STRAIT DYNAMICS
OF
TROPICAL TIDAL INLETS

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December 1996

dedicated to my beloved parents...

DECLARATION

I hereby declare that the thesis entitled, "STRAIT DYNAMICS OF TROPICAL TIDAL INLETS" is an authentic record of research work carried out by me under the supervision and guidance of Dr. A. N. Balchand, Reader, Department of Physical Oceanography in partial fulfilment of the requirements for the Ph.D. degree of Cochin University of Science and Technology and that no part thereof has been presented for the award of any other degree in any University.

Cochin - 16)
December 1996)

(K. Ajith Joseph)

CERTIFICATE

This is to certify that this thesis entitled, "STRAIT DYNAMICS OF TROPICAL TIDAL INLETS" is an authentic record of the research work carried out by Sri K. AJITH JOSEPH, under my supervision and guidance at the Department of Physical Oceanography, School of Marine Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph.D. degree of Cochin University of Science and Technology under the Faculty of Marine Sciences and no part thereof has been presented for the award of any degree in any University.

Cochin - 16)
December 1996)

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CONTENTS

CHAPTER - 1	INTRODUCTION	1 - 26
	1. Introduction	1
	2. Straits and Inlets	3
	3. Relevance of the topic	4
	4. Review on tidal inlet dynamics	7
	5. Environmental setting of the study area	21
	6. Scheme of the work	25
CHAPTER - 2	MATERIALS AND METHODS	27 - 43
	1. Introduction	27
	2. Station network fixing and Description of the area	27
	3. Data collection and analysis	32
	4. Theory and approach to the problem	38
CHAPTER - 3	STRAIT DYNAMICS OF COCHIN TIDAL INLET	44 - 93
	1. Introduction	44
	2. Environmental setting	45
	3. Results and discussion	49
	A) Flow characteristics	49
	B) Temperature	55
	C) Salinity	57
	D) Sigma-t	61
	E) Suspended solids	63
	F) Tide	71
	G) Volume transport across Cochin inlet	72
	H) Dilution and flushing characteristics	76

I) Stratification and circulation features 80

J) Morphodynamic behaviour of the Cochin tidal inlet 81

CHAPTER - 4 STRAIT DYNAMICS OF ANDHAKARANAZHI TIDAL INLET 94 - 135

1. Introduction 94

2. Environmental setting 95

3. Results and discussion 97

A) Bathymetry 97

B) Flow velocity 98

C) Salinity 101

D) Suspended solids distribution 103

E) Beach profile 104

F) Grain size distribution 108

G) Standard deviation 111

H) Skewness and Kurtosis 112

I) Median size 114

J) Weight percentage distribution of grain size 116

K) Bivariate plots 120

L) Tide 124

M) Breaker zone characteristics and longshore sediment transport 124

N) Design of a jetty improved channel 130

CHAPTER - 5 SUMMARY 136 - 144

REFERENCES 145 - 162

APPENDIX - I
Abbreviations and symbols

APPENDIX - II
Program on stability analysis

APPENDIX - III
List of publications

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CHAPTER - 1

INTRODUCTION

The tropical regions of the world feature mainly perennial rivers which discharge large quantities of freshwater into adjacent coastal zone. This is influenced by the quantum of rainfall and its pattern which in turn bring about the presence of heavy load of terrestrial borne suspended solids at downstream regions. The surface hydrological pathway commences from small streams originating in highlands and converging to give rise to tributaries of a main river (in a basin), followed by the trunk of the river proper which runs through midlands and reach (low) coastal plains: an ideal scenario often encountered in tropics. Inadvertently, before ending up in the adjacent oceans, rivers give rise to a network of waterways, present likely along with the formation of estuaries (or large expanse of waterbodies - backwaters) and bays and finally embrace the sea front via inlets - mostly tidal inlets.

Tidal inlets are the connecting waterways between estuaries and nearshore regions in the exchange of water and sediments and provide navigational facilities into/out of harbours. Coastal sea - inlet - estuary system which forms a major part of the coastal zone requires considerable attention in the realm of integrated management plans. They are frequently under the influence of coastal engineering activities for harbour and hinterland development and also are sites where often capital to maintenance form of dredging is practised. The (tropical) tidal inlets are nevertheless spared which connect estuaries to the adjacent seas. They play a dominant natural role in the transport of terrestrial borne materials into the nearshore regions as well behave as a pathway for return of marine borne material back into the bay region. The above features exhibit characteristic variations in relation to coastal processes.

Cochin estuary on southwest coast of India and its tidal inlets form a typical tropical bay - inlet system(s) which had undergone very many coastal zone modifications during the last few years. Changes brought about in the distribution of estuarine surface area, channel configuration, tidal regime and cross-sectional area have had direct implications on the hydraulic as well as the morphodynamic behaviour of this sea - inlet - estuary system in terms of channel morphology, flow velocities and basin tidal prism. This thesis encompasses the results of the studies of various aspects of tropical tidal inlets while highlighting the hydrodynamic stability and the dynamic equilibrium flow conditions for this system. The natural coastal processes continue to dominate while inland area is susceptible to engineered structural modifications. A pertinent coastal process at tidal inlets are the formation of sand bars in relation to depositional and dispersal characteristics arising out of the interaction between terrestrial inputs (run-off cum sediment transport) vs. oceanic factors. This fact is also given due consideration within the scope of the thesis.

2. Straits and Inlets

From a physical oceanographic point of view, straits are constrictions in the free flow of water between ocean basins, where the boundaries and the configuration of the constrictions have a fundamental influence on the flow (Bryden and Kinder, 1991). Straits have been grouped with estuaries in many respects because the dynamics of the two layer exchange presents similar problems in both estuaries and straits. Stommel and Farmer (1952, 1953) noted that internal hydraulic control at the mouth of the estuaries could determine the exchange through tidal inlets that connect the estuaries with the open oceans. Similarly tidal inlets are grouped under straits because synonymously in the tidal inlets the boundaries have a fundamental influence on the flow similar to that which occur in straits. The similarity of hydraulic control theory of straits as applied to tidal inlets has been authenticated by Bryden and Stommel (1984), Armi and Farmer (1986) and Bryden and Kinder (1990). The effects of strait flows on the circulation of coastal waters and the physical configuration of the strait is also an important factor to be considered in the control of amount of exchange between the protected embayment and the sea. Predictions of the inflow and outflow transports and the salinity differences between them - also provide an emphasis on the need to develop a fully time - dependent hydraulic theory for the exchange through the straits. Bryden and Kinder (1990) had also documented and explained the applications of two layer hydraulic control models in understanding the dynamics of flow through the straits.

As stated above. straits have been grouped with estuaries in many respects. Zubov (1956)and Tolmazin (1974) have grouped straits into categories of " vertical exchange", "horizontal exchange" and "shallow water". For straits separating basins with waters of different densities. the first two categories of straits that are with "vertical exchange" and those with "horizontal exchange" can be interpreted as a comparison of the natural width of the currents to the strait width. In straits with wide boundaries. horizontal exchange occurs and those with narrow boundaries. vertical exchange occurs whereby the width of the counter flowing currents prevent them from flowing side by side.

3. Relevance of the Topic

The shores of the tropical regions are embedded with coastal beach- estuary -lagoon -swamp complex which is set environmentally as a sustainable ecological system. Extensive estuaries impress the coastal features of south east Asia; the tropics of intense rainfall run volumes of freshwater discharges in conjunction with gently shelving coastal plains. In the tropical waters, unlike in temperate regions. the freshwater inflow tends to dominate the hydrology and hydrological cycle and hence influences the variability of salinity patterns, turbidity maxima build-up and inland water currents. Many investigators (Shigemura, 1980; Kinsey and Soudheimer, 1984; Zhang, 1987) have discussed the outstanding aspects of the coastal morphology of tropical Asia.

Barrier beaches and their associated tidal inlets cover approximately 13% of the world's coastline, most of which occur in areas of low to moderate tidal range (King, 1972). Inlets, by themselves, are the nodes through which water and material exchange takes place; in a broad sense, such locations serve as major pathways for transport of materials from the lithosphere to the hydrosphere. In very early centuries too, their significance was well emphasised in the realm of navigation. Often at centres of immense cultural importance (early locations - Venice, Cadiz, London etc.), the present day civilization finds coastal inlets and its suburbs to be an indispensable entity in trade, commerce and development (list of present day major seaports and coastal cities are innumerable but obvious). Whereas earlier studies viewed inlets as crucial gateway(s) in conduct of marine navigation alone, present day state of art in technology has evolved more applications in the use(s) of coastal tidal inlets - such as land reclamation, farm aquaculture, transportation, inland fisheries, ports and harbours. Also with advancement of time, science is currently probing the likely impacts of long term climatic changes, unchecked exploration of coastal resources, rapid rate of developments in urbanisation/agglomeration and application of (appropriate) technology which can balance with traditional practices on coastal inlets.

The investigation on inlets place more emphasis on their continued existence and probe the likelihood of their closure mechanisms. The formation of sand bars on the seaward side of inlets brought about mainly by land derived inputs, controlled mostly by the littoral environment. often is an hindrance to navigation. Considering the importance of inlets in the upkeep of regional stability and ensuring continued support of harbour operation(s), it becomes imperative on the part of scientists and managers to focus adequate attention to such locations. World over, special investigations are held time-to-time on the manifestation of coastal processes which influence tidal inlet stability and suitable approaches are practiced and amendments made to rectify the situation (Kamel and Johnson, 1963; Aubrey and Gaines, 1982; Kirk, 1992). The west coast of India is no exception, often a region of many geomorphological changes, where two major ports viz. Bombay and Cochin are located along the sub-continental boundary, well characterised by the presence of tidal inlets.

The significance of tidal inlet research studies pertains to the following major objectives: (apart from other minor ones like formation of an inlet and primary causes attached to thereof - prolongation of the inlet channel(s), severe storm events, inlet bifurcation and meandering)

(a) Why are new inlets formed and how do they persist to grow (b) The mechanism behind the seasonal bar formation at the inlet mouth (c) The role of coastal processes in hinterland development and critical issues in coastal zone regulation and management (d) The physics behind the stability of tidal inlets (e) To seek an insight into the hydrodynamic control by the tidal inlets on the bay within and the role in land-sea exchange of materials and its influence on the protected embayment and (f) Any climatic change or the variability in river discharge which is likely to alter the hydrodynamic balance within the tidal inlets. Answers to the above are now made available in toto or partially as the situation demands subject to capabilities on investigation and resource base.

4. Review on Tidal Inlet Dynamics

The origin of tidal inlets and its associated coastal processes were explained in detail by Bruun and Gerritsen (1960) with emphasis on stability of channels along littoral drift coasts. The conceptual factors which determine the size and permanence of inlets were evolved by Escoffier (1940) followed by a publication on inlet classification and investigation on the hydraulics and dynamics of inlets which form a part of the General Investigation of Tidal Inlets (GITI), Report U.S. Army (Escoffier, 1977). van de Kreeke (1967) has attempted a model study on water level fluctuations and flow in tidal inlets. A better understanding of the inlet hydraulics and its sedimentary responses were presented by O'Brien and Dean (1972). Tidal prism vs. cross sectional area relationships and tidal velocities of inlets were studied by Riedel and Gourlay (1980). Tidal, subtidal and seasonal scale variations are significant in both tidal inlets/estuaries because of the variations in local morphology and the geometry of the basins. The seasonal scale variation in the parameters like salinity, suspended sediment and current velocity becomes significant as far as the response characteristics of many tidal inlets are concerned. The difference in response to similar forcing are well established by Wiseman and Inove (1993) in two neighbouring estuaries of Louisiana, USA.

Monsmith et al., (1993) have described a simple model of vertical mixing in a stratified tidal flow that might be observed in shallow estuaries like San Francisco Bay. Mixing is caused by the interaction between the instabilities developed due to the substantial tidal time scale velocity shear caused by stratification. The report speaks of vertical mixing as accomplished by the combined effect of shear instability and tidal stirring. The shear instability at the top weakens the stability of the bottom mixed layer, which is well mixed due to turbulence produced at the estuary bottom so that the tidal stirring affects the entrainment of lighter fluid into the mixed layer below and accentuate vertical mixing. Imberger and Di silvio (1993) assessed the role and influence of the buoyancy created by the freshwater inputs on the dispersion of lagoon waters. Their studies showed that the tidal flow in the canal system is a mixture of barotropic and baroclinic flows and the degree of baroclinicity being dependent on the phase of the tide and is strongest in the areas of salinity difference due to direct freshwater inputs.

The complexity of the temporal and spatial distribution of the tidal flow in the navigational channels were well explained by the current profile studies by Trenaman and Metcalf (1992). Godefroy (1993) has stated the importance of velocity and salinity fluctuations in the turbulent mixing layer since for the stratified flows the mass transport is from the denser salt water layer through the turbulent mixing layer into the upper freshwater layer. Kusuda and Futawatari (1992) used Lagrangian sediment transport model to simulate sediment transport processes which pertain to the formation and maintenance of turbidity maximum. Their estimation on the transport of suspended sediments in a tidal river at an inlet were based on the transport rates by turbidity currents, the erosion and deposition of sediments and consolidation of fluid mud to the river bed. Kawanisi and Yokosi (1993) had related the sediment suspension to the large scale turbulence associated with the cluster of ejections and its ejection motions often encountered in narrow straits and inlets. The influence of consolidation process on the role of sediment transported in a macrotidal estuary at an inlet was investigated by Le (1993). Simulation studies showed that sediment patterns due to turbidity maximum and fluid mud location are dependent on consolidation. The residual deposition and net transport of sediment through an estuary after a spring/neap tidal cycle is mainly influenced by consolidation within and out of the inlet location. However consolidation process is conjugate with turbulence damping so that both processes are equally important in considering the sediment deposition and transport mechanisms. Lucke (1934) and Nummedal and Fischer (1978) identified the factors which control sediment distribution in tidal inlets. Paulson et al., (1993) had observed sediment particle fluxes during spring tide condition which was about 5 times greater than during neap tides on the Amazon prodelta, indicating that tide induced processes are important in controlling the transport of suspended sediments through tidal inlets.

The siltation in the dredged channels is attributed to the fluidization of the bed which results in the formation of fluid mud by wave action or hintered settling (Roberts, 1993). The fluid mud, once it is formed, moves under the influence of gravity and the overlying tidal currents leads to considerable siltation. Tsuruya et al., (1993) studied the inlet siltation mechanism in the approach channels on large scale muddy tidal flat based on field investigation and numerical simulation. Their simulation studies pointed out that the resuspended bed materials by waves from the surrounding tidal flat play an important role in the siltation process in the approach channel. Prasad (1995) in his study on the sediment movement and silting in the approach channels of Indian ports, found that suspended sediment load values near bottom fluctuate both at the estuarine mouth and nearshore regions with changing season.

Boon and Byrne (1981) report on the specific aspects of basin morphology and conveyance channel characteristics, which modify net tidal flow behaviour in inlets. They have considered basin hypsometry, i.e. the distribution of basin surface area with height instead of basin geometry. An earlier approach by O'Brien (1931) related the cross sectional area of harbour entrances as proportional to the volume of the tidal prism raised to the 0.85 power for channels of approximate scouring conditions. This is analogous to streams where the sectional area of the stream varies as a power of the discharge. He has investigated the inlet area - tidal prism (A - P) relationship for San Francisco Bay and Newport Bay inlets. Costa (1978) surveyed the equilibrium relation for smaller harbours as they permit to attain a condition of equilibrium with tidal flow and observed good agreement with O'Brien's inlet area tidal prism relationship of $A = C P^n$, where 'C' and 'n' are constants. O'Brien (1969) analysed about twenty jettied inlets and eight unjettied inlets along sandy coasts with spring tide conditions for the computation of tidal prism and found that $A = 4.072X\ 10^{-2}P^{0.85}$ and $A = 6.562X10^{-2}P$ respectively for jettied and unjettied inlets.

Laboratory studies by Nayak (1971) for jettied inlets estimated $A = 3.580\ X\ 10^{-2}P^{0.85}$. Whereas the investigation on the characteristic behaviour of Pacific coastal tidal inlets with jetties by Johnson (1973) gave a correlation of $A = 5.78X10^{-2}P^{0.90}$. But for a single tidal inlet the equilibrium cannot be defined due to the statistical characteristics of this method. However the investigations by Gao and Collins (1994a) at Christ Church Harbor, U. K., recognised that the identification of regional and local controls pertaining to a single inlet based on analytical approach can contribute to the understanding on equilibrium for individual inlet systems. The concept of an equilibrium cross sectional area by the same authors implies that for any entrance channel, with its seabed covered with loosely consolidated sediments, the cross-sectional area will evolve to a stage when it fluctuates only around a mean value such that $A_E=1/T_o \int_0^{T_o} A dt$, where A is the cross sectional area and

T_o is the time-scale on which equilibrium is considered.

However Kondo (1975) studied the throat areas of inlets on sandy beaches based on data from O'Brien (1969) and Johnson (1973) and postulated a relationship based on tidal period (T), the semi amplitude (a_s)of the tide in the sea and the loss coefficient (K) of the tidal flow due to roughness of the inlet throat as $(P/A)_{max} = K.\ a_s.g.T.$

Shigemura (1980) had critically reviewed the studies by various investigators and identified that most inlets used for the above analyses as located on long sandy beaches where considerable rate of littoral drift occurs along the adjacent shorelines. He had further observed that the inlet area - tidal prism relationship had been investigated mainly by regression analysis and the relationship determined by O'Brien (1969) hold true for inlets in other countries too. Byrne et al., (1980) have studied the tidal prism - inlet area relations for smaller tidal inlets and also concluded that the smaller inlets with cross sectional area less than 100 m^2 depart from the relations between inlet throat area and tidal prism developed for oceanic inlets. The examination of the inlet width versus depth indicates a departure from ocean inlet geometry which occurs at cross sectional area values between 100 and 500 m^2. The maximum velocity in smaller inlets is significantly less than in oceanic inlets as it gives velocity values varying from 0.35 to 1.00 m/s.

Review on the inlet closure mechanism by Schmeltz et al., (1982) explained that a breach/inlet system was probably unstable towards closure when the tidal prism prior to the closure of the breach was inadequate to maintain the cross sectional area of the system. Due to the formation of the barrier beach across the inlet channel, the likelihood of inundation of the backyards as well as the agricultural fields will occur and stagnant water conditions may prevail in the estuary/lagoon side. Decreased oxygen content of the inland water, algal blooms and deteriorated water quality are the major consequences of the inlet closures. On other hand, the natural or artificial breaching of the barrier beach during the monsoon periods lowers water levels and restores tidal circulation in the inland waters. Goodwin et al., (1993) have identified and studied the physical processes associated with inlet opening and closure and the influence of these processes on the estuarine ecosystem. The cycle of opening and closing mechanism of an inlet causes a rapid fluctuation in salinity and flushing of freshwater resources leading to an opportunistic ecology of the estuary or lagoon. The duration difference in ebb and flood currents due to varying efficiency in water exchange at large basin area at high water with lower basin area at low water was studied by Nummedal and Humphries (1978) at North Inlet S.C.

According to Boon and Byrne (1981), the evolutionary sequence of a lagoon will be initiated by advection of flood delta sand deposits into the lagoon from the littoral drift system. In very early years, Lucke (1934) had explained the mechanism of inlet closure as that due to the filling of the inlet system, the potential tidal prism of the system continually diminished resulting in the closure of the inlet(s). Studies by Byrne et al., (1974) and Byrne and Boon (1976) have observed that some inlet systems may change their bedload transport tendency from flood dominant to ebb dominant as the lagoon opens and after being filled to close respectively. The ebb dominated channel transport results when the basin area varies with tidal stage as the lagoon starts to fill (Mota Oliveira, 1970 and Boon, 1975). The effect of varying basin area on the inlet hydraulic processes was demonstrated by King (1974) and Seelig and Sorensen (1978) using analogue and numerical models.

The significance of critical cross sectional area (A_{cr}) in the context of stability of tidal inlets for which the maximum value of the velocity averaged over the flow area (Ac) $Vmax^*$ reaches a maximum was evaluated by Escoffier (1940). A graphical representation of the maximum flood or ebb velocitites as a function of gap area or depth which is defined as the closure curve was explained by Dronkers (1964). The concept on closure curve was modified by O´Brien and Dean (1972) which brings out the relationship between (V_{max}) or (τ_{max}) and A, inlet - cross sectional area. On these curves there is a critical cross sectional area (A_{cr}) which is related to the peak value of either V_{max} or τ_{max}. The authors suggested that an inlet is stable against closure if its equilibrium cross sectional area (A_E) is considerably larger than the (A_{cr}); otherwise it is unstable. The critical cross sectional area represents a division between stable and unstable conditions. van de Kreeke (1992) emphasised that while considering a maximum channel velocity of 1 m/s or values nearer to that with respect to cross sectional area, two points on the closure curve will be intersected; for all values of cross section less than the value of the first intersection point, constitutes a class of unstable inlets. All other inlets which have a cross section greater than the above will indicate features of stability covering values which come under equilibrium interval.

Yet another aspect probed in the studies associated with inlets are the features on the adjacent shorelines - the presence/absence of sand bars, their formation and dissipation. Scouring of sand bars due to overflowing are mainly dependent on slope inclination, pressure gradient and shear stress gradient. Experimental and theoretical studies by Xiaomin et al., (1993) had given the significance of these three important factors in the different stages of the scouring of sand bars. The shear stress gradient and slope inclination are dominant in the early stages of scouring except in a very narrow region at the top of the sand bar. Whereas in the later stages when the shear stress gradient is less, the scouring action is mainly dependent on the pressure gradient and slope inclination. These aspects have a dominant role while considering the stability of inlets and the likelihood of their closure.

Inlet stability has to be reckoned within the context of dredging operations which may alter the substrate characteristics and tidal regimes of estuarine and coastal systems, potentially affecting aquatic communities (Milward, 1993). A range of numerical model studies had been undertaken by Treloar et al., (1993) for investigating entrance improvement works and associated hydrodynamic processes of Lake Illawara, New South Wales and quantified the potential changes in tidal prism, water quality and changes in tide and flood levels. A detail study by Ward (1982) on the impact of deepening the shipping channel at Pass Cavallo, in Texas indicated that the entrance channel could capture tidal prism by a considerable volume and will result in the reduction of current speed associated with this loss of tidal prism effecting more deposition at the channels. Hicks and Hume (1993) has critically reviewed a broad range of inlet types and associated sand bodies deposited by the flooding and ebbing flows along the New Zealand coast. Their studies have established the factors which control the morphology and dimensions of these deltas and related them to the configuration of headlands, barriers, bays and the degree of wave exposures. The role of stabilized navigational channels maintained as jetties and forming long straight waterways, permitting the passage of tidal flows and water waves into harbours, lagoons or rivers has been analysed by Darlymple (1993). He studied the decay of the waves down the channel arising from energy losses within the jetties.

Zheng et al., (1993) used time series photographs from space shuttle to derive the tide related parameters of the Delaware Bay. They calculated the tidal influx from mean high water and mean low water areas and also the tidal range. The velocity of flood tide at the bay mouth is determined using the tidal flux and an integral of the velocity distribution function at the cross section. This novel approach has manifold applications in the studies related to bay geomorphology and related stability analysis of small or large inlet openings.

Model studies on tidal inlets predominantly discusses the flow patterns. Most of the hydrodynamic models used for tidal flow regime analysis are based on two dimensional hydrodynamic equations, by averaging with respect to vertical co-ordinates so as to be lumped in the equations to derive the vertical direction of flow. Numerical model studies by Davies (1993) demonstrated the importance of near bed resolution to the computed value of the frictional velocity and its influence on the total tidal velocity profile. His studies also depicted the influence of stratification on the computed tidal profiles. Utnes and Brors (1993) have applied a numerical model of 3-D circulation to a wind driven flow in a simple basin and the tidal circulation in a Norwegian Fjord mouth. They assumed a constant density in their model studies and realized that the present prediction with constant density value(s) represent some of the main features of fjord circulation and can be fairly predicted eventhough the stratification effects are not been included in their studies. Sin (1992) had recommended a finite different method to study the dispersion features due to variable tidal velocity conditions. Nasseti and Bikangaga (1993) applied Taylor - Galerkin finite element method for the simulation of tidal dynamics and transport of pollutants in a branching river estuary system.

Field investigations by Tanaka and Shuto (1993) at the mouth of a Nanakita river in Japan identified the equilibrium conditions in terms of maximum velocity and this worked out to be 1.00 m/s at the throat sections. His studies also explained the mechanism of sand transport into river mouth which is well influenced by wave heights in the vicinity of river mouths. Inman and Frautschy (1966) related the size of the entrance channels to the volume of the tidal prism in the lagoon. The equilibrium condition of the tidal inlet was mainly attributed to the tidal currents which keeps the channel open and the longshore transport of beach sands that tend to close them down. Hence the equilibrium stage of an inlet maintains a constancy in the relation between tidal flow and channel cross section; however, it does not directly imply the state of stability of the channel location. An entrance channel that maintains a constant cross sectional area which has attained an equilibrium with the tidal flow across a sand bar is often referred to as a scouring channel.

Hromadka et al., (1992) and his co-workers have used a hydrodynamic model to simulate two dimensional surface water flows in the Batiquilos lagoon, California, by neglecting the inertia terms and determined the local flow velocities and circulation patterns in the lagoon caused by the incoming and outgoing tide. The tidal flushing of a small, well mixed embayment was simulated by Sanford et al.,(1992) based on tidal prism flushing formations. In this context, a parametric model study has been performed at the inlets viz. Cochin and Andhakaranazhi (see chapters 3 and 4), by changing the channel dimensions to simulate channel improvement with varying bay area(s); due recognition was given to incorporate the tidal conditions in this exercise since a major dynamic force which controls the flow through these inlets is the tidal currents due to the velocity head between the ocean tide and the bay tide. Suggestions and earlier illustrations from Mehta and Ozsoy (1978) in this regard have been useful. The effect of freshwater flow on tidal inlet dynamics is negligible in these cases except during the monsoon periods. During monsoon periods there exists a unidirectional flow outward from the estuary/bay region and the velocity peaks up such that it satisfies the stability conditions for the inlets. Hence the effect of the freshwater flow in connection with the equilibrium condition for these inlets is comparatively insignificant during the monsoon periods with large freshet discharges.

Inlets also play a critical role in flushing of pollutants. Sanford et al., (1992) studied the significance of return flow factor in the flushing process of effluents from the estuarine regions into the open coastal sea through the tidal inlets. The plume water exits through the embayment mouth on ebb tide, mixes with coastal waters and partially returns to the embayment on flood tide. This return flow factor is primarily dependent on the relative phases and speeds of the embayment channel currents and coastal currents and also on the amount of mixing which occurs outside the embayment. Kuo and Hou(1993) have performed a numerical study to investigate the relationship between the navigation channel improvement and the estuarine environment changes under the various sea level rise conditions. Their two dimensional time - depended finite difference numerical model studies have considered the boundary condition of streamflows at the upstreams and tidal heights at the downstream with sea level rise and also attempted to survey the flushing of estuarine pollutants.

Also the tidal flow investigation studies at Carquinez strait, USA by Agostini et al., (1993) enabled them to analyse the characterisation of flood flow and ebb flow and the transitions between them. Stigebrandt et al., (1995) investigated the magnitude of baroclinic water exchange in straits, as functions of forcing frequency and the topography of the straits. Dedrick and Chu (1993) have prepared a historical atlas of tidal creeks along the San Francisco Bay, California, from maps of 1852-1980's and observed that most of the tidal creeks had suffered a major decrease in width and depth and a majority of them are dammed and could not serve as navigational waterways. George (1991) by using a simple model had studied the hydrodynamic stability of the flow through the Gibraltar straits with rectilinear variation of the velocity and constant variation of density and found that the occurrence of absolute instability in the strait is due to the flow reversal by the water inflow from the eastern Atlantic. A number of parallel works in strait dynamics having direct applications in tidal inlet dynamics are available in the review (Bryden and Kinder, 1991).

5. Environmental Setting of the Study Area

A short description of site selection is as follows. The coastal zone of Kerala is blessed with quite a large number of inlets and estuaries and about 20 out of 48 inlets in Kerala show permanent nature of opening whereas 28 inlets remain open (temporary) during the monsoonal period only (Nair et al., 1993). They are listed hereunder:

Temporary

1. Morgal
2. Kalanadu(Creek)
3. Kottikulam(Creek)
4. Bekal Hole (Creek)
5. Chittari Hole
6. Puthiyngadi- N
7. Puthiyngadi -S
8. Cannanore Kararinagam
9. Iringal
10. Kadalundi
11. Puraparamba
12. **Andhakaranazhi**
13. Kottamkulangara
14. Kochankulangara
15. Kattukada
16. Aryad South(1)
17. Aryad South (2)
18. Tumboli
19. Kanjirmachira
20. Vadakkal
21. Thottapalli
22. Paravur pozhi
23. Edava
24. Muthala pozhi
25. Veli
26. Panathura
27. Karichal
28. Puvar

Permanent

1. Ullal (Talapady)
2. Uppala
3. Shriya-Kumbla
4. Chandragiri
5. Karingote
6. Taliparamba (Valapattanam)
7. Anjarakandi
8. Dharmadam
9. Mahe
10. Murat
11. Korapuzha
12. Kallayi
13. Beypre (Chaliyar)
14. Ponnani (Bharathapuzha)
15. Veliyankode
16. Chetwai
17. Periyar
18. **Cochin**
19. Kayamkulam
20. Nindakara (Ashtamudi)

In order to delineate the dynamics and the associated stability analysis of tidal inlets from tropical environments, two sites viz. Cochin tidal inlet-estuary system (9^{o} 58´N and 76^{o} 15´E; permanent inlet relatively large bay area and high volume transport) and Andhakaranazhi inlet (9° 45'N and 76° 17'E; (temporary inlet with small bay area and less volume transport) have been chosen for this study because they represent many such systems of the tropical region among those listed above. The location maps are provided in Chapter - 2 of this thesis. In the case of these two inlets, the equilibrium cross sectional area will evolve to such a stage that it fluctuates only around a mean value (elaborately discussed later). For the tidal inlets of tropical regions with abundant sediment supply, the equilibrium is controlled largely by sediment availability. These inlets reached their equilibrium within a relatively short time period due to the effect of dynamic forces like tidal influx/outflux and strong freshwater discharges. The presence of a net freshwater outflow during monsoon seasons would favourably influence the stability of the inlets. It is quite obvious that the dynamics and stability criteria of tidal inlets connecting bays/ estuaries and harbours to the coastal ocean are confronted with problems like closure and migrating mechanisms. The hydrodynamic control and the morphodynamic behaviour of these (port) inlets will hence require considerable attention as far as the (dynamic) stability is concerned. It is now widely understood that among the factors which control sediment distribution in tidal inlets of certain areas, the tide induced transport whose magnitude depends on the local oceanic tide range takes predominance, whereas in other areas, the nearshore wave energy and the supply of sand within the littoral drift system in the vicinity of the tidal inlet is of prime importance. These problems can be characterised in terms of quantity and quality of these physical features which control the mechanisms. Towards this, two characteristic representative tidal inlets which exhibit typical tropical climatic setting are selected for the investigation in this study, one dealing with relatively large amount of bay area and large volume transport and tidal prism and stable on an alluvial shore and the other with smaller quantities with less bay area and comparatively less volume transport on a sandy coast which is seasonally unstable.

The study includes in this respect the tropical tidal inlet at Andhakaranazhi, where natural coastal processes continue to dominate while inland area is susceptible to engineered structural modifications. This location, on the south west coast of India and its adjoining coastal zone have been the recent target of large scale developmental activities, a potential site with respect to the influence from natural coastal processes which lead to destabilising conditions. Longshore sediment transport associated with the refracted high energy waves leads to the deposition of beach sands at this tidal inlet during pre-summer months resulting in a seasonal coastal morphological feature, magnitude of which do changes from year to year. This temporal coastal change has resulted in large scale excavation of sand for hinterland development and as well as raw material for quartz industry. However this beneficial utilization, crossing conservative limits have posed a threat to the protection and development of the region and management of the ongoing programmes. Major issues pertain to the erosion of the adjoining beaches, the shoreline modification, salt water intrusion into the low lying (paddy) fields and wave action on coastal protective structures all of which are of adverse nature. Subsequently, this situation may manifest to curtail the proposed port construction, navigational facilities and expansion in fisheries. The thesis highlights comprehensive planning and scientific management for this coastal zone which draws a genuine interest towards the right utilization of the coastal resources, especially for a developing country like India, where high percentages of human agglomerations have concentrated on a narrow belt of the coastal zone.

In this context, the tidal inlet-estuarine research in India have been inferred from available literature. A major part is covered in chapters - 3 and 4 which pertain to the dynamics of Cochin and Andharakanazhi inlets respectively; to list a few, Gopinathan and Qasim (1971) reported on the siltation in the navigational channels of the Cochin harbour area. Bruun (1976) has given a description on the hydraulics and the cross sectional characteristics related to the stability of some tidal entrances along the Indian coasts. Vaidyaraman et al., (1978) and Galvin (1982) studied the stability of coastal inlets on the east coast of India. Chandramohan (1988) computed the longshore sediment transport in the vicinity of certain tidal inlets around India. Joseph and Kurup (1989) reported on the volume transport and estuarine features of the Cochin inlet. Nair et al., (1993) applied remote sensing techniques in the study of migration and offset in the vicinity of Cochin inlet.

6. Scheme of the work

A major objective of the present study was to analyse critically the stability criteria and associated hydraulic parameters at the selected typical tropical inlets. The doctoral thesis consists of five chapters. In Chapter 1, apart from the general introduction to the topic, a detailed description on the characteristic features of tropical tidal inlets are given. A review on the various aspects of tidal inlet research programme on a global perspective is also presented.

The theory and approach to the problem and the methods of sampling and analysis of the data is given in Chapter 2.

In Chapter 3, the environmental setting and stability studies conducted at Cochin inlet are documented. The theory and application of inlet dynamics as applied to the site and the morphodynamic response of this inlet system to harbour engineering activities, inland reclamation and freshwater diversions are highlighted. The sediment distribution. hydrographic characteristics and shoreline features also form part of this chapter.

Chapter 4, discusses the features of Andhakaranazhi inlet, which is seasonal in formation and does not have a stable configuration. Field studies, similar in approach as conducted at Cochin inlet were also carried out here. The stability analysis for developing this into a small fisheries harbour is suggested in this chapter. The results on beach profile features and grain size analysis at this seasonal barrier beach are also covered in this session.

Chapter 5 deals with the summary and conclusion of the present study providing an insight into the hydraulic aspects of the inlets of tropical origins. The physical forces which determine the stability criteria for port inlets and the associated coastal zone management issues are critically analysed in the light of harbour operations.

The outcome of the present study will largely benefit the port operations and cover aspects regarding development within the bay and adjacent coastal zone at Cochin in relation to stability of the inlet. The development of Andhakaranazhi inlet as a fisheries harbour is also presented in favourable terms with due consideration to the overall economic and commercial advancement of the State. Part of the scientific aspects covered in this thesis will serve as a guideline in approaches to be adopted in managing coastal inlets of tropical manifestations towards developmental causes.

CHAPTER - 2

MATERIALS AND METHODS

1. Introduction

The dynamics and associated stability analysis of tidal inlets situated on the southwest coast of India, namely Andhakaranazhi ($9^{o}45'00''$N and $76^{o}17'29''$E) and the other at Cochin harbour inlet ($9^{o}58'04''$N and $76^{o}14'50''$E) have been conducted.

A detailed study on the inlet regime of Cochin barmouth (permanent in nature) was attempted so as to elucidate information on: (a) channel characteristics (b) tidal hydraulics and (c) stability of the inlet. In this connection, a naturally occurring seasonal sandbar formation at Andhakaranazhi, near Sherthallay, about 20 km south of Cochin inlet, was also chosen as a site of study. The study brought out conclusively the dynamical aspects of (1) tidal influx/outflux (2) channel morphology (3) sedimentation regime and (4) stability and factors related to stability of these locations. The above aspects are supported by suitable mathematical formulations to describe the associated coastal processes, wherever applicable.

2. Station Network Fixing and Description of the Area

The Cochin harbour and its adjoining backwater system (9^{o} $30'$-10^{o} $12'$N; $76^{o}10'$- $76^{o}29'$E) of area approximately 320 km^2, on the southwest coast of India is a major port situated on the international maritime route. Cochin harbour was developed for intermediate drafted vessels during the period from 1922-36 (Bristow, 1967). The navigational channels of this harbour consist of an approach channel of length 9.5 km, approximately and two inner channels of width 200m viz. Ernakulam channel of length 3 km and Mattancherry channel of length 4 km. These two channels were dredged since 1928 to a depth of 10.8m and then since 1985 to 11.9m. Considerable area of the estuarine and backwater region had been reclaimed for various harbour engineering works and agricultural and aquacultural purposes as well as for urban development, resulting in shrinkage of nearly 35% of the total area (depth to width wise) due to such activities upto 1980 (Gopalan et al., 1983). During the period 1980-1985 substantial amount of capital dredging work had been carried out at Cochin harbour. The approach channel was widened from 137m to 200m and the dredged depth was increased from 11.5m to 12.8m to accommodate deep draft vessels into the harbour.

A network of 11 stations were fixed, one each on either extremity (one inside the bay and other outside the inlet on the coastal sea side) of the Cochin tidal inlet (figure 1). Selection of stations for the study were fixed in such a way that the surface, mid-depth and bottom hydrographic parameters could be covered to obtain observations at 9 stations (3 levels) in a cross section, three stations selected laterally across the tidal inlet at three segments. These stations were fixed across the inlet in a grid pattern with 3 vertical levels to cover, thus providing altogether 33 sampling locations within the cross section during one survey. Stations 4,5 and 10 lie along the Fort Cochin bank and stations 2,7 and 8 are located along the Vypeen bank. The

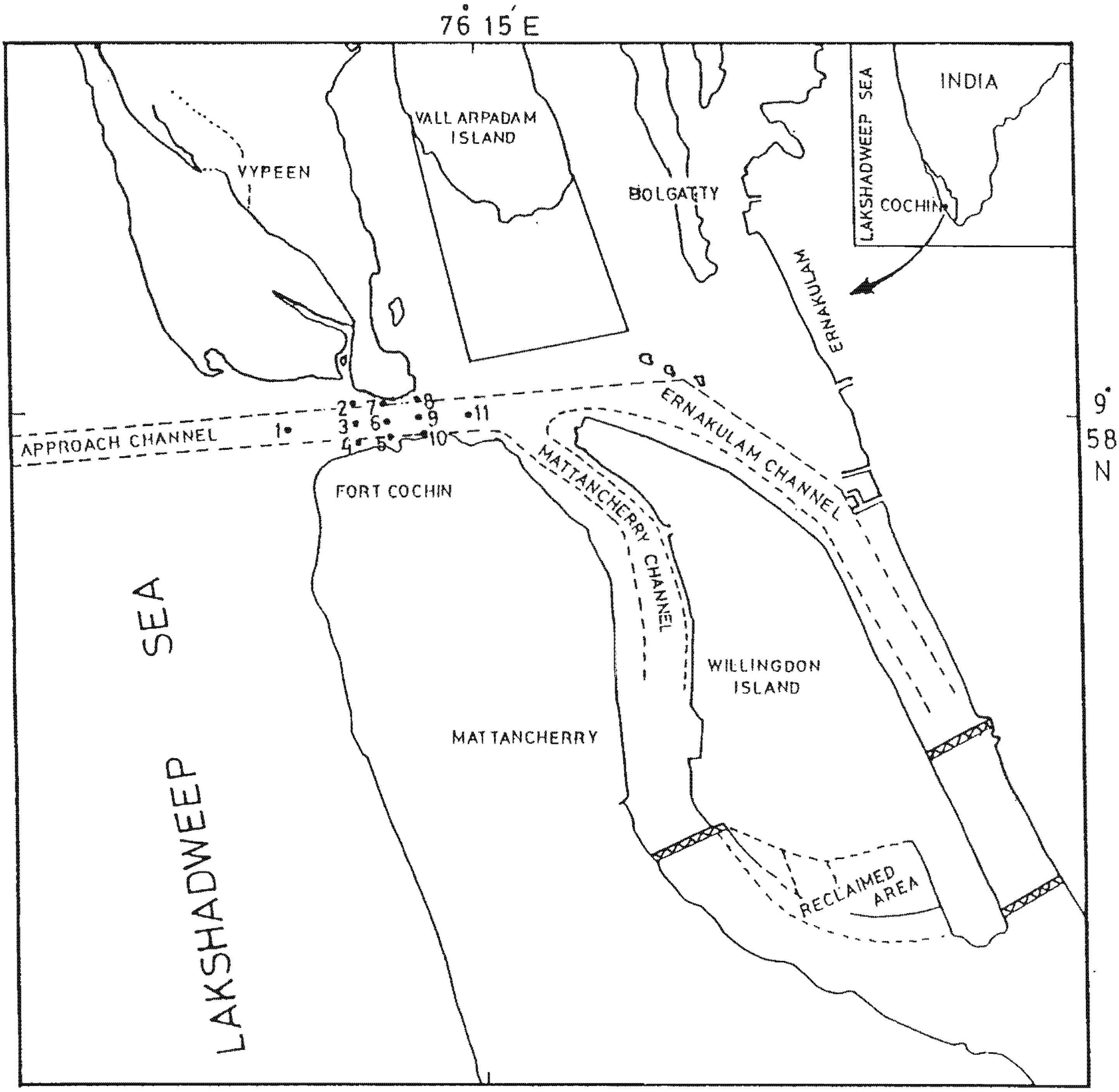


Fig. 1. Location map of Cochin tidal inlet indicating stations 1 - 11.

shallow regions of the inlet were also included in the station grid. Thus the selection of the grid helped to conduct a thorough investigation on the dynamics of the inlet system.

The data on current speed, direction and salinity in relation to tide was collected during the period 1993-94 onboard research vessel R.V. Nautilus, 12m long (with inhouse laboratory). Hourly observations were made while collecting the data; the current meter observations made use of Eulerian type of direct reading current meter(s) (Emcon make) of accuracy ($\pm$ 2cm/s); salinity ($\pm$ 0.01) was measured using Hydrobios Temperature - Salinity - Bridge. The channel configuration and morphology was monitored by making use of STD meter (CIFT make) and corrections, if any, were incorporated by verifying the depth contours with bathymetric chart of Cochin Port Trust. The cross sectional area of the harbour entrance was calculated from these charts during the period under study. The real time tidal observations were provided from the tide gauge installed at the harbour region (GLOSS approved network station). Spring and neap tides were also chosen during the study to account for the extreme characteristics in the hydrography and dynamics of the inlet. Similarly the flood and the ebb phases of the tide were also considered at appropriate junctures to explain the estuarine behaviour in relation to hydrodynamical approach.

An adjacent area investigated was also on the southwest coast of India which featured a seasonal beach/tidal inlet namely, Andhakaranazhi ($9^{\circ}45'00''$N and $76^{\circ}17'29''$E), connected to the Vembanad Lake, through a network of waterways; two local streams located north and south of this seasonal opening drain flood waters (figure 2a). The inlet serves as an outlet for the flood waters from the vast paddy fields during monsoon (June - September). The inlet mouth and the lagoon inside the beach is generally shallow (2m) and the tidal prism was calculated as 17.20×10^6 m^3 during monsoon. The inlet remains open only for 5 to 6 months a year, mostly during the southwest monsoon and upto January; the inlet then gradually closes as a result of less discharge of water and high deposition of littoral drift material resulting from wave action. There are two regulators, close to the inlet, inside the bay, across the two local streams for preventing saline water intrusion into the paddy fields. The hinterland of this region is constituted by five major villages, of an area approximately 72 km^2. About 80% of the farmers from this region depend on the deposited sand material for land restructuring and wasteland management. The utilization of fertile soils deposited in the streams is also practiced by sand mining activities for agricultural lands as part of their livelihood.

Figure 2b shows the geographical location map of the study area investigated from January 1993 to June 1994 covering a full cycle of events. The inlet at Andhakaranazhi was initially closed by the formation of sand bar; but later it completely opens during the southwest monsoon with shallow depths across the entrance where waves (approach southwesterly: 210°-230°) of periods 5-8s plunges. The

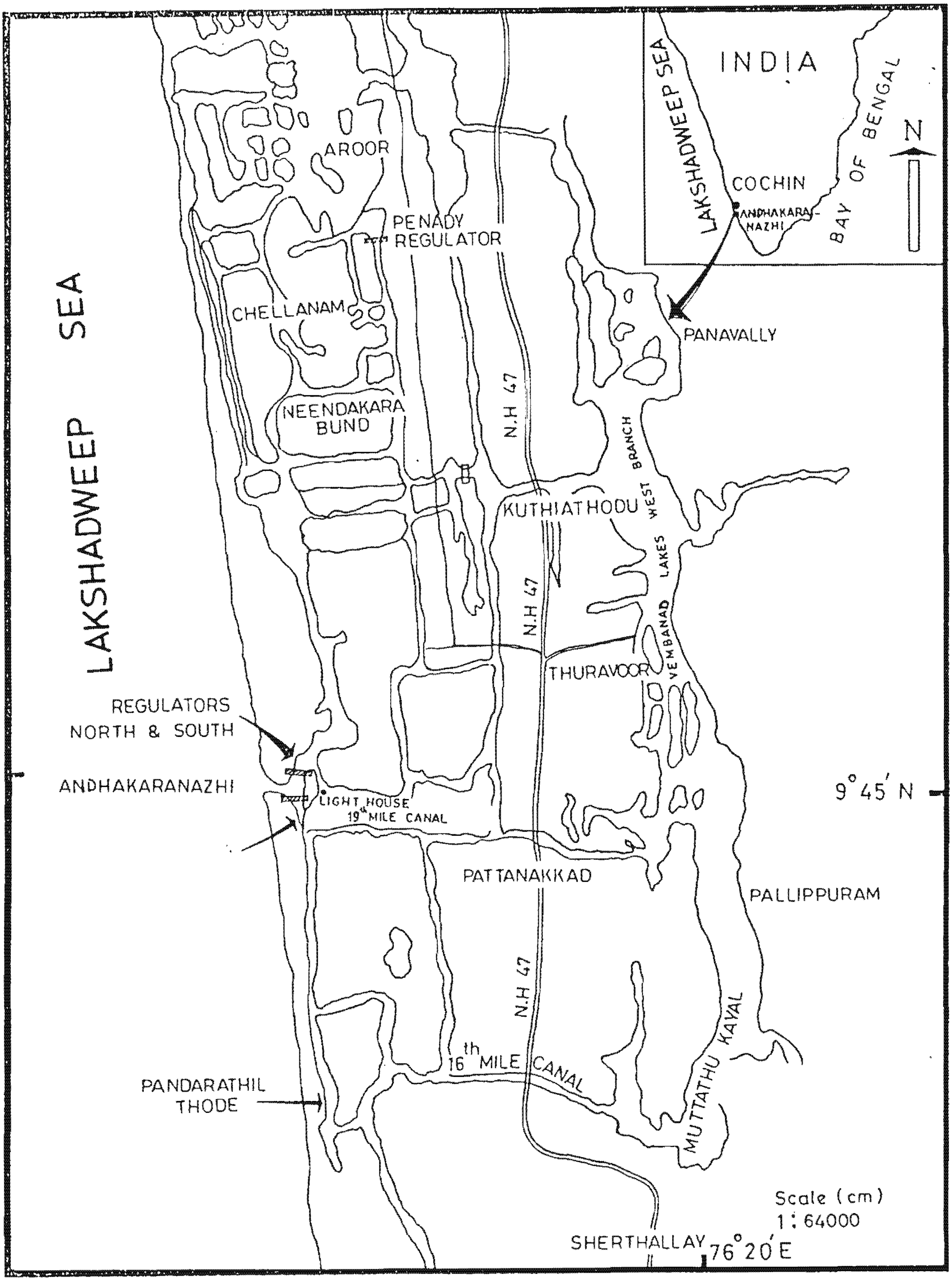


Fig. 2a. Location map of Andhakaranazhi inlet and hinterlands.

