STUDIES ON SILTATION IN COCHIN HARBOUR — DYNAMICS OF SUSPENSATE

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By
J. SUNDARESAN PILLAI, M.Sc.

SCHOOL OF MARINE SCIENCES,
COCHIN UNIVERSITY OF SCIENCE AND TECHNOLOGY,
COCHIN - 16

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CERTIFICATE

This is to certify that the thesis bound herewith is an authentic record of the research carried out by Shri.J.Sundaresan Pillai, M.Sc., under my guidance and supervision in the School of Marine Sciences, in partial fulfilment of the requirements for the Ph.D. Degree of the Cochin University of Science and Technology and that no part thereof has been presented before for any other degree in any university.

Dr. P.N.K. NAMBISAN
(Supervising Teacher)
Director
School of Marine Sciences
Cochin University of
Science and Technology

Cochin-682016,

February, 1989.

DECLARATION

I hereby declare that the thesis entitled 'Studies on Siltation in Cochin Harbour - Dynamics of Suspensate' is an authentic record of the research work carried out by me under the supervision and guidance of Dr.P.N.K.Nambisan, Director, School of Marine Sciences, Cochin University of Science and Technology, in partial fulfilment of the requirements for the Ph.D. Degree of the Cochin University of Science and Technology and that no part of it has previously formed the basis for the award of any degree, diploma or associateship in any University.

Sundaresan pillai
(J. SUNDARESAN PILLAI)
School of Marine Sciences
Cochin University of
Science and Technology

Cochin-682016,
February, 1989.

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CONTENTS

CHAPTER 1

INTRODUCTION

The fluvial processes of erosion, entrainment and deposition of sediments are complex and multicomponent. The detachment of particles during erosion processes occurs through the changes in kinetic energy or rain drop impact or by the forces generated on water flow; entrainment and transport of the sediment depend on the shape, size and weight of the particles and also the forces exerted by waterflow. When these forces diminish to the extent that no transport is possible, the deposition of particles occurs.

Sedimentation is the act or process of forming or accumulating sediment in layers, including such processes as the separation of rock particles from the material from which the sediment is derived, the transportation of these particles to the site of deposition, the actual deposition or settling of the particles, the chemical and other (diagenetic) changes occuring in the sediment, and the ultimate consolidation of the sediment into solid rock (Bates and Jackson, 1980). The weathering processes that act mechanically and chemically to break-up pre-existing rocks, the processes of transportation by which the material is carried from its source to the depositional site, the processes of deposition in the sedimentary environment, and the post-depositional processes or diagenesis by which the sediment is compacted and hardened, all play their role in sedimentation. Some of the principal external agents of sedimentation are water, wind, gravity and ice.

The process of sedimentation is known to create environmental problems such as (1) damage to agricultural land resources due to outwash of fertile material and impairment of natural drainage; swamping due to channel aggradation associated with flood plain scour and bank erosion (2) deposition of suspensate in harbour and navigable channels (3) enhancement in cost of maintenance in the capital value of drainage enterprises (4) fill-up of storage reservoirs used for power generation, water supply, irrigation, flood control, navigation, recreation and other multiple uses and (5) increasing cost of water purification as a result of excess turbidity.

The topic under discussion is of vital concern in the conservation, development and utilization of our soil and water resources. There were many instances of civilizations that declined because of problems from sedimentation (Lowdermilk, 1935). Reports indicate that in the United States early settlements along the shores of Chesapeake Bay dispersed because the harbour area was rapidly being sedimented (Gottschalk, 1945). Sedimentation processes are often encountered in estuaries, the marginal marine environment. Through the late Pleistocene epoch, sedimentation rates in the marine and estuarine environment have altered four times, from relatively intense deposition to periods of extremely slow deposition or wholescale erosion and deep weathering (Emery, 1967). The rate of sediment supply in the Pleistocene was controlled largely by sea level oscillations, while geographic locations and the topography of the area receiving the sediments influenced the amount of material accumulated.

Sediments deposited by mechanical action, by currents of one kind or other, are called clastic sediments. The fine grained clastics are by far the most abundant sediment type and are found either alone or mixed with other sediment types in almost every environment of deposition like estuaries. It is most convenient to subdivide clastic sediment on the basis of particle size, as the size and sorting are dependant on a genetic factor, the current type and strength. The particle size that passes a $\frac{1}{16}$ mm sieve is loosely defined as 'silt' or 'mud'; it is more appropriate to divide it still further into silt ($\frac{1}{16}$ mm - $\frac{1}{256}$ mm) and clay ($<\frac{1}{256}$ mm) (Ippen, 1966).

The source of sediments to estuarine systems may be external (introduced by freshwater run-off), marginal (shoreline erosion) or internal (principally biological production). Each of these inputs may dominate over the others under favourable conditions. In addition, bottom material within the system may be re-suspended and re-distributed by currents and wave action. Particulates in estuaries prior to sedimentation undergo back and forth transport by ebb and flood currents and are recycled in a complex fashion. Eventually sediments are either filtered from estuarine water (deposited) or flushed into the sea (transported). Consequently, the type and amount of sediments discharged from an estuary may differ markedly from the nature of sediments received.

The estuarine sediment deposition mechanism follows the clastic format of energy gradients (Rouse, 1965). The sediment flux proceeds from the area of high energy to the area of lower energy; the suspended or tractive sediment concentration is thus directly proportional to the transportation of energy. The rate at which the sediment accumulates in an estuary is dependent, however, not only upon its source of supply and geographic position but also on its local climate. In humid areas, with major riverine sources, the rate of sediment accumulation may be very high; on the other hand in arid zones the reverse is true (Fu, 1987).

The penetration of marine sediments into estuaries can occur during the tidal inflow along the bottom layers. Another aspect of hydrological structure in estuaries also deserves attention. Berthois (1958, 1960 a, 1960 b) found that in a number of estuaries [the Loire (France), small Breton rivers and Konkoure river (French Guinea)] a motionless lens of water persists near the bottom during a large part of the tidal period. The position and duration of this motionless lens of water body vary with estuaries and within the same estuary, with varying river discharge and tidal range. The lens act as a weir in which the coarse particles moving along the bottom are trapped, whereas the finer elements flowing in suspension in the upper water layer pass over it. If the lens is located out of the river-mouth, a delta can be built but if it is located upstream, the fluvial sediment settles before they reach the middle and lower part of the estuary.

Sediments are moved into an estuary as suspended load or bed load. Bed load movement occurs intermittently in a thin layer, several grain diameter thick, or in close contact with the bed (Ibad-zade, 1986). Energy is transmitted by intergrain contact through rapid and frequent collisions manifested in rolling or discrete jumps. Suspended load may move about as fast as the mean flow velocity whereas bed load movement occurs at a slower rate. The mode of sediment transport is also affected by the magnitude of current flow and bed characteristics. Under turbulent flow, suspended particles are not necessarily maintained in suspension because there may be a continuous exchange between the suspension and the bed (Dyer, 1972). Although the relative importance of bed load transport to suspended load is not well established, suspended load is usually the prominent feature in most estuaries (Officer, 1981).

The transport of suspended load may be by processes generally known as advection and diffusion (Wright, et al. 1980). The term advective transport means movement of suspended material in a given water mass from one point to another without changing its spread. Usually there is a net horizontal movement. Diffusive transport changes the spread and transport sediment from a zone of higher concentration to one of lower concentration. Turbulance caused by waves and tides is mainly responsible for diffusive transport.

The vertical distribution of suspended load within a flow field depends on the degree of turbul~~a~~ence and on the particle settling velocity (Owen, 1971). The faster the settling velocity, the more turbul~~a~~ence will be required to maintain sediment in transport and hence higher the bottom shear stress. With proportionally fast settling velocities, the sediments tend to travel near the bed, whereas, with slow settling velocities the sediment is mixed throughout the depth (Owen, 1971).

The temporary emplacement of suspended particles on the bed, by deposition, is largely controlled by sediment concentration, settling velocity and fluid shear. Consequent to settling and accumulation of sediment on the bed, buried materials get consolidated through bedding down of particles and escape of pore water. Consolidation depends on the weight of the overlying sediment forcing out most of the liquid. In estuaries with high suspended concentration, the rate of deposition during decelerating tidal current and near slack water is too fast to permit a normal self-weight consolidated mud to form (Inglis and Allen, 1957). Consequently, over many tidal cycles, layers of dense suspensions called fluid mud accumulate to considerable thickness on the bed and on becoming static, the suspensions slowly consolidate. However under the influence of accelerating tidal currents, upper mud layer is redispersed in the media (Kirby and Parker, 1977).

In estuaries, circulation is controlled by freshwater flow, friction and tidal mixing. Many estuaries are characterised by a landward flow of saltwater along the bottom and seaward flow of freshwater near the surface; the freshwater head being not sufficient to prevent the saltwater intrusion into the estuary. Due to presence of tidally regulated seawater and the constant freshwater flow along surface layer, a mechanical mixing of water takes place between the two layers which necessitates, a net landward flow of shelf-water to make good the loss from the lower layers (Pond and Pickard, 1986). The result is a nontidal circulation, typified by more vigorous and persistent flood tide currents within the intruding bottom layers. Fluvial sediments entering this type of system is observed to move seawards with the freshwater outflow. As a result the saline underflow induces the coarser materials to settle. These may be carried along the lower layers to upstream by saline wedges. Entrainment of water from the bottom layers carry fine sediments back into the surface layers and the system thus "recycles". One direct result of this recirculation is the turbidity maximum located near the landward end of saltwater (Postma, 1967; Schubel, 1971). This probably promotes flocculation and agglomeration of fine particles by increasing particle collisions and particle residence time.

To understand mud accumulation fully, one must consider the unique ability of muds to resist current scour. There is a difference between the current velocity required to transport clay and silt and the velocity required to resuspend the same sediment. Thus fine sediment that are able to settle to the bottom in areas where average tidal velocities are reduced or during slacktide periods will accumulate unless much higher current velocities are reached later. In this context, it may be said that different locations around the world have varying depositional characteristics influenced by more than one of different forces discussed above, to exhibit wide ranging sedimentary features.

Of the many depositional sedimentary environments, the tropical regions deserve special attention due to the large amount of fluvial discharge. One such area, the Cochin estuary situated on the southwest coast of India, has been a location of intense siltation ever since its construction. The port is maintained navigable by continuous dredging at considerable cost. A close understanding of the sediment behaviour and siltation processes, described above, will be helpful to circumvent the largely unabated problems.

In recent years, better innovative techniques have been evolved in the science of harbour engineering (Nichols, 1988). The research work reported in this thesis had been initiated to provide a good coverage of the complex estuarine behaviour of Cochin harbour area in order to gain comprehensive information on the dynamics of suspended solids transport and depositional behaviour. The study critically examines the role of river discharge and tidal currents influencing the distribution of suspensate.

1.1 THE COCHIN HARBOUR

Cochin port is situated at the southwest coast of Indian peninsula at Lat 09°58'N and Long 76°14' E. The harbour comprises of a seaside region and a vast expanse of backwater which may be called the lake side region. The harbour is connected to the extensive and sheltered inland backwaters of 256 km^2 area, running parallel to the coast line (Uppal, 1981). This natural harbour provides safe anchorage even in roughest monsoon months (June-September). Its location on the southwest coast of India makes it an easily accessible port on the sea routes from Europe and middle east to Japan, far east and Australia.

1.2. IN RETROSPECT

The architect of the present Cochin port was Sir Robert Bristow. Bristow described the birth of the Cochin Port in the following words:

"From the farthest, that is the mainland, came the silt bearing streams, down from the north came what we might call the flood arm or overflow of Periyar, up from the south came the discharge from the vast reservoir of the Vembanad lake region. From the sea came the ground swells of monsoons and the wind waves from the southwest and northwest all struggling, pushing and jostling each other in strong endeavour to workout a system. Slowly, very slowly masses of sands were deposited, staged a while and were pushed aside, streams widened and deepened. Spits of land from north and south joined, parted joined again first below water and above water. A possible temporary opening at Alleppey closed itself. A possible temporary opening at Anthikadavu opened and closed again. Forces begun to unite and concrete at Cochin. The combination of hightides and heavy rains with a long push and a strong push out to sea were the beginnings of the famous Cochin harbour. Nature has put Cochin where she wanted it" (Bristow, 1959).

The newly formed gap widened and deepened due to the action of waves from the west and the tidal flows. The new gap was known as 'Cochazhi' (small gap). The place came to be known by the name 'Cochi' later Europeanised as Cochin.

1.3. PRESENT PORT FACILITIES

Cochin port is based at the Willingdon Island which has an area of 321.74 ha. The major port facilities include (1) twelve berths on Willingdon Island including nine wharf berths with cargo handling equipments and sheds (2) two tanker berths in Ernakulam channel connected to the Ernakulam shore (3) railway connected to port (4) dredging fleet (5) tugs, launches, water barges and other floating crafts (6) workshop, dry dock and other maintenance facilities (7) fishing harbour and (8) inshore oil terminal (Fig.1). Deep water facilities, jetties, wharfs and stream moorings are provided on the two ship channels viz. Ernakulam channel and Mattancherry channel. Mattancherry wharf also has four berths, Q1 to Q4 of length 167.5 m, each. The permissible draught is 9.14 m. (above details after Jayachandran, 1983).

1.4. IMPORTANCE OF COCHIN PORT

Cochin port plays a vital role in the economy of this region, since it is a centre of international trade and is backed by a vast fertile hinterland. Cochin port is an all weather port, where ships of various category viz. oil tankers, coal liners, food grainers etc. have anchored during the last decade.

Cochin port showed considerable increase in traffic compared to other ports of India. Cochin's share in the major port traffic in India increased from 3% in 1960-61 to 6% during 1981-82 (Table 1). The traffic projections for Cochin port is indicated in Table 2.

The total value of trade handled through the port has risen from Rs.53.57 crores during 1950-51 to Rs.1424.24 crores in 1981-82 (Engineers India, 1986). The share of Cochin Port in India's foreign trade increased from 4.3% to 6.7% from 1950-51 to 1981-82 (Table 3).

1.5. SCOPE OF THE PRESENT STUDY

Siltation is the major factor contributing to the progressive shallowing of Cochin harbour area. In the course of fifty years, the average depth of Cochin estuary has been reduced from 6.7 metres to 4.4 metres.

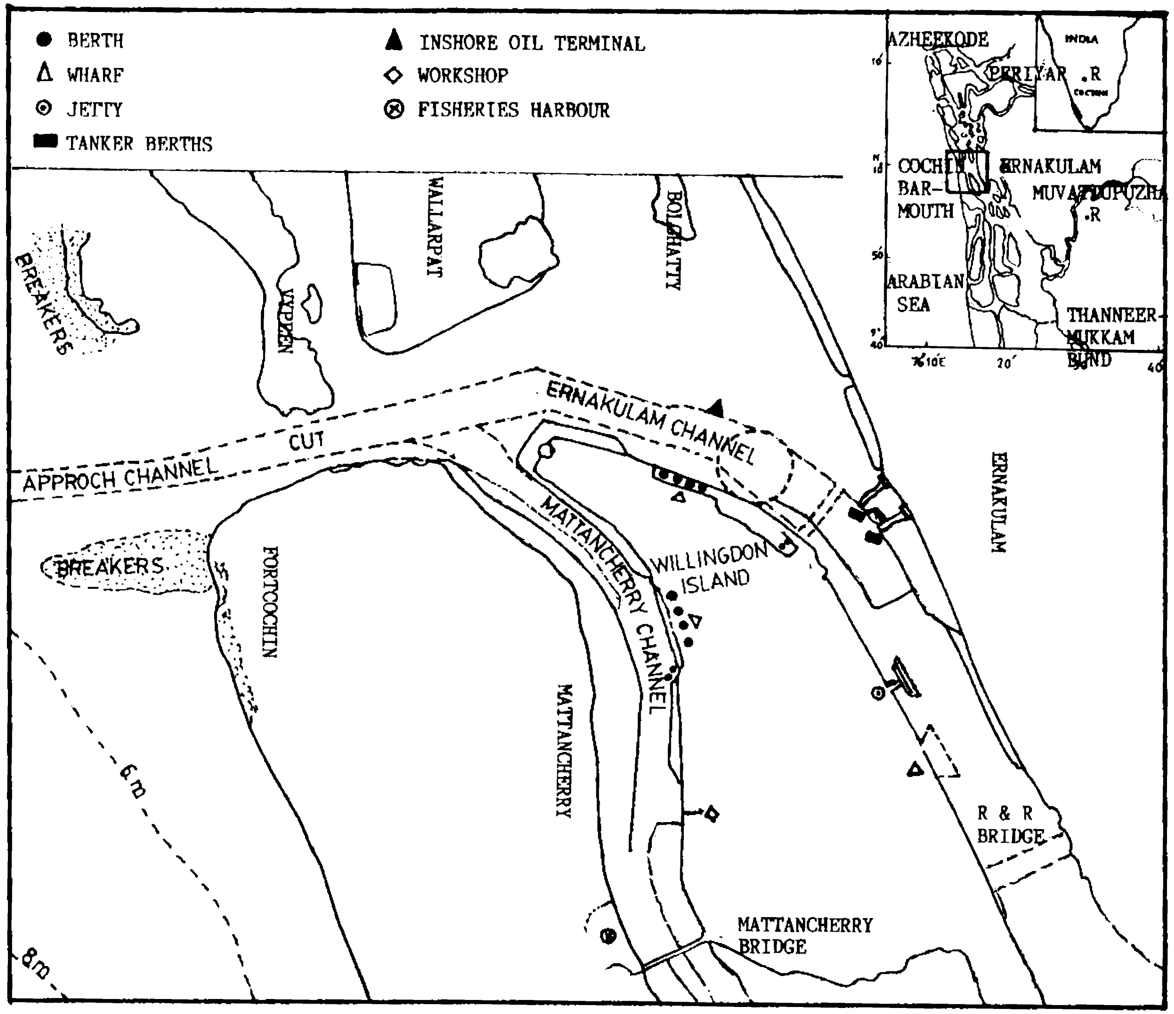

Fig.1.Map of Cochin Harbour.

Table 1. Share of Cochin Port in major port traffic of India (in lakh tonnes)

Port	1960-61	1965-66	1970-71	1975-76	1977-78	1979-80	1980-81	1981-82
Kandla	12	19	9	24	27	73	88	95
Bombay	110	135	116	142	120	160	167	196
Marmagoa	64	77	147	123	107	145	139	149
New-Mangalore	-	-	-	3	2	9	10	20
Cochin	10	16	37	32	39	55	52	55
Madras	22	37	63	74	74	100	104	118
Visakhapatnam	32	38	84	84	94	102	103	123
Paradip	-	-	22	33	27	23	23	22
Calcutta/Halida	65	68	43	58	56	86	93	98
Total	305	390	481	574	550	777	804	893
Cochin's share	3%	4%	8%	6%	7%	7%	6%	6%

Table 2. Traffic projections for Cochin Port (in lakh tonnes)

Commodity	Import/Export	1981-82	1985-86	1990-91	1995-96	2000-01
Crude oil/ Petroleum products	Import	32.00	46.48	55.47	69.72	95.66
	Export	9.76	12.04	10.14	7.16	5.75
	Total	41.76	58.52	65.61	76.88	101.41
Fertilizer and raw-materials	Import	5.30	9.62	10.32	10.33	10.33
	Export	-	-	-	-	-
General cargo	Import	2.39	3.12	3.60	4.08	4.80
	Export	3.22	4.68	5.40	6.12	7.20
	Total	5.61	7.80	9.00	10.20	12.00
Containerised cargo	Total	1.47	3.90	5.40	7.14	8.40
Other dry bulk cargo	Import	2.34	3.00	3.60	4.30	5.00
	Export	-	-	-	-	-
	Total	2.34	3.00	3.60	4.30	5.00
Total	Import	42.03	62.22	72.99	88.43	115.79
	Export	12.98	16.72	15.54	13.28	12.95
Grand total		55.01	78.94	88.53	101.71	128.74

Table 3. Share of Cochin Port in India's foreign trade (in crores of Rupees)

Year	Foreign imports			Foreign exports			Total		
	India	Cochin	Percentage share	India	Cochin	Percentage share	India	Cochin	Percentage share
1950-51	650.21	17.78	2.7	600.64	39.79	6.6	1250.40	53.57	4.3
1955-56	678.84	25.76	3.8	596.32	57.16	9.6	1275.60	76.92	6.0
1960-61	1139.69	35.64	3.1	660.22	58.55	8.9	1799.91	94.19	5.2
1965-66	1408.53	66.11	4.7	805.64	84.44	10.5	2214.17	150.55	6.8
1970-71	1634.20	147.68	9.0	1535.16	163.86	10.7	3164.36	271.50	8.6
1975-76	5265.20	349.69	6.6	4042.25	325.38	8.1	9307.45	675.07	7.3
1980-81	12524.00	759.44	6.1	6711.60	511.17	7.7	19235.00	1270.61	6.6
1981-82	13579.00	850.15	6.3	7781.14	574.14	7.4	21360.00	1424.24	6.7

As a result of the reduction in area and depth, the total volume of brackish water system between Alleppey and Azhikode has been reduced to 22.83%, since the beginning of this century to 1985 (Gopalan et al. 1987).

The Cochin harbour has a dredged approach channel 7.8 km long and 200 m wide, with a dredged depth of 12.8 m and two inner channels viz. Ernakulam channel (6 km long, 255 m wide and 9.75 m deep) and Mattancherry channel (5 km long, 225 m wide and 9.75 m deep). The annual maintenance dredging in the approach channel is above 1.5 m^3 per square metre. The cost of maintenance dredging incurred by the Port was about Rs.862.80 lakhs per year during 1984-85.

There are many investigations pertaining to physical and ecological aspects of the Cochin estuary. Attempts were made to study the hydrographic characteristics of the backwaters, the hydrographic conditions at the harbour inlet, the distribution pattern of the sediment, current pattern in the channels around Willingdon Island with respect to tidal rhythm and its effect on the salinity changes (Shah, 1961; Cheriyan, 1963; George and Kartha, 1963; Ramamirtham and Jayaraman, 1963; Murty, 1965; Cheriyan, 1967; Qasim and Gopinathan, 1969; Josanto, 1971; Wellershaus, 1971; Murty and Veerayya, 1972; Wyatt and Qasim, 1973; Shynamma and Balakrishnan, 1973; Josanto, 1975; Balakrishnan and Shynamma, 1976; Devassy and Gopinathan, 1970; Rama Raju et al. 1979; Sarala Devi et al. 1974; Qasim and Madhupratap, 1981; Udaya Varma et al. 1981; Lakshmanan et al. 1982; Sankaranarayanan et al., 1986).

A few investigations on the problems associated with the sedimentation, viz. the distribution of suspended material, the variation in the siltation rates during different years at several sections of the outer channel etc. had been made earlier (Bristow, 1938; Ducanfe et al. 1938; Gole and Tarapore, 1966; Sunda Raman, 1968; Gopinathan and Qasim, 1971; Rama Raju et al. 1975 and 1976; Anto et al. 1977).

Though these studies described the hydrography, ecology and dynamics of the Cochin estuary in which the harbour is situated, they do not throw much light on the process of siltation in the harbour area.

There are many variables that have to be considered in sediment transport studies in this estuary. Practically no detailed study was conducted on the variations of current with seasons and tidal cycle and the intensity of the current at the surface and subsurface levels and the associated exchange and mixing of the estuarine water with the coastal waters.

The present study is an attempt to elucidate the sedimentation regime of the harbour and its environment. These investigations include detailed studies on the hydrography of the harbour region of the estuary, estuarine circulation, spatial and temporal variations of the amount and texture of bottom sediments. A note on the dredging is also given in the Annexure.

1.6. SCHEME OF THE PRESENT WORK

The thesis is presented in six chapters. Chapter 1 presents a short history on the development of the Cochin Port, present facilities and perspectives and introduces the problem of siltation, behaviour of suspensate in the estuarine environment and the scope of the present studies.

The Chapter 2 details the materials and methods adopted in this study.

The Chapter 3 deals with the hydrography of the Cochin harbour area and its estuarine environment. Monthly data on temperature and salinity collected from Mattancherry channel, Ernakulam channel and Approach channel (a total of 28 stations) are presented and discussed. Time series tidal variations of these parameters on a spring and a neap day were worked out at five selected stations. The freshwater fractionsin each of these channels are calculated.

The Chapter 4 on estuarine circulation reports the results of the studies of water currents measured from fifteen stations in the harbour area. The longitudinal and vertical variations in the speed and direction of estuarine currents caused by the interaction of tides and river discharges have been closely observed. Current variations in the three channels have been discussed separately and supplemented with data on tides and river discharges. Current measurements were also made during springtide and neaptide cycles and the temporal and spatial variations included in this chapter.

The temporal and spatial variations of the amount of suspensate and texture of surficial sediments are presented in Chapter 5. The dynamics of the suspended material is clearly presented. Surface sediment samples were subjected to sieve and pipette analysis and sand, silt and clay fractions are plotted on equilateral triangular diagrams. The discussion of results is followed by comments on the extent of tidal influence on suspended solids distribution and discussion on nature of sedimentation in these coastal waters. The role of estuarine dynamics in modifying the harbour physiography is presented in detail.

Chapter 6 summarises the results of the study and recommends remedial measures. Suggestions for further investigations are also made. Annexure I provides a brief account on the dredging operations conducted in Cochin harbour compiled from the bathymetry charts of the Port.

CHAPTER 2

MATERIALS AND METHODS

2.1. PHYSIOGRAPHY OF COCHIN HARBOUR

The Cochin port is situated in the vast expanse of backwaters formed by the confluence of two major rivers - Muvattupuzha, from the south and Periyar from the north, discharging freshwater through a permanent opening (Cochin barmouth or cut) into Arabian sea* (Fig.1). Two bars along the shore at Vypeen and Fort Cochin, protect the harbour from oceanic perturbances. The river discharges are low during premonsoon

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*recently renamed as Lakshadweep Sea.

(February-March); but during the monsoon season (June-September) the freshet discharge from the north is about 1267 Mm^3 $month^{-1}$ from the Periyar and from the south, 1077 Mm^3 $month^{-1}$ from Muvattupuzha and 394 Mm^3 from the rest of the streams. Freshwater discharge from the rivers make this backwaters a typical positive estuary as per Pritchard's classification (Pritchard, 1967; Fairbridge, 1980); the run-off plus precipitation exceeds evaporation.

An Approach channel is dredged with a east-west orientation (bearing 081°) and this facilitates entry into the harbour area through the cut. This channel within the port area bifurcates (west and east of Willingdon island) into the Mattancherry and Ernakulam channels. The Approach channel is dredged throughout the year to maintain a depth of 11.6 m and the inner channels are maintained at 9.75 m (Manoharan, 1987).

2.2. LOCATION OF THE AREA OF STUDY

The area of investigation and the location of twenty eight stations sampled are given in figure (2). Data on salinity, temperature, suspensate and surficial sediments were collected in Ernakulam channel (stations 1 to 9), northern parts of Ernakulam channel (stations 10 to 12), Cochin cut (stations 13 to 15), Approach channel (stations 16 to 19) and Mattancherry channel (stations 20 to 28). Figure 3 shows the location of fifteen stations at which water current was measured.

In the inner channels (Ernakulam and Mattancherry channels) the stations have been fixed so as to provide coverage of both longitudinal as well as transverse sectors. The period of study extended for twelve months from October 1984 to September 1985; the 25 footer R.V.Sagitta of the School of Marine Sciences was employed for the survey.

Climatologically three prominent seasons can be traced for this region as: (i) premonsoon (February-May), (ii) monsoon (June-September) and (iii) postmonsoon (October-January).

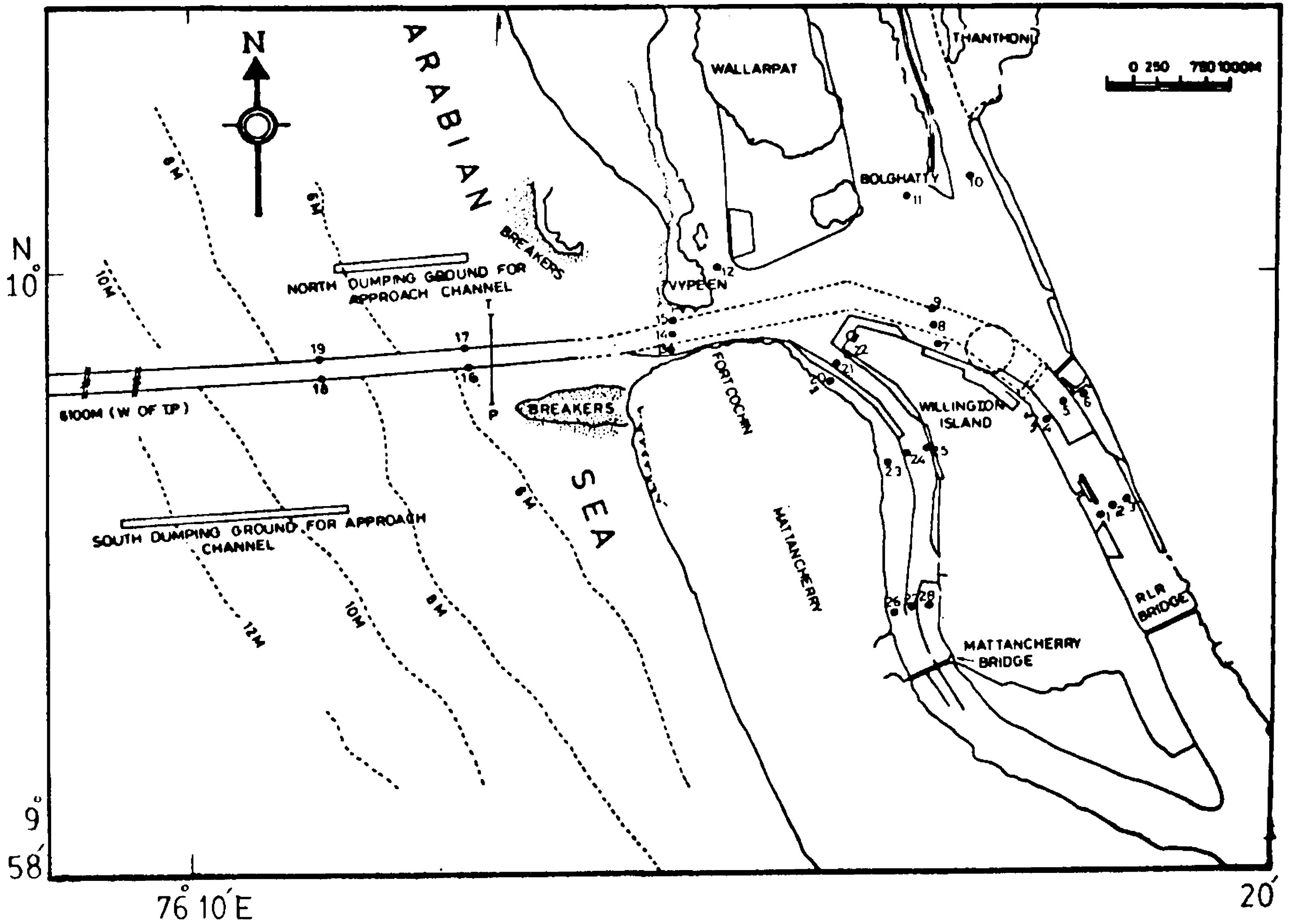


Fig.2. Map showing location of stations 1 - 28.

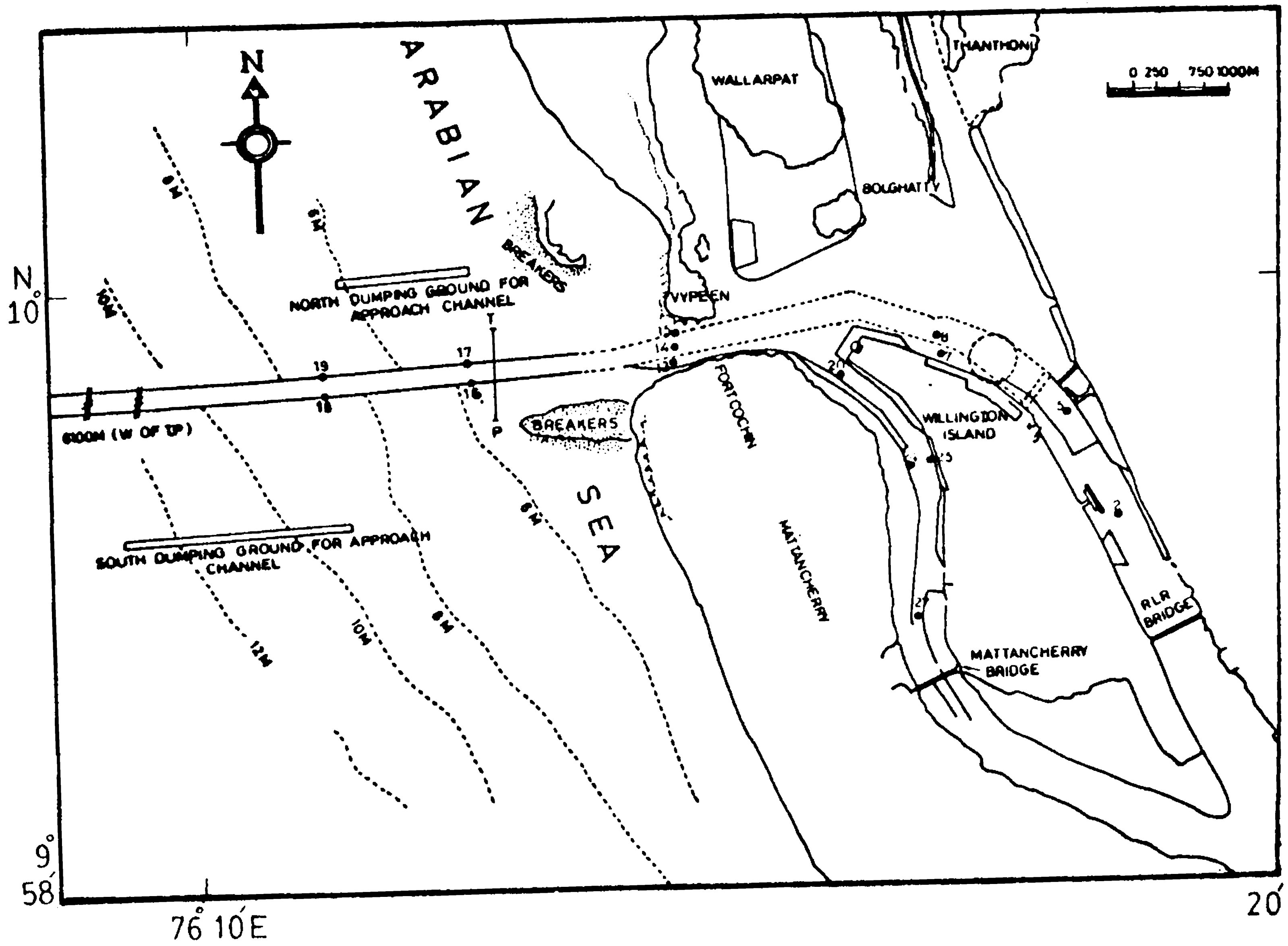


Fig. 3. Map showing location of 15 stations at which water current was measured

Tidal variations of salinity, temperature, water current and suspensate were also studied at five fixed stations (Fig.4); one each in Ernakulam channel (station 1) and Mattancherry channel (station 2) and three stations across the Cochin cut (stations 3 - 5). These observations were made on the full moon (14th September 1984) and new moon (30th November 1984) days to study the variations under springtide and neaptide conditions. The field observations were made at an interval of one and a half hours.

Vertical variability in the harbour area for the parameters such as temperature, salinity, water current and suspensate samples were registered by sampling at 1 m below surface, at mid depths and 1 m above the bottom at each station.

2.3. ENVIRONMENTAL SETTING OF COCHIN HARBOUR AREA

2.3.1. Wind

Wind stress plays a variable but dominant role depending on the local tides and characteristics of wind speeds, in the exchange of water between the coastal bays and inner continental shelf (Gabrielson and Lukatelich, 1985; Setre et al. 1988). Onshore winds are reported to intensify the currents at the bottom and offshore winds at the surface (Arsenyev and Shelkovnikov, 1984). Wind is also shown to have a dominant effect on the mixing processes in a microtidal estuary (Eugen, 1975). Also wind driven currents play an important part in modifying the tidal circulation (Srivastava and John, 1977).

The table (4) shows the wind records for Cochin port for the period 1939 to 1973 (Engineers India, 1986). The predominant wind direction during the months July to September, especially during the peak of the monsoon season, remains persistently northwest, both during morning and evening hours and the effect of land breeze is not at all dominant. The wind direction changes frequently during other months of the year and is from north-east during morning hours and from west during the evening, thus showing the influence of land and sea breezes for this coastal region. The maximum wind speed observed between the years 1939 to 1973 was 112 km hr^{-1} from west-southwest direction.

