts as a sediment trap in which sedimentary materials of either fresh or marine origin may be circulated many times. High concentration of suspended matter may be accumulated.

In a turbidity maximum zone under a given set of conditions only a restricted size range can be present. Particles of smaller size sinking slowly will escape to the open sea, as there will not be sufficient time to settle to the bottom layers. Particles of larger size sinking rapidly, vertical mixing will not be able to carry them back to the surface layer. Hence only suspended matter of a specific size will be repeatedly recirculated and contribute to the formation of the turbidity maximum.

Estuaries may contain coarse grained sediments as well as fine grained deposits, out of these two which is more important depends on the shape of the estuary, river flow, the amount of fine grained suspended matter available and the strength of the tidal currents.

Estuarine sediments ranged all the way from fine granular sand common in most beaches to very fine colloidal materials in suspension. Intrusion of the sea water into the mouth near the bottom, which combined with low river discharge produce a predominance of upstream velocities near the bottom. When the upstream velocities are very high for a short period, they can move much larger quantities of suspended sediment than which carried in the lower ebb velocities over a longer period. The effect of upstream net flow in higher velocity range near the bottom was not balanced until the river discharge assumes higher values.

The local sources of sediment are 1) Marsh areas adjacent to the estuary 2) in large estuaries materials eroded from shores move into large deeper portions by density currents 3) by dredging or propeller wash 4) from organic materials 5) industrial and human wastes 6) windborne sediments. In an actual estuary the sediment transport is a complex processes of erosion and deposition, dispersion and consolidation, variable with the change of tides and freshwater flow.

6.1 Longitudinal distribution of suspended sediment concentration during flood and ebb tidal phases.

The observations during the flood and ebb tide in all months during the period of study were used to isolate the effect of tide on the suspended sediment distributions, which are presented in Fig. 6.1.1 - 6.1.3

The suspended sediment concentration was always higher at high tide than at low tide. From Fig. 6.1.1 and 6.1.2 it can be seen that during the postmonsoon and premonsoon season higher concentration of suspended matter was observed during flood tide. But in the monsoon season the entire study area was found to be highly concentrated in suspended matter at both the tidal phases (Fig. 6.1.3). In October suspended matter concentration ranged from 16mg/l to 44mg/l from surface to bottom at river mouth during flood tide. During ebb tide it ranged from 12mg/l to 16mg/l from surface to bottom. During November and December a similar type of distribution was observed during flood and ebb tidal phases. The sediment concentration was found to increase in January and February and higher concentrations were observed during flood tide and lower concentrations were observed during the ebb tide. In March, April and May higher values of suspended sediment were observed due to the high influx of saline water during flood tide which cause the resuspension of bottom material especially in the lower reaches of the estuary. These suspended matter were taken to the upper reaches by the strong tidal currents. The maximum value of the suspended load in the premonsoon season was observed during May. At flood tide the suspended sediment distribution during this month became vertically stratified with a near bottom value of 70mg/l and a surface value of 32mg/l. The surface to bottom variation during ebb tide was negligible compared to that in flood tide during this season.

During the monsoon season the large flux of freshwater with its high suspended sediment load caused several modifications in the suspended sediment distribution. The entire study area of the estuary was found to be highly turbid during this season due to the sediment brought by the high river flow. Higher values of suspended particulate matter was obtained during June, July and August. A maximum value of 120mg/l was obtained in July at bottom of the river

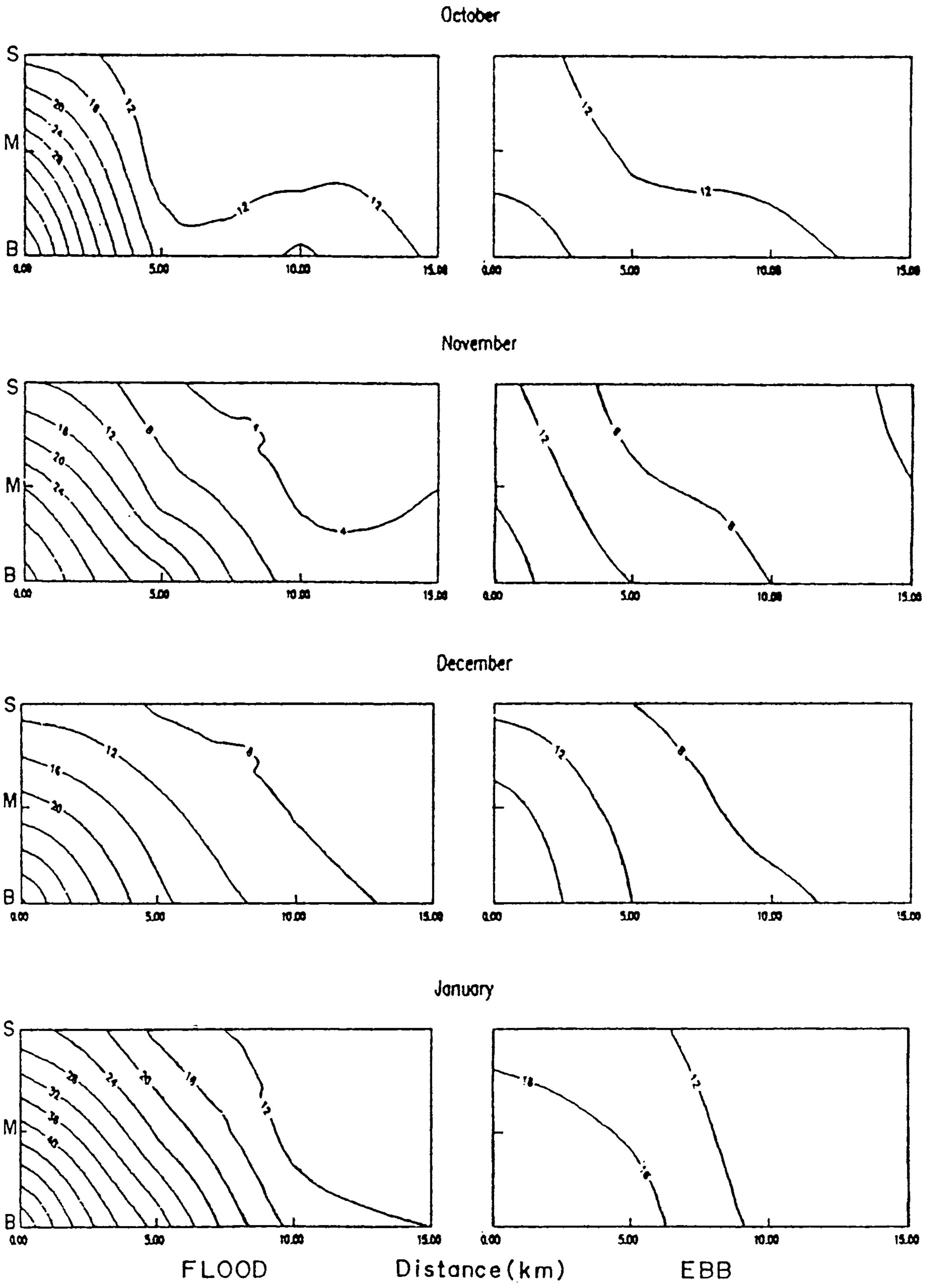


Fig. 6.1.1 Longitudinal variation of the suspended sediment concentration during flood and ebb tidal phases.