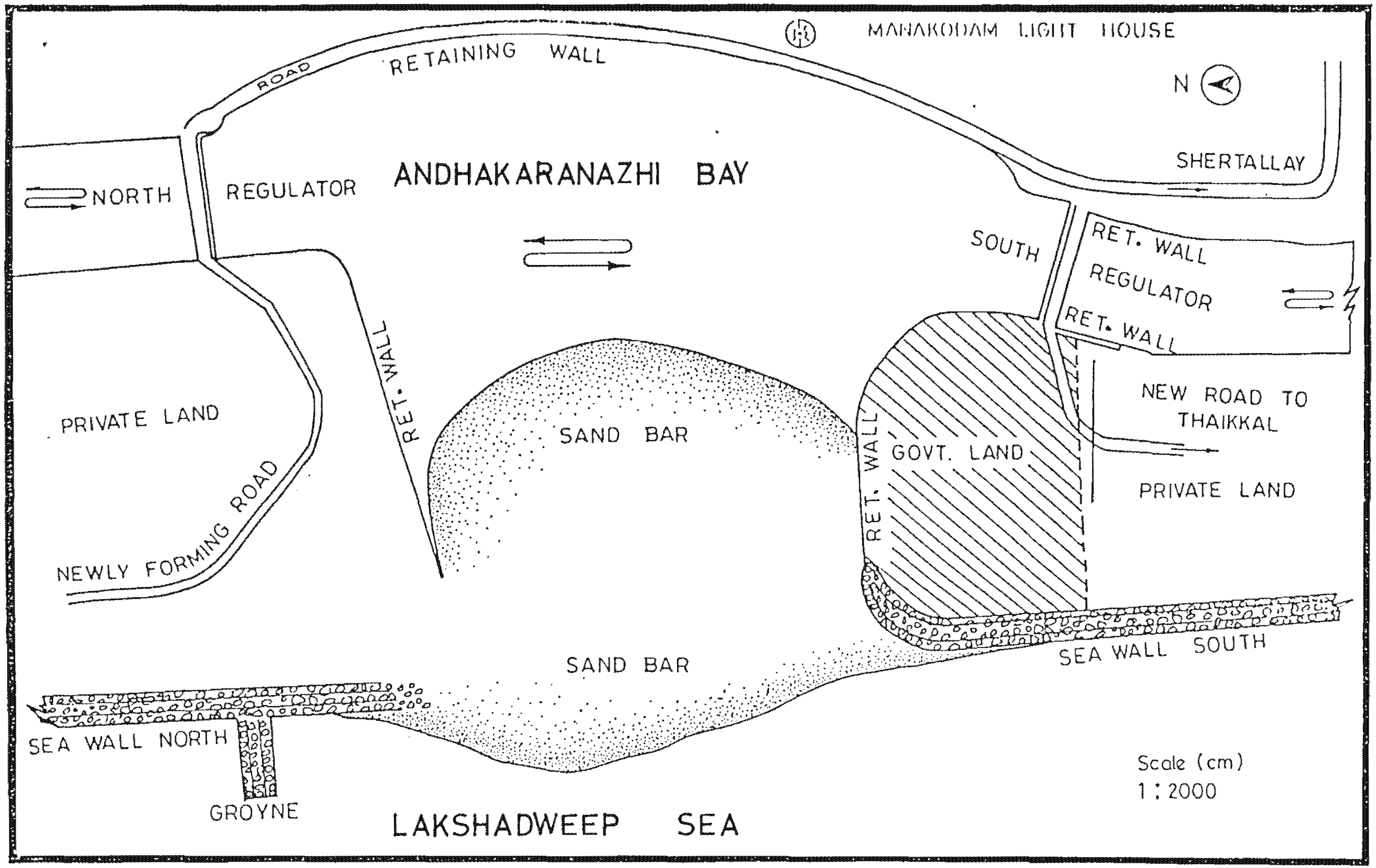


Fig. 2b. Geographical location map of Andhakaranazhi inlet.

commencement of southwest monsoon brings about changes in the environmental setting and the combined influence of tides and south westerly waves and run-off from the hinterland drives the water exchange between the bay and the nearshore regions. The dominant waterflow was directed offshore during the rainy season facilitating navigation at the tidal inlet channel at a depth approximately 2m (occasionally depths upto 4.5m were observed on the northern part of the inlet). The adjacent catchment area are low lying plains which flood during monsoon and the run-off is directed to the inlet area through the two sluice gates (regulators) north and south of the opening. Waves of period 8s break 30m offshore from the inlet gorge and the circulation pattern is so set that there is no scope for any terrestrial material, transported offshore, to settle within the bay area, at or on either sides of the inlet. As the rainy season retreats, the interactive forces give rise to the development of a bar at the tidal inlet, commencing first from the southern end and gradually extending northward across the entire opening. The tidal range at this region is 1.2m. The boundary banks of the inlet are protected by sea walls and the bay within occupies an area of approximately 0.12km^2. The sluice gates are opened only during the monsoon period (June - September) to drain inland waters which help to regulate the flood levels in hinterland areas. The two regulators are closed during the postmonsoon and premonsoon season (October-May) to prevent entry of sea water during the intervening periods.

Hydrographic data was collected at Andhakaranazhi inlet during the period when the inlet was open. As the dimension of this inlet system is comparatively far less than that of the Cochin inlet by a factor of 2.5 (width), a network of 6 stations (H1 - H6) were selected, for 2 layer sampling in a cross section (detailed station map is provided in Chapter - 4). During the period of closure of the inlet, the Andhakaranazhi bay exhibits the features of a semi enclosed system with only limited exchange of water between the bay and the coastal sea. During this period, the depositional and dispersal features of the beach that was formed at the inlet mouth was frequently investigated with additional surveys. Towards this, 4 transects (A1 - A4) were selected, each made up of 4 stations across the shoreface starting from backshore to the low water mark to cover a maximum of 16 sampling points across the beach; progressive coverage was made with the advancement of the beach across the inlet (map showing stations selected for beach profile study is separately given in Chapter - 4).

3. Data collection and Analysis

Investigation at the two sites, namely Cochin and Andhakaranazhi inlets, were carried out at monthly periodicity in addition to specific short interval time surveys. Distances were determined in field; other details on environmental features were read off from field maps, otherwise specifically stated from charts made available from the Office of the Surveyor General of India and Cochin Port Trust, Ministry of Surface Transport. The standard suite includes study on temperature, salinity, currents, tidal hydraulics, suspended solids content, and wave conditions; alongshore current measurements were also attempted. The data constitutes 1m below the surface, middle and 1m above the bottom. Instrumentation, field and computational techniques applied in this study are:

A) Temperature and Salinity

The temperature and salinity readings were obtained from a Hydrobios make Temperature-Salinity Bridge Model MC-5. Accuracy of thermistor was ± 0.1°C and inductively coupled salinometer was ± 0.05.

B) Current speed and direction

These parameters were determined by direct reading current meter(s) (EMCON make) of accuracy (± 2cm/s) which suits to read as integrated current value, utilizing savonious rotor plus magnetic compass of directional sensitivity ± 5°; the final current value was taken as the average of 3 consecutive readings.

C) Suspended solids

Suspended solids concentration (in JTU) was determined in the field by making use of an in-situ turbidity meter which makes use of the optical scattering principle (in range of 0 to 1000 JTU, ±2%) make CIFT. Linear calibration was achieved by means of the following method. Water samples collected in a Hytech water sampler of 1.2 litre capacity from surface, mid depth and bottom were filtered at 0.45μm (Whatman filter cum Millipore unit) and dry weight of filtrate was determined and instrumental readings calibrated (48 data sets) to report values in mg/l.

D) Tide

The predicted tide data was obtained from the tide tables and compared with observed values recorded at the gauging station of Cochin Port Trust. The data was analyzed to obtain the tidal period and amplitude for the spring and neap tides. The tide at Andhakaranazhi was observed with a graduated tide staff.

E) Bathymetry - as stated under station network fixing.

F) Volume transport

Volume transport was computed at the cross sectional area by accounting for the mean cross sectional velocity with the tidal range and the duration of the tide.

G) Freshwater fraction

The freshwater fractions and dilution factors were computed for the period of study at the inlet. The amount of freshwater contained at any location at the inlet is

$$F = \frac{So - Sn}{So}$$, where F is the freshwater

fraction, and Sn is the salinity at the point of observation and So is the salinity of the source water (Ketchum, 1969 and Officer, 1976). For the salinity of source water the values at a station about 8 km seawards from the harbour entrance was taken (Qasim and Sen Gupta, 1981; Joseph and Kurup, 1989). R is the dilution factor which is reciprocal of fresh water fraction, R = 1/F.

H) Stratification circulation diagram

The variation in stratification and circulation features were investigated by making use of stratification-circulation diagram by Hansen and Rattray (1965,1966). The dimensionless theoretical stratification parameters $\delta s/S_0$ and the circulation parameter U_s/U_f are being used for monitoring the variation of estuarine characteristics at the inlet.

I) Beach profiling

The beach profile studies conducted at Andhakaranazhi barrier beach signifies the variation in the depositional feature of the sand bar during different months at the site. The monthly depositional rate gives an indication on the development of sand bar at the tidal entrance. Beach profile studies were conducted based on the method by Emery (1961) and the profiling was carried out at 5m interval from backshore to the low water mark using a beach staff, dumpy level and a measuring tape on a monthly basis during the period of occurrence of the beach. The above profiles were taken over a period of seven months during spring low water when maximum area of the beach width stands exposed. The data was then reduced with reference to the bench mark.

J) Grain size analysis

Beach sediment samples were collected from the assigned stations across the Andhakaranazhi barrier beach at a depth of 5cm with a cylindrical core. The sand samples were thoroughly washed and dried and the weighed samples, after conning and quartering were taken for dry sieving. The samples were mechanically sieved for differentiating sand particles of different size groups to determine the various statistical parameters like mean, median, mode, skewness and kurtosis of the given samples based on Folk and Ward (1957) method.

K) Littoral environmental observation

The littoral environmental observation study at Andhakaranazhi region provides data on various wave parameters like wave period and direction, breaker height, width of the surf zone, and longshore current speed and direction. In the absence of sophisticated instrumentation techniques to collect data from the highly dynamic surf zones (Sajeev, 1993), visual observations were carried out during the period of study.

K. i) Breaker wave characteristics

The significant wave height was determined from the average heights of ten consecutive breakers and the wave period was measured using a stop watch to note the average time taken by ten consecutive wave crests to pass a fixed point. The breaking wave angle was measured using a surveyor's magnetic compass.

K. ii) Longshore current

Longshore current velocity and direction were measured by Lagrangian method with neutral buoyant floats released at the surf zone region. The distance covered by the floats in two minutes was measured and the direction to which it travelled was also noted to represent the speed in m/s. The average value is determined by repeating the experiment. The approximate width of the surf zone was also visually estimated and the average value was taken.

K. iii) Longshore sediment transport

Longshore sediment transport and the amount of littoral sediments drifting across the inlet entrance has a predominant role to play in deciding the stability of an inlet. Studies by Bruun (1978) emphasized that littoral drift is a major factor controlling the stability of tidal inlets as the potential energy of the tidal prism and the capacity of the tidal flow to flush out the littoral sediments maintains the inlet open.

Many investigators (Saville, 1950; Longuet - Higgins and Stewart, 1962; Longuet - Higgins, 1970; Komar and Inman, 1970; Galvin, 1972) have applied various methods to calculate the amount of longshore sediment transport along coastlines. The applications of commonly used longshore sediment transport equations (Shore Protection Manual, 1975) which are based on the assumption of long and open beaches with adequate sand supply has certain limitations when applied to regions which are intermittently intercepted by headlands. As the west coast of India is intercepted with quite a large number of inlets, a realistic estimation of the sediment transport rates can be computed by the Walton's equation, based on Walton and Bruno (1989), since it takes into consideration the measured longshore currents. Studies by Chandramohan et al., (1990), Sajeev (1993) have authenticated the applicability of the above method for the estimation of longshore sediment transport rates.

Walton's equation is given as:

$$Q = \frac{1290\ \rho\ g\ Hb\ W\ V\ C_f}{0.78\ (5\pi/2)\ (V/Vo)}$$

Where Q is the annual longshore sediment transport rate in m^3/year.

C_f = frictional coefficient = 0.01

ρ = 1025 Kg/m^3

g = 9.81m/s^2

Hb = Breaking wave height in m.

W = Surf zone width in m

V = Longshore current velocity in m/s

V/Vo= Theoretical dimensionless longshore current velocity

= (0.2 (x/w)) - 0.714 x/w Log_n (x/w), where x, is the distance from the shoreline such that x/w =1/3. (Longuet-Higgins, 1970)

4. Theory and Approach to the Problem

Governing equations applied in the inlet-bay problem are discussed hereunder (see list of abbreviation and symbols as in Appendix - I):

For an idealized inlet-bay system, an inlet is considered to be similar to an open channel with a constant cross sectional area A_c equal to the throat area, depth h_c equal to the mean depth at the throat and length L_c.

The ocean tide represents the boundary condition at one end of the channel and the bay storage volume imposes a boundary condition at the other end.

The dynamics of the inlet-bay system are considered under the following assumptions (Metha and Özsoy, 1978):

a) Inlet and bay banks are vertical.

b) The ocean and the bay are deep so that bed frictional dissipation in these water bodies may be neglected.

c) Kinetic head due to flow within the ocean and the bay may be ignored.

d) The range of tide is small compared to depth of water every where.

e) The bay surface remains horizontal at all times, i.e., the tide is "in phase" across the bay.

f) There is no density stratification.

g) Ocean tide is represented by a single harmonic.

h) Length of the inlet is small compared to the tidal wavelength.

i) Effects of ocean waves and of sediment movement are ignored.

The one dimensional shallow water momentum equation for the inlet is given by

$$\delta\bar{u}/\delta t + \bar{u}\,(\delta\bar{u}/\delta x) = -g\,(\delta\eta/\delta x) - f\,(\bar{u}\,|\bar{u}|\,/\,8h_c) \qquad (1)$$

where $\bar{u}=\bar{u}(x,t)$ is the depth averaged flow velocity in the x direction, t=time, $\eta = \eta(x,t)$ is the local elevation with respect to mean water level and f= Darcy-Weisbach friction factor in the dissipation term.

If $\eta_o(t)$ = ocean elevation and $\eta_B(t)$ is the bay elevation represent the end condition for the surface elevation in the channel, the integration of equation(5) over "L_c" with the inclusion of entrance/exit losses yields.

$$\eta_o - \eta_B = Lc/g(\delta\bar{u}/\delta t)+(K_{en}+K_{ex}+(fLc/4h_c))\,\bar{u}|\bar{u}|/2g \qquad (2)$$

i.e., the total head ($\eta_o - \eta_B$) is the sum of four separate contributions:

(1) entrance loss, $K_{en}\,(\bar{u}^2/2g)$

(2) exit loss, $K_{ex}\,(\bar{u}^2/2g)$

(3) head loss due to friction $(fLc/4h_c)\bar{u}^2/2g$ and

(4) head due to inertia $(L_c/g)\,\delta\bar{u}/\delta t$

A turbulent loss at the entrance of the channel occurs due to the convergence of the flow into the channel and a head loss at the exit region of the channel occurs due to the loss of kinetic head, when the flow separates as it enters the bay or the ocean, depending on whether it is flooding or ebbing.

Equation (2) can be substituted by including a frictional loss coefficient or an "impedance",

$$F = (K_{en} + K_{ex} + fL_c/4h_c) \qquad (3)$$

as $$(L_c/g)\,(\delta\bar{u}/\delta t) + F\,(\bar{u}|\bar{u}|/2g) + \eta_B = \eta_o \qquad (4)$$

As a result of the integration over x, $\bar{u} = \bar{u}(t)$ only. Application of the momentum equation (4) additionally requires a continuity expression for the bay storage volume V. If 'A_B' is the bay surface area, the discharge Q through the inlet is related to the rate of change of 'V' and the rate of change of freshwater flow 'Q_f' from any upstream source.

Hence $Q = dV/dt + Q_f$ (5)

where $Q = \bar{u} A_c$ and $V = \eta_B A_B$

such that equation (5) becomes $\bar{u} = A_B/A_c (\delta\eta_B/\delta t) + Q_f/A_c$ (6)

combining equations (4) and (6) with $Q_f = 0$ yields

$$d^2\eta_B/dt^2 + (F/2L_c) A_B/A_c (d\eta_B/dt) |d\eta_B/dt| +$$

$$+ (gA_c/L_c A_B)\eta_B = (gA_c/L_c A_B)\eta_o \quad (7)$$

Consider a sinusoidal representation of the ocean tide

according to $\eta_o = a_o \sin\sigma t$ (8)

By introducing the dimensionless parameters

$$\hat{\eta}_B = \eta_B/a_o , \quad \hat{t} = (gA_c/L_c A_B)^{1/2} t \quad (9)$$

equation (7) becomes

$$d^2\hat{\eta}_B/d\hat{t}^2 + \beta\, d\hat{\eta}_B/d\hat{t}\, |d\hat{\eta}_B/d\hat{t}| + \hat{\eta}_B = \sin \alpha\hat{t} \quad (10)$$

and the continuity equation (6) becomes (with $Q_f = 0$)

$$\hat{U} = 1/\alpha\, (d\hat{\eta}_B/d\hat{t})$$

Where the dimensionless tidal frequency

$$\alpha = (L_c A_B/gA_c)^{1/2} \sigma$$

and the dimensionless damping coefficient

$$\beta = (F/2L_c)(A_B/A_c).a_o \quad (11)$$

and dimensionless velocity

$$\hat{U} = (\bar{u}/a_o \sigma) A_c/A_B$$

For a semidiurnal condition, Drapeau (1988) had estimated the inlet hydraulic constants on the basis of the physical dimensions of the inlet and the lagoon within using the algorithm developed by Mehta and Özsoy (1978).

If A_c is the cross sectional area of the inlet, L_c is the inlet length, A_b the surface area of the lagoon, H_o and H_b are the tidal amplitudes in the coastal sea and the bay respectively, T the tide period (for semidiurnal, T = 12.42hrs) and R_c the hydraulic radius of the inlet, then the friction loss coefficient F is defined as:

$$F = Ki + Ke + (fL_c/4R_c) \qquad (12)$$

in which Ki and Ke are the entrance and exit loss coefficients. Earlier investigators, O'Brien and Dean (1972) and Drapeau (1988) use the values of Ki + Ke = 1.3 and f = 0.03.

The dimensionless tidal frequency G is defined as:

$$G = (\surd(L_c A_b/gA_c))2\pi/T \qquad (13)$$

and the dimensionless damping coefficient B is defined as

$$B = (F/2L_c)(A_b/A_c)H_o \qquad (14)$$

Mehta and Ozsoy (1978), Drapeau (1988) have thence defined a coefficient M as

$$M = (16BG^2)/3\pi \qquad (15)$$

and the ratio between the bay tide amplitude and the sea tide amplitude $R = H_b/H_o$, such that R is given by

$$R = \left(\frac{((1-G^2)^4 + M^2)^{0.5} - (1-G^2)^2}{0.5M^2} \right)^{0.5} \qquad (16)$$

and the angle of the phase lag for the tide in the lagoon is given by

$$E = \tan^{-1}((M*R)/2(1-G^2)) \qquad (17)$$

The maximum value of the velocity averaged over the flow area (A_c) is

$$V_{max} = \sqrt{\left(\frac{2gH_o \sin E}{F}\right)} \qquad (18)$$

where g is the acceleration of gravity.

The dimensionless maximum channel velocity over a tidal cycle is given by

$$V'_m = \frac{A_c T V_m}{2\pi H_o A_b} \qquad (19)$$

The above mathematical formulations (12-19) have been applied in this study; see Appendix - II for program on stability analysis. The maximum channel velocity averaged over the flow area for two different bay areas and increasing channel depth(s) was calculated and compared with actual field values observed at Cochin inlet as discussed in Chapter - 3. An analytical application of the above stability analysis has been made for the design of a jetty improved channel at Andhakaranazhi inlet. In this context, siting of a fisheries harbour is detailed in Chapter - 4.

CHAPTER - 3

STRAIT DYNAMICS OF COCHIN TIDAL INLET

1. Introduction

The dynamics of coastal sea- tidal inlet- estuary system plays a critical role at harbours/ports of commercial importance. The system which forms a major feature of the coastal zone requires considerable attention in the realm of harbour operations. Cochin estuary on southwest coast of India and its inlet channels form a typical tropical bay - inlet system which had undergone very many coastal zone modifications in recent years. The changes brought about in the distribution of estuarine surface area, inlet channel configuration, tidal flux regime and cross sectional area have had direct implications on the hydraulic, hydrodynamic and the sediment dynamics as well as the morphodynamic conditions of this sea-inlet-estuary system. This chapter critically reviews the above changes while highlighting the hydrodynamic stability and the dynamic equilibrium flow conditions.

This chapter also deals with the impacts on the system due to the altering status on estuarine hydrodynamics. The dilution and flushing characteristics of this coastal inlet is of prime concern due to the fact that a large number of industrial production concerns like ceramics, fertilizers, metallurgy, oil refinery including terminal and ship building yard are situated along the river-estuarine banks, locations often where dredged spoil disposal (resulting mainly from maintenance dredging) finds its way (Rasheed et al., 1995b).

Specifically elucidated are decadel variation in the tidal inlet characteristics and estuarine features of this tropical region including variation in volume transport and stratification circulation features.

2. Environmental setting

The Cochin inlet acts as an active morphologically evolved land-sea interfacial, physical and geographical system compatible to fluvial processes of tropics elsewhere. This region under study on the south west coast of India (figure 1) and its adjoining waters exhibits tropical characteristics of a region that is dominated by transport and settling of voluminous amounts of suspended material of terrestrial origin (Balchand and Nambisan, 1988; Ajith and Balchand, 1994). Additionally, bedload movements were also postulated from textural studies in the lower reaches of the rivers of this region which empties into the inlet system (Padmalal, 1992). Hydrodynamic behaviour of this natural harbour was mainly attributed to the controlling parameters - estuarine surface area and tidal prism, magnitude of tidal currents as well as the fresh water discharges from Muvattupuzha and Periyar rivers, which bring about the stratification and circulation features within the harbour (Joseph and Kurup, 1989). This harbour region and adjoining coastal zone had undergone very many engineering modifications like inland reclamation, wasteland management, waterways development, construction of bridges and deepening of the shipping channels (Rasheed et al., 1995c; Ajith and Balchand, 1996) which have time to time influenced the variability of the hydrodynamic aspects of the bay-inlet-nearshore system. Studies on tidal characteristics at Cochin by several investigators have explained that the tides are of mixed with predominantly semidiurnal character having a maximum range of 1m (Qasim and Gopinathan, 1969; Josanto, 1971; Rama Raju et al., 1979; Varma et al., 1981, Joseph and Kurup, 1987 & 1989, Ajith and Balchand, 1994). Previous studies by Defant (1961) and Dronkers (1964) too based on the important harmonic components strengthened the fact that the tides at Cochin are of mixed but predominantly semidiurnal.

The dynamics of this region show seasonal variations in characteristics. The monsoon season (June-September), postmonsoon (October- January) and premonsoon (February - May) exhibit different circulation and stratification features. During the monsoon season, the estuarine circulation is mainly attributed to the interaction between the enhanced freshwater runoff from heavy rains and the high dense saline water from the sea side. The estuary -inlet system is a well mixed type during the premonsoon months when the freshwater fraction is almost negligible. The estuarine features at Cochin inlet vary from month to month as observed by Joseph and Kurup (1989) from that of a salt wedge type to a highly stratified condition prevalent during southwest monsoon season. A partially mixed to moderately stratified condition occurs during the postmonsoon months due to the influence of freshwater runoff from the widespread/sparsely northeast monsoon rains. During southwest monsoon (June - September) dominant stratification features are noticeable at the barmouth and near its vicinity especially within the inner channels. However the river management approaches and freshwater diversions at the upstream regions and the changes brought about in the distribution of estuarine surface area, tidal regime and variation in channel configuration due to various coastal engineering activities, influenced the hydrodynamics as well as the sediment dynamic behaviour of this highly dynamic inlet-estuary system (Ajith et al., 1995a). Details on the geographical setting and network of waterways, sedimentation pattern and dredging operations in the channels and information on upcoming projects have been detailed elsewhere (Rasheed et al., 1995b & d).

Previous studies on the sedimentation and hydrodynamics at Cochin estuary have been conducted by a number of investigators (Ramamritham and Jayaraman, 1963; George and Kartha, 1963; Qasim and Reddy, 1967; Cherian, 1967; Josanto, 1971; Wellershaus, 1971; Joseph, 1974; Balakrishnan and Shynamma, 1976; Lakshmanan et al., 1982; Sankaranarayanan et al., 1986; Joseph, 1989; Sundaresan, 1991, Rasheed et al., 1995a & c). However only limited studies have been conducted on tidal inlets (Indian region), especially on the one situated at Cochin (see Plate). Rama Raju et al.,(1979) had studied the hydrodynamic characteristics and tidal prism at Cochin harbour mouth; this study was mainly based on the tidal prism of Cochin estuary. Dixit (1987) made an observation on the change in the mixing characteristics at this inlet due to the widening of the Ernakulam channel. Study of volume transport and estuarine features at Cochin

Plate. View of Cochin inlet from offshore.

inlet by Joseph and Kurup (1989) gave an insight into the significance of tidal range and duration, quantity of fresh and saline water intrusion on the volume transport at the inlet. The studies on density currents at Cochin by Chandramohan (1989) explained the influence of channel configuration and morphology on the features of density currents at the gut of the Cochin inlet.

The migration and offset of coastal inlets of Kerala was studied with remote sensing imageries by Nair et al., (1993). Since then, no detailed investigation had been conducted at Cochin tidal inlet on the flow dynamics and the suspended sediment distribution, in particular; the studies on the distribution of suspended solids in relation to the oscillatory currents at Cochin inlet by this author (Ajith and Balchand, 1994) elucidated the characteristics of oscillatory currents and its predominant role in the suspended solids distribution at the inlet (details incorporated later in this chapter). Also noted in this thesis are the published results on my findings at Cochin tidal inlet (Ajith et al., 1995a ; ; Rasheed et al., 1995a, b, c & d; Ajith and Balchand, 1996). The salient features of the dynamics of the flow through the inlet and its influence on the estuarine circulation as well as the morphodynamic behaviour of this inlet-estuary system with emphasis on the inlet stability and its allied aspects are discussed hereunder.

3. Results and Discussions

A) Flow characteristics

Flow characteristics in a tidal inlet or harbour entrance is exemplified by virtue of the magnitude and direction of the flow and the characteristics of the tide which determine the extent of safe navigation. Aspects of flow characteristics also helps in the understanding of the exchange of water. The transport of sediments between estuaries and nearshore regions are controlled by flow conditions at any inlet. According to Mehta and Ozsoy (1978) the inlet flow dynamics is dependent upon inlet and bay geometry, freshwater flow, ocean wave and tide characteristics and sediment movement; however, the combined influence of all these factors results in a complex situation in judging the flow conditions. The dilution and flushing characteristics of an estuary/bay is also contingent on the features of flow through the inlet which connects the estuary to the nearshore regions - in the transport and disposal of industrial effluents, sewage and dredged spoils. Otherwise stated, the major driving force for flow through the inlet in the absence of freshwater outflow from the estuary is the velocity head between the ocean tide and the bay tide.

Table 1 gives the values of current vectors for three depths (surface, mid depth and bottom) during different months at stations 1 to 11 located at the Cochin inlet. The study on inlet flow characteristics were purposely held under different tidal stages in different seasons to elucidate information on freshwater/seawater mixing at inlet, altering

Table 1. Current vectors at stations 1 - 11 located at Cochin inlet for three depths surface, mid depth and bottom from March 1993 to June 1994.

Station		March'93		August '93		October '93	
		vel.	dirn.	vel.	dirn.	vel.	dirn.
1	surface	022	330	080	245	043	296
	mid depth	012	050	109	104	073	095
	bottom	014	110	131	125	117	106
2	surface	032	288	020	176	168	292
	mid depth	006	280	013	166	132	112
	bottom	017	176	163	102	067	095
3	surface	014	325	035	268	218	301
	mid depth	020	054	018	166	214	043
	bottom	034	102	120	126	202	107
4	surface	033	175	033	330	126	276
	mid depth	038	114	028	092	098	102
	bottom	028	102	075	108	058	072
5	surface	021	155	043	251	063	284
	mid depth	026	087	068	087	061	128
	bottom	024	060	164	097	067	090
6	surface	052	188	045	240	094	302
	mid depth	051	147	018	350	124	175
	bottom	057	120	165	098	073	100
7	surface	017	260	008	190	106	295
	mid depth	013	150	025	356	187	127
	bottom	011	125	040	072	214	116
8	surface	079	280	025	295	186	230
	mid depth	020	233	030	317	165	277
	bottom	013	245	018	286	196	076
9	surface	057	020	023	202	080	182
	mid depth	061	027	044	056	112	082
	bottom	036	028	162	091	088	078
10	surface	033	340	038	258	138	274
	mid depth	022	030	016	073	071	088
	bottom	024	145	118	090	037	091
11	surface	067	269	009	265	160	270
	mid depth	027	248	021	275	113	052
	bottom	013	116	086	103	159	110

(velocity (cm/s)) Direction in degrees from true north.

(Con't....2)

Station		November'93		December'93		January'94	
		vel.	dirn.	vel.	dirn.	vel.	dirn.
1	surface	024	180	021	104	080	237
	mid depth	160	132	030	120	064	170
	bottom	364	104	020	112	152	120
2	surface	326	092	207	006	138	330
	mid depth	338	085	141	238	150	122
	bottom	273	009	202	325	126	117
3	surface	015	322	353	085	075	178
	mid depth	020	090	291	125	087	223
	bottom	023	077	228	090	108	078
4	surface	014	110	183	200	154	280
	mid depth	017	066	078	176	124	240
	bottom	022	068	083	160	104	150
5	surface	018	209	303	330	141	327
	mid depth	020	086	353	344	136	300
	bottom	020	080	334	292	157	087
6	surface	111	061	204	246	141	268
	mid depth	029	079	190	285	131	312
	bottom	036	062	175	220	113	095
7	surface	016	273	256	208	094	175
	mid depth	021	085	204	252	076	265
	bottom	040	355	338	302	073	096
8	surface	050	069	380	076	111	278
	mid depth	044	005	337	050	088	165
	bottom	071	117	213	046	070	036
9	surface	028	296	098	259	036	352
	mid depth	065	319	042	250	092	040
	bottom	075	301	023	250	202	088
10	surface	062	097	230	003	189	348
	mid depth	060	096	142	037	198	025
	bottom	041	080	037	045	100	067
11	surface	095	060	397	185	111	003
	mid depth	127	124	348	047	032	040
	bottom	186	347	350	104	045	036

(Con't....3)

Station		February'94		March'94		June'94	
		vel.	dirn.	vel.	dirn.	vel.	dirn.
1	surface	181	090	119	096	174	116
	mid depth	132	091	276	118	044	118
	bottom	065	108	313	097	052	120
2	surface	214	074	057	113	105	120
	mid depth	232	100	077	128	141	117
	bottom	242	100	055	055	166	115
3	surface	183	286	112	039	162	099
	mid depth	013	067	161	030	109	108
	bottom	016	069	196	021	159	112
4	surface	104	087	143	065	072	119
	mid depth	010	049	107	083	094	081
	bottom	031	307	169	093	137	111
5	surface	016	043	142	053	069	078
	mid depth	018	340	070	070	119	120
	bottom	020	021	083	084	147	116
6	surface	276	022	109	029	077	107
	mid depth	015	084	100	082	126	097
	bottom	024	064	148	086	145	099
7	surface	112	064	181	105	034	085
	mid depth	038	090	200	090	027	116
	bottom	112	086	129	146	027	219
8	surface	026	150	148	070	059	078
	mid depth	069	094	170	095	019	148
	bottom	060	106	268	115	019	229
9	surface	061	137	187	105	219	127
	mid depth	077	113	147	091	180	102
	bottom	113	114	125	102	105	115
10	surface	140	127	097	138	031	307
	mid depth	237	100	049	351	067	152
	bottom	106	117	263	104	047	089
11	surface	306	078	099	102	130	125
	mid depth	367	093	166	111	119	110
	bottom	399	100	178	112	089	119

flow conditions and its overall response to seasonal changes.

March 1993 study was begun at the start of the ebb flow; the surface currents were directed offshore to indicate an outflow of water at the inlet with surface values ranging from 14 cm/s at Station 3 and 79 cm/s at station 8. However the mid depth currents along the Fort Cochin bank and at mid channel were directed inward into the bay with values ranging from 12 cm/s at station 1 to 61 cm/s at station 9. But the mid depth currents along the Vypeen bank was directed offshore as an outflow with values ranging from 6 cm/s to 27 cm/s at station 2 and station 11 respectively. The bottom currents at stations along the Fort Cochin bank and also at the mid channel showed an inward flow; however the current flow along the Vypeen bank was directed along the ebb flow direction, with values ranging from 13 cm/s at station 11 to 57 cm/s at station 6. This indicates the horizontal transverse flow at the inlet which is likely to induce large circulatory motions generally reported at tropical river-estuary mouths due to coriolis force (Dyer, 1979).

The results and discussion on current vectors in May 1993 is scheduled later within this chapter to account for 4 stages of the tide.

August 1993 survey was at flood stage, during monsoon; the surface currents at all the stations along the inlet were directed offshore with surface values ranging from 9 cm/s at station 11 to 80 cm/s at station 1. However the mid depth current along the Fort Cochin bank and along the mid channel were directed into the bay; the direction of mid depth current at station 11 followed that of the surface current. The direction of flow at the bottom was towards the bay invariably at all stations along the inlet consistent with that of the flood tide stage. The bottom current values ranged from 18 cm/s at station 8 to 165 cm/s at station 6. The influence of freshwater outflow through the inlet over a saline bottom layer gave rise to a stronger flood at the bottom than at the surface. The presence of stronger ebb than flood at the surface and a stronger flood than ebb at the bottom was already evidenced by Mehta and Ozsoy (1978) at many a number of inlets.

Results of October 1993 survey indicated the surface currents to be directed seaward along the inlet at all stations with values ranging from 63 cm/s at station 5 to 218 cm/s at station 3 at the start of the ebb current. However the mid depth currents were flowing into the inlet with the exception at station 8 where the flow of the surface current was also in the same direction. The values of the mid currents ranged from 61 cm/s at station 5 to 214 cm/s at station 3. Similarly the values of the bottom currents at all the stations in the inlet did follow that of the mid currents, up the inlet, into the bay with values ranging from 37 cm/s at station 10 to 202 cm/s at station 3. The significance of change in direction of surface current with the tide was particularly noticed as the mid depth and bottom currents were still flowing in the flood tide direction, up the inlet. This vertical circulation corresponds to the classical estuarine circulation pattern with seaward flow near the surface and return flow of the saline bottom waters as reported by Soucy et al. (1976) in St. Lawrence river estuary.

November 1993 survey results are depicted in table 1 which corresponds to the flood stage. The surface currents at the boundary stations 4,5,10 were comparatively of less magnitude; however a marked variation was observed in the values of the surface, mid and bottom currents at station 2. The surface currents at stations 8,10 and 11 were directed into the estuary. The maximum velocity observed was at surface, 326 cm/s at station 2, near Vypeen whereas the lowest velocity observed was again at the surface (14 cm/s) at station 4. The bottom current velocity at station 1 and station 2 were very high (364 cm/s, 273 cm/s respectively). But the current values at station 1, from bottom to surface showed a decrease in magnitude (364, 160 and 24 cm/s) during the flood stage.

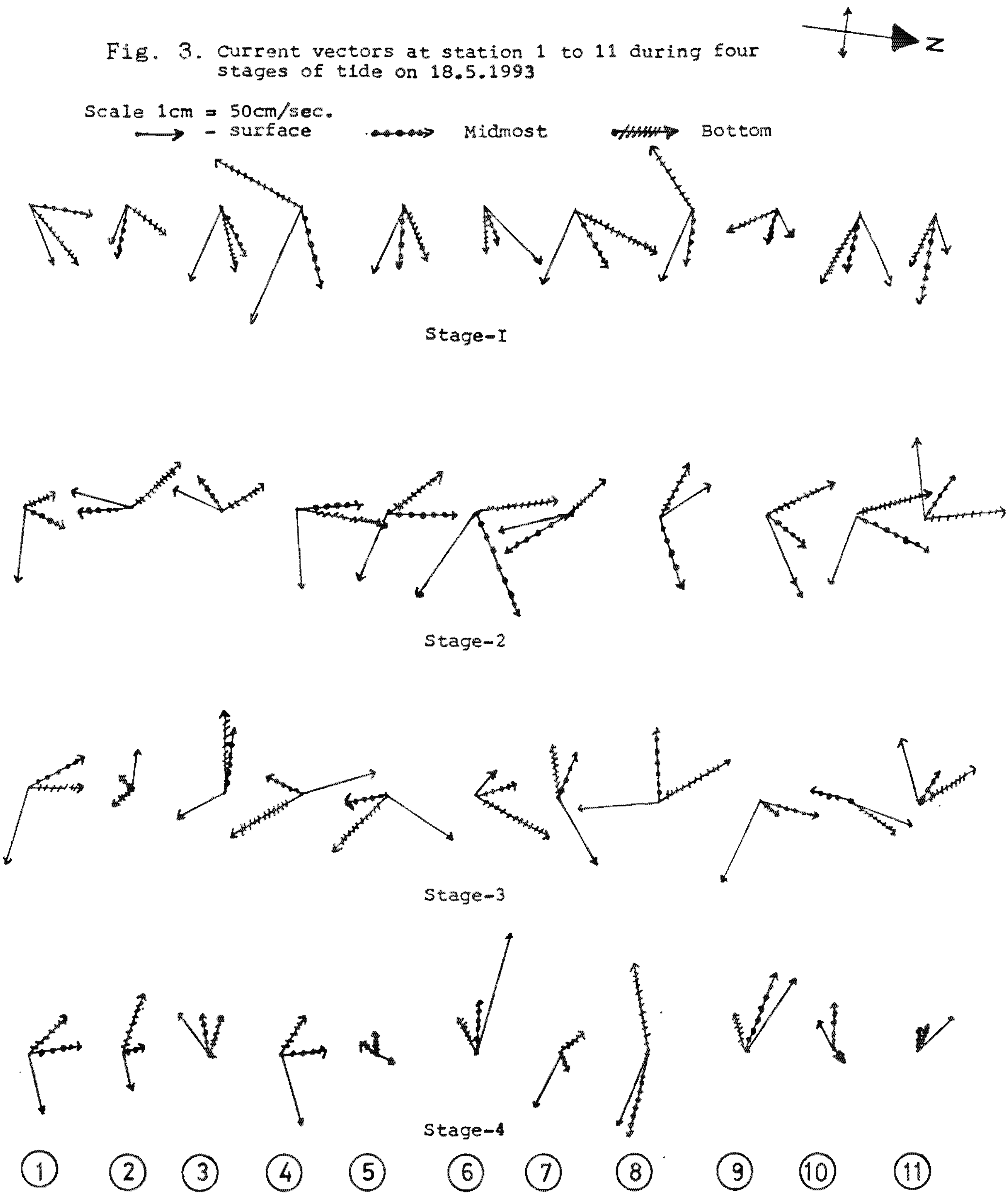
During December 1993 survey, the results on the current at station 1 indicated low values compared to the values at all other stations. The surface currents were very high at all stations other than 1 as well as at mid and bottom depths with highest values reaching 397 and 350 cm/s respectively at station 11. Continuing the study through January 1994, the surface currents were unidirectional and were towards the sea but the bottom currents were directed inwards into the bay; the mid depth current vectors at the inlet mouth were directed offshore but those at the bay region were directed inwards into the estuary. The offshore direction of the surface and mid currents and the inward direction of the bottom currents indicate the continued ebbing at the surface and mid depth and the start of the flood at the bottom layers.

February 1994 saw the surface currents to be directed up the estuary through the inlet, however the magnitude was very high compared to the magnitude of flow at the mid and bottom depths. The maximum flow values were observed at station 11. where the bottom and mid currents were higher as compared to the surface current. The least values were observed along the channel boundary stations. The study in March 1994, during the flood stage, exhibited the surface, mid and also all bottom currents to be directed into the estuary with maximum values at bottom of stations 1 and 10, locations at either ends of the inlet.

In June 1994, the surface currents were unidirectional towards the estuary at the inlet with maximum values ranging from 174 cm/s at station 1, 162 cm/s at station 3 and 219 cm/s at station 9. But the surface currents along the inlet boundaries were comparatively weak with values ranging from 31 cm/s at station 10 to 105 cm/s at station 2. Similarly, the mid depth currents, invariably, at all stations along the inlet channels, did follow the typical flood current direction, flowing into the estuary with values ranging from 19 cm/s at station 8 to 180 cm/s at station 9. But the bottom currents at station 7 and 8 with values 27 cm/s and 19 cm/s respectively, were directed opposite to the flow up the inlet, as noted at all other stations with minimum and maximum values 52 cm/s at station 1 and 166 cm/s at station 2 respectively.

In order to understand the flow pattern at the inlet during the premonsoon season (May 1993), when circulation at the inlet is mainly attributable to the tidal currents, current meter observations were made to cover four different stages of the tide (figure 3). Stage 1 corresponds to the flooding stage during which time the surface flow at all the stations were directed towards inland. The maximum velocity observed at the surface was 161 cm/s and the least observed was 39 cm/s at station 11, located farthermost within the inlet. Similar velocities had been reported by Varma et al., (1981). The mid and the bottom currents too follow a similar pattern. During the 2nd stage, the tides were altering from flood to ebb (just after high slack time), when the current vectors indicated a change of direction more predominantly in the lower layers and definitely at surface of station 11 resulting in an outflow. The direction of the bottom current helped to deduce a counter clockwise orientation of water movement invariably at all stations. Hydrographic characteristics and tidal prism studies at Cochin barmouth by Rama Raju et al., (1979) had highlighted the effect of changes in the directionality of currents. The pictorial representation of current vectors indicates the presence of tidally induced residual flows at stations 3,4 and 9,11. The current velocities as compared between surface and bottom are nearly equal in magnitude but definitely skewed in direction giving rise to the velocity shear between the layers. Findings by Hamblin et al., (1988) in St.

Fig. 3. Current vectors at station 1 to 11 during four stages of tide on 18.5.1993



Lawrence river Estuary also mention the presence of such physical processes at tidal inlets.

Figure 3 also describes the current vectors during the 3rd stage of the tide (ebb maximizing) when stronger flow occurred in the midmost and lower layers from the estuary to open sea. This flow was predominantly observed along the northern parts (Vypeen bank). On the other hand, the surface flow was directed northward and subsurface flow southward along the Fort Cochin bank (stations 4,5 and 10). Summarizing, this stage of the tide give rise to horizontal transverse flow at the inlet which is likely to induce large circulatory motions generally reported at tropical river-estuary mouths due to coriolis force (Dyer, 1979). The above result is supported by surface currents directed inland from the south westerly area of Cochin inlet. Stage 4 denotes the current vectors towards the end of the ebb tide cycle which signifies the net flow from the estuary to the sea; the magnitude of the current being relatively lesser compared to values shown in the previous stages of the tide. The commencement of the flood is indicated by the direction of currents at surface and midmost layers. The current velocity during the flood phase do generally exceed the ebb phase as observed from the above features.

B) Temperature

The following paragraphs discuss the temperature variation at different stations at the inlet during certain representative months of different seasons.

August 1993 - the temperature values were higher at the surface and decreased towards mid depth; the least values were observed at the bottom. The surface temperature varied from 27.4°C to 28.2°C, the mid depth values varied from 25.5°C to 28.0°C whereas the variation at the bottom was from 22.6°C to 26.8°C.

December 1993 - the temperature at the surface varied from 28.6°C to 29.2°C, at mid depth from 28.6°C to 28.8°C and at bottom, the temperature values at all the stations were 28.6°C. The minimum and maximum values at the surface, mid depth and bottom were comparatively higher during December spring flood than that in August 1993 spring flood.

January 1994 - The temperature at the surface varied from 28.0°C to 29.2°C between stations at the inlet. The mid depth values ranged from 28.2°C to 28.6°C considering all the stations except stations 10 and 11. The bottom values during this month of observation remained constant at 28.2°C at all stations with a single marginal variation, a value of 28.4°C at station 10. During January 1994, partial to well mixed conditions prevailed such that the vertical temperature variation from mid depth to bottom remained constant.

March 1994- The surface temperature varied from 29.6°C to 30.0°C during the March neap flood. Whereas at the mid depths, the temperature values varied in a range (29.5°C - 30.0°C) between the stations, the bottom values falling in the range of 29.2°C- 29.8°C. During this period the vertical distribution was noteworthy with marginal temperature increase from surface to mid depth and then a decrease to bottom at stations 2, 3 and 4.

June 1994- The surface temperature values varied in the range 26.6°C to 29.4°C and the mid depth values in the range of 24.4°C to 24.8°C whereas at the bottom, the temperature ranged between 23.8°C and 25.2°C. During this spring flood stage, the profile of vertical temperature indicated values to decrease from surface to bottom.

C) Salinity

An understanding of the distribution of salinity at the inlets helps to elucidate the dynamic processes established at tidal inlets in relation to freshwater and sea water mixing, the tidal flow and the circulation and stratification features. The following paragraphs discuss the distribution of salinity (values are given only in text) in vertical and horizontal at Cochin tidal inlet. The hydrographic conditions prevailing in the estuary over a tide cycle has been studied and the information gathered from the same has been utilised to arrive on the stratification and circulation characteristics of this inlet.

May 1993 study indicated a surface salinity range from 24.00 to 33.00 and at mid depths, the value ranged from 26.00 to 35.00 and the vertical salinity gradient was increasing from surface to mid depth. From mid depth to bottom the salinity values increase gradually at all stations. The bottom values vary in the range 29.00 to

35.00 and higher values were observed at stations near the mouth of the inlet and lower values to occur at the bay side of the inlet.

During August 1993, the surface salinity was very low due to the outflow of freshwater from the upstream estuarine regions through this inlet. The surface values varied in the range 0.80 - 1.50 between the stations. At the mid depth, the salinity values were comparatively high due to the presence of saline wedge - it varied in the range 1.50 - 13.50. But at the bottom the vertical salinity gradient was higher and a sharp gradient could be observed at stations 3, 4, 7 and 11. The representative values at the bottom falls in the range 22.50-31.80.

The horizontal salinity distribution at the surface and bottom were almost uniform. However, at mid depth, a sharp horizontal gradient was observed between stations 4 and 5 on the south west side of the inlet mouth; and again similarly between stations 6, 7 and 8. This signifies the interaction between fresh surface water and the saline bottom water resulting in a layer of inter mixing at mid depth during this month.

The surface salinity was comparatively low with minimum value of 2.75 at station 11 and a maximum value of 4.00 at station 4 during October 1993. A sharp vertical gradient was observed at all the stations between surface and mid depth with minimum mid depth value (9.50) at station 11 and maximum (21.50 and 21.55) at stations 1 and 4 respectively. An uniform increase was noticed at all stations from mid depth to bottom with the exception at station 11 inside the bay where a sharp vertical gradient in salinity was observed (9.50 to 19.00)

The horizontal section of the surface salinity featured values to vary from 2.75-4.00 and at mid depth, from 9.50-21.55 while the bottom value varied from 17.25-23.50. The salinity differences from surface to bottom indicate that the freshwater inflow which is caused by the presence of northeast monsoon rains results in stratification at the inlet. The horizontal distribution of surface salinity is restricted to a narrow range of values among all the stations covered in this study. At mid depths, the horizontal distribution is not uniform whereas the bottom distribution of salinity is similar to that at surface.

November 1993 survey indicated the surface salinity to vary from 14.50 at station 11, to 21.75 at station 1; and the mid depth values to vary from 28.50 at stations 11 and 5 to 30.75 at station 1. A considerable vertical salinity gradient was also observed from surface to mid depth but mid depth to bottom, partial to well mixed conditions prevailed at the inlet cross section stations while the vertical salinity gradient was weak at the bay side stations 10 and 11.

In December 1993, the vertical salinity gradient from surface -mid depth- bottom is not prominent as compared to the other months in monsoon season. The surface salinity varied from 29.20 at station 11 to 30.50 at stations 4, 5 and 8, at the sides of the channel. At the mid depth, the salinity values varied from 30.50 to 31.50 between stations and the bottom values varied from 31.50 to 31.75 with maximum value at the entrance station and the minimum value at the bay side station.

January 1994 showed the surface salinity to vary from 24.00 to 26.00 between the stations. The vertical salinity gradient from surface to mid depth and to bottom is very weak and this observation during January exemplifies that the inlet stations were occupied by vertically mixed homogeneous water. March 1994 study showed that the surface salinity values ranged from 27.50 to 29.25 between stations; and increased from surface to mid depth sharply and then increased marginally from mid depth to bottom. The mid depth values ranged from 30.50 to 31.75 and the bottom values varied from 32.00 to 32.50. The horizontal distribution of salinity indicated that the surface, mid depth and bottom values were uniformly distributed with slight variation only in the surface distribution.

The investigations in June 1994 indicated that the surface to mid depth salinity values to vary drastically and then the gradient to lessen from mid depth to bottom compared to surface to mid depth. The surface values ranged from 5.50, 5.75, 6.00 and 6.10 at stations 7, 11, 8 and 2 respectively. The mid depth values varied from 13.50 to 32.60, whereas the bottom values ranged from 28.50 to 34.15. The extent of stratification is due to the presence of freshwater at surface over the bottom saline waters due to the influence of the onset of monsoon rains which is noticed at all the stations.

D) Sigma -t

The sigma-t values are expressed at atmospheric pressure and estimated by making use of the equation of state of the sea water (Fofonoff and Millard, 1983). The change of sigma-t with a change of salinity is almost uniform, but the variation with temperature change is distinctly non uniform. At high temperatures, σt varies significantly with temperature (t) at all salinities but as temperature decreases, the rate of variation with t decreases particularly at low salinities, like in estuaries (Pickard and Emery, 1990). The (selected) monthly Sigma - t analysis at inlet is presented hereunder inclusive of data. August 1993- The surface σt values showed the presence of freshwater; the mid depth values varied in a range of 0.80 to 7.05 at the inlet stations. The bottom values were higher ranging from 14.21 to 29.80. The presence of denser saline water at the bottom with less saline and freshwater at the surface can be well authenticated from the change in σt values at inlet stations.