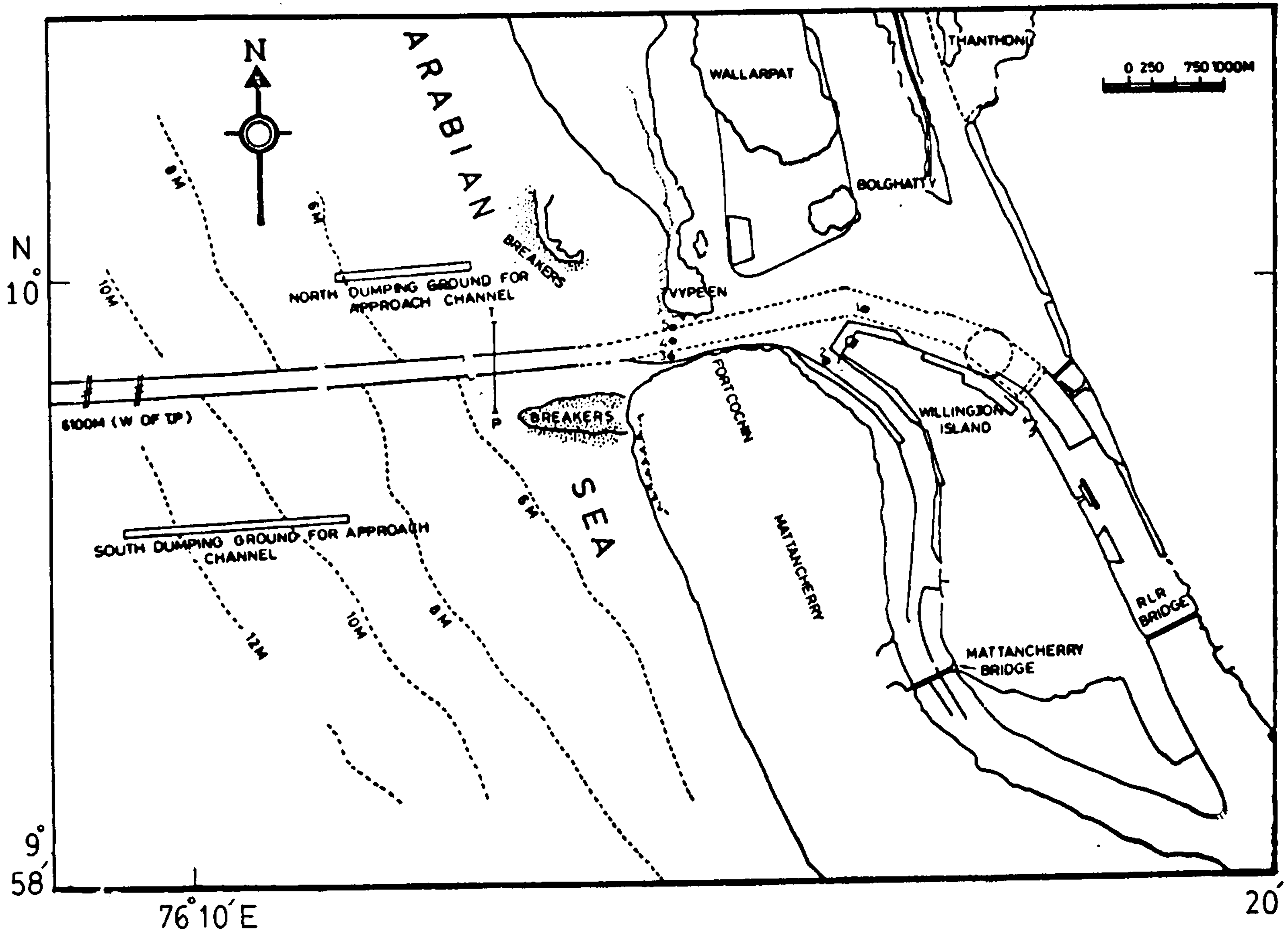


Fig.4. Map showing location of 5 stations selected for semidiurnal observations

Table 4. Monthly maximum wind speed and direction observed in Cochin harbour area during the period 1939 to 1973 (Engineers India, 1986).

Month	Maximum velocity km/hr	Direction	Predominant direction
January	58	SSE	W
February	53	N	W
March	80	SSW	W
April	88	SSW	W
May	112	WSW	W
June	86	WNW	W
July	93	SW	NW
August	93	NNW	NW
September	77	WNW	NW
October	67	NNW	W
November	69	WNW	W
December	64	SSE	W

2.3.2. Waves

Deep water waves are long waves or swells and as they invade shallow estuarine regions their circular motion become more elliptical and asymmetrical. This causes a shear velocity which in turn initiates the sediment movement (Anderson, 1983; Fu, 1987). Waves also retard settlement of suspended material which are transported into channels by the tidal current (Mehta, 1987). Flood tides move them landward and lead to turbidity maxima in rivers (Richard; 1985; Inman and Jenkins, 1987).

Wave action off Cochin is having only limited role in the sedimentary environment of the inner harbour because of the narrow entrance. The wave conditions reported by various naval and merchant vessels traversing the area were analysed by Engineers India (Table 5). Generally, rough conditions prevailed during June, July and August (monsoon) while calm conditions were observed during rest of the year.

2.3.3. Tides

Tides contribute a major share of energy in estuaries during the mixing of fresh and saline waters and also, towards resuspending sediments from the bed. The role of tides and associated tidal currents in transporting suspended sediments seawards or landwards has been discussed by many workers (Dingler and Clifton, 1984; Uncles et al. 1985). The phenomenon is better described as reversing currents associated with the tides, mostly conspicuous in the vicinity of the river mouths, in transporting the bottom sediments in conjunction with the currents (Johnson, 1966). In the coastal environment, tidal flow must be taken into account to study the dynamic processes (Saloman, 1985). Tides also affect the sedimentary behaviour in estuaries through three fundamental processes:(1) tide wave deformation with distance landward, (2) tidal discharge and channel stability and (3) cyclic tidal current fluctuations (Nichols and Biggs, 1985).

The tides in the Cochin estuary are of a mixed type, predominantly semidiurnal (Qasim and Gopinathan, 1969). The highest high water spring is 1.05 m, mean higher high water 0.90 m, mean lower high water 0.79 m, mean sea level 0.64 m, mean higher low water 0.56 m, mean

Table 5. Normal wave condition off Cochin (Engineers India, 1986).

Month	Average significant height in m	Predominant direction
January	0.80	N
February	0.70	N
March	0.90	N
April	0.90	NW
May	1.10	NW
June	1.30	WSW
July	1.60	W
August	1.30	W
September	1.20	W
October	1.00	W
November	1.00	W
December	0.90	N

lower low water 0.29 m and lowest low water spring 0.20 m (Frederick, 1974). The average range of tides for the premonsoon, monsoon and postmonsoon season is 0.46 m, 0.47 m and 0.43 m respectively (Udaya Varma et al. 1981).

On the west coast of India, mean sea level is lower than normal during monsoon months due to the divergence of the surface layers of the sea and the consequent upward flow of the cold dense water from deeper layers. This over compensates the effect of the low density surface waters on the mean sea level, due to fresh water influx during the southwest monsoon season. The lowering of the mean sea level aids the quick flushing of the estuarine water through the barmouth (Karl, 1968).

The exact time interval of the monthly collections in the harbour area are given in figures [5 (i & ii)]. As far as possible all the collections were attempted to coincide with the same phase of the tide in the respective channels. However, for the months of October, 1984 and February, March, April, June, July, August and September 1985, Ernakulam channel was in the flood phase and the rest, ebbing at the time of observations. The Mattancherry channel exhibited ebbing in October, 1984 and January, April, June, July, August and September 1985 and flood phase in the rest of the months. An extensive study was conducted at five stations to understand the behaviour of salinity, water current and suspensate on a spring tide (14.09.1984) and neap tide (30.11.1984).

2.3.4. River Discharge

River discharges supply significant amounts of freshwater to the Cochin estuary. River inflow causes longitudinal and vertical salinity gradients which in turn cause a unique estuarine circulation pattern for dispersal of sediments (Gibbs, 1977; Army Corps, 1984 and Sambasiva Rao, 1987). River flooding can also produce exceptionally different hydrodynamic conditions with important sedimentological consequences. During flooding, more sediment is supplied to an estuary within a few days than during months or years of average inflow.

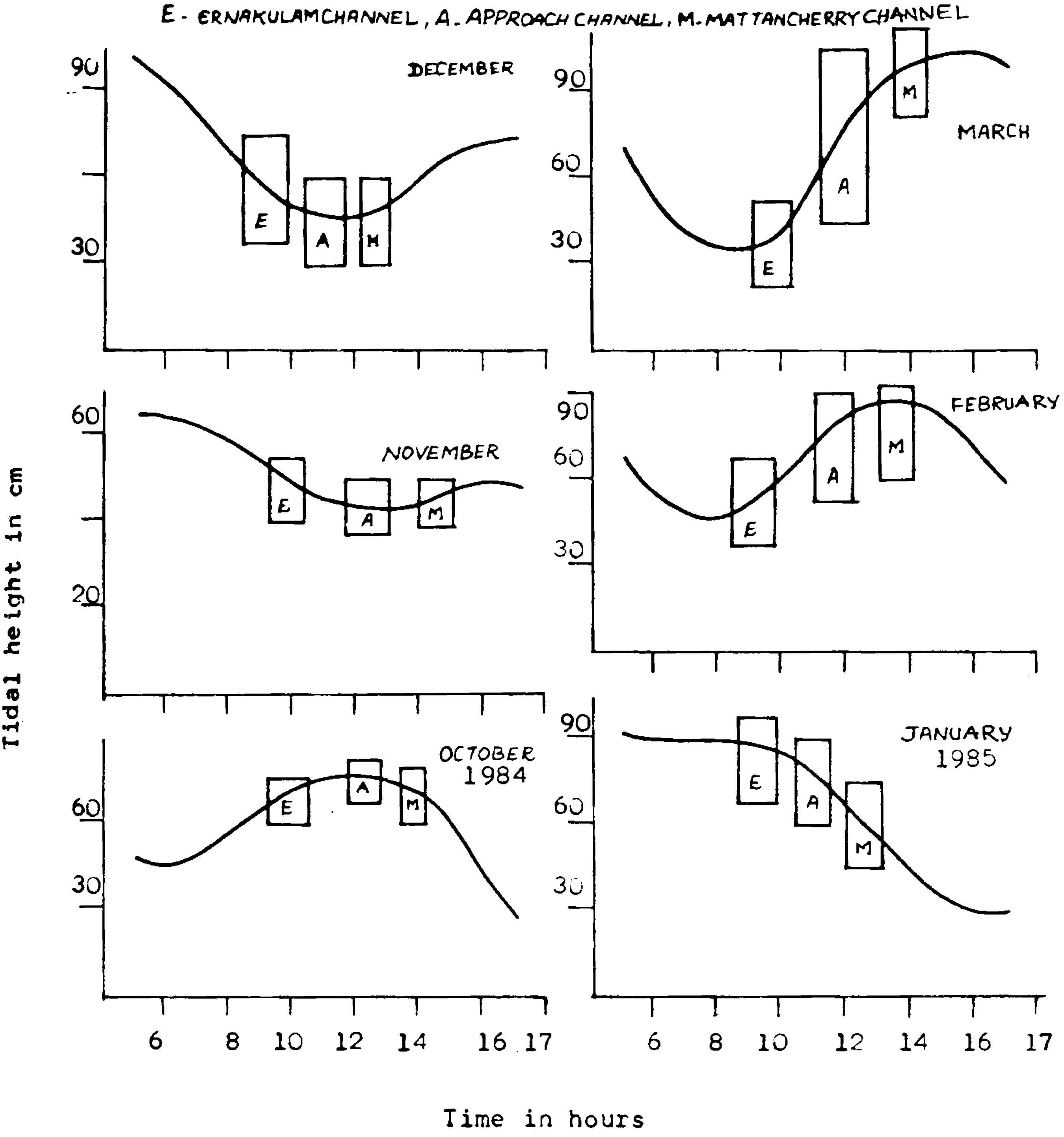
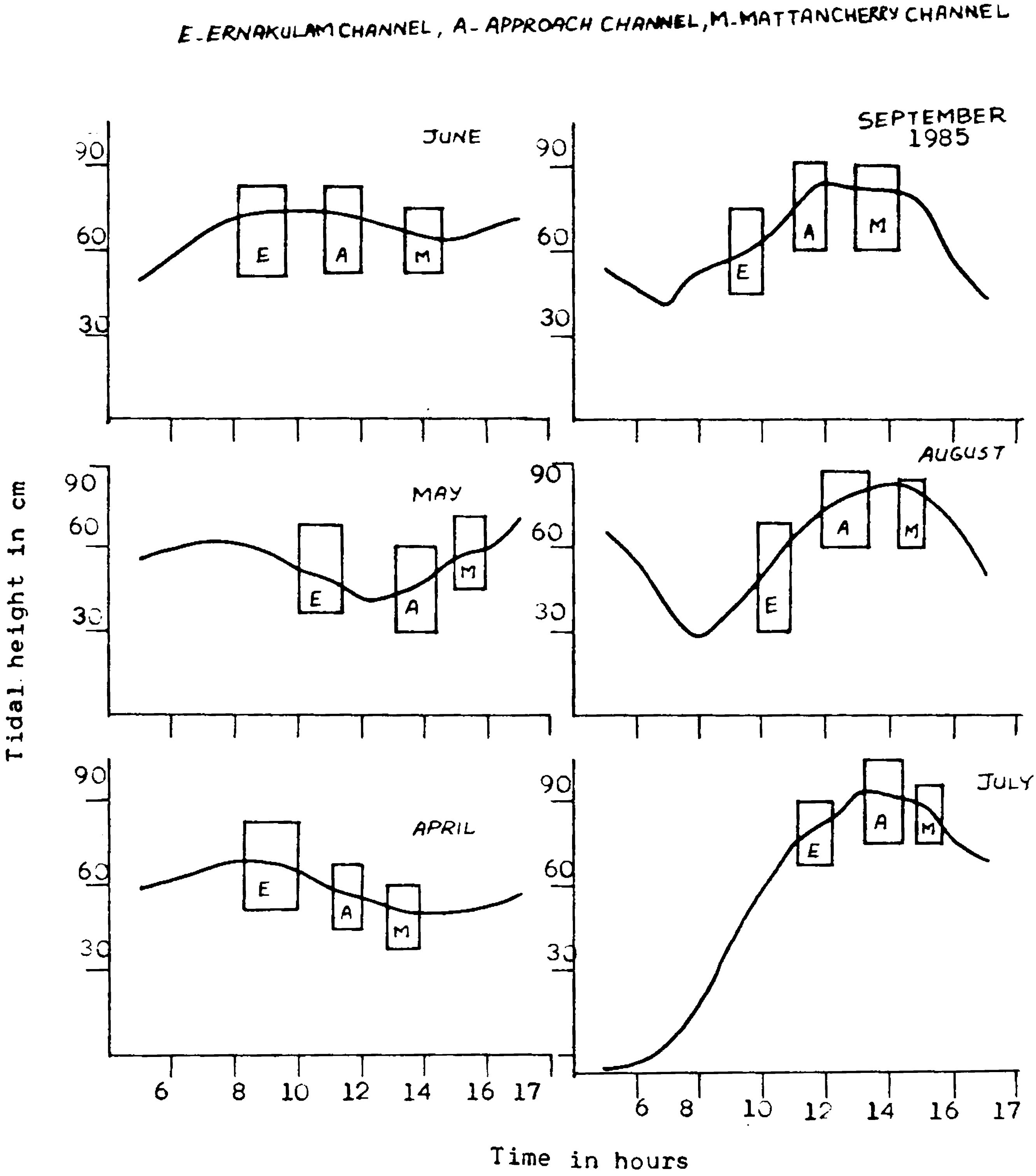


Fig. 5(i). Tidal height variations at Ernakulam, Approach and Mattancherry channels - October 1984 to March 1985



Time in hours

Fig. 5(ii). Tidal height variations at Ernakulam, Approach Mattancherry channels - April to September 1985.

Hydrology of the Muvattupuzha river is controlled by the discharge of tail race water from the Idukki hydroelectric station; this largely influences the hydrography of the southern parts of Cochin backwaters (Lakshmanan et al. 1982). During May 1985, the discharge from Periyar river was 112 Mm^3 (Table 6). While the amount of discharge from Muvattupuzha increased from 124 Mm^3 in February 1985 to 1422 Mm^3 and 1511 Mm^3 in June and July, 1985 respectively, the discharge in Periyar river was 1597 Mm^3 and 1590 Mm^3 in these months. In August while the discharge from Muvattupuzha river marginally decreased to 930 Mm^3, the quantity flowing through Periyar river remained around 1368 Mm^3.

The Periyar river discharge was 29 Mm^3 in February 1985 which rose to a very high value of 1597 Mm^3 in June 1985 and then decreased gradually. The discharge was measured as minimum in February and March of 1985 for Periyar river and the minimum in February for Muvattupuzha river. The table also supplements the monthly river discharge from rivers Achencovil, Manimala, Pamba and Meenachil encompassed within Thanneermukkam Bund.

2.3.5. Rainfall

The total rainfall in the Cochin harbour area during the period October 1984 to September 1985 was 322 cm (Marine Survey Division, 1985). The seasonal variations are depicted in the figure 6, which indicate heavy monsoonal rainfall in Cochin. Analysis of long term data also reveals singular very high maxima of rainfall in the coastal regions of Cochin to occur during monsoon months (Ananthakrishnan et al. 1979). Copious rainfall was recorded during the last week of May 1985 due to the earlier date of onset of monsoon. In postmonsoon season, especially during the month of October, a secondary maximum in rainfall was also observed. The varied seasonal rainfall can produce exceptional hydrodynamic conditions with important sedimentological consequences.

Table 6. Monthly river discharge (rounded to a whole number) in Mm^3 and suspensate load (10^6 Kg).
(Year Book on Surface Water; 1984 and 1985)

Rivers	1984			1985									
	OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER	
Muvattupuzha	467	202	133	162	124	147	161	240	1422	1511	930	447	
Periyar	775	170	71	80	24	34	59	112	1597	1590	1368	513	
Achencovil (+)	358	149	70	117	52	28	52	56	433	615	204	170	
Pamba (+)	505	203	81	153	71	65	63	104	1160	1000	366	296	
Meenachil (+)	149	36	25	-	-	26	66	103	613	309	119	46	
Manimala (+)	156	61	18	46	19	7	14	46	412	363	124	76	
	SUSPENDED LOAD												Total
Muvattupuzha *	11.68	6.06	2.66	2.92	2.48	2.65	2.42	4.8	56.86	52.89	27.9	13.4	186.72
Periyar *	19.38	4.76	1.42	1.20	0.29	0.51	1.18	2.46	47.91	39.76	27.36	15.39	161.62

(+) Suspended load contribution to Cochin estuary relatively insignificant due to impoundment at Thanneermukkam Bund.

(* Personal Communication, Nair, S.M., unpublished data.)

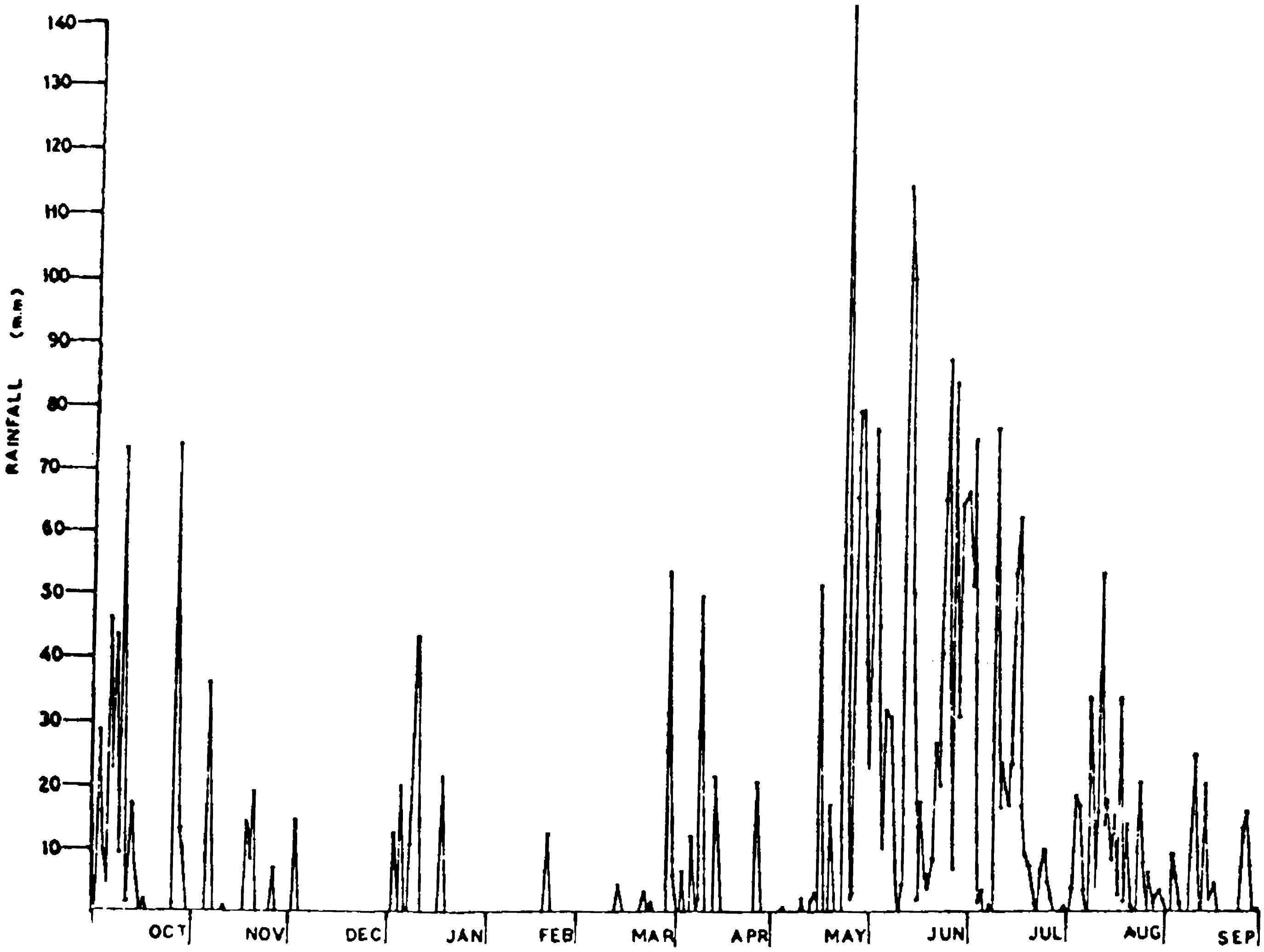


Fig.6. MONTHLY RAINFALL AT COCHIN DURING OCTOBER 1984 TO SEPTEMBER 1985

2.4. FIELD-DATA SAMPLING PROCEDURES

2.4.1. Salinity, Temperature and Depth

A S.T.D. digital meter (make - Central Institute of Fisheries Technology, Cochin) was used for instantaneous measurement of salinity, temperature and depth in the estuarine waters; the instrument operates in the range 0 - 38 x 10^{-3} (accuracy ± 0.01 x 10^{-3}) salinity, 10 - 35°C (± 0.1°C) temperature and 0 - 30 m (± 0.1m) depth. The calibration was checked by standard procedures (Grasshoff et al. 1983).

2.4.2. Water Currents

Observation on water currents were made by a direct reading Digital Current Meter (make - Central Institute of Fisheries Technology, Cochin). The unit consists of an underwater probe and an electronic readable unit. Current speed was measured by propellor drive mechanism and direction sensed by means of an electromagnetic compass installed inside the probe. The signals from the underwater probe are electrically conveyed to the onboard unit through a copper cable and displayed on a digital counter. The magnitude of current is determined in the range of 0 - 400 cm sec^{-1} (accuracy ± 1 cm sec^{-1}) and direction to within ± 5°. The instrument was calibrated by standard methods (Sivadas, 1983).

2.5. LABORATORY ANALYSES

2.5.1. Suspended Solids Content

Water samples collected from the surface, middle and bottom depths by a Hytech sampler of 2 litre capacity were subjected to filtration by suction as described by Buller and Mc Manus (1979). One litre of the homogeneous representative suspension was filtered through preweighed No. 42 Whatman filter using a Buckner funnel; the filters were washed with small volumes of distilled water to eliminate salt content, if any, in the suspensate. The filters were dried at room temperature in a desiccator over anhydrous calcium chloride to constant weight and the amount of suspended solids determined as difference of weights.

2.5.2. Textural Analysis of Surficial Sediments

Surficial sediments were collected monthly from all twenty eight stations using a van Veen grab; a total of 336 samples were collected. The top 5 cm of the sediment was carefully skimmed, homogenised and subjected to mechanical analysis by the technique described by Krumbein and Pettijohn (1938) and Selley (1988). Of these, 28 sandy samples were analysed by sieving method and the remaining, by the combined sieving and pipetting techniques.

Sandy sediment samples were coned and quarted and representative portion of about 100 g taken for analysis. The repeatedly washed sample was dried and sieved for fifteen minutes on a mechanical Ro-Tap sieve shaker using a set of standard ASTM Endecott Sieves of unit phi intervals. The fractions left over in each sieve were separately weighed.

In the grain size analysis of muddy sediments, 10 g of dry sample was dispersed in 0.025 N solution of sodium hexametaphosphate with about 300 ml of distilled water and allowed to stand overnight. The coarse fraction was isolated by wet sieving of 230 mesh size and again dried to constant weight. The filtrate of silt-clay fraction was transferred into a graduated 1 litre measuring jar and after making up the volume to one litre using distilled water, the suspended material was stirred thoroughly until a homogeneous suspension was formed. 20 ml pipette samples were drawn at fixed time intervals and depths from the suspension jar as per the settling time given by Krumbein and Pettijohn (1938), computed according to Stokes law. The collected aliquots were oven dried and weighed accurately. The results are computed in a probability chart as the cumulative weight percentage plotted against the respective grain sizes (in microns). From the above size frequency chart the 5,16,25,50,75,84 and 95 percentiles (in microns) were found out, which were later converted into phi units using the phi-milli meter conversion table given by Page (1955). For those clay sediments which do not attain higher percentiles, the conventional extra-polation method suggested by Folk and Ward (1957) was followed.

CHAPTER 3

ESTUARINE HYDROGRAPHY

3.1. INTRODUCTION

The hydrography of the estuarine environment plays an important role in characterising the fluvial and siltation processes (Skelly, 1985). These studies are important while quantifying sedimentation rates with regard to harbour design and marine traffic routing. The hydrographical conditions of most estuaries mainly depend on seawater intrusion, controlled by tidal currents and freshwater influx from rivers. Additionally climatic changes, topography of the estuary and the geographical shape have marked influence on the hydrographical setting.

Several researchers have studied the hydrography of the Cochin estuary (Ramamirtham and Jayaraman, 1963; George and Kartha, 1963; Qasim et al. 1968; Sankaranarayanan and Qasim, 1969; Josanto, 1971; Wellershaus, 1971; Haridas et al. 1973; Shynamma and Balakrishnan, 1973; Manikoth and Salih, 1974; Rama Raju et al. 1979; Udaya Varma et al. 1981; Lakshmanan et al. 1982; Sankaranarayanan et al. 1986). These investigations on the distribution of temperature, salinity and water currents in this tropical estuary have provided valuable information on hydrographical changes.

The studies on salinity variations in Cochin backwaters by Josanto (1971) reveal the distribution pattern of salinity at the bottom layers to be influenced by the freshwater inflow. During the freshet season the saline waters in this estuary are confined to a small portion at Cochin barmouth. The northern parts of the estuary are subjected to higher salinity wedging and have comparatively higher temperatures than the southern parts (Lakshmanan et al. 1982). The rapid build-up of stratification in the lower estuarine regions have been observed by Rama Raju et al. (1979) and Udaya Varma et al. (1981). Again during monsoon months significant vertical gradients in temperature were noticeable between surface and bottom layers (Rama Raju et al. 1979). Sankaranarayanan et al. (1986) point out to the seasonal changes of salinity in this waterway, varying the estuarine conditions from a partially mixed type during monsoon to homogeneous during post and premonsoon. However, the above studies cover various parameters other than suspensate.

In very recent years, environmental changes have influenced the hydrographical conditions of Cochin estuary. It has been considered pertinent to obtain detailed and accurate information on the range of variation and distribution of these hydrographical features. An attempt is made to describe the hydrographical features of Cochin estuary in conjunction with studies on suspended solids distribution and associated siltation processes during the period of survey (October 1984 to September 1985).

3.2. EXPERIMENTAL

The materials and methods employed in this study are described in Chapter 2.

3.3. RESULTS & DISCUSSION *

3.3.1. Temperature

The estuarine distribution of temperature is dependent largely on mixing of inflowing river water and tidally influenced seawater. Seasonally, solar radiation and evaporation add to the factors influencing temperature variations; localised heat discharges too alter the temperature of the receiving body. Two sets of phenomena govern the behaviour of sediment-laden flows with changing water temperatures. One of these involves the change in fall velocity of the sediment grains with change in viscosity associated with varying water temperature. As the temperature lowers, the fall velocity of the sediment grain diminishes which would cause the concentration of suspended sediments to become more uniformly distributed over the depth of flow (Army Corps, 1969). Franco (1968) found by flume studies that for a given velocity, a drop in temperature results in an increase in sediment discharge. Taylor (1971) observed that the effect of temperature on the removal of particles of different size fractions are dependent on Reynolds number R_*; for the value of R_* in the range, less than 13 to near 20, a decrease in water temperature would cause a decrease in the discharge of the finer fractions and an increase in that of the coarser ones. A drop in temperature and consequently fall velocity, tends to increase the suspended load in the upper levels of the flow relative to those near the bed. Since the flow velocity in the upper level is higher than near the bed, an increase in concentration in these levels will also tend to increase the suspended solids discharge (Vanoni, 1977). The second phenomenon, rather obscure, is the effect of temperature on stream bed surface and the reduced bed form heights diminishing resistance to flow (Taylor and Vanoni, 1972). The hypothesis is that a drop in temperature (or increase in viscosity) tends to protect the bed by increasing the laminar sublayer thickness (Franco, 1968).

The viscosity of the medium, functionally related to temperature influences the suspensate concentration in overlying waters . Generally, viscosity of a liquid decreases with rise in temperature. The decrease is appreciable, about 2% per degree rise of temperature in many cases (Glasstone, 1962). Hence a change in temperature is likely to cause variation in seston content.

The effect of temperature on the suspended solids distribution in streams is a topic of continued interest of study. The phenomena and associated processes are still being probed in-depth. The scope of investigating the variation of temperature and its implied effects on sedimentation in Cochin harbour area is however limited to the study of this parameter to describe the hydrographical features. The spatial and temporal variability of temperature likely to influence the suspensate distribution is deduced in explaining the siltation features.

3.3.1.1. Temporal and Spatial Variations in Temperature

The water temperature at surface and bottom in the harbour area observed monthly from october 1984 to September 1985 at 28 stations is presented in Table 7; Figure 7 indicates graphically the temperature variations (both surface and bottom) of selected stations in the three channels — Ernakulam channel: stations 2, 5 and 8; Approach channel: stations 14,16 and 18 and Mattancherry channel: stations 21,25 and 26.

In general, the surface water temperature of the harbour varied between 29.7°C and 31.4°C and between 29.7°C and 31.1°C at bottom during the premonsoon season (Table 7); between 24.5°C and 30.3°C at the surface and between 21.4°C and 30.2°C at the bottom during monsoon

Table 7. Monthly water temperature (^{o}C) at stations 1-28 at surface and bottom.

Station No.	Depth in (m)		Months											
			1984			1985								
			OCTOBER	NOVEMBER	DECEMBER	JANUARY	FEBRUARY	MARCH	APRIL	MAY	JUNE	JULY	AUGUST	SEPTEMBER
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	3.5	Surface	29.3	28.9	28.0	28.2	29.3	30.5	30.3	23.7	25.6	25.7	28.0	29.1
		Bottom	28.4	28.7	28.2	28.5	29.3	29.6	30.3	23.4	25.6	21.4	27.1	28.6
2	9.0	Surface	28.2	28.5	28.0	28.4	29.4	30.6	30.4	24.4	24.7	27.0	28.3	30.2
		Bottom	26.6	28.5	28.1	28.4	29.3	30.6	30.1	24.0	25.9	22.5	23.8	28.9
3	3.0	Surface	28.5	28.7	28.1	28.3	29.3	30.7	30.5	24.3	26.6	26.3	28.2	29.2
		Bottom	28.1	28.5	28.1	28.2	29.3	30.6	30.2	24.3	25.4	23.4	27.8	29.2
4	3.5	Surface	28.6	28.9	28.0	28.4	29.5	30.6	30.4	24.4	26.4	26.0	28.5	29.0
		Bottom	28.5	28.8	28.2	28.2	29.3	30.6	30.3	24.4	26.0	22.7	28.4	28.4
5	10.0	Surface	28.1	29.0	28.0	28.7	29.5	30.6	30.5	25.6	25.9	25.7	28.3	28.9
		Bottom	26.7	28.9	28.2	28.4	29.3	30.6	30.1	25.2	24.7	23.0	24.1	28.8
6	2.5	Surface	28.2	29.1	28.0	28.4	29.4	30.6	30.5	25.0	25.5	25.4	28.2	29.2
		Bottom	27.8	28.8	28.1	28.2	29.4	30.6	30.4	24.8	25.4	24.6	28.1	28.6
7	9.2	Surface	28.6	29.0	28.1	28.7	29.5	30.6	30.5	26.0	26.2	25.5	28.4	28.6
		Bottom	27.7	28.7	28.0	28.2	29.1	30.5	30.1	25.0	25.2	24.4	26.5	26.9

... 2.

Table 7. Contd.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
8	10.0	Surface	28.6	29.3	28.6	28.5	29.4	30.6	30.4	25.9	26.4	25.6	28.3	28.7
		Bottom	27.6	29.0	28.3	28.4	29.3	30.5	30.1	25.2	25.1	23.5	24.3	28.7
9	4.0	Surface	28.7	29.5	28.7	28.4	29.3	30.9	30.5	25.4	26.4	25.5	28.1	28.9
		Bottom	28.4	29.0	28.2	27.5	29.3	30.9	30.1	25.4	26.4	24.0	27.8	28.6
10	5.0	Surface	28.2	29.9	28.9	28.3	29.9	31.2	30.8	25.8	26.4	26.6	27.3	28.6
		Bottom	27.2	29.1	28.3	28.0	29.3	30.9	30.4	25.8	26.0	25.1	27.1	28.4
11	3.5	Surface	28.4	29.8	28.7	28.5	30.1	31.5	30.8	26.0	26.6	25.6	27.4	29.1
		Bottom	27.7	29.0	28.4	28.2	29.5	30.7	30.4	25.6	26.4	24.7	27.4	28.8
12	5.0	Surface	30.0	29.8	28.6	28.3	29.7	31.1	30.8	26.0	27.1	24.8	28.7	30.2
		Bottom	28.8	29.7	28.4	28.2	29.3	31.0	30.2	25.6	26.6	23.6	28.0	28.7
13	12.0	Surface	28.5	29.9	28.8	28.5	29.8	31.0	31.0	25.8	25.8	25.1	28.9	28.5
		Bottom	27.2	29.2	28.3	28.2	29.3	30.5	30.0	25.5	25.0	22.4	23.2	27.0
14	12.0	Surface	29.8	29.8	28.7	28.5	29.8	31.0	31.0	25.8	27.4	26.4	28.4	28.7
		Bottom	27.4	28.9	28.2	28.4	29.3	30.5	30.1	25.8	25.9	23.7	23.2	27.5
15	7.0	Surface	29.4	29.5	28.6	28.4	29.8	31.4	31.0	25.9	27.1	26.4	28.5	29.4
		Bottom	28.1	29.2	28.3	28.3	29.8	31.4	30.4	25.8	26.0	24.7	23.5	28.6
16	9.0	Surface	29.1	29.8	29.1	28.5	29.8	30.9	31.1	25.8	27.4	26.4	28.3	29.3
		Bottom	28.0	29.0	28.3	28.5	29.4	30.3	30.0	25.6	25.4	21.9	24.1	28.5
17	9.0	Surface	29.4	29.5	28.6	28.5	29.5	31.0	30.8	25.5	26.6	26.3	28.7	29.7
		Bottom	28.0	24.8	28.3	28.2	29.10	30.2	30.2	25.6	25.9	23.1	23.3	28.0
18	9.5	Surface	29.8	30.1	28.7	28.6	29.8	31.0	31.4	-	26.8	26.3	24.5	28.8
		Bottom	27.6	28.6	28.3	28.5	29.1	29.6	30.2	-	24.5	21.8	23.2	27.4

... 3.