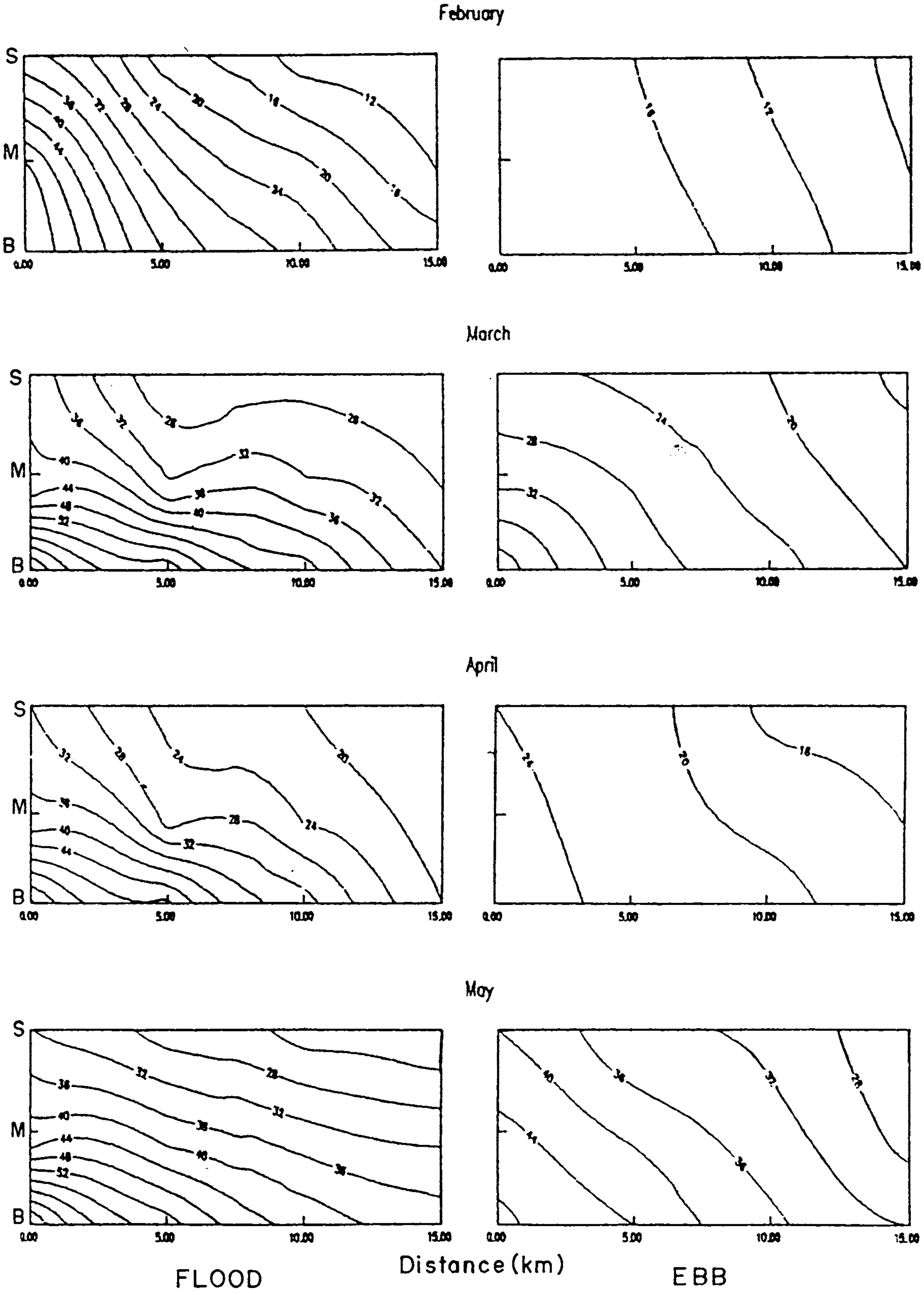


Fig. 6.1.2 Longitudinal variation of the suspended sediment concentration during flood and ebb tidal phases.

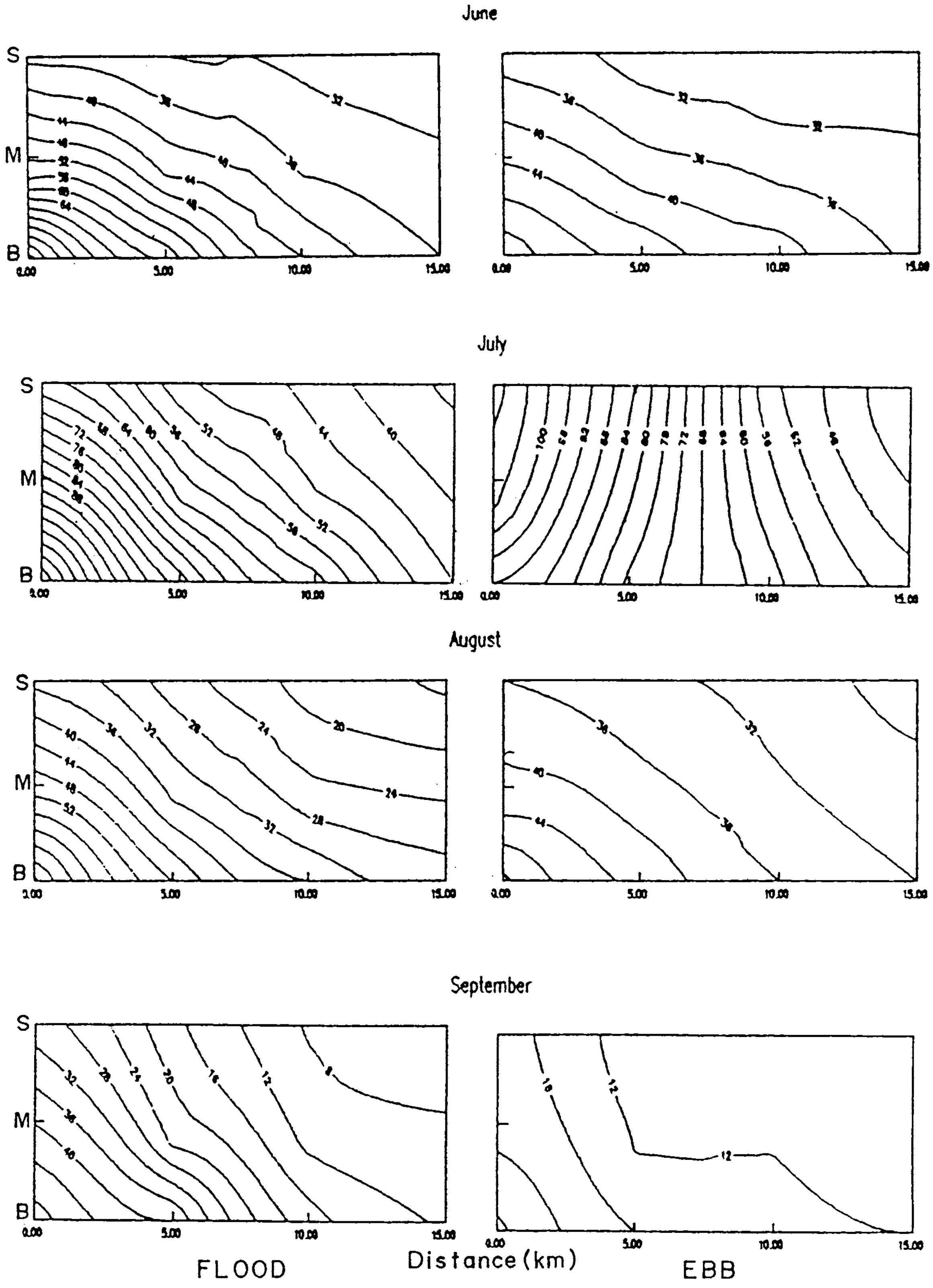


Fig. 6.1.3 Longitudinal variation of the suspended sediment concentration during flood and ebb tidal phases.