December 1993- The sigma-t of the surface waters at the inlet stations during December spring flood varied from 16.77 to 18.76 among the stations, whereas at the mid depth the σt values varied in the range 19.57 to 19.76. The surface σt varies uniformly with a change in salinity between the stations. A significant indication of mixing can be inferred from the variation in σt values at mid depth. However the waters at bottom levels were near stable in a well mixed state there was no variation in σt at the inlet mouth stations with the exception of stations located on the bay side (stations 7, 8, 9, 10 and 11). However in the vertical, the water column is stable with less denser water at the surface and higher denser water at the bottom. More denser water at the mid depth was observed on the Fort Cochin side and the mid channel as compared to that on the Vypeen side at the mid depth.

January 1994- During the spring flood in January the σt values varied in the range 13.90 - 15.52 at the surface and 16.33 - 17.64 at the middle and in the bottom the σt values varied from 17.58 to 18.47. During this period, the vertical σt gradient was uniform such that the water column in the vertical was stable. The significant variation in the σt values in horizontal indicates that non-linear mixing occurs at the mid depth and bottom. The variation at the surface can be attributed to the changes in surface temperature values.

March 1994- The surface σt values varied in a range 16.06-17.49; at mid depth, in a range 18.43-19.77. At station 7, near the Vypeen bank, denser water was observed at mid depth than the bottom which is not expected generally. However, at all other stations, vertical σt profile showed a more stable water column. The surface σt values are almost uniformly distributed whereas indications of vertical mixing was observed between mid depth and bottom. No prominent variation in the horizontal distribution of σt was observed among the stations at all levels unlike during the spring flood of June 1994.

June 1994- The surface σt values varied in the range 0.54 - 16.83 and at mid depth, in the range 6.36 - 21.71; at bottom, the values were in the range 18.47 - 23.02. In the vertical, the σt increased from surface to bottom at all the stations and the presence of more denser water was observed along the Fort Cochin side of the channel and also in the mid channel whereas less denser waters were observed on the northwestern side along the Vypeen bank. Similarly, at the bottom also, the denser waters are observed along the Fort Cochin side of the channel and less dense waters on the northwest side along the Vypeen bank. Similar was the case at the surface too. In general, at the inlet, during spring flood of June 1994, higher σt values were observed along the Fort Cochin bank compared to Vypeen bank.

E) Suspended solids

Investigation on the suspended solids content (figures 4a, b & c - vertical distribution and figures 5a to h - horizontal sections of surface, mid depth and bottom) held concurrently points out to complex distribution of (suspended) material at the tidal inlet. A common observation was that the bottom layers did contain the highest amounts of suspended solids than the midmost which was higher than the surface. The role played by suspended sediment in the transport and fate of contaminants have led to closer observation of suspended solids at tidal inlets. However due to the complex geometry, strong tidal currents and the turbulent mixing and density gradients due to freshwater and saline water mixing have varied influences on the distribution and transport of suspended solids at tidal inlets. The emphasis on currents having a predominant effect over the rate of transport as well as on settling rate is well documented (Adams et al., 1990). According to Bruun and Gerritsen (1978) the suspended sediment load in the inlet flow has its origin either caused by the turbulent flow due to tidal currents which cause the stirring up of bed material or due to the silt load from upland rivers moving into the estuary and to the inlet or due to suspended material stirred up by wave action and being transported as littoral drift into the inlet channel. The Cochin inlet and its adjoining backwaters receive terrestrial inputs which include large quantities of alluvial material brought in as suspended solids which settle in the coastal regions including in areas within the estuary and the channels (Gopinathan and Qasim, 1971). The following passage discusses the distribution and transport of suspended solids at this tidal inlet. The horizontal sections (figures 5a - h) have been generated on computer using inverse distance method which has resulted in overflow of contours on all sides of the grid. However the station locations are plotted distance wise correctly and indicated in figure 5(a) middle depth.

In the month of May 1993, the vertical distribution of suspended solids (figure 4a) showed an increasing tendency from surface to mid depth (flood stage). Similarly from mid depth to bottom there exists a sharp increase in suspended solid concentration except in station 3 and station 6. The representative values at the surface fall within the range,

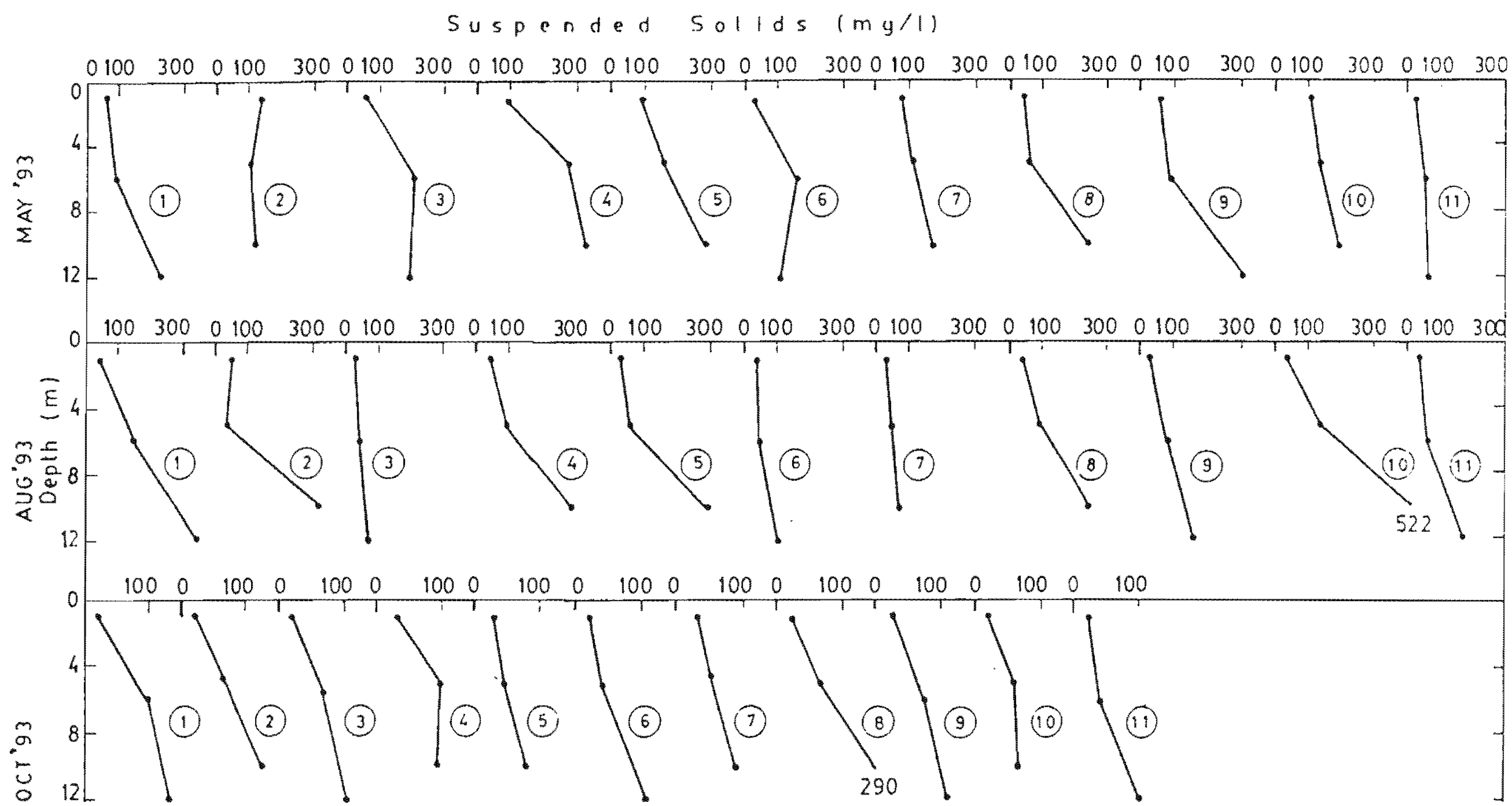


Fig. 4a. Vertical distribution of suspended solids(mg/l) at stations 1-11 during May, August and October 1993.

40 mg/l to 140 mg/l. But the mid depth concentration ranges from 44 mg/l to 325 mg/l and the bottom values in the range 60 mg/l- 330 mg/l at all stations. Higher gradient between surface and mid depth was observed at stations 3, 4 and 6. The increase of suspended solids concentration from mid depth to bottom is also high at stations 1, 5, 8 and 9.

In the analysis of horizontal section (figure 5a), the suspended solids concentration at surface was observed to be localized between stations 2, 3 and 7 so that it seemed to be concentrated along the Vypeen bank of the channel at the entrance. Whereas at the mid depth, the higher suspended solids concentration was observed to be localized between stations 3, 4 and 5 on the Fort Cochin side of the channel. At the bottom layer the distribution between stations was within the limited range of values except that it was less at station 11.

August 1993 survey established the following features. The vertical distribution from surface to mid depth was prominent in variation at stations 1 and 10, whereas at all other stations the values were uniformly distributed (figure 4a). From mid depth to bottom the vertical distribution did show a sharp variation except at stations 3, 6 and 7. A range of representative values fall at the surface, as 25 - 50 mg/l. But at the mid depth the values fall in the range 35 - 155 mg/l and at the bottom in the range 70-522 mg/l. At surface, in the horizontal section (figure 5b), the suspended solids concentration was observed to be highly localized between stations 2 and 7 i.e., on the Vypeen side

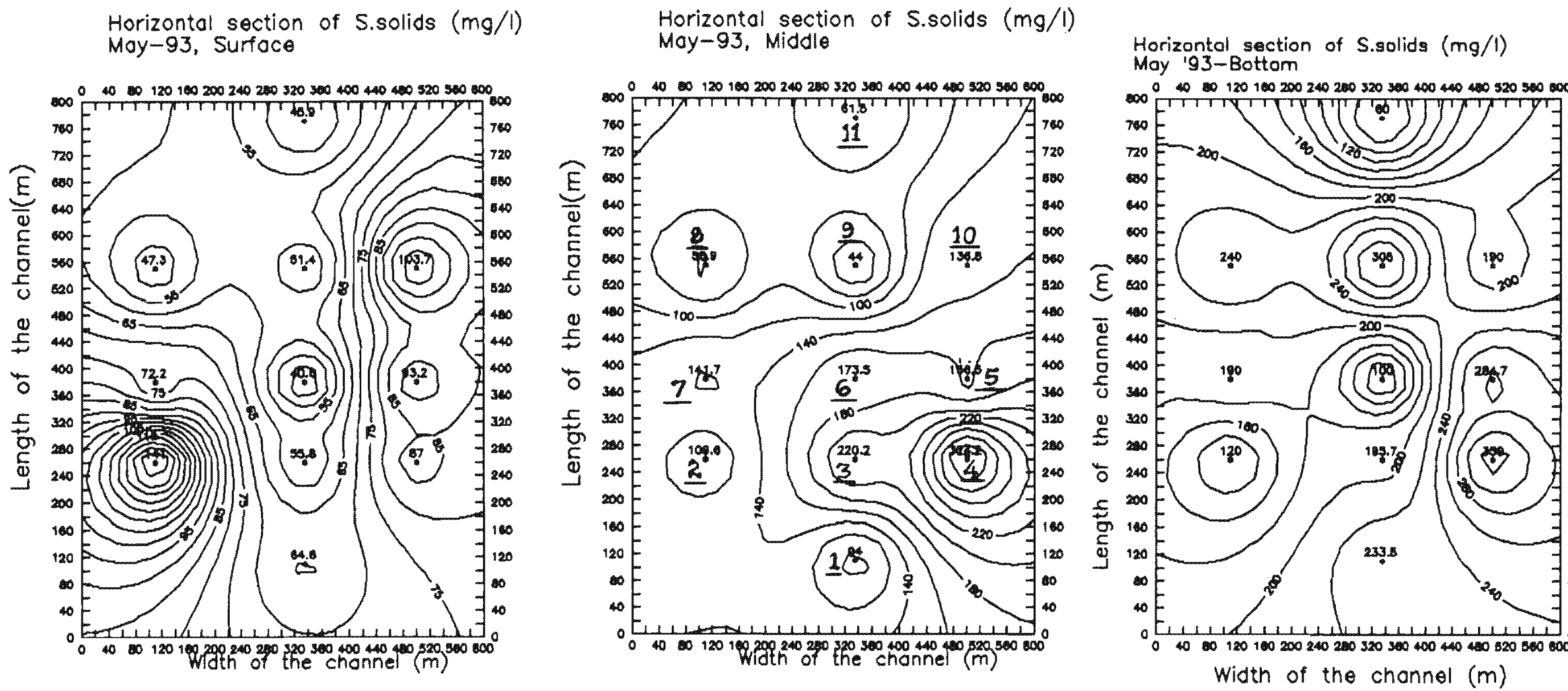


Fig. 5a. Horizontal section of suspended solids during May 1993.

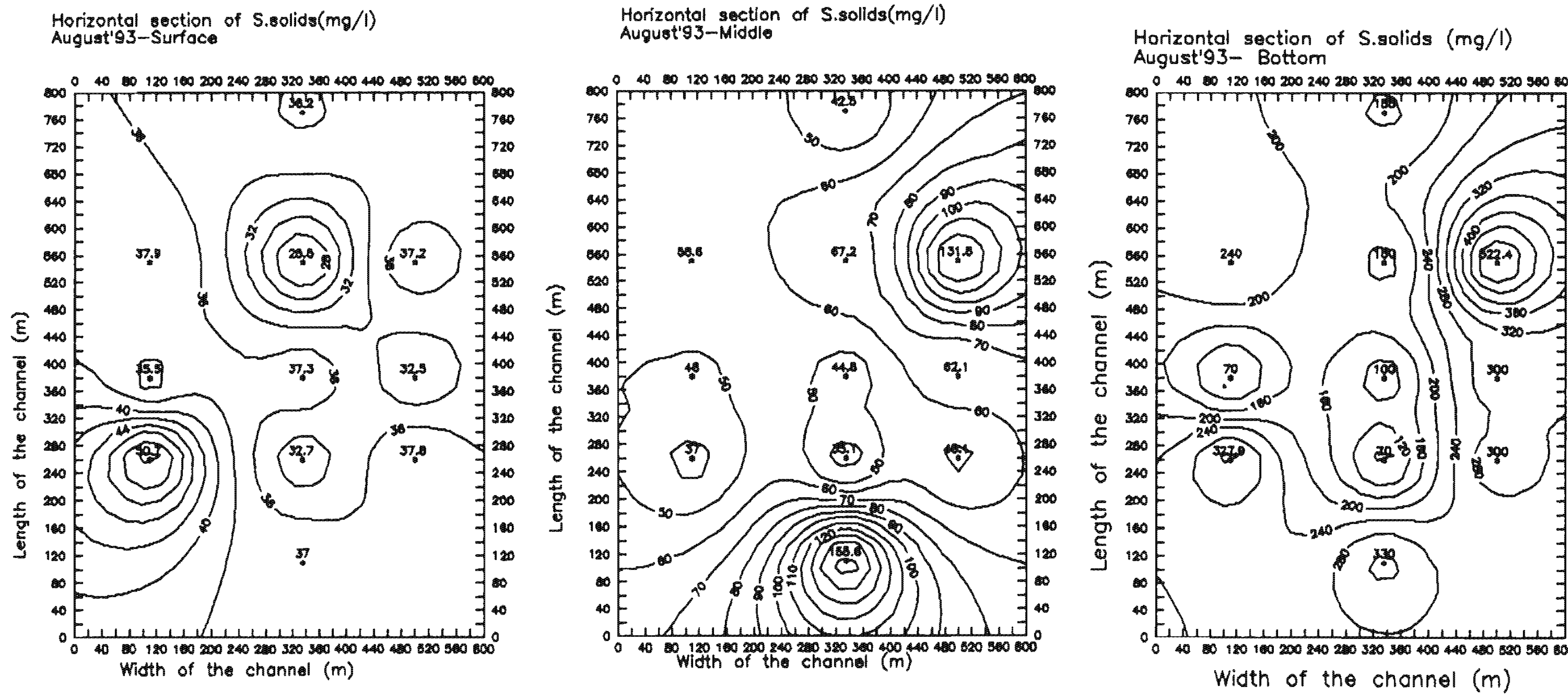


Fig. 5b. Horizontal section of suspended solids during August 1993.

of the channel near the entrance. Likewise at bottom, the suspended solids concentration was observed to be varying significantly between stations 2, 3 and again between stations 5, 6 and 10 . A notable feature during this monsoon month is that the turbidity maximum was observed at the bottom on the Fort Cochin side of the channel.

October 1993 survey results point out that the suspended solids concentration increased from surface to mid depth at all stations and there existed a very sharp increase from surface to mid depth at stations 1 and 4 (figure 4a). From mid depth to bottom there was no significant variation except at station 8 which exhibited a sharp increase in suspended solids content.

The horizontal section (figure 5c) brings out the surface values that was almost identically distributed with values ranging from 20 - 35 mg/l. A sharp horizontal gradient was observed between stations 2 and 7. But at the mid depth, the horizontal distribution was more localized on the south western side of the channel along the Fort Cochin bank . The mid depth values ranged from 38 to 96 mg/l. Along the bottom, the horizontal distribution of the suspended solids exhibited prominent features of higher concentration at stations 7 and 8 on the north western side of the channel on the bay side i.e., along the Vypeen bank; the bottom suspended solids values varied from 65 mg/l to 290 mg/l.

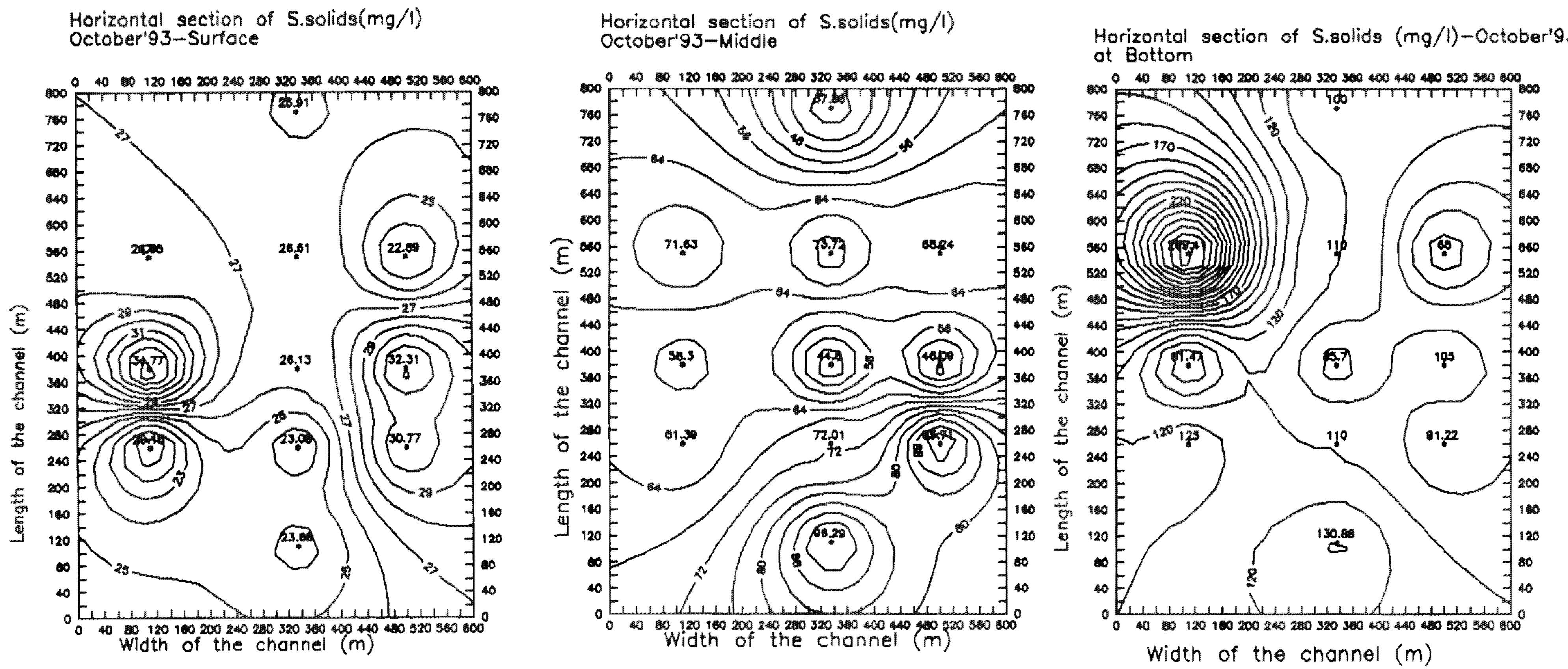


Fig. 5c. Horizontal section of suspended solids during October 1993.

Results of November 1993 survey (postmonsoon season) exhibited the amount of suspended solids to be comparatively less but maintaining appreciable vertical gradient from surface to mid depth with the exception at station 11. However the suspended solids concentration from mid depth to bottom appreciably decreased at stations 2 and 8 (figure 4b). The surface values ranged from 21 to 35 mg/l followed by the mid depth values which ranged from 34 to 74 mg/l and the bottom values from 40 to 76 mg/l. The horizontal distribution (figure 5d) at the surface was uniform with no high value pocket(s); similar feature continued at mid depth except for high concentrations between stations 7, 8 and 11. However at the bottom, the distribution showed concentration of suspended solids to be evenly distributed. These observations reveal the presence of dominant influence of tidal currents on the resuspension and transport of sediments; the resulting marked variation in the suspended solids concentration in the lateral direction may be as explained by Panuzio (1965) in a similar instance. Uncles et al., (1985) have also explained the presence of lateral variation in the distribution of sediment transport in a partly mixed estuary. The features as observed in this study at Cochin inlet is consistent with observations made elsewhere. To quote, a persistent zone of high turbidity on the west side of the estuary was reported by Geyer et al., (1996) in Hudson river estuary which signify the influence of shallow regions on the western side compared to eastern side. December 1993 results on the vertical distribution of suspended solids (figure 4b) at different stations showed

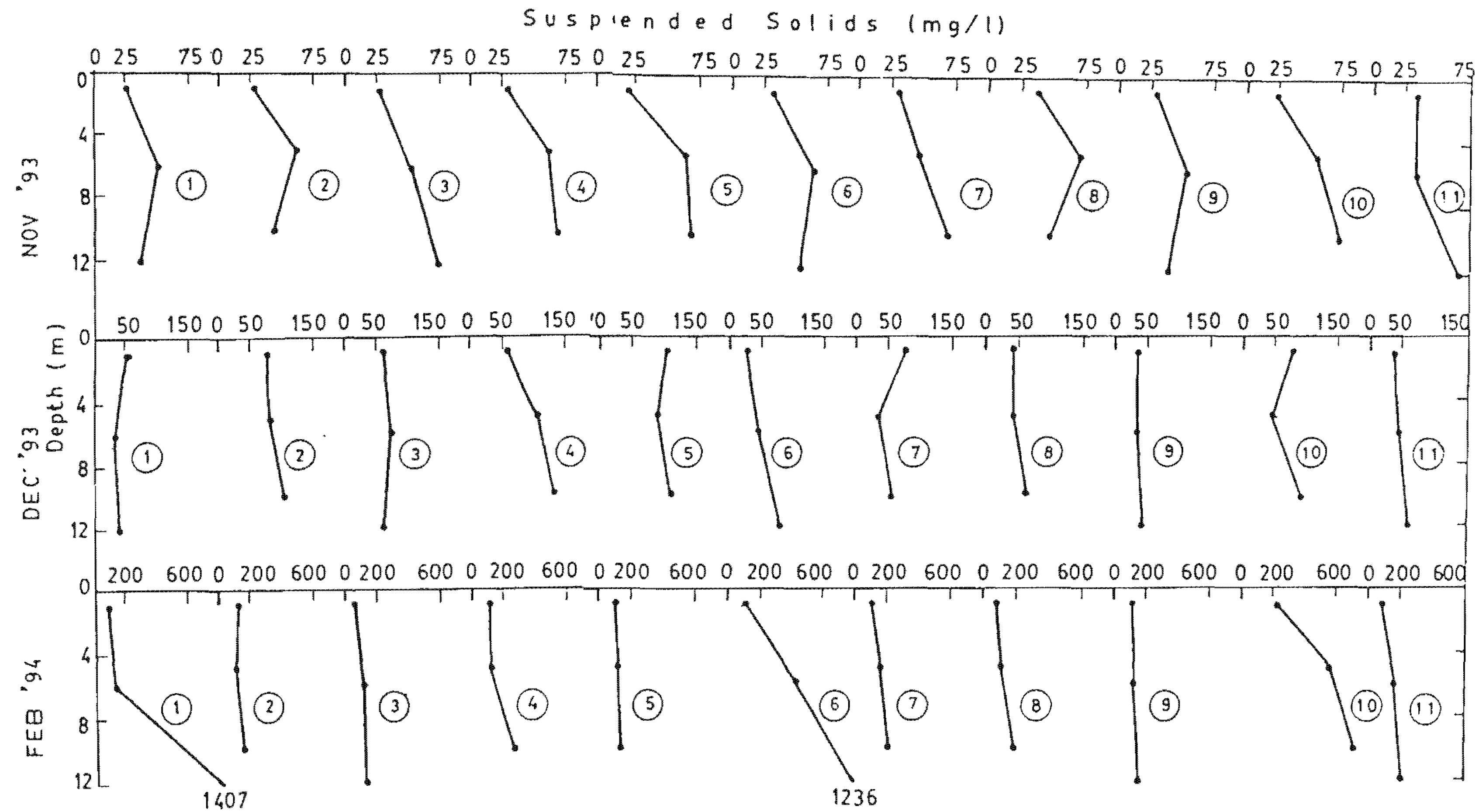


Fig. 4b. Vertical distribution of suspended solids (mg/l) at stations 1-11 during November, December 1993 and February 1994.

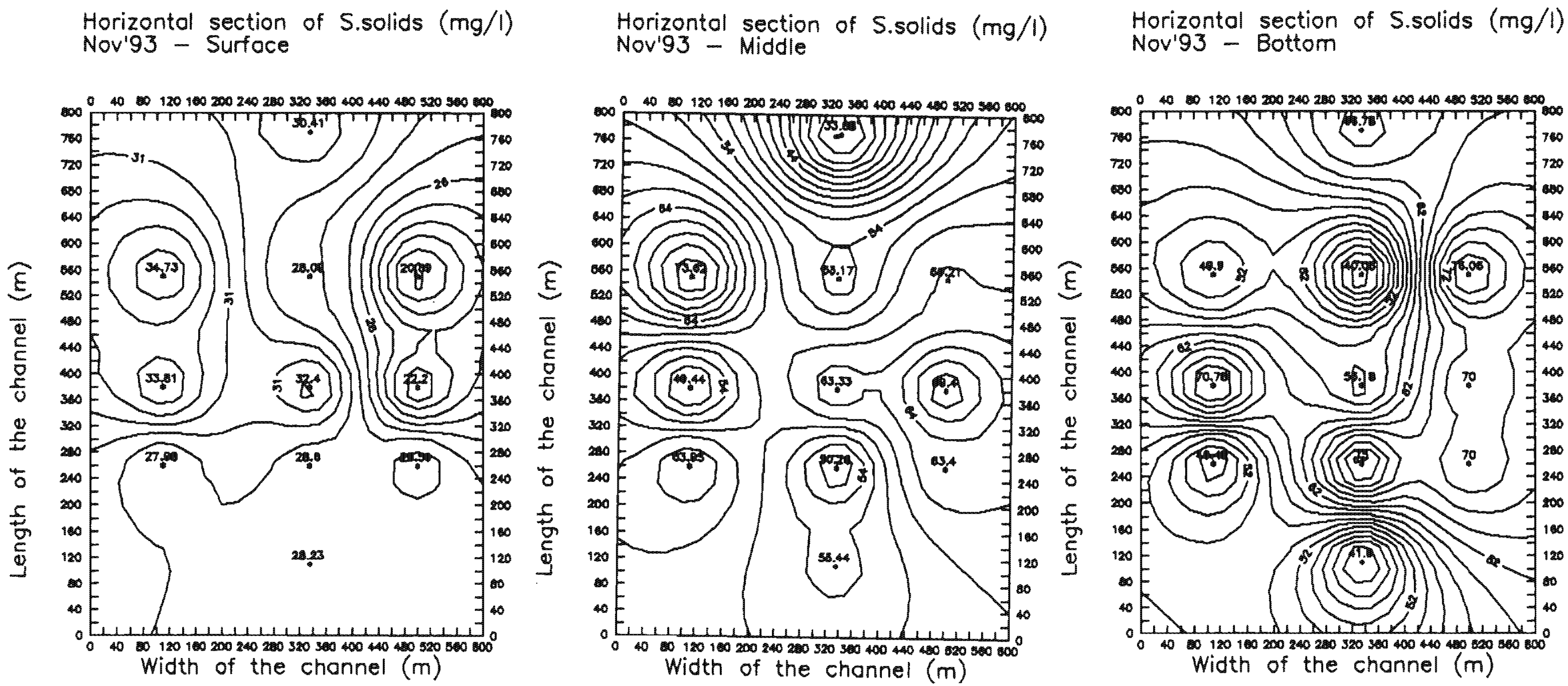


Fig. 5d. Horizontal section of suspended solids during November 1993.

that the mid channel stations contained comparatively less concentration than that along the boundary stations. The surface values were generally in the range 25 - 105 mg/l, whereas the suspended solids concentration at the mid depth was in the range 35 - 105 mg/l. Similarly the bottom values ranged within 40 - 145 mg/l.

In the horizontal distribution charts prepared for December (figure 5e), the surface suspended solids concentration was observed to be more localized between stations 4, 5 and 6. However the distribution between stations 1, 3 and 4 were almost evenly featured. A sharp horizontal gradient was observed at mid depth between stations 3, 4, 5 and 6. However at all other stations the distribution was within a small range. In the bottom layers the distribution was highly uneven; higher concentration was very evident on the Fort Cochin bank side giving rise to a sharp horizontal gradient between the channel boundary stations and mid channel stations. The earlier findings in November 1993 is further substantiated during this month too when the estuarine conditions were that of a partially mixed estuary.

February 1994 survey helped to bring out the following features. The surface values ranged from 92 mg/l to 213 mg/l; mid depth values from 100 mg/l to 647 mg/l and the bottom values ranged from 115 mg/l to 1407 mg/l (figure 4b). Near vertically homogeneous suspended solids concentration was observed at all the stations from surface to mid depth except at station 6 and 10. However the range between mid depth and bottom values at stations 1 and 6 are higher as

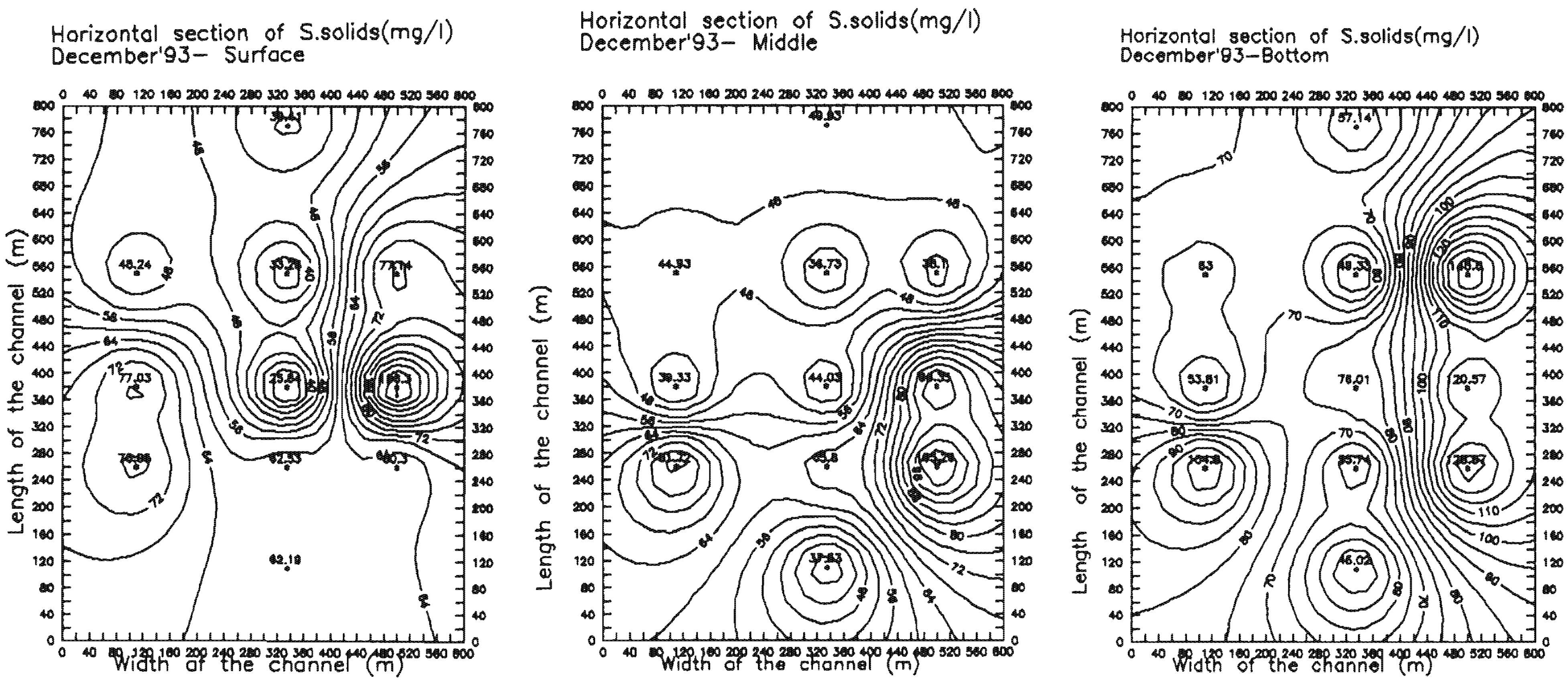


Fig. 5e. Horizontal section of suspended solids during December 1993.

compared to the other stations (147 - 1407 mg/l and 413 - 1236 mg/l respectively).

The horizontal section of the surface showed highly fluctuating values at stations 9 and 10, similarly to that at mid depth also (figure 5f). A peculiar feature noticed during February was that at the bottom, the mid channel stations held high amounts of suspension unlike the boundary stations; but the mid depth and surface boundary stations along the Fort Cochin bank of the channel contained high suspended solids content too.

March 1994 study revealed the surface values to range from 74 mg/l to 147 mg/l and the mid depth values from 66 mg/l to 171 mg/l (figure 4c). The suspended solids concentration from surface to mid depth at all the stations were vertically homogeneous except at station 10, (147 mg/l to 1400 mg/l). But at stations 1, 3 and 6 the suspended sediment concentration was increasing sharply in the vertical from mid depth to bottom. However at all the other stations the distribution in the vertical was almost homogeneous.

The horizontal section of surface layer exhibited a sharp horizontal gradient between stations 5, 6, 9 and 10 situated as boundary stations along the Fort Cochin side of the channel (figure 5g). Again at the mid depth and bottom, significant horizontal gradient was observed between stations 9 and 10. In general, the suspended solids content was concentrated along the Fort Cochin bank of the channel, comparatively heavily, as compared to the other stations on the opposite side.

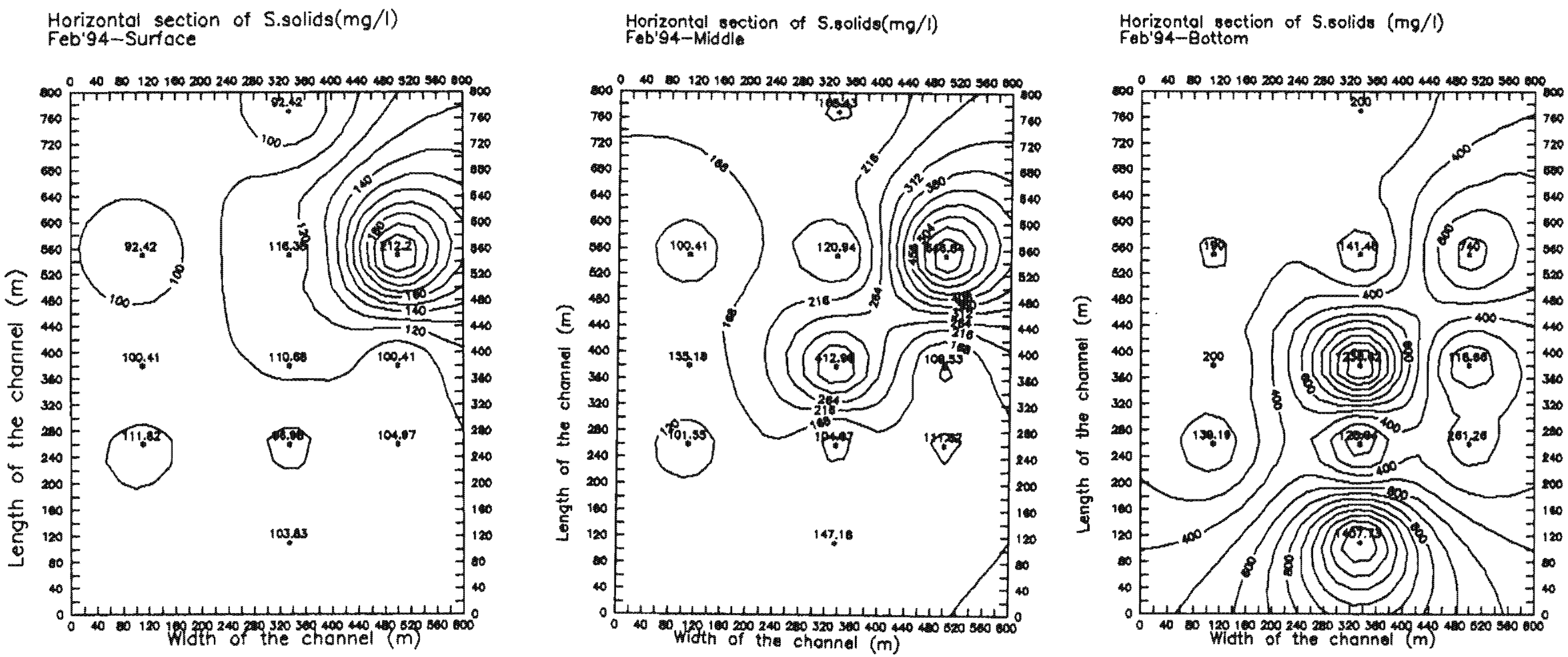


Fig. 5f. Horizontal section of suspended solids during February 1994.

The investigation during June 1994 at the time of monsoon (figure 4c) exhibited fluctuating tendencies in suspended solids in vertical. The surface to mid depth distribution changes were very high at station 4 only; almost homogeneous at all other stations. The content at the surface, mid depth and bottom varied in the range 2 - 166 mg/l, 26 -355 mg/l and 75 -1032 mg/l respectively. Localized concentration was observed between stations 9 and 10 of the channel along the Fort Cochin bank in the surface horizontal section (figure 5h). Similarly along the mid depth , the suspended solids content was observed to be high along the bank sites of Fort Cochin. However, the bottom layers showed suspended solids concentration to be very high at station 8 and a sharp horizontal gradient between stations 2 and 7. Similarly between stations 4 and 5 too, the horizontal gradient in the distribution was very high.

The suspended solids content at the inlet during different stages of the tide in the three layers during a premonsoon month (May 1993) elucidated the salient features of its distribution (table 2). At the time of flood (1000 IST) the suspended solids content at mid depth and bottom were exceedingly higher than at surface. This was clearly evident from the high content of suspended solids around 250 mg/l at stations 1, 4, 5, 7 - 10 at bottom. Ajith and Balchand (1994) had observed that oscillatory currents at tidal inlets have a predominant role on the distribution of suspended solids. The flood currents often bring about the

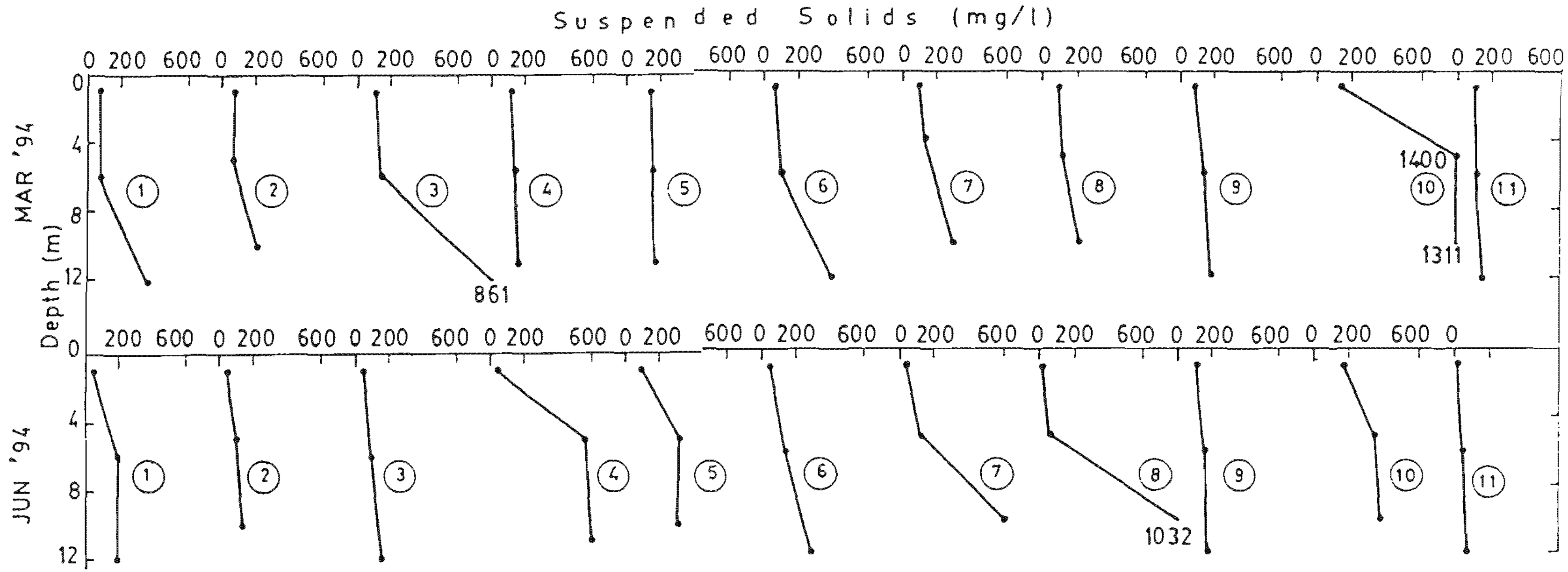


Fig. 4c. Vertical distribution of suspended solids (mg/l) at stations 1 - 11 during March & June 1994.

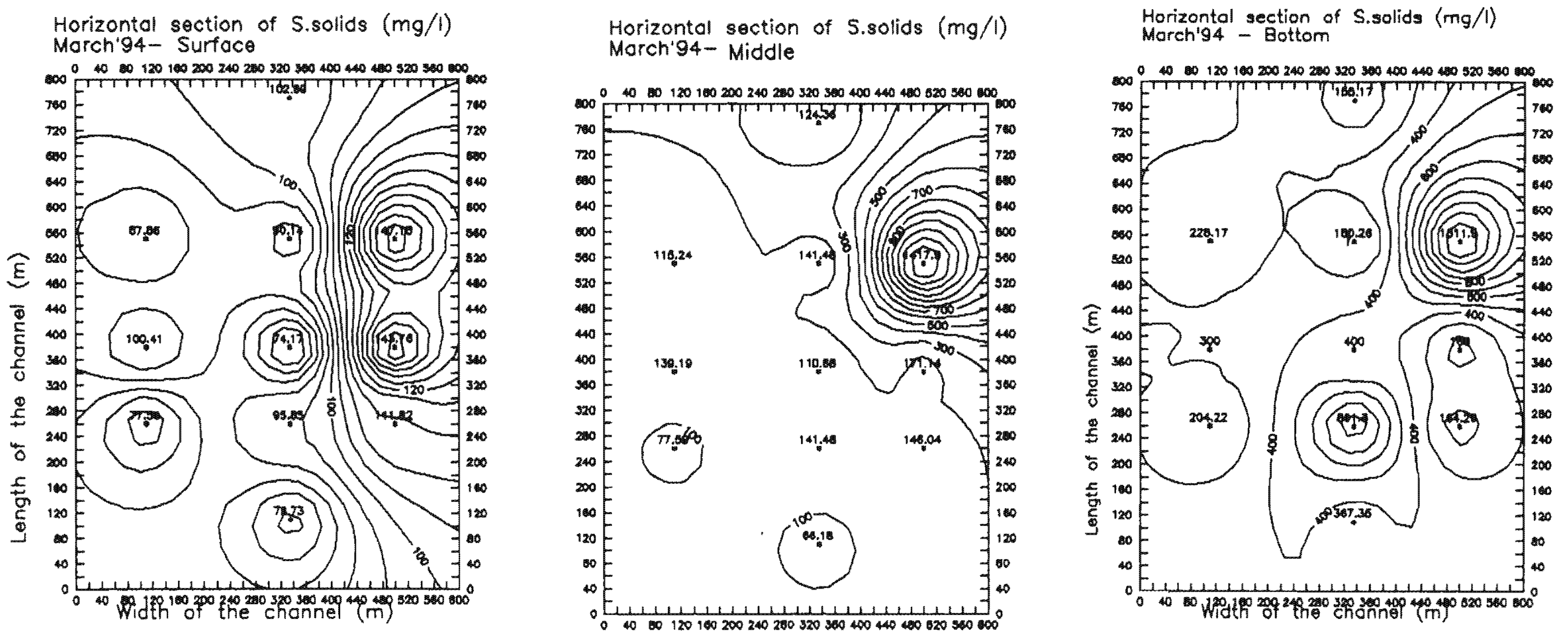


Fig. 5g. Horizontal section of suspended solids during March 1994.

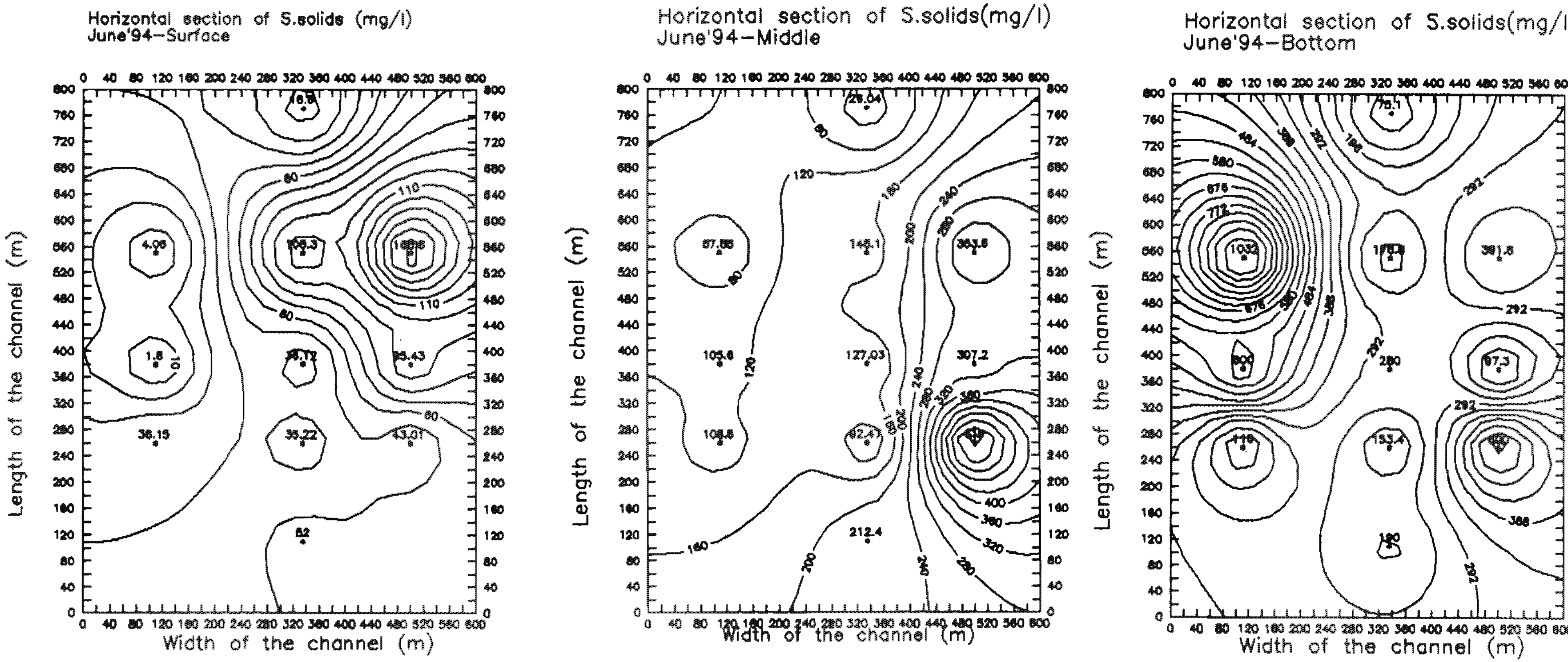


Fig. 5h. Horizontal section of suspended solids during June 1994.

Table 2. Suspended solids content (mg/l) at stations 1 - 11 during fou stages of the tide in three layers.