Table 7. Contd.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
19	8.0	Surface	29.5	29.7	28.4	28.4	29.5	30.5	31.5	-	27.0	25.8	28.6	29.2
		Bottom	27.10	28.9	28.3	28.3	29.4	30.5	30.7	-	25.2	21.4	23.5	28.0
20	3.0	Surface	29.1	30.4	28.8	29.4	29.8	31.4	31.0	25.6	27.7	25.8	29.0	29.8
		Bottom	29.0	30.4	28.7	28.6	29.3	30.5	31.0	25.0	27.1	23.7	26.7	29.1
21	10.0	Surface	29.9	30.8	28.8	28.7	29.9	31.3	31.3	25.5	26.8	25.2	29.3	29.3
		Bottom	27.6	28.8	28.4	28.7	29.3	30.4	29.9	25.4	26.0	22.5	23.4	28.2
22	3.0	Surface	30.1	30.2	29.4	28.8	29.8	30.7	31.3	25.5	28.5	24.8	29.2	29.3
		Bottom	27.9	29.5	28.9	28.8	29.5	30.5	30.7	25.4	26.0	22.7	25.2	28.9
23	2.7	Surface	30.1	30.7	29.5	28.8	29.8	30.7	31.3	25.5	28.6	25.0	29.1	29.7
		Bottom	29.2	30.5	29.2	28.7	29.8	30.9	30.6	25.1	27.2	22.4	26.2	29.1
24	8.0	Surface	30.0	30.6	29.2	29.3	30.2	31.3	31.2	25.8	29.6	25.3	29.2	30.2
		Bottom	27.4	29.1	28.7	28.8	29.1	30.6	30.0	25.6	27.5	22.7	26.6	26.6
25	9.2	Surface	30.0	31.0	30.2	29.3	29.9	31.1	31.3	25.8	28.7	25.1	29.3	30.3
		Bottom	27.8	29.0	28.8	28.7	29.3	30.3	30.0	25.2	27.7	22.3	25.6	27.4
26	3.0	Surface	29.8	30.4	29.8	29.1	30.2	31.4	31.0	25.1	27.9	25.0	28.6	29.3
		Bottom	28.1	29.7	29.0	28.8	29.5	30.7	30.4	24.2	27.2	21.9	27.6	28.5
27	3.9	Surface	29.5	30.9	29.2	29.1	30.1	31.1	31.1	25.25	29.3	25.5	29.4	29.5
		Bottom	28.9	29.3	28.9	28.8	30.1	31.1	30.1	25.0	28.3	21.9	24.7	28.3
28	2.5	Surface	30.4	30.6	30.0	29.0	30.1	31.1	31.7	25.8	30.6	25.4	29.4	30.3
		Bottom	30.1	30.6	29.3	29.0	30.1	31.1	31.7	25.0	27.8	24.4	29.8	29.4

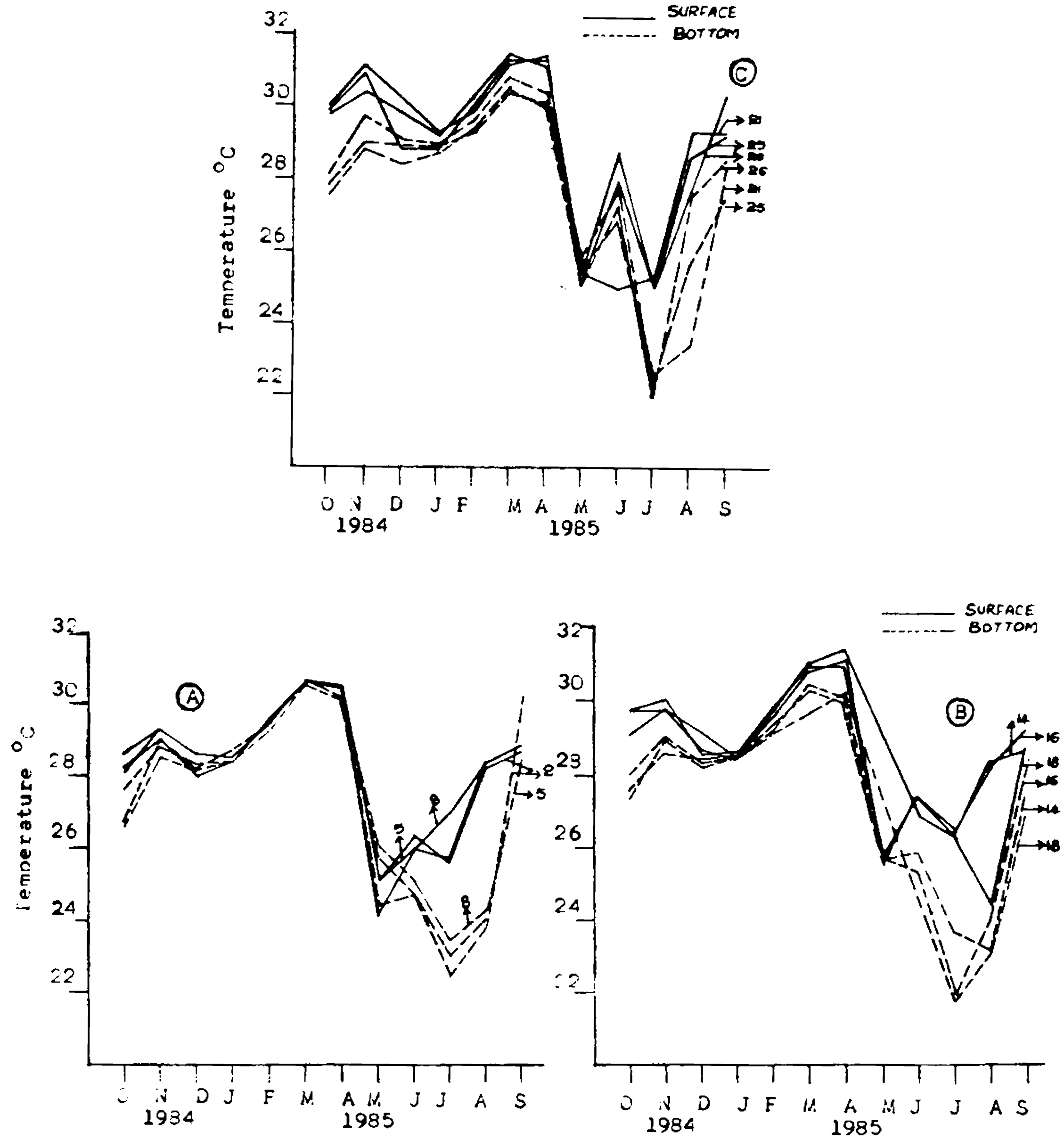


Fig.7. Temperature variations at surface and bottom from October 1984 to September 1985 at stations
A) Ernakulam channel - 2,5 and 8
B) Approach channel - 14,16 and 18 and
C) Mattancherry channel - 21,25 and 26.

season and 28.1°C and 30.4°C at the surface and between 26.6°C and 30.1°C at the bottom during postmonsoon. In May, the temperature of the whole water body was considerably low compared with the surface temperature 31°C and bottom temperature 30°C of the previous month, April. The range of values recorded in May were 23.7°C to 26°C at surface and 23.4 to 26°C at bottom.

The surface temperature values were less during the monsoon months and higher during the premonsoon months. The low temperature during monsoon months is the result of decrease in solar radiation because of overcast skies (Portman and Ryznar, 1971), increased evaporation (Venketeswaran, 1956; Jagannathan and Ramasastry, 1964); cold freshwater influx from rivers (Lakshmanan et al. 1987) and incursion of cool upwelled waters (Rama Raju et al. 1979).

The semidiurnal variations in temperature of the waters of the Cochin estuary depend on the range of the tide, the maximum variation being about 1.6°C under neaptide conditions and about 2.6°C under springtide conditions. The increased temperature gradient at the springtide may be due to the low temperature at the surface levels in monsoon season.

The lowest annual water temperatures in Cochin backwaters usually occur during the monsoon season. This had been the observation made by Ramamirtham and Jayaraman (1963), Karl (1968), Gopinathan and Qasim (1971) and Rama Raju et al. (1979) in this estuary. Gopinathan and Qasim (1971) reported the lowest value of temperature as 23°C. This observation was explained as due to the incursion of cold upwelled water from shelf region into the backwaters. The temperature of the nearshore waters at 20 m depth was read as 20-23°C during monsoon (Rama Raju et al. 1979). The upwelled water reaches the surface by May and the intensity of upwelling weakens with the strengthening of the southwest monsoon (Sharma, 1978). The direct influence of this feature is to lower the outer estuarine water temperatures.

The lowest temperature observed during this study was 21.4°C which is less than the earlier reported value of 23°C. The earlier observations were mostly made in the inner harbour waters. Presence of cooler water (21.4 - 22.7°C) recorded in the lower parts of estuary are attributed to stronger upwelling and its incursion into the estuary. Both these factors are likely to influence the suspended solids distribution in these parts of the water body during monsoon.

In the Ernakulam channel, the temperature was maximum during March and April 1985 and minimum during May and July (Fig.7). After the monsoon season, the temperature increased to a secondary maximum as observed in November 1984 (31.0°C) and by the end of postmonsoon season of 1984 the value decreased by about 1°C. In the Mattancherry channel also the seasonal variations of temperature at surface and bottom exhibited similar trends as in the case of Ernakulam channel. The increase in temperature during June, after the initial spell of heavy rains during the last week of May 1985, was more conspicuous in the Mattancherry channel than in Ernakulam channel. The variability of temperature in the Approach channel was higher than in the two inner channels.

3.3.2. Salinity

The inflow of freshwater. mixing and flushing affect salinity distribution in the estuarine waters. Wide ranging differences of several parts per thousand is often encountered in spatial and temporal distribution of salinity (Paul, 1967). In the lower reaches of the estuaries where surface to bed difference in salinity are of the order of several parts per thousand, gravitational circulation is an important component of the residual flow (Uncles et al. 1985). The transport of suspended sediments and the formation of the turbidity maximum, have often been attributed to gravitational circulation and the existence of null point (Festa and Hansen, 1978; Officer, 1980). During transport and after deposition, the estuarine suspensate may also undergo many physico-chemical changes as a result of salinity variations. Mixing processes in estuaries influence the settling velocity of suspensate, while flocculation and deflocculation processes affect their distribution (Postma, 1967). The variability of salinity in the three channels of Cochin harbour, considered separately, are presented and analysed by means of isohaline contours drawn within scaled diagrams.

3.3.2.1. Ernakulam Channel

The salinity distribution at surface, middle and bottom waters of Ernakulam channel are given in figures 8, 9 and 10.

During October 1984 of the postmonsoon season, the surface salinity decreased towards the southern end of the channel (Fig. 8). This was due to the increased and continued freshwater discharge from Muvattupuzha river. But streaks of high saline water extends through the bottom layers of this ship channel as the flood tide progresses. The salinity gradient in the deeper parts of the channel together with the high saline streaks reveal the presence of convergent frontal phenomena driven by the buoyancy forces associated with freshwater discharge (due to the extended monsoon). Similar observations are reported by Nunes and Simpson (1985) in an estuary in North Wales during the flood tide. The figure further depicts that more mixed water in November, December and January was present in the channel than in the month of October, though the observations were taken during the ebbtide phase. The range of salinity values were also narrow to define any significant variability.

During the premonsoon months (Fig. 9) observations were taken during flooding in the months of February and March and high slack in April and of ebbing in the month of May. The thinned and curved nature of the isohalines i.e. the thickened watermass depicts comparatively mixed water column in this season. The salinity of bottom water in April (31.5×10^{-3}) was very high due to the reduced freshet. However, this also reveals that the salinity in the channel was always less than the coastal waters. Udaya Varma et al. (1981) had also observed this characteristic feature of high salinity in the bottom waters of the channel. At the commencement of flood in Ernakulam channel, during the observations in February and March 1985, the first indication of tidal currents pushing saline waters upstream started at bottom as a wedge gradually spreading to surface. The pattern of isohalines also point out that the higher salinity waters penetrate upstream with an inclination along the outer curvature of the channel. This generates transverse gradients in this channel, likely to cause

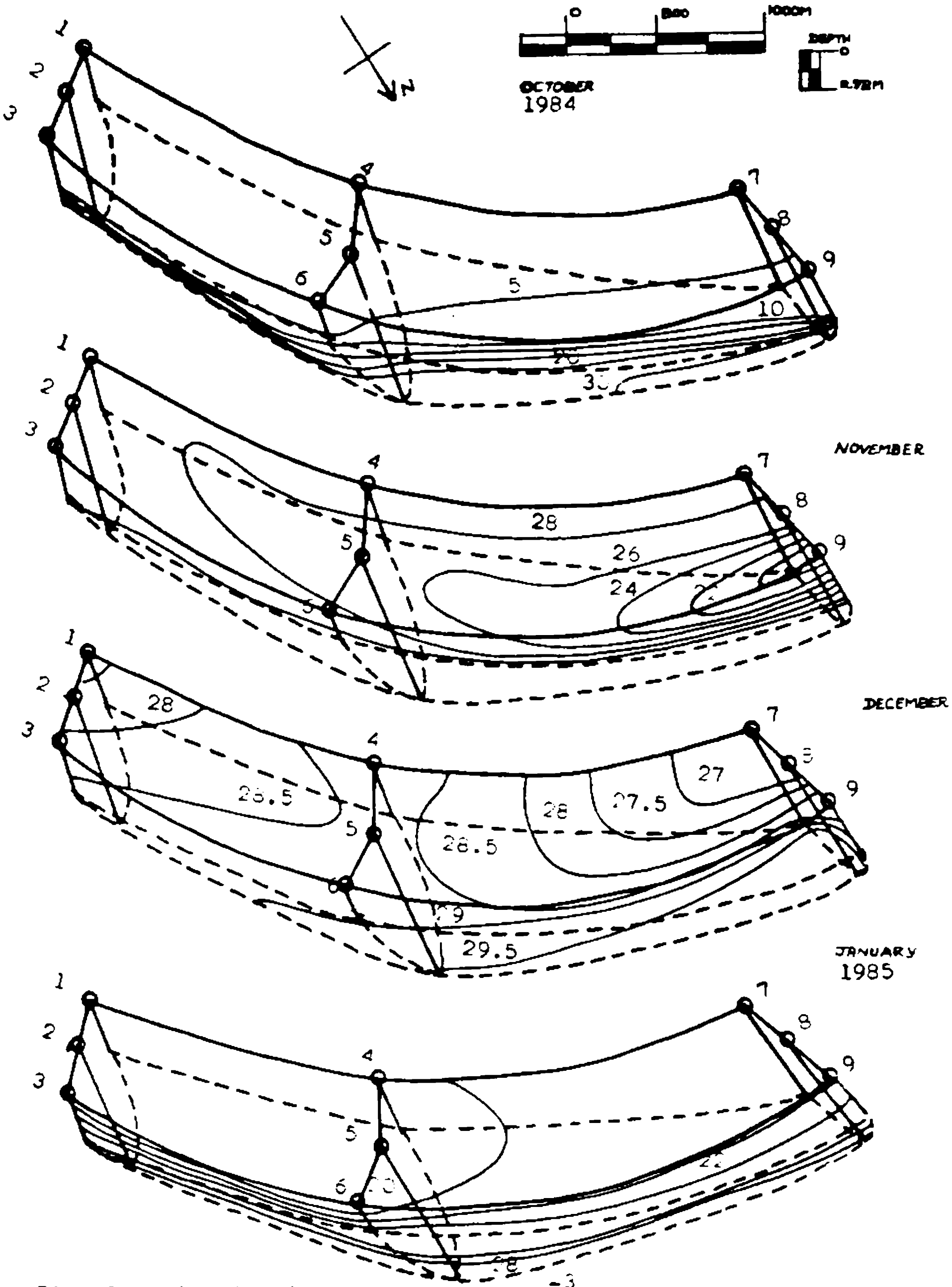


Fig. 8. Distribution of salinity (10^{-3}) in Ernakulam channel (stations 1 - 9) during postmonsoon season

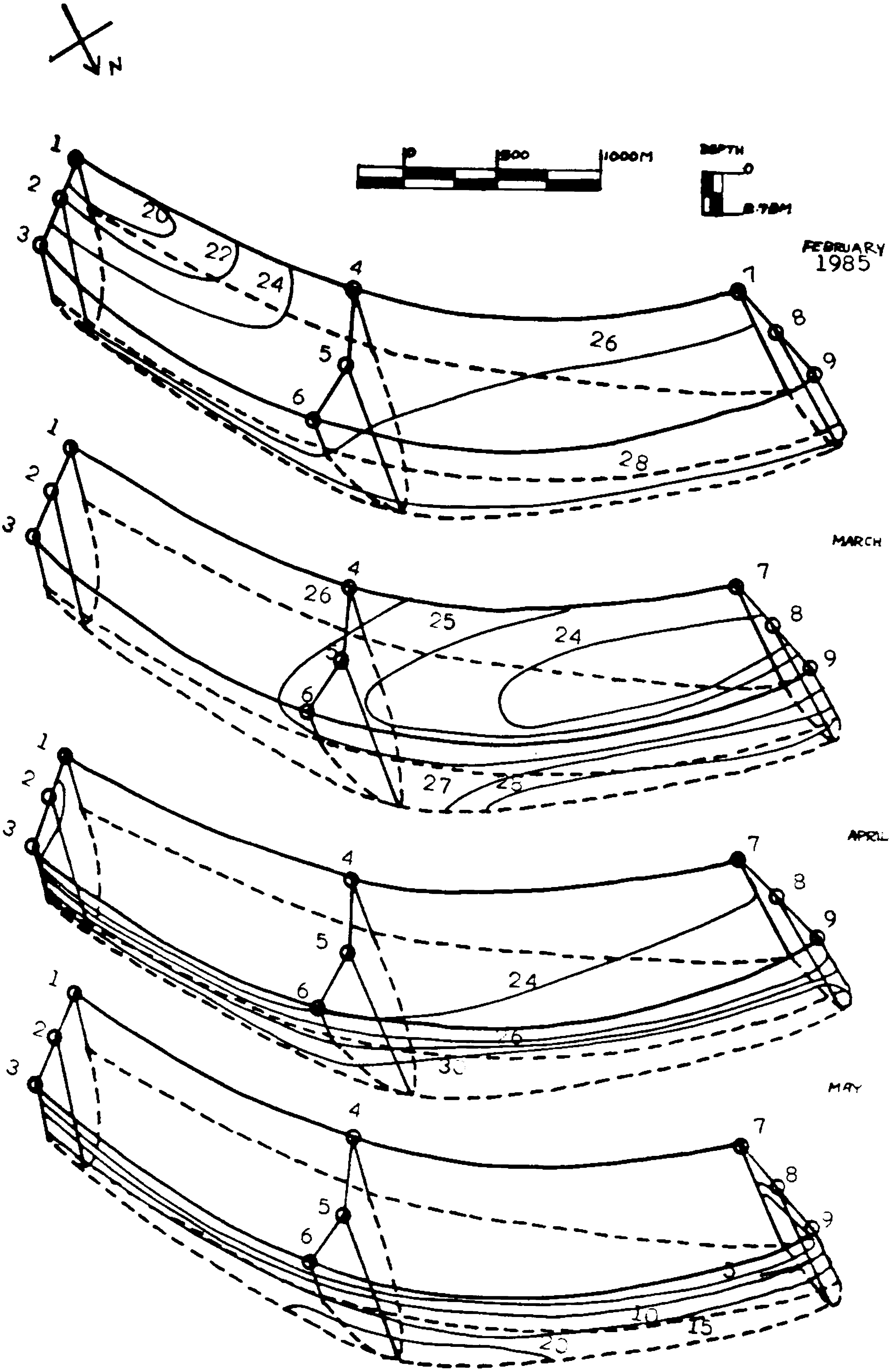


Fig. 9. Distribution of salinity (10^{-3}) in Ernakulam channel (stations 1 - 9) during premonsoon season.

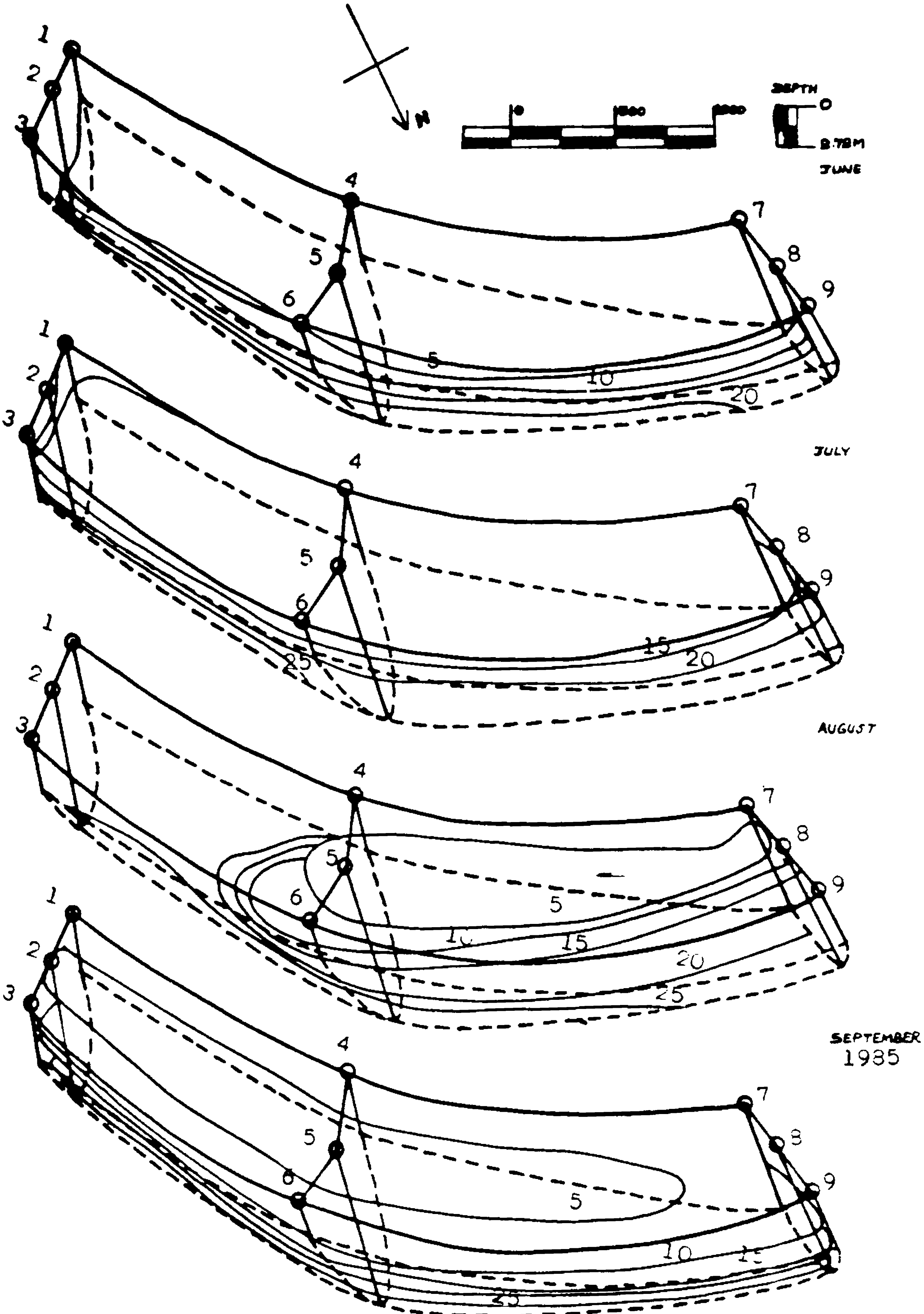


Fig. 10. Distribution of salinity (10^{-3}) in Ernakulam channel (Stations 1 - 9) during monsoon season.

"trap zones" along the river bank. The salinity distribution at the time of observation in April and May was marginal in longitudinal variability between the two end member values, with little or no transverse changes.

The surface, middle and bottom water salinity during monsoon months were measured during floodtide conditions. The thickened watermass (Fig. 10) revealed high stratification in the channel. As the monsoon commenced a pycnocline with cold seawater at the bottom and warmer freshwater at the top was present. Thus, a salinity gradient may lead to gravitational circulation which forms an important component of residual flow in this channel. Matsukawa and Suzuki (1986) has highlightened the role of density driven flow in estuaries causing longitudinal salt dispersion. The maximum vertical salinity gradient was observed in June (0.5×10^{-3} - 23.8×10^{-3}). As the monsoon strengthens, the disturbances due to waves, wind and internal shear due to density gradient causes vertical mixing. This was confirmed by the decreasing salinity gradient in the rest of the seasons i.e. the shallow seawater zone at the bottom layers which gradually gets enlarged and reduces the freshwater column above it into a thinner zone towards the seaward side of the channel (eg. 4.2×10^{-3} to 10.9×10^{-3} to 16.6×10^{-3} at stations 2 - 5-8). Similar processes were also observed by Sankaranarayanan and Qasim (1969) in the Cochin harbour area.

3.3.2.2. Approach Channel

The salinity pattern at surface, middle and bottom waters of the Approach channel are shown in the figures 11, 12 and 13.

During the postmonsoon season, comparatively high saline water was present in the Approach channel except in October. The vertical salinity gradient was minimum in December (1.6×10^{-3}). The maximum saline water was recorded during November survey (32.4×10^{-3}) which reveals that the nearshore water well mixed with the freshet in the Approach channel.

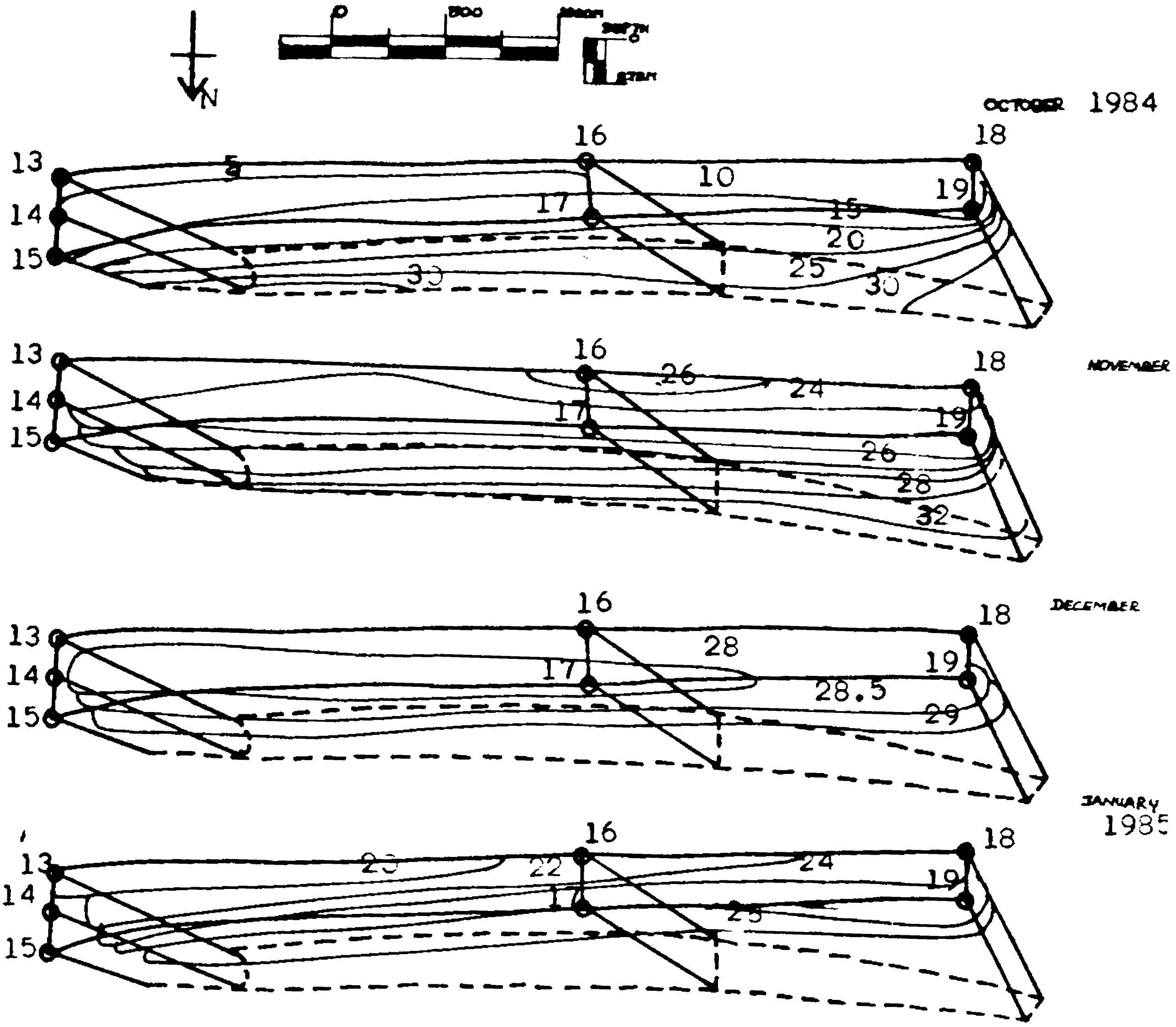


Fig. 11. Distribution of salinity (10^{-3}) in Approach channel (stations 13-19) during postmonsoon season.

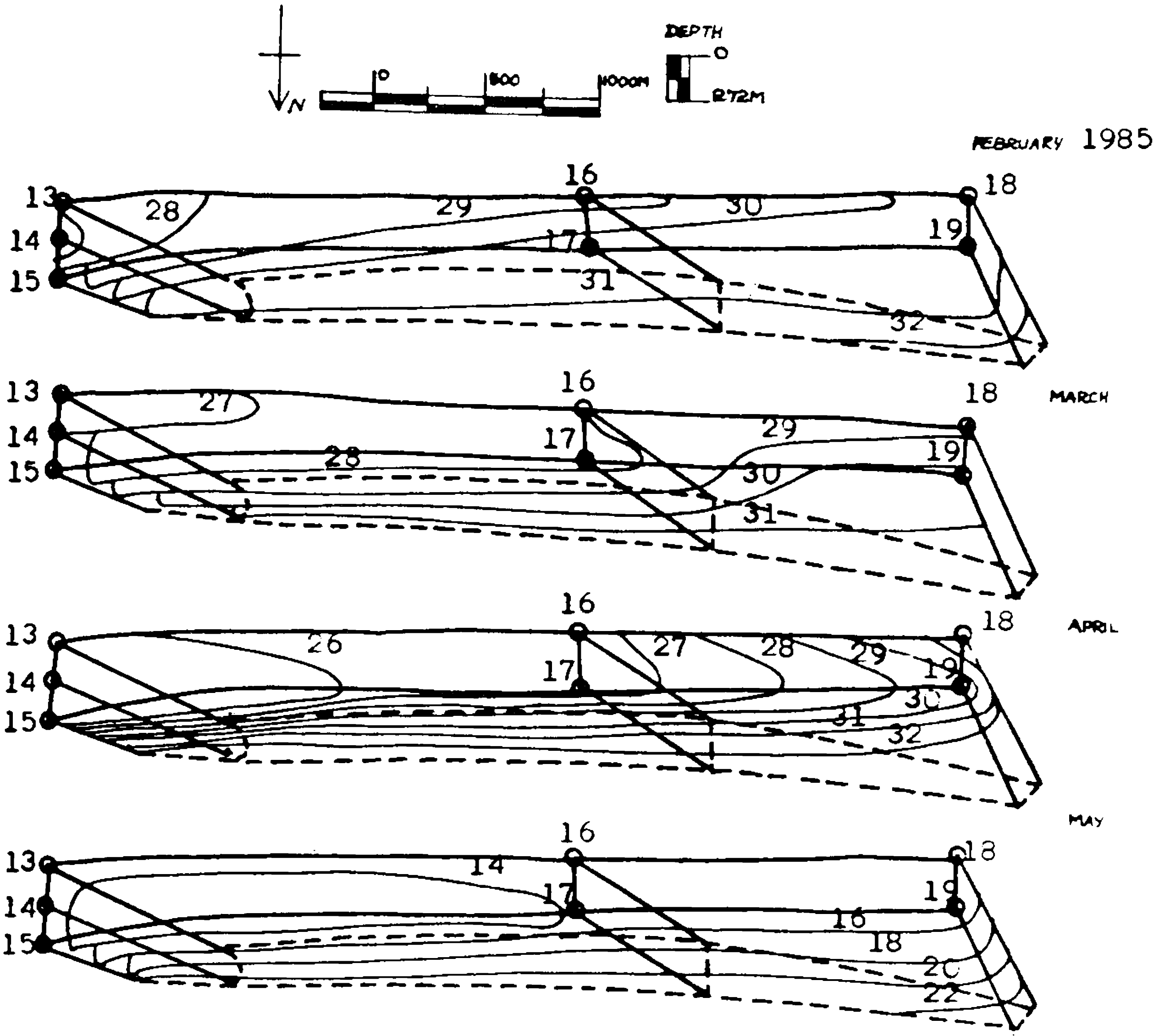


Fig. 12. Distribution of salinity (10^{-3}) in Approach channel (stations 13 - 19) during premonsoon season.

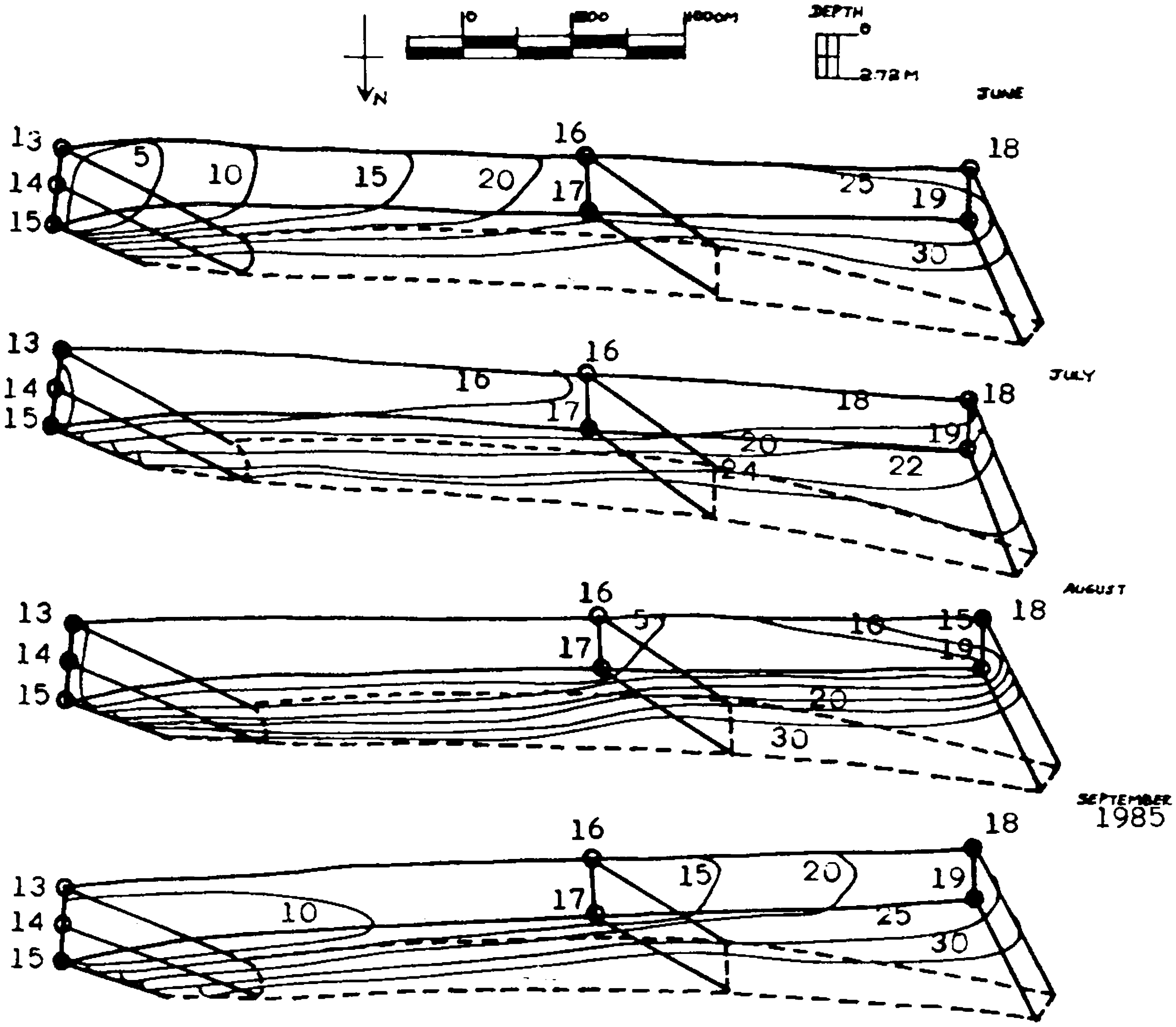


Fig. 13. Distribution of salinity (10^{-3}) in Approach channel (stations 13 - 19) during monsoon season.

The figure (12) exhibits vertically more mixed water during the premonsoon season. The thickness of segments towards the seaward side revealed that salinity gradient was minimum in this sector of the channel compared to that of the cut region. The maximum salinity was observed in March and April (33 x 10^{-3}), the observations being made during the flood and ebbtide phases respectively. This reveals the incursion of coastal waters by tidal energy into the harbour area which is a predominant factor in determining the salinity distribution in the Approach channel during premonsoon months.

During monsoon months, the observations were taken during ebbtide in June and July and during floodtide in August and September. As the monsoon commenced (June 1985) steep salinity gradients developed at Cochin cut with near freshwater conditions at surface (1.5 x 10^{-3}) and a very high saline intruded nearshore waters (34.1 x 10^{-3}) at the bottom. Similar salinity characteristics were reported by Rama Raju et al. (1979) at the cut region. Beyond the month of June, the vertical salinity gradient in the channel marginally reduced, due to the churning action of waves in the channel, the gravitational circulation developed due to the steep salinity gradient and the weakening upwelling with strengthening monsoon as shown by Sharma (1978). The salinity pattern reveals that mixing was more towards the seaward side than the cut region.

3.3.2.3. Mattancherry Channel

The salinity distribution in the Mattancherry channel is shown in the figures 14, 15 and 16.

The postmonsoon months exhibited comparatively low vertical salinity gradient except during October. Intrusion of streaks of high saline coastal waters through the cut during this season were noted. The figure (14) reveals that more mixed water was present in December.

The figure (15) shows that highly mixed saline water was present in the Mattancherry channel during the time of observations in premonsoon months except during May due to the earlier onset of monsoon, though high saline bottom waters were present in the ship channel (31 x 10^{-3}).