mouth section and 65mg/l at surface during flood tide. During ebb tide surface related maximum value of 110mg/l was obtained in July. This surface related maxima may be due to the transportation of sediment from upper regions of the estuary. Though the distribution shows a two layer transport process during this period of high river discharge the seaward transport greatly exceeds the upstream transport of the suspended matter. Observations in August showed a bottom value of 70mg/l and a surface value of 30mg/l at river mouth during flood tide. Not much vertical variations were found during low tide. In September the suspended particulate matter concentrations at river mouth varied from 30 mg/l to 50mg/l from surface to bottom during flood tide. During ebb tide the concentrations were very less and no noticeable variation was found.

Most of the observation periods the dynamics of the Beypore estuary was dominated by the tidal currents. River sediment input was higher during the monsoon season. During the postmonsoon period the suspended particulate matter concentrations was less compared to the other seasons. The suspended sediment concentration rise and fall as a function of the semidiurnal tide.

6.2 Semidiurnal and seasonal variation of suspended sediment concentration

The maximum value of the suspended sediment concentration during postmonsoon season was obtained at the river mouth section during flood tide. It varied between 15mg/l to 55mg/l from surface to bottom at the peak flood period (Fig. 6.2.1a). The upstream current velocity was 10cm/s during the peak flood period. A surface related higher concentration of suspended sediment at the river mouth was found during this season due to comparatively high river discharge. The suspended load during the peak flood period varied only between 10mg/l to 15mg/l from surface to bottom at the upper reaches of the estuary (Fig. 6.2.1b). The concentration of suspended sediment during this season was maximum at the peak flood period, due to the resuspension created (Fig. 6.2.1a) at the lower reaches of the estuary.

Higher tidal influx was observed during the premonsoon period. The estuary was well mixed due to the higher intrusion of saline water. From Table 6.1 it has been found that sediments of sections I & II contain more silt and clay percentage. So these sections are capable of getting more suspended load compared to section III & IV, which are composed of 90 to 99% sand and the strong currents produce high resuspension in the lower reaches of the estuary. Sediment concentration in the water column varied between 40mg/l to 60mg/l from surface to bottom at flood tide at the river mouth section (Fig. 6.2.2a). The variation was more predominant at the lower reaches of the estuary. The bottom related maxima of the suspended sediment was due to the tidal resuspension of the bed sediments. There was a net upstream transport in the bottom layer which mostly compensate the

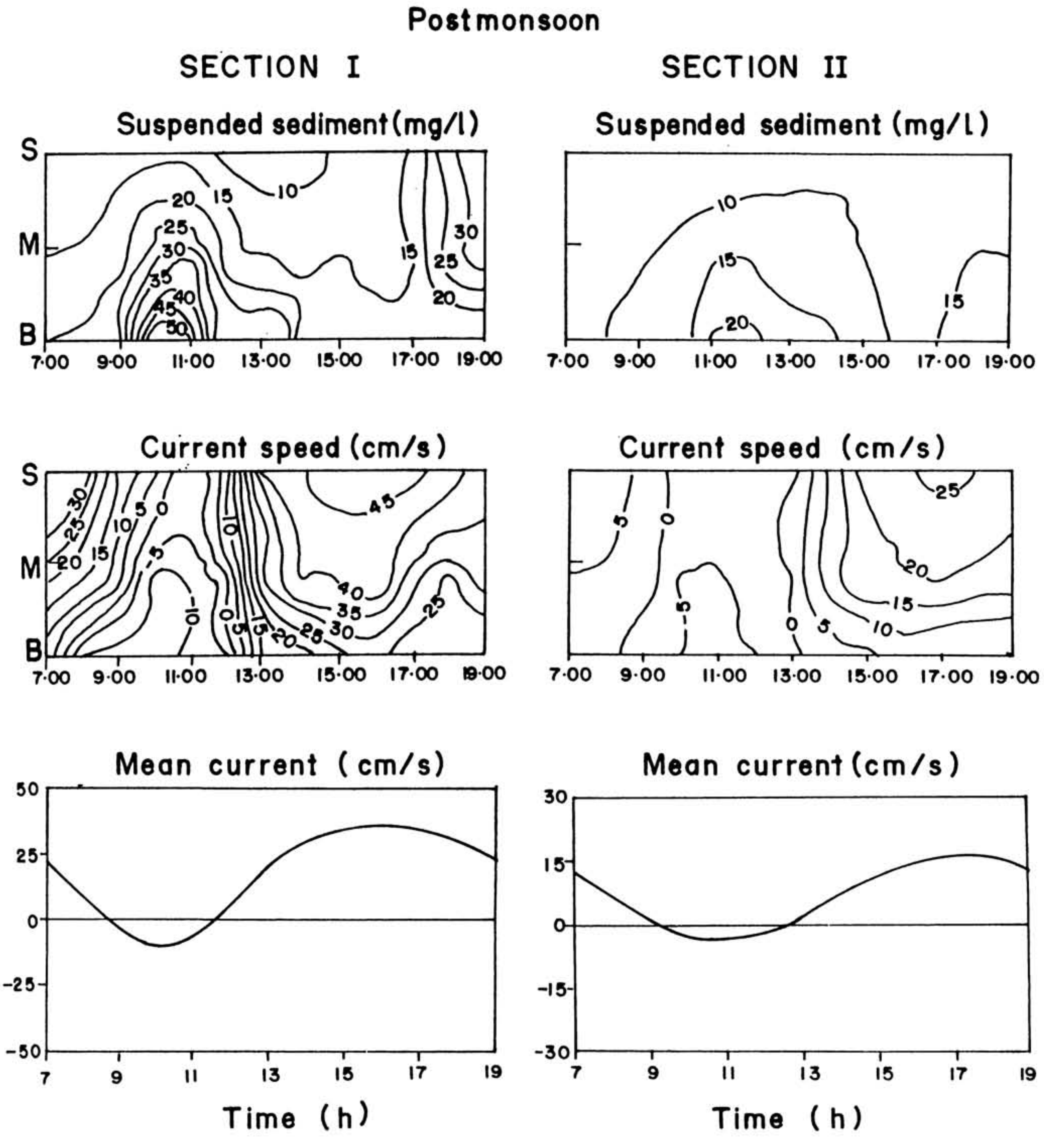


Fig. 6.2.1a. Semidiurnal variation of suspended sediment concentration during post-monsoon season.