Time (IST)	Stations	1	2	3	4	5	6	7	8	9	10	11
	surface	064	141	056	087	093	041	072	047	051	103	046
1000	middepth	094	109	220	324	156	174	141	057	044	137	062
	bottom	233	125	016	334	284	089	221	288	216	216	057
	surface	072	071	078	068	064	132	178	076	119	066	065
1300	middepth	063	065	094	081	068	149	062	105	073	073	068
	bottom	068	067	074	073	080	174	070	194	083	179	065
	surface	047	048	042	047	052	092	061	048	045	044	042
1600	middepth	048	048	055	088	112	064	062	068	056	100	080
	bottom	047	084	059	064	054	070	117	059	051	088	051
	surface	117	090	056	130	062	084	157	059	088	075	051
1900	middepth	-	-	-	-	-	-	-	-	-	-	-
	bottom	070	050	059	105	068	102	059	051	050	046	059

development of a turbidity maxima at the inlet. The following phase (ebb flow- 1300 IST) brings about a gradual decrease in the concentration of suspended material, first at the outer boundary stations (stations 1-4) compared to inner stations within the barmouth (stations 6-10: 66-194 mg/l). The distribution of suspended solids during the slack time of the ebb tide (1600 IST) indicated more or less homogeneous conditions in the content of suspended solids within the inlet area (approximately 45- 100 mg/l). The change over of the tidal phase from ebb to flood (1900 IST) is well indicated in the increase of suspended loads at the investigating site- higher content at the outer boundary stations (1 and 4) compared to the inner stations 8-11.

F) Tide

Tidal characteristics were studied at Cochin by several investigators as stated earlier; their findings explain that the tides are of mixed with predominantly semidiurnal character having a maximum range of 1m. The tidal response and circulation of the Cochin estuary was reviewed by Joseph and Kurup (1987) and it was found that during the period 1985-1986, the difference in the height between the observed and the predicted tides ranged upto 25 cm and that flood currents were faster than the ebb currents depending on the phase of the tide. But the range and duration of the spring flood was greater than that of spring ebb tide in all the months during the period of study. However it was observed that the ebb tide duration was longer than that of flood tide, in 1993-1994, the period of this study. The average tidal range remained almost constant throughout the year eventhough there was a marked monthly variation in the mean sea level. The maximum occurrence of tide was in the range 60-70 cm and the least occurrence in the range 120-130 cm. Josanto (1971) had remarked that the average range of tide was about 90 cm with the highest known tide being 1.75m.

G) Volume transport across Cochin inlet

The volume transport of water through the inlet cross section which is a function of the average current velocity, tidal range and duration has been attempted in this section. Swenson and Chuang (1983), have explained the volume transport through the estuary on the basis of law of conservation of volume such that transport of water through the upstream section must equal the transport through the down stream section of the estuary. Speer and Aubrey (1985) have documented the effects of tidal distortion caused by bay geometry on tidal flows near the inlet mouths and the variation in ebb or flood velocities at inlet mouths to ebb or flood tide duration to preserve the continuity.

Figure 6 shows the cross-section of the Cochin inlet during the period under study. The cross sectional area during 1993-94 was found to be 4234.28 m^2 below the chart datum. It may be noted that often the cross sectional area at inlets are subject to variations in time scales for obvious reasons. Byrne et al., (1975) had explained that the changes in channel morphology in rapid time scales can occur in response to variations in discharge due to storms or spring neap cycle when inlet cross sectional area fluctuate

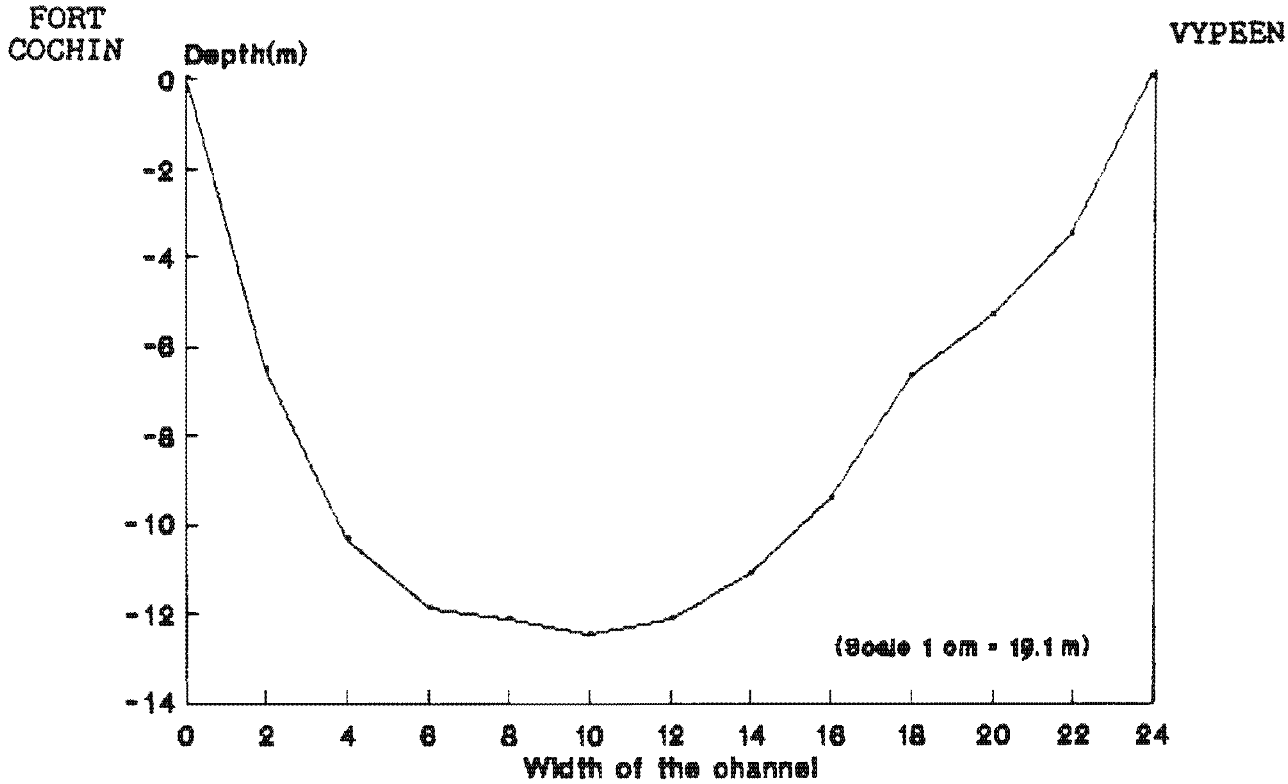


Fig. 6. The cross sectional configuration of Cochin inlet.

by 10-15 percentage. The cross sectional area at Cochin inlet however retains a constant value indicating the relative stability of this inlet which is the resultant of interacting hydrodynamical forces. It may noted that the inlet gorge is not subjected to maintanence form of dredging as is practised in the inner channels and its vicinity of the Cochin port area proper.

The volume transport at Cochin inlet during different months was computed for flood and ebb periods of the spring and neap tides (table 3).

The results during spring flood (March and June) of 1994 indicated volume transport to be higher than those at all other months of investigation. In June 1994, during south west monsoon, the spring flood range was 95 cm and duration 8 hours 30 minutes; the resultant volume transport was found to be the highest as 176.99 Mm^3. This temporal variation in volume transport is attributed to increase of vector averaged velocity of the flood during this period. But in the case of neap flood (August 1993 and January 1994) these features are not quite evident. The variation in volume transport during the above two months is due to the variation in current velocities at the inlet mouth and the tidal range and duration. The volume transport during the pre-monsoon season in May 1993 during the phase of neap ebb was 10.38 Mm^3. Similar near equal values (10.54 Mm^3) was observed by Joseph and Kurup (1989) for tides of almost equal duration and range in 1985-86. In November 1993, during the neap ebb, the value of volume transport (55.79

Table.3

Volume transport at Cochin inlet for flood and ebb periods of the spring and neap tide in 1993-1994.

Month	Tidal phase	Tide levels (cm)	Duration (hr)	Avg.cross area (m^2)	Volume-transport $m^3 (x\ 10^6)$
May 1993	Neap Ebb	085-064	1200-1630	4577.59	10.38
August 1993	Neap Flood	021-086	0700-1330	4481.47	39.95
October 1993	Spring Flood	055-080	0830-1330	4545.56	32.73
November 1993	Neap Ebb	082-022	1045-1830	4472.32	55.79
December 1993	Spring Ebb	093-049	0300-0900	4559.29	66.97
January 1994	Neap Flood	058-091	1100-1530	4577.60	07.42
March 1994	Spring Flood	062-087	0530-1030	4577.60	76.63
June 1994	Spring Flood	(-01)-094	0530-1400	4449.42	176.99

Mm^3) was found to be higher. This is attributed to the increased ebb velocity from higher river discharge of more active northeast monsoon in 1993-94 (IDWR, 1994). The spring ebb in December 1993 provides a value of the volume transport which was marginally higher (66.97 Mm^3). On comparing these two values, lower volume transport in November was associated with higher range (60 cm) and longer duration (7 hours 45 minutes) and higher volume transport (66.97 Mm^3) in December was associated with lower range (44 cm) and shorter duration (6 hours). This clearly indicated that volume transport is highly dependent on the velocity of flow. In January 1994 during neap flood, the volume transport was minimal (7.42 Mm^3) whereas in March 1994 the value was high (76.63 Mm^3). Earlier studies by Rama Raju et al., (1979) have documented that the tidal prism at Cochin in the pre-monsoon season was found to be 31.50 Mm^3 and during the other season the value ranges between 9.50 Mm^3 and 132.00 Mm^3, indicating the extent of range of values which may be encountered at Cochin inlet. Increased volume transport in March spring flood to that of October spring flood for near equal values of range and duration shows the effect of increased velocity (vector averaged) in March. And vice-versa the decreased velocity in October was due to the opposing effect of river discharge against flood currents and the weak tidal currents which is evident from the salinity profile and the freshwater fraction at the inlet during this month.

The highest value occurred during the spring flood in monsoon season (176.9×10^6 m^3) and the least value

($7.42 x 10^6 m^3$) occurred during the neap flood in January 1994 of post monsoon season. The volume transport at this inlet is predominantly controlled by the flow velocities and partially by tidal duration and range. Rasheed et al., (1995a) observed the silt wedge and the development of turbidity maxima at this inlet during peak flood period which also carried large amounts of suspended solids into the bay, thus enhancing chances of higher sedimentation rate. Similar features of flood dominance due to the effect of flow asymmetry by tidal distortion has been well explained by Aubrey and Speer (1984) at Nauset inlet, VA, USA. The fact remains that channel cross sectional area is maintained by the flow itself by the asymmetry in flood and ebb currents. Wolanski et al., (1980) explained the effect of asymmetry between ebb and flood currents which contributes to the maintenance of a deep self sustaining drainage channel even in the presence of large sediment input from surrounding coastal waters. In general, the volume transport during neap ebb was less and the least in May 1993, again at neap ebb tide at this inlet. Studies by Joseph and Kurup (1989) also observed less volume transport during neap ebb in the month of May. As regards the magnitude of flow, higher values were associated with higher tidal ranges during spring flood but lower tidal ranges of neap flood are not associated with lower speeds of flow (Joseph, 1989). At Cochin inlet the volume transport during flood tide in monsoon season was comparatively lower than that during other seasons for tides of almost equal duration and range as reported by Joseph (1989). Observations in monsoon season during 1993-94 reveal that substantial volume of transport could take place across the inlet during the flood tide. In the same period the flood tide duration was less than that of the ebb tide giving rise to higher flood velocities which points out the likely change over of this estuary-inlet system from ebb dominance to flood dominance. This mechanism would result in more transport of suspended solids into the bay region which would settle within than be flushed out into the nearshore regions as illustrated by Aubrey (1986). Aubrey and Speer (1983) studied the non-linear growth of tidal distortion in shallow estuaries due to bay geometry and identified that the long term fate of estuaries is partly a function of net import or export of sediment in an inlet/bay system. Over the decade, the basin geometry of the Cochin estuary has definitely altered which would lead to contemplate on the tidal distortion at the inlet region. The flood dominant estuaries are characterised by longer falling tides and stronger flood currents (applicable to Cochin estuary) and vice versa for ebb dominant estuaries (Speer, 1984). Aubrey (1986) also opined that flood dominant estuary systems have a tendency to be filled up more quickly with sediments than those otherwise.

H) Dilution and Flushing Characteristics

The dilution and flushing characteristics of this coastal inlet also is of prime concern due to the fact that a large number of industries like fertilizer factory, oil refinery, and ship building yard are situated along the estuarine banks which discharge liquid waste and to some extent, the dredged spoil due to maintenance dredging. Aubrey and Speer (1983) have identified that the inlet behaviour and flushing are important elements of coastal water quality studies and implications associated with pollution and its control.

The dilution and flushing characteristics of estuaries/inlets are mainly dependent on the freshet discharge and the volume transport into/out of the estuary through tidal inlets. This mechanism will influence the salinity distribution as well as flushing of effluents within/from the estuary since the fresh water discharge into the estuary vary seasonally and sometime quite drastically. Qasim and Sen Gupta, (1981) discussed the influence of monsoon on the environmental characteristics of the Mandovi-Zuary estuarine system in Goa. Zingde et al., (1987) estimated the flushing time and pollution assessment of Purna River estuary, India, based on freshwater method. Sankaranarayanan et al., (1986) Joseph and Kurup (1989), and Revichandran (1993), have also studied the average seasonal freshwater fraction and dilution factor at tropical tidal inlet-estuary systems. The dilution and flushing characteristics of this tropical estuarine-inlet system under investigation was found to be highly susceptible to river management approaches and hence the variation in these estuarine characteristics are mainly attributed to the recent developmental and freshwater diversions at the upstream regions. Ajith et al., (1995a) critically reviewed the impact assessment on the characteristics of this tropical estuary in relation to river management approaches.

Table 4 gives the average freshwater fraction (F) and dilution factor (R) of three stations across the inlet during different months of monitoring in 1993-94. It was observed that the average freshwater fraction was minimum as 0.13 and maximum, 0.62, during 1993-94 as observed in December 1993 and October 1993 respectively. Similarly a secondary maximum freshwater fraction (0.60) was also observed in August 1993. Hence it is ascertained that the freshwater discharge during southwest monsoon period has a high influence on the freshwater content in the estuary-inlet system. Similar characteristic features were observed at Cochin tidal inlet-estuary system by Joseph and Kurup (1989) however the average freshwater content was observed to be less during 1993-94 periods as compared to that in 1985-86, indicating decrease in freshwater discharge into this estuary-inlet system which exemplifies the impact of freshwater diversions in the upper regions.

The average dilution factor was observed to be high in December (7.69) and the least in August (1.67), followed by October (1.63). From the observations under study, it is found that higher values of dilution factor during December 1994, was due to negligible freshwater flow resulting in more saline water intrusion. Throughout the year 1993-94, it was also observed that the average freshwater content diminished in almost all seasons compared to that in 1985-86 period except in the month of October. The figure 7 shows the fluctuation in freshwater fraction corresponding to average dilution factor during different months and this helps to clearly understand the influence of freshet

Table 4. Average Freshwater fraction and dilution factor (R) at Cochin inlet during 1993-1994

Month	Salinity (So)	Freshwater fraction (Average F)	Dilution factor (Average R)
May 1993	36.43	0.16	6.17
Aug	32.43	0.60	1.67
Oct	34.57	0.62	1.63
Nov	35.13	0.27	3.73
Dec	35.68	0.13	7.69
Jan 1994	36.21	0.25	4.08
Mar	36.09	0.17	5.81
June	33.48	0.24	4.26

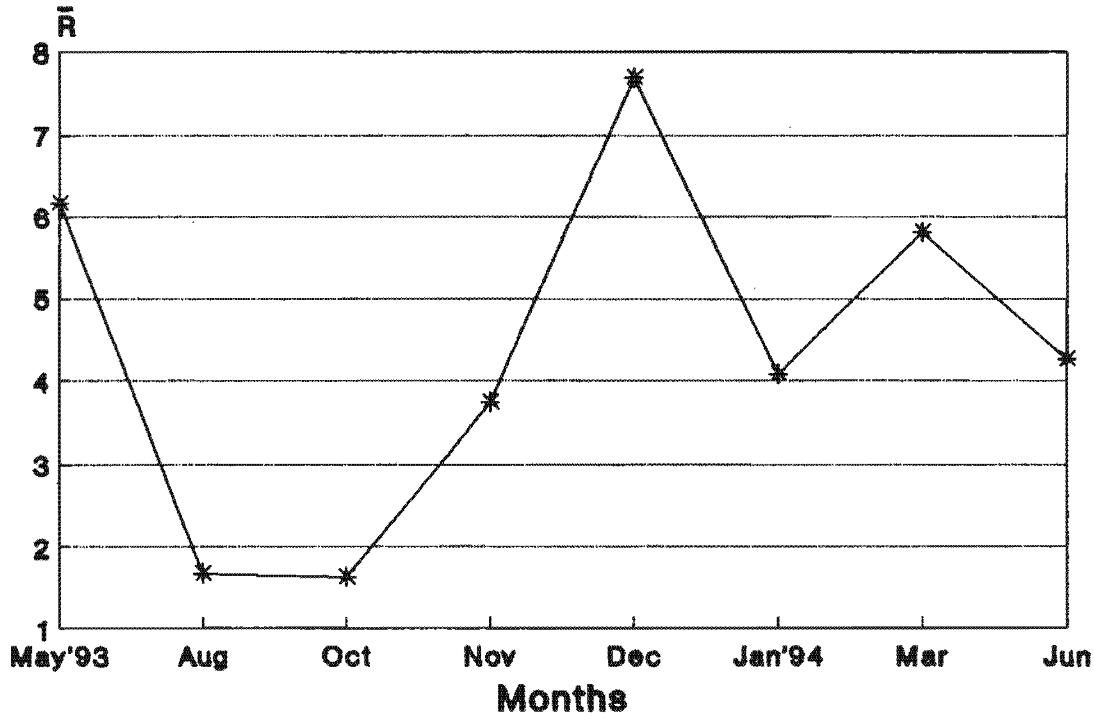


Fig. 7. Monthly variation of average dilution factor during 1993-1994 at Cochin inlet.

discharge into the estuary - its gradual decrease during the pre-monsoon season and the effect of peak freshwater fraction as monsoon turns active. The freshwater content in 1993-94 increases from May (0.16) to October (0.62) and thereafter it decreases. Higher values of dilution factor (6.17 and 7.69) occur during premonsoon season and postmonsoon season when the freshwater flow was negligible ; compared to 1985-86, the dilution factor had varied from 4.00 to 4.55 for the period (Joseph and Kurup, 1989). Qasim and Sen Gupta (1981) and Joseph (1989) have explained the flushing of pollutants based on the dilution factors. During non-monsoon season, any pollutant therefore released into the estuarine system has to be diluted more than 6 to 7 times by seawater before it finally reaches the open sea. This clearly indicates that the pollution in this estuary - inlet system will have to be diluted more than what it required a decade ago (1985-86) and is more susceptible as a pollutant sink rather than a source, due to the recent estuarine management issues. The commissioning of Muvattupuzha river valley project for multi purpose objectives like irrigation of 178 km² of lands, supply of 19.92 cumecs of water to Newsprint factory and 1.84 cumecs to Greater Cochin water supply scheme and generation of 6 MW electricity etc. are definitely identified as the reasons for these impacts on the estuarine characteristics. If this scarcity of freshwater flow is continuing, the abatement of estuarine pollution would become more cumbersome and which in turn would adversely affect the ecosystem of this tropical estuary, in future.

I) Stratification and Circulation Features

The action of gravity upon the density difference between seawater and fresh water tends to cause vertical salinity stratification and a characteristic convective flow will follow in estuarine circulation (Hansen & Rattray, 1966). Studies by Das et al., (1972) suggested that the problems of sedimentation and pollution through waste disposal is influenced by the circulation features in estuaries and nearshore. Simpson et al., (1990) explained the estuarine stratification in relation to tidal straining and density currents. Uncles et al., (1990) have observed stratification- destratification events in tropical estuaries. In the stratification - circulation diagram of Hansen and Rattray (1966), seven types of estuaries have also been delineated.

Table 5 shows the stratification -circulation parameters during various months for this region of the year(s) 1993-94. At Cochin inlet, the estuarine features do vary from month to month. Comparing seasons, higher values of stratification parameters were observed in monsoon months (August and October 1993 & June 1994). The circulation parameters feature higher values in October and November (1993) compared to other months of the study period. The least values of stratification parameters were observed to be in December 1993 and March 1994 (0.067 and 0.153) respectively. In the case of circulation parameters, in 1993-94 the least values were observed in months of June 1994 and January 1994 (2.26 and 2.32) respectively.

Table 5. Stratification - Circulation parameter values at Cochin inlet during 1993-1994

Month	Stratification Parameter $(\delta s/So)$	Circulation Parameter (U_s/U_f)
May 1993	0.273	3.37
August	2.210	2.89
October	1.233	5.11
November	0.506	4.25
December	0.067	2.91
January 1994	0.176	2.32
March	0.153	3.35
June	0.590	2.26

From the figure 8, during May 1993, the Cochin inlet estuarine system exhibited a partially mixed condition and in October, it exhibited the salt wedge type. This peculiarity is attributed to the incessant northeast monsoon rains and associated river runoff during this month. Whereas, during November to January, this system behaves as a partially mixed type; in June it was moderately stratified or partially mixed.

J) Morphodynamic behaviour of the Cochin tidal inlet

Morphodynamics of coastal sea - tidal inlet - estuary system play a critical role where harbours/ports are situated of commercial importance. In this context, the tidal inlets which connect waterways between estuaries and nearshore regions to exchange water and sediments, while concurrently providing navigational facilities, have attracted keen attention of harbour engineers and planners. These regions are often places where coastal engineering activities are routinely held for harbour/port development involving construction, dredging and land reclamation (Graaf et al.,1991). The quantitative and qualitative approach in tidal hydraulic studies relating to nearshore - inlet - estuary system may collectively be termed as morphodynamics (Wright, 1976) and evidently is inclusive of the stage of evolutionary development of such a system. Hubbard et al., (1979) investigated the morphologic variability in tidal inlets with respect to sedimentary structures and sand bodies. Byrne et al., (1975),

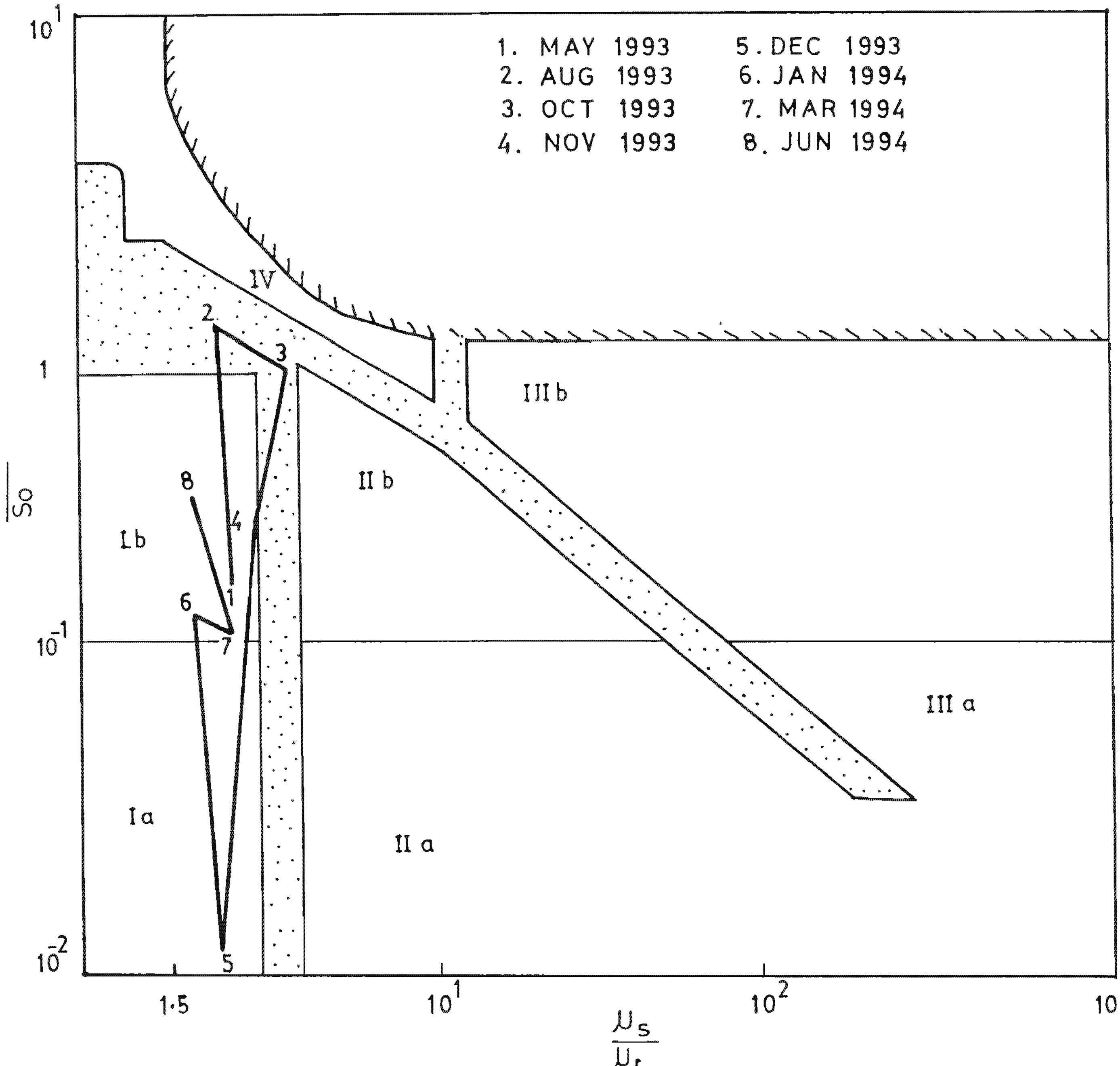


Fig.8. STRATIFICATION - CIRCULATION DIAGRAM OF COCHIN TIDAL INLET.

Boon and Byrne (1981) had investigated the morphodynamic response of coastal inlets in relation to basin hypsometry. Wright et al., (1982 & 1985), Wang et al., (1991), Steigin and Hartsuiker (1992) and Wang (1995) explained the modelling of morphodynamics of macrotidal beaches and bay - inlet systems. Aubrey and Speer (1983) identified the influence of bay geometry on the non linear growth of tidal distortion in shallow estuaries and explained that the long term fate of estuaries is partly a function of net import or export of sediment in an inlet/bay system. Aubrey and Speer (1985) and Speer and Aubrey (1985) explained the non- linear tidal propagation in shallow inlet/estuarine system, Bruun (1986), van de Kreeke (1988) related the complicated flow pattern in tidal inlets to irregular geometry due to large variations in depth and width. The role of geometry of cross - section in generating flood dominance in shallow estuaries was explained by Shetye and Gouveia (1992). Friedrichs (1993) had conducted a detailed investigation on the hydrodynamics and morphodynamics of shallow tidal channels and intertidal flats. Mann and Mehta (1993) studied the response of mean water level in bays constricted by tidal inlet channels and observed that changes in channel morphology due to anthropogenic actions or natural events can cause measurable corresponding changes in the net hydrostatic head in the bay.

The Cochin inlet acts as an active morphologically evolved land - sea interfacial physical geographical system compatible to fluvial processes of tropics elsewhere. As to date, no attempt has been made to demonstrate the intrinsic processes that control and regulate the flow within the inlet channel nor there has been studies related to the stability of the inlet. This section attempts to study the morphodynamics of Cochin tidal inlet -bay area in terms of modifications brought about in distribution of estuarine surface area, inlet channel configuration, tidal inlet regime and associated aspects of tidal hydraulics.

For a semidiurnal condition, Drapeau (1988) had estimated the inlet hydraulic constants on the basis of the physical dimensions of the inlet and the lagoon within using the algorithm developed by Mehta and Ozsoy (1978). The mathematical formulations as described in Chapter 2 have been applied in this study; the maximum channel velocity averaged over the flow area for different bay areas and increasing channel depth(s) was observed to be in good agreement with field values as discussed below. The real time (field) values for maximum channel velocity was collected onboard the research vessel R/V Nautilus at Cochin inlet location to develop the data base. The effective channel length was taken as the distance along the channel axis between the points on each end where the velocity was 20% of the average velocity as chosen based on derivation by Sorensen (1977).

The tide at Cochin inlet is semidiurnal with a maximum range of 1m (as stated before) and the current values averaged over the flow area, was observed to vary from 0.83 m/s in January 1994 to 1.47 m/s in December during the flood tide. The maximum channel velocity averaged over the flow area over a tidal cycle, as computed based on analytical formulations stated above, gave values which were in good agreement with the observed values (figure 9a) during the months of January, February, March & May (premonsoon) and October, November & December (postmonsoon). But during peak southwest monsoon season (June - September) when the freshwater flow is directed away from the estuary through the inlet towards the coastal sea, the computation has limited applicability. At bottom, denser waters protrude into the bay region resulting in a shearing effect as suggested by Wellershaus (1971).

The possible impact on deepening the shipping channels in terms of flow regime variations and nearshore circulation phenomena are arrived at as in table 6 (applying equations 12 - 19) which otherwise controls the shoreline modifications nearer to the harbour entrance. The present state of affairs of dredging activities concormitant with the reclamation of the bay area have direct implications on the response characteristics of time lag between the ocean tide and the bay tide, the tidal range, tidal prism and the maximum velocity averaged over the flow area at the inlet.

The following matrix explains the morphodynamic response of this tropical tidal inlet-estuary system under the present hydraulic conditions:

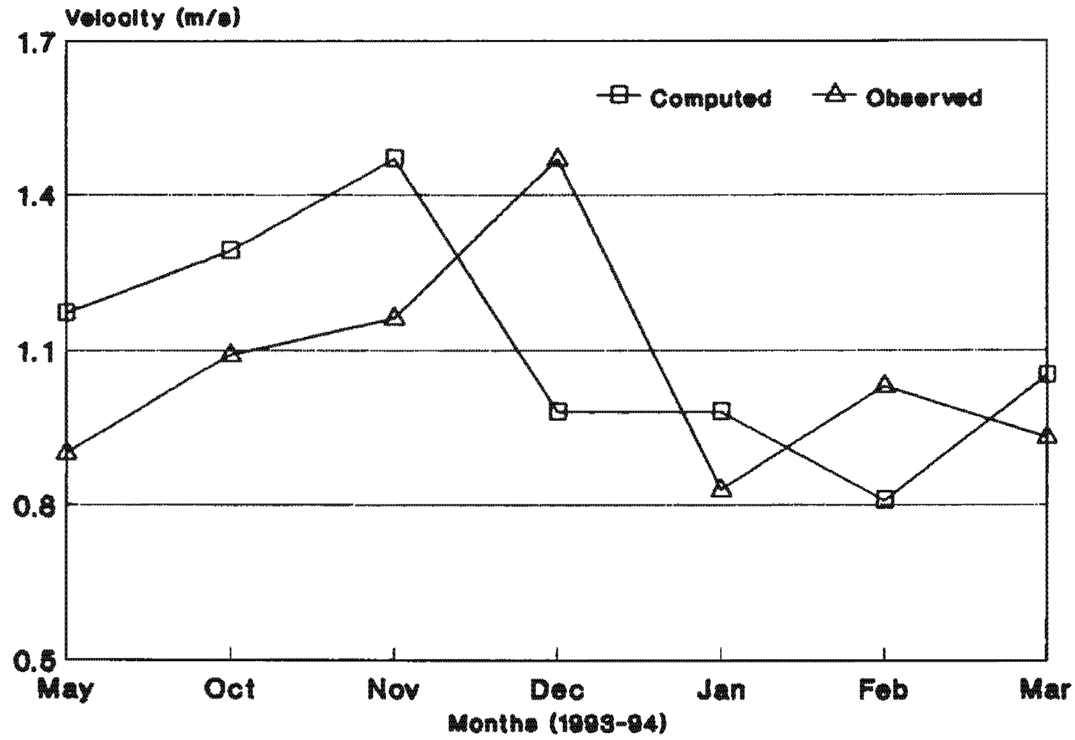


Fig. 9a. Computed and observed values of maximum channel velocities.

Table 6. Stability analysis of Cochin inlet for two different bay areas. (As - Tidal amplitude, Ab - Bay area (m^2), TMLAG- Time lag (hours), Range (m), Prism (m^3), VMI- Maximum channel velocity (m/s) and VMD - Dimensionless channel velocity.

Width 457.76m, As=0.50m, Ab= $1.4198x10^8$
Channel length = 1320m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	82.85	2.86	.18	25826560.0	1.38	.17
4.00	71.89	2.48	.38	53758730.0	1.64	.35
6.00	59.93	2.07	.57	81291620.0	1.73	.53
7.00	53.96	1.86	.66	93689940.0	1.73	.61
8.00	48.17	1.66	.74	104721500.0	1.71	.68
8.90	43.21	1.49	.80	113316800.0	1.68	.74
9.25	41.35	1.43	.82	116303000.0	1.66	.75
10.00	37.56	1.30	.86	122031600.0	1.62	.79
11.00	32.91	1.14	.90	128304400.0	1.56	.83
12.00	28.76	.99	.94	133166800.0	1.49	.86
12.80	25.81	.89	.96	136185500.0	1.43	.88
13.00	25.12	.87	.96	136834700.0	1.42	.89
13.50	23.48	.81	.97	138293600.0	1.38	.90
14.00	21.96	.76	.98	139540200.0	1.35	.91
15.00	19.26	.66	1.00	141500600.0	1.28	.92
18.00	13.29	.46	1.02	144572700.0	1.10	.94
20.00	10.62	.37	1.02	145353000.0	1.00	.94

Stablity analysis - width 457.76m, As=0.50m, Ab= $1.36x10^8$
Channel length = 1320m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	82.40	2.84	.19	25813120.0	1.38	.17
4.00	70.94	2.45	.39	53608600.0	1.63	.36
6.00	58.51	2.02	.59	80692780.0	1.72	.55
7.00	52.35	1.81	.68	92705680.0	1.72	.63
8.00	46.41	1.60	.76	103245400.0	1.69	.70
8.90	41.36	1.43	.82	111325400.0	1.65	.75
9.25	39.49	1.36	.84	114098700.0	1.63	.77
10.00	35.67	1.23	.88	119359200.0	1.59	.81
11.00	31.05	1.07	.92	125011900.0	1.52	.85
12.00	26.97	.93	.95	129296100.0	1.45	.88
12.80	24.10	.83	.97	131902000.0	1.39	.89
13.00	23.44	.81	.97	132456100.0	1.37	.90
13.50	21.86	.75	.98	133691900.0	1.34	.91
14.00	20.41	.70	.99	134736700.0	1.30	.91
15.00	17.83	.62	1.00	136354400.0	1.23	.92
18.00	12.23	.42	1.02	138793100.0	1.05	.94
20.00	9.76	.34	1.02	139365200.0	.95	.94

Conditions		Response		
Bay area	Channel depth	Timelag and V max	Range and Dimension less vel.	Tidal prism
decreases	Constant	decrease	increase	decrease
decreases	increase (dredging)	decrease	increase	decrease
Constant	increase	decrease	increase	increase

The matrix indicates that for constant depth of the channel, a decrease in bay area (due to reclamation and landscaping) will result in decrease of tidal prism and maximum flow velocity at the inlet with increase in bay tidal range. This would likely bring about retardation in flushing of suspended material which will thence enhance sedimentation within the harbour region. For a given condition such that bay area is constant with increasing channel depths, the tendency will be an increase in bay tidal range(s) and appropriate magnification of the tidal prism. Under the above condition too, the maximum flow velocity at the inlet decreases; however, calculations indicate that in the above event, an increase in cross sectional area is counter productive leading to increase in flow velocity upto a critical value and there after diminishes.

The tidal inlet hydraulic analysis at Cochin harbour based on formulations by Drapeau (1988) points out that though the tidal prism into the harbour increases by deepening the channel, the maximum channel velocity over a tidal cycle will show a decrease in magnitude for a given particular bay area and channel length (figures 9b and 10). The predictive analysis evidence that for decrease in bay area and increase in channel depth (m), the tidal prism and the maximum channel velocity initially increases and subsequently decreases. The critical cross- sectional area (A_c*) at this tidal inlet for which the velocity averaged over the flow area (A_c) over a tidal cycle is maximum was found to be 3497.29 m^2 for a channel length of 1320 m. The actual cross sectional area was observed to be 4527.25 m^2 (below MSL).

O'Brien and Dean (1972) explained the significance of critical cross sectional area of stable and unstable tidal inlets and the flow velocity regime. Studies by Drapeau (1988) had identified the critical cross sectional area as dependent on the channel length and so the velocity maximum varies with increase of channel length. Similarly predictive analysis on the dimensions of tidal inlets by Skou and Fredsoe (1990) have also signified the critical cross sectional area as the division between stable and unstable tidal inlets. The reduction in current velocities due to the increase in channel length and its implications on the sediment transport capacity resulting in gradual decrease of inlet cross-sectional area was authenticated by van de Kreeke (1985). In this context, it is evident that the tidal inlet system at Cochin has cross sectional area larger than the critical area ($A_c > A_c$*) such that an increase in cross-sectional area by dredging will have a counter effect on

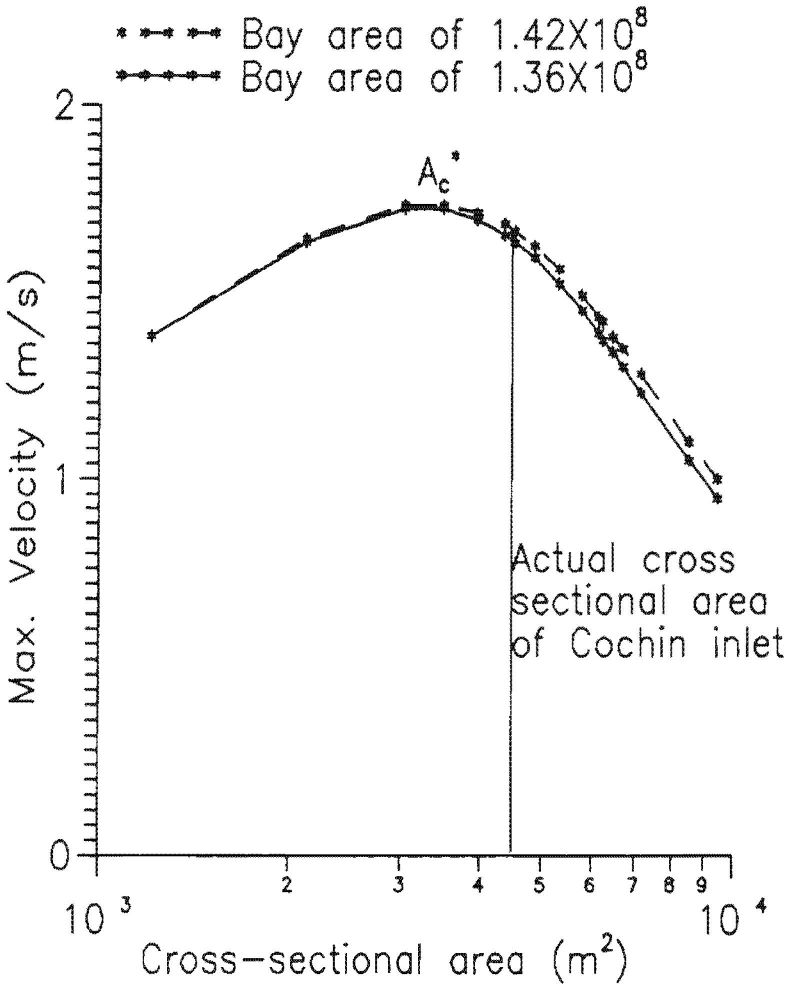


Fig. 9b. Variation in maximum channel velocity with cross sectional area.

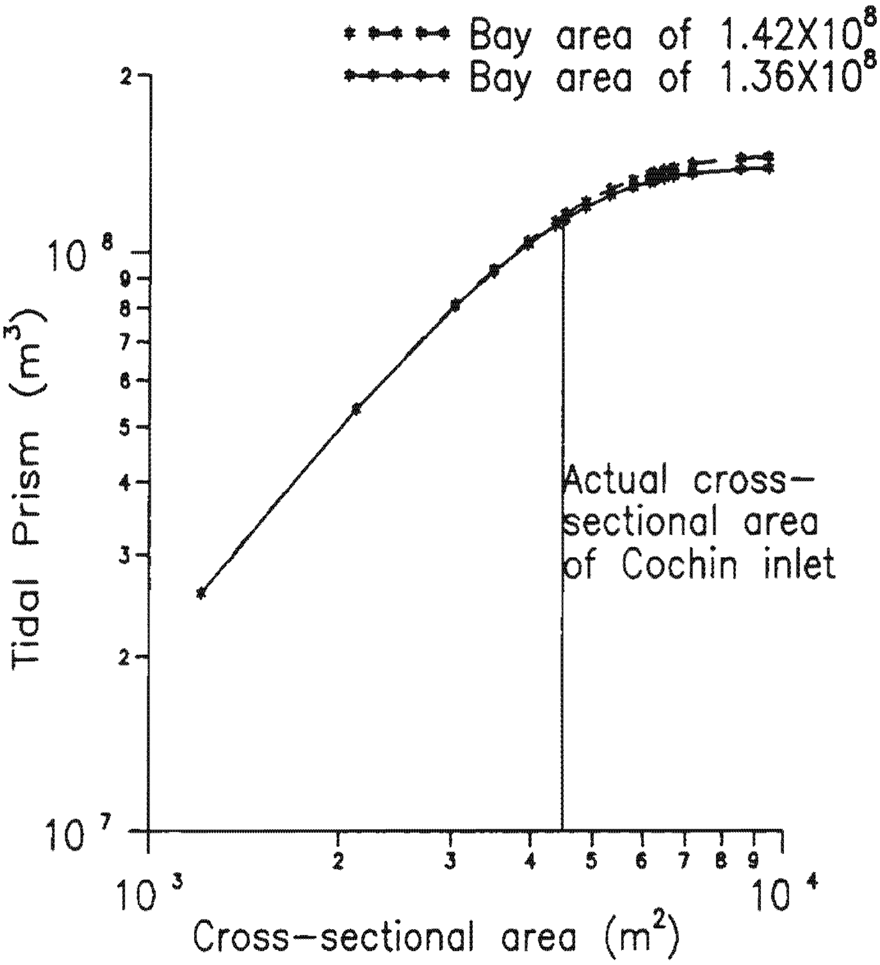


Fig. 10. Variation in tidal prism with cross sectional area.

the velocity maximum as it would decrease (figure 11). This feature may in turn augment sedimentation in the harbour necessitating further more dredging, adversely affecting the economy of the port. And also with decreased bay area and less tidal prism, the tidal range being significant, there is a possibility of salt wedge to entrain further up into freshwater streams. However, a decrease in inlet cross sectional upto the critical cross sectional area results in increase of velocity maximum and the capacity to transport sediments, helping to establish near equilibrium conditions. The scouring as well as the shoaling mode of an inlet due to the variation in the tidal maximum of the bottom shear stress to the equilibrium shear stress was explained by van de Kreeke (1990); this is another factor to be considered for the equilibrium state of an inlet, so that an inlet attains its stability, when after a small change, the cross-sectional area returns to its equilibrium value. Under the prevailing circumstances, alterations in depth (by dredging and/or sedimentation and/or scouring) is likely to upset the equilibrium conditions by way of variations in shear stress; otherwise channel stability remains intact due to the congruity in cross sectional area, maximum inlet velocities and the length of the inlet. Alternatively an increase in the effective channel length from existing 1320m would result in the critical cross sectional area to increase marginally but calculations indicate that the velocity maximum and the capacity to transport the sediments will decrease (figure 11).

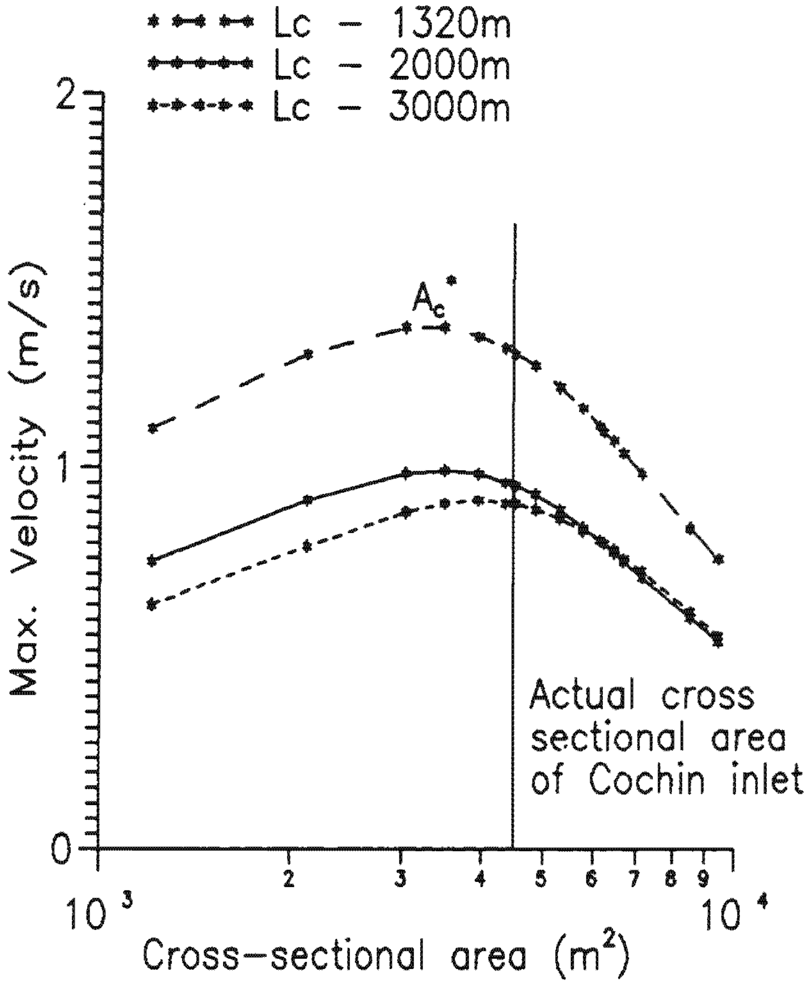


Fig. 11. Relation between cross sectional area and maximum velocity for different channel lengths.

A recent approach in the analysis of stability of tidal inlets brings out the concept of stable and unstable equilibrium and the introduction of equilibrium interval with regard to Escoffier's diagram generally referred as closure curves (van de Kreeke, 1992). Herein, from the general shape of the closure curve the maximum velocity approaches zero as the cross sectional area approaches zero. This is because the bottom friction force per unit mass in the inlet is inversely proportional to area as stated by van de Kreeke (1992). For most inlets, the maximum velocity equals an equilibrium velocity value approximately 1.00 m/s (exact value a function of littoral drift, sediment characteristics, wave climate and tidal period) such that the closure curve will be intersected at two points; the corresponding first point denotes a value of the cross section and all values lower to that as at unstable equilibrium. And the second intersection denotes stable equilibrium when the cross sectional area is obviously higher than the value at the first point of intersection. The interval between the two intersection points on the curve signifies the equilibrium interval and includes all cross sectional areas greater than the first point covering the second too; nevertheless falling within the stable criteria for coastal inlets. In equilibrium cases, for a given cross sectional area, the maximum velocity is just large enough to remove the sediment carried into the inlet by the littoral drift as explained by van de Kreeke (1992). The above situation applies in the case of Cochin tidal inlet where the value of actual cross section lies in the equilibrium interval given that the equilibrium velocity is assumed to be a value around 1.00 m/s. Alternately for large cross sections, the maximum velocity, following the features of the closure curve, leads to non-removal of material transported into the inlet, thereby causing reduction in area till stable equilibrium conditions are reached (the second intersection point). For cross sectional areas lying within the two points (in the equilibrium interval as in the case for Cochin inlet) the tendency may be to transport material off the inlet region from those sources like littoral drift which would maintain inlet stability on one hand and simultaneously attempt to move over to a more stable conditions by increasing the cross- sectional area (to reach a value closer to the second point). Conversely, if the maximum velocity decreases considerably and falls below the value, at the first intersection, the corresponding unstable equilibrium junction on the closure curve, the inlet will close.