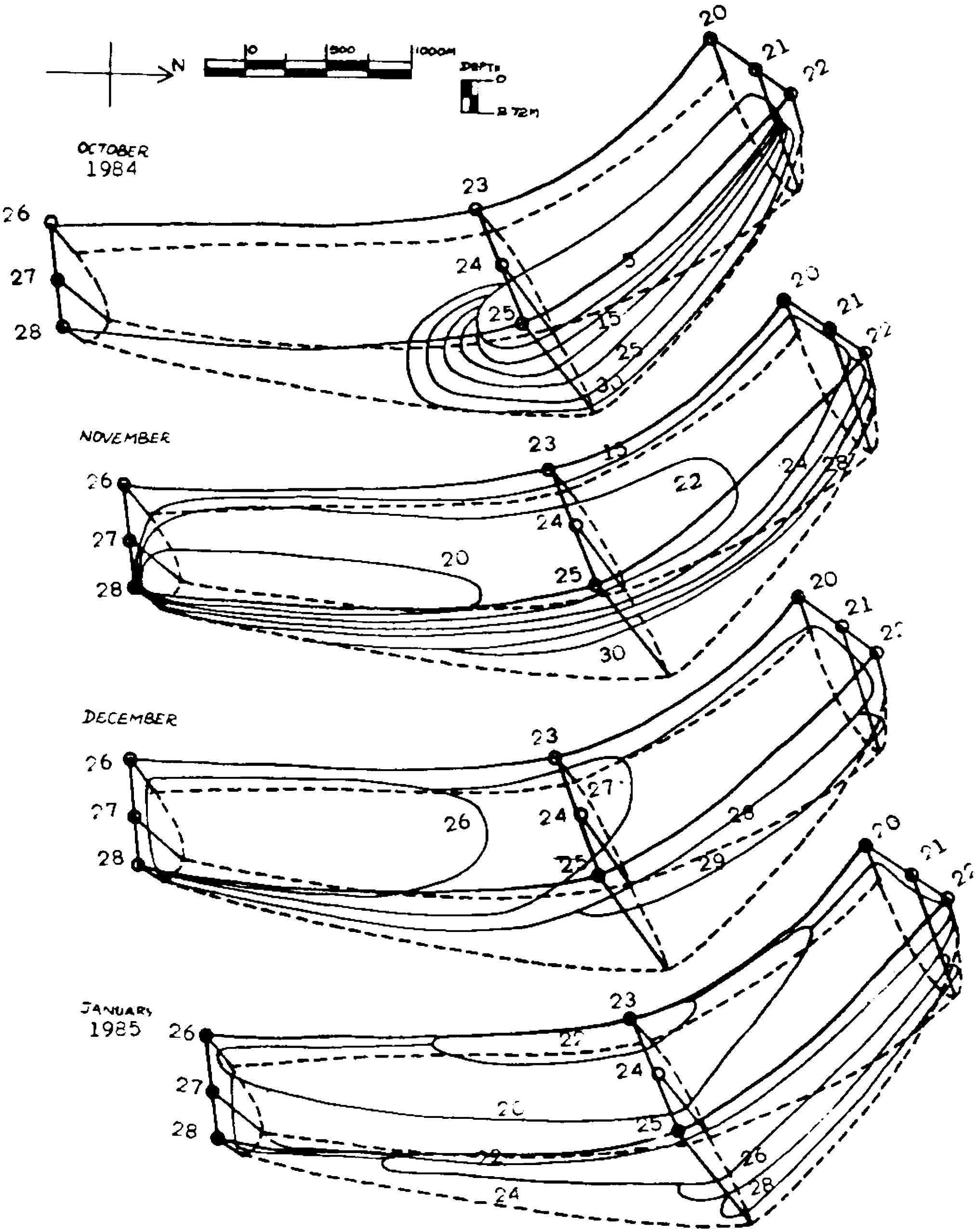


Fig. 14. Distribution of salinity (10^{-3}) in Mattancherry channel (stations 20 - 28) during postmonsoon season.

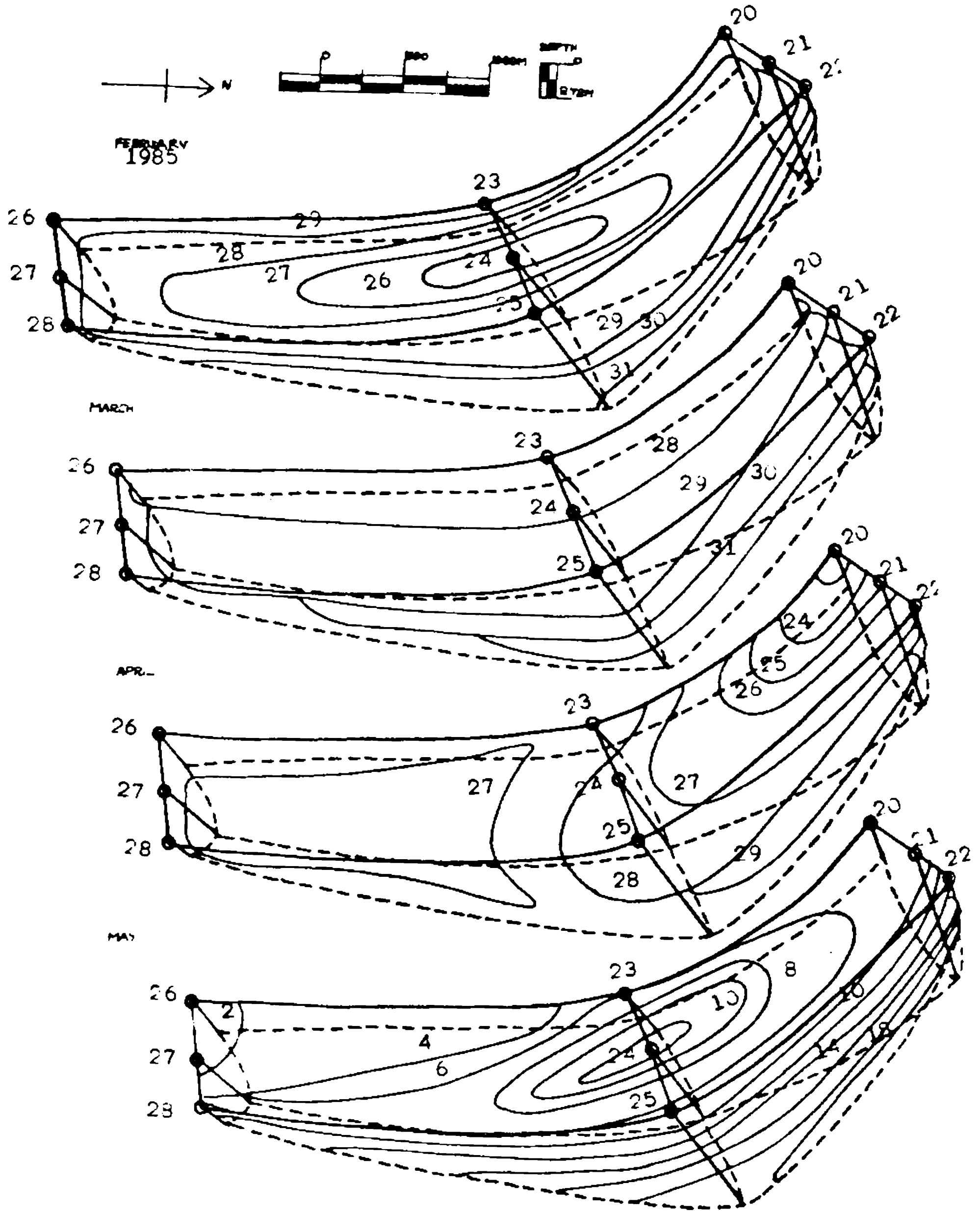


Fig. 15. Distribution of salinity (10^{-3}) in Mattancherry channel (stations 20 - 28) during premonsoon season.

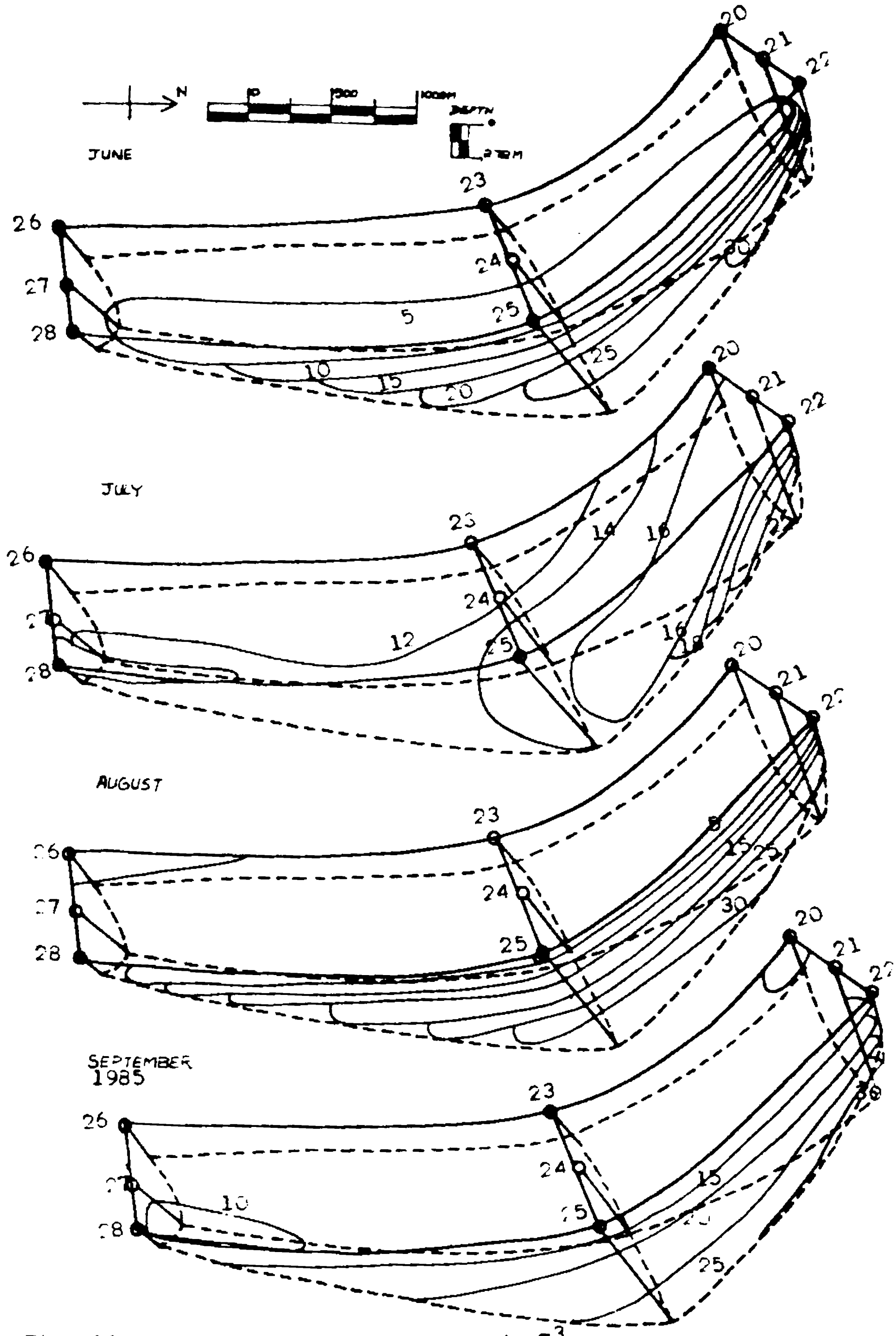


Fig. 16. Distribution of salinity (10^{-3}) in Mattancherry channel (stations 20 - 28) during monsoon season.

The vertical salinity difference towards the south of the Mattancherry Wharf was 1.1 x 10^{-3} and that at the ship channel towards the seaward side was 2.25 x 10^{-3} (March 1985). This may be due to the increased depth difference of the channel. The segments towards south and north of the Mattancherry wharf exhibited different mixing characteristics. This is attributed to the proximity of northern parts, to coastal waters, channel orientation and unequal depths.

During monsoon months, the observations were conducted during the ebbtide (Fig. 16). The water types are thinned and run parallel to each other which revealed that the water column was highly stratified in the vertical. The vertical salinity gradient was maximum in June (1.6 x 10^{-3} to 30.5 x 10^{-3}). The water column exhibited,a high saline tongue which was the extension of coastal waters through the bottom layers with a thick layer of freshwater at the surface. The water column was more mixed in July, due to the churning action of waves, and internal shear force that developed due to the salinity stratification.

The overall results of studies on salinity distribution in Cochin harbour area point out to the seasonal stratification, predominantly in the cut region. Rapid vertical mixing of surface and bottom waters were observed in both the Ernakulam and Mattancherry channels during premonsoon season. The dominant factor affecting the salinity distribution in these channels, seasonally, is the freshwater discharge from the adjoining rivers. This has also been the observation of Udaya Varma et al. (1981). During late premonsoon and early monsoon, streaks of cold, high saline upwelled water was observed to occupy the bottom layers of lower estuary. The estuary and its lower regions were found to alternate between a highly stratified water body during monsoon to a partially mixed type in postmonsoon. The conditions were homogeneous during the premonsoon season.

3.3.2.4. Semidiurnal Variations in Salinity

The semidiurnal variations at surface, middle and bottom waters at five stations (Fig. 4) located in the cut region, Ernakulam channel and Mattancherry channel during springtide of 14 September 1984 and neaptide of 30 November 1984 are depicted in the figures (17-22).

3.3.2.4.1. Springtide

The figure (17) shows the surface salinity fluctuations during springtide at five stations. Salinity changes exhibit varied relation with tide especially at the Cochin cut and Ernakulam channel. Semidiurnal variation of surface salinity was less in the inner channels compared to that at the cut. Mattancherry channel showed minimum fluctuation in surface salinity (13. 8 x 10^{-3} to 25.5 x 10^{-3}) while the salinity in the Ernakulam channel varied from 13.6 x 10^{-3} to 27.8 x 10^{-3}. This was obviously due to the increased freshwater influx and depth of the Ernakulam channel. Surface salinity variation was maximum in the south of the cut (11.25 x 10^{-3} - 32.1 x 10^{-3}). Salinity changes do exhibit a time lag compared to the tidal response. Inner channels exhibit gradual changes of salinity as compared to the cut. Salinity fluctuations were varying and rapid at the cut due to the increased and concentrated tidal current flows at this region.

Figure 18 reveals that the mid-water salinity changes were more in symmetry with the tidal response. The changes in salinity were large in the inner channel stations. The middle water salinity fluctuations were maximum in Ernakulam channel (18.8 x 10^{-3} - 29.45 x 10^{-3}). The salinity rise was gradual and exhibited slight fluctuations before attaining maximum values, while during ebbflow the values of salinity dropped rapidly.

From figure (19) it was observed that there was a strong influence of coastal waters along the bottom layers of the estuary during the flood phase of the tide. Variations in salinity of the bottom waters of Ernakulam channel was limited: 29.4 x 10^{-3} to 32.0 x 10^{-3}. During the slack floodtide stage, salinity values were found to be fluctuating due to unequal mixing. Moderate salinity changes were observed in Mattancherry channel (24.5 x 10^{-3} - 29.7 x 10^{-3}). Higher salinity values occurred at the high water and correspondingly lower salinity values at low water stage. Inner channels exhibited identical features in salinity fluctuations though they differed quantitatively.

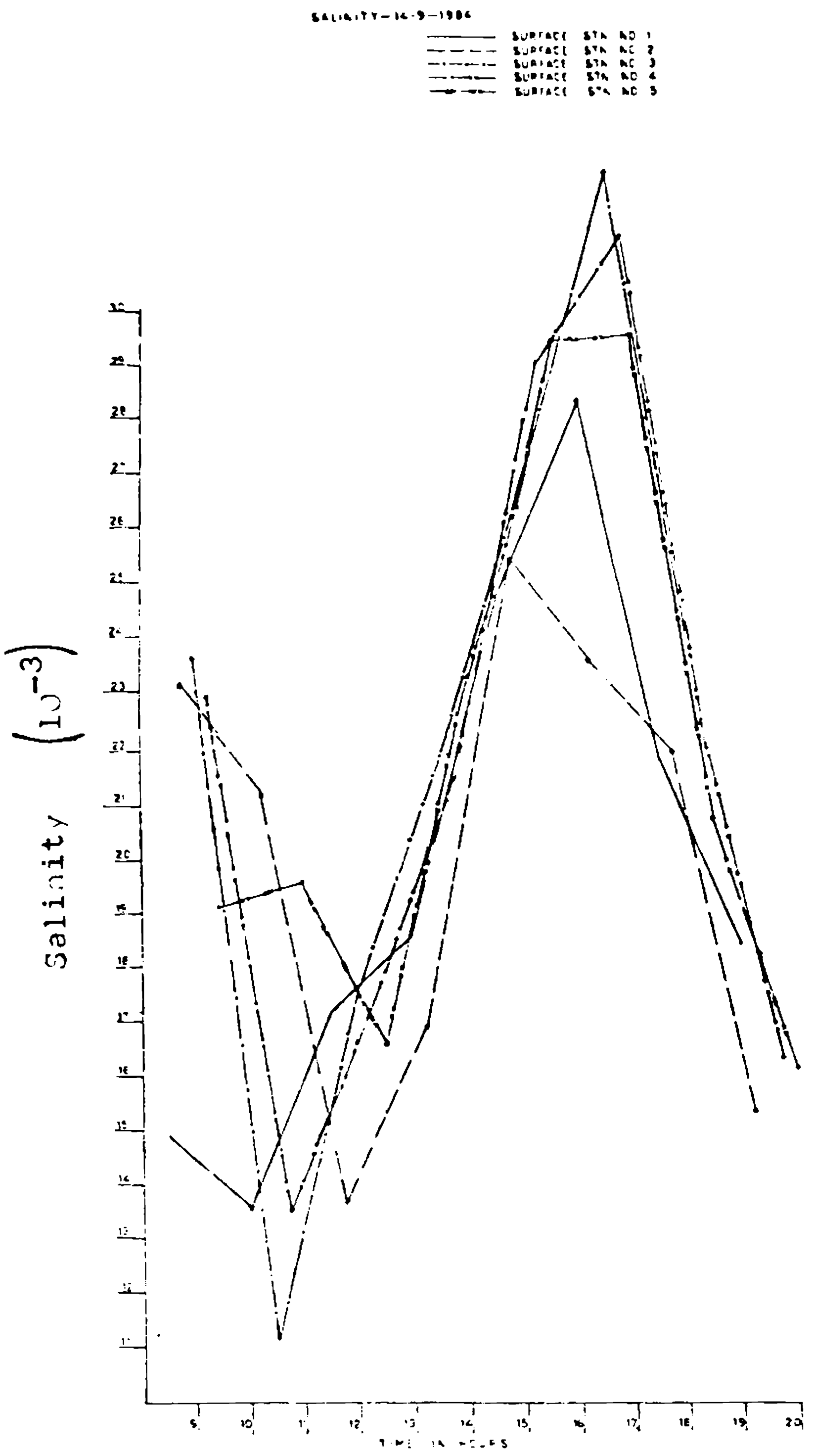
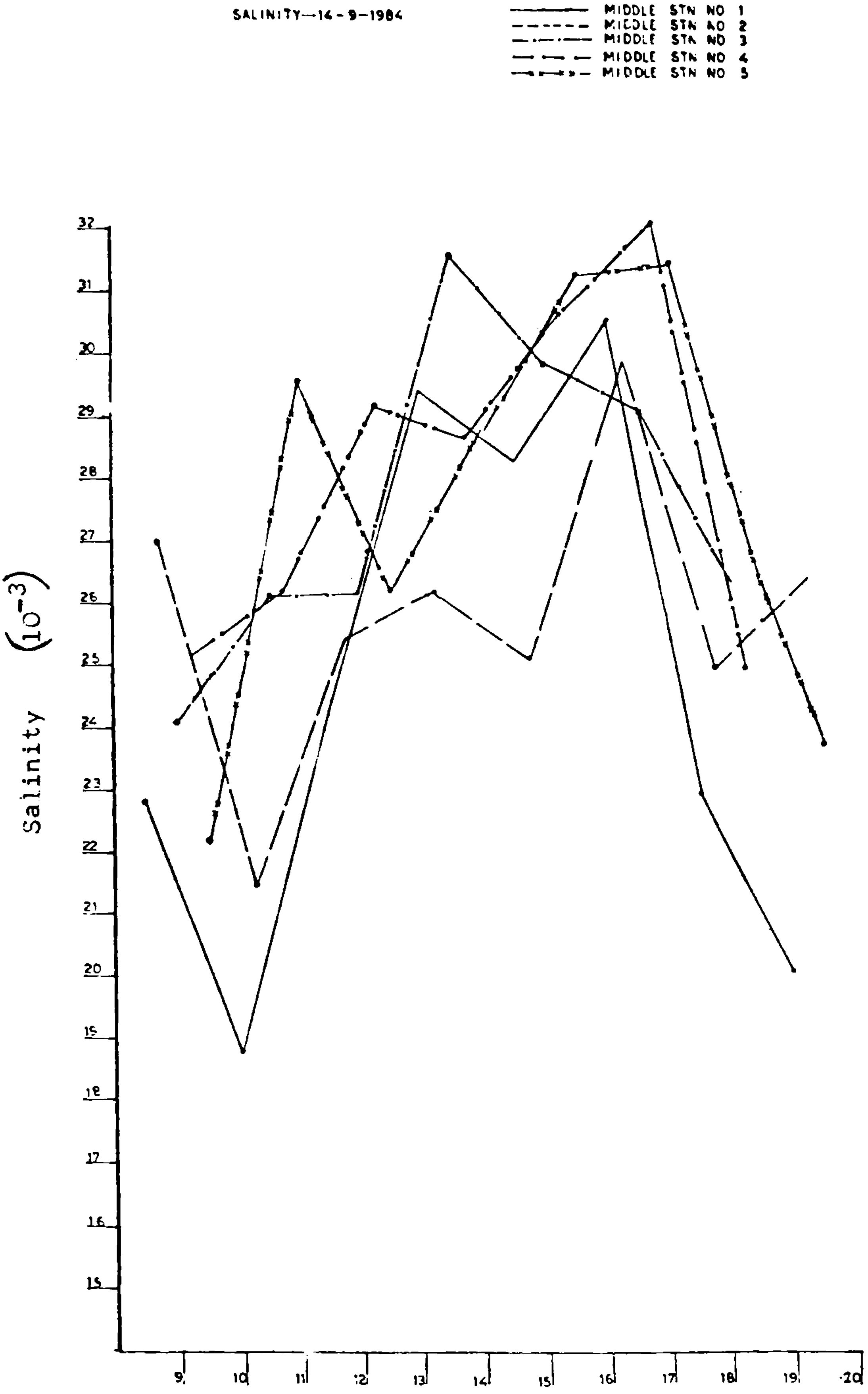


Fig. 17. Distribution of surface water salinity at Cochin cu
Ernakulam and Mattancherry channels during springti



SALINITY—14-9-1984

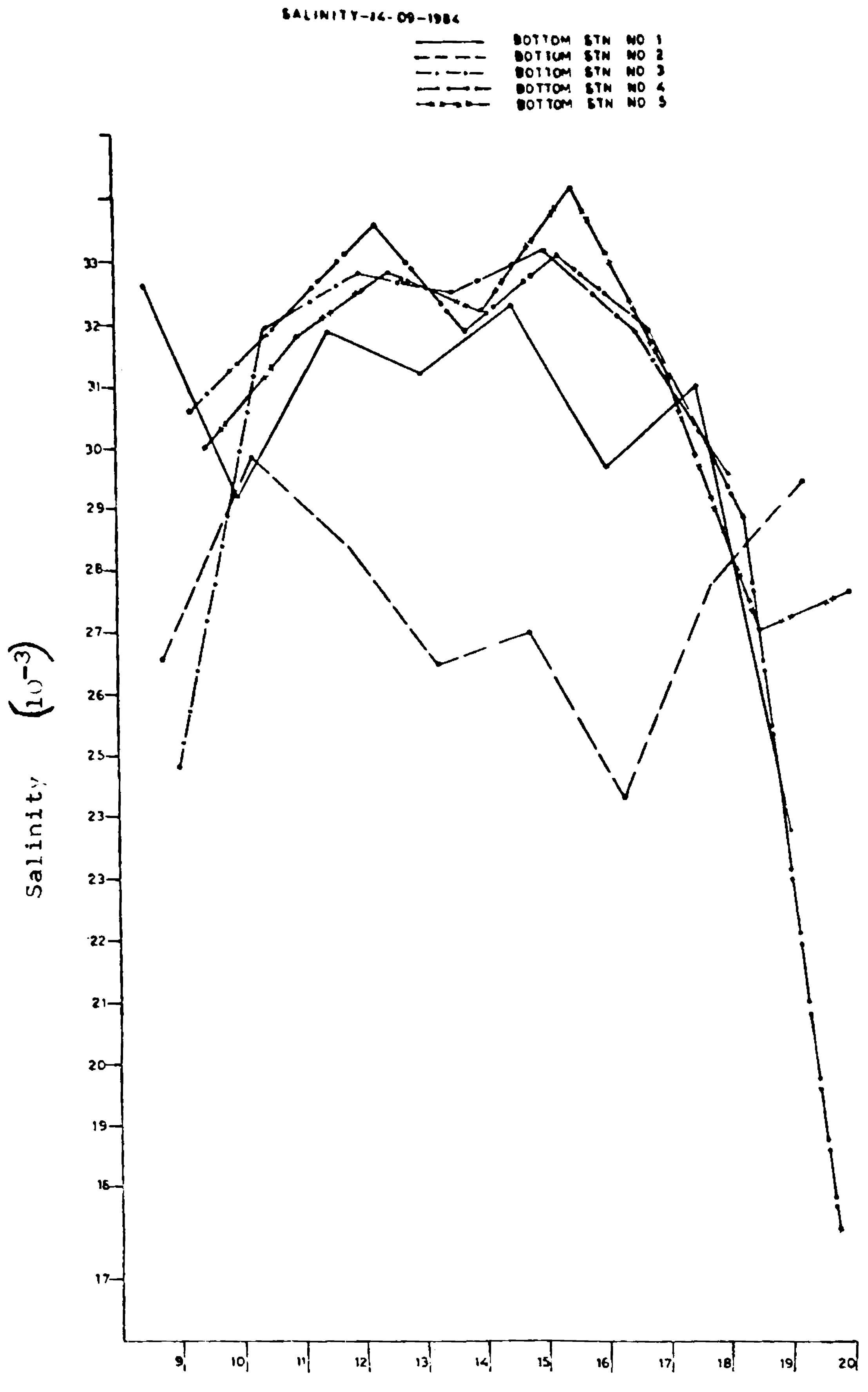


Fig. 19. Distribution of bottom water salinity at Cochin cut, Ernakulam end..Mattancherry channels during springtid

3.3.2.4.2. Neaptide

Semidiurnal variation in surface salinity at the five stations during neaptide is depicted in the figure (20). Ernakulam channel exhibited the maximum salinity fluctuations (17×10^{-3} - 31.5×10^{-3}). The stations 1 and 4 exhibited identical salinity fluctuations during the ebbflow. Surface waters of stations 3 and 5 and that of station 2 in the Mattancherry channel showed prolonged influence of high saline waters.

Surface salinity fluctuations were moderate in the Mattancherry channel (20.1×10^{-3} - 31.4×10^{-3}). During neaptide, all the stations exhibited a lag in the timing of high water and the maximum salinity value and vice-versa, at low water and minimum salinity. This lag was about two to three hours. At the low tide level the response of salinity changes were equally very slow.

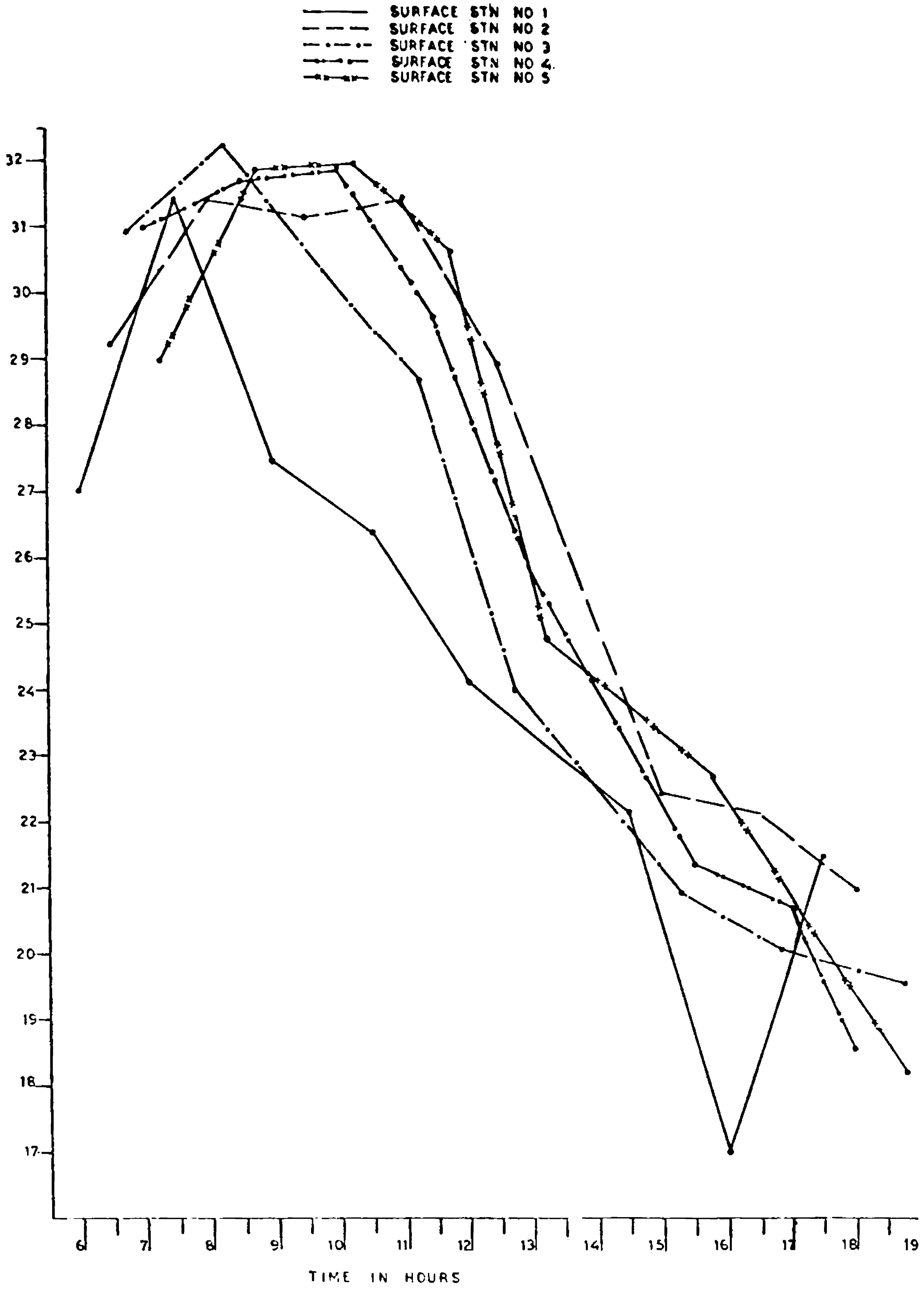
Salinity distribution at the mid water during neaptide of 30th November 1984 is depicted in the figure (21). High saline waters were persistently observed at the cut region for a longer period compared to that in the inner channels. A sharp salinity fluctuation was present at station 3 (26.5×10^{-3} - 32.6×10^{-3}). Salinity decrease during ebbtide was regular and began from the inner channel. It is inferred from the figure that the coastal saline water incursion was prominent at the mid water levels.

The salinity changes at the bottom waters during the neaptide of 30th November 1984 are exhibited in the figure (22). High saline water was present at all the stations during the observation period. Maximum bottom water salinity fluctuation was present in Mattancherry channel (27.2×10^{-3} to 32.8×10^{-3}). During ebb flow identical salinity changes were recorded at stations 4 and 5. The response of salinity changes with tide was much delayed compared with surface or midwater layers.

3.3.3. Dilution of seawater

The freshwater fraction at a point can be used as a tracer for the dilution of seawater. Bowden (1980) suggested that the amount of

SALINITY—30-11-1984



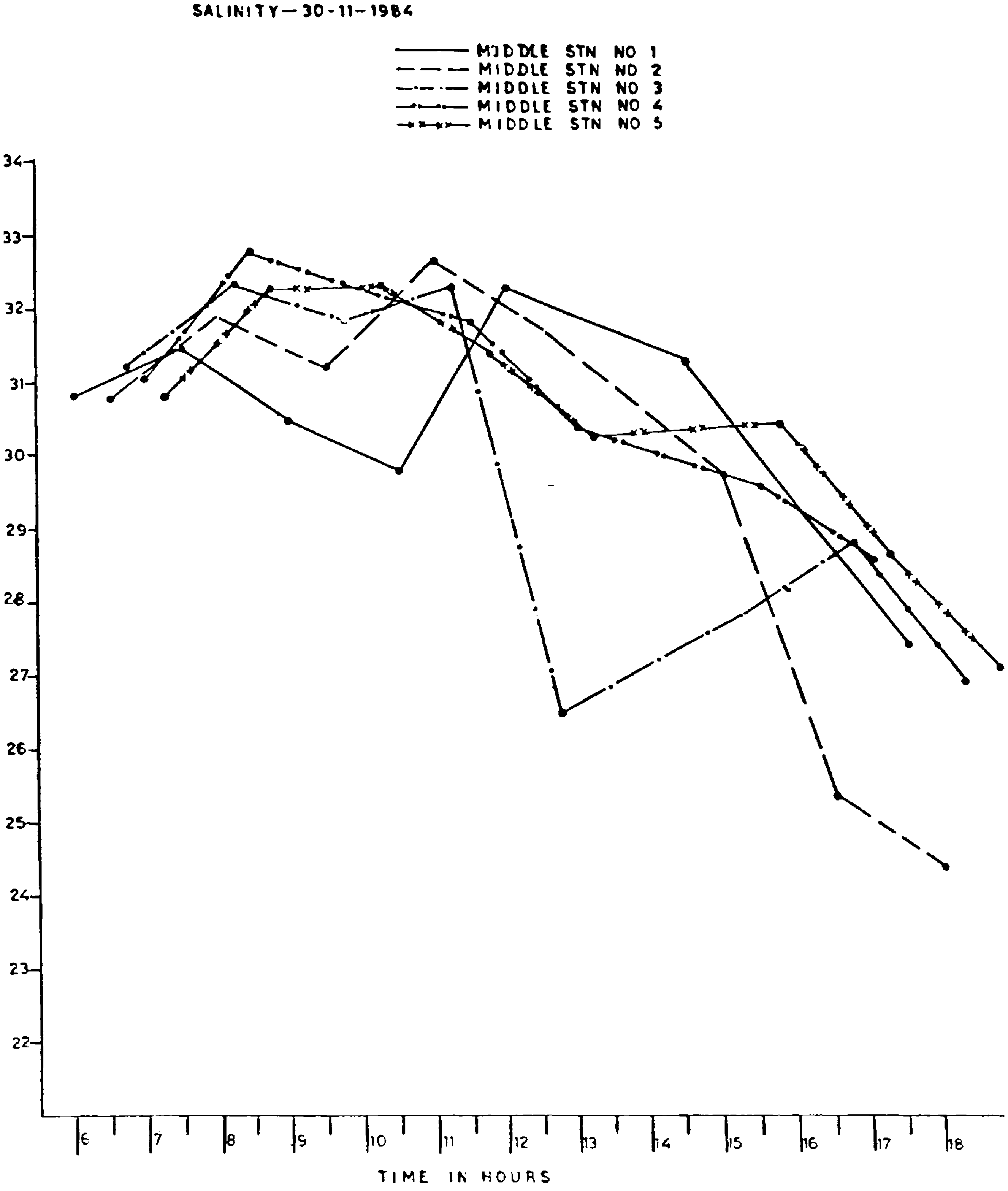


Fig. 21. Distribution of middle water salinity at Cochin cut, Ernakulam and Mattancherry channels during neaptide.