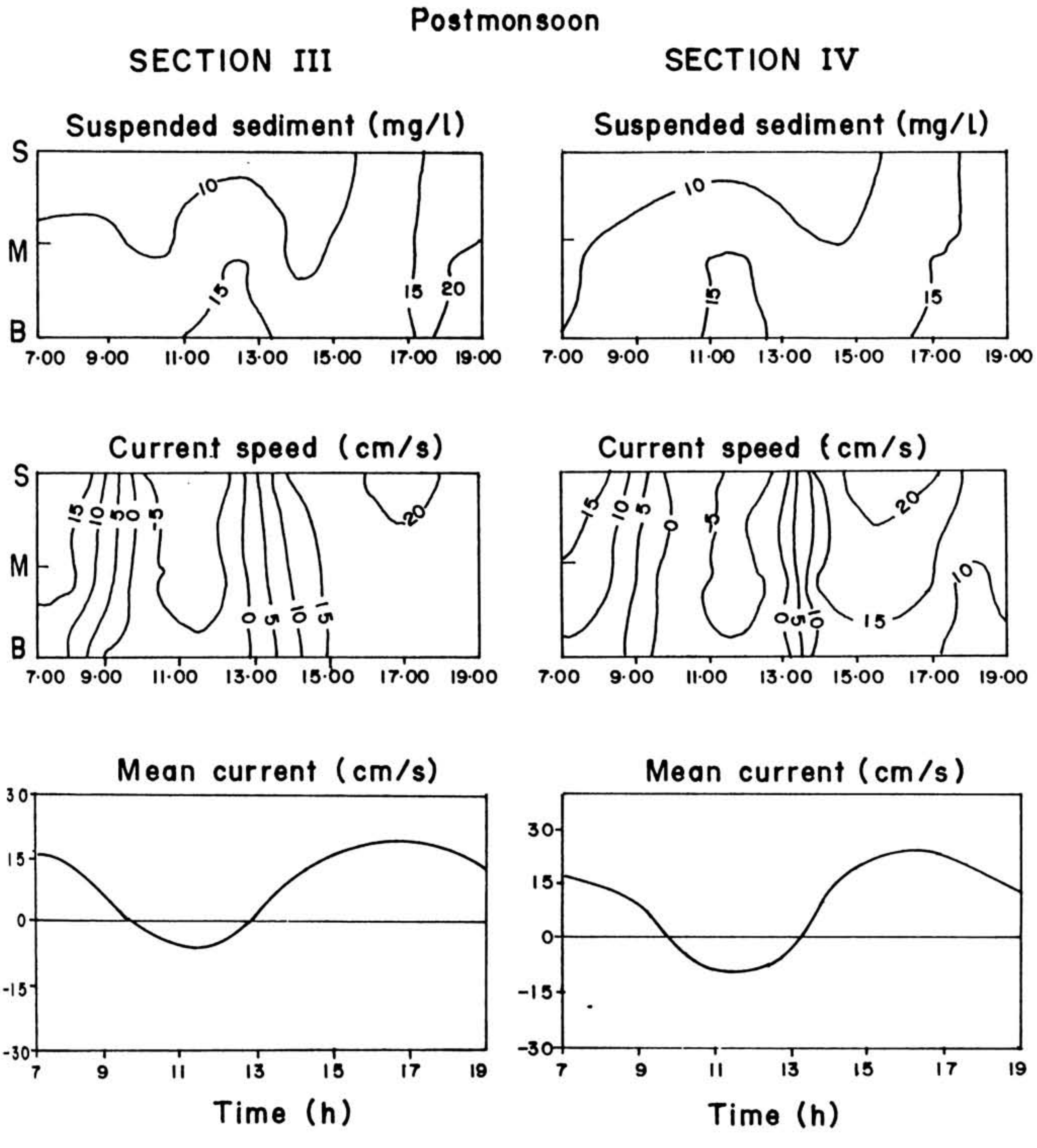


Fig.6.2.1b. Semidiurnal variation of suspended sediment concentration during postmonsoon season.

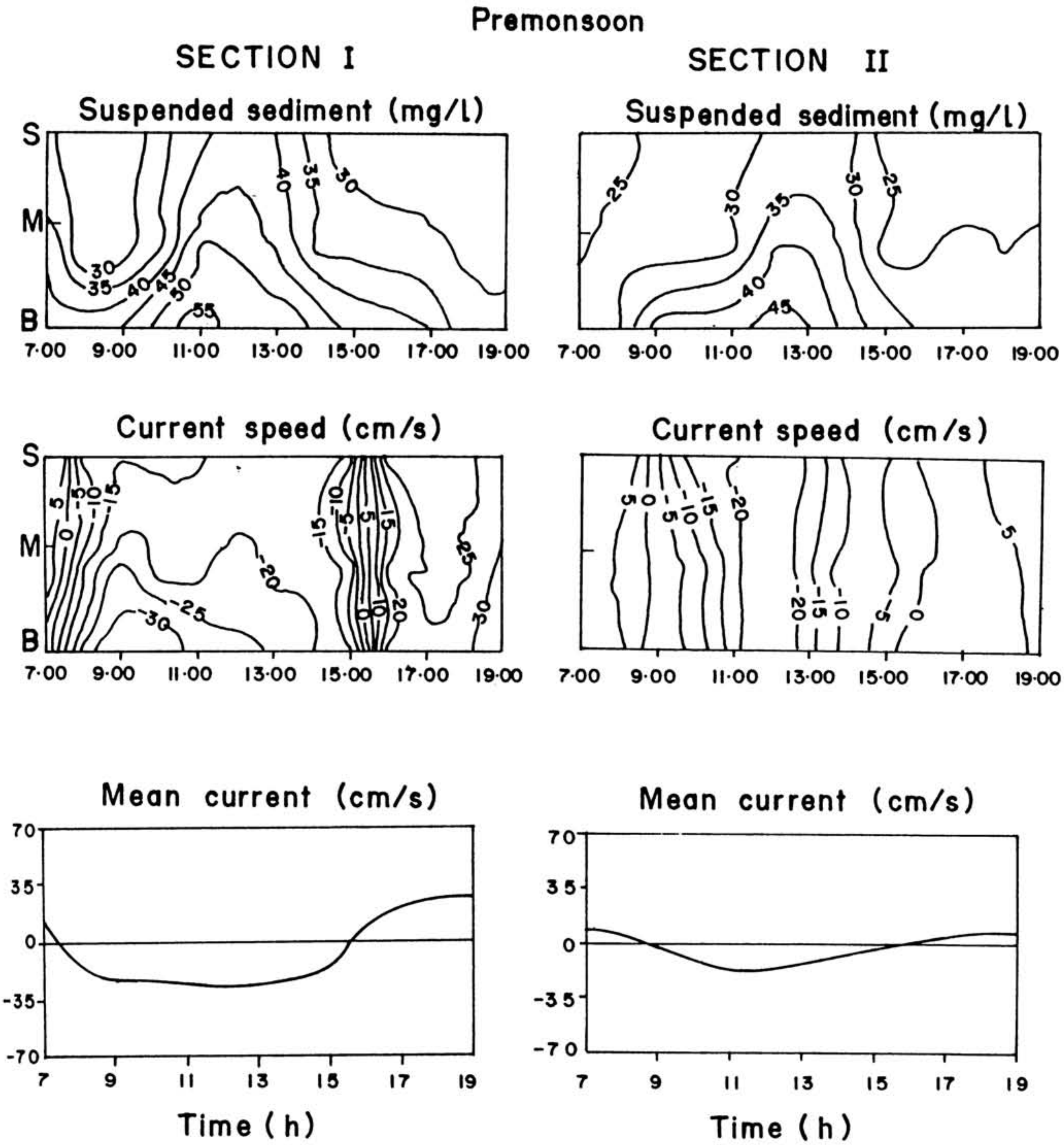


Fig. 6.2.2a. Semidiurnal variation of suspended sediment concentration during premonsoon season.