In this context, applying the above equilibrium stability concept, the Cochin inlet cross sectional area works out to a value nearer to the stable equilibrium value which assigns a large capacity to the maximum flow velocity to carry away sediments that are moved into the inlet and concurrently there exists a tendency for this inlet to increase its cross sectional area provided that the equilibrium velocity value equals maximum velocity near unity. It follows that the Cochin inlet, viewed from hypothesis of earlier analysis and the most recent one falls under the category of stable inlets, more precisely, to be designated as critically stable. Thence it should be clearly

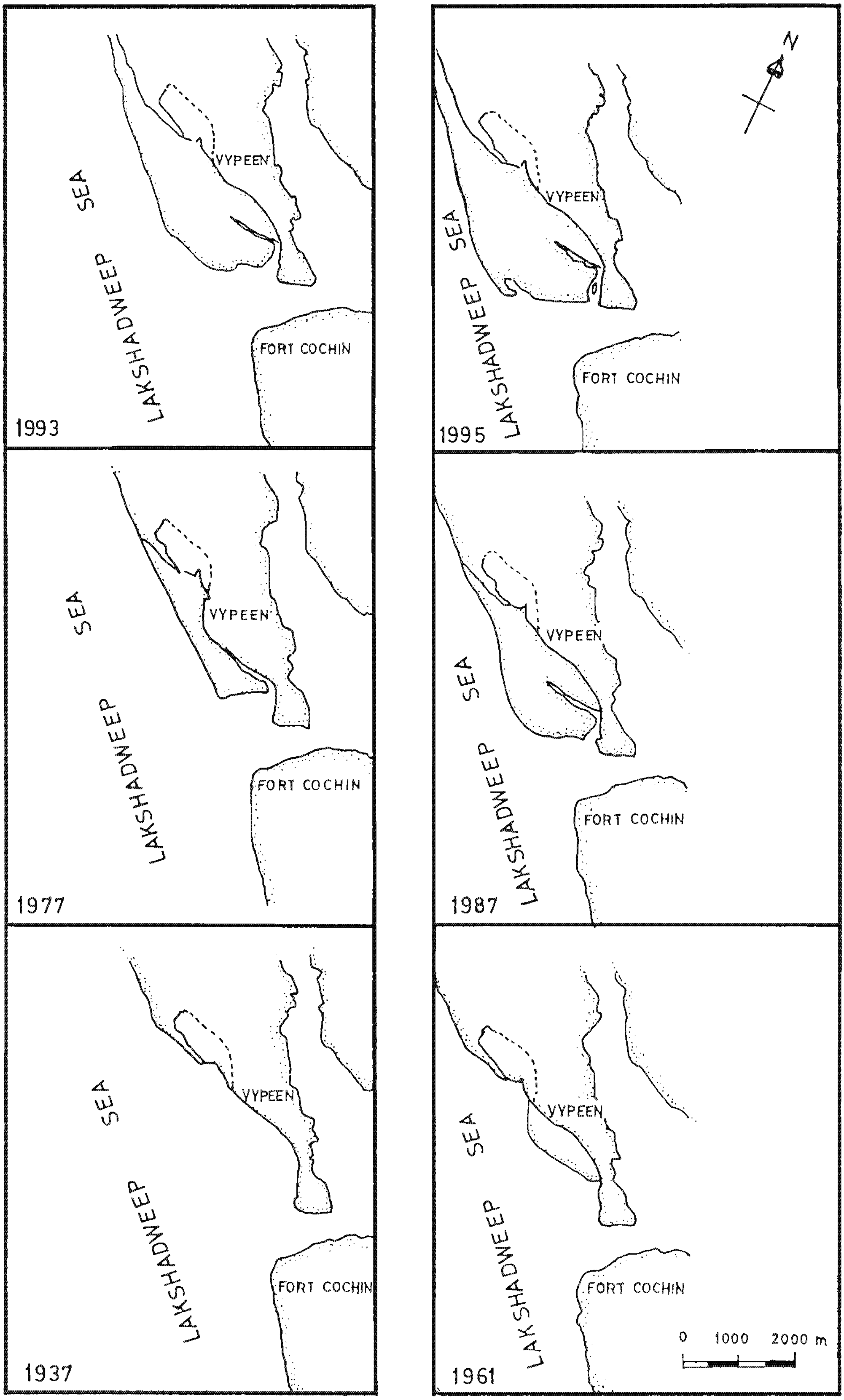


Fig. 12. Historical variation of shoreline north and south of Cochin inlet (1937 - 1995).

noted that changes in basin geometry (by way of land reclamation) leading to tidal prism variations, alterations in depth (by dredging operations) and nearshore erosion/deposition (arising out of littoral drift) and widely acclaimed effects of changes in wave climate due to catastrophic events will definitely upset the existing equilibrium conditions.

This study also attempts to bring out the nearshore features of the harbour entrance where comparatively strong tidal currents for a given critical hydraulic depth would result in the decrease of sediment supply to the downdrift side of the inlet (receeding beach) and conversely, the shoreline on the updrift side would exhibit deposition -indeed it did (Rasheed et al.,1995b). The historical variation of the shoreline at Cochin tidal inlet is depicted in the figure 12. The shoreline since 1937 at Vypeen stands well withdrawn from as compared to the Fort Cochin sector. The years 1961, 1977 and 1987 indicates the gradual development of the landform caused by the deposition of littoral material. In very recent years 1993 and 1995 the Vypeen shoreline continued to advance further offshore. Nair et al.,(1993) reviewed the coastal inlets and the related land forms of Kerala coast and revealed that coastal inlets are of migratory and offset in nature. The shoreline feature at Cochin inlet shows a depositional environment on the updrift side from which the sand is driven. Galvin (1971) and Escoffier (1977) recognized four different groups on classification of inlets based on the variation in updrift and downdrift shore configurations. The predominant longshore sediment transport direction at this shoreline is southernly during most of the months (0.977×10^6 m^3/yr) and the northerly transport is 0.69 $\times 10^6$ m^3/yr (Chandramohan, 1988; Chandramohan et al., 1990 and Sajeev, 1993). The inlet at Cochin comes under the type (2a) According to Galvin's classification which exhibits a significant offset on updrift side. However the inlet gorge is maintained at stable equilibrium as the actual cross sectional area is comparatively higher than the critical cross sectional area of this inlet. Bruun and Gerritsen (1960), Bruun (1978) and Gao and Collins (1994a) explained the stability of tidal inlets in terms of the rate of change in geomorphological characteristics and evaluated the stability in terms of tidal prism per cycle, maximum discharge and the total quantity of littoral drift transported at the inlet system due to longshore drift. The stability analysis by Bruun and Gerritsen (1960) and Bruun (1989) as applied to Cochin inlet region shows that the dimensionless parameter r = Mnet / Qmax = 288 (the gross longshore sediment transport {Mnet} is 1.667 x $10^6 m^3$/year and the volume transport {Qmax} equals 0.00578 x $10^6 m^3$/sec. The process is hence predominantly bar bypassing as r > 200-300 which indicates the likely formation of typical bar or shoal at the inlet. Considering the actual situation at Cochin inlet, the bar formation is observed to be on the updrift side (northern parts of the inlet) and development of any shoal is prevented by maintenance form of dredging time to time within the bay. Stability defined in terms of the ratio between tidal prism and total amount of littoral drift gave a value near to 60, which signifies the category of this inlet to be predominantly supporting transfer of sand on (shallow) bars or shoals across the inlet entrance while rather indicating unstable conditions, seaward off the inlet. More realistic approach to the stability factors at Cochin inlet warrants careful consideration in future with regard to bay area reclamation projects (changes effecting tidal prism) and operations in the coastal zone which may bring about changes in littoral drift conditions. Vaidyaraman et al., (1978) investigated the behaviour of a tidal inlet at the tropical environment at Madras (east coast, India) and suggested a method for increase of the backwater area in order to increase the tidal prism so as to maintain the inlet stability which will minimize the cost on maintenance dredging. The studies by Nair et al.,(1993) using remote sensing imageries observed that during the last 23 year period the northern arm of the barrier spit at Cochin tidal inlet showed a remarkable growth by 1237.50m in length. Rasheed et al., (1995b) stated that this had been due to the effect of dredged sediment dumped at the offshore site off Cochin and it being reworked by the nearshore waves onto the shoreline. It is concluded that from the shoreline variations and the amount of longshore sediment transport observations, that this mechanism of deposition is mainly attributable to the offset on the updrift side and partly due to the sediment provenanced from the dumping sites offshore. The hydraulic features of this harbour is thence highly susceptible to variability to the recently proposed developmental plans for this region (road linkage between islands by bridges, Vallarpadam project - container terminal and Perumanoor project - super tanker berth) and may be vulnerable to engineering modifications.

CHAPTER - 4

STRAIT DYNAMICS OF ANDHAKARANAZHI TIDAL INLET

1. Introduction

A pertinent coastal process at tidal inlets are the formation of sandbars in relation to depositional and dispersal characteristics arising out of the interaction between terrestrial inputs (runoff cum sediment transport) vs. oceanic factors (wave induced sand transport cum tidal influences). Most inlets had been cut through a barrier which had been built by wave action and only a few created in this way will remain stable in cross section (Amein, 1975); in time, they would be choked off by littoral drift deposits caused by insufficient tidal flow to flush out the littoral material.

The tropical fluvial environment is largely controlled by drainage from the hinterland areas in relation to rainfall/runoff pattern. These materials derived from highlands are transported to the downstream estuarine regions by riverine processes and are carried from lower river reaches to nearshore regions. These materials may ultimately deposit (and/or translocate) at the downstream part of the harbour entrances or along the longshore drift regions of the coastal zone to form sandbars. These peculiar natural coastal features are either permanent or seasonal, often noticed in tropical coastal areas. Studies on coastal processes at tidal inlets and formation of seasonal sandbars are available in published literature vide Klein (1976), Bruun and Gerritsen (1978), Oscanyan (1978), Sternberg and Marsden (1979), Mason(1981), Mengshu(1988), Malikides et al., (1989), Xu Zhifeng et al., (1990), Li Chunchu et al., (1991) and Park and Yoo (1992). These regions also have attracted attention towards better use for navigation, prevention of saline water intrusion, at times excavation of deposits formed in the inland reaches or studies on the shoreline characteristics with respect to erosional and depositional behaviour.

The coast of Kerala with its long coastline of about 560 km has 48 number of inlets and nearly 28 out of them are confronted with typical features including their remaining open only during the monsoonal period - listed in Chapter -1 (Nair et al., 1993). Andhakaranazhi, south of Cochin (on the south west coast of India) is one such location where seasonal sandbar formation hinder most marine traffic operations. The following sections discuss the features of formation, dissipation and stability of the seasonal sandbar brought about by the forcing factors which are partly due to the ongoing natural coastal processes. The various aspects of nearshore features, the grain size distribution to understand the dynamical forcing and nature of depositional environments along with the beach profiles are critically presented hereunder.

2. Environmental setting

Andhakaranazhi (figure 2a), a location on the south west coast of India ($9^{o}45'00''$N and $76^{o}17'29''$E) which features a seasonal barrier beach and a tidal inlet, connects the Vembanad lake with the Lakshadweep sea through two streams mainly from north and south of the opening. It also serves as an outlet for the flood waters from the vast paddy fields during monsoon (June - September). The inlet mouth and the lagoon inside the barrier beach is shallow (2m) and the tidal prism was calculated as 17.19×10^6 m^3 during monsoon. The inlet remains open (Plate - 1) only for 6 to 8 months a year, mostly during the southwest monsoon (figure 13) and upto January; the inlet then gets closed as a result of low discharge of water and high deposition of littoral drift material resulting from wave action (Plates - 2, 3 & 4). There are two regulators (sluice gates) close to the inlet inside the bay on either sides for preventing the saline water intrusion into the paddy fields. The hinterland of this region is constituted by five major villages, of an area approximately 71.7 km^2. About 80% of the farmers from this region depend on the deposited sand for land reclamation and wasteland management. The utilization of fertile soils deposited in the streams is also practiced by sand mining activities for agricultural lands as part of their livelihood farming activities.

The inlet is completely open during the south west monsoon season with shallow depths across the entrance; the waves are very strong of periods 5 - 8s. The commencement of south west monsoon brings about changes in the environmental setting and the combined influence of tides and south westerly waves and runoff from the hinterland drives the water exchange between the bay and the nearshore regions. The dominant water flow was directed offshore during the rainy season facilitating navigation at the tidal inlet channel

Plate 1. View of Andhakaranazhi inlet when completely open.

Plate 2. Sand bar development on the southern side of Andhakaranazhi inlet (seaward view).

Plate 3. View of Andhakaranazhi inlet when partly closed featuring meandering channel on the northern side.

Plate 4. View of Andhakaranazhi inlet when completely closed

Fig. 13. Map of Andhakaranazhi inlet when completely open.

of depth approximately 2m. The adjacent catchment area are low lying plains which flood during monsoon and the runoff is directed to the inlet area through the two sluice gates north and south of the opening. The semidiurnal tides at this region were of the range 1.2m. The boundary banks of the inlet are protected by sea walls and the bay within occupies an area of approximately of 0.12 km^2. The sluice gates at either sides, north and south of the bay, are opened only during the monsoon period to drain inland waters while helping to regulate the flood levels in hinterland areas. The two regulators are closed during the postmonsoon season and premonsoon season (October to May) to prevent entry of sea water during the intervening periods.

3. Results and Discussion

A) Bathymetry

The average depth at the inlet was 1.5m in June 1993 and the depth of the canal on south of the southern side shutter was deeper (7m) than that on the north side of the south shutter (4m) inside the bay. Particularly noted during August 1993 was the depth on the north side of the inlet to be much deeper, about 4m.

The depth at south of the north shutter was 5.5m and the depth on the north of the north shutter was about 8m. More deeper portions were observed at times on south as well as on the north of south sluice gate while shallow depths in the range 1.0-2.5m were observed in most regions inside the bay. The depth at the inlet mouth was 1.5m during this period (August 1993) and shallow regions with more sand deposits were noticed on the northwest bay side of the north channel. During November 1993, the inlet was partially filled with littoral sediments and the width of the inlet mouth had decreased considerably. The inlet channel exhibited features of meandering, lying in northwest - southeast direction. The maximum depths within the bay was on the southern sluice gate side (5.5m) and also on the northern side of the bay near the north channel (6.5m). During the early part of December 1993, the inlet mouth was observed to be shifted further to the north western side in a meandering manner into the bay and the width stood reduced to 65m (figure 14). The depth was 2m at the inlet mouth at the seaward side. By the end of December 1993, the inlet mouth was completely closed due to the continued deposition of littoral sediments and in effect, a barrier beach developed across the inlet (figure 2b). During June 1994, the bar eroded completely due to the combined influence of freshwater run off and the wave action resulting in partial opening with a width of 145m and an average depth 1.5m at the inlet mouth.

B) Flow Velocity

The flow velocity at the sluice gates during the period when the inlet remains open was considerably influenced by the hydraulic head between the levels inside of the bay and that outside in the canal region due to the piling up of water by the breaking waves at the inlet mouth coupled with the volume transport into the inlet due to the tidal currents. During August 1993, the depth averaged velocity

Fig. 14. Map of Andhakaranazhi inlet when partly closed.

during flood stage at the south sluice gate, west and east side were 155.30 cm/s and 182.60 cm/s respectively. Similarly at the northern side the depth averaged velocity at east side shutter was 144.67 cm/s and that at the western side is 198.30 cm/s. But at the channel side of the north east and north west sluice gates the depth averaged velocity were 66.33 cm/s and 94.30 cm/s respectively.

The ebb phase velocity, depth averaged, through the south sluice gate, at western and eastern sides were 52.33 cm/s and 146.7 cm/s respectively, inside the bay. Along the channel side of the southwest sluice gate and southeast sluice gates the flow velocities were 59.33 cm/s and 170.33 cm/s respectively. But at the northern side the depth averaged velocity at northeast and northwest sluice gates are 77 cm/s and 146 cm/s, respectively inside the bay. However at that channel side of the shutters the flow velocities were 105 cm/s and 151.33 cm/s, at the east and west sides respectively. The variation in flow velocity at both sides of the sluice gate during flood and ebb period is attributed to the loss of kinetic head as the flow separates when it enters past sluice into the inner channels during flood or when it is directed seawards during ebb. Conditions similar to above, when the flow velocity decreases by way of loss in kinetic head has been reported by Mehta and Ozsoy (1978).

During October 1993, the flood waters from the hinterland regions, during the northeast monsoon season, was drained off through both the sluice gates into the sea; the flow through the southeast and northwest shutters of the south and north gates were faster than the other two openings as observed in August 1993. In November 1993, the flow through the inlet was only 40 cm/s at the ebb stage as the two sluice gates remained closed to prevent saline water intrusion into the paddy fields; concurrently, the inlet width decreased considerably due to the deposition of littoral sediments at the mouth. During December 1993, the flow velocity at the mouth of the inlet further reduced considerably (29 cm/s) as compared to the velocity (311 cm/s) at the constricted portion of the inlet by sand deposition. As the width of the inlet was considerably reduced due to littoral deposition at the updrift side, the increased flow velocity at constriction in the inlet has been explained by Mann and Mehta (1993) when maximum velocity of flow will be accounted at narrow constrictions.

The inlet mouth opened completely and permitted water exchange between the bay and the nearshore regions in June 1994 while the two sluice gates were opened to drain the flood waters outward into the sea. The depth averaged flow velocity during ebb tide through the southwest sluice gate was 101.20 cm/s and that at the southeast sluice was 158.20 cm/s. Similarly the depth averaged flow velocity at northwest sluice was 139.10 cm/s and that at the northeast sluice gate was 61.44 cm/s. During the flood tide, the depth averaged flow velocity at southeast sluice gate was 145.70 cm/s whereas that at the southwest sluice was 109.8 cm/s. Similarly at northwest shutter during flood the depth averaged flow velocity was 126.70 cm/s and the flow at northeast shutter was 87.67 cm/s.

C) Salinity

The salinity variation in the bay during the period of inlet closure and opening was monitored at stations H1 to H6 as shown in the location map of the study area (figure 15) and is discussed hereunder providing values wherever necessary.

During March 1993, after the complete closure of the inlet, the water exchange between the bay and the coastal sea was hindered and only limited freshwater entered the bay through either of the sluice gates on north or south of the bay. A salinity difference of 11.00 was observed at either side of the sand barrier during this month when the salinity of water sample on the sea side was 36.00 and that on the bay side was 25.00. During June 1993, the salinity values indicated the influence of the freshwater inflow and the resulting mixing with the sea water at the bay region. Identical salinity values were observed at stations H1 on the south of the south shutter and also at station H2 at the north side of the south shutter - salinity value was around 10.00. Similarly at all other stations the salinity distribution was almost homogeneous with values ranging from 11.00 to 12.00. The salinity values during the flood stage in August 1993 showed almost uniform distribution from 31.80 to 32.50 with higher values at stations (H3 and H4) north of the bay near the sluice gates and the least values along south and central stations inside the bay (H2 and H5). But during the ebb stage, salinity ranged from 31.50 to 32.65 inside the bay. The highest salinity value was observed at station H4 as 32.65. Observations during the ebb period in November 1993

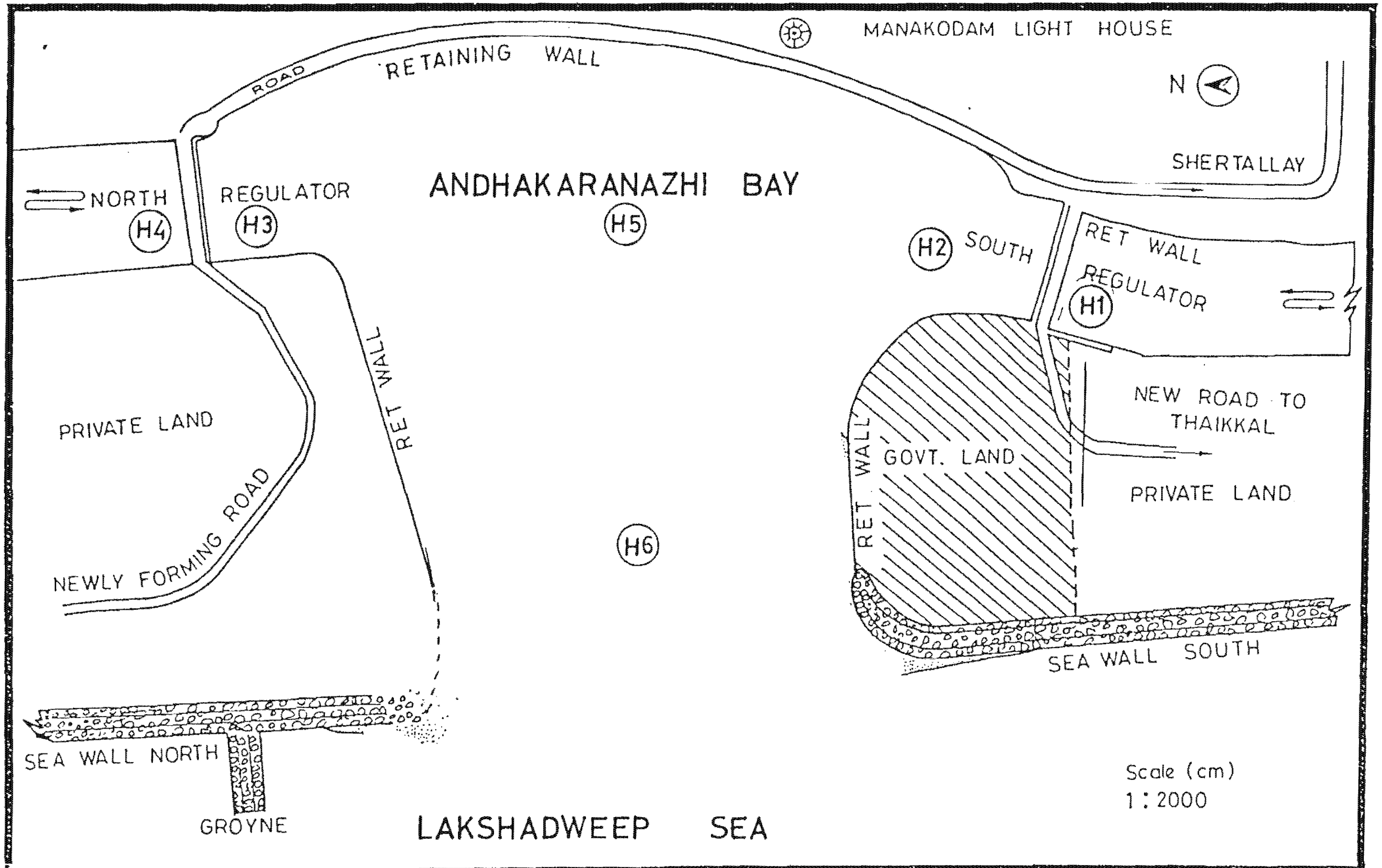


Fig. 15. Location map of hydrographic stations H1-H6 at Andhakaranazhi bay - inlet.

indicated the salinity values to vary from 15.25 at station H4 to 28.00 at station H2. However at stations H1 and H5, the salinity values were 20.25 and 22.00 respectively. At the inlet mouth, station H6, the salinity was 18.00. The low salinity values observed at the northern stations compared to the southern stations was due to the intermittent freshwater discharge through the north sluice gate only, during the ebb period.

In December 1993 the surface salinity at station H1 was only 8.00 whereas the bottom salinity value was 23.00; hence a sharp vertical salinity gradient is inferred at this station. This was indicative of the bottom high saline water intrusion into the upstream regions even on the closure of the sluice gates during this month. The salinity values was observed to be nearly the same in vertical at station H2. However at station H4, a vertical salinity gradient was observed with surface salinity to bottom variation from 11.50 to 24.00. Though a vertical salinity gradient was observed at the upstream stations outside the bay region, homogeneity prevailed in the vertical distribution at stations H5, the central bay station and H6, at the inlet mouth. In February 1994, after the closure of the inlet due to the barrier beach formation, the salinity value inside the bay was only 4.50 whereas the seaside salinity was 32.50. This indicates the role played by the seasonal barrier beach as a natural barrier to prevent saline water intrusion into the upstream reaches of this region. Ground water movement or infiltration is also hence ruled out. The implications could well be on the hydrographic conditions influencing coastal productivity. Studies by Torres-Moye et al., (1993) along three Mexican coastal lagoons observed that due to inlet closures, stagnant water conditions develop within and consequently physico-chemical changes ensued affecting the biological productivity.

D) Suspended Solids Distribution

The suspended solids (SS in mg/l) distribution was monitored at the inlet and the bay during the period under study and is discussed in the following text with values.

In August 1993, the SS concentration during the flood and ebb stages were estimated and it was observed that the SS concentration during the flood stage was higher compared to the ebb stage. The SS concentration was observed to be highest at the south sluice gate region inside the bay (151.65 mg/l) whereas during the ebb it was observed as 125.68 mg/l again at the same location. The least value of SS observed during the flood was 127.14 mg/l at station H1 and during the ebb stage, it was found to be 101.87 mg/l. But during the ebb tide, the least value of SS (87.14 mg/l) among all the stations was observed at the central bay station (H5). In October 1993 SS concentration inside the bay varied in the range 32.78 mg/l at station H4 to 112.61 mg/l at station H6 at the inlet mouth. However an exceptional increase in SS content (284.49 mg/l) was found at station H2 inside the bay region near the south sluice gate. In December 1993 the surface SS content was observed to vary from a low value of 16.60 mg/l at station H4 to 80.00 mg/l at mid depth of the station H5 and to 89.65 mg/l at station H2. The variation of SS content in vertical at the inlet mouth was limited, nearly homogeneous due to the shallowness in depth. However a notable increase in vertical SS concentration was observed from surface to bottom at station H2 in the range 36.00-43.00-89.65 mg/l. Since January 1994, the inlet remained closed, concluding the studies on suspended solids at Andhakaranazhi.

E) Beach Profile

A pertinent coastal process which depicts shoreline features in tropics are the barrier beaches which reflects predominant deposition. The interaction between terrestrial inputs as run-off from hinterlands and the sediment transport due to wave action coupled with tidal currents generally influence the barrier beach dynamics. Meistrell (1966) opined that beach profile is a reflection of given wave conditions. The slope of the beach is governed by the intensity of the swash and the resulting onshore- offshore sand transport (Komar, 1976). According to Shepard (1963) beach slope is predominantly a function of grain size of the beach material and secondarily a result of the wave energy. The beach with coarser and poorly sorted sediment has a steeper slope in the range 5°-15° whereas the beach with slope gradient 4°- 10° has finer and well sorted sediments.

The beach profile studies conducted at this barrier beach signifies the variation in the depositional feature of the sand bar during different months at the site. The monthly depositional rate gives an indication on the development of sand bar at the tidal entrance. This section deals with the erosion and accretion of beach sediments at this inlet mouth, by profiling at four transect stations (figure 16), two each south and north of the inlet. At station A1 (south of the south bank of the inlet) the beach elevation shows a gradual slope extending upto 25m for the months April and May 1993 (figure 17a). The commencement of the deposition of material at this station was indicated by short sweep extending only upto 10m during November and December, 1993. January and February 1994 showed a considerable extent of beach development alongside the inlet extending upto 30m. Similarly during May 1994 the beach had fully developed and more accretion was observed compared to other months of observation. The berm crest was observed to be advancing along with the beach development as observed in January, February and May 1994. During June to October 1993, the beach front was completely eroded off due to the peak monsoon wave activity and the outflow from the inlet regions which did not facilitate profiling. Station A2 located on the south bank of the inlet indicated more interesting features; the presence of the sandbar can be inferred from the profiles of April and May 1993 (figure 17a). Subsequently the bar development was indicated in the profiles of November and December 1993 extending upto 30m from the reference point. The complete development of the bar and the adjoining beach can be clearly inferred from the profiles for the months January, February and May 1994. Station A3 on the north depicts the features of the inlet as well as the beach in terms of the elevation chart (figure 17b). April 1993 indicated the presence of a wide beach front compared to the

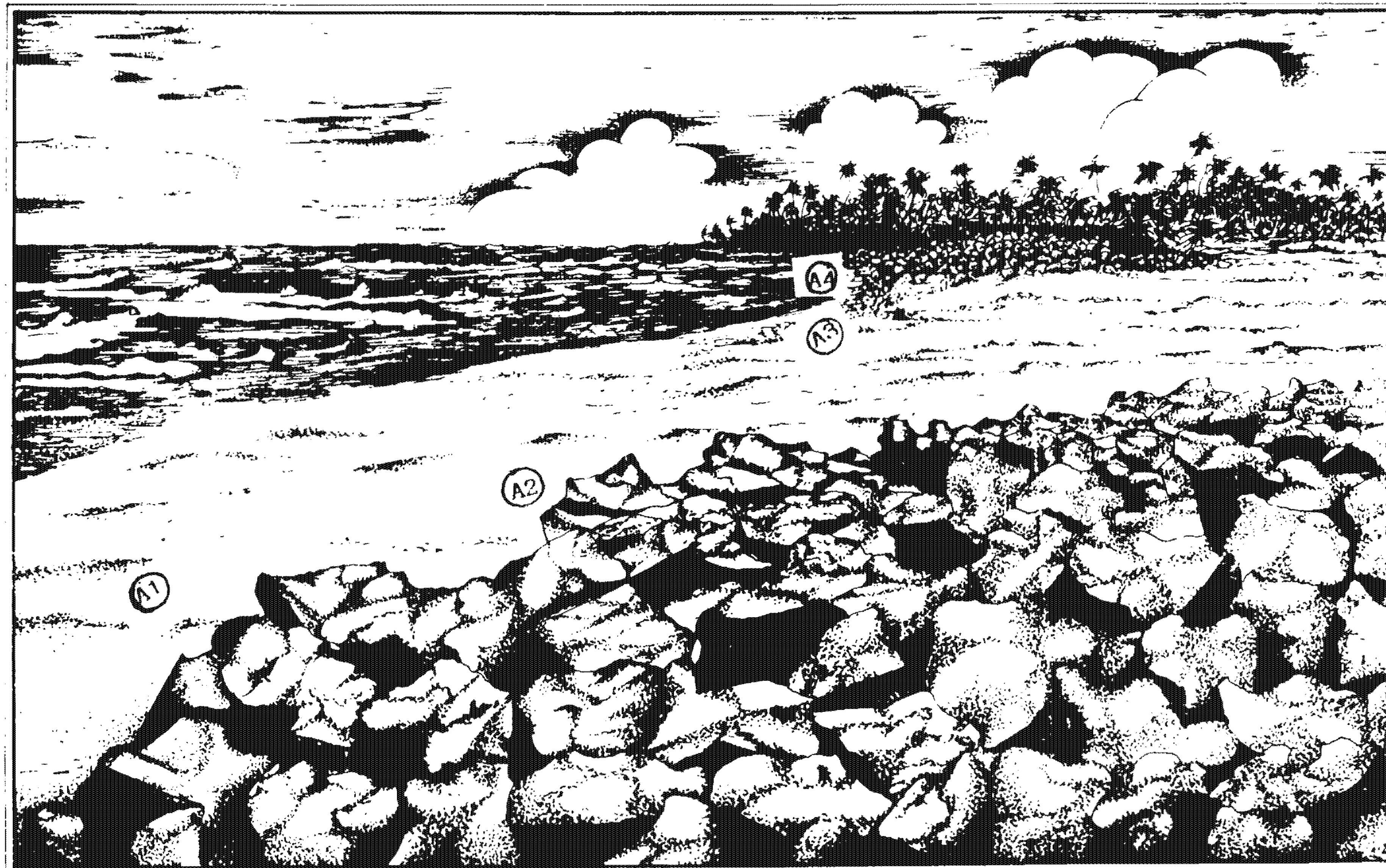


Fig. 16. Location of beach profile stations A1-A4 at Andhakaranazhi.

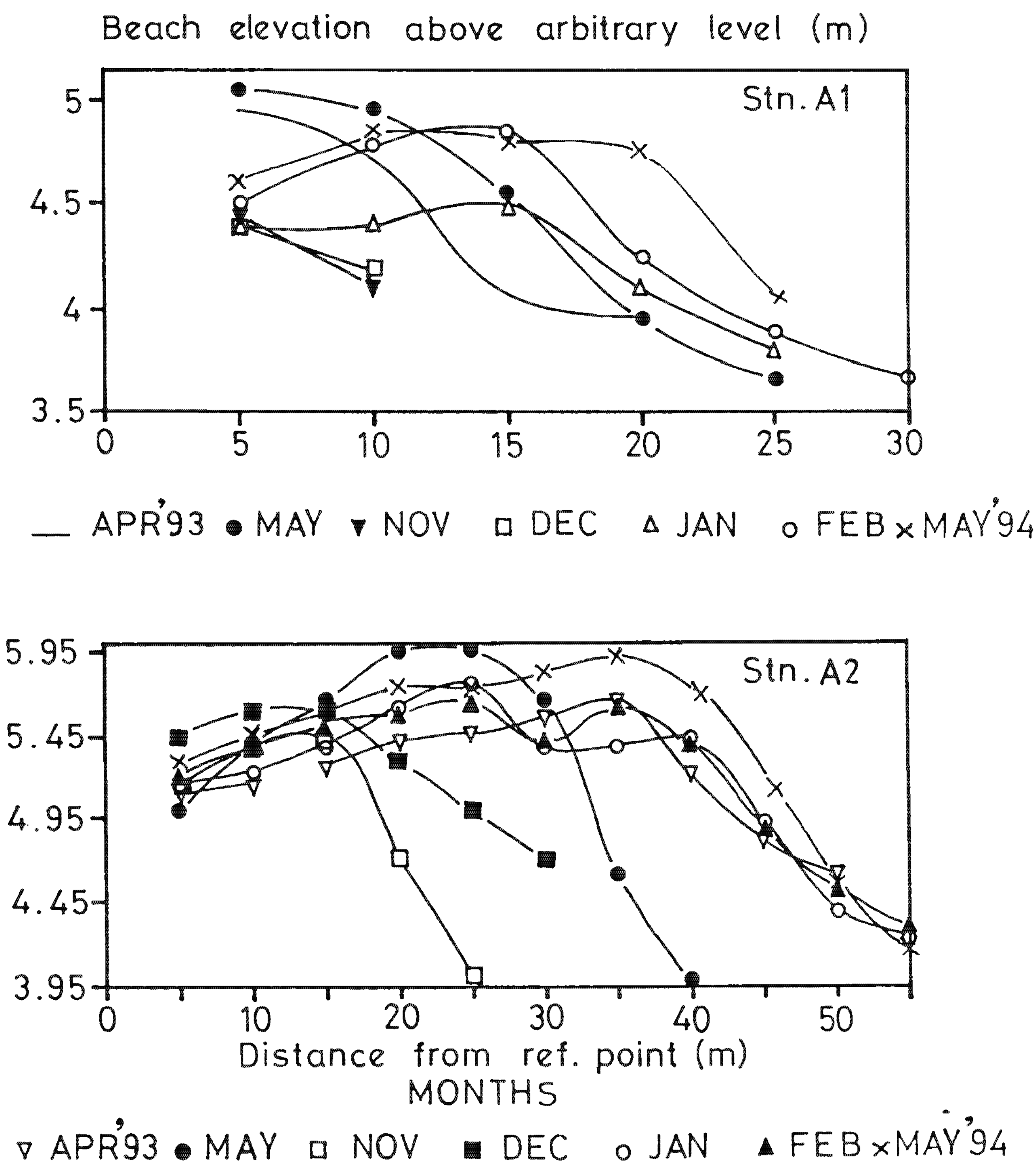


Fig. 17a. Beach profile at stations A1 and A2.

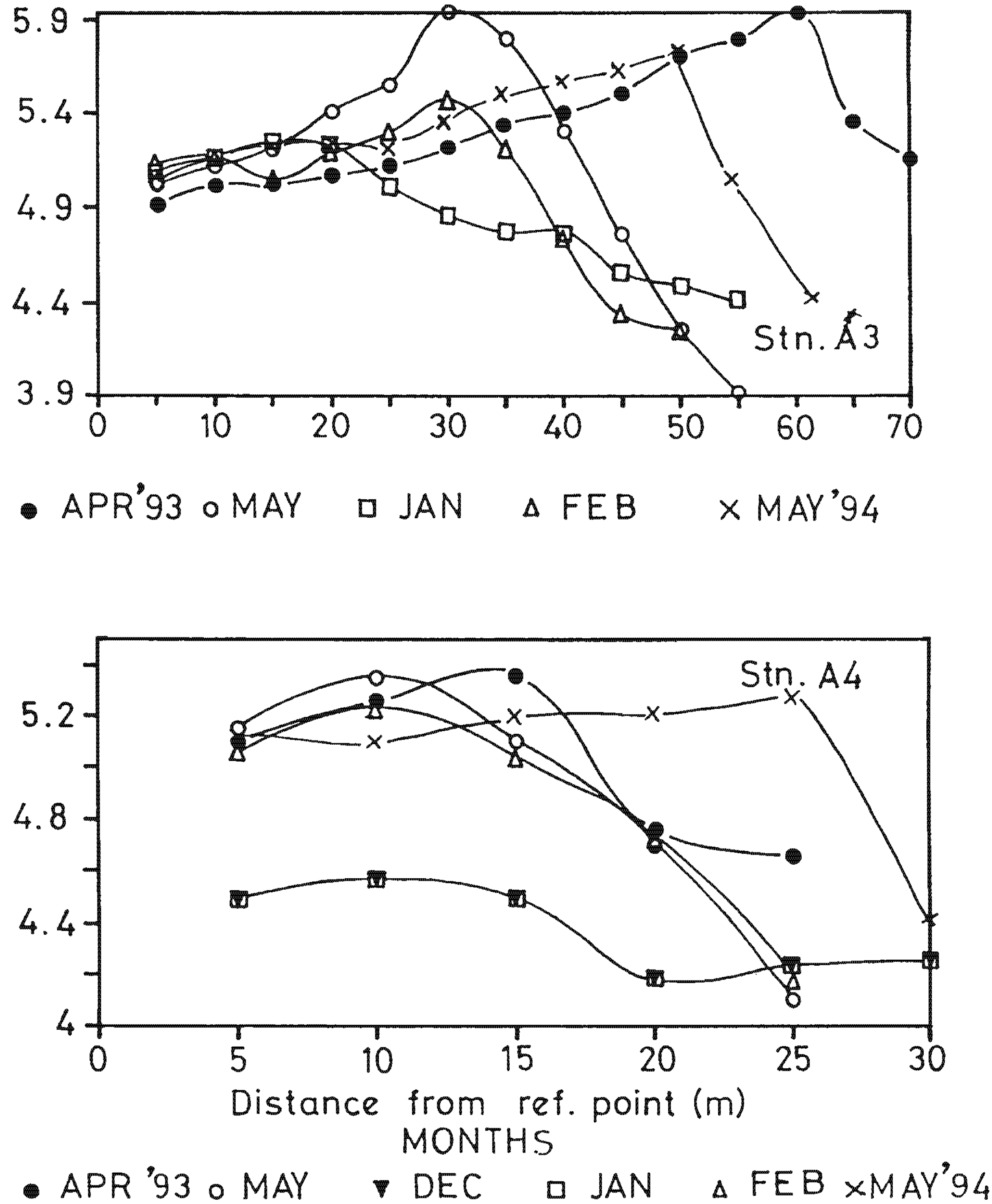


Fig. 17b. Beach profile at stations A3 and A4.

profile during May 1993, a period when inshore site was largely eroded within distances of 40 to 70m from the reference point. During June to December 1993 this location was devoid of any beach features. A shallow beach was first formed in January 1994 and subsequently, in February 1994 further development ensued. But during May 1994 considerable accretion was observed at this station compared to January and February 1994 and extended upto 62m from the reference point. Compared to station A2 it is evident that the northern part of the inlet was developing at a later stage than the southern regions. An earlier work by Shenoi and Prasannakumar (1982) indicated the seasonal opening which remains as such throughout the monsoon season and suggested that considerable accretion of beach material for wave direction approach at 300° compared to erosional features for directions within 240°-280°. Station A4 on the far northern side of the inlet indicated less variations compared to the other 3 stations (figure 17b). The premonsoon (April - May) and postmonsoon (January - February) features are more or less identical except for February 1994. The low beach elevation during December and January was due to the subsequent beach development after the complete erosion during the period of monsoon months (June- September). The foreshore slope of the beach during February was steep compared to the previous month of observation and the beach had developed completely upto 25m from the reference point. The significant difference in foreshore slope resembles the changes in grain size distribution. Generally the longitudinal extent of the barrier beach was greater at the two stations A2 and A3, compared to the other stations A1 and A4 which were on south and north of the inlet banks. During the month of April 1993 the beach face showed a gradual slope towards the low water line, throughout the length of the beach, and the longitudinal extent was greater at station A2 and A3, and during May 1994 the beach slope gradient was less at station A1, whereas steep gradient was observed at station A2 and A3 on the southern and northern side respectively. The longitudinal extent was about 40m from the reference point at station A2. Though in April 1994 the length was about 50m from the reference point, some erosion was observed during this month too. However, the slope gradient at station A4 was gentle. The investigation during May 1993 spelt out the first indication of changes in the wave climate influencing the stability of the bar.

Ajith and Balchand (1995b) explained that the commencement of south west monsoon bring about changes in the environmental setting by way of erosion of the bar by combined influence of tides and south westerly waves and freshwater discharge through the inlet. During June, the beach had been eroded off and the inlet was completely opened with shallow depths across the mouth and remained open with sand deposits noted on the northern as well as on the southern side of the inlet - bay region and no accretion was found to occur at stations A2 and A3. The inlet remained completely opened till October and the build up of the beach starts from November onwards from southern end. From December onwards, the barrier beach developed fully across the inlet mouth. The above observations of barrier beach development was similar to the beach profiles observed by Baba (1988) as a wide beach with steep foreshore and a well developed berm characterising a fully developed beach during premonsoon season along the beaches from Trivandrum to Calicut. The width of the inlet mouth at Andhakaranazhi decreased to about 65m (figure 14) and did shift towards northern side. Similar observations of rebuilding of erosional beaches which starts from September and attains an initial position by December/January was explained by Thomas and Baba (1986). The presence of gently sloping beach face with multiple berms indicative of a developing beach during postmonsoon along Kerala coast was also further explained by Baba (1988). The inlet mouth was closed due to the full development of the barrier beach as the tidal prism reduced and discharge through the two sluice gates on either side of the inlet was very low as compared to the volume of littoral drift transported into the inlet region. The mechanism of inlet closure due to the filling of the inlet system by littoral drift thereby diminishing the potential tidal prism of the system resulting in the closure of the inlets was noted way back by Lucke (1934). Similar observations of inlet closure mechanism was explained by Schmeltz et al., (1982).

F) Grain size distribution

The mechanism of transport and deposition of sediments can be inferred from the study of grain size distribution as there exists a fundamental relationship between the sediment distribution and the physical forces involving the transport and deposition. Reineck and Singh (1975) explained that high energy environments are associated with coarser sediments and low energy environments are related to fine sediments. Beach sediment samples collected during the period 1993-1994 except the monsoon period when no beach development took place, were analysed and the results are presented hereunder. Figure 18 provides the mean grain size variation during the premonsoon season at four locations, namely, at backshore, berm, foreshore and low waterline.

Station A2 contained fine grained sediments at the berm and foreshore whereas medium to fine sands were observed at the backshore. Similarly at station A3 also the mean grain size decreased from backshore to foreshore and slightly increased in mean size at the low water mark. But at station A1 and station A4 of the barrier beach, the mean size increased from backshore to berm and foreshore. However a decrease in size from foreshore to low water at station A4 and at station A1 could be observed.

Figure 19 shows the variation in mean grain size of the sediments from January 1993 to May 1994 at 3 locations (figure 19 - station A1 : southwest [foreshore]; station A4 : northwest [foreshore] and bay side [backshore of transect station A2]) at the seasonal sand bar at Andhakaranazhi. During January 1993 the mean grain size decreased from south west to north west and the decrease in grain size continued towards the bay side of the sand bar. Similarly in May, November, and December 1993 also the mean grain size decreases from south west to north west; the minimum grain

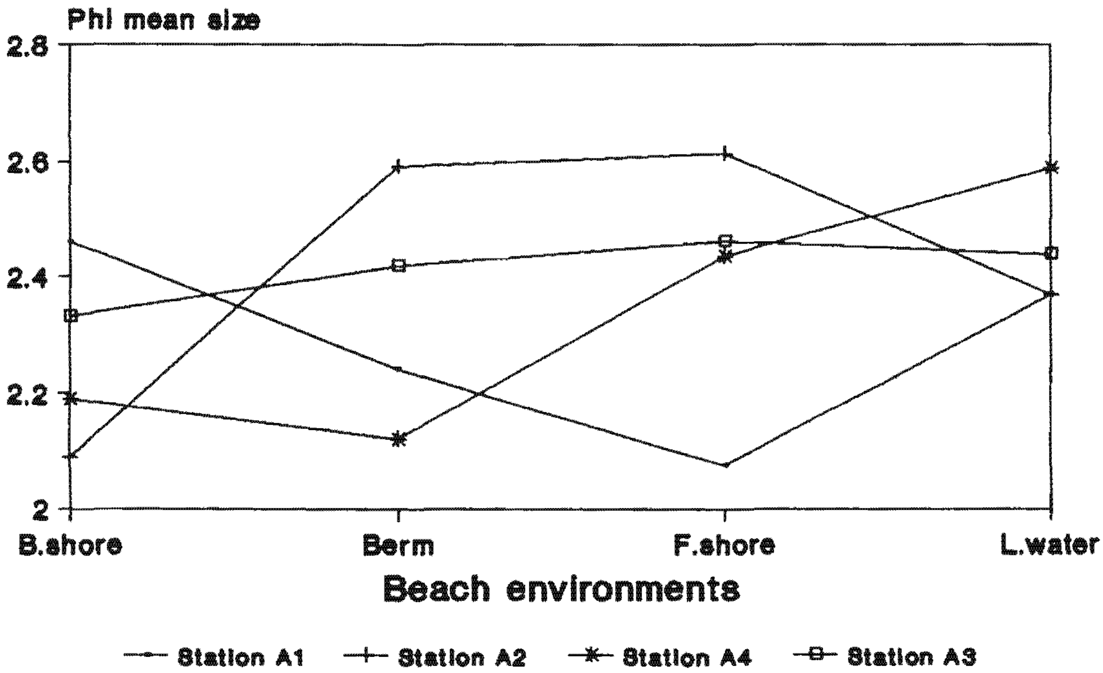


Fig. 18. Mean grain size variation across the beach in premonsoon at Andhakaranazhi inlet.

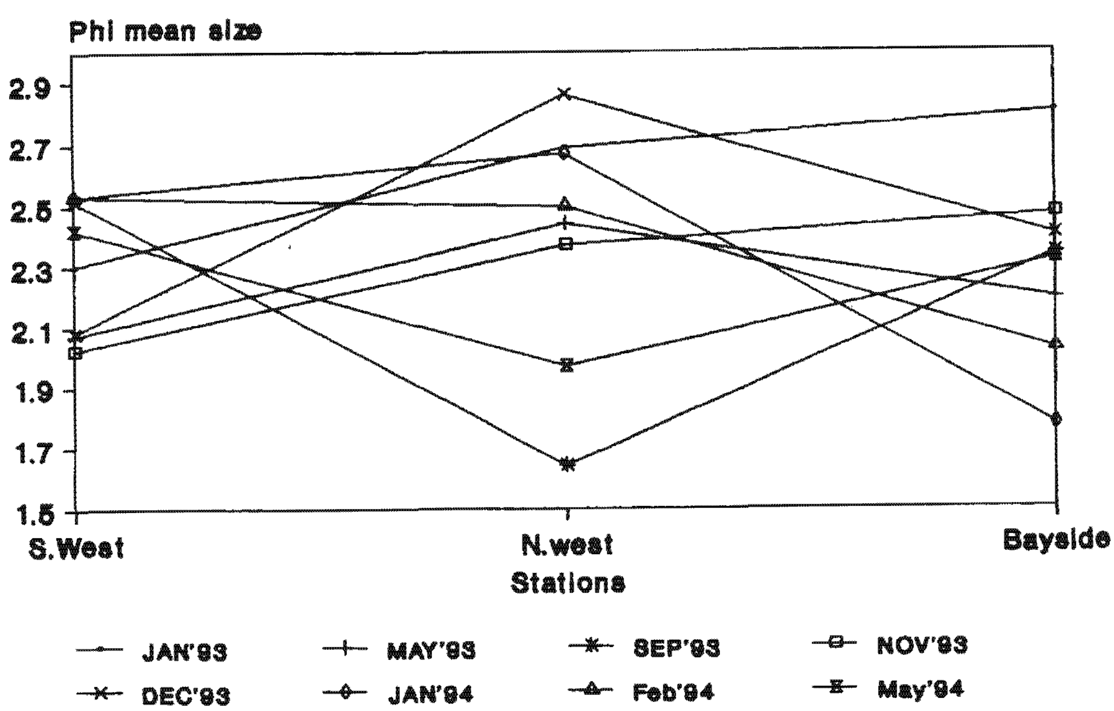


Fig. 19. Mean grain size variation during the months of deposition.