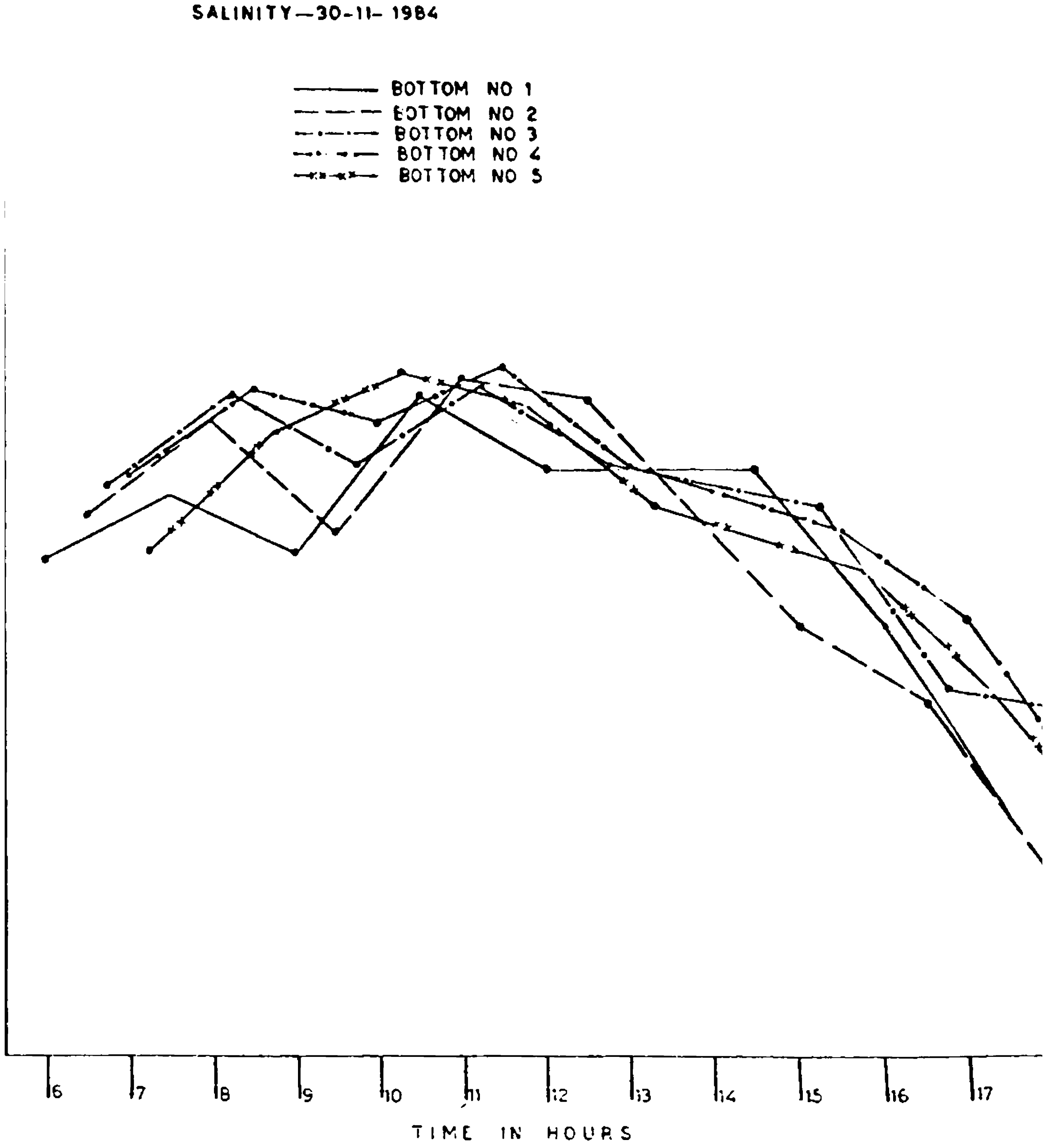


Fig. 22 Distribution of bottom water salinity at Cochin c Ernakulam and Mattancherry channels during neapti

freshwater removed by flushing is the same as that is being added by river discharge. Indirectly freshwater can be used as an indicator to provide information on the mixing processes. The conditions in an estuary change greatly with the variations in the volume of water flowing into it.

The freshwater content (F) at any point in the estuary can be calculated in terms of salinity.

$$F = 1 - \frac{S_1}{S_2}$$

'S_1' is the salinity of the water collected from the location inside the estuary and 'S_2' is the salinity of the coastal water (Officer, 1976). The surface and bottom freshwater fractions at all stations in Ernakulam, Approach and Mattancherry channels during October and December months of postmonsoon 1984, February and April of premonsoon 1985 and June and August of monsoon 1985 are shown in the figures 23(i) and (ii).

3.3.3.1. Ernakulam Channel (Stations 1 - 9)

During the months of postmonsoon (October and December) the surface layers exhibited varying amounts of freshwater. The freshwater content varied from 84.57% to 96.57% during October (flooding stage) and 17.21% to 21.71% in December (ebbing stage). The amount of freshwater in December 1984 reveals that the whole water body wasunder the spell of coastal waters and comparatively more well mixed.

During February and April months of premonsoon season the amount of freshwater at the surface level was less than 50% and at the bottom layers was less than 35%. And bottom freshwater content was minimum during April at slack high tide (10% at station 5). During both the premonsoon months, comparatively better mixed vertical water columns were observed.

During monsoon months, the freshwater fraction present at the surface was recorded as 93 - 100%. Large amount of freshwater was observed at the shallow stations on either side of the channel. The amount of

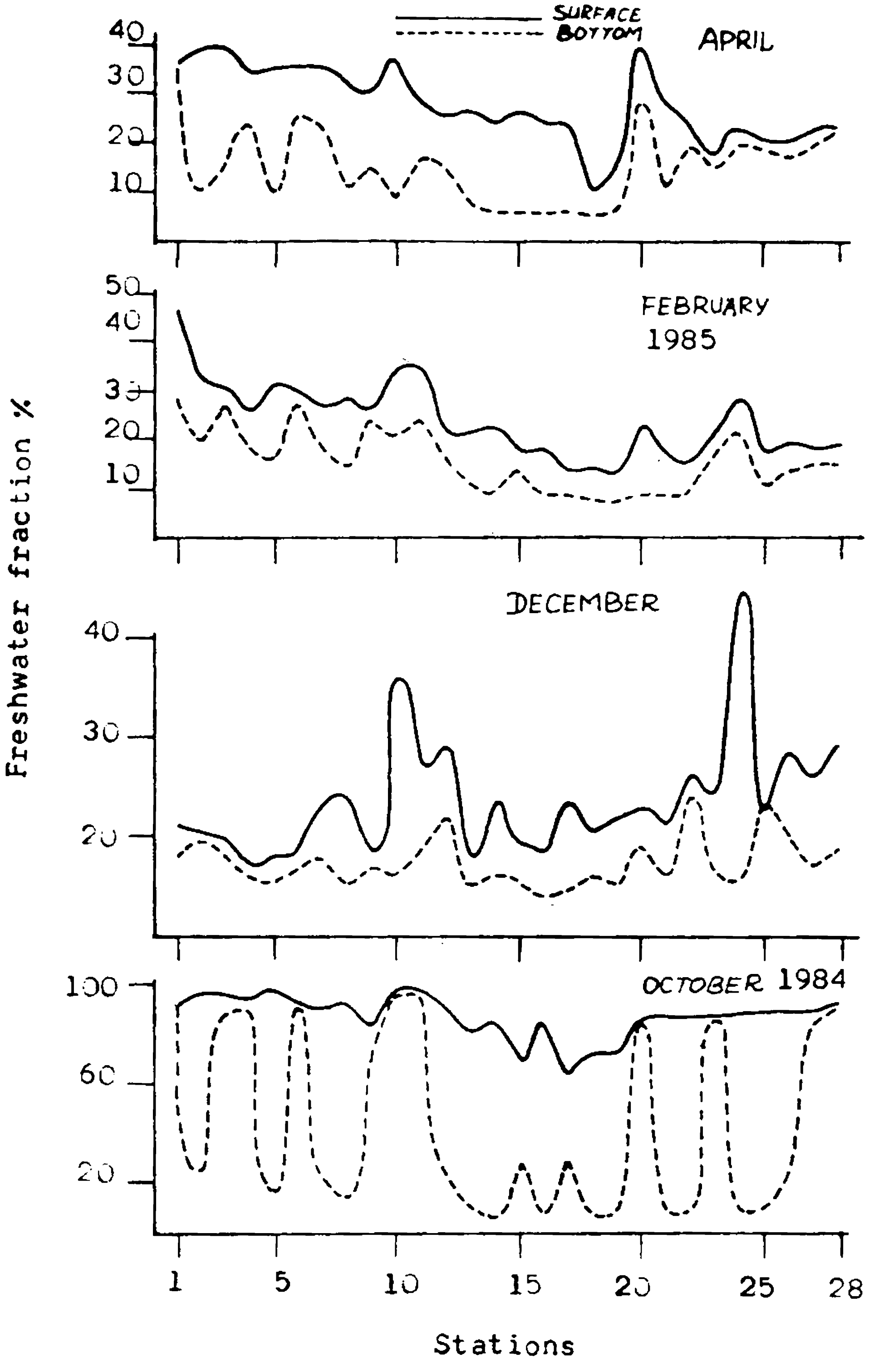


Fig. 23(i). Percentage freshwater fraction (surfac and bottom) at Cochin harbour area

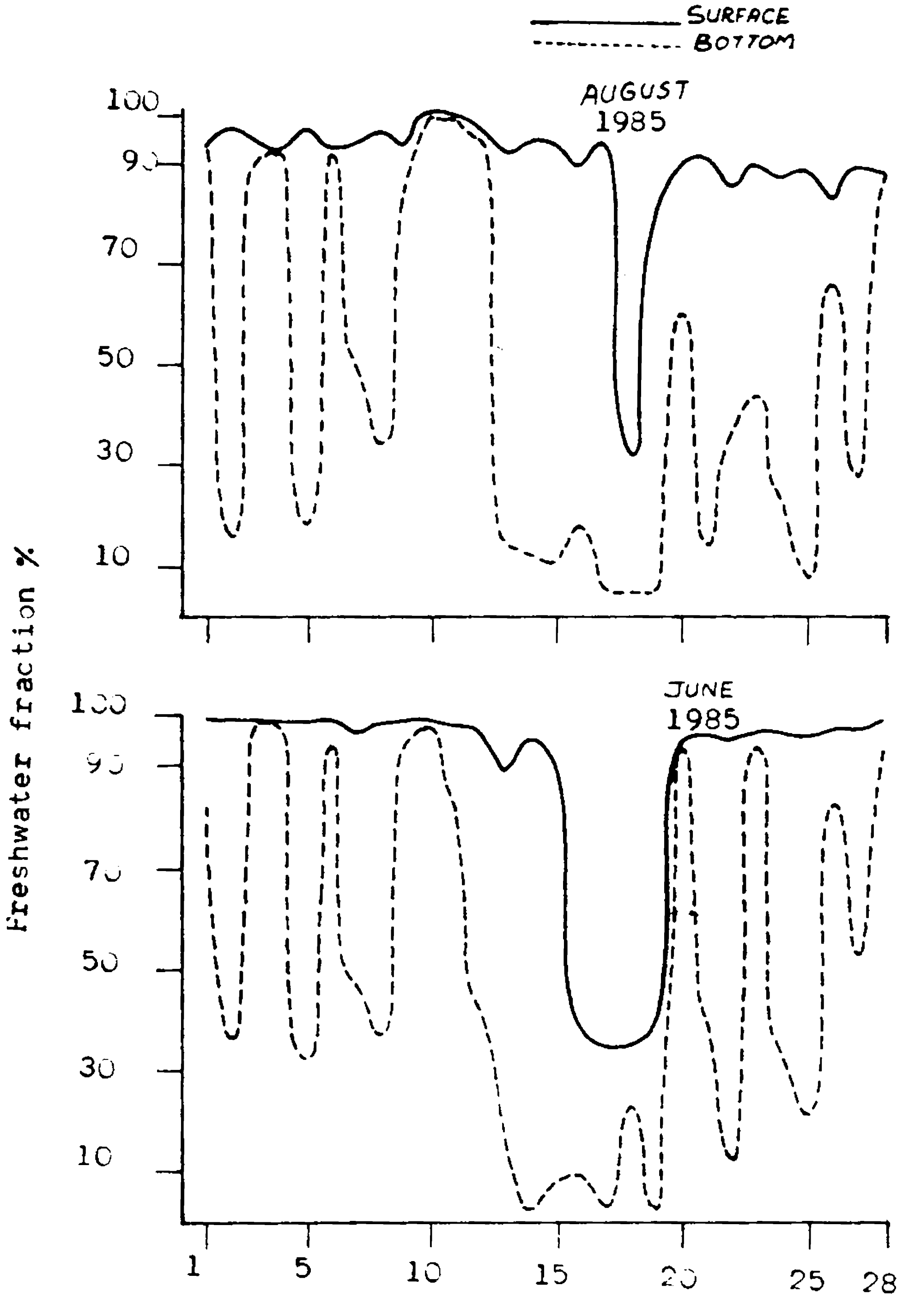


Fig. 23(ii). Percentage freshwater fraction (surface and bottom) at Cochin harbour area freshwater was comparatively less in the bottom waters at the deeper parts of the channel. Highly stratified conditions were present intermittently in these regions of the channel during monsoon months.

Stations 10 - 12 are located further north of Ernakulam channel. The features at these stations were also accounted for while discussing the dilution behaviour in Ernakulam channel.

3.3.3.2. Approach Channel (stations 13 - 19)

The freshwater content at the surface waters of the postmonsoon months, October and December was 70% and 25% respectively. Bottom water contained less than 10% freshwater during October and between 14% to 18% during the month of December. These values reveal that the channel was highly stratified in October and comparatively more mixed during December. These observations have due relevance with respect to the stage of the tide.

During the premonsoon months of February and April, 1985 the amount of freshwater towards the seaward side was less than 27%. The amount of freshwater was however minimum during April ($<$ 7%) as the tide was ebbing at bottom.

During June and August, the freshwater content at the surface layer was more than 90% in the Cochin cut though flood tidal conditions prevailed. The relative amount of freshwater decreased seaward of the cut in June and beyond stations 16 and 17 in the month of August. Bottom water exhibited lower amounts of freshwater compared to surface. During the monsoon months, highly stratified conditions at the cut is inferred from this analysis; this feature was found to be decreasing towards the seaward side.

3.3.3.3. Mattancherry Channel (stations 20 - 28)

The amount of freshwater at the surface during the postmonsoon months of October and December 1984, showed considerable variability. The freshwater content at the surface was more than 85% in October (ebb phase) and less than 30% during December (flood phase). Comparatively this indicates more mixing during December.

During February and April 1985, the premonsoon months, the freshwater content of the water column was less than 40%. Less variability in the amount of freshwater in this channel reveals comparatively better mixing during this season at slack tide stages.

During monsoon months, June and August, large amounts of freshwater were observed at the surface layers (> 95% in June and > 83% in August). The large freshwater fraction reveals the influence of monsoonal discharges from rivers diluting seawater at barmouth area irrespective of tidal stage. During the month of June, comparatively better stratification was noted in the deeper parts of this channel and the sides of the channel were mostly occupied by freshwater.

CHAPTER 4

ESTUARINE CIRCULATION

4.1. INTRODUCTION

Circulation is an important integral physical aspect to be investigated in the study of an estuary. The identifiable major forces that cause circulation are (1) winds, (2) waves, (3) tidal currents and (4) river discharges. These unequal influences on estuarine hydrodynamics result in shear effects which tend to increase vertical and transverse salinity gradients and hence to increase gravity induced currents (West and Shiono, 1985). Opposing tides and freshwater flow cause complicated water movements, much affecting the transportation and fractionation of suspended solids in the estuary. Fine grain material is observed to move in suspension following the residual water flow (Nelson, 1967; Postma, 1967 and Dyer, 1972). The existence of essentially closed circulation system is characteristic of water movements in estuaries which tend to cause the entrapment of particles.

Water passes freely through these areas, but particulate matter is trapped or its escape to open waters often retarded (Lauff, 1967). Consequently, the estuarine circulation pattern has a predominant role in determining the sediment movements (Bowden, 1967; Bowden and Gilligam, 1971).

The information regarding the intensity of the currents in the surface and subsurface levels of the Cochin harbour area and the associated exchange and mixing of the estuarine waters with the coastal waters lack detail. Rama Raju et al. (1979) observed that during monsoon season, ebb currents predominate in intensity and duration at all depths and in the other seasons, rhythmic variations of flood and ebb currents take place throughout the vertical, corresponding to rising and falling tides. According to Narayana Pillai et. al. (1973) the average surface velocity during the ebb is comparatively higher than the corresponding flood velocity in this estuary. These investigations were not held in conjunction with studies on other physical estuarine processes like the sedimentation or vertical mixing or while investigating the effects of tidal currents in the transport of particulates. In the present study, an attempt has been made to observe the pattern of water currents in the inner and approach channels of the harbour area at fifteen stations from October (1984) to September (1985) at monthly frequency and also during the springtide in September 1984 and neaptide in November 1984.

4.2. MATERIALS AND METHODS

The materials and methods employed in this study are described in Chapter 2.

4.3. RESULTS AND DISCUSSION

4.3.1. Ernakulam Channel

The figure 24 depicts the flow during the postmonsoon months in Ernakulam channel. During the month of October (1984) the magnitude of flow decreased upstream and the velocity of bottom waters were slightly more than that of surface waters. This was due to the

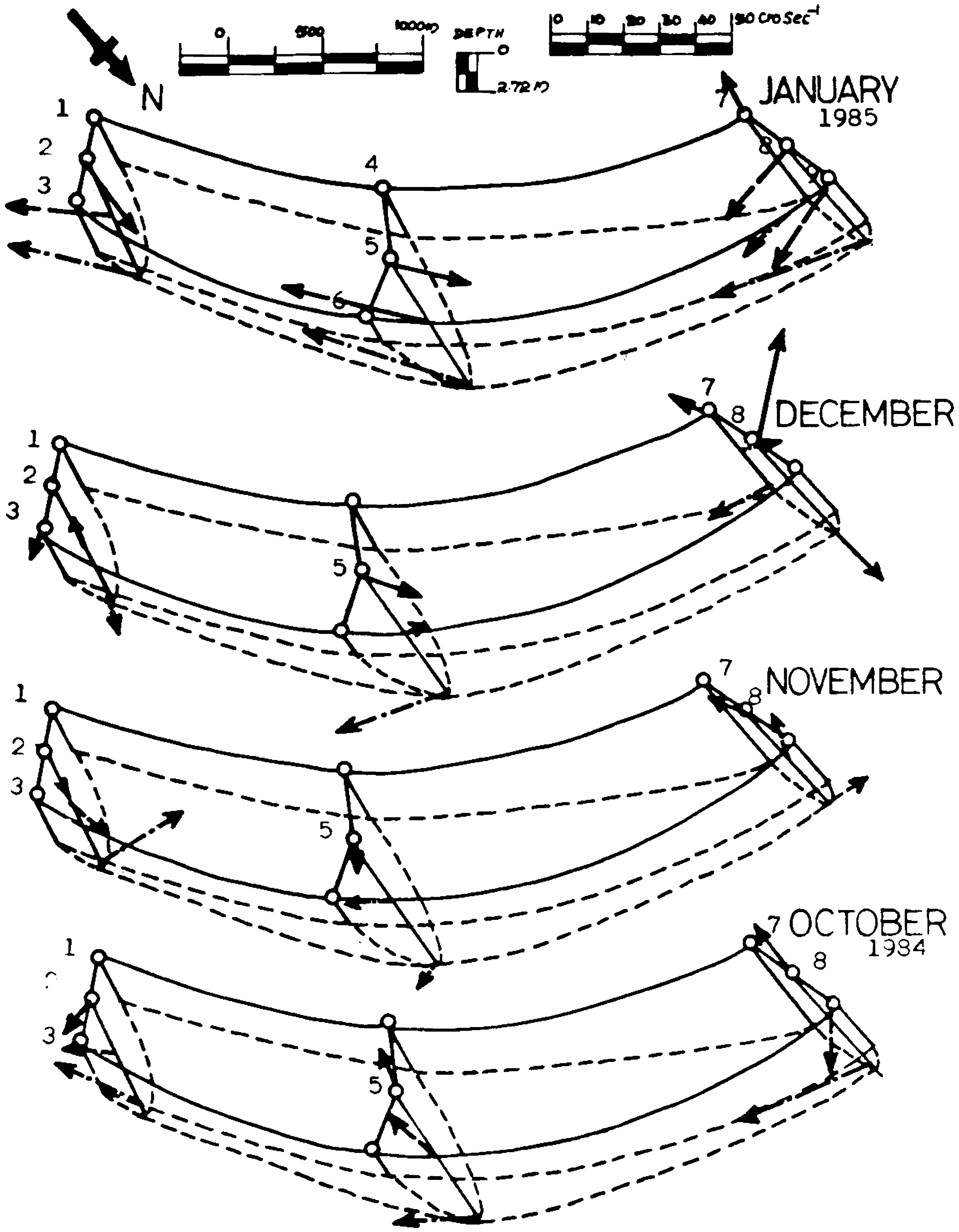


Fig. 24. Water currents in Ernakulam channel (stations 2,5,7 and 8) at surface, middle and bottom during postmonsoon season.

interaction between the flood phase of tide at the time of observation and fluvial fresh water supply due to the extended monsoonal activity. The comparatively low (6 - 26 cm sec^{-1}) magnitude and presence of translatory currents in the ebb phase of tide in November shows the effects of secondary currents arising from the interference of the typical back and forth tidal movement magnified by reduced fluvial supply. In the month of January, observations indicated mid water and bottom water flow towards the landward side and the magnitude of flow to be more (10 - 45 cm sec^{-1}) compared to the other measurements taken during postmonsoon months. A two layer flow was present during the time of observations in the months of October 1984 and January 1985. The landward movement of the whole water column in the lower reaches of the channel even during ebb tide phase in January showed the presence of incursion of coastal waters in this channel. During October, the flood tide current swept back the fluvial inflow further south, paving the formation of a tidal intrusion front in the transverse section at stations 4, 5 and 6. Similar observations were also noted by Simpson and Nunes (1981) in some estuaries.

The bottom water flowed towards the upper reaches of the channel in the premonsoon months (February and March) revealing the tendency for incursion of coastal waters into this channel (Fig. 25). The comparatively strong flow (74 cm sec^{-1} middle, 84 cm sec^{-1} bottom) in May, may be due to the cumulative effects of upwelled water [as shown by the temperature and salinity observations (chapter 3)] and the inflowing bottom currents. The presence of tidal intrusion fronts in this channel upto the tanker berth, station 5, in February, indicated landward flowed of magnitude 38 cm sec^{-1} at mid depths and 62 cm sec^{-1} at bottom. In March, the surface, middle and bottom waters at the Ernakulam wharf (station 7) flowed seawards while that at station 8 of the same transverse section flow landwards, showing the presence of a gyre which may have profound effects on the sediment transport mechanism.

The water flow in monsoon months were measured during the flood tide phase. The increased speed of currents in this season was due to the enhanced runoff from monsoonal rainfall (Fig. 26). Comparatively

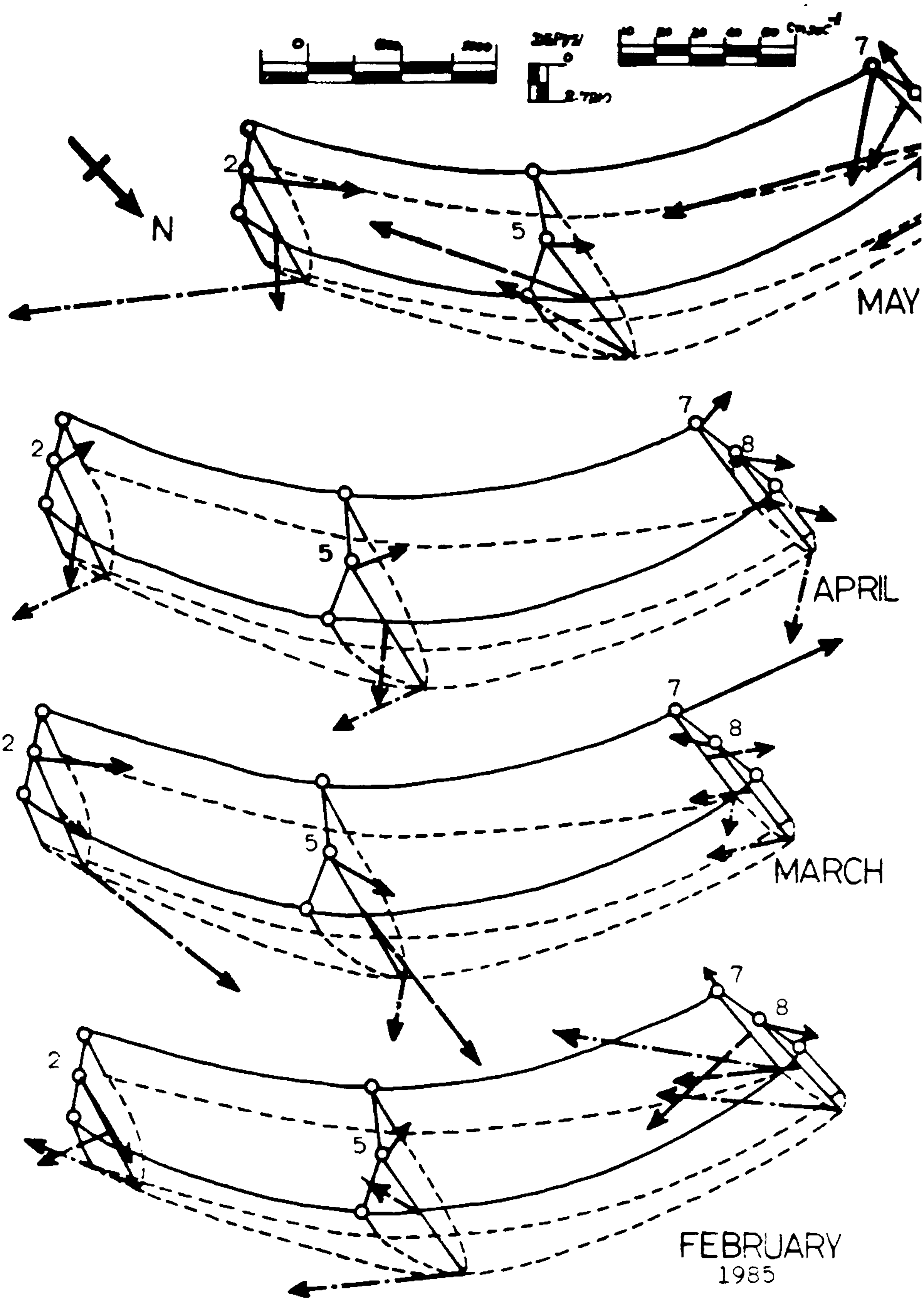


Fig. 25. Water currents in Ernakulam channel (stations 2,5,7 and 8) at surface, middle and bottom during premonsoon season.

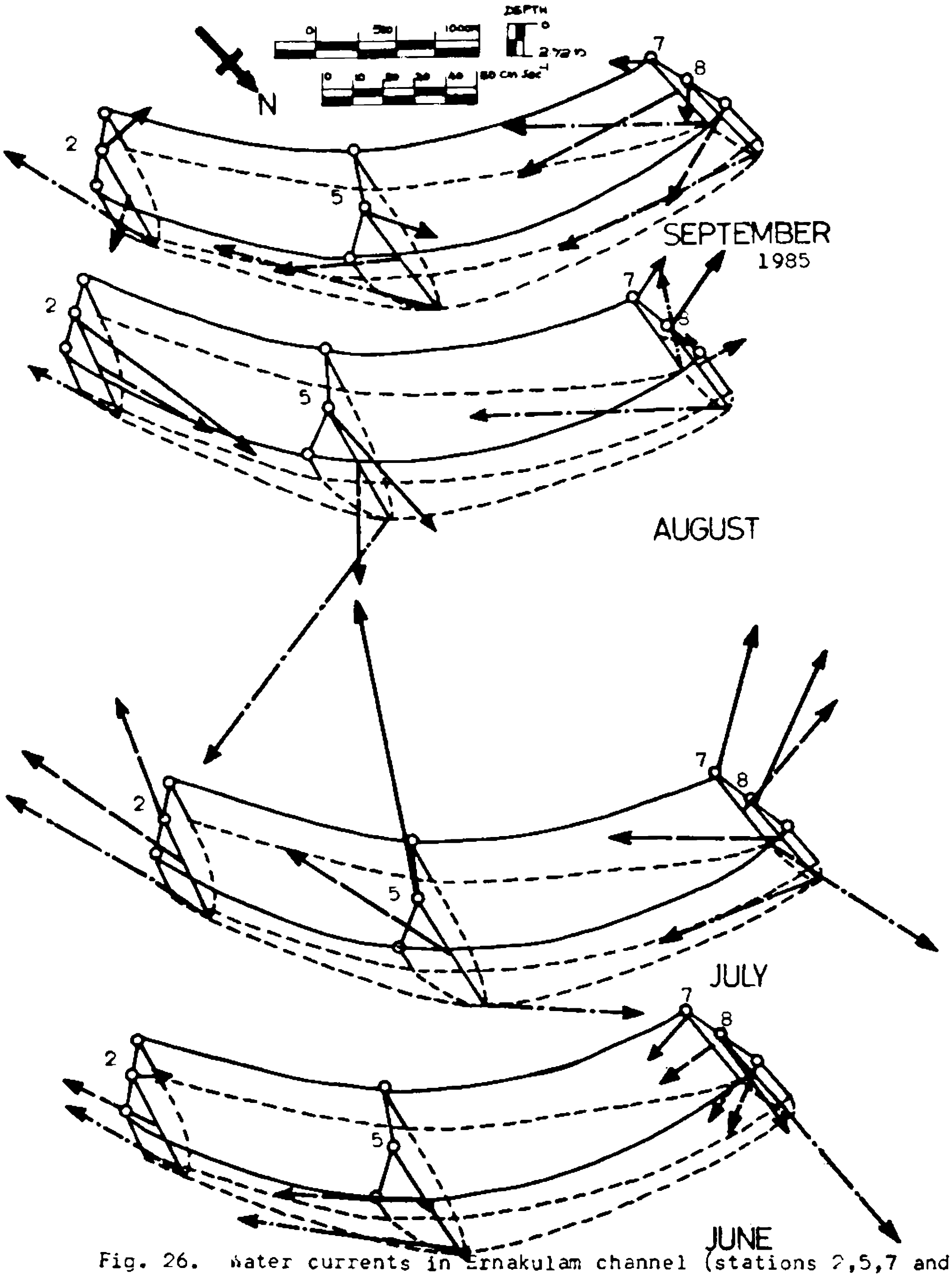


Fig. 26. Water currents in Ernakulam channel (stations 2,5,7 and 8) at surface, middle and bottom during monsoon season,

stronger water currents were observed in July (81 - 88 cm sec^{-1}) and August (66 - 83 cm sec^{-1}) ; the role of high monsoon waves may also influence the estuarine currents. Earlier studies by Central Water Power Research Station (1969), also revealed, the presence of the wave induced currents in the Cochin harbour area. In the month of July, the bottom waters at station 8, flowed in the landward direction; the direction of flow at middle and surface layers of station 5 inclined slightly towards west of the channel and the water column in Ernakulam channel (station 7) exhibited a gyre type circulation pattern. However, in August, the bottom waters of stations 7 and 8 in the same transverse section flowed in opposite direction. The geomorphology of the channel and the increased freshwater supply interact in subsurface layers to exhibit this type of a feature. A two layer flow was observed in this channel during August and September, 1985. The translatory nature of the water flow during July and August is accounted by the strong interaction between flood tide flow and fluvial supply from the Periyar on the northern side of the channel and from the Muvattupuzha and other rivers on the southern parts of the estuary. Similar type of estuarine circulation due to the interaction of different waterways and the tides have been observed by Sujilan and Wangkanshan (1986) in Changjiang estuary (China).

4.3.2. Approach Channel

The flow pattern in the Approach channel during the postmonsoon, premonsoon and monsoon months are presented in the figures 27, 28 and 29 (i) & (ii).

During October, the channel exhibited ebbing at the surface layers of the cut region and upto the turning point (stations 16 and 17). The direction of flow reveals that ebbing persisted in the surface layers even at the commencement of high tide. The direction of flow at rest of the stations exhibited northeasterly currents. In November, intense ebbing (76 cm sec^{-1}) was present at the subsurface layers of the cut and also along the surface water of the Approach channel (flows towards the seaward direction with southwest inclination). During November and December, the outer most stations 18 and 19

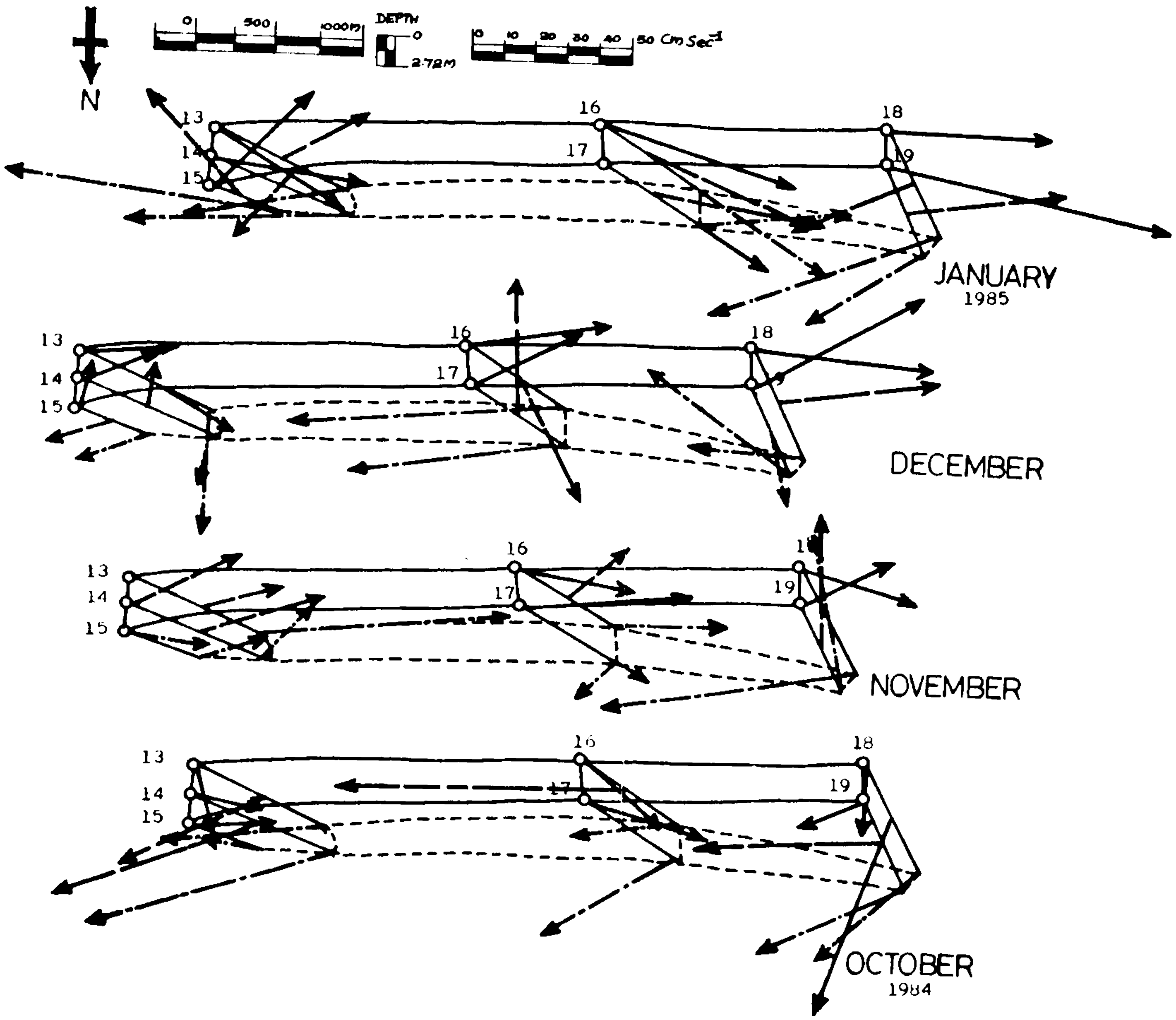


Fig. 27. Water currents in Approach channel (stations 13 - 19) at surface, middle

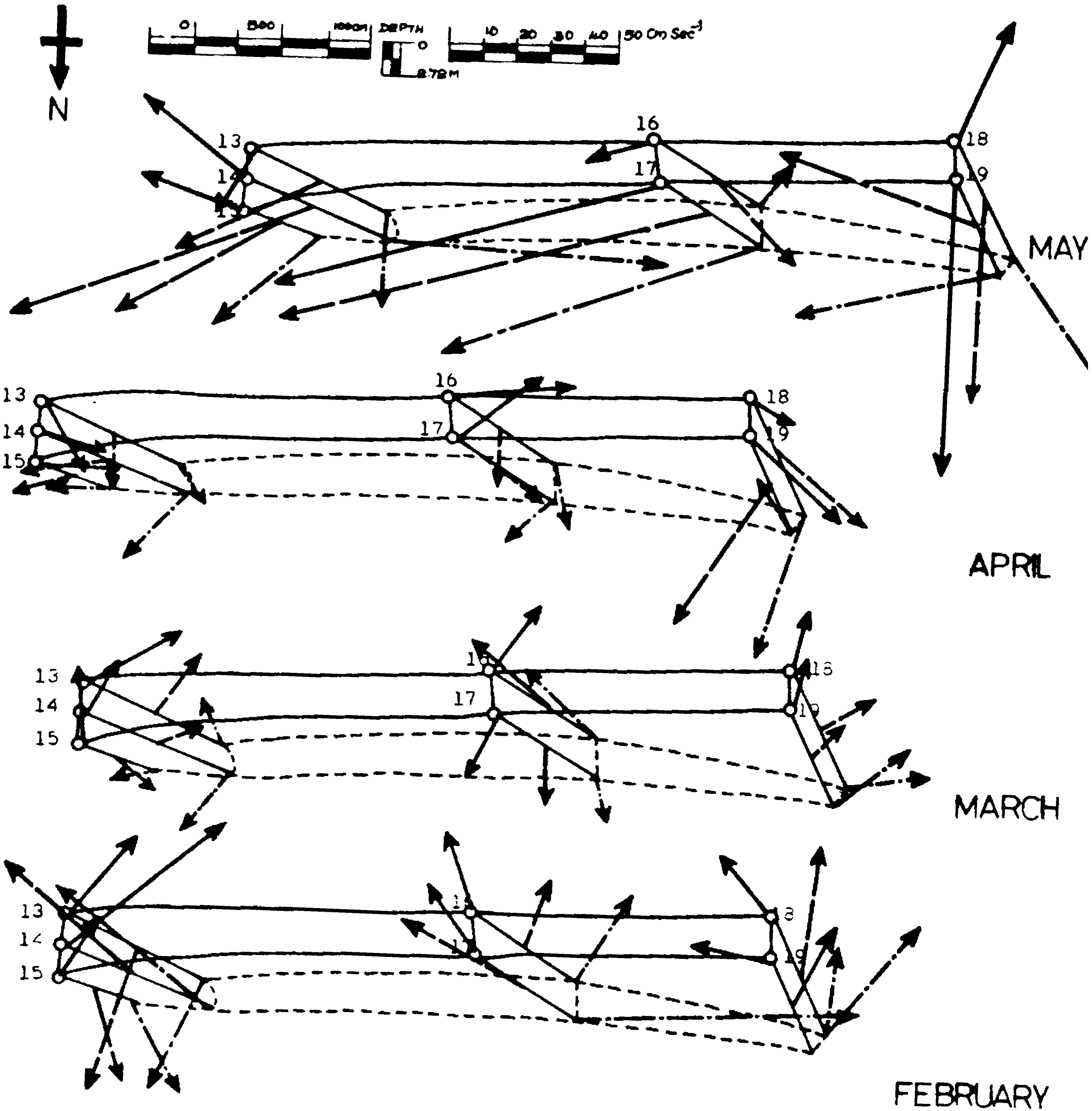


Fig. 28. Water currents in Approach channel (stations 13 - 19) at surface, middle and bottom during premonsoon season.