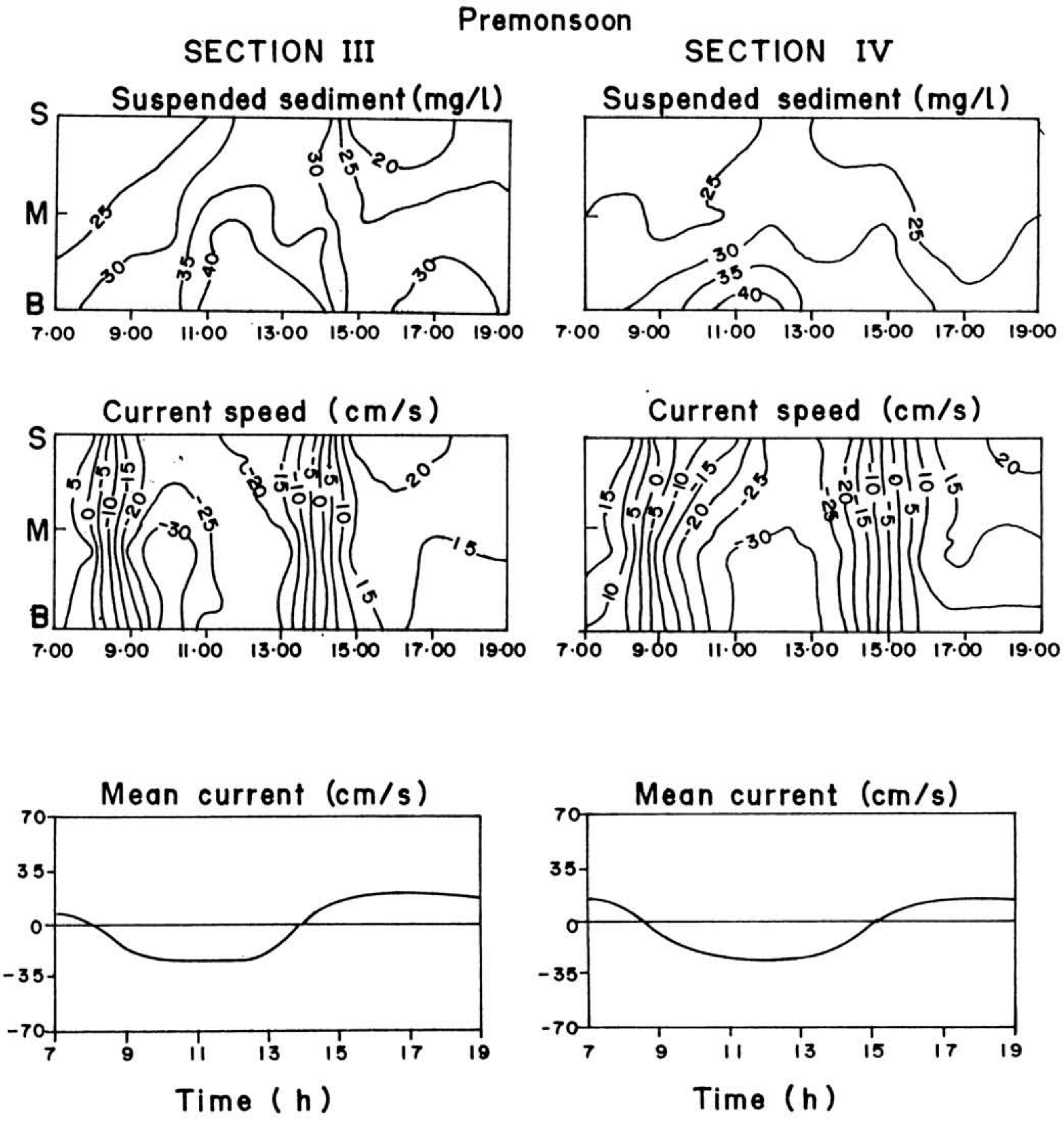


Fig. 6.2.2b. Semidiurnal variation of suspended sediment concentration during premonsoon season

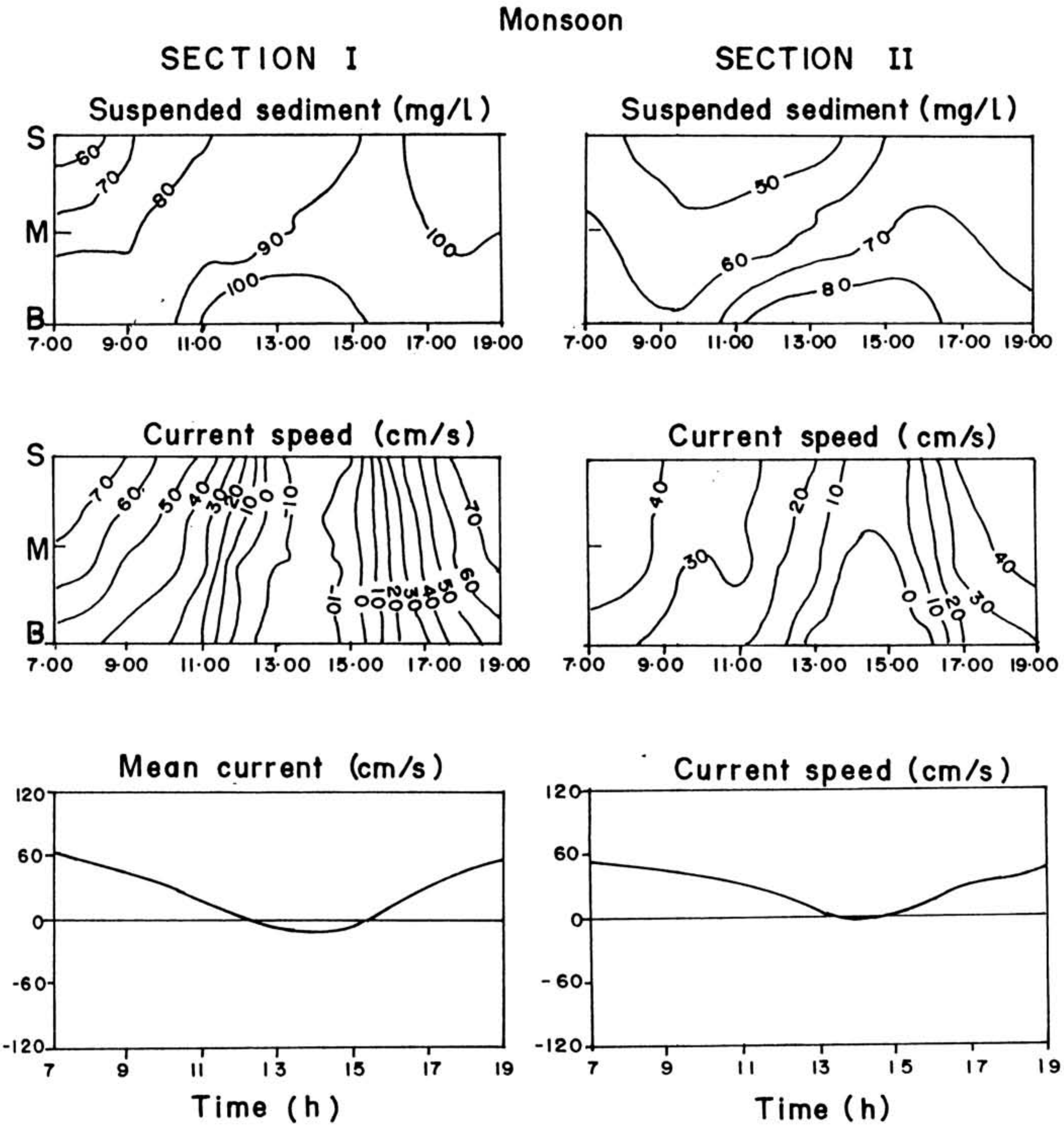


Fig.6.2.3a. Semidiurnal variation of suspended sediment concentration during monsoon season.

seaward transport. Fig. 6.2.2b shows that at the upper reaches of the estuary the suspended sediment concentration varies between 25mg/l to 40mg/l. The high values of upstream current and resuspension of sediment were observed during this season.