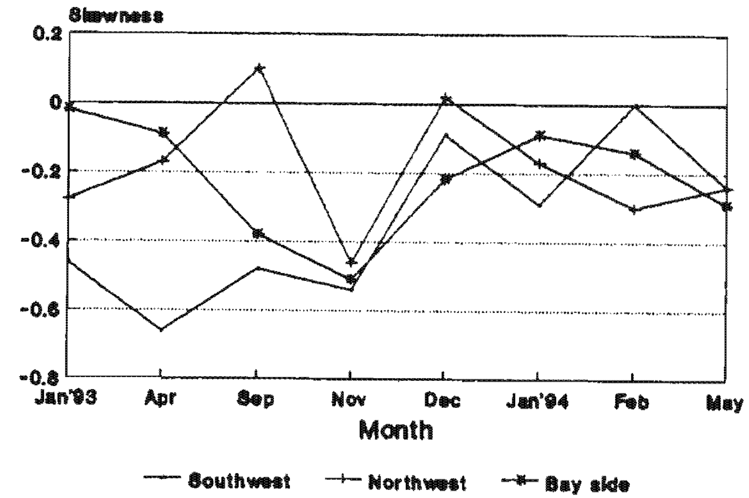
size observed was in during December on the north west side of the sandbar. But during September the mean grain size was observed to be higher on the north west side and it decreases towards south west and also towards the bay side. The seasonal variation of grain size can be attributed to the energy input at these sites. The influence of wave climate on the beach sediment size was reported by Baba (1988). Slightly high waves (of height approx. 1.35m) were observed on the northern sides compared to the low waves (1.05m) at the southern side, during the period of observation in September. Fine sand (2.55Ø) was observed on the south west side with well sorted, very coarse skewed and very leptokurtic sediment size distribution. Whereas medium sands (1.56Ø) with moderately well sorted and positively skewed and mesokurtic distribution was observed on the north west side. The slight decrease in grain size towards the bay side may be due to the transportation of finer sediments by tidal currents into the bay region. The presence of fine grained sediments at the backshore region was explained by Chakraborty (1977) in his study of beach sands from the east coast of India.

The median grain size of sand at bayside was comparatively low during January, April, September and November of 1993 but increase in grain size was observed during December 1993,January and February of 1994(figure 20). Similarly a marginal decrease in median size was observed in May, 1994. On the south west side, the median grain size was almost uniform throughout the survey period. But, on the northwest side, the median grain size increased during September 1993 and decreased from November, 1993 to January 1994 followed by an increase of median size in May, 1994.

G) Standard Deviation

The standard deviation gives an idea of the dispersion of the grain size from the mean grain size of the sample. A better sorting of the sediment is reflected from steep cumulative curves whereas poor sorting of the sediments can be inferred from broad flat curves. The sediment distribution on the southwest side during all the months of observation were seen as well sorted except during November when the sediments were moderately sorted (figure 21). But on the northwest side, moderate sorting of sediments were observed during September, 1993. However during all other months, the sediment distribution was more or less well sorted. At the bay side, very well sorted sediments were observed during January and April 1993. But during September, November 1993 and February, May 1994 a well sorted distribution and during December 1993 and January 1994 moderately sorted sediments were observed. In general, a marked variation in sorting was observed during September and November whereas almost uniform sorting was observed, in spatial, across the barrier beach during remaining months of beach development. Well sorted to moderately well sorted sediment distribution was observed on the southwest side except in February 1994, when it was a very well sorted sediment distribution. On the northwest side of the beach, very well sorted

Fig.22



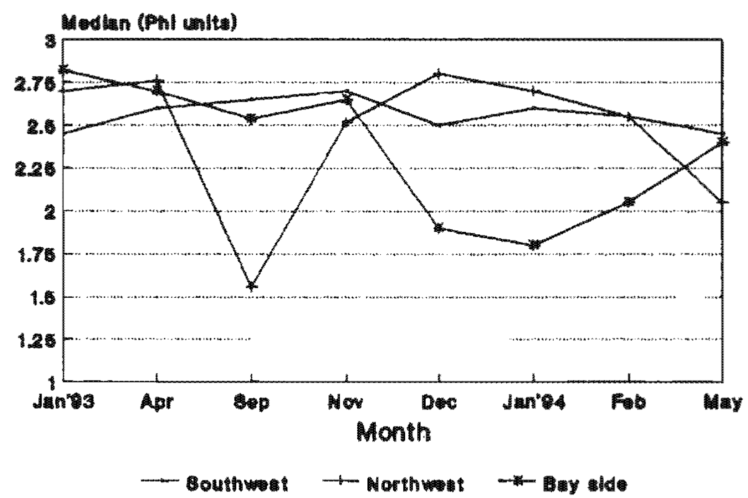


Fig.20

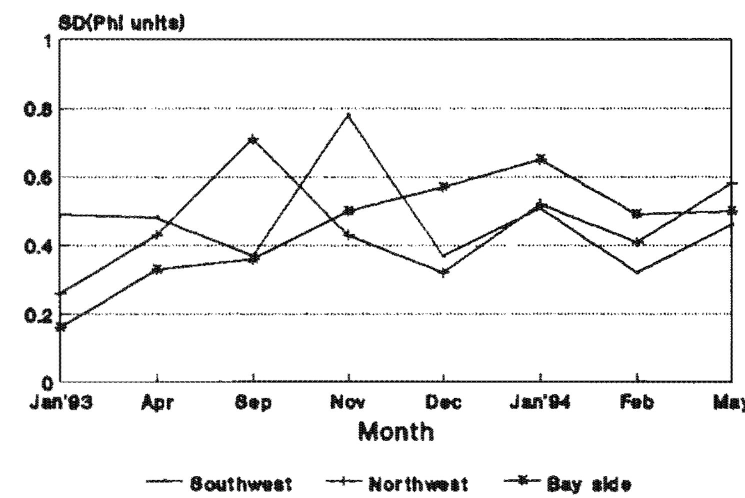


Fig.21

Figs.20. 21 & 22. Variation of median grain size, sorting coefficient and skewness of the beach samples from Andhakaranazhi inlet.

distribution existed in January 1993 and December 1993 and during all the remaining months, well to moderately well sorted sediment distribution was observed.

H) Skewness and Kurtosis

The studies on skewness and kurtosis, the asymmetry of the grain size distribution in a sample, helps to identify the measure of dissimilarity observed in sorting of sediments in the central part of the particle size distribution curve; it also points out the tails and the degree to which the particles are concentrated near the center of the curve. King (1972), Prakash et al., (1984) and Harish (1988) have studied the erosional and accretional pattern of the beaches based on skewness. The coarse skewness in sediment distribution can be related either due to the addition of materials to the coarser terminal or due to the selective removal of fine particle from a normal population by winnowing action as authenticated by Martin (1965).

Figure 22 gives the asymmetry of the grain size distribution in the beach samples at Andhakaranazhi region. The grain size distribution on the southwest side showed a negatively skewed distribution in all the months except February 1994 when the distribution was near symmetrical. During December 1993 and February 1994, near symmetrical distribution was observed but during all other months, the sediment distribution was coarse skewed to very coarse skewed.

On the northwest side, in September and December months, positively skewed distribution was observed and the distribution was fine skewed to near symmetrical; during all the other months coarse to very coarse skewed distribution was noted. During September 1993 to February 1994 and again in May 1994, at the bay side region, the distribution was very coarse skewed to coarse skewed but in January 1993 & 1994 and April 1993, the grain size distribution was near symmetrical.

In general, a positive skewness was observed only during the fag end of September and postmonsoon month (December) at the northwest side of the barrier beach and a near symmetry was observed during February on the southwest side. But during all other months a negatively skewed asymmetry was prominent in the grain size distribution of the beach samples of the southwest, northwest and bay side of the barrier beach. The negative skewness indicated a continuous erosional tendency of this seasonal barrier during most of the period of observation. Yeo and Risk (1981) stated that the sand bar sediment size distribution curves are usually negatively skewed and indicate good sorting. It is true that almost during all the months of observation, negative skewness with high sorting and low grain sizes were observed for the erosional phase of the seasonal barrier at Andhakaranazhi except in September and November 1993, on the northwest side and the southwest side respectively, where comparatively moderately sorted positively skewed with high grain size sediments were observed in the depositional phase.

Trask and Johnson (1955), Trask (1956) and Komar (1976), Prakash et al.,(1984) and Harish (1988) have reported similar observations for the erosional as well as for accretional phases of beaches. The presence of fine sand with moderate sorting to well sorting is in good agreement with the studies by Prasannakumar (1985).

I) Median Size

To understand the grain size distribution of the barrier beach at the time of full development, samples were collected across the beach from backshore to the low water mark during April 1993, February 1994 and May 1994. The figures 23a and b provide results on median size and skewness respectively and that on sorting coefficients are given in figure 24.

In the month of April 1993, the median size of the sample were observed to be more or less uniform and lies in the range 2.5 - 2.7Ø units except at foreshore (1.97Ø) at station A1, backshore (2.15Ø) of station A2; the median grain size in phi units at station A3 was found to be lowest at berm crest and almost uniform at station A4 with the minimum median size observed at the backshore (2.52Ø). A positively skewed moderately well sorted sediment distribution at station A1 indicated the accretional trend of the beach; however, a negatively skewed well sorted sediment distribution at all other stations showed an erosional phase during April 1993.

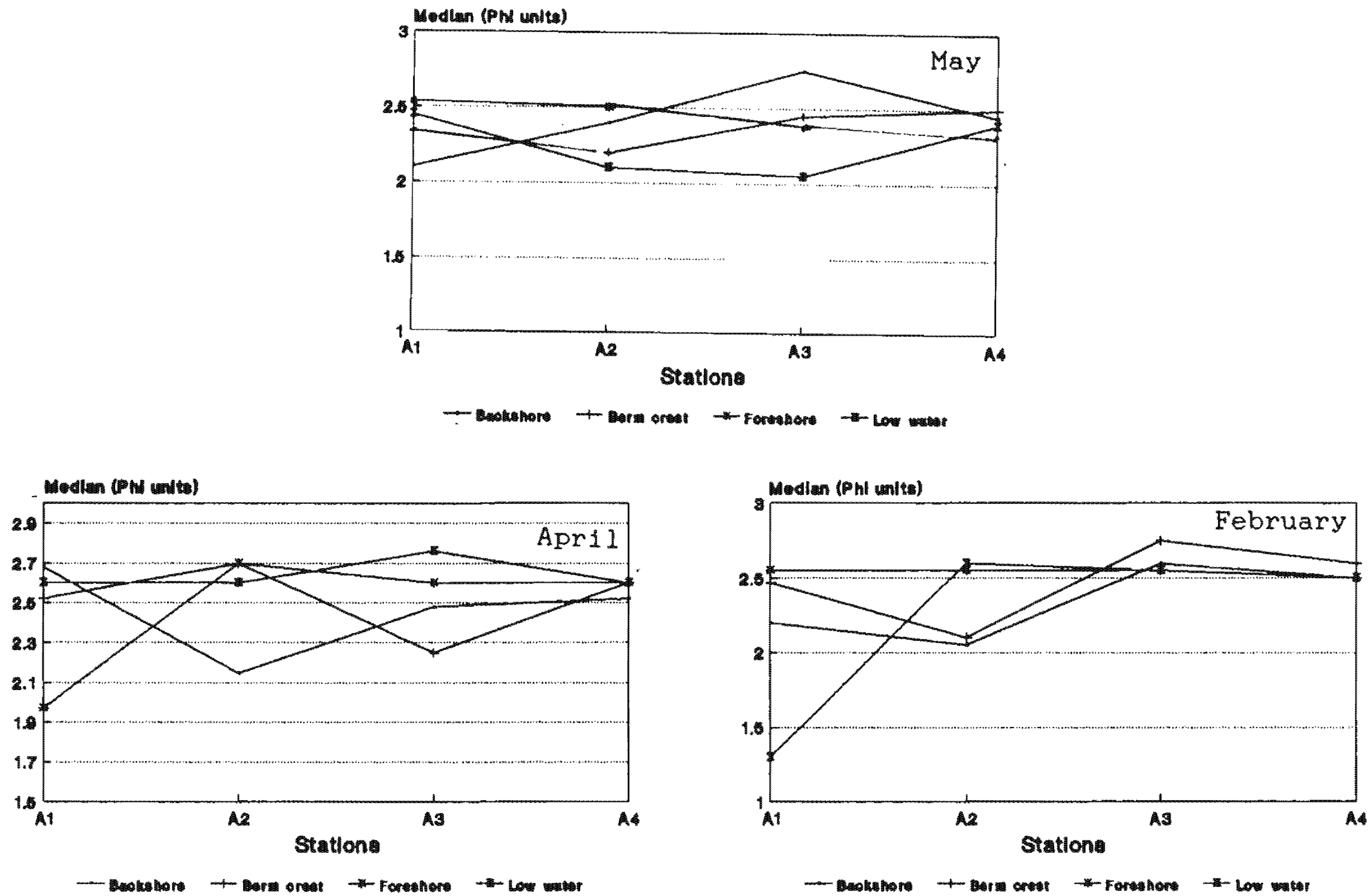


Fig. 23a. Median grain size variation during February, April and May 1994.

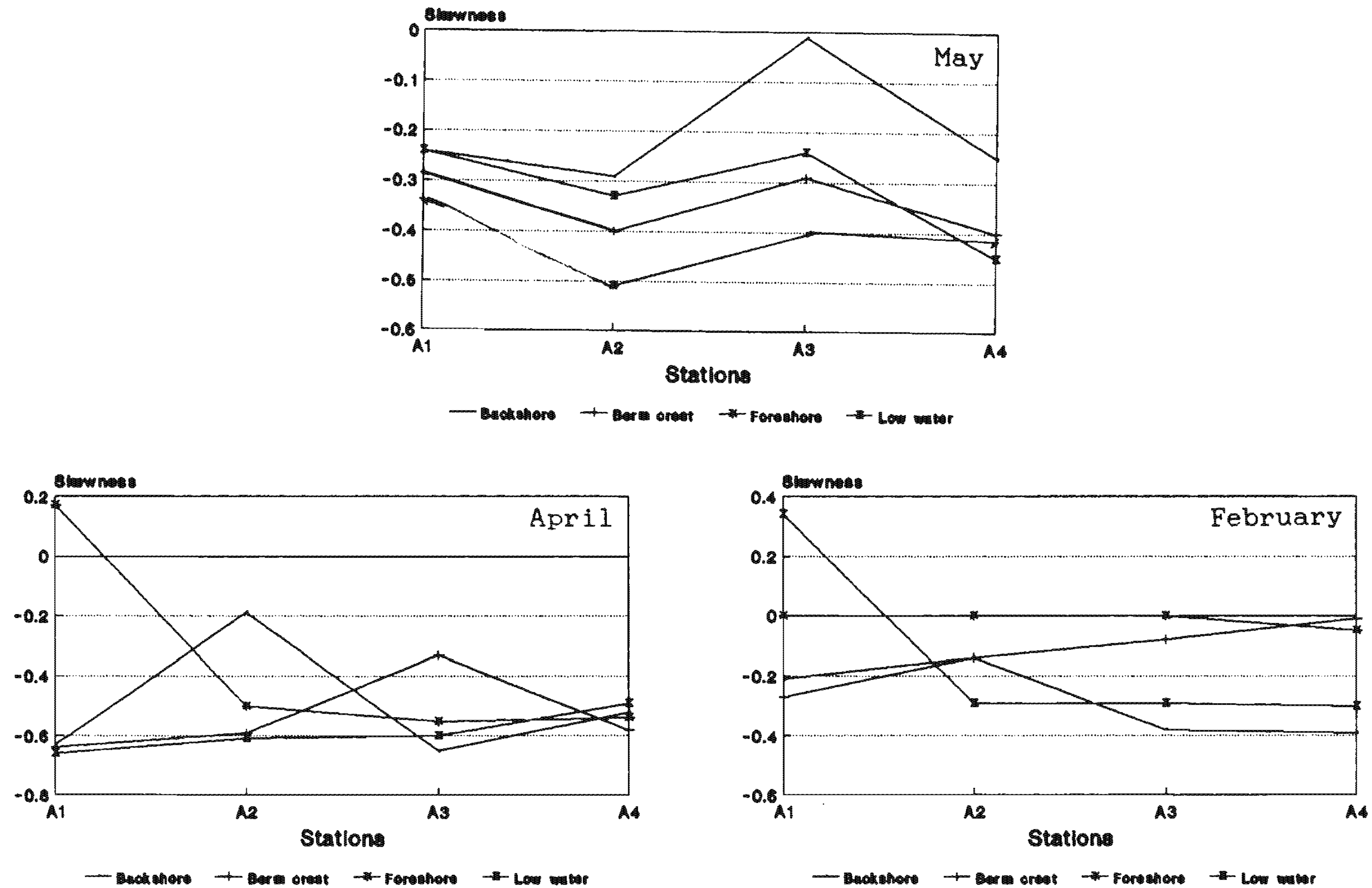


Fig. 23b. Skewness of the beach samples collected in February. April and May 1994.

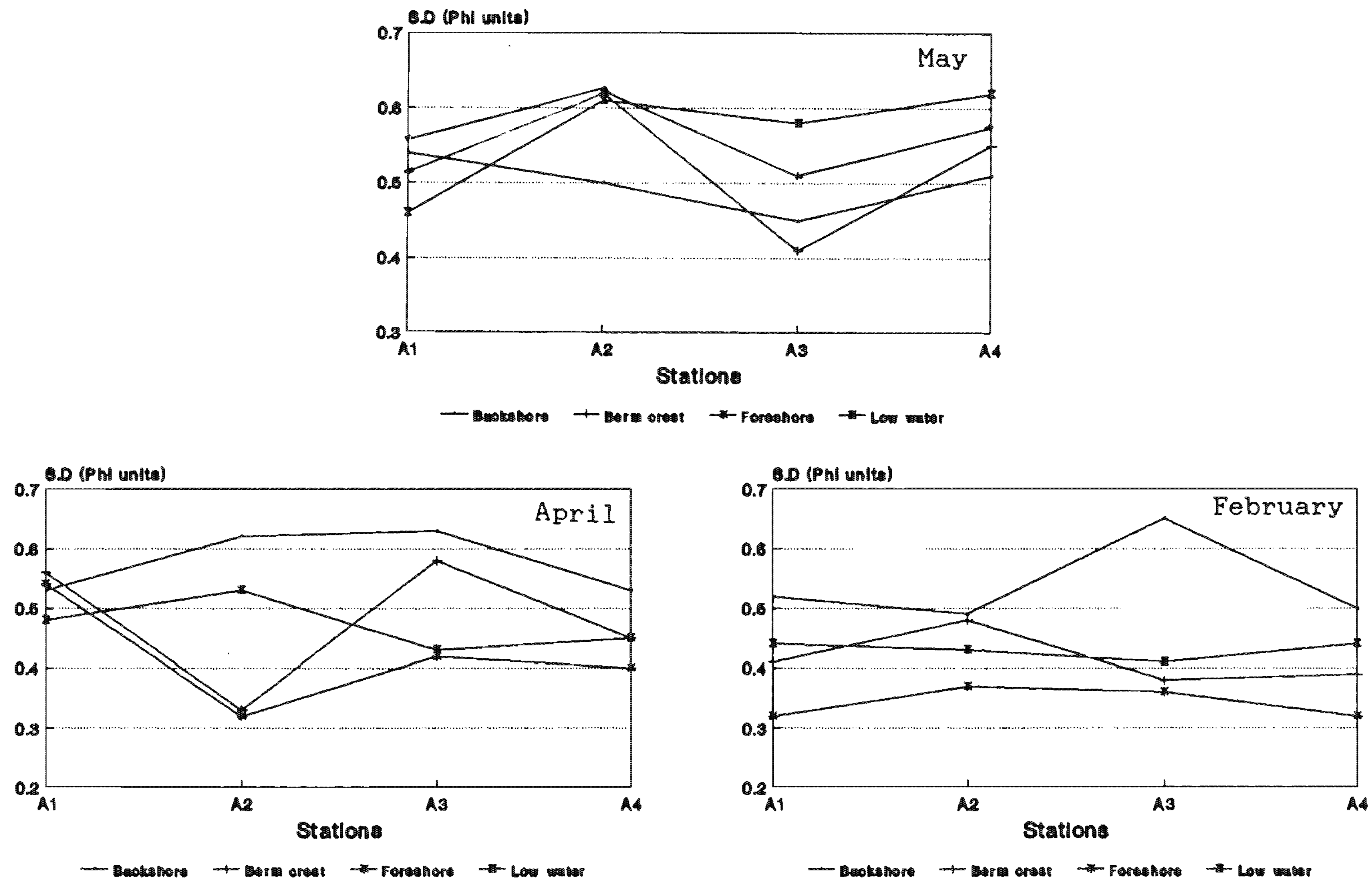


Fig. 24. Sorting coefficient of the beach samples collected in February, April and May 1994.

Similarly during February 1994, the median grain size falls in the range (2.10-2.55Ø) with the exception of higher median size (1.3Ø) at low water for station A1. More finer particles were observed at station A3 and A4 from backshore to low water mark during February and moderately coarser fractions on the southern side, stations A1 and A2. The measure of deviation of the grain size from the mean grain size was observed to be varying from 0.32 - 0.52Ø and the highest sorting coefficient (0.65Ø) was observed at backshore of station A3 on the north bank of the inlet. A negatively coarse skewed, well sorted sediment distribution was observed at the backshore, berm crest and the low water mark of all the stations with the exception for the foreshore sediment at station A1 where a positive very fine skewed sediment was observed. An interesting feature regarding the sediment distribution at the foreshore of all the stations on south side and also at station A3, on the north bank of the inlet was that a near symmetrical distribution was noticeable during February, 1994. The presence of nearly symmetrical skewed samples at the foreshore of stations A1, A2 and A3 indicates an equal proportion of different modes.

Studies in May 1994 indicated that the median grain size varied in the range 2.05 -2.75Ø and moderately well sorted to well sorted sediment were present with negatively coarse skewed sediment distribution. Well sorted sediment distribution was observed at station A3 and moderately well sorted distribution at station A4. The negatively coarse skewed sediment distribution indicates the erosional tendency of the beach as suggested earlier and the value of the kurtosis which lies always greater than unity at all the stations across the beach show greater fluctuations in the velocity of the depositing medium as suggested by Verma and Prasad (1981) and Padmalal (1992).

J) Weight Percentage Distribution of Grain Size

The most abundant grain size in a sediment sample can readily be determined in the field from the analysis of modes; this helps to deduce the information on the size characteristics and also to understand the gross depositional trends in a large sediment body. Figures 25 a, b & c, 26 a, b, c & d, 27 a, b, c & d and 28 a, b, c & d give the histogram of the grain size distribution during different months of observation and the results are discussed hereunder.

Observation during December 1993 indicated that at station A1, the backshore sample is coarser than low water mark sample and the former exhibits a bimodal distribution; in the later sample, a unimodal distribution was observed, but both the samples contain significant quantities of coarser fractions (figure 25a). Eventhough the sediment pattern at the low water mark is unimodal, a significant quantity of coarser fraction was present and the samples are hence identical in nature. This may be due to the marginal width of the bar during the initial development of the beach in postmonsoon period. Similarly, at station A2 also (figure 25b), the backshore sample was coarser than the low water

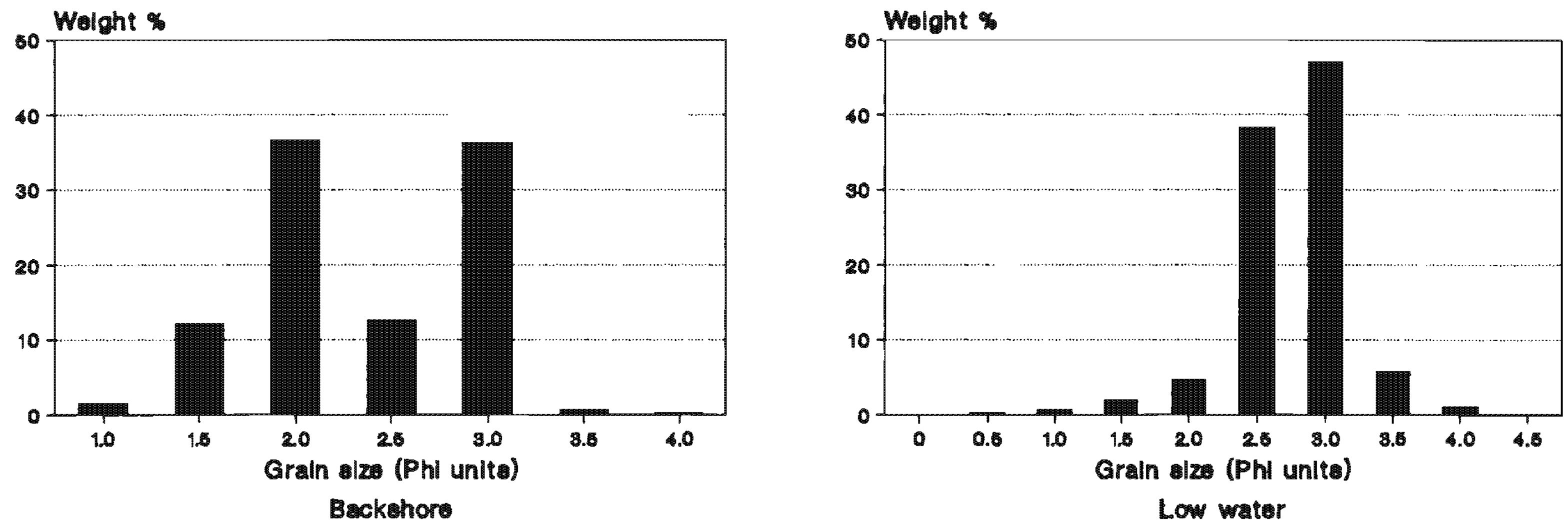


Fig. 25a. Grain size distribution (wt%) at Station A1- December 1993

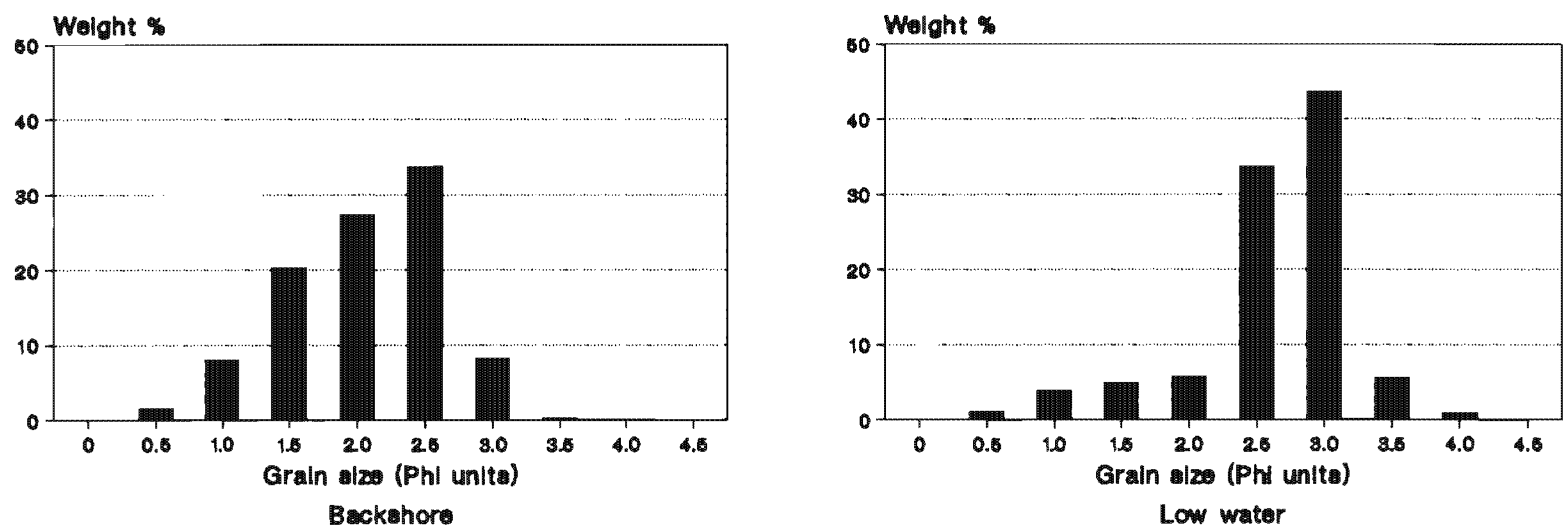
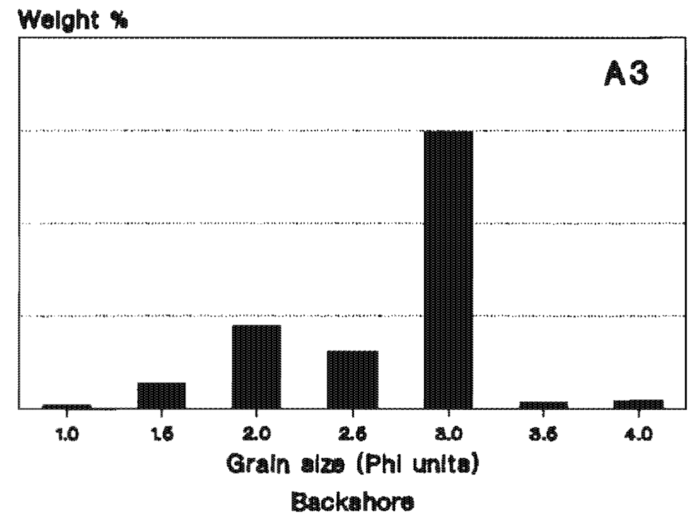


Fig. 25b. Grain size distribution (wt%) at Stn.A2 - December 1993

sample. In both the samples, significant contribution was from the coarser fractions as observed from the figure 25b. But at station A3, (figure 25c), all the samples showed modes in 3Ø and the backshore sample was finer with significant contribution from the coarser fraction. Foreshore samples also showed the same features, but coarser and finer fractions were present almost in same quantities. The low water mark sample was mostly composed of finer fractions unlike the general trend in the grain size distribution with finer fractions at the backshore compared to the low water for well developed beaches and all the samples being unimodal in nature.

In April 1993, at station A1, the grain size increased from backshore to foreshore; but low water mark sample was finer than foreshore but coarser than that of backshore and berm crest samples (figure 26a). All are unimodal in nature and the coarser grains were observed at foreshore. All are unimodal with mode at 3.0Ø except at the foreshore, where coarser fractions were more prevalent than fine fraction. Hence, except at foreshore, all samples showed general features of a well developed beach.

At station A2, the grain size turned finer towards foreshore but again became coarser at the low water mark which was comparatively finer than the backshore sample (figure 26b). This trend is in contrast with the general features of a well developed beach where coarser fractions are normally found at low water mark. At station A3, observations indicated the presence of coarser fractions at



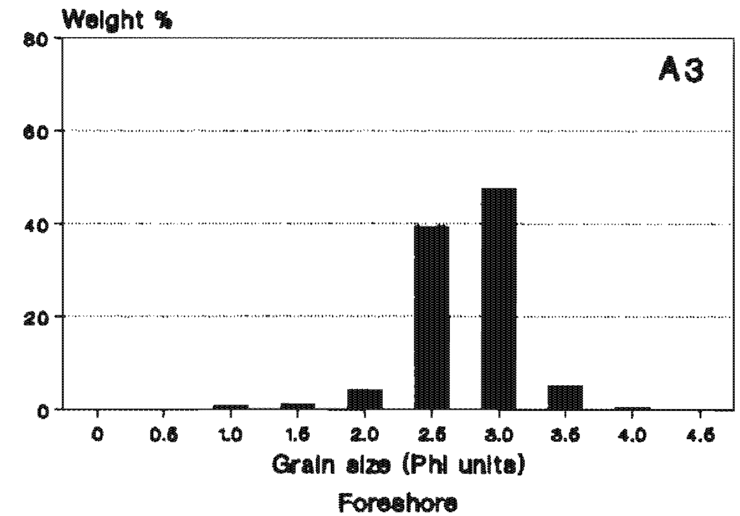
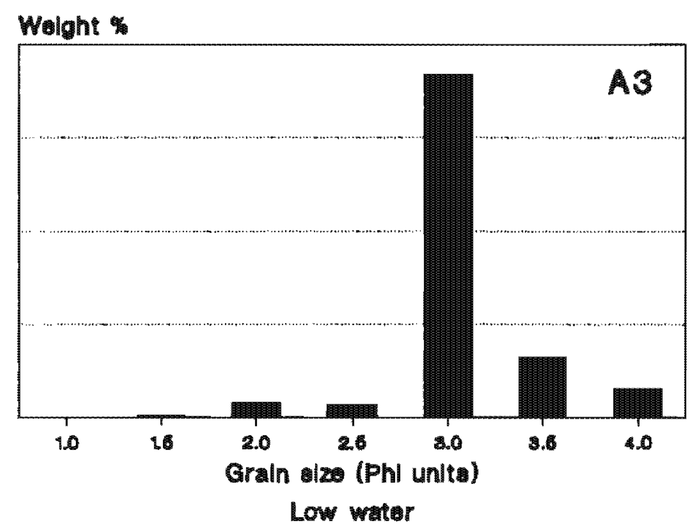
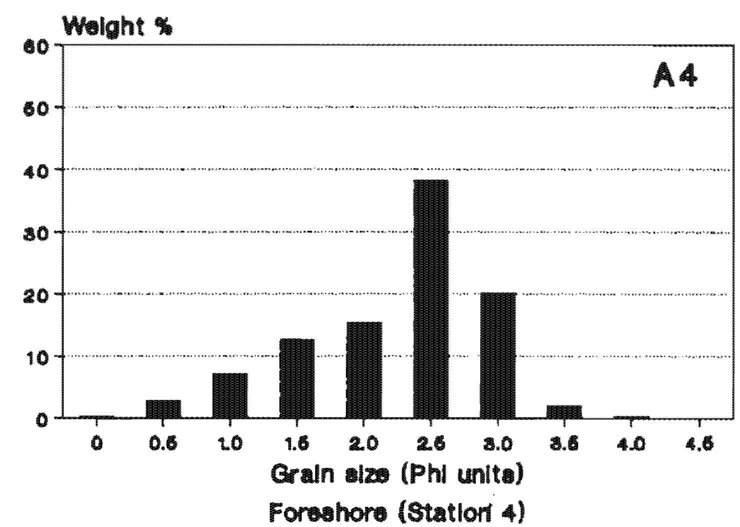


Fig. 25c. Grain size distribution (wt%) at Station A3-A4 December 1993





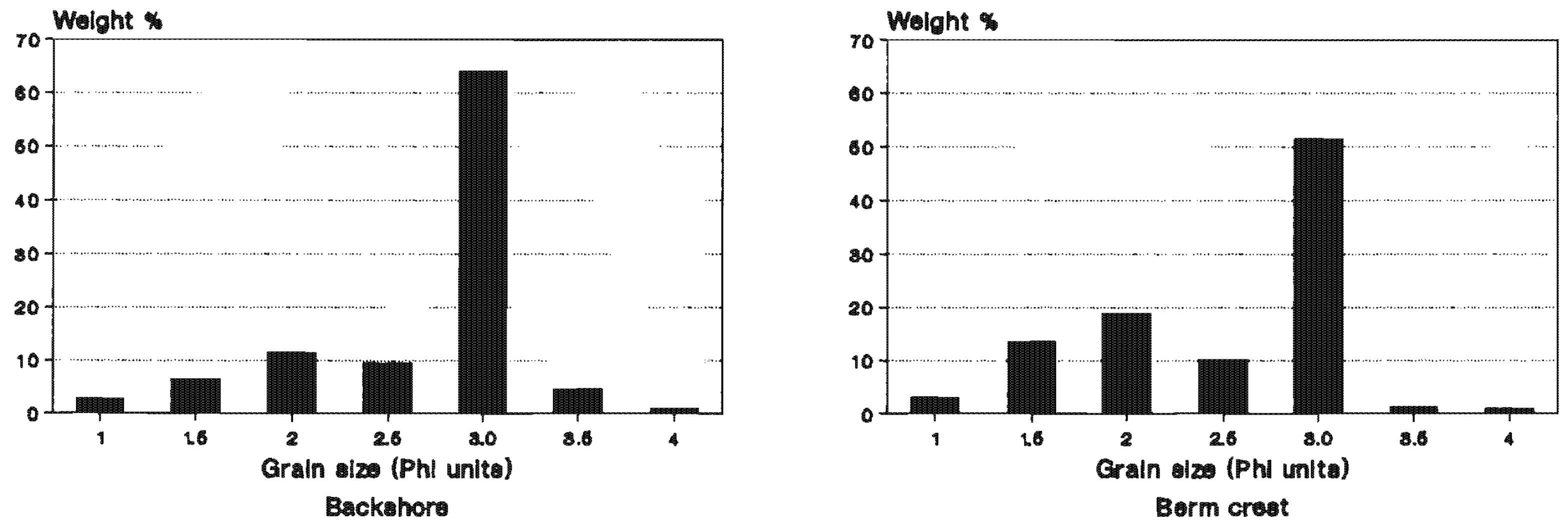
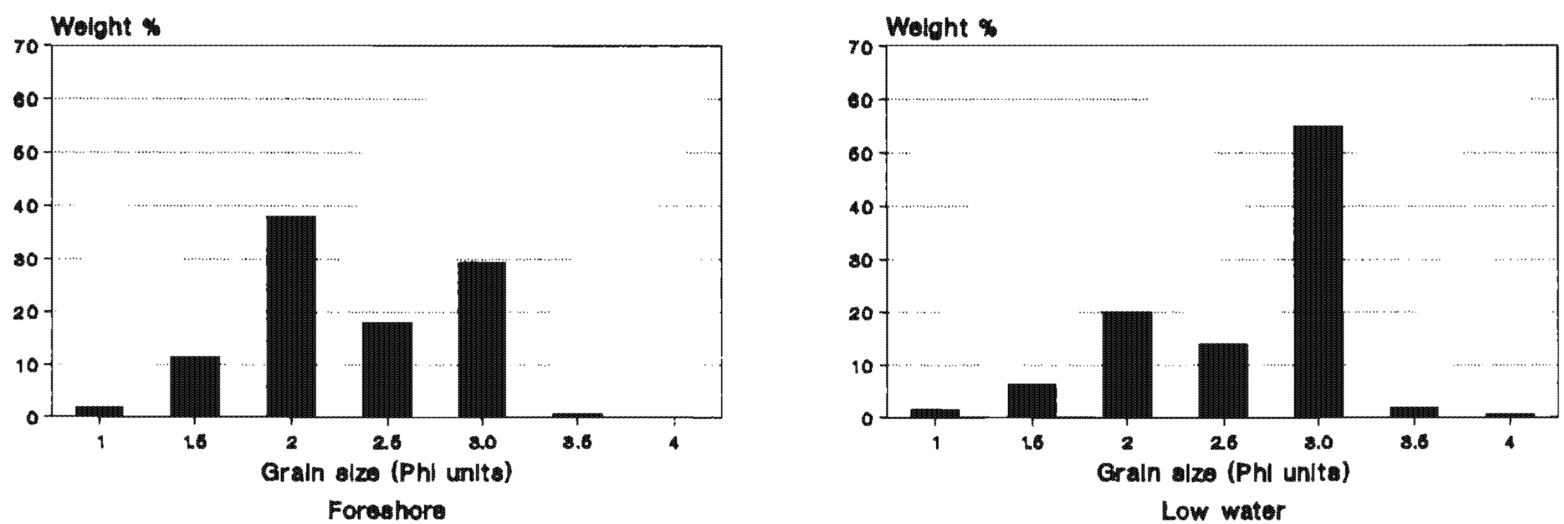


Fig. 26a. Grain size distribution (wt%) at Station A1 - April 1993



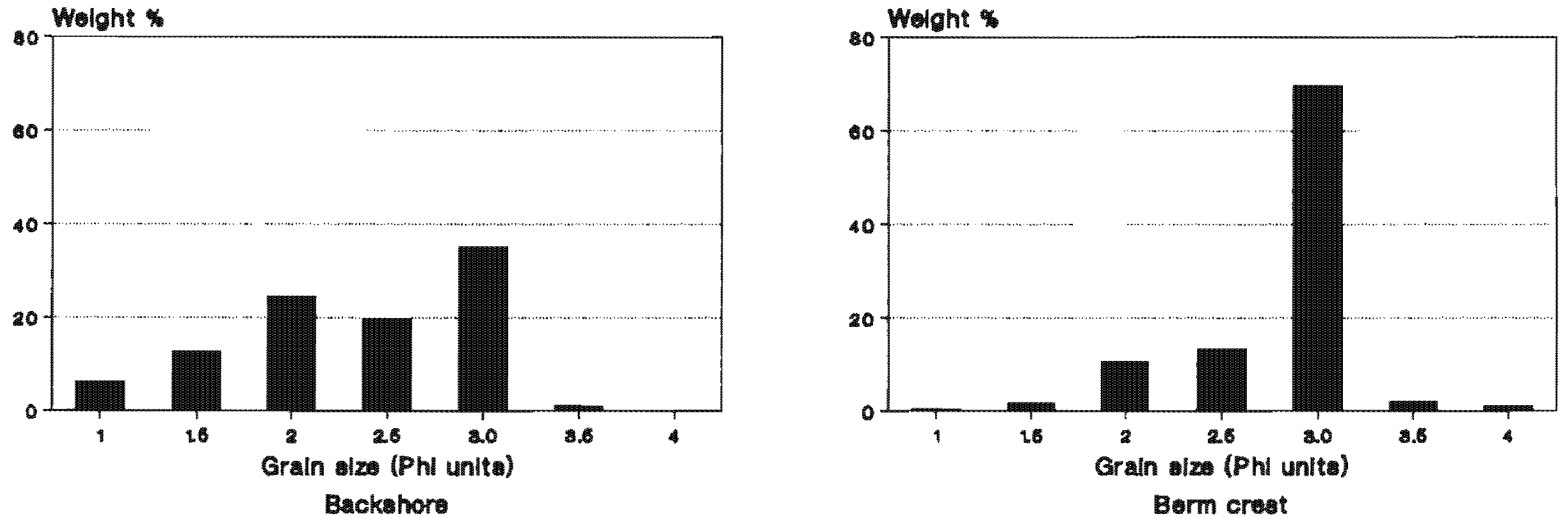
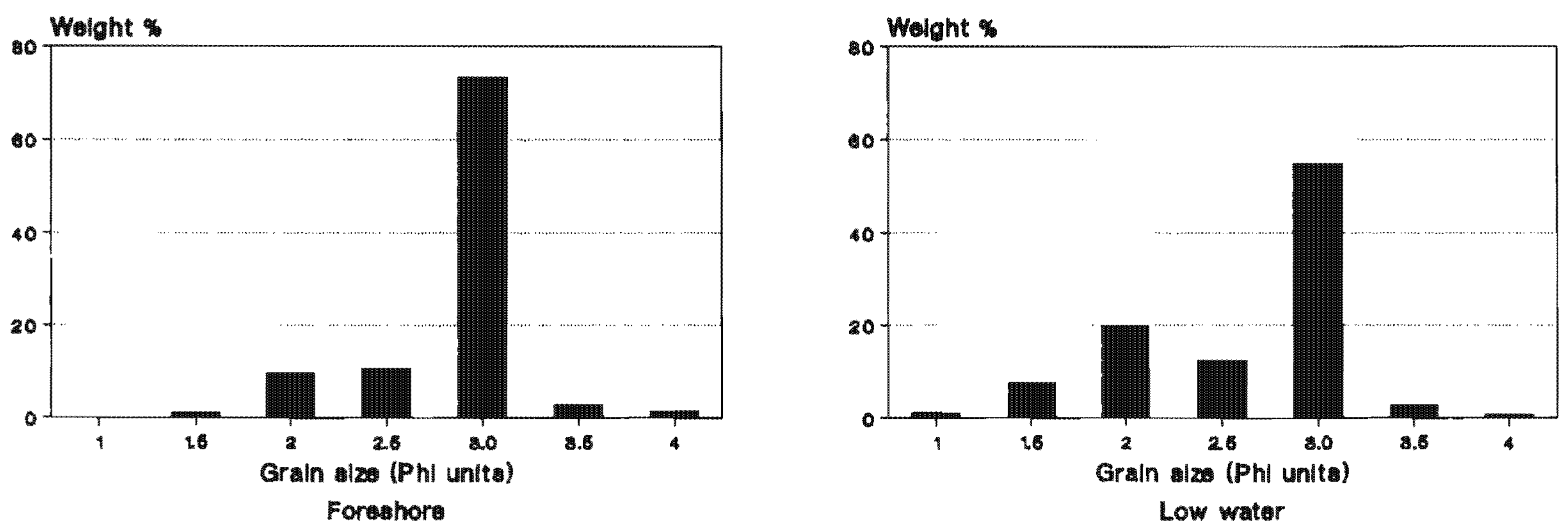


Fig. 26b. Grain size distribution (wt%) at Station A2 - April 1993



the backshore and as well as at the berm crest (figure 26c). Whereas the percentage composition of the finer fractions was more at the foreshore and also at the low water mark, in unimodal nature the distribution was at 3.0Ø. But at backshore and bermcrest though the mode was 3.0Ø, the coarser fractions are more prevalent than the finer fractions. At station A4, mode of all samples were 3Ø and a fine grained trend was observed from backshore to foreshore except at low water mark, where the grain size was coarser than the foreshore and berm crest samples but finer than backshore sample (figure 26d). This also indicates the general trend in grain size distribution of a well developed beach.

The last survey in this series during February 1994 helped to note the following features. At station A1, all samples were unimodal except at berm crest. Backshore sample mode is at 2.5Ø whereas at the berm crest, the two modes were 3.0Ø and 2.5Ø, followed by foreshore at 3Ø and for low water mark it was 1.5Ø (figure 27a). Hence a coarsening trend which partly reflects the general trend of a full developed beach was indicated at the backshore and low water mark. The berm crest and foreshore samples show a fining trend.