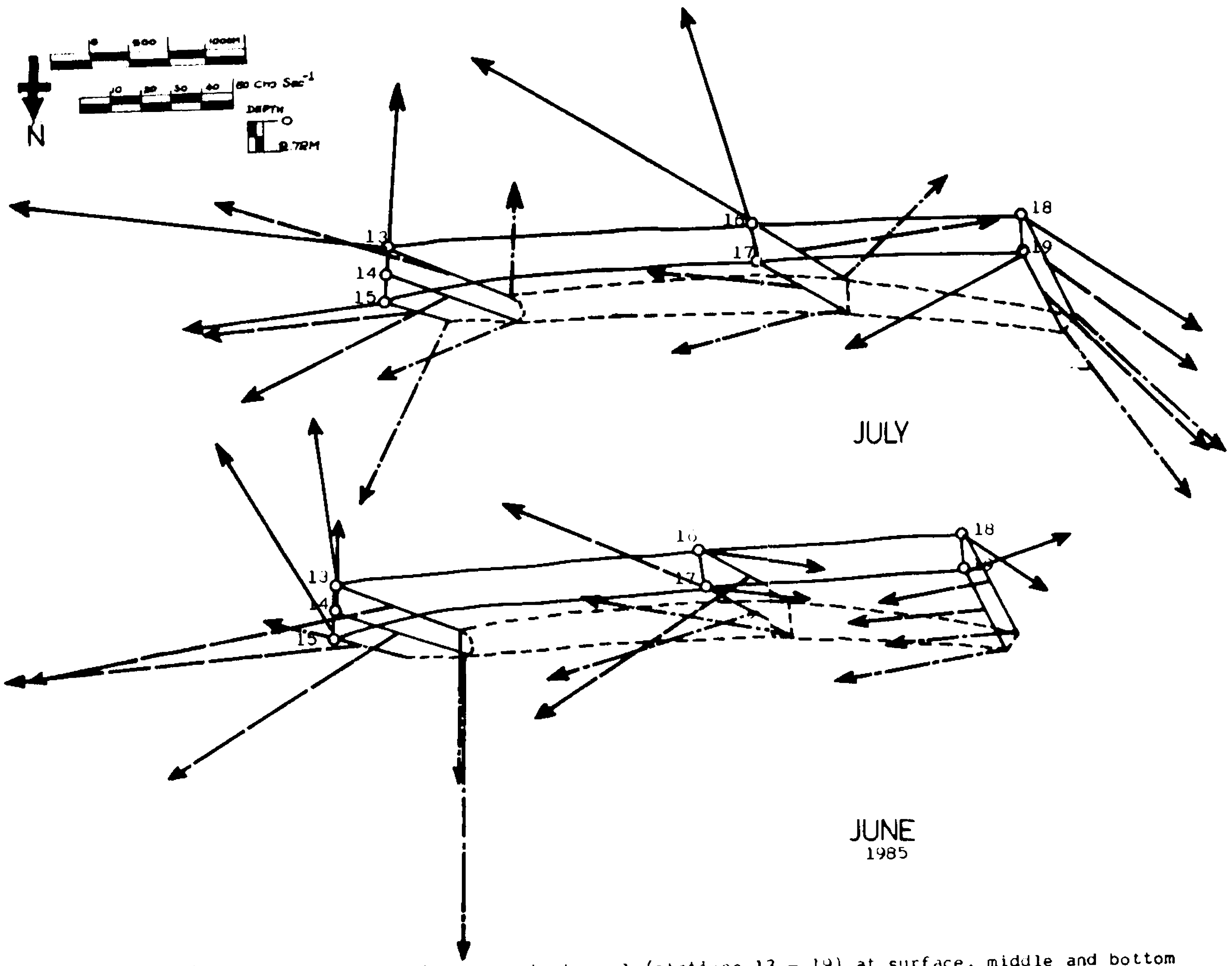
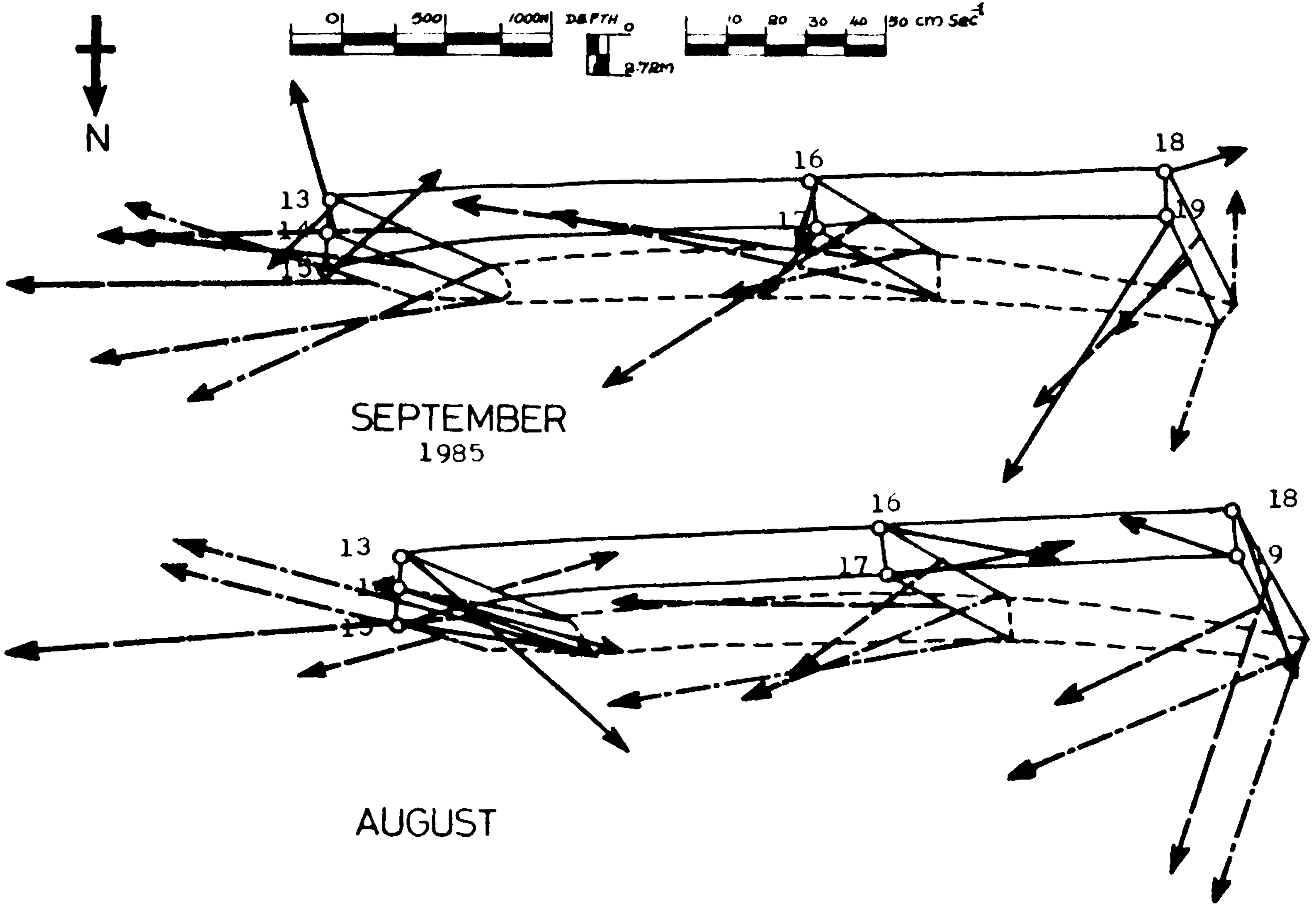


Fig. 29(1). Water currents in Approach channel (stations 13 - 19) at surface, middle and bottom during monsoon season.


N
0
500
1000M
DEPTH
0
2.72M
10
20
30
40
50 cm Sec^{-1}
13
14
15
16
17
18
19
SEPTEMBER
1985
13
16
17
18
9
AUGUST

indicated flow of bottom waters towards the inner channels. Nearly similar results were observed in the Approach channel region by Prasannakumar et al. (1983). Very evidently, in this study, two layer flows were observed throughout the Approach channel during December survey with bottom waters mainly directed towards northeast. The seaward end of the Approach channel (stations 18 and 19) and the cut region alone exhibited two layer flow in January 1985. Water currents were directed towards the seaward side from the turning point (stations 16 and 17) while bottom currents flowed landwards from the seaward end of the Approach channel (stations 18 and 19) which is likely to favour heavy sedimentation in this segment. Siltation beyond 2 km distance from the Cochin cut reported by Anto et. al. (1977) may be due to the circulation pattern presently observed in this segment. It is observed that the Approach channel was characterised by two distinct circulation patterns, one from the Cochin cut to the turning point area (stations 16 and 17) and that beyond it, towards the seaward side. The narrowness of the Cochin cut may have a prominent role in generating the above explained circulation pattern.

During premonsoon months, the magnitude of bottom and midwater currents were stronger than the surface currents. Comparatively, low magnitude currents were present in February (20 - 58 cm sec^{-1}), March (12 - 28 cm sec^{-1}) and April (16 - 44 sec^{-1}) in the Approach channel. In February and March, the water flowed in the southeast and southwest directions (stations 13, 16, 18, 19) except at the subsurface layers on the sides of the cut region in February. The flow at station 17 in March exhibited northeast motion of water while surface flow at station 15 was southerly. This is presumably due to the combined effect of the northerly and northwesterly waves in this season (Monthly Meteorological Charts, 1958) that cause a net southerly flow. In April, the surface flow was seawards at surface and the subsurface water flowed towards the northeast and northwest directions; hence the presence of a two layer flow was detectable. Very high magnitude currents flowing towards northeast (landward direction) were present in the Approach channel (though the observation was taken during the ebb tide) in April. This is due to the incursion of upwelled waters as confirmed from the salinity and temperature data measured simultaneously during the course of observation.

The figures 29 (i) & (ii) exhibited comparatively high magnitude water flow in monsoon months due to the increased fluvial supply, wave induced currents and increased intensity of winds. The maximum value of water flow was present at the southern tip of the cut (126 cm sec^{-1}) in July. During June, the subsurface waters flowed towards the northeast and northwest directions while seaward flow was minimal at surface layers. The water flow in the cut region during July indicated currents towards the inner channels lagging the ebb phase of the tide. This was caused by the onshore component of strong winds increasing the sea surface slope along the shore and also due to the wave induced currents at the peak of the monsoon season. Srivastava and John (1977) highlights the role of wind speed in modifying the circulation pattern while studying the current regime in the Gulf of Kutch. Shenoi and Murty (1986) observed that the onshore component of strong winds could give rise to increased sea surface slopes along the shore in this season. In August, the subsurface water flow was in the northeast direction except at the cut, where the flow was directed towards the Mattancherry channel. In September, the water column at stations 16 and 17 flowed within the channel landwards. It can be seen from the current pattern that during the monsoon months, the orientation of flow in the cut region may be influenced considerably by numerous factors viz. tide, wave, wind and fluvial supply apart from outer sea influences. The narrow orifice of the cut at the barmouth may also cause jetting effect of water currents during the tide phases which in turn leads to two layer flows in the outer extension of the Approach channel.

4.3.3. Mattancherry Channel

The pattern of water flow during the different seasons viz. postmonsoon, premonsoon and monsoon at definite phases of tidal stages are shown in the figures 30 (i) & (ii), 31 and 32 (i) & (ii).

During the postmonsoon months, two layer flow was present in the downstream reaches of the channel, except in December, when the net water

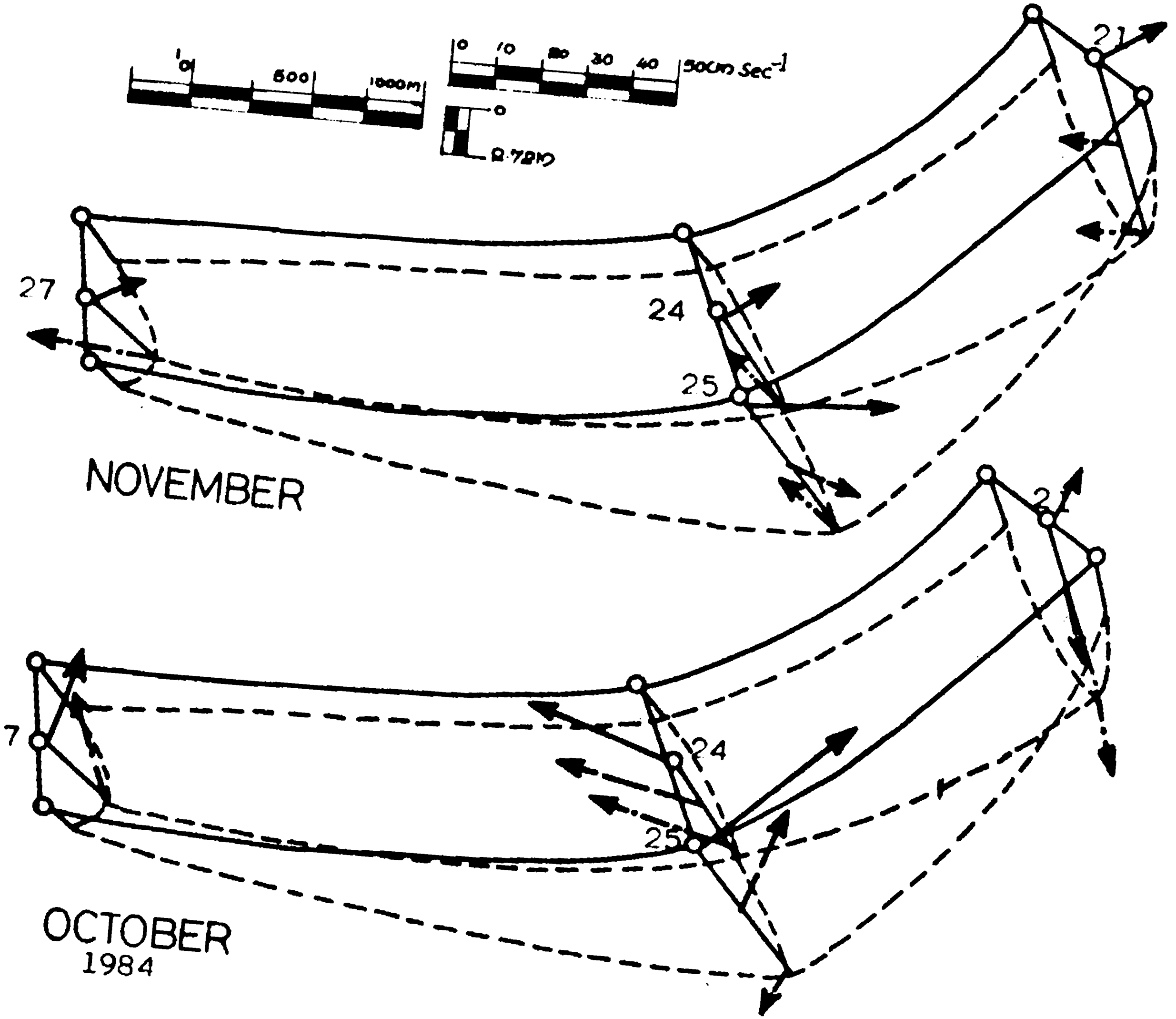


Fig. 30(i). Water currents in Mattancherry channel (stations 21,24,25 and 27) at surface, middle and bottom during postmonsoon season.

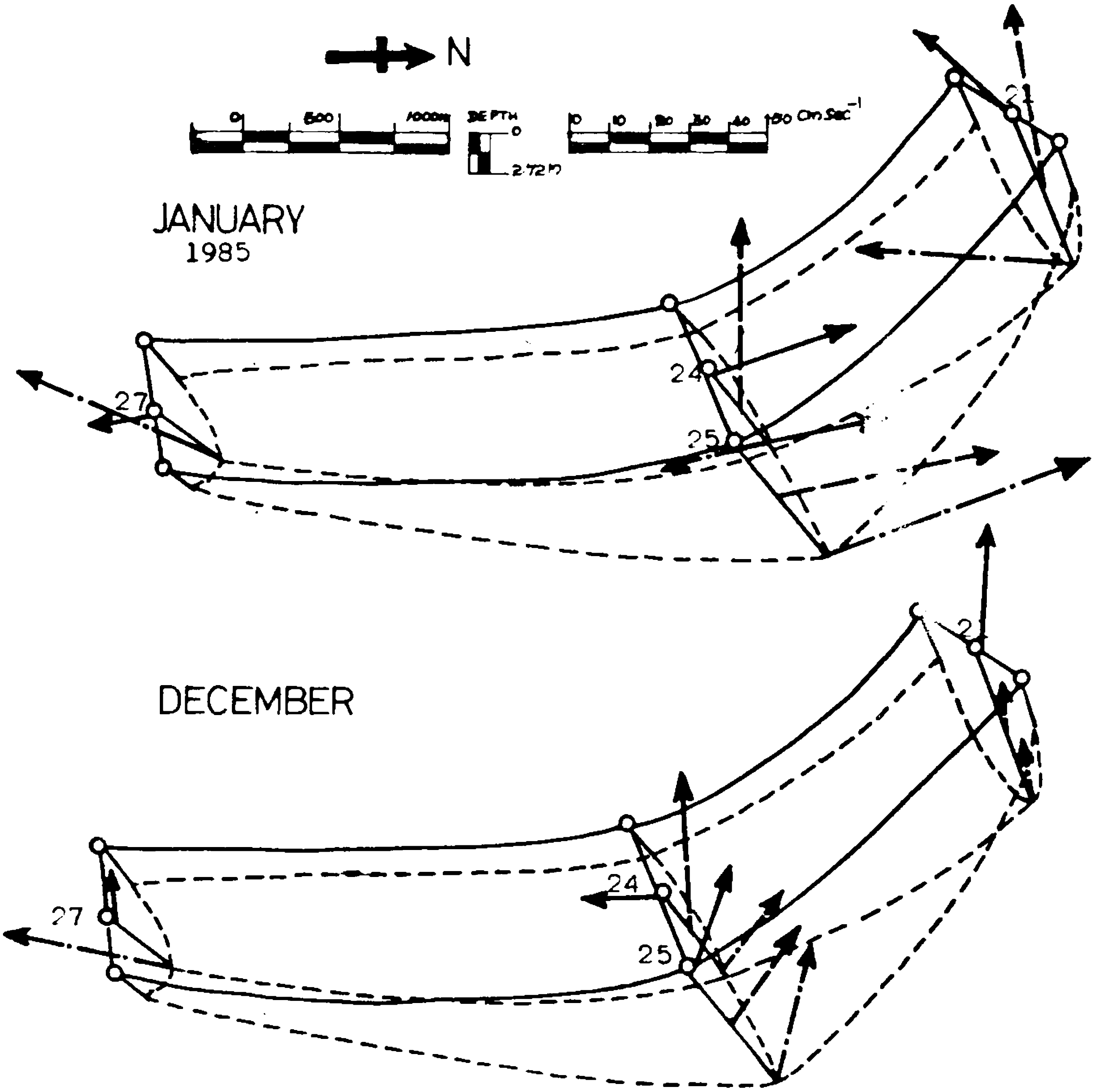


Fig. 30(ii). Water currents in Mattancherry channel (stations 21,24,25 and 27) at surface, middle and bottom during postmonsoon season.

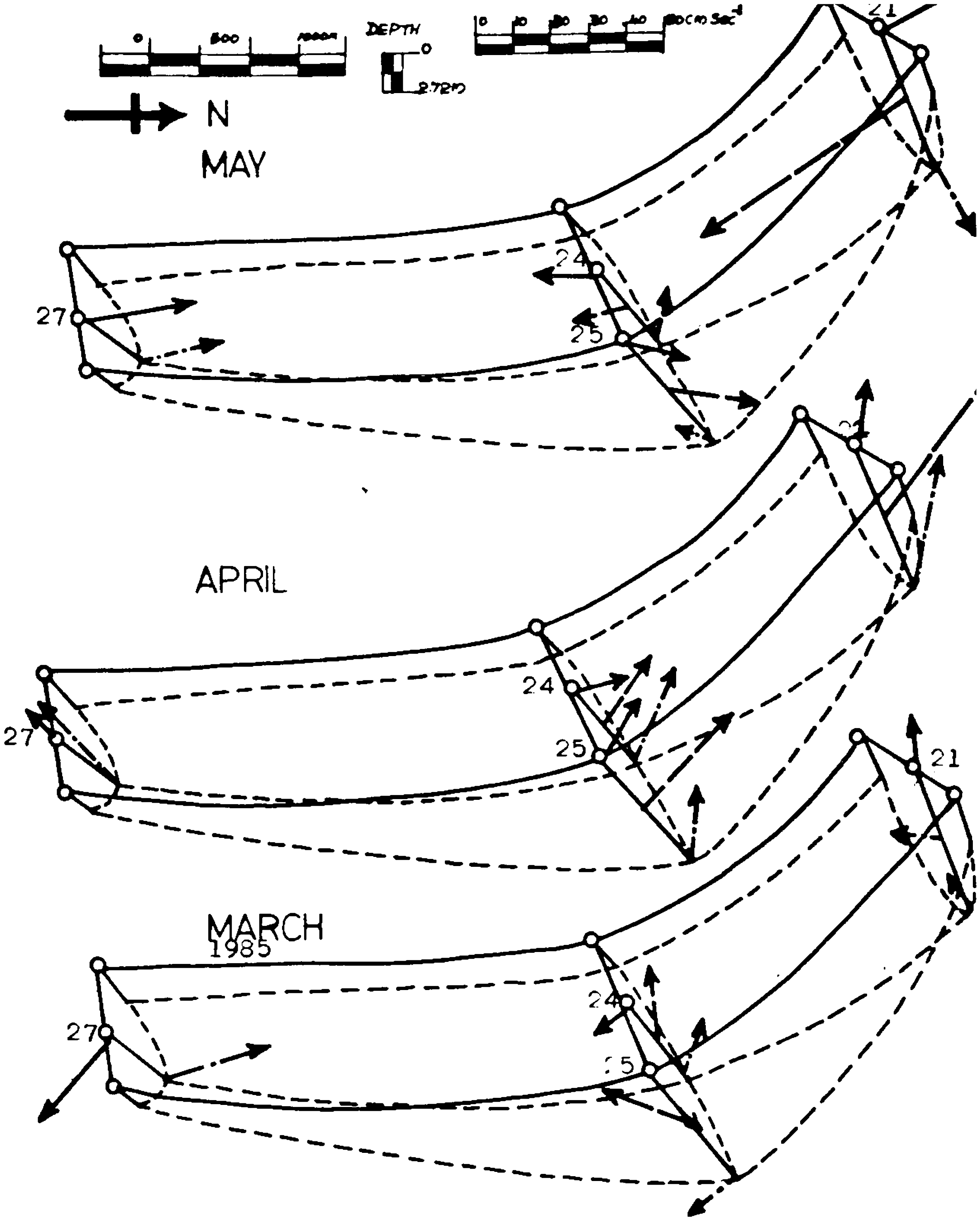


Fig. 31. Water currents in Mattancherry channel (stations 21,24,25 and 27) at surface, middle and bottom during premonsoon season.

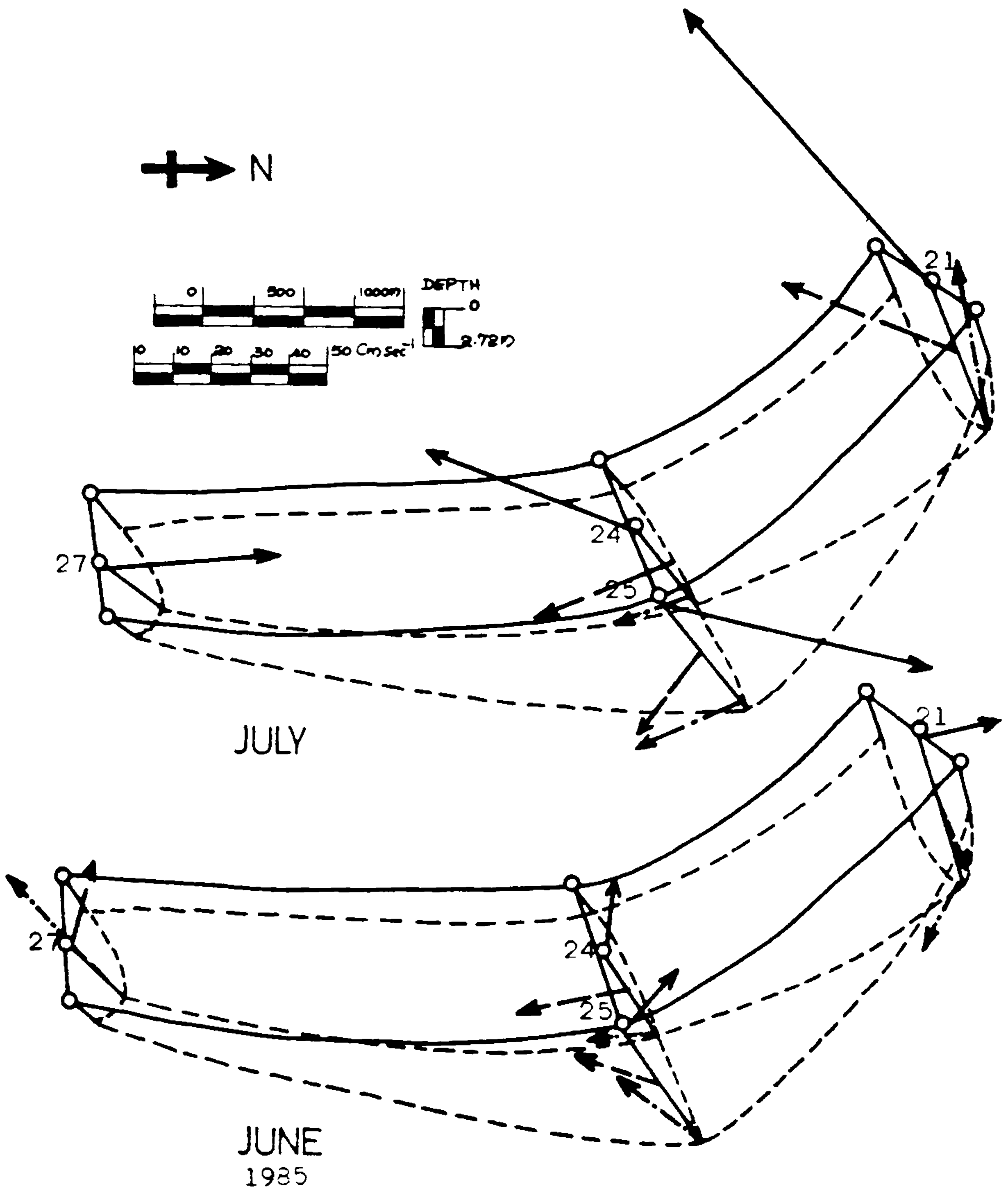


Fig. 32(i). Water currents in Mattancherry channel (station 25 and 27) at surface, middle and bottom during season.

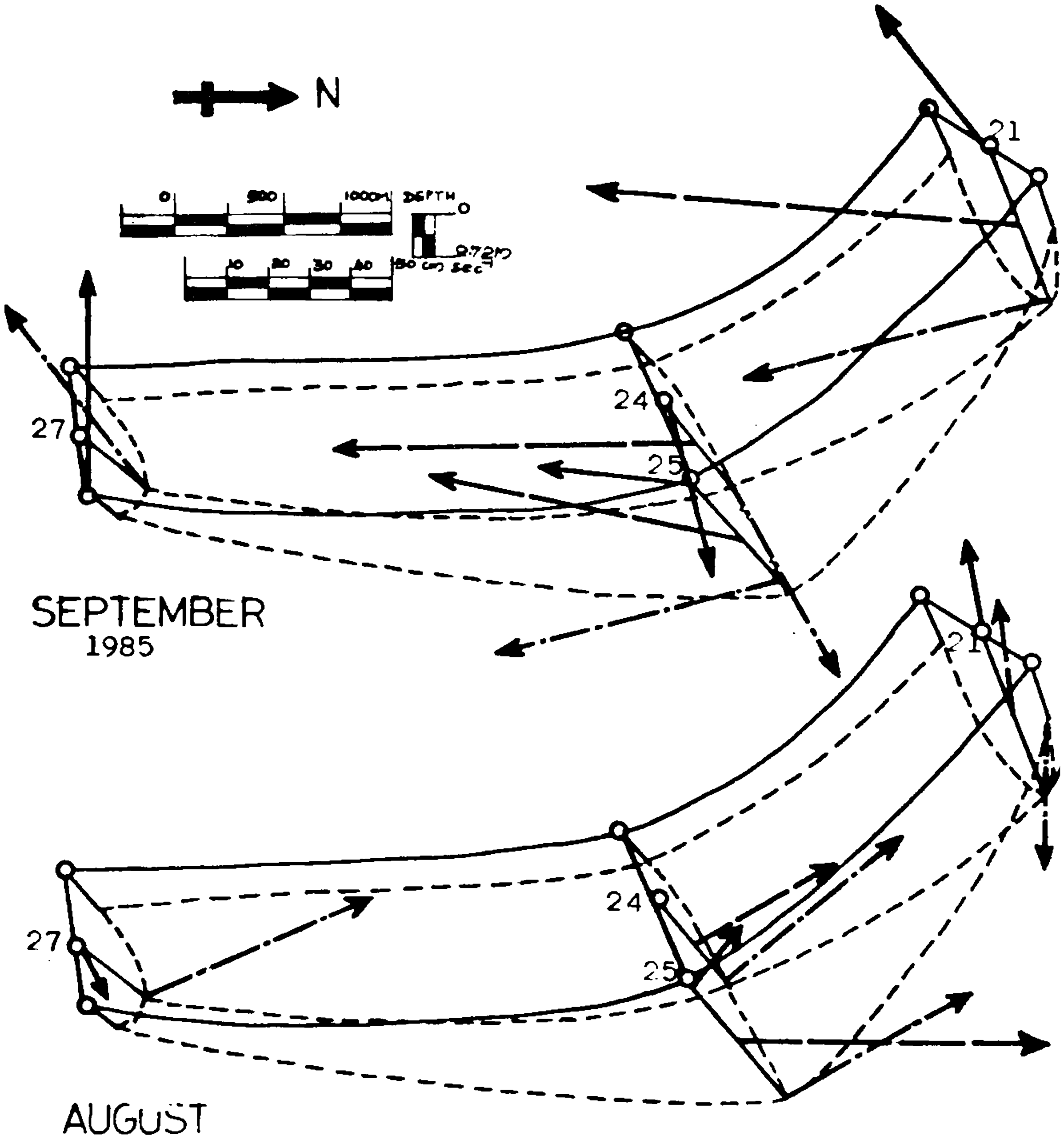


Fig. 32(ii). Water currents in Mattancherry channel (stations 21,24,25 and 27) at surface, middle and bottom during monsoon season.

flow was seawards. The study reveals the intensity of tidal incursions to act dominantly at the subsurface levels in this channel and in December, the ebb flow reversed the subsurface water flow. The magnitude of water flow was lower than other seasons and was a minimum in November (9 - 34 cm sec^{-1}). In October, the surface and midwaters of the stations in the same transverse section (station 24 and station 25) exhibited flow in opposite directions which may facilitate the deposition of the suspended material. The bottom waters were directed landwards in October and was of low magnitude (10 - 33 cm sec^{-1}). This slow speed may act as a sink causing the deposition of suspensate. Similar observations were made by Bartholdy (1984) during his studies on the transport of suspended matter in a bar-built Danish estuary. The figure 30 (i) also exhibited the presence of a gyre at station 25 in November (bottom waters flow southwest, midwater north-northwest and surface water towards north - northeast direction). In January, the whole vertical water column exhibited seaward flow in the transverse section of the Mattancherry wharf. Tidal and fluvial flows interacted giving rise to translatory flow in the form of secondary circulation pattern in the lower reaches of this channel. The circulation pattern in postmonsoon months revealed that the currents did not follow the expected tidal rhythms ; the ebb flow towards sea and the flood flow towards the land, lag considerably in this channel. The presence of secondary circulations that arises from the freshwater flow fluctuations, geographical orientation of the channel, the irregular depth variations due to dredging and topographical unevenness are reasons for the peculiarities observed in this channel with regard to current flow variations during this season. Such external influences on estuarine flow was also discussed by West and Shiono (1985) in their studies on turbulent perturbations in partially mixed estuaries.

During premonsoon months (no data for the month of February 1985) speed of water flow was marginally reduced in this channel and was minimum in March (8 - 29 cm sec^{-1}); the fluvial flow and the tidal incursion effects were low to moderate in this channel. The stations of the same transverse section in Mattancherry wharf area (stations

24 and 25) exhibited water flow in the opposite direction and hence gave rise to circulatory currents in this segment of the channel. In April the whole water column flowed seawards, much influenced by the ebb phase of the tide and also owing to the decrease in sea level due to processes like upwelling and calming-down of waves. Also noted here is the baroclinic adjustment of sea surface slope for a southerly flow, that gives rise to difference between the sea level and the water level in the backwater system (Shenoi and Murty, 1986). Two layer flows observed in May indicate the strong incursion of coastal waters. The increased turbulence due to earlier onset of monsoon also contribute to this.

The water flow in monsoon showed considerable variation in magnitude: 30 - 97 cm sec^{-1}. A two layer rotational flow was present in June at Mattancherry channel stations. During July, the maximum value of current flow at surface (97 cm sec^{-1}) was observed at station 21 in the southwest direction. Water flowed in opposite directions near the Mattancherry wharf area (stations 24 and 25) due to the circulatory currents caused by the curved orientation of the channel. During August, the water currents were directed downstream in this channel whereas in September, the flow was reversed. The maximum flow velocity recorded in July was 97 cm sec^{-1} and in September, 103 cm sec^{-1} in the mid-water levels at station 21. The surface and bottom waters at station 24, in September, were directed towards the Mattancherry wharf jetty which may induce the transport of suspended material towards the wharf. Increase of estuarine water level during monsoon as a result of rainfall and associated land run off has been attributed to the magnification of strong downstream flows, mostly fresh water. To compensate the enhanced outflow, the landward bottom current accelerates to maintain equilibrium according to the equation of continuity as explained by Pond and Pickard (1986). The effects of increased churning action of waves, intensified winds and orientation of Mattancherry channel considerably influence the water circulation characteristics as revealed from this study.

4.4. SEMIDIURNAL VARIATIONS IN CURRENT VELOCITY

Semidiurnal variations in water current speed and direction were measured at the surface, middle and bottom layers of Ernakulam channel (station 1), Mattancherry channel (station 2) and Cochin cut (stations 3, 4 and 5) (Figs. 33-36).

4.4.1. Springtide (14.9.1984)

The figure 33 showed that in the inner channels and in the Cochin cut region there was a time lag of 1 to 2 hours for the flood current to extent to the surface layers and the ebb current to reach the bottom. The relative time lag was observed to be more at the cut region. The duration of flood flow was less at the surface compared to bottom. Similar results were reported by Gopinathan and Qasim (1971) and Rama Raju et al. (1979). The overall flow pattern observed in this season was governed by the combined action of monsoonal freshet and tidal intrusion.

In Ernakulam channel (station 1) the surface current flowed mainly in the southwest direction while middle and bottom waters flowed in the north and southeast directions respectively at the time of commencement of tide revealing that the tidal response of surface and subsurface waters were unequal in this channel. In the inner channels, the ebb current was predominant in intensity and duration affecting the whole water column (Ernakulam channel ebb flow 113 cm sec^{-1} and flood flow 59 cm sec^{-1}; Mattancherry channel - ebb flow 112 cm sec^{-1} and flood flow 33 cm sec^{-1}). The figure 35 indicated that in Ernakulam channel the percentage surface flow was predominantly towards the southwest direction (37.5%), middle water to north (25%) and bottom water towards southeast (37.5%); hence a clockwise rotor flow from surface to bottom due to the shear force originated by water flowing in opposite directions was noted. In the Mattancherry channel the surface water predominantly flowed in the northwest direction (50%); middle water north-northwest (37.5%) and bottom water towards west (25%); hence near equal intensity and duration of ebb currents were predominantly observed at all depths of the Mattancherry channel.