River discharge was maximum during the monsoon season and most of the suspended sediment present during this month was mainly carried by the river discharge and the entire estuary was found to be river dominated and a surface related maximum value was observed due to the strong freshwater discharge. High sediment concentration observed in the entire estuary was due to the high river discharge. The surface related maximum value (110mg/l) observed during this season (Fig. 6.2.3a) was not from the resuspension but may be due to the sediment carried by the river runoff. The higher value of the bottom sediment concentration (120mg/l) was observed during the flood tide. During this season the seaward transport dominates the upstream transport.

6.3 Annual variation of river flow and suspended sediment concentration.

The monthly variation of the river discharge and depth averaged sediment concentration at the upper most section is given Fig. 6.3. Both the river flow and depth averaged value of the suspended sediment concentration at the upper most section showed a pronounced seasonal variation. During the premonsoon and postmonsoon season the flow varied between $1.6m^3/s$ to $80.36m^3/s$ but during monsoon (July) the flow has

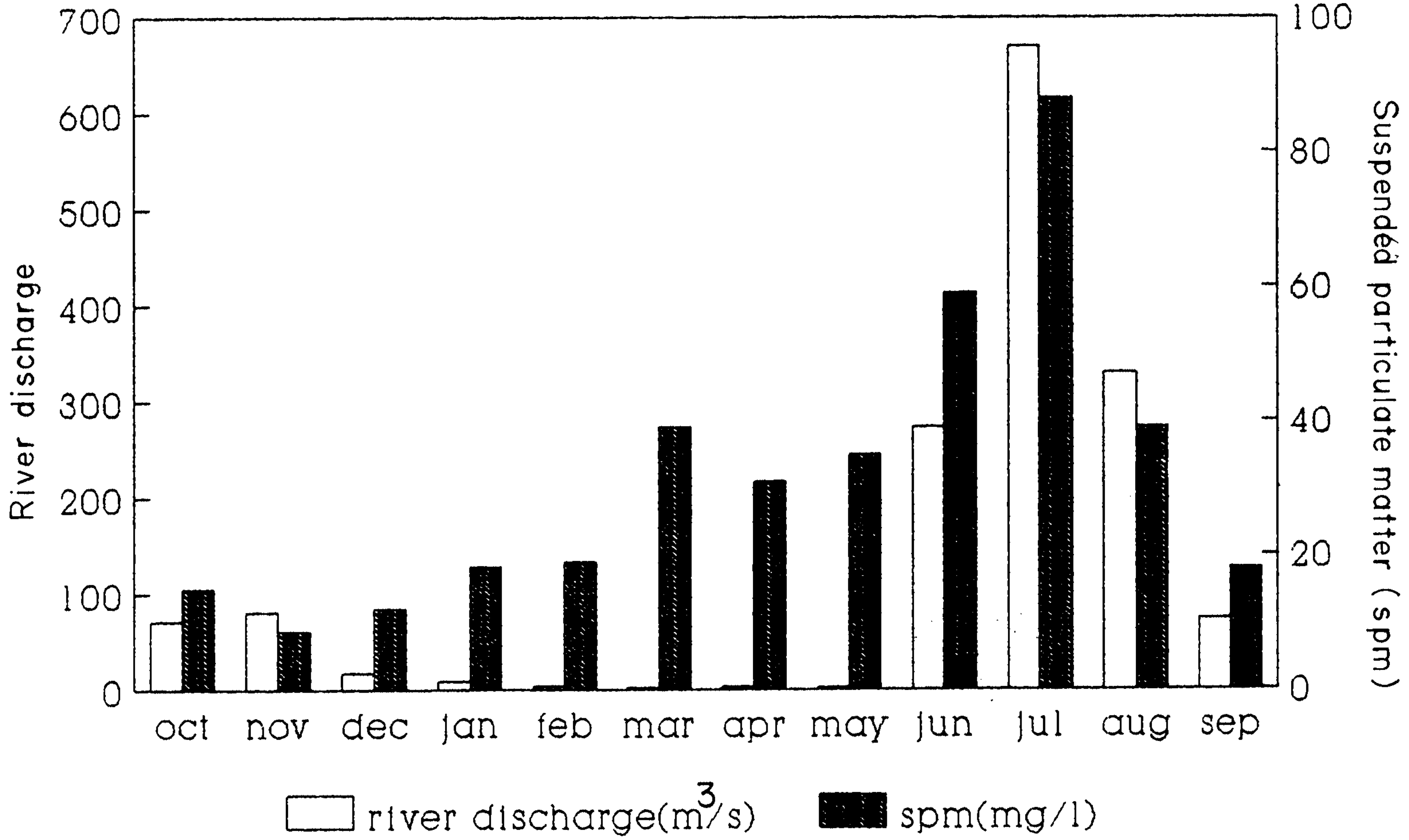


Fig. 6.3. Annual variation of river discharge an suspended sediment concentration.

reached 670m^3/s. The minimum value of the suspended matter was obtained in the postmonsoon season that is during the moderate river flow period. During this season the depth mean value of the suspended matter concentration varied from 9mg/l to 18mg/l. During the premonsoon period the influence of the tidal current was very high and the suspended matter in the lower reaches was high in concentration due to the high percentage of silt and clay materials present in the river mouth and the second section. These materials were carried even to the upper reaches by the strong tidal force. During these low river flow period the depth averagrd value of the suspended matter varied from 19mg/l to 39mg/l. The depth averaged value of the suspended matter was 88mg/l during July and was the maximum value obtained in the entire period of observations.

6.4 Flux of Suspended Sediment

The residual transport of suspended sediment and the formation of the turbidity maximum have been often attributed to density gradient circulation and the existence of its associated null points (Festa and Hansen, 1978; Officer and Nichols, 1980; Officer, 1980). However the possible importance of tidal resuspension of bottom sediments in meso tidal and macro tidal estuaries has been recogonised for sometime (Officer, 1981). Stern et.al. (1986, 1991) have measured seasonal nutrient and suspended solid fluxes in a riverine influenced tidal freshwater bay in Lousiana. Their study showed that the variation in water flux and seasonal sediment concentration causes the sediment variation in flux of the suspended sediment load.

6.4.1 Suspended Sediment Fluxes in the Beypore Estuary

A detailed and systematic study on the fluxes of suspended sediment concentration in the Beypore estuary was not done so far. Therefore an attempt has been made here to study the suspended sediment fluxes through four cross sections in the Beypore estuary. The result is analysed to determine the relative influence of riverine and tidal forcing on the fluxes.