The backshore and berm crest samples of station A2 (figure 27b) showed modes at 2.5Ø, but mode of foreshore and low water mark samples were set at 3.0Ø. So samples near to the sea are finer than samples near to the bay. On the bay side, the berm crest samples were finer than backshore. Likewise, considering the samples on the seaward side, low water mark sample was finer than foreshore sample. At

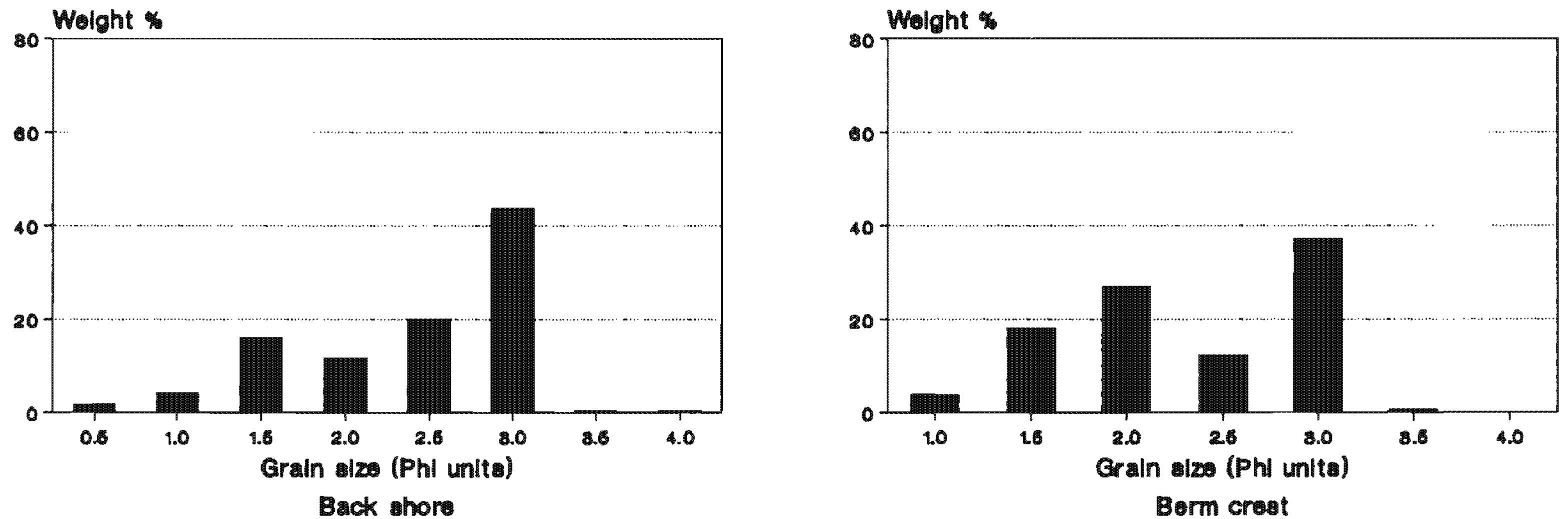
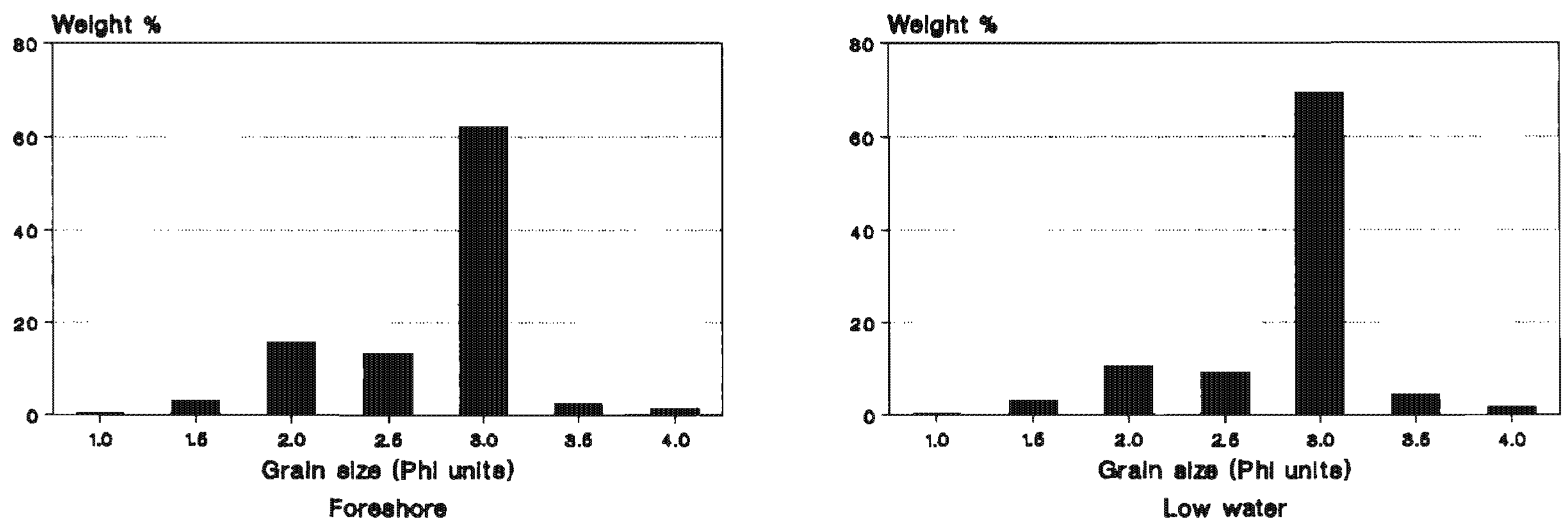


Fig. 26c. Grain size distribution (wt%) at Station A3 - April 1993



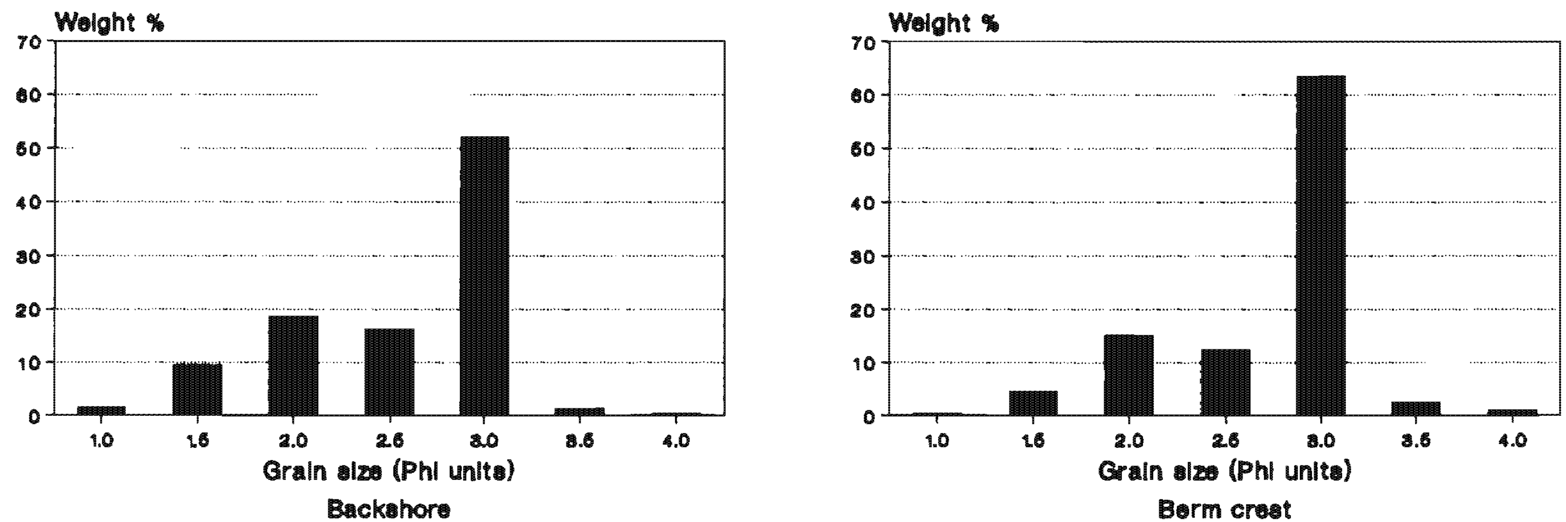
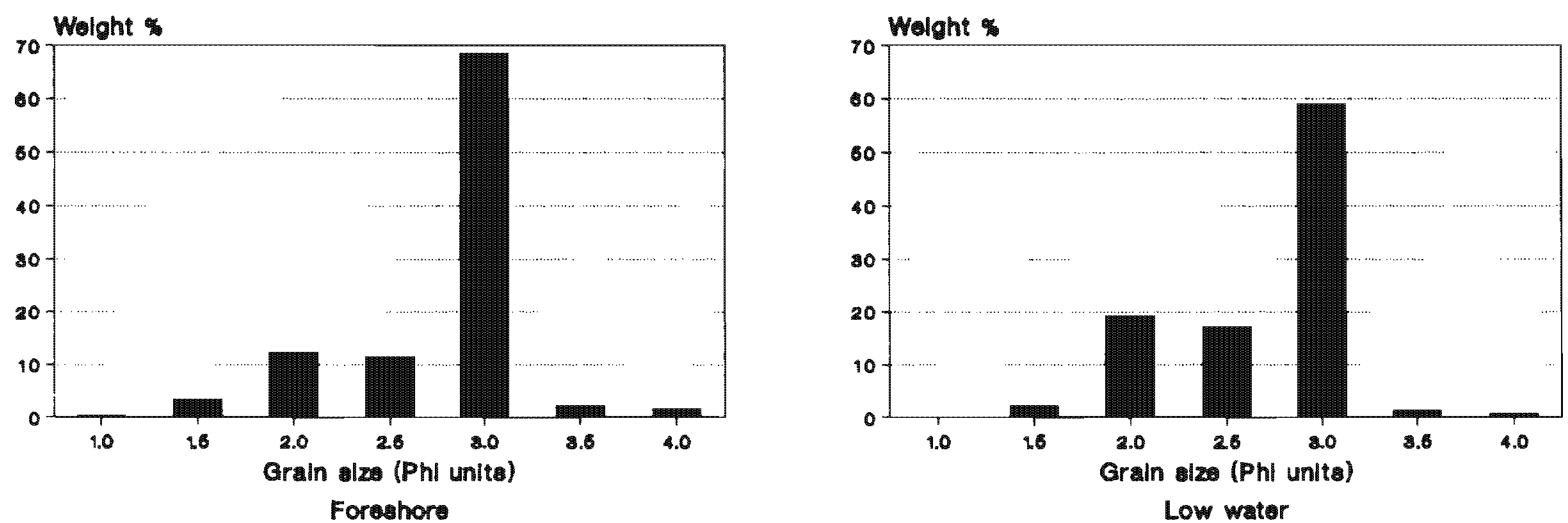


Fig. 26d. Grain size distribution (wt%) at Station A4 - April 1993



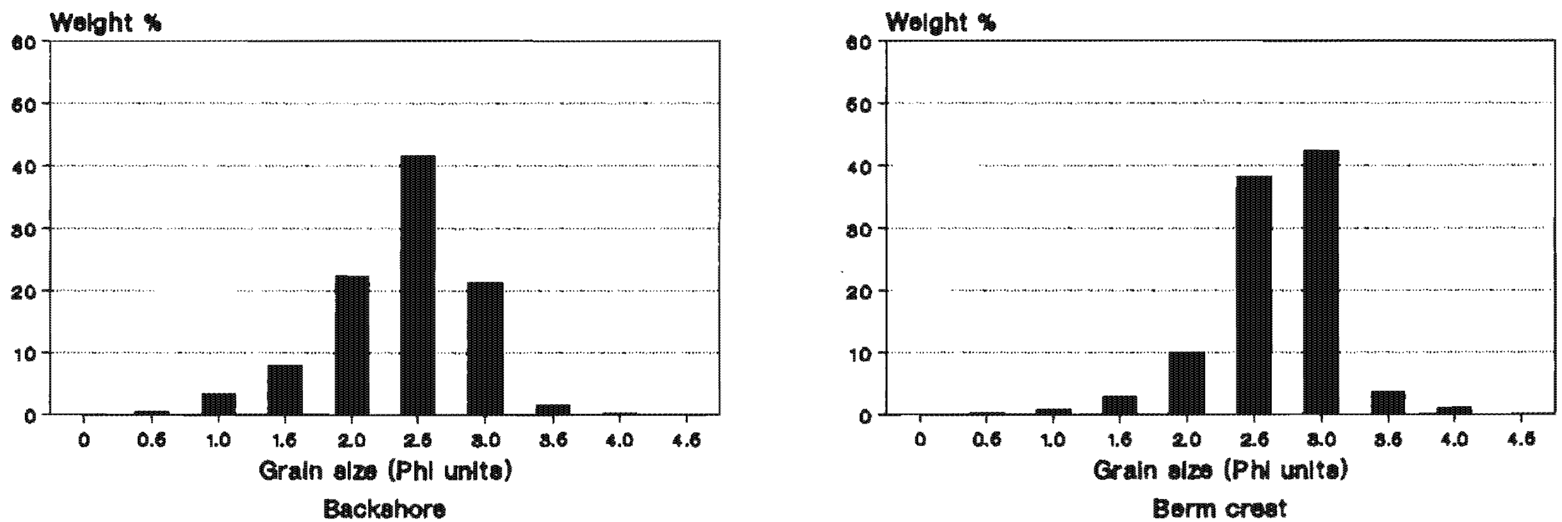
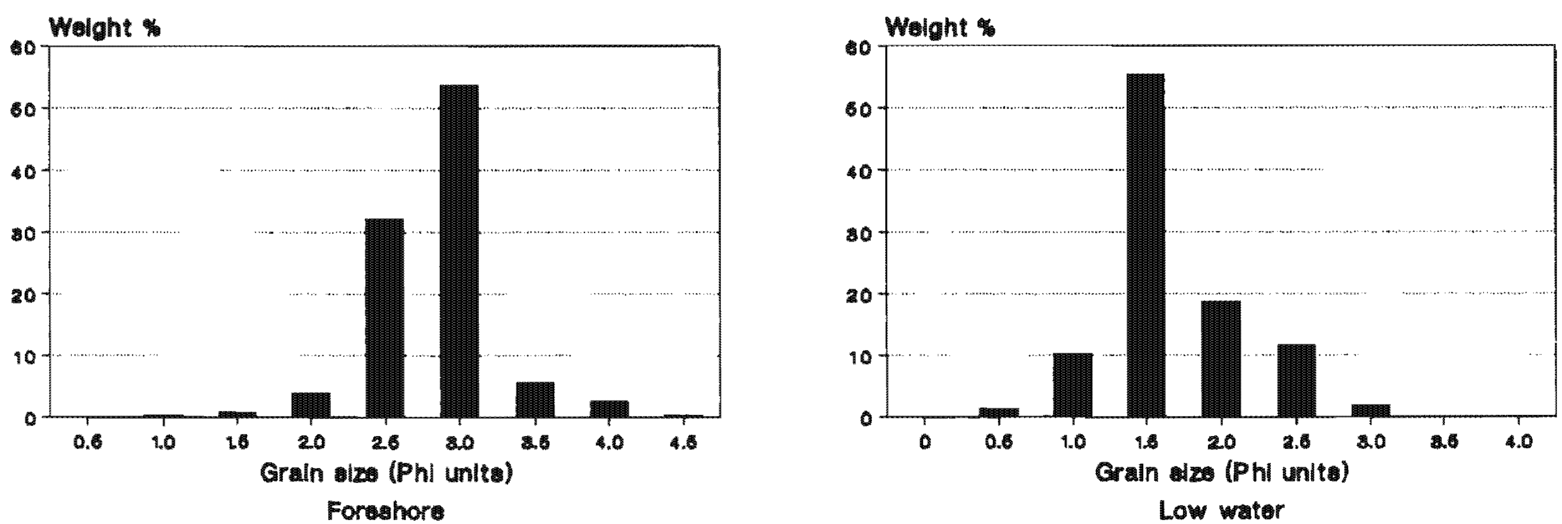


Fig. 27a. Grain size distribution (wt%) at Station A1 - February 1994



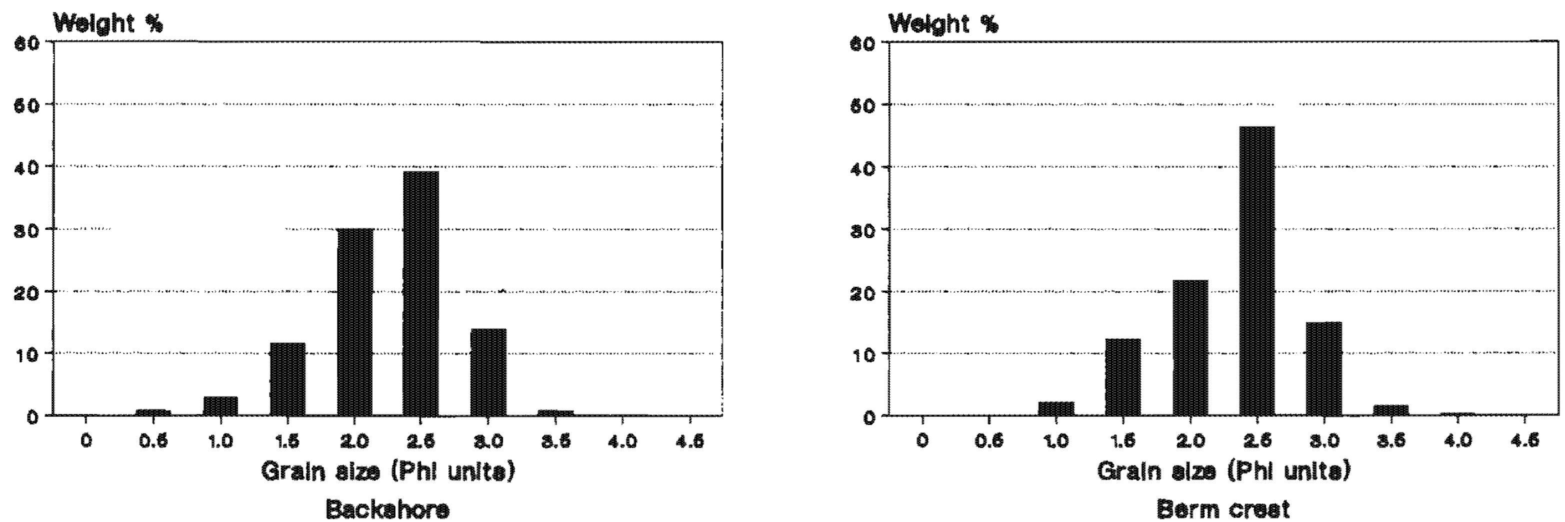
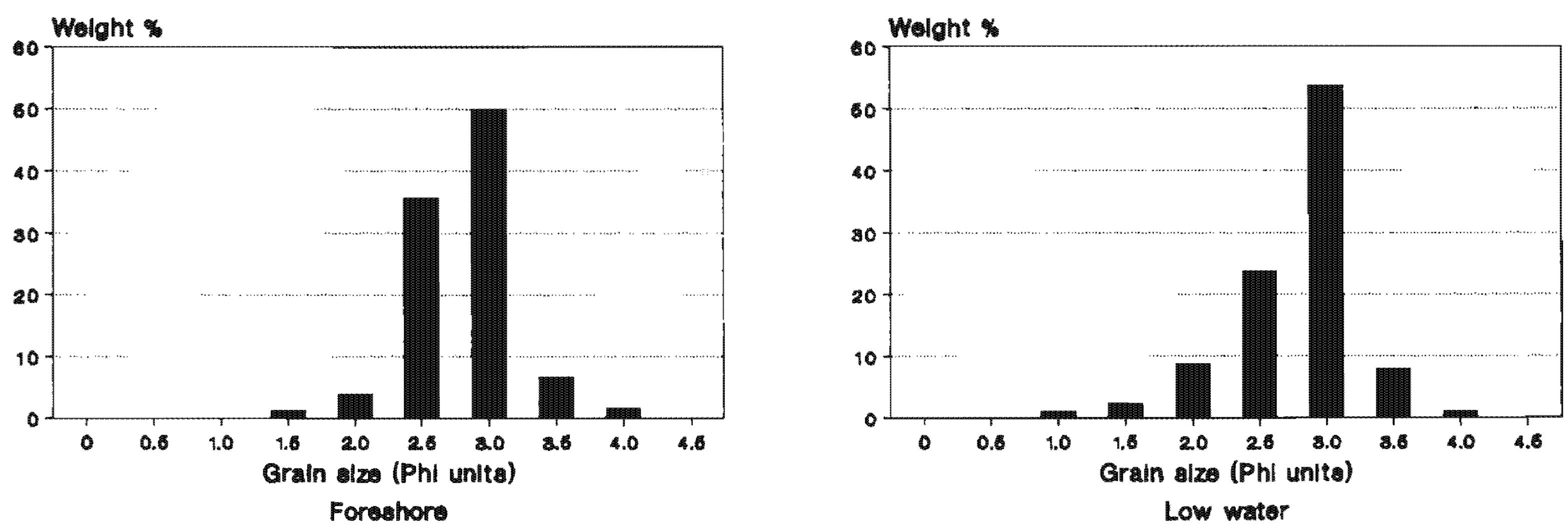


Fig. 27b. Grain size distribution (wt%) at Station A2 - February 1994



station A3, for all samples, the mode was 3.0Ø. Low water mark samples are finer than backshore sample; but finest sample was observed at berm crest (figure 27c). No general trend could be observed and to continue the study, at station A4, (figure 27d), both samples showed mode at 3.0Ø. Low water mark sample was coarser than backshore sample which follows the general trend of a beach. In backshore sample also, a significant contribution of coarser fractions were observed.

In May 1994 at station A1, unimodal distribution in grain size was observed at the backshore and the mode was at 2.5Ø whereas the foreshore sediments followed bimodal in the range 2.5Ø and 3.0Ø (figure 28a). At station A2, the grain size showed unimodal distribution at the berm crest, foreshore and low water mark except at the backshore where bimodality was observed (figure 28b). The mode value for berm crest, foreshore and low water mark arė 2.5Ø, 3.0Ø and 2.5Ø respectively. But the bimodal distribution of backshore was with modes 2.5Ø and 3.0Ø. Fine grained sediments are thus generally present at all the subenvironments except at the backshore. At station A3, unimodal distribution was noted at backshore and low water mark but a bimodal distribution was obtained at the foreshore (figure 28c). Coarser fractions were observed at the low water mark (2.5Ø) and finer fractions at the backshore (3.0Ø). However at the foreshore region the contribution of coarser fraction and fine fraction (3.0Ø) were almost the same with slight increase in coarser

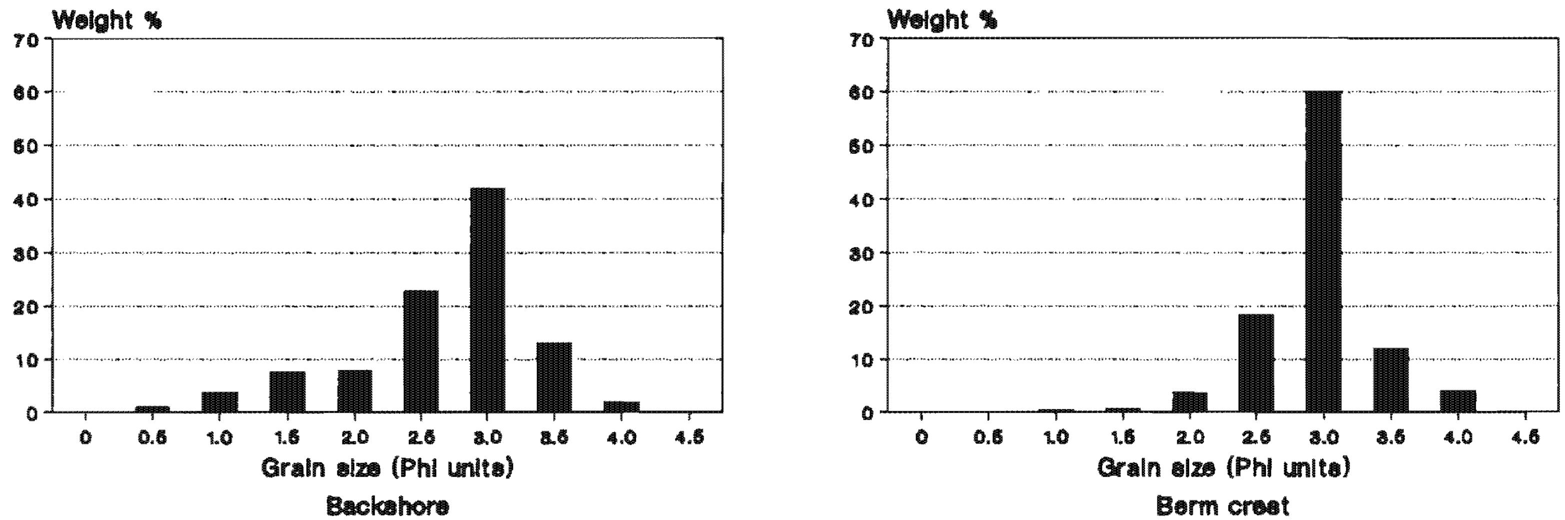
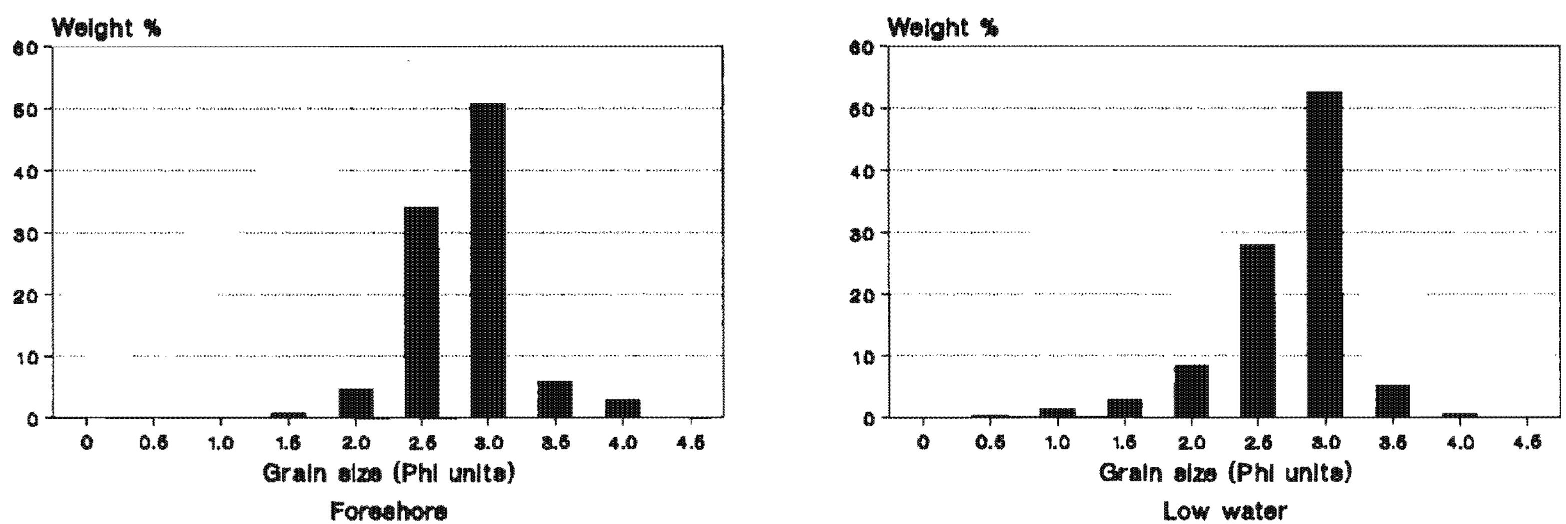


Fig. 27c. Grain size distribution (wt%) at Station A3 - February 1994



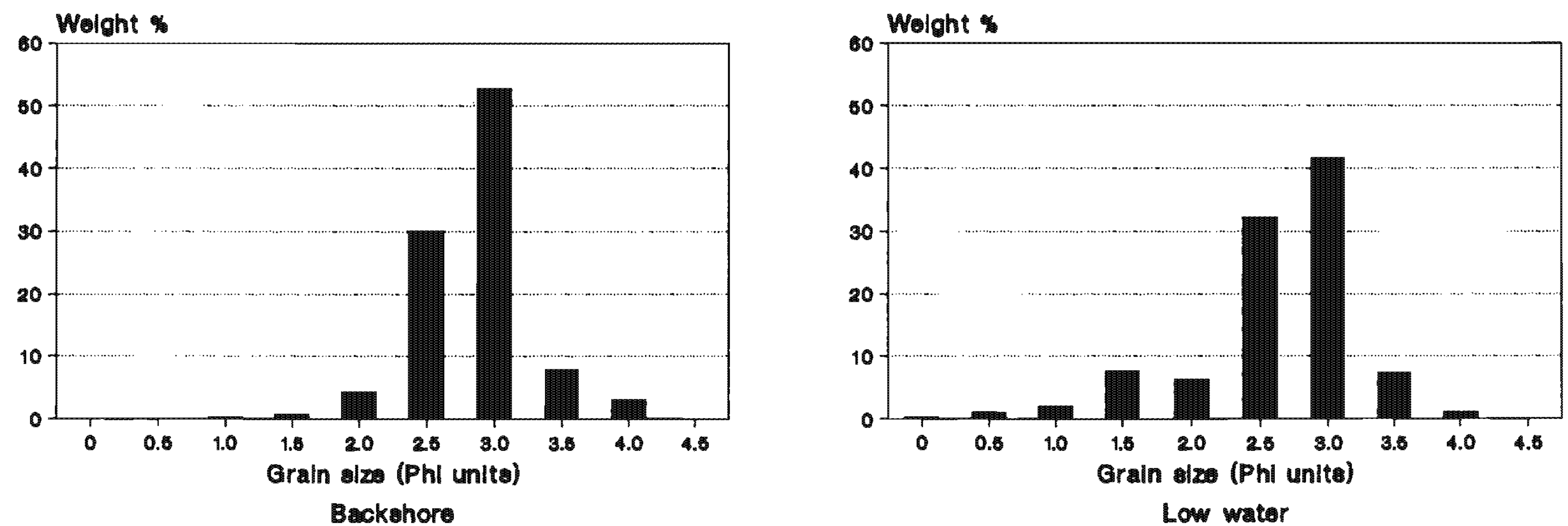


Fig. 27d. Grain size distribution (wt%) at Station A4 - February 1994

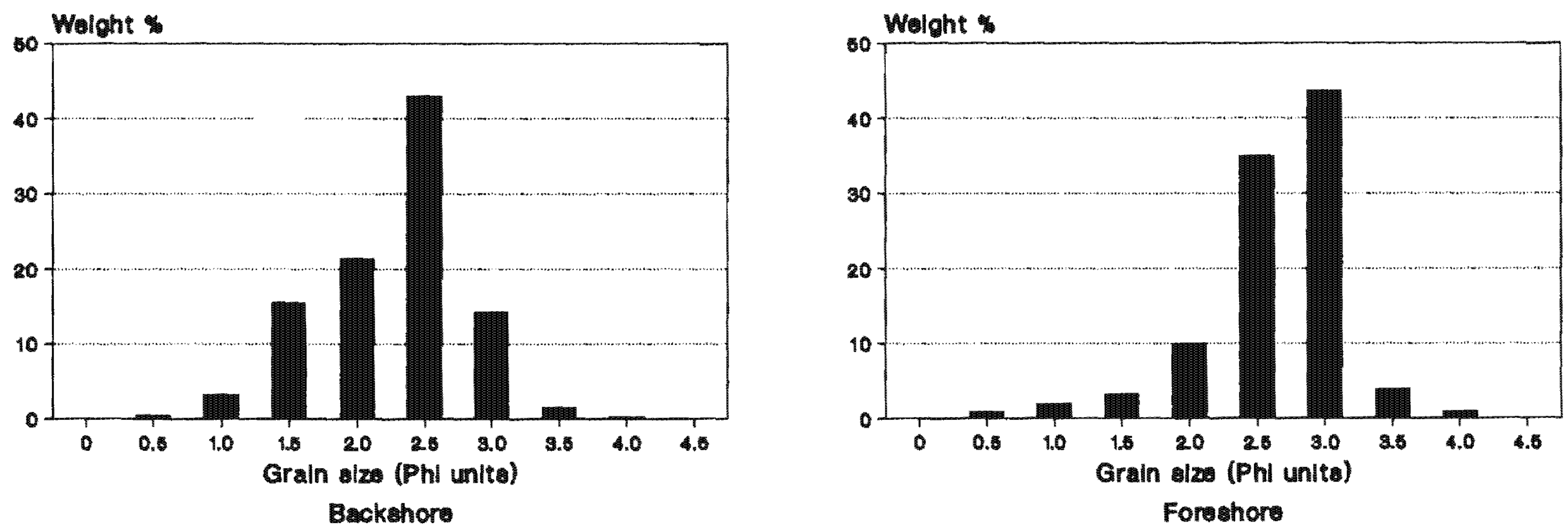


Fig. 28a. Grain size distribution (wt%) at Station A1 - May 1994

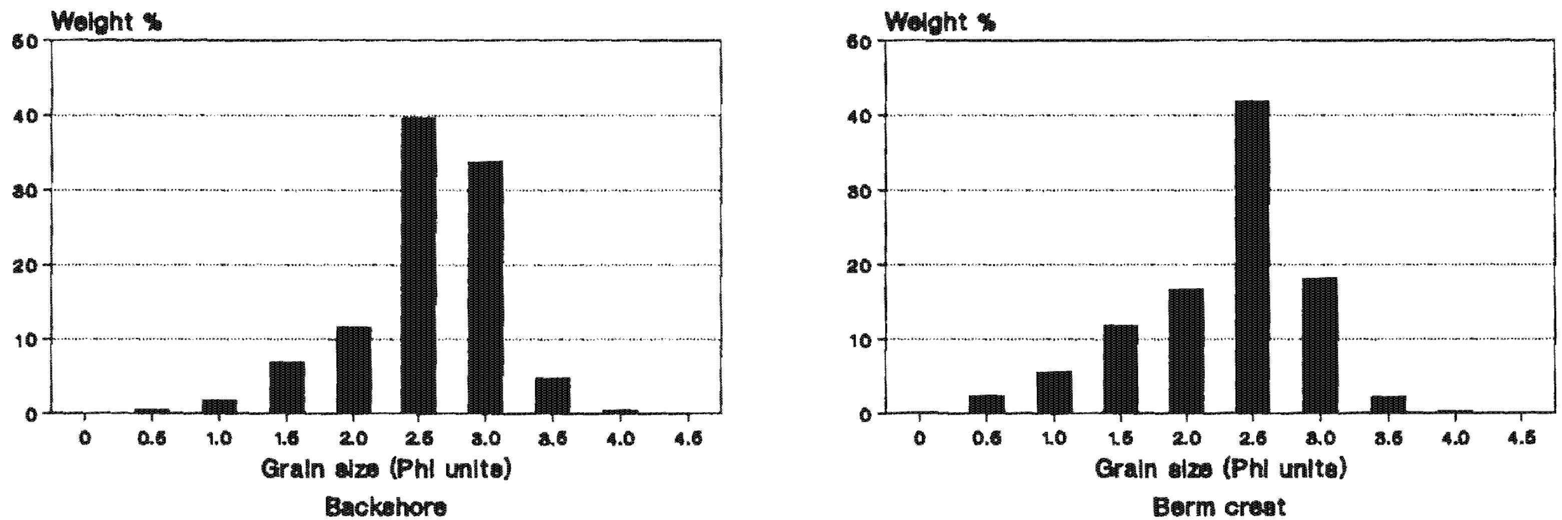
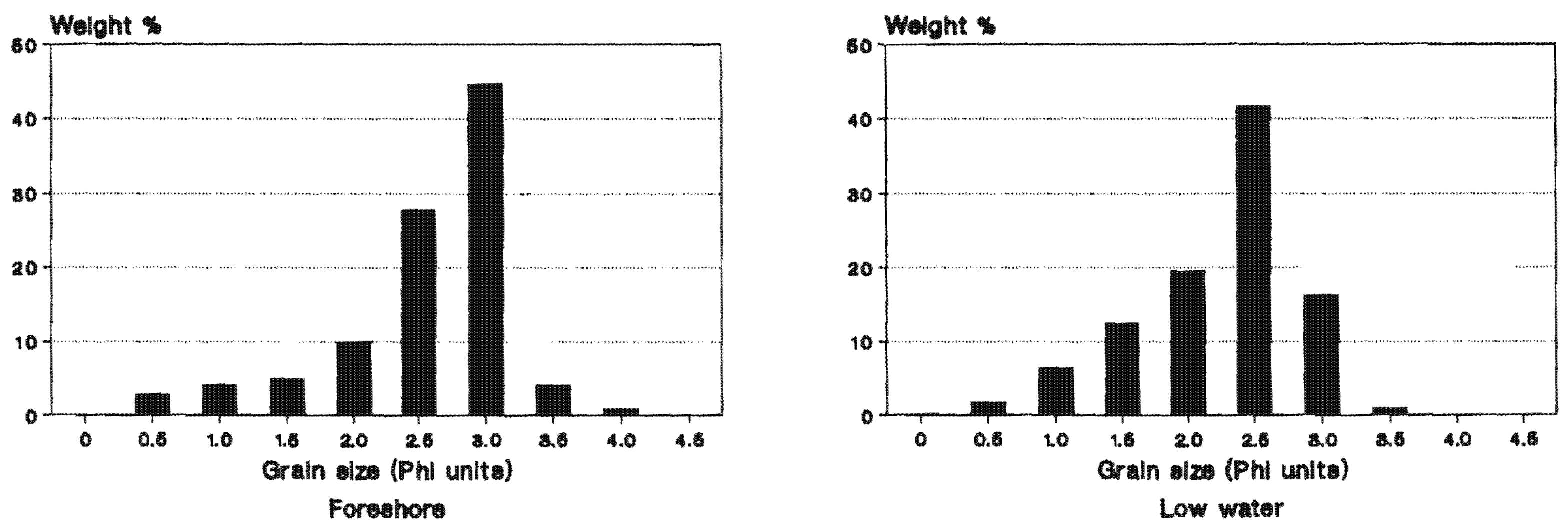


Fig. 28b. Grain size distribution (wt%) at Station A2- May 1994



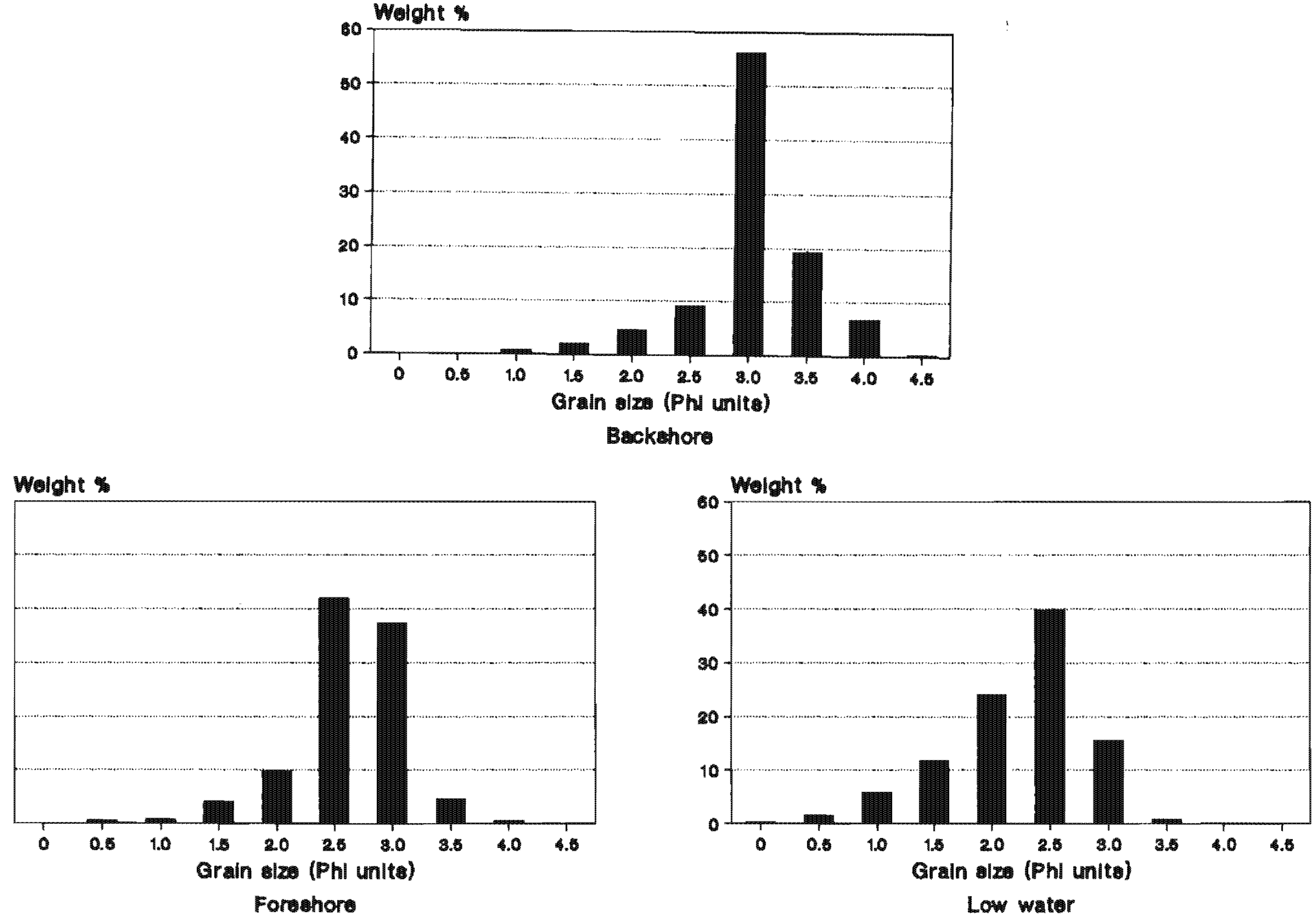


Fig. 28c. Grain size distribution (wt%) at Station A3 -May 1994

fractions (mode at 2.5Ø). At station A4, on the northwest side (figure 28d), bimodality was present in the distribution of grain size at the backshore with modes at 2.5Ø and 3.0Ø and similarly, at the low water mark sample also this type of distribution was evidenced. But at the foreshore, the most abundant grain size was in the 3.0Ø class and the percentage composition of coarser fractions and finer fractions were almost in equal proportion. But at the backshore and low water mark the percentage of coarser fractions were higher compared to the finer fractions though a bimodality distribution was observed in the 2.5Ø and 3.0Ø class.

K) Bivariate Plots

The significance of scatter plots in understanding the interrelationship between various grain size parameters and to further elucidate any trend between them was adopted by Folk and Ward (1957), Friedman (1967), Abed (1982) and Khan (1984). Similarly a number of investigators (Shenoi, 1984; Prasannakumar, 1985; Unnikrishnan, 1987 and Harish, 1988) had used the scatter plots to study the grain size parameters of beach sands of the Kerala coast. Figures 29 and 30 give the bivariate plot between mean size (Ø) and standard deviation, mean size vs. skewness, standard deviation vs. skewness, at stations A1, A2, A3 and A4 across the barrier beach at Andhakaranazhi.

Figure 29 gives the bivariate plot between mean size (Ø) and standard deviation at stations A1, A2, A3 and A4. At station A1, on the southwest side of the inlet, all the subenvironments like backshore, berm, foreshore and low water

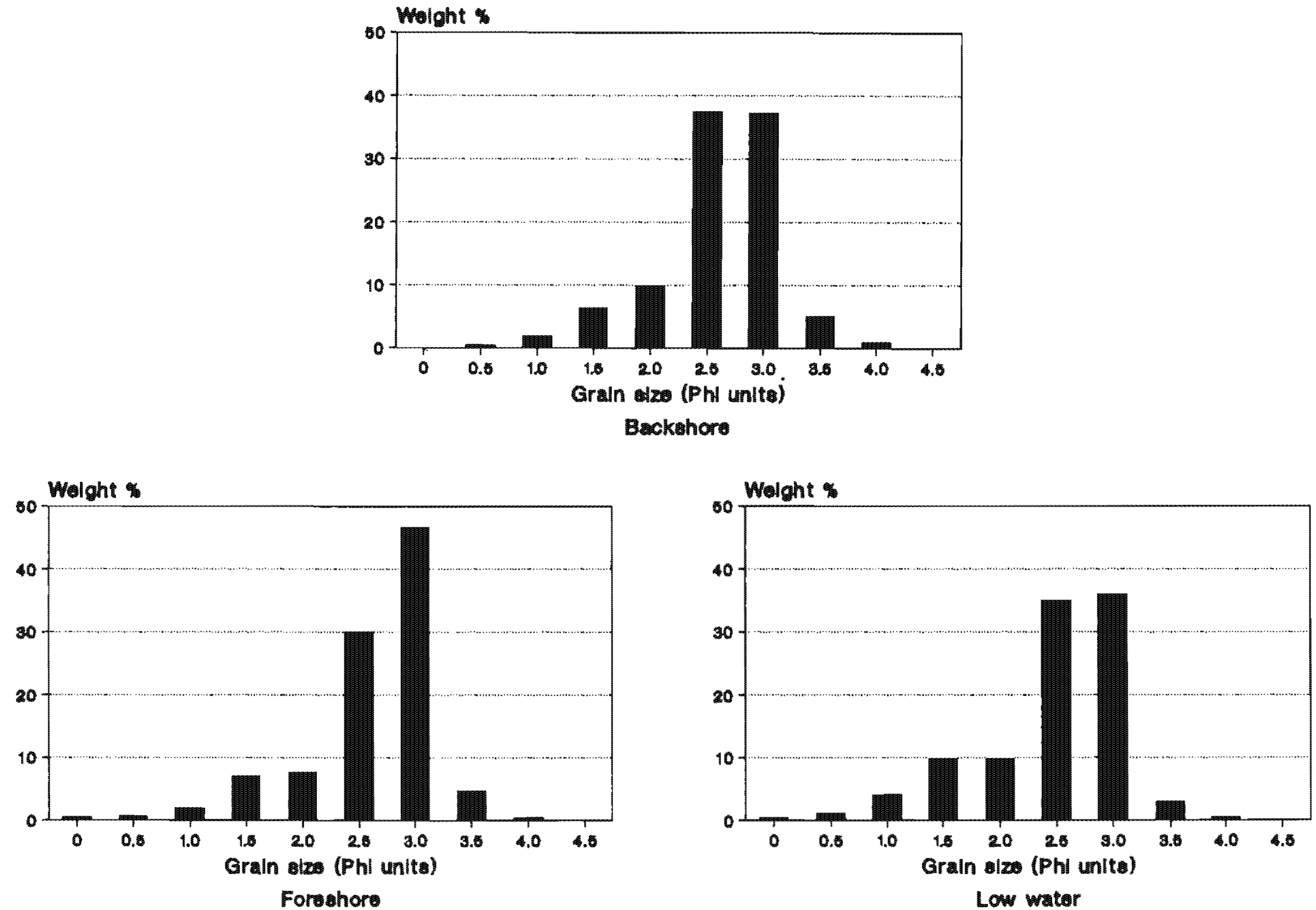


Fig. 28d. Grain size distribution (wt%) at Station A4 - May 1994

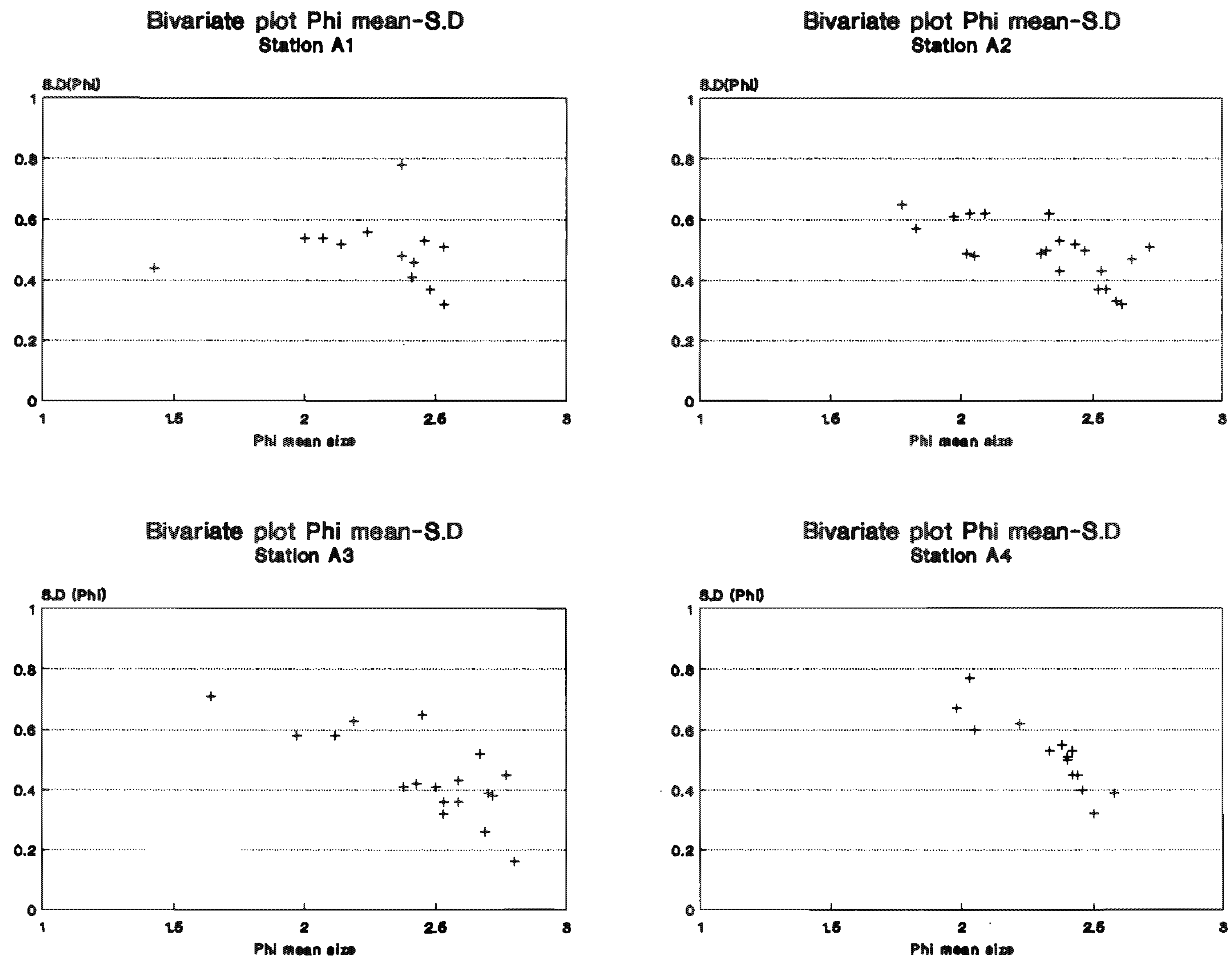


Fig. 29. Bivariate plot of phi mean size vs. S.D. at stations A1 - A4.

mark indicated that in about 93% of the samples, the phi mean size falls in the range 2.00-2.50Ø (fine sand) and are well sorted to moderately well sorted (s.d >0.40Ø <0.60Ø) while the rest are moderately sorted medium sand. For an increase in grain size the sorting tends to be less. But at station A2 and A3, on the north and south bank of the barrier of the inlet site, the grain size parameters show different features. At station A2, the mean grain size varies in the range 1.75Ø - 2.75Ø, i.e. medium to fine sand. As the phi mean grain size decreases the sorting also decreases. About 86% of the samples are fine sand and the remaining 14% are medium sands. Out of the fine sands, about 62% of the samples are well sorted and the remaining are moderately well sorted. Similarly at station A3 also, the grain size varies in the range (1.50Ø -3.00Ø), more clustered towards 2.50Ø. About 88% of the samples are fine sands and the rest of the samples are medium. The phi mean size and the standard deviation are linearly correlated; the graph shows that as the phi mean grain size decreases the sorting also decreases. About 59% of the samples are well sorted and the rest are moderately well sorted.

On the northwest side, at station A4, the phi mean size of majority of the sediment samples fall in the range 2.00-2.50Ø (fine sand); about 72% of the samples were clustering towards 2.50Ø range and are well sorted to moderately well sorted (s.d > 0.35Ø <0.60Ø) and the rest are less finer at 2.00Ø with moderately sorted. The trend between the phi mean grain size and the standard deviation indicates that at this station also the sorting becomes less with increase of mean grain size.

In general, medium to fine sands were observed on the south and north bank of the inlet however the percentage composition of fine sand is greater compared to medium sand whereas only fine sands are presented at the southwest and northwest side stations (A1 and A4) inclusive of all subenvironments.