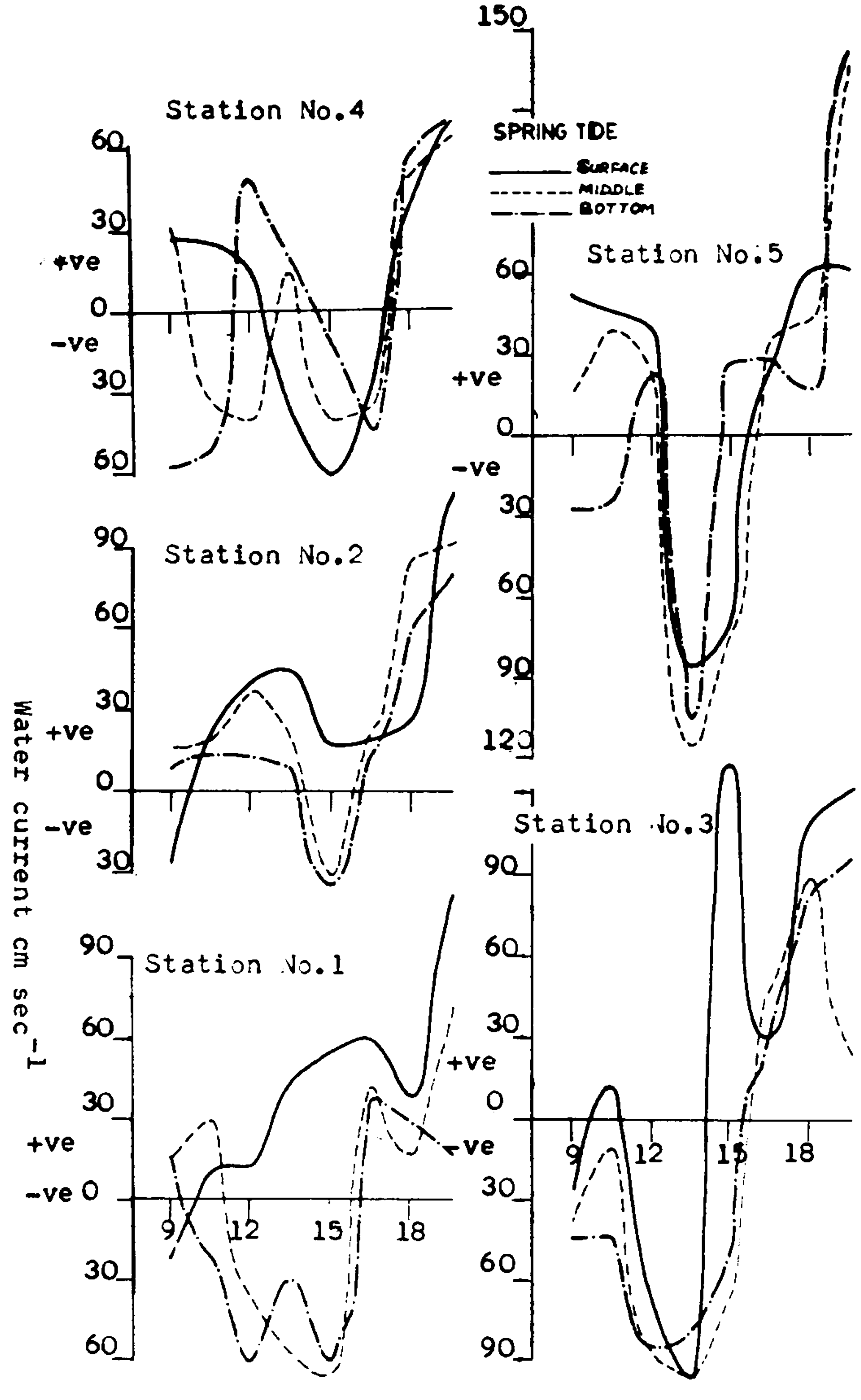


Fig. 33. Semidiurnal variation in water current at stations 1 - 5 during springtide (14.9.1984).

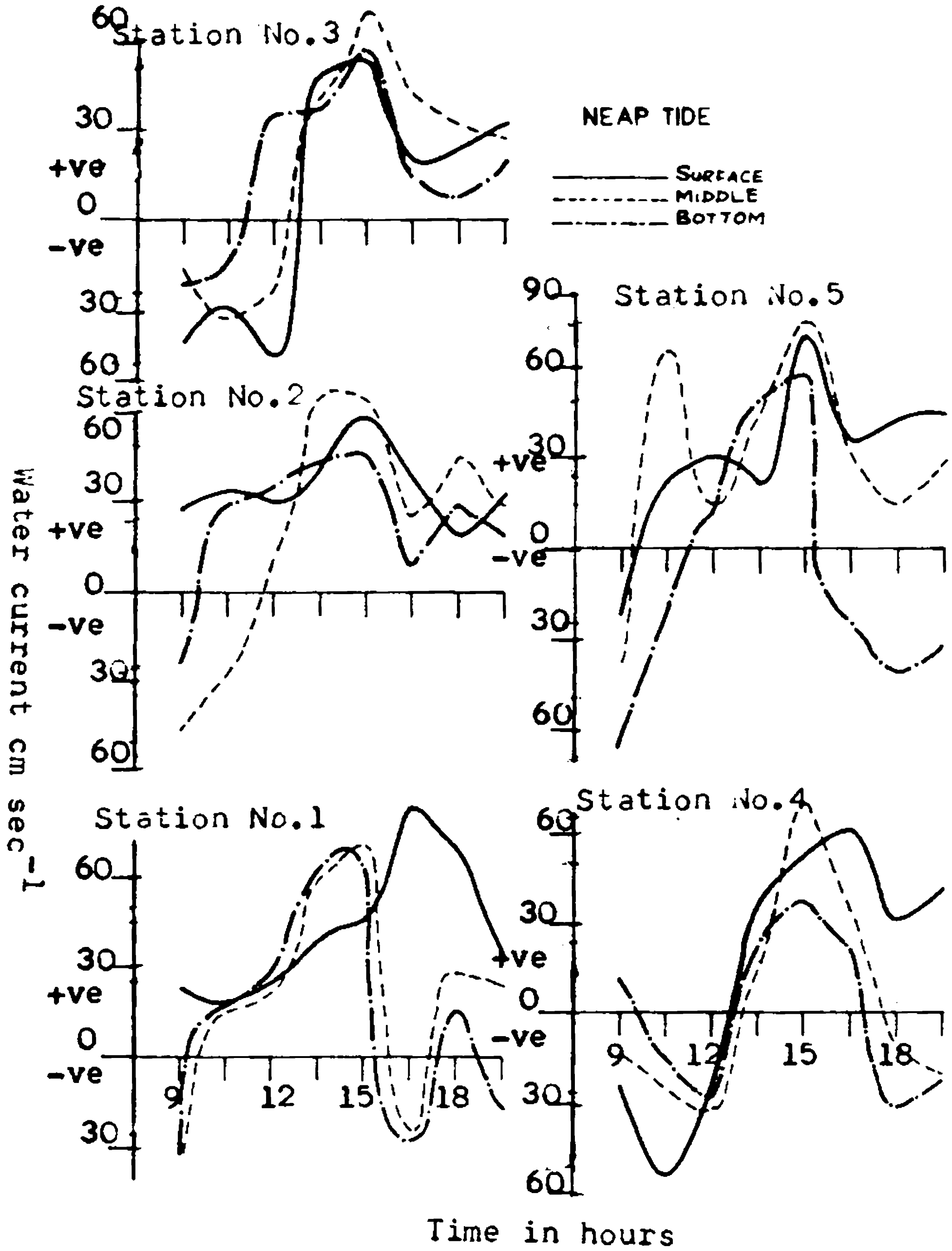


Fig. 34. Semidiurnal variation in water current at stations 1 - 5 during neaptide (30.11.1984).

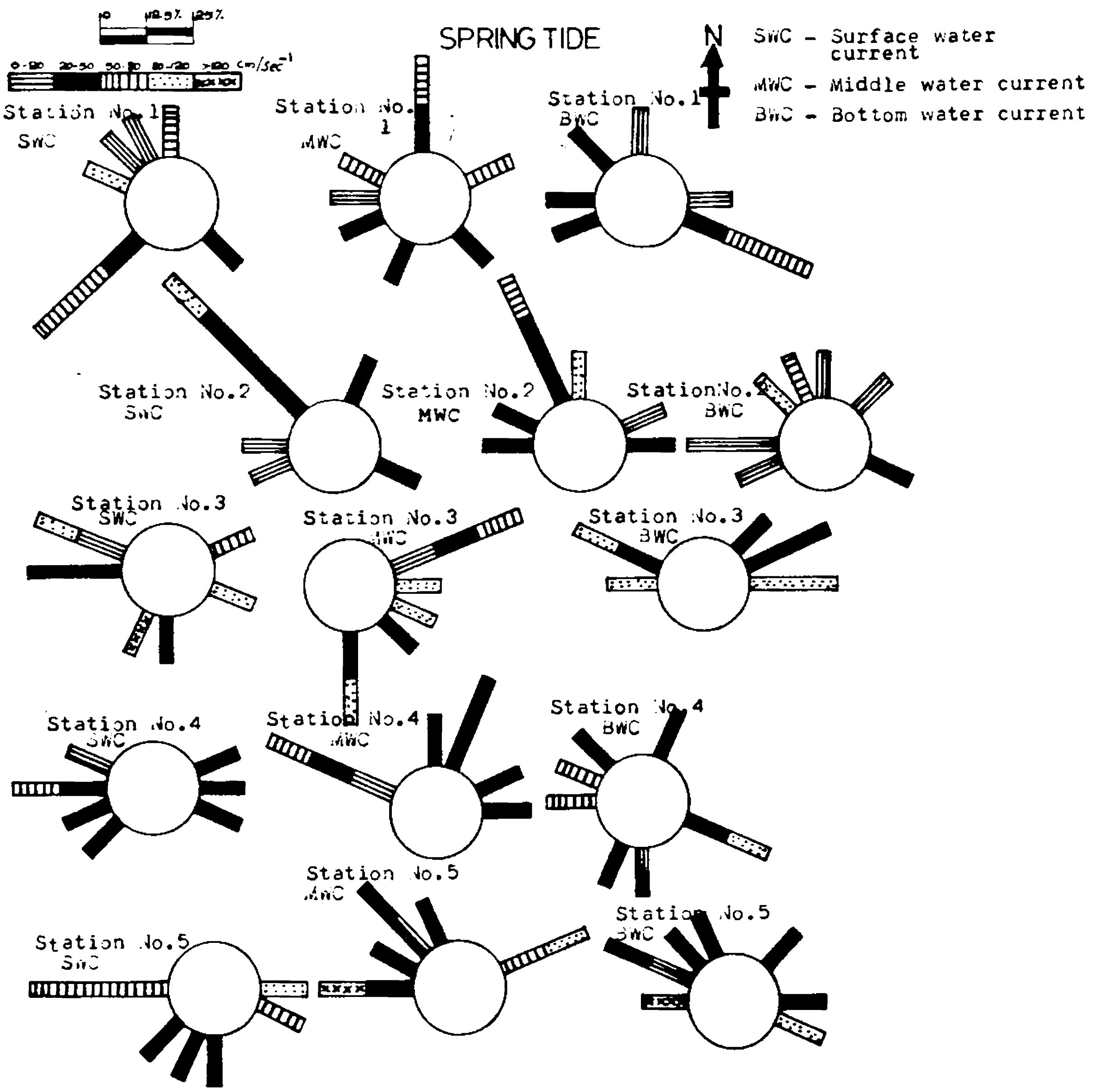


Fig. 35. Current vectors at stations 1 - 5 during springtide (14.9.1984).

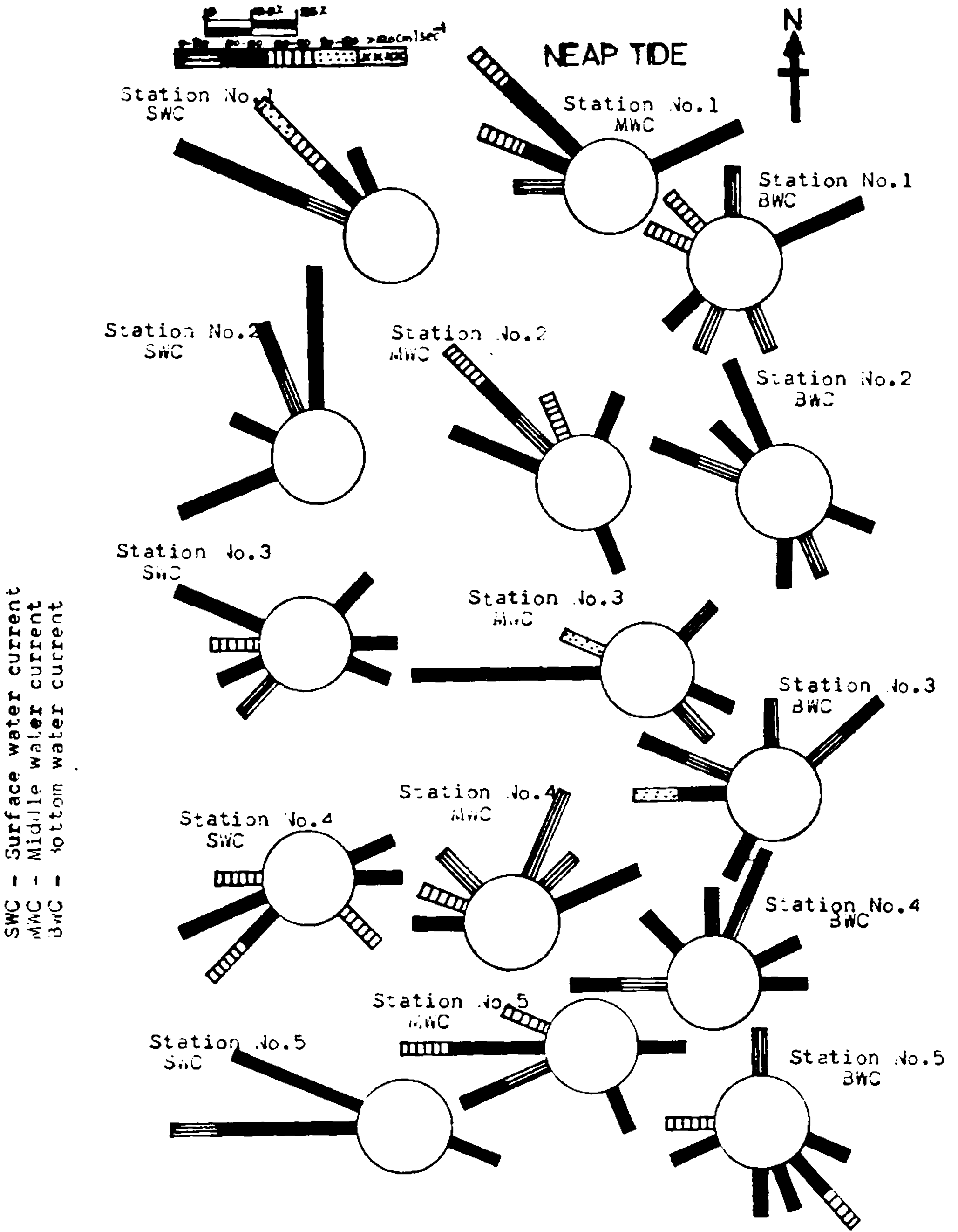


Fig. 36. Current vectors at stations 1 - 5 during neaptide (30.11.1984)

This may be due to the voluminous monsoonal discharge displacing the tidal waters of flood.

The highest current velocity at the Cochin cut was observed during the ebb flow on the northern side of the inlet; 137 cm sec^{-1} (132 cm sec^{-1} at the south of the cut and 69 cm sec^{-1} at middle). The surface waters of the cut mainly flowed between northwest direction while middle and bottom flow oscillated in all directions; hence rhythmic fluctuations in speed and direction of surface, middle and bottom waters with tides along with complete reversal in water flow at bottom layers were particularly noted for the cut region. The stations on the two side of the cut exhibited increasing higher current speeds than the centre station. The flow pattern at the centre station of the cut (at middle and bottom layers) followed the tidal response than the transverse stations on either sides. The phase of current nearly lagged that of the tide by 90° at these two side stations.

4.4.2. Neaptide (30.11.1984)

Semidiurnal variation in the speed and direction of water flow along the surface, middle and bottom waters during the neaptide at Ernakulam channel (station 1), Mattancherry channel (station 2) and the Cochin cut (stations 3, 4 and 5) are presented in figures 34 and 36.

It was observed that at the very commencement of ebb tide surface flow at station 1 was directed downstream. In the inner channels as well as in the cut region there was considerable time lag (of about 2 hours) between the tide phase and surface or bottom waters; a two layer flow was present at all the three channels at the commencement of ebb flow.

During neaptide, the surface and mid-water currents mainly flowed in the west-northwest (100% - 75%) direction in Ernakulam channel while in the Mattancherry channel the flow was in the north-northwest direction (75% - 75%) (Fig. 36). Rama Raju et al. (1979) and Udaya Varma et al. (1981) also observed similar conditions in the inner channels. The maximum current was present at the surface levels of the inner channel, Ernakulam channel 82 cm sec^{-1} and Mattancherry middle 76 cm sec^{-1}. The percentage flow values reveal that the duration of ebb flow was more in the Mattancherry channel than in the Ernakulam channel.

The nature of the current roses and the percentage of the predominant direction indicate that the surface water direction reverses at the inlet with the tidal phase except on the north part of the cut. The surface and mid-waters on the north and south of the cut flow mainly towards west; this may be due to the increased fluvial supply from the Ernakulam channel while the direction of bottom water flow reverses with the flood tide. The role of local circulation to modify the flow to the above mentioned conditions are not however excluded. The maximum flow at the inlet was on the north of the cut (71 cm sec^{-1}). It is inferred from the figures that the direction and flow at the centre of the inlet responded more symmetrically to tidal fluctuations.

CHAPTER 5

SUSPENSATE AND SURFICIAL SEDIMENTS

5.1. INTRODUCTION

Suspended solids (synonymously, suspensate) in the highly dynamic estuarine environment are subjected to back and forth transport by ebb and flood tidal currents and are recycled many a times prior to deposition. Many of the estuarine circulation systems cause the entrapment of some amount of suspended solids; the study on distribution of this material is significant with regard to both its estuarine behaviour and sedimentological features. The particle dynamics in coastal waters has been a special subject area wherever surveys on pollutant dispersal were considered (Officer, 1981; Varadan et al. 1985).

Estuarine waters are often more muddier than the rivers flowing into them or the sea beyond, due to presence and availability of varying amounts of suspended solids (McCave, 1979). Sediments principally move in suspension prior to deposition in regions of accretion in an estuary (Almos, 1987). Definition of suspended load used here is the one recommended by the sub-committee on sediment technology (Dyer, 1979). The material moving in suspension in a fluid, being kept up by the upward components of turbulence or by law of the colloidal mixtures is termed suspended load. This conveys the dynamic sense of 'suspension' as a process that is controlled by the hydrodynamic conditions. Many have observed the existence of an active interchange between the suspended load and bed load and also between the bed load and bed itself (Graff, 1971; Adalph, 1982; Parker, 1987).

Grain size analysis is frequently used by sedimentologists to characterise the depositional environments of clastic sediments (Nayak and Chavadi, 1988). The grain size of a clastic sediment is a measure of the features of the depositing medium and the energy of the basin of deposition (Reineck and Singh, 1980). In general, the coarser sediments are found in high energy environments and finer sediments in lower energy realms (Hashimi et al. 1978; Mavis et al. 1985; Dyer, 1987).

The studies on the problems associated with the suspensate and surficial sediments of the Cochin harbour area had been made by Ducanfe et al. (1938), Das et al. (1966), Sunda Raman (1968), Central Water Power Research Station (1969), Josanto (1971), Gopinathan and Qasim (1971), Veerayya and Murty (1974), Anto et al. (1977) and Rama Raju et al. (1979). According to Gopinathan and Qasim (1971) the water column of the Cochin harbour area has a maximum suspended load during the monsoon period but its quantity declines progressively through the postmonsoon and premonsoon months. However, Rama Raju et al. (1979) observed a general increase in the sediment load from monsoon to premonsoon through postmonsoon seasons during 1975-1976. Studies by Veerayya and Murty (1974) on the sediments of Vembanad lake during postmonsoon months, revealed that the finer sediments were present in the estuarine region of the lake and this was due to the deposition of suspended load by flocculation and by the supply of fine material from the sea brought in by tidal currents during these months. Josanto (1971) reported that during premonsoon months, the grain size distribution of the Cochin backwater sediments indicated presence of silty clay around Willingdon island and that the sediments in the Mattancherry channel region were of finer texture than those in the Ernakulam channel.

In recent years, extensive harbour development work has been conducted in the Cochin harbour area and its vicinity. Cochin Port Trust has already carried out substantial capital dredging work for the execution of the Integrated Development Project during the period 1980-1985 (Manoharan, 1987). These developmental works have much practical importance on the distribution of suspended material and the textural pattern of the harbour area sediments and hence, on the sedimentary environment. The earlier studies on the suspensate and surficial sediments are, therefore, no longer valid. The distribution of suspended material in the Approach channel and simultaneous studies on surficial sediments and other physical parameters were not investigated by the earlier researchers. The studies regarding the suspensate and surficial sediments of this harbour area is lacking since 1979. In the present study, the horizontal and transverse distribution of the suspended load in the harbour area from 28 stations, monthly and the semi-diurnal tidal variation of suspensate from the inner and Approach channels were thoroughly analysed and presented. The monthly textural analysis of the surficial sediment samples collected along with the suspensate are also reported. The variations from previously reported values are discussed in relation with the changing physical processes operating in these areas. In this context, the terms suspended matter, suspended solids, suspensate and seston all refer to total solids held in suspension in water, though operationally it is what that is retained in a filter (Kramer, 1988). These terms have been used synonymously and are interchangeable.

5.2. MATERIALS AND METHODS

The materials and methods employed in this study are described in Chapter 2.

5.3. RESULTS AND DISCUSSION

5.3.1. Suspensate

5.3.1.1. Ernakulam Channel

The suspended solids distribution at the surface, middle and bottom waters of Ernakulam channel, in postmonsoon months, are shown in the figure 37. The surface water seston content was relatively low in this season (47 - 200 mg l^{-1}). It was observed that during October, slightly more suspensate was present at the upper reaches especially along the southeastern side (station 3) of the channel due to the extended monsoonal effects. The figure shows that the surface water seston content was low along the central stations (stations 2, 5 and 8) compared to the shallow stations on the two sides of the channel. The closely placed curved isolines in October and November months revealed that the bottom water suspensate was considerably more (588 - 1061 mg l^{-1}) towards the lower reaches of the channel due to rapid deposition of material in this region. The whole water column in December and in January (except stations 4 and 6) showed low suspensate and less fluctuations (86 - 160 mg l^{-1}). This is due to the reduced freshet discharge of low suspended solids and also due to the lower order turbulence from disturbance caused by winds and waves of the coastal region. The bottom waters at the transverse section in the tanker berths (stations 4 and 6) in January showed suspensate content to be slightly more (333 - 577 mg l^{-1}) than at other stations due to the resuspension of the fine material deposited in this salt-wedge region of the channel.

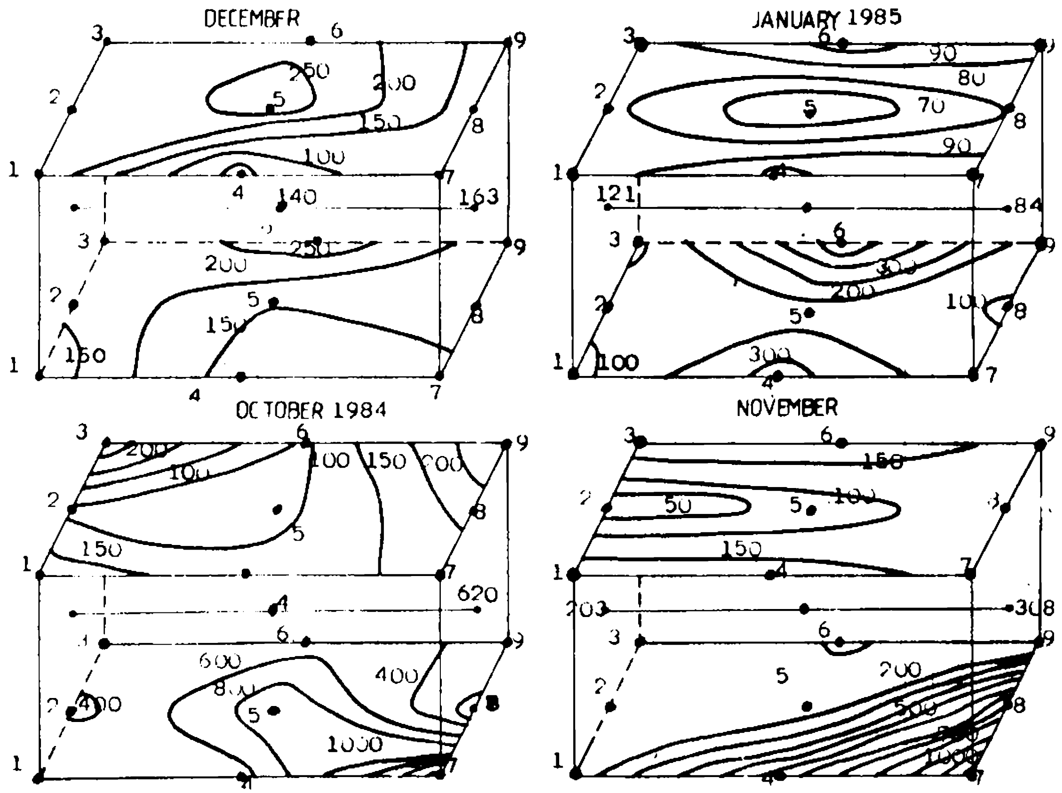


Fig. 37. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Ernakulam channel (stations 1 - 9) during postmonsoon months. Seston content at middle station are also denoted.

The figure 38 shows that the water column of Ernakulam channel contained high amounts of suspensate in premonsoon months except during April. In February, the surface water suspensate was more on the eastern parts (376 mg l^{-1}) compared to the other regions of the channel. The bottom water suspensate was greater on the two sides of the channel due to the increased resuspensation of the bottom material by the tidal currents in the shallow sections. This is explained as due to the lateral internal seiching produced by the interaction of the surface seiche with the shallow side of the estuary. Such a phenomenon was also observed by Dyer (1982) in Southampton waters. The increased seston content on the eastern side of the channel denotes that a turbidity maximum zone was present in this region; the high mid-water seston at the transverse section of the tanker berth being due to the local circulation system that caused water fronts as explained by Nunes and Simpson (1985) regarding the behaviour of suspended solids in estuarine flows. The presence of suspensate was observed more towards the upper reaches of the channel in the month of May (bottom water contained upto 2000 mg l^{-1}). This was due to the fluvial discharge of heavy seston load as a result of the earlier onset of monsoon. The seston content was more at the shallow stations than the deeper one, presumably due to the tidal current disturbances that resuspend the material. Gopinathan and Qasim (1971) observed that during premonsoon months, the suspended material in the water column throughout the harbour area was relatively low. The observations of Rama Raju et al. (1979) as well as results of the present study show that the amount of suspensate was more during the premonsoon months in this channel (551 - 2000 mg l^{-1}). This is attributed to the effect of Thanneermukkam bund commissioned in 1976 regulating the extent of intrusion of saline waters. In effect, the resultant maximum reach of tidal incursions have been much reduced allowing energy convergence towards increased resuspensation of bottom sediments in the harbour area.

The suspended load was observed to be higher towards the upper reaches of the channel in June (6 - 255 mg l^{-1} at surface and 133 - 1350 mg l^{-1} at bottom) and in July (140 - 270 mg l^{-1} at the surface and 180 - 1156 mg l^{-1} at bottom) (Fig. 39). The increased silt laden fluvial

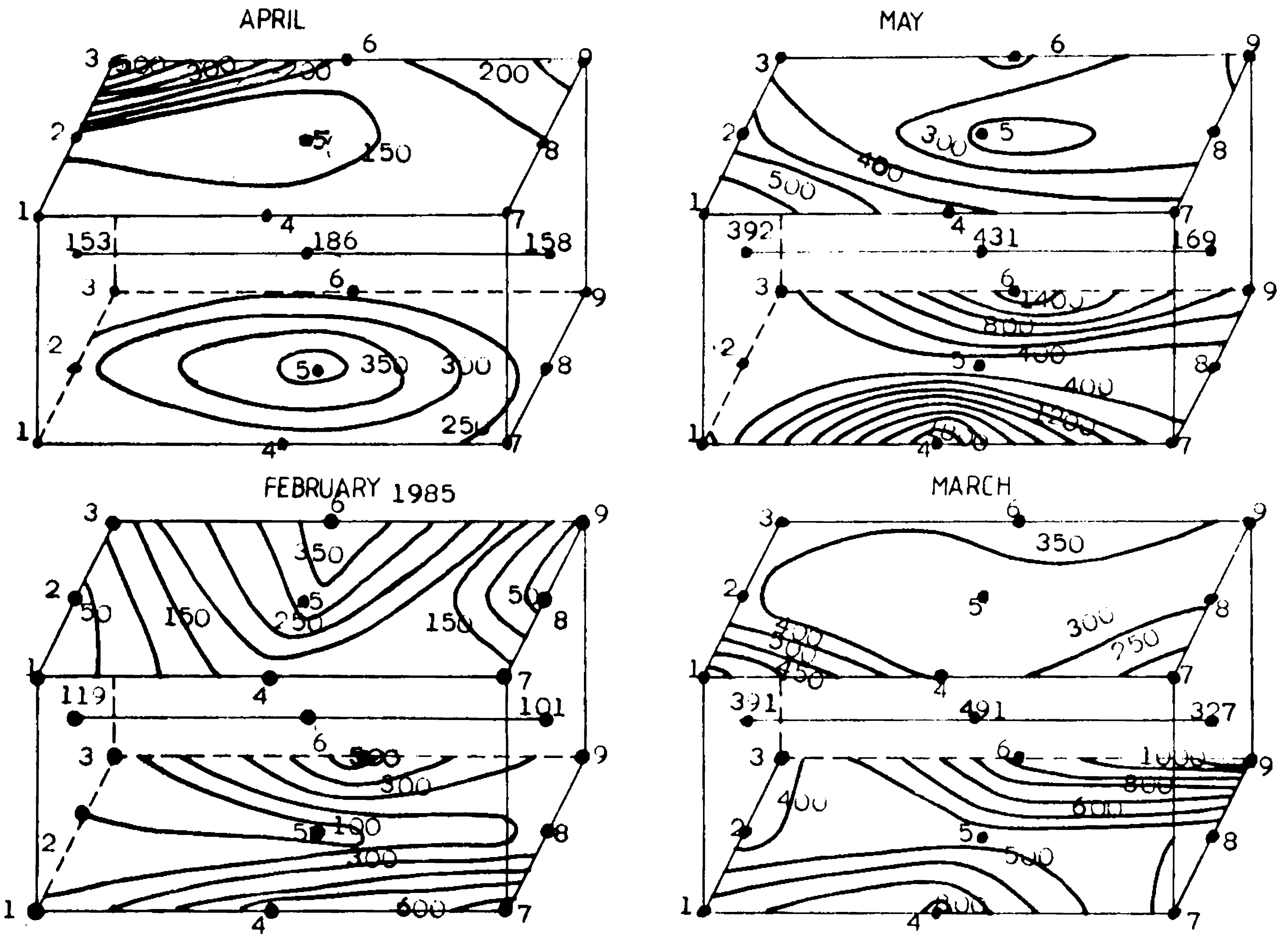


Fig. 38. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Ernakulam channel (stations 1 - 9) during premonsoon months. Seston content at middle station are also denoted.

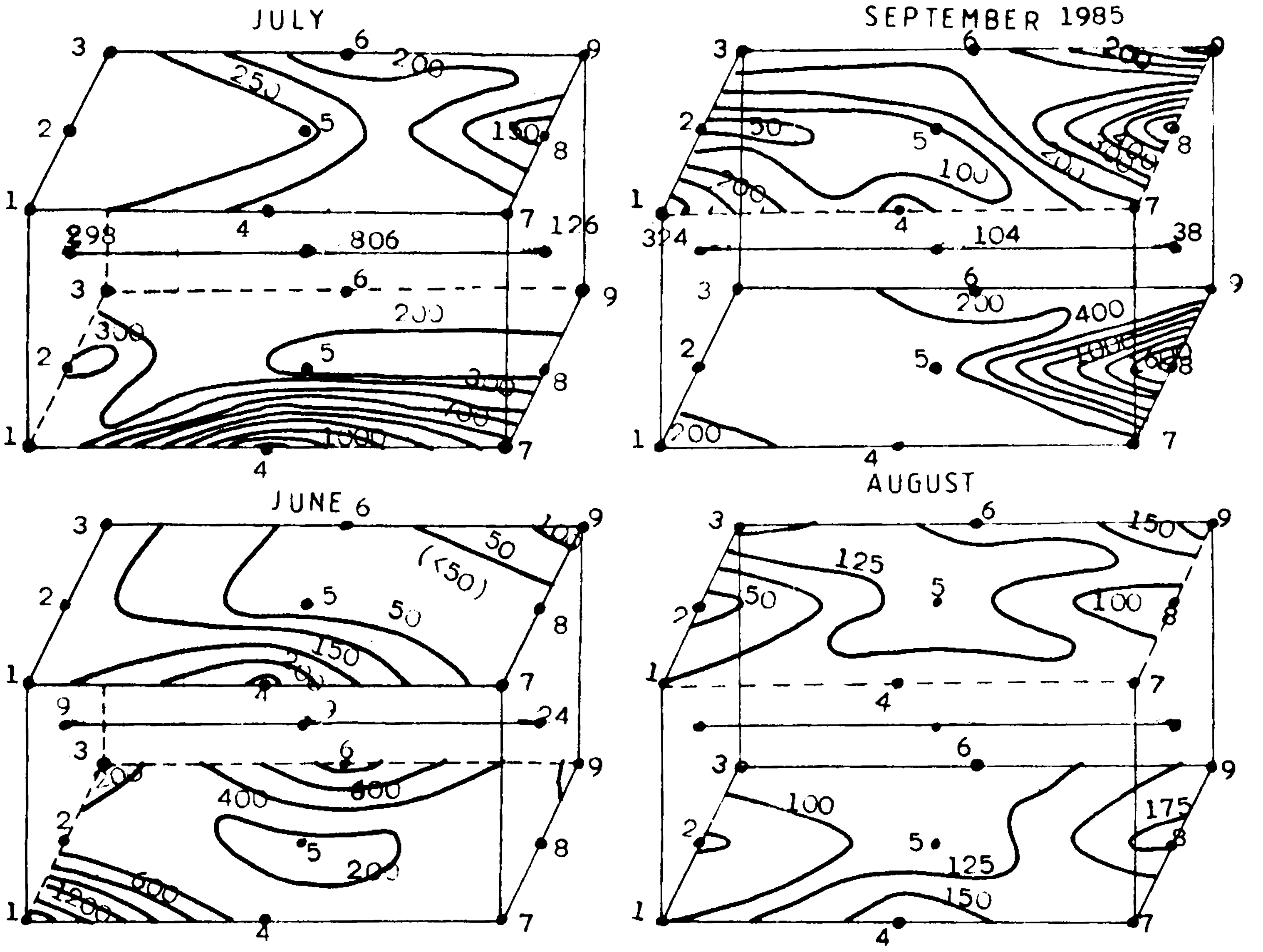


Fig. 39. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Ernakulam channel (stations 1 - 9) during monsoon season. Seston content at middle stations are also denoted.

discharges during monsoon months cause this increase. Similar chara teristic features of estuarine turbidity maxima along the south coa of English channel were described over a range of time scales a seasonal fluctuation of river discharge by Avoine and Larsonne (1987). The figure exhibits that in June, the bottom water sest variation was more at the eastern side of the channel than the weste side. Eastern side of the channel is the place of confluence waterways of Periyar river from north and the lake water from sout giving rise to sedimentary environments. The turbidity maximum zo present in the transverse section of the tanker berths may be due the presence of a saltwedge in this segment of the channel. T surface and subsurface water column showed low seston concentrati (<150 mg l^{-1}) in August except in bottom-water layers at Ernakul wharf station. In September, the surface water seston was slight more towards the south of the channel (194 - 273 mg l^{-1}) while t surface and bottom waters of station 8 showed high values (508 mg l^{-} and 1741 mg l^{-1} respectively). The figure exhibits that in monso months relatively low seston concentration was observed in th channel compared to premonsoon months and the bottom water sest content was more than the surface content. Gopinathan and Qasim (19 stated that during monsoon months the seston content increased sharp throughout the water column which is contrary to the present result This marked change is due to the commissioning of the Idukki proje permitting controlled flow in the Muvattupuzha river and hence t regulated output of suspended particulates (Balchand and Nambisa 1986).Saxia reservoir acts as a location for deposition of considerab amounts of suspensate from the Changjiang river (China) as also obse ved by Lin (1987).