The net flux of suspended sediment through four cross sections in the estuary are schematically represented in Fig. 6.4 and the monthly values of fluxes (in $mg/cm^2/s$) are given in Table 6.2. These fluxes can be converted into $kg/m^2/s$ and multiply with the area of cross section for the computation of the net transport of suspended sediment through each cross section (Table 6.3)

Generally the net flux increases from riverine end to the marine end of the estuary. Most noticeable thing is that the flux shows a comparatively minimum value at section-II. Large positive fluxes (towards the sea) are observed during the monsoon season. It is due to the high discharge of the river water and seaward current velocity is maximum during this period. The maximum flux of the suspended sediment is obtained during July ($1220.97 mg/cm^2/s$) at the lower most

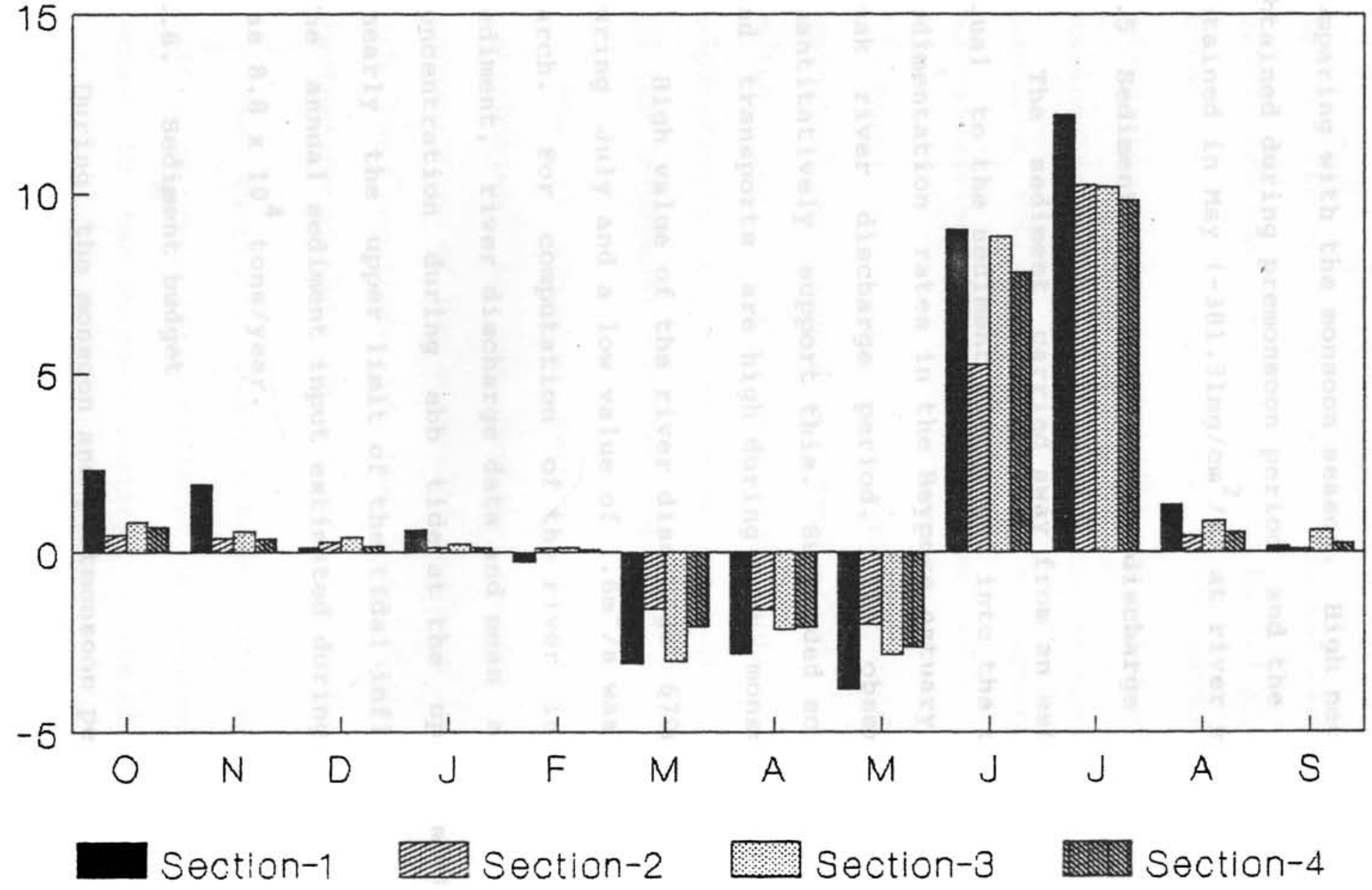


Fig.6.4. Annual variation of the suspended sediment fluxes in the Beypore estuary. ($\times 10^2 mg/cm^2/s$)

section of the estuary and is positive. During the post monsoon season fluxes are positive but lesser in value comparing with the monsoon season. High negative fluxes are obtained during premonsoon period and the higher value is obtained in May (-381.31mg/cm^2/s) at river mouth.

6.5 Sediment input due to river discharge

The sediment carried away from an estuary may not be equal to the sediment discharged into the estuary. Highest sedimentation rates in the Beypore estuary occur during the peak river discharge period. The observations made are quantitatively support this. Suspended solid concentrations and transports are high during peak monsoon period.

High value of the river discharge 670m^3/s were observed during July and a low value of 1.6m^3/s was observed during March. For computation of the river input of suspended sediment, river discharge data and mean suspended sediment concentration during ebb tide at the upper most section (nearly the upper limit of the tidal influence) are uesd. The annual sediment input estimated during the study period was 8.8 x 10^4 tons/year.

6.6. Sediment budget

During the monsoon and postmonsoon period the sediment transport was towards the sea. During the premonsoon period the sediment transport was towards upstream. During the peak monsoon period the rate of sediment transport in the entire study area of the estuary was nearly equal because sedimentation in the estuary during this season was mainly due to the river discharge. The net sediment transported towards the sea was estimated to be 5.7 x 10^4 tons/year. The annual entrapment of sediment in the estuary was obtained by taking the difference between the total river input and net seaward transport. As a result the estuary is a sink for the suspended sediment. The annual entrapment of the sediment was calculated to be 3.1 x 10^4tons/year.

Both the river flow and the suspended sediment concentration showed a pronounced seasonal variation. During low river flow the concentration showed a comparatively higher value due to high influx of sea water and the resuspension of the sediment.

The 12 synoptic surveys of the suspended sediment distribution in the Beypore estuary showed that the concentration of the suspended sediment in the estuary varies with the amplitude of the tide, with the semidiurnal fluctuation of the tide and with the freshwater inflow.

The Turbidity Maximum Zone (TMZ), defined as an area with high suspended sediment concentration is a distinct factor in the Beypore estuary. It is characterised by the maximum suspended load concentration. The location of the TMZ is associated with high salinity variability and strong currents and with gravitational circulation. The higher percentage of silt and clay made the lower sections a turbidity maximum zone, especially during premonsoon seasons.

Observations during low river flow are used to isolate the effect of the tide on the suspended sediment distributions. Distribution of the suspended sediment concentration in the entire study area of the estuary corresponding to low and high tide during the periods of low moderate and high river flows are shown Fig. 6.1.1, 6.1.2 and 6.1.3. The area included in the turbidity maximum increased with the tidal amplitude and covered the entire area of study at low tide. The turbidity maximum during high tide was confined to the bottom.