Figure 30 shows the relationship between phi mean and skewness. At station A1, a positive skewness is observed for decrease in phi mean grain size and more negative skewness is observed for increase in phi mean grain size. About 76% of the sand samples are coarse skewed to very coarse skewed and about 15% are fine skewed and the remaining are near symmetrical in distribution. At station A2, all the samples are negatively skewed and the sediment distribution shows a tendency towards positive skewness with decrease in phi mean grain size. About 62% of the samples are very coarse skewed with only 29% in the coarse skewed distribution category and the remaining (%) shows near symmetrical distribution. Studies on samples at station A3 indicate that the sediment distribution falls in a wide scattering range with a negatively skewed distribution. A curvilinear distribution was observed in skewness vs. phi mean size while about an equal percentage of the samples (38%) are near symmetrical and very coarse skewed and out of the remaining, 25% of the samples are coarse skewed. Similarly at station A4 also, 57% of the samples show very coarse skewed distribution while of

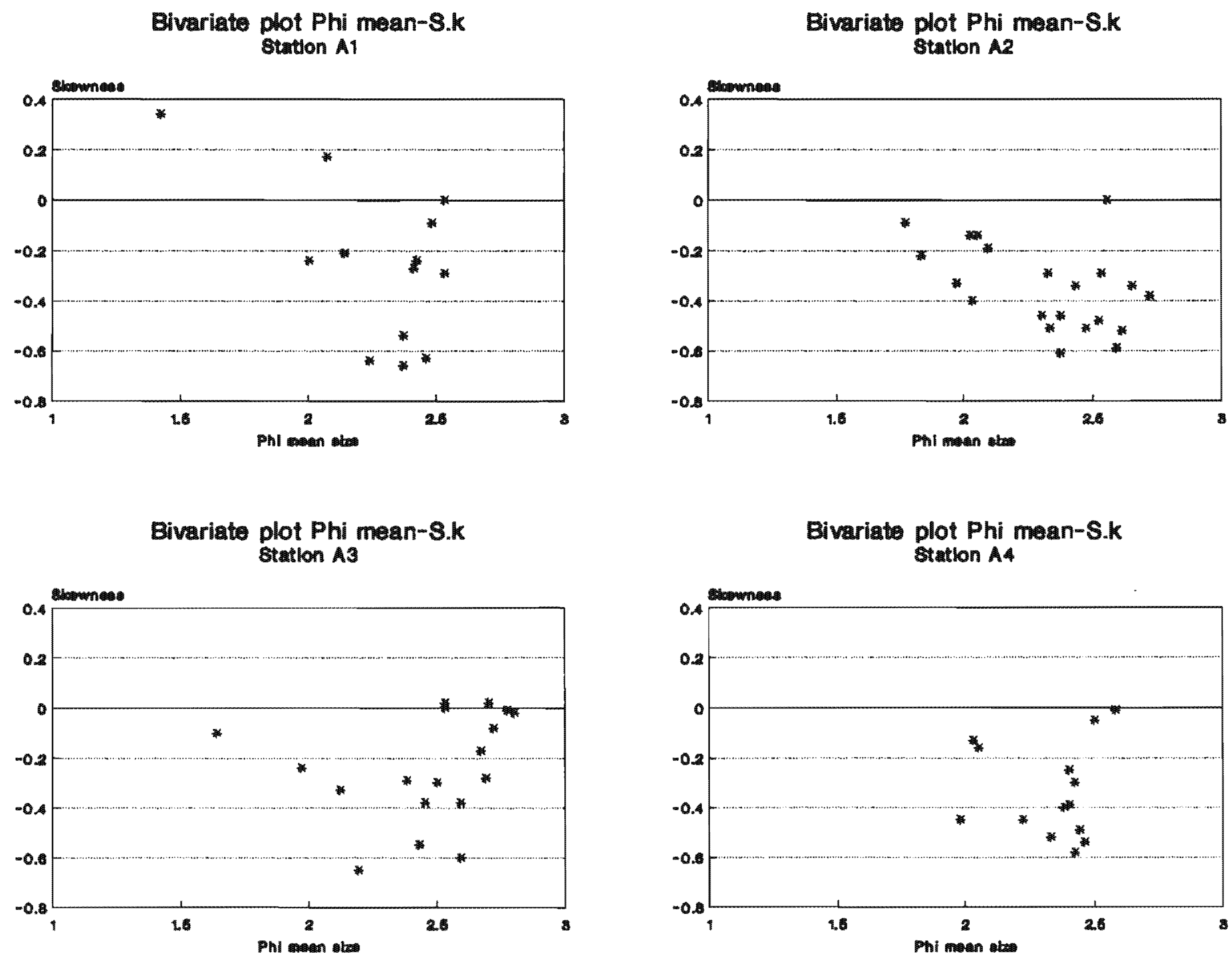
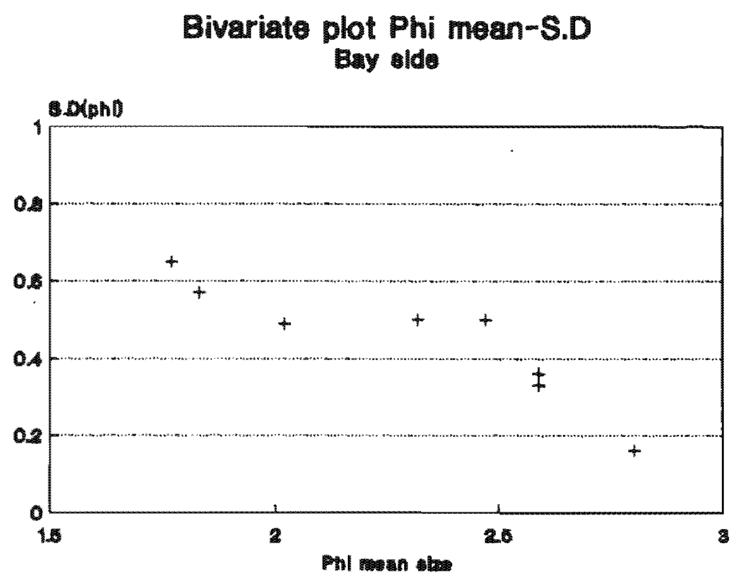


Fig. 30. Bivariate plot of phi mean size vs. skewness at stations A1 - A4.

the remaining samples, 21% are near symmetrical and coarse skewed. The skewness shows an increasing tendency from negative to positive as the phi mean size increases or decreases from a mean phi of 2.25Ø. The grain size distribution at station A4 also shows a curvilinear feature as observed similar to station A3. The grain size distribution observed at stations A3 and A4 are agreeable within a set of peculiar features like those which are nearly symmetrical and negatively skewed. Similar features of negatively skewed fine sands at Andhakaranazhi region was observed by previous investigators too (Unnikrishnan, 1987 and Prasannakumar, 1985).

Figure 31a indicates the trend between phi mean size and standard deviation at bay side of the beach. It shows an almost linear relation with decrease in phi mean size (i.e. increase in grain size) when the sorting becomes less. Higher sorting is observed for phi mean size in the range 2.50Ø - 3.00Ø (i.e., for fine sand). Most of the beach sample on the bay side falls in the range 2.25Ø - 2.85Ø (fine sand) and with well sorted to very well sorted distribution; they are negatively skewed and for samples which are finer, the figure indicates samples that are coarse skewed to very coarse skewed. The remaining samples fall in the range 1.50Ø - 2.10Ø (medium sand) with moderately well sorted sands. On the northwest side (figure 31b), about 75% of the sample fall in the range 2.45Ø - 2.75Ø and in the well to very well sorted range (s.d >0.20Ø <.55Ø) and coarse skewed for finer fractions. The remaining (%) fall in the range 1.50Ø 2.00Ø



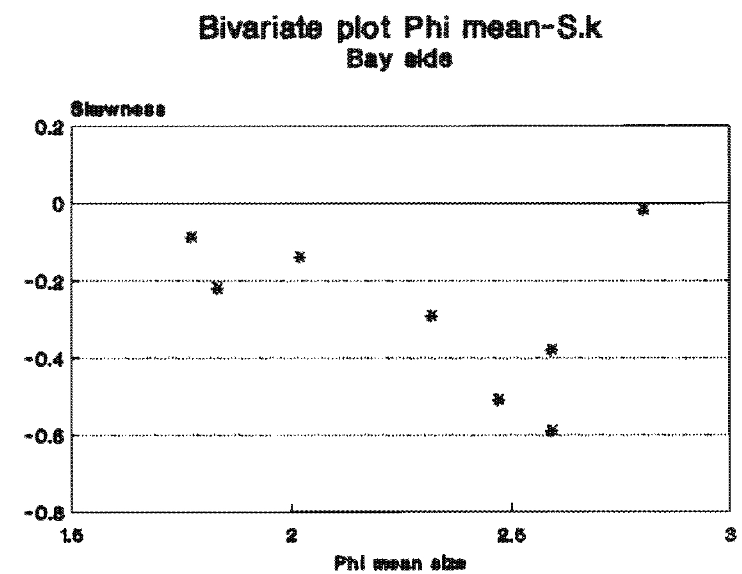


Fig.31a. Bivariate plot of phi mean size vs. S.D. at the bay side.

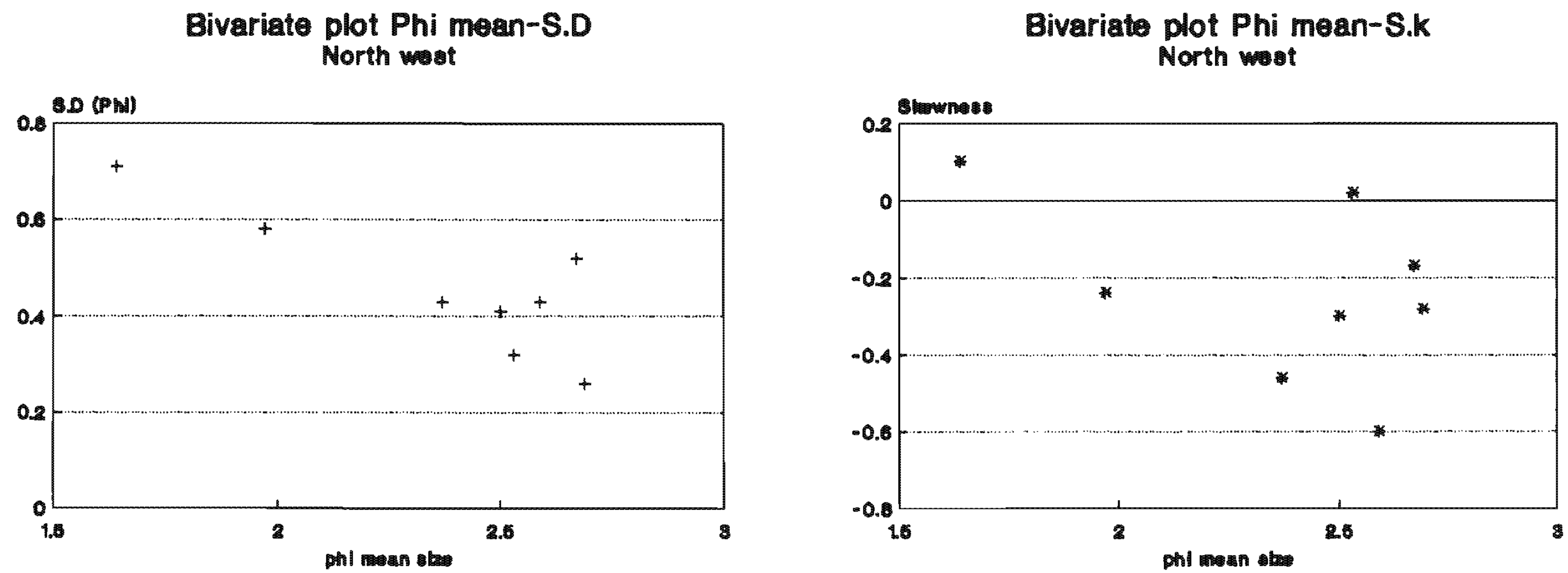


Fig.31b. Bivariate plot of phi mean size vs. S.D. at the north west side.

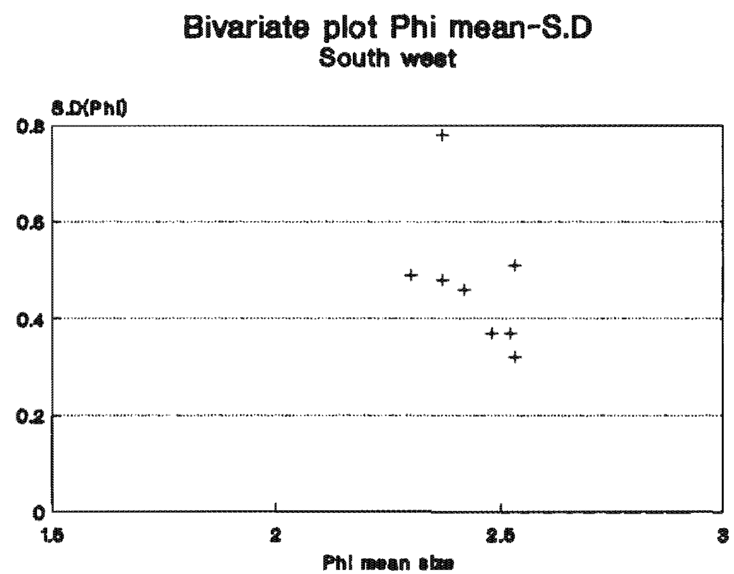
(medium sand) and are moderately well sorted (s.d >0.55Ø <0.80Ø). The sorting diminishes with decrease of phi mean grain size on the northwest side. At the southwest side, as indicated in figure 31c, the samples fall in the range 2.25Ø - 2.55Ø (fine sand) and are well sorted (s.d >0.35Ø < 0.50Ø). Higher sorting features are observed for samples with mean size 2.50Ø which are well sorted.

L) Tide

The tide at Andhakaranazhi was semidiurnal with a period 6 hours and 21 minutes with tidal range of 1.20m. It shows a phase difference of 1 hour and 15 minutes late from the tide stage from that at Cochin. The slack period lasts for 20 to 30 minutes to change over from flood/ebb to ebb/flood. Similar observations were made by Shenoi (1984).

M) Breaker Zone Characteristics and Longshore Sediment Transport

Longshore currents are dependent on the alongshore variation in breaker height, direction of wave approach and/or a combination of both as explained by Bowen and Inman (1969) and Komar (1975), Shore Protection Manual (1975) and Walton and Bruno (1989). Many investigators have studied the longshore currents along the south west coast of India (Narayanaswamy et al., 1979, Samsuddin, 1986; Shenoi and Prasannakumar, 1982; Chandramohan, 1988; and Sajeev, 1993). Further Hameed et al., (1986) explained the significance of breaker approach angles for the variation in longshore current speed which is not proportional to the wave intensity.



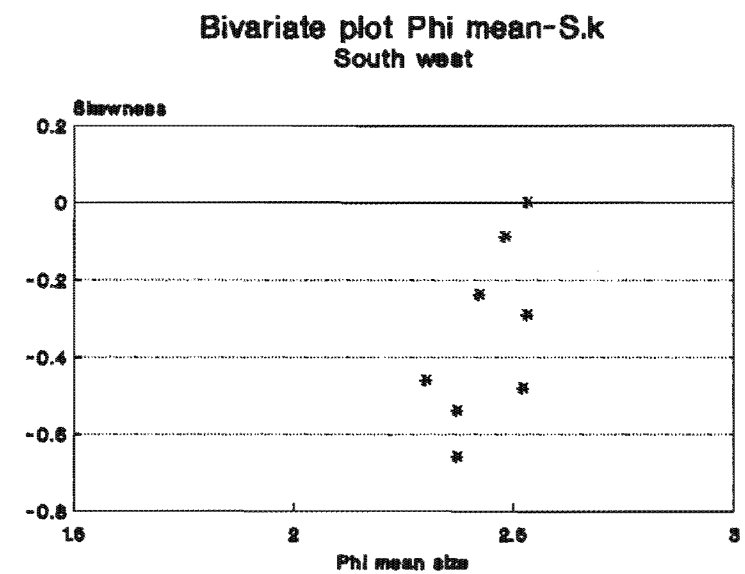


Fig.31c. Bivariate plot of phi mean size vs. S.D. at the south west side.

This study attempts to bring out the breaker zone characteristics and longshore sediment transport and the associated coastal processes during the period under investigation at Andhakaranazhi as discussed hereunder.

In March 1993, comparatively high breaking waves (0.90m) occurred on the northwest side than that on the southwest side with a period of 10-13s. In June 1993, the inlet was completely opened with shallow depths across the mouth. The waves of height 1.8m break at the inlet mouth and travel towards the head of the bay with periods 6-9s. Similarly during August 1993 the waves of period 8-10s with average breaker height 1.5m on the southwest side at a direction southwesterly was active in Andhakaranazhi. The surf zone width was about 45m and average breaker height was 1.0m. Baba (1988) reviewed the wave characteristics and beach processes of the southwest coast of India and observed that the highest wave activity along the coast is during monsoonal months (May to October) and generally the wave height decreases from south to north along the coast. Studies in September 1993, indicated that although the average breaker height on the northwest side was marginally higher (1.35m) than that on the southwest side (1.05m) with periods 8-10s, the average breaker height at the mid site of the inlet mouth was 0.75m only. Sand deposition of dimension 65m X 12m was observed on the north west side of the inlet while there existed no deposition on the south west side. Baba (1988) had identified a southerly uniform drift during the southwest monsoon and a northerly drift during the rest of the year for the Kerala coast from Trivandrum to Calicut. The above feature at Andhakaranazhi may be due to the southerly direction of littoral transport during the monsoon months as also observed by previous investigators (Shenoi and Prasannakumar, 1982; Sajeev, 1993). The average wave period during October 1993 was 10-12s, higher compared to that in September and the wave direction was predominantly northwesterly. The average breaker height was very low at 0.5m on northwest side compared to the breaker height (0.70m) on southwest side. The domination of higher periods during premonsoon and postmonsoon seasons had been reported by Baba (1988) along the Kerala coast. The surf zone width was about 30m during the month of October. The direction of longshore current was northerly during this month and sand deposition of 60m X 6m size was observed on the southwest side. The sand deposition observed in September 1993 at the northwest side had eroded during the postmonsoon months in the presence of northerly longshore currents. The presence of inlet acts as a littoral sediment sink that deprives sediment transfer further to the downdrift side.

In November 1993, the wave periods were 10-12s with breaker height of 0.90m and the direction of wave approach varying between 270° - 280°. The alongshore current velocity was observed as 0.24 m/s in the northerly direction. Considerable accretion of sand was observed on both the southwest side and northwest side of the inlet. Sand deposit of length 65m was observed along the coastline with limited seaward extent on northwest side. This feature later eroded away towards the end of November. The surf zone width at southwest side was 55m and on the northwest side, 75m and that at the middle portion of the barrier was about 100m. altogether which formed into a crescent shaped bar. The presence of crescentic form of the outer bar formed due to the relative role of tidal currents and wave incidence as evidenced by Dean and Walton (1974) and Walton and Adams (1976). Similarly, Bruun et al., (1974) and Bruun (1976) have observed that outer bar increases in volume with decreased wave exposure as observed here during the month of November. Such features have also been authenticated by studies by Oertel (1974) at ebb tidal deltas in Georgia coasts. In December 1993, the wave period was 8-10s and the breaker heights were marginally greater on southside of the inlet (0.90m) than on the north (0.75m); the surf zone width was about 55m. The variation in breaker height at southwest and northwest sides of the inlet banks is due to the variation in water depth as explained by Masselink (1993) from the analysis of surf zone wave records that the wave height is limited by the local water depth. The influence of bottom friction on the wave steepness also could be one of the reasons for this variation in breaker characteristics as explained by Kurian (1987). The average longshore current velocity was 0.44 m/s, directed towards north and the inlet had migrated towards the northwest side in a meandering manner; the width of the inlet mouth reduced to 65m. Considerable amount of deposition was observed to occur along the south bank of the inlet which forced the inlet opening to migrate in a northwest direction. This migratory mechanism of the inlet in the direction of the prevailing littoral drift was further explained by Bruun (1976) as it depends on the magnitude of littoral drift. the velocity of tidal currents and other associated coastal currents and also on the phase difference between any longshore tidal current and tidal currents within the inlet. Bruun (1976) had also explained that deposition on the updrift side resulting in the shifting of inlet channel into the downdrift side caused erosion at the downdrift side of the inlet. Similar observations of migratory mechanism of inlet under the prevailing direction of littoral drift was observed by Moni (1972) at Azhikode inlet along the Kerala coast. In January 1994, the waves were north westerly with long periods of 12-13s; the surf zone width at north had been reduced to 20m with average breaker height of 0.65m. However the beach width at south was about 30m and that on the north side was 35m. The surf zone width at south side was less (15m) compared to the north side with comparatively steeper slope on the north side. This variation in surf zone width can be attributed to the back and forth sweep of the surf zone as explained by Massel et al., (1993) that in micro tidal environments the back and forth sweep of the surf zone across a considerably long beach profile causes continual variation in the surf zone characteristics. The average longshore current velocity in the northerly direction was observed to be very less (0.16 m/s) as compared to the previous month and the inlet mouth closure was completed by the end of this month. In February 1994, the waves were northwesterly with average period 10-12s at a breaker height of 0.60m. The surf zone width on the northside was about 10m whereas that on the south side was 15m and the average longshore current velocity was observed to be 0.28 m/s in the southerly direction. During May 1994, the average breaker wave height was 1.0-1.2m with average wave period of 8-10s from westerly direction when the surf zone width increased to 35m. The average longshore current speed was 0.36 m/s towards south. The nearshore features altered during June 1994, when the wave direction was predominantly between 160°-170° with a wave period of 8-9s. This month of monsoon period exhibited high waves with breaker height of 1.7m. The surf zone width considerably increased to 60m due to the spreading up of the sand bar sediments to offshore sites under the action of high waves and freshet discharge through the inlet. The alongshore current velocity was observed to be 0.08 m/s in the southerly direction.

The longshore sediment transport rate varied both in the northerly and southerly directions. During the months of November and December 1993, the calculations indicate transport values of 0.77112 x 10^5 and 1.13788 x 10^5 m^3/month in the northerly direction. This period coincides with the development of the bar across the inlet. The next two months January and February 1994 indicated southerly transport values of 0.12450 x 10^5 m^3/month which is a period of fair weather. Investigation in May 1994 gave northerly transport rates (0.80888 x 10^5 m^3/month) while during June 1994 the value was 0.43653 x 10^5 m^3/month, in the southerly direction. The change in direction is incident with the onset of monsoon.The pattern of longshore transport is consistent with earlier studies at this region (Chandramohan et al.,1990 and

Sajeev, 1993). Only marginal variations from the values of previous studies have occurred which are otherwise expected and would not lead to conceptual changes in the understanding of littoral environment in the surroundings of this inlet.

N) Design of a Jetty Improved Channel

From the foregoing discussion, the hydraulic factors of the existing inlet reveal that the site could be developed into a fisheries harbour by offering appropriate shore protection structure(s). The available means for improving an inlet include bank protection, dredging, artificial bypassing and jetties. More information on the actual methods of improvement are available elsewhere (Escoffier, 1977; Galvin, 1982). The construction of a jetty will stabilize a channel across the bar and prevents the migration of the inlet. They also reduce wave action within the harbour and to a large extent excludes deposition of littoral material at the harbour mouth. The proper siting and dimensions of a jetty for improvement of a coastal inlet requires a careful study of the existing hydraulic features of the inlet, the sedimentation pattern and observation on the littoral environment.

At Andhakaranazhi inlet the tidal prism and cross section of the gorge in its natural settings permit the improvement of the inlet so as to serve as a fisheries harbour (Ajith and Balchand, 1995b). This is simply feasible because of the seasonal tendency of the bar to open permitting discharge of flood waters through a large cross section. Historical changes in inlet position and dimension have not varied since the last two decades. This refers to the length, width, and the cross section of the inlet throat. The tidal distortion (range and time relationship) is minimal while considering locations inside and outside the inlet. because of the basin geometry at Andhakaranazhi. The influence of storm surge or wind setup on this particular inlet is also ruled out because of the relatively calm condition prevailing in the Lakshadweep sea. Of course, during the southwest monsoon rough sea prohibits fishing operations along the coastal zone of Kerala state which otherwise will have to be adhered for safety reasons. The tidal prism of the bay and the effects of freshwater inflow into the bay is already regulated by the two regulators (sluice gates) on either ends of the bay. Presence of other inlets or tidal and wind induced currents are absent for this bay inlet system. A significant factor which plays a crucial role in the closure of the inlet is the deposition of littoral material by way of sand advection.

The functional design requirements for the improvement of an inlet evolves around improved sediment flushing capacity of the inlet (offshore transport during ebb tide greater than sand brought within, during flood tide), stabilising the inlet (fixed cross sectional area and length, non migrating), and at the same time, provides adequate means of navigation. The major hydraulic conditions which are required in the development of the Andhakaranazhi inlet by means of a jetty satisfy the assumption put forward by King (1974), Sorensen (1977) which would facilitate the stabilisation of the proposed jetty improved channel. The critical design parameters are the dimension of the existing inlet and the proposed jettied channel and associated improvements to control unwarranted littoral drift.

The existing bay affords adequate tidal prism, depth requirements and limited land derived sediment loads. The inlet when fully open, has a cross sectional area of 180.00 m width and minimum 2.00 m depth (variable depth 4.00 m). During monsoon seasons shoaling of waves may be expected at the outer boundaries of the inlet. The bar formation at the inlet generally has a width extending upto 150.00 m, when the inlet stands completely closed. It may be noted that closure mechanism follows a gentle deposition of materials on the southern side, progressively developing due north, while still permitting navigable depths in the meandering channel having a tendency to shift northward (Plate - 3). In this context, a jetty improved channel would take care of this location permitting entry/exit of fishing boats and the smaller non mechanised country boats as well as maintenance of fishery vessels. The proposed channel while protecting the bay within from wave action, coastal cross currents and undesirable sediment/littoral deposition will be a channel of adequate dimensions extending from just within the bay across the bar to a point where the natural depth is equal to the design depth. Considering the above factors which will permit the establishment of a stable inlet, mathematical stability analysis, as referred in Chapter 2, Appendix II was performed for three different cross sectional areas and two cases of tidal amplitudes.

The results of the analysis (Table - 7) indicates that for width 3 m. 6 m. and 10 m and for tidal amplitudes 0.50 m, the channel maximum velocity varies as 0.94 m/s, 0.50 m/s and 0.29 m/s. respectively. On decrease of tidal amplitude value to 0.30 m, the maximum velocity values work out to be 0.58 m/s, 0.30 m/s, 0.18 m/s, respectively, corresponding to the three width values stated above.

All the above maximum velocity values refer to a minimum design depth of 2.00 m; table 7 also provides velocity maximum values for increasing depths. The stability analysis was also performed for two length of the channel varying from 100m to 500m, but did not indicate any change in the maximum channel velocities in all the above cases, which is obviously because of the smaller fixed bay geometry and non distortion features of the tide. For a stable inlet, the preferred maximum channel velocity should be selected near to value of 1.00 m/s for a given cross sectional area (Escoffier, 1977 and van de Kreeke, 1992). In case the velocity is less than the preferred value, the inlet cross sectional dimension in relation to velocity should still remain in the equilibrium interval such that stable conditions may prevail.

The above analysis point out the establishment of a jetty improved channel of assured stability when the design parameters are selected as 300m (meeting adequate channel length requirements), width 3.00 m, depth 2.00 ± 0.50 m. Alternately, the realistic flow velocities in the channel may be around 0.50 m/s (lesser than 0.94 m/s in the first case)

Table 7. Stability analysis of Andhakaranazhi inlet for three different width. (As - Tidal amplitude, Ab - Bay area (m^2), TMLAG- Time lag (hours), Range (m), Prism (m^3), VMI- Maximum channel velocity (m/s) and VMD - Dimensionless channel velocity.

Length = 300m, Width = 3m, As = 0.50m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	17.42	.60	.96	115559.2	.94	.89
4.00	5.62	.19	1.00	120049.0	.56	.92
6.00	2.68	.09	1.00	120306.8	.39	.92
7.00	2.00	.07	1.00	120307.0	.34	.92
8.00	1.56	.05	1.00	120291.4	.30	.92
8.90	1.27	.04	1.00	120271.0	.27	.92
9.25	1.18	.04	1.00	120269.3	.26	.92
10.00	1.02	.04	1.00	120256.2	.24	.92
11.00	.85	.03	1.00	120240.1	.22	.92
12.00	.71	.02	1.00	120222.3	.21	.92

Length = 300m, Width = 6m, As = 0.5m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	3.85	.13	1.00	120280.4	.49	.92
4.00	1.11	.04	1.00	120288.3	.28	.92
6.00	.52	.02	1.00	120214.9	.20	.92
7.00	.38	.01	1.00	120180.6	.17	.92
8.00	.30	.01	1.00	120217.6	.15	.92
8.90	.24	.01	1.00	120133.7	.14	.92
9.25	.22	.01	1.00	120204.6	.13	.92
10.00	.19	.01	1.00	120181.4	.12	.92
11.00	.16	.01	1.00	119991.0	.11	.92
12.00	.13	.00	1.00	120240.8	.10	.92

Length = 300m, Width = 10m, As= 0.5m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	1.27	.04	1.00	120303.8	.29	.92
4.00	.36	.01	1.00	120161.3	.17	.92
6.00	.16	.01	1.00	120097.9	.12	.92
7.00	.12	.00	1.00	120306.6	.10	.92
8.00	.09	.00	1.00	119899.5	.09	.92
8.90	.08	.00	.99	119299.0	.08	.92
9.25	.07	.00	1.01	120676.6	.08	.92
10.00	.06	.00	1.00	119827.9	.07	.92
11.00	.05	.00	.99	118856.0	.07	.92
12.00	.04	.00	.97	116383.9	.06	.91

(Con´t....2)

Length = 300m, Width = 3m, As= 0.3m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	10.96	.38	.59	71340.3	.58	.91
4.00	3.39	.12	.60	72250.4	.34	.92
6.00	1.61	.06	.60	72233.6	.23	.92
7.00	1.20	.04	.60	72211.2	.20	.92
8.00	.93	.03	.60	72191.3	.18	.92
8.90	.76	.03	.60	72175.8	.16	.92
9.25	.71	.02	.60	72169.2	.16	.92
10.00	.61	.02	.60	72162.1	.15	.92
11.00	.51	.02	.60	72150.1	.13	.92
12.00	.43	.01	.60	72141.9	.12	.92

Length = 300m, Width = 6m, As= 0.3m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	2.31	.08	.60	72272.4	.30	.93
4.00	.67	.02	.60	72185.1	.17	.92
6.00	.31	.01	.60	72124.5	.12	.92
7.00	.23	.01	.60	72103.1	.10	.92
8.00	.18	.01	.60	72099.3	.09	.92
8.90	.14	.00	.60	71999.1	.08	.92
9.25	.13	.00	.60	72130.6	.08	.92
10.00	.12	.00	.60	72183.2	.07	.92
11.00	.10	.00	.60	72287.4	.07	.92
12.00	.08	.00	.60	72360.8	.06	.92

Length = 300m, Width = 10m, As= 0.3m

DEPTH	LAG	TMLAG	RANGE	PRISM	VMI	VMD
2.00	.76	.03	.60	72197.3	.18	.92
4.00	.21	.01	.60	72075.1	.10	.92
6.00	.10	.00	.60	72190.1	.07	.92
7.00	.07	.00	.60	71944.5	.06	.92
8.00	.06	.00	.60	71894.8	.05	.92
8.90	.05	.00	.60	71784.8	.05	.92
9.25	.04	.00	.60	71692.6	.05	.92
10.00	.04	.00	.59	71027.9	.04	.92
11.00	.03	.00	.59	71313.6	.04	.92
12.00	.02	.00	.58	69142.3	.04	.90

due to the influence of the prevalent tide conditions at Andhakaranazhi. but still may be within the equilibrium interval values of the cross section. It may be pointed out that a width of 3.00 m may be inadequate to conduct smooth navigation for fishing vessels. Accepting a width of 6 m, which is most ideally suitable for a channel connected to a fisheries harbour, the velocities within may vary from 0.30 m/s to 0.50 m/s for a channel length of 300m and depth of 2.00 m. In case, the width has to be further extended (10m) the velocity will fall below 0.30 m/s. The feasible dimension will be a choice to mainly support logistical fisheries operation where the main inhibiting factors at Andhakaranazhi would be the movement and deposition of littoral material within and at the entrance of the proposed jetty channel. The minimum acceptable flow in the channel as worked out from the analytical formulation will guide in the actual design and construction of the jetty. During fair weather season(s) the wave action is limited and restricted to the entrance of the jetty. It is preferred that in order to circumvent the large scale littoral drift and the subsequent deposition of material at the inlet, commencing from the southern end, the alignment of the jetty improved channel be mainly in the east west with appropriate orientation in the northwest-southeast direction. This would guarantee no direct advancement of the sand deposits which progressively build ups across the inlet into the channel. Further more the establishment of a jetty improved channel has to be augmented by construction of revetments within the bay and also the extension of the existing sea wall on the southern part of the inlet towards north. A full fledged physical model would ideally serve the purpose incorporating the hydraulic data provided herein along with information on waves, tides and littoral drift covered in this study to ensure cost effectiveness.

CHAPTER - 5

SUMMARY

The thesis attempts to critically analyse the stability of two tropical tidal inlets - one permanent (Cochin inlet) and the other temporary (Andhakaranazhi inlet).

The Cochin inlet manifests the following salient features which are documented hereunder. From the studies on stability analyses at Cochin inlet, it qualifies to be placed in the criteria - neutrally stable. The forcing factors are critically balanced and the present hydraulic conditions are so set to maintain a near critical maximum channel velocity to sustain neutral stability at the inlet. The stability of Cochin inlet may be offset in the event of extreme river flow, excessive dredging, bay area reclamation, changes in littoral environment and as well as due to the variability in the estuarine flushing capacity. Bar bypassing is predominantly noted at this inlet which explains one of the mechanisms of shoreline variation in the outer vicinity of Cochin inlet.

In the case of (seasonal) inlet at Andhakaranazhi, the inlet is highly unstable and the forcing factors identified include the nearshore wave climate which influence bar formation. Hinterland development strategy currently practiced has to be reviewed towards establishment of a permanent inlet.

Briefly, studies on flow characteristics at Cochin inlet indicates flood dominance at the inlet. Generally the surface currents are unidirectional into and out of the

estuary depending on the stage of the tide with the exception of transverse flows along the boundaries of inlet. Higher current velocities were generally observed along the Vypeen bank during ebb tide and during the flood tide along the Fort Cochin bank. The oscillatory currents play a significant role in the distribution of suspended solids at any inlet. At Cochin inlet high load of suspended solids were observed, higher concentrations along the Fort Cochin bank compared to the Vypeen bank. The enhanced suspended solids content in the down estuarine regions, especially at tropical tidal inlets, is a specific manifestation, often referred to as turbidity maxima. Unlike in subtropical estuarine waterways, where this feature is observed in the upper reaches of the estuary (mixing regions of freshwater and very low saline water), the tropical waterways modify the distribution of suspended solids by way of translocating the position of occurrence of higher suspensate. Of course, the presence of turbidity maximum is prevalent at the inlet during the flood stage of the tide. The freshwater-seawater mixing phenomena at the inlet depicts three seasonal features: premonsoon-partially mixed, monsoon-stratified and postmonsoon-salt wedge (transitional, at times partially mixed). Under the above conditions, the circulation at the inlet and within the bay is influenced mostly by tides during premonsoon while the predominant driving force during monsoon is attributed to freshwater outflow. Thus the bay-inlet system evidently modifies the tidal components which in turn results in deciding the values of the flow velocities at the inlet. Here it may be remarked that the volume transport across the inlet is significantly controlled by the flow velocities and partially by the tidal duration and range. The inlet hydrodynamics also point out to the enhanced dilution that has to be afforded because of increased demands currently placed on the quantum of freshwater inflow into the estuarine reaches and the amount available at the inlet.

The stability of inlets are considered from the perspective view point of them being unstable, neutrally stable (falling within the equilibrium interval) and stable. The above three conditions are arrived by considering the relation between cross sectional area and maximum channel velocity. The significance of maximum channel velocity is related to the degree of freedom enjoyed at the tidal inlet to maintain a net outward transport of water and material while the dimension of the inlet gorge (gut) is retained or improved in its geometry. Necessarily, where locations are subjected to considerable wave activity, coastal currents and associated scouring action, the inlet stability depends mostly on the maximum channel velocities. Again an equilibrium size of the inlet is often referred to in terms of the prevailing stability conditions which are determined by the ocean tidal amplitude and period, the inlet channel length and depth, hydraulic resistance and bay surface area. Analytical solution favour the qualitative description of stability in terms of a closure curve for a given channel length and width, bay area and tidal amplitude. The analysis at Cochin brought out the status of this inlet as falling under the category of neutrally stable inlets as stated earlier. In this context, it implies that the cross sectional area in relation to maximum channel velocity locates the Cochin inlet at near stable conditions with an inclination to attain stable features. A more realistic scrutiny of the closure curve reveals that the inlet may be qualified to be addressed as critically stable. This has relevance to the response ability of the inlet to modification in relatively shorter time scales in basin geometry, tidal prism variations, transitional changes in depth by way of dredging and evident remodelling of shoreline features. The forcing factors of stability are therefore to be considered as critically balanced at Cochin tidal inlet such that neutral stable conditions may prevail. The characteristics of such an inlet connected to a bay which is constantly being modified through engineering activities are definitely susceptible to alterations in stability status such that often an equilibrium interval period may prevail in deciding the division between unstable to permanently stable conditions. A better picture could be evolved on the likelihood of (any) inlet closure by comparing the status of number of such inlets along a coast which provide a hydraulic response curve (area versus prism relationship) reflecting the status of inlets and their stability at that region.

The study was extended to a temporary inlet manifesting seasonal characteristics viz. at Andhakaranazhi. Obviously this inlet is highly unstable because of the negligible outflow to keep the inlet mouth open to counter the littoral sediments depositing at its entrance. Conversely, for all monsoon seasons, a "seasonal stability" prevails when adequate freshwater outflow results across the inlet. With the withdrawal of rains and associated decrease in runoff the nearshore wave climate and tides brings about a progressive development of bar formation eventually leading to the inlet closure. This study has covered the full sequence of the naturally driven processes at Andhakaranazhi and elucidates information on relevant depositional and dispersal characteristics supported by data. The barrier beach at Andhakaranazhi is seasonal in nature and showed an erosional tendency. The sediment size distribution is negatively skewed with fine sands at the barrier, in the moderate to well sorted class. The flow velocities through the regulators for the drainage of flood waters, exhibit variations on either side of the channel and the salinity distribution in the bay (inlet completely open) does not show much variation in horizontal.

Briefly, the sand bar formation and dispersion at Andhakaranazhi tidal inlet is the resultant of the interactive forces of limnological importance coupled with nearshore processes. The bar erodes under the combined effect of wave action in the nearshore region - secondary in importance but primarily due to runoff from the hinterlands. The depositional characteristics are related mainly to the longshore transport of beach material which effectively transpose material into the bay area and across the entire width of the inlet as well as help the development of adjacent beaches aided by waves and tides at the site.

However, tides play a limited role in deciding the longitudinal extent but influence the vertical height of the sand bar. The depositional characteristics are promoted by decreased land runoff and predominant changes in wave approach direction. The bar first forms on the southern parts and progressively develops towards the northern bank.

The depositional and dispersal features which include the formation, dissipation and stability of the seasonal sand bar at this tidal inlet has been identified to be mainly brought about by the forcing factors of the ongoing natural coastal processes. Hence any non conservational development of this region would invariably have wide implications due to the intrinsic depositional and dispersal features as often found at many other deteriorating tidal inlets. The impact on Andhakaranazhi inlet is related to the deposition of longshore transported material which develop into a sand bar closing the inlet and subsequent sand mining of the same for hinterland development. This study accounts for the amount of sand excavated from within the inlet mouth for hinterland development as approximately half of the total volume of material deposited at the inlet region. The optimum use of beach sand now remains within the conservational limits and none of the environmental issues as far as coastal management is concerned has not taken dominance. However this beneficial utilization is likely to cross conservational limits. The cyclic deposition and dispersal feature of sand bar coupled with regular excavation of sand could give rise to a serious conflict between optimum use and exploitation with regard to the protective coastal measures. In this context, human activities can seriously alter the balance of the beach and sand bar dimensions which control the shoreline and bay within under consideration.

It is summarised that the present scenario of sand mining could offset plans to establish a fisheries harbour at this inlet and would likely lead to multidimensional management issues. Any conflict can then be resolved by a multiuse management plan in which environmental management and land use guidelines are closely integrated. The natural barrier beach incidentally act as a sand barrier to protect saline water intrusion into the paddy fields and thereby maintain the freshwater quality of the region. The practice should be highly restrictive on a minimum optimum use of depositional sand for hinterland development, without causing any disturbance to the coastal readjustments. It is suggested to evolve a comprehensive coastal zone management plan based on careful analysis of the natural processes operating in this area, with an inventory of all natural features and resources and an acceptable approach towards multiuse when development of hinterland can be compatible with geomorphic integrity, which must protect the important ecological system and respond to the demands of urbanization and support traditional agricultural practices.

On a developmental perspective, a jetty improved channel is suggested to facilitate navigation at Andhakaranazhi. This could, of course, preclude the availability of material for sand mining but substantially improve operational facilities for fisheries and associated industries at this coastal township. From the list of available means to improve an inlet, ascribing to a better stability status, the option will be the construction of a jetty improved channel which would prevent the migration of the inlet, sand bar formation and reduce the wave action within the new harbour. Chapter - 4 of this thesis has detailed the functional hydraulic parameters with relevant values to attain such a status. The actual construction of the jetty and its structural features can be thence evolved by taking lead from the analysis of tidal inlet hydraulics and stability provided herein.

To conclude, tropical tidal inlets are morphodynamically active. They comprise multitudinal features reflecting short to long term changes covered in the the paleogeographical domain. Local and regional reconstruction indicating past relationship between biogeomorphological components and major forcing processes could lead to a better understanding of potential future coastal changes. In the above background, length of shorelines sheltering tidal inlets play an important function in nearshore processes. Well illustrated are the roles tidal inlets play in the transport and exchange of water, sediment, bioavailable nutrients and a wide spectrum of contaminants, concurrently providing pathways for migrating organisms that such locations become significant environmental entities of coastal zones. The scientific concern is no less defined in terms of efforts that would lead to the understanding of such regional coastal features, improve the existing knowledge in the underlying processes and would contribute to the ongoing research to bring out prediction on tidal inlet behaviour and strive to resolve the developmental issues so as to meet tomorrows needs.

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(* not referred to in original)

APPENDIX - I

Abbreviations and Symbols

a_o - Sea tide amplitude

P - Tidal prism

T - Tidal period

A_E - Equilibrium cross sectional Area

A_B - Bay surface area

A_{cr} - Critical cross sectional area

A_c - Cross sectional area of the inlet

g - acceleration due to gravity

L_c - Length of the channel

R_c - Hydraulic radius of the inlet

f - Darcy - Weisbach coefficient

η_o - Ocean elevation

η_B - Bay elevation

α and G - Dimensionless tidal frequency

β and B - Dimensionless damping coefficient

M - the coefficient based on dimensionless tidal frequency and dimensionless damping coefficient

K_{en} - Entrance loss coefficient

K_{ex} - Exit loss coefficient

F - Frictional loss coefficient or impedence

Q - discharge through the inlet

V - Bay storage volume

Q_f - rate of change of freshwater flow from upstream source

h_c - Depth of the channel

$\bar{u}(x,t)$ - depth averaged flow velocity in x direction

V^*_{max} - Critical maximum channel velocity

U_{max} and V_{max} - Maximum channel velocity averaged over the flow area

V_m' - the dimensionless maximum channel velocity over a tidal cycle.

τ_{max} - Maximum shear stress

R - the ratio between bay tide amplitude and sea tide amplitude.

E - phase lag for the tide in the lagoon.

GLOSS - Global Sea Level Observing System

JTU - Jackson Turbidity Units

APPENDIX - II

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C     PROGRAM ON STABILITY ANALYSIS OF TIDAL INLETS
C     A(I)  =DIFF DEPTH VALUES
C     B     =WIDTH
C     CL    =CHANNEL LENGTH
C     AE    =BAY AREA
C     AS    =SEA TIDE AMPLITUDE
C     AREAC =CROSS SECTIONAL AREA
C     HYDRAD=HYDRAULIC RADIUS
C     FRIC  =FRICTION LOSS COEFFICIENT
C     TIDFQ =DIMENSIONLESS TIDE FREQUENCY
C     DAMCOF=DIMENSIONLESS DAMPING COEFFICIENT
C     COTD  =COEFFICIENT BASED ON TIDAL FREQUENCY AND DAMPING
C     RATIO =RATIO BETWEEN BAY TIDE TO SEA TIDE AMPLITUDE
C     TANE  =TAN OF TIDAL PHASE LAG
C       E   =TIDAL PHASE LAG IN THE BAY
C      VM   =MAXIMUM CHANNEL VELOCITY
C      VMR  =DIMENSIONLESS CHANNEL VELOCITY
C     PRISM =TIDAL PRISM IN THE BAY
C     TMLAG =TIME LAG IN HRS. IN THE BAY
C------------------------------------------------------------
 DIMENSION A(50),
 AREAC(50),HYDRAD(50),FRIC(50),TIDFQ(50)
 DIMENSION TIDFQE(50),DAMCOF(50),COTD(50),RATIO(50)
 DIMENSION TANE(50),PRISM(50),E(50),VM(50),VMR(50),D(50)
 DIMENSION RANGE(50),TMLAG(50)
      READ(*,*)B,CL,AE,AS
C     WRITE(*,*)'ENTER VALUE OF M'
C     READ(*,*) M
C     WRITE(*,*)'ENTER THE VALUE OF AS'
C     READ(31,*) (AS(J), I=1,M)
C     DO 32 J=1,M
      WRITE (*,*) 'NO OF VALUES'
      READ (*,*) N
      WRITE (*,*) 'ENTER THE VALUES OF DEPTH'
      READ (1,*) (A(I), I=1,N)
C     CALCULATE THE AREA
      DO 10 I=1,N
      AREAC (I)=(A(I) * B) + (AS*B)
      HYDRAD(I)=AREAC(I)/((2*A(I))+ B)
      FRIC(I)=1.3 +((0.03*CL)/(4.0*HYDRAD(I)))
      TIDFQE(I)= ((CL*AE)/(9.8*AREAC(I)))**0.5
      TIDFQ(I) = TIDFQE(I)*((2*3.14)/(12.42*3600))
      DAMCOF(I)=(FRIC(I)*AE*AS)/(2*CL*AREAC(I))
      COTD(I)=(16.0* DAMCOF(I)*(TIDFQ(I)**2))/(3*3.14)
      G=(TIDFQ(I))**2
      F=(COTD(I))**2
      X=(((1-G)**4) + F)**0.5
      Y=(1-G)**2
      Z=0.5*F
      RATIO(I)=((X-Y)/Z)**0.5
      TANE(I)=(COTD(I)*RATIO(I))/(2*(1-G))
      E(I)=(ATAN(TANE(I)))*(180/3.14)
      PRISM(I)=2.00*(RATIO(I)*AS)*AE
```

```
      RANGE(I)=2.00*(RATIO(I)*AS)
      D(I)=E(I)*3.14/180
      TMLAG(I)=(E(I)*12.42)/360
      VM(I)=((2.0*9.8*AS*SIN(D(I)))/FRIC(I))**0.5
      VMR(I)=(AREAC(I)*12.42*3600*VM(I))/(6.28*AS*AE)

10    CONTINUE
      WRITE(14,22)
22    FORMAT (2X,'DEPTH',4X,'AREA',6X,'HYDRAD',4X,
     *'FRIC',4X,'TIDFQ',3X,'DAMCOF',5X,'MI',8X,'RI')
      WRITE(16,55)
55    FORMAT(2X,'DEPTH',4X,'LAG',4X,'TMLAG',4X,'RANGE',4X,
     *'PRISM',8X,'VMI',4X,'VMD')
      DO 15 I=1,N
      WRITE(14,33)A(I),AREAC(I),HYDRAD(I),FRIC(I),
     *TIDFQ(I),DAMCOF(I),COTD(I),RATIO(I)
33    FORMAT(1X,F6.2,4X,F7.2,4X,F5.2,4X,F4.2,4X,
     *F4.2,4X,F5.2,4X,F5.2,4X,F5.2)
      WRITE(16,44)A(I),E(I),TMLAG(I),RANGE(I),PRISM(I),
     *VM(I),VMR(I)
44    FORMAT(F5.2,4X,F5.2,4X,F4.2,4X,F4.2,4X,F10.1,4X,
     *F4.2,4X,F4.2)
15    CONTINUE
32    CONTINUE
      STOP
      END
```

APPENDIX - III

List of Publication/Presentation of Papers in Seminars/Conferences

Ajith, J. K. and Balchand, A. N., 1994. Studies on oscillatory currents and distribution of suspended solids at a tidal inlet. Proceedings of 6th Kerala Science Congress, Trivandrum, 85-87.

Ajith, J. K., Rasheed, K. and Balchand, A.N., 1995a. Impact assessment on tropical estuarine characteristics in relation to river management approaches. IAPSO Symposia, Hawaii, Abstract PS 05, pp. 117.

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Ajith, J. K., Rasheed, K. and Balchand, A. N., 1995c. The role of natural coastal processes at a tropical tidal inlet in hinterland development. Proc. Int. Conf. Coastal Change 95', Bordomer-IOC, Bordeaux, 373-377.

Ajith, J. K., Rasheed, K. and Balchand, A.N., 1995d. The dynamics of a seasonal barrier beach vis-a-vis coastal ocean processes in Tropical fluvial environments. IUGG XXI General Assembly, Boulder, Colorado, Abstract OB12A-3, B312.

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