5.3.1.2. Approach Channel

The distribution of suspensate in the surface, middle and bott waters of Approach channel area are shown in figures 40, 41 and 4

The surface water suspensate content was relatively low (≃ 200 mg l in postmonsoon months except in the month of December (≃ 300 mg l^{-1} The figure shows that in the month of October the amount of seston w decreasing towards the seaward side of the Approach channel. T

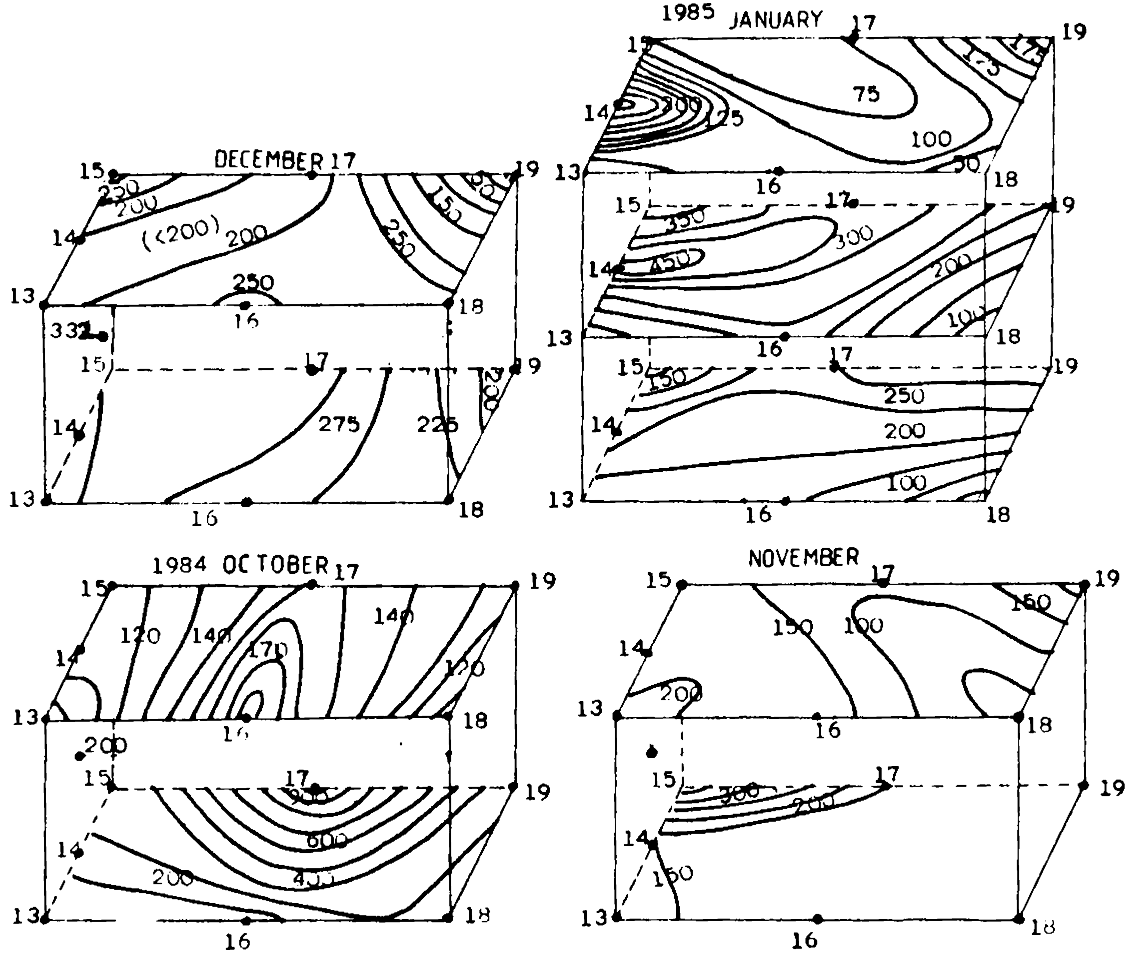


Fig. 40. Suspensate (mg l^{-1}) distribution at surface and bottom layers (January 1985 - middle layer) of Approach channel (stations 13 - 19) during postmonsoon season. Seston content at middle station 14 is denoted.

trend of isolines in the transverse direction is perpendicular to the longitudinal channel orientation revealing the equitransverse suspensate distribution and the influence of littoral transport in the suspensate distribution. A mid-channel turbidity maxima was observed in the vertical during the observation in October; during the rest of the months the seston content was relatively low in amount. The turbidity zone may be due to the result of confluence of higher freshet (present in the beginning of postmonsoon months) and the prevailing coastal currents. The trend of isolines reveals that the seston maximum was shifted more towards the northern side of the channel (1000 mg l^{-1}) and its distribution was more uniform, longitudinally on the south side of the channel. In the months of November, December, 1984 and January, 1985 the bottom water seston was less than 315 mg l^{-1} except at station 15 in November (445 mg l^{-1}). The trend of isolines show that the suspensate distribution was longitudinal, hence parallel to the channel orientation in the month of January; this may be due to the intense ebb flow present in the Approach channel. Also in January, the mid-water seston content was more (500 mg l^{-1}) and was decreasing towards the seaward side of the channel. It is also observed that in postmonsoon months the bottom suspensate content was relatively more towards the northern side of the channel.

The suspensate distribution in the surface, middle and bottom waters of Approach channel in premonsoon months is shown in figure 41. The surface water suspensate in the harbour area exhibited lesser variations in February ($<$150 mg l^{-1}), March (200 - 350 mg l^{-1}) and April ($<$200 mg l^{-1}). Increased seston content was present in May (600 mg l^{-1}) at the cut and was less than 200 mg l^{-1} towards the west of the channel. The increase in seston content at the cut region is presumably due to the high freshet outflow attributed to the earlier onset of monsoon. The figure exhibits that the mid-water suspensate was decreasing towards the west of the channel in premonsoon month except in the month of May. The gradient of isolines in May reveals that high turbidity zones were present in the mid-water and bottom water layers of the Cochin harbour region concentrating on the southern parts of the cut and middle of the channel ($\simeq$2250 mg l^{-1} at

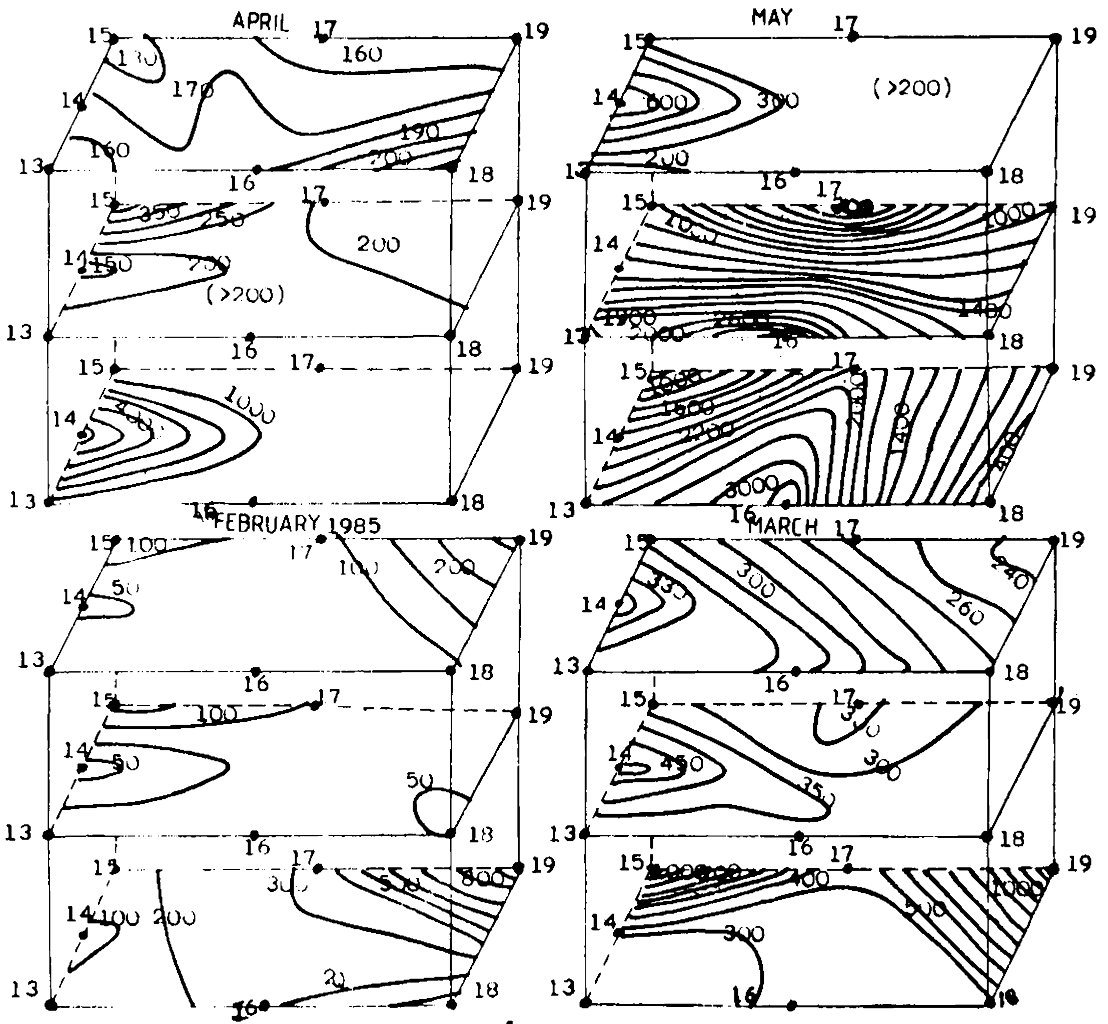
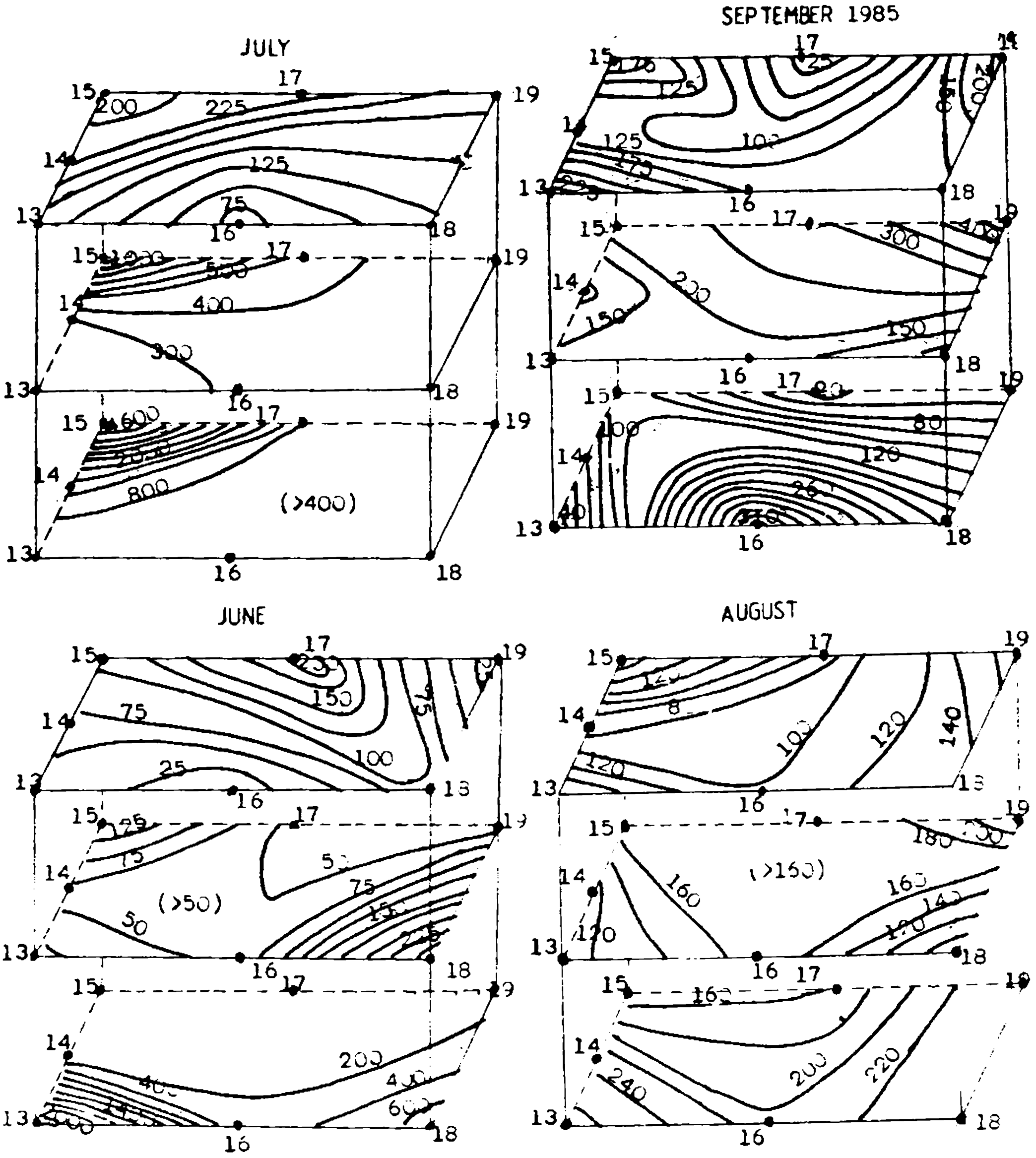


Fig. 41. Suspensate (mg l^{-1}) distribution at surface, middle and bottom layers of Approach channel (stations 13 - 19) during premonsoon season.

the mid water and 3138 mg l^{-1} at bottom). It is also seen that the bottom water seston content was more towards the southside of the channel decreasing towards the seaward side. The presence of higher suspended solids is attributed to the churning action of waves of the coastal waters seasonally acting (Chapter 4, Page 39). In March, the concentration of suspensate was more on the northern side of the channel (station 15, 1153 mg l^{-1} and station 19, 1412 mg l^{-1}). It is inferred from the suspensate study of premonsoon months that the source of seston was from the coastal waters and the tractive forces were the littoral currents of these coastal regions causing suspended material transport. The river inputs during these months were extremely low (2.77 - 7.26 x 10^6 Kg $month^{-1}$) compared to values greater than 90 x 10^6 Kg $month^{-1}$ in monsoon months (Table 6).

During the monsoon months, the surface water seston content was low ($\leqslant$180 mg l^{-1}) except on the south of the cut in the month of September (310 mg l^{-1}). The mid-water suspensate exhibited considerable spatial variations and was generally less than 450 mg l^{-1} except in July (1000 mg l^{-1}). The figure brings out the feature of mid-water seston distribution to be more varied towards the seaward side in the months of July, August and September 1985. The bottom suspensate content was more concentrated towards the southern side of the channel in June (2100 mg l^{-1} at station 13 and 600 mg l^{-1} at station 18 in June) and considerably lower in September (250 mg l^{-1}). The high seston content present in July at the subsurface levels may be due to the high wave activity which undergo refraction; hence this initiates the sediment movement due to the churning action. Weir and Mc Manus (1987) has detailed a comparable wave generated seston pattern in the Tay estuary during the estuarine sedimentation processes. The resultant currents in this case may hence transport the material towards the channel. The steep topographical slope on the south side of the channel (Shenoi and Prasannakumar, 1982) also facilitate the waves to interact more with the channel bottom, giving rise to higher suspensate concentrations.



JULY

SEPTEMBER 1985

JUNE

AUGUST

Fig. 42. Suspensate (mg l^{-1}) distribution at surface, middle and bottom layers of Approach channel (stations 13 - 19) during monsoon season.

5.3.1.3. Mattancherry Channel

The distribution of suspensate in Mattancherry channel during different seasons is presented in the figures 43, 44 and 45.

During the postmonsoon months (Fig. 43), low amounts of seston (<250 mg l^{-1}) was present in the surface layers of this channel, except in January (<320 mg l^{-1}). The trend of isolines show that the surface layer seston content was greater on the sides of the channel than at mid stations. This was due to the increased resuspension of the fine material at the bottom due to the intense bottom flow at the shallow stations. This feature was also observed in the Ernakulam channel. The seston in surface waters were slightly more in the upper reaches of the channel. This may be due to the extended monsoon effects and hence the continued fluvial seston supply in October and tidal action in January. Bottom suspensate showed considerable variability in this season (150 - 2000 mg l^{-1}). The trend of isolines reveal that the variation were more in the transverse direction than longitudinal; the closely packed isolines exhibited greater variation on the western sides of the channel in October and turbidity maximum zone was observed at station 23 of this channel. This is caused by the channel orientation and the interference of water fronts in this region as described in chapters 3 and 4. The bottom layer suspensate content was increasing towards the lower reaches of the channel in October and November: this again, is due to the increased flocculation and the resultant settling of the particles. A middle channel turbidity maximum was observed in the month of January in this channel. The increased suspensate on the western side of the channel may be due to the shallow nature of the channel than the eastern side; the increased shear effects of the flow that will resuspensate the bottom fine material increase the suspended load of the water column in these parts of the waterway. Sujilan and Wangkanshan (1986) observed in Changjiang estuary that the depth difference contributed to the spatial variation of the suspensate. The spatial bottom water suspensate variation was greater in October (150 - 1500 mg l^{-1}) and was minimum in December (300 - 800 mg l^{-1}).

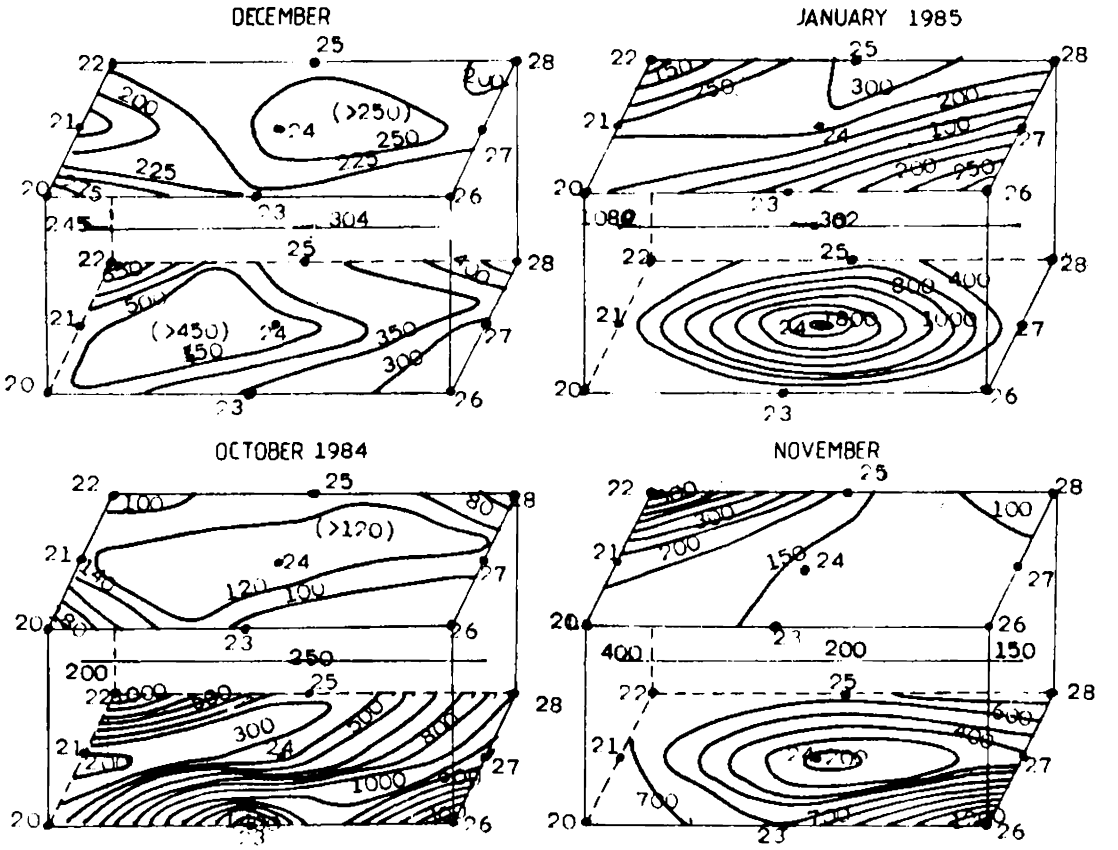


Fig. 43. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Mattancherry channel (stations 20 - 28) during postmonsoon season. Seston content at middle stations are also denoted.

The distribution of suspensate in premonsoon months exhibited (Fig,44) that the surface suspended load was lower in February and April ($\lesssim$250 mg l^{-1}). However, the suspended load concentrations were observed to be higher in the lower reaches of the channel during February and March. This results from the increased mixing in the lower reaches between bottom and surface waters due to the tidal forces. In May upper reaches of the channel showed higher surface seston (upto 1500 mg l^{-1}) almost equal to that present in the Ernakulam channel. The bottom layer suspensate concentrations were always higher in this section and was a maximum in the month of March (650 - 5600 mg l^{-1}). The mid channel region was a zone of turbidity maxima in March; this may be due to the gyral circular pattern in the region aided by the orientation of channel towards the eastern side (Chapter 4 - Page 41 - 42). The studies of Chitale (1988) on alluvial canals and rivers also revealed that the width, depth and slope of channels are inter-dependent and controls the bed material characteristics and sediment transport. The bottom suspended material concentration was always greater on the western side of the channel due to depth difference and the increased shear effects at bottom. In premonsoon months, the subsurface water suspended load showed that this channel was a sink for the suspensate. The reduced current speeds and lower amounts of fresh water supply through this channel compared to Ernakulam channel (Central Water Power Research Station, 1969), and better accessibility to the cut region may be the causative factors for high bottom water suspended load in this channel. Gopinathan & Qasim (1971) and Rama Raju et al. (1979) also observed that more material was brought into this channel by the tidal effects. Studies of Salomons and Mook (1987) also highlights that the marine sediments may be transported even past the fresh water boundaries and this may contribute to the estuarine sedimentation, a view which supports the results of the present study. The effect of Thanneermukkam bund that reduces the fresh water supply from the southern parts into the Ernakulam channel is a causative factor for the persistence of more tidal waters in this part of the estuary; this results in increased flocculation and the settlement of these floccules towards the bottom.

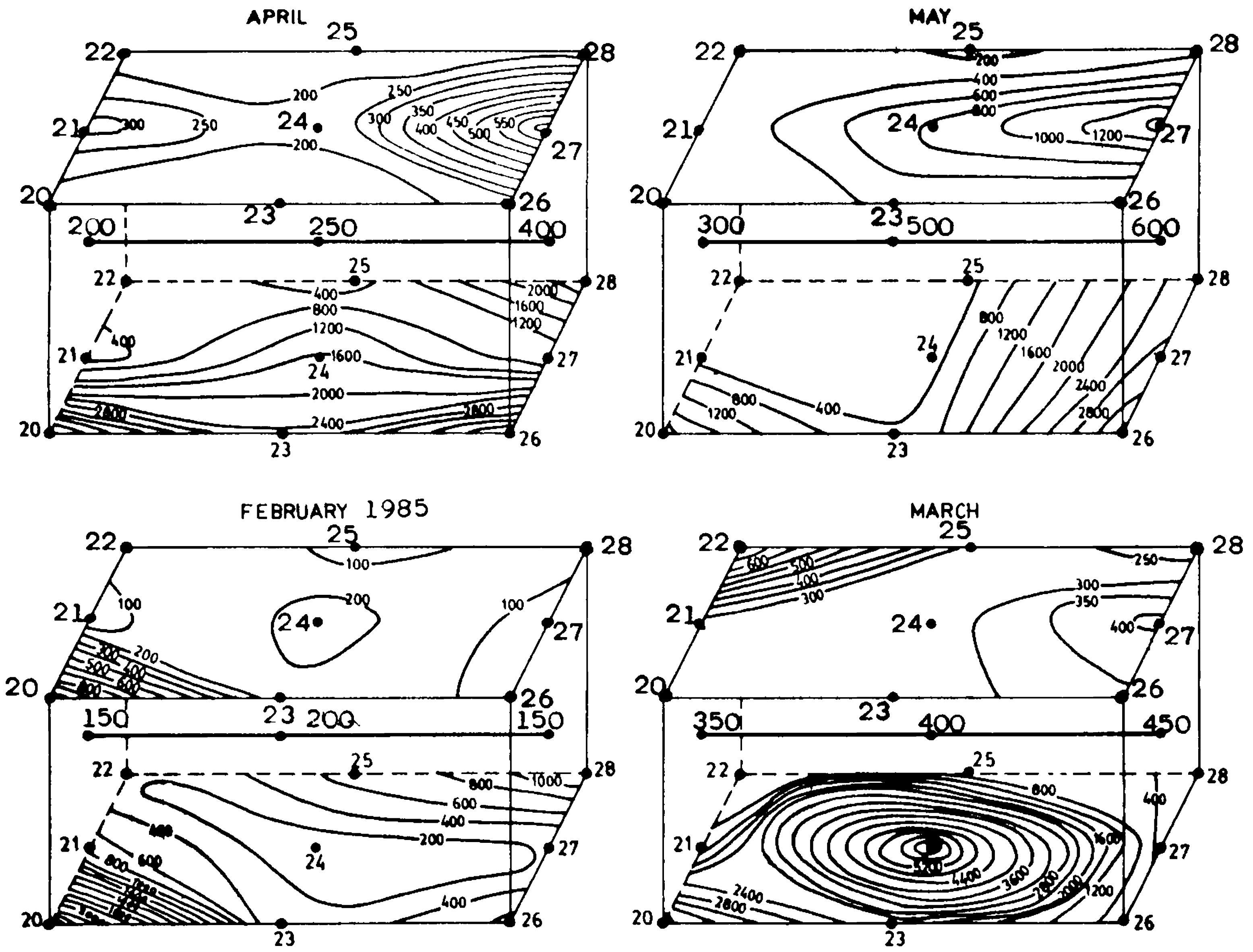


Fig. 44. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Mattancherry channel (stations 20 - 28) during premonsoon season. Seston content at middle stations are also denoted.

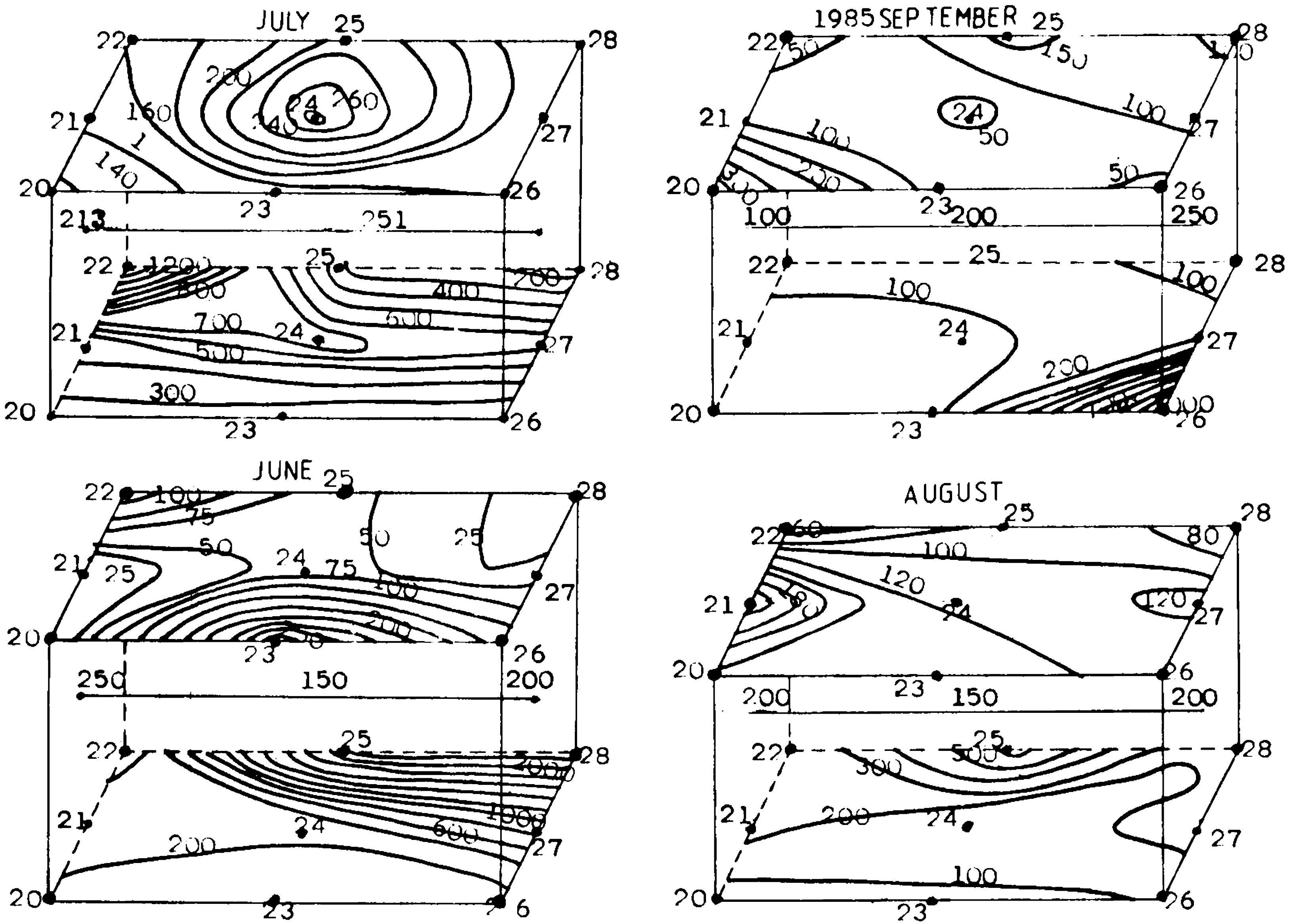


Fig. 45. Suspensate (mg l^{-1}) distribution at surface and bottom layers of Mattancherry channel (stations 20 - 28) during monsoon season. Seston content at middle stations are also denoted.

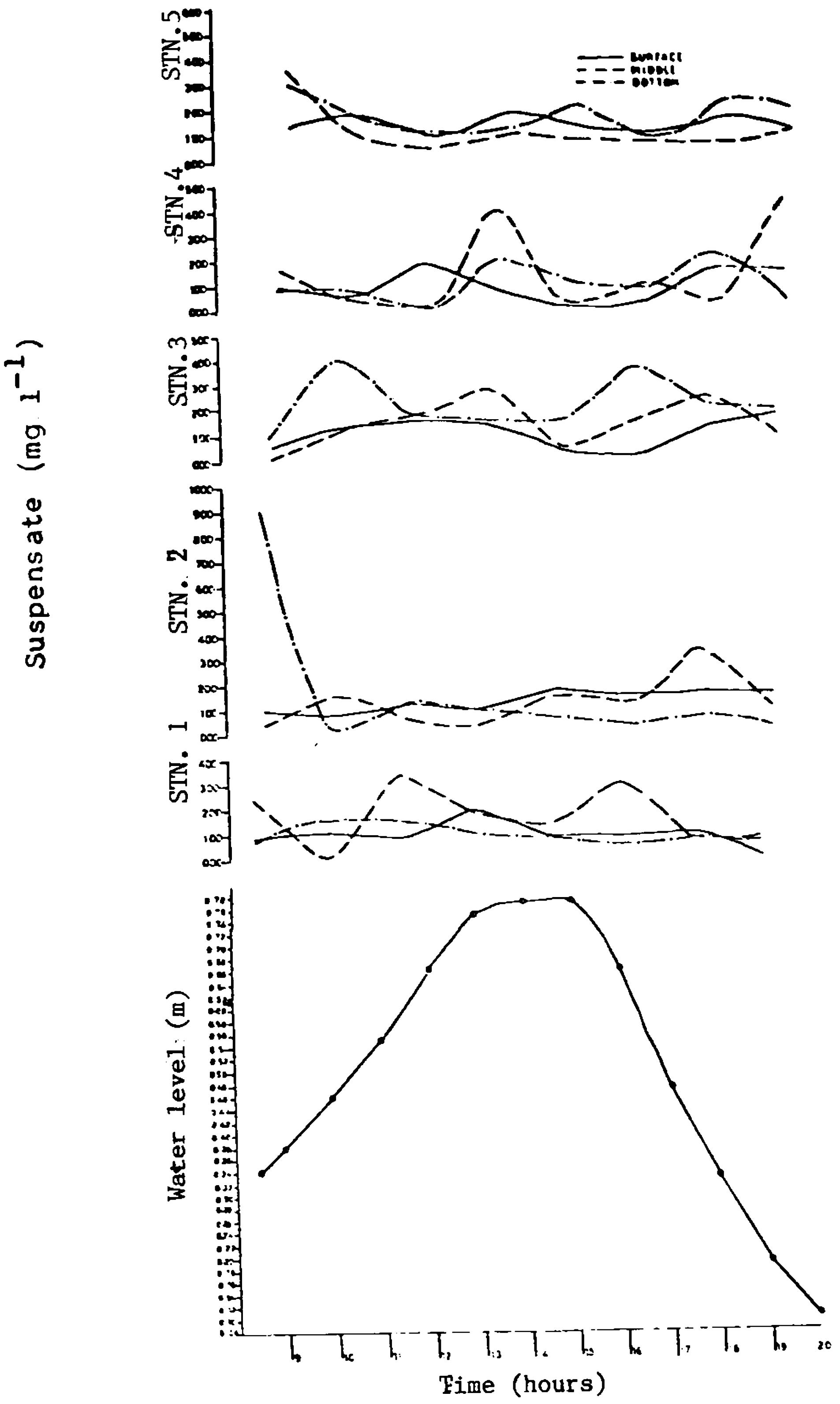
During monsoon months, the surface seston content was less than 300 mg l^{-1} and minimum in June (3 - 272 mg l^{-1}). Surface suspensate variations were lesser in August and September too. In July, amount of suspensate was more in the mid channel regions and this may be inferred as a result of increased mixing occurring in this channel. The channel orientation facilitates the increased mixing in this channel. The channel orientation also facilitates the increased effect of wave (Cochin Port Trust Administration Report, 1985) to act in this channel during July. The enhanced values of bottom seston present in the lower reaches of the channel in July also confirms the transport of coastal water containing higher amounts of suspended solids derived as a result of churning action of water. During June, the upper reaches of the channel exhibits high concentrations of seston at bottom (2400 mg l^{-1}); this may be due to the fluvial supply and the resultant settling of suspended load in the bottom layers of flocculation. The isolines reveal longitudinal homogenity in the spatial distribution of bottom suspensates in June and July. Bottom water suspensate variations were less in June and July relative to other months of this season. This is brought about by the spatial distribution of suspensate of the fluvial supply and the increased wave and wind effects during these months.

5.3.2. Semidiurnal Variations of Suspended Solids

5.3.2.1. Springtide(14.9.1984)

The changes in suspensate concentration in the Cochin harbour area during the springtide of 14th September 1984 are given in figure 46.

The trend in suspensate variation was in a mixed type with the tidal conditions in the inner channels, especially Mattancherry channel. However, the surface seston variations were more in Ernakulam channel (10 - 200 mg l^{-1}) than Mattancherry channel. The maximum seston content was noted after the time of high water in Mattancherry channel and one and a half hours before high water in Ernakulam channel. In the inner channels the seston content varied more in the mid-water level (10 - 340 mg l^{-1}); also the suspensate variations were lesser



Variations in surface, middle and bottom water suspensate at Ernakulam (station 1), Mattancherry (station 2) channels and Cochin cut (stations 3,4 and 5) during springtide.

in the ebbing phase than flooding from which it is inferred that more particles move into the harbour with flood currents. The near identical trends in surface and middle layer seston content revealed that surface and middle water columns were subjected to similar operative conditions.

The seston in the cut region during the springtide at surface was low in content at the Cochin cut (station 3: 10 - 170 mg l^{-1}; station 4: 60 - 190 mg l^{-1} and station 5: 100 - 190 mg l^{-1}). The seston content attained a maximum value just before high water time. As the ebb flow begins the amount of suspended sediments decreased at the Cochin cut while during the flood phase the surface and subsurface suspended loads increased hence more suspensates enter the inner harbour channels during floods predominantly along the south side ($\simeq$ 200 mg l^{-1}) and along the nodal station (station 4, middle $\simeq$ 400 mg l^{-1}) of the cut. Bottom waters contained the maximum seston concentration much earlier than the timing of hightide at the south side of the cut but at the instance of high water it is observed more on the northern parts of the cut.

5.3.2.2. Neaptide (30.11.1984)

The changes in suspensate content at Cochin harbour area during neaptide conditions (30.11.1984) are depicted in figure 47.

The surface seston content varied between 50 - 200 mg l^{-1} in Ernakulam channel and between 60 - 200 mg l^{-1} in Mattancherry channel. The inner channel exhibited more surface seston content than at the Cochin cut during the ebb tide. Middle water seston exhibited moderate variations in the inner channels (70 - 230 mg l^{-1} at station 1 and 80 - 200 mg l^{-1} at station 2) and the maximum value of mid water suspensate was observed just before the low water level. Ernakulam channel shows a high value in seston concentration ($\simeq$ 790 mg l^{-1}) at bottom layers during ebbing.

The suspended solids variations in surface waters at the south of the cut were of limited range (50 - 150 mg l^{-1}). It can be seen from the figure that the seston content in surface and middle waters showed