Table 6.1 Sediment characteristics of various sections in the Beypore Estuary.

SECTIONS	TEXTURE(%)		
	SAND	SILT	CLAY
POSTMONSOON			
SEC. I	72.75	17.55	10.20
SEC. II	78.95	16.25	4.80
SEC. III	95.60	3.85	0.55
SEC. IV	94.45	4.75	0.80
PREMONSOON			
SEC. I	64.80	22.30	12.90
SEC. II	66.30	20.60	13.20
SEC. III	92.50	6.00	1.50
SEC. IV	90.40	7.45	2.15
MONSOON			
SEC. I	71.45	26.20	2.35
SEC. II	70.10	28.40	1.50
SEC. III	99.70	0.30	0.00
SEC. IV	99.50	0.50	0.00

Table 6.2 Monthly values of suspended sediment flux (mg/cm^2/s)

Months	Section - I	Section - II	Section - III	Section - IV
OCT	232.09	48.08	84.25	69.38
NOV	190.54	40.00	58.20	37.50
DEC	149.17	30.10	40.80	16.89
JAN	61.52	13.64	23.77	12.77
FEB	-26.12	10.40	13.36	7.40
MAR	-308.17	-156.68	-303.84	-205.90
APR	-281.54	-160.10	-215.17	-208.90
MAY	-381.31	-200.81	-284.27	-264.98
JUN	900.86	523.66	881.28	780.99
JUL	1220.97	1023.52	1018.59	980.22
AUG	132.88	45.13	87.42	55.66
SEP	-16.51	8.99	62.71	25.68

Table 6.3 Net transport of suspended sediment (kg/s)

Months	Section - I	Section - II	Section -III	Section - IV
OCT	2.64	0.49	0.76	0.51
NOV	2.14	0.41	0.53	0.27
DEC	1.71	0.31	0.37	0.13
JAN	0.66	0.13	0.21	0.09
FEB	-0.26	0.10	0.11	0.05
MAR	-3.51	-1.61	-2.75	-1.52
APR	-2.65	-1.41	-1.73	-1.28
MAY	-3.94	-1.90	-2.42	-1.78
JUN	-9.49	7.23	7.33	5.33
JUL	13.57	10.32	9.09	7.05
AUG	1.30	0.41	0.72	0.35
SEP	1.97	0.45	0.74	0.43

CHAPTER VII

SUMMARY

The aim of this work is to describe the influence of Chaliyar river discharge on the dynamics of the the Beypore estuary and the concentration and distribution of the suspended sediment in the estuarine region during different seasons. The hydrodynamics and sediment transport processes in the estuary is mainly affected by the tidal influence, rainfall and river discharge.

High river discharge and high rainfall was observed during the monsoon months and the temperature was minimum during this period. There was a difference of 9°C between the highest and lowest values of temperature during the entire period of observations. The influence of tide on the temperature was very less but the maximum value was observed during premonsoon period because the surface temperature mainly depends on the short wave radiation coming from the sun and so the diurnal variation dominates the tidal effect. High value of temperatures in the upstream sections were observed except during Jun-July, because of the shallow nature of the estuary. The maximum value of temperature (34.2°C)was observed during April at the upper most section. Low temperatures observed in the monsoon season is due to the precipitation and high river runoff. The minimum value of 26°C was also observed at 15kms upstream during July.

The estuary can be classified according to the intrusion of salinity and the vertical stratification observed during different seasons. During the monsoon season the influence of the saline water was only upto 5km upstream and the estuary can be classified as saltwedge because the stratification was high during this period. During postmonsoon period there was a moderate river discharge and the estuary was found to be highly stratified. Due to the high influence of saline water the estuary has shown a well mixed condition during the premonsoon period. The lateral variation in salinity was insignificant compared to the longitudinal variation. High stratification in salinity were observed during postmonsoon and monsoon seasons and the maximum salinity gradient (24×10^{-3}) was observed in November at section-II during high tide. High salinity values ($>35 \times 10^{-3}$) were observed at the river mouth section during the premonsoon season.

Change of direction in the residual currents were observed with the increasing depth especially during postmonsoon and premonsoon period. In monsoon period residual currents were in seaward direction from surface to bottom. High value of residual current (nearly 50cm/s) was observed during the monsoon season. The residual salinity values were high during premonsoon period. The variation of salinity values due to the influx of sea water was most predominant in lower sections of the estuary. At upper sections freshwater flow was the dominating factor especially during postmonsoon and monsoon period.

Eulerian residual currents flows towards upstream during premonsoon period. During other seasons it flows towards sea. Stokes drift decreases towards upstream and in most of the periods of observation it was in the upstream direction. Salt transport due to tidal pumping and vertical shear were negligibly small compared to salt transport due to residual flow of water and were predominant only in the lower sections of the estuary. In most of the periods of observation the salt transport due to tidal pumping and vertical shear were directed towards upstream. During the postmonsoon and monsoon seasons the salt transport due to vertical shear showed a noticeable variation.

The longitudinal coefficient of eddy diffussivity was almost equal at the four sections during the premonsoon period, which shows the less influence of freshwater and well mixed condition of the estuary. The predominant variation in the longitudinal coefficient eddy diffusivity was obtained during July at section-I.

The flushing time shows maximum value of 14.85 tidal cycles during March. Due to the high river discharge the flushing time during the monsoon season was very less. In July it was found to be 0.221 tidal cycles.

The Richardson's number essentially compares the stabilising effect of density stratification to current shear which leads to mixing. Higher values of Richardson's number (Log R_L = 3.08 at section-I and Log R_L = 3.88 at section-II) were obtained during the high stratification period (postmonsoon season). During the premonsoon period the estuary was well mixed and the computed value of Richardson's number was found to be very low. During monsoon season high stratification was obtained at the lowermost section so that $LogR_L = 2.38$ at this section during the flood phase of the tide.

Silt and clay percentage are very high in lower sections of the estuary. Resuspension of sediments were high at lower sections during the premonsoon months. Concentration of suspended sediment were high at bottom during flood tide. Higher values of suspended sediment concentration (120mg/l at bottom) observed during monsoon months was due to high river discharge. The surface related maximum value of suspended sediment (110mg/l)was obtained during peak monsoon period and was due to the downstream transport of suspended sediment by the high river discharge. Net fluxes of the suspended sediment increases from riverine end to marine end. High value of fluxes were obtained during monsoon period and was directed downstream. The fluxes were directed upstream during premonsoon period.

The annual sediment input into the estuary was 8.8×10^4 tons per year. The net sediment transport towards the sea was estimated to be 5.7×10^4 tons per year. Therefore the annual entrapment of the sediment was 3.1×10^4 tons per year.

A detailed study on the flushing characteristics of the Beypore estuary was undertaken. The industrial and domestic wastes released into the Chaliyar river may pollutes the river. From the flushing time computed for different months it can be suggested that a pollutant introduced in the Beypore estuary will not be flushed out easily during the premonsoon season because the boyancy of the incoming freshwater was insufficient to overcome the mixing due to strong tidal currents. But during the monsoon months domestic and industrial wastes discharged into the estuarine system will be flushed out easily due to high river runoff.

Thus the dynamics of the estuary changes from season to season affecting the salinity structure and the current pattern of the estuary which subsequently affects the distribution and flushing of sediments and pollutants introduced into the estuary from time to time.

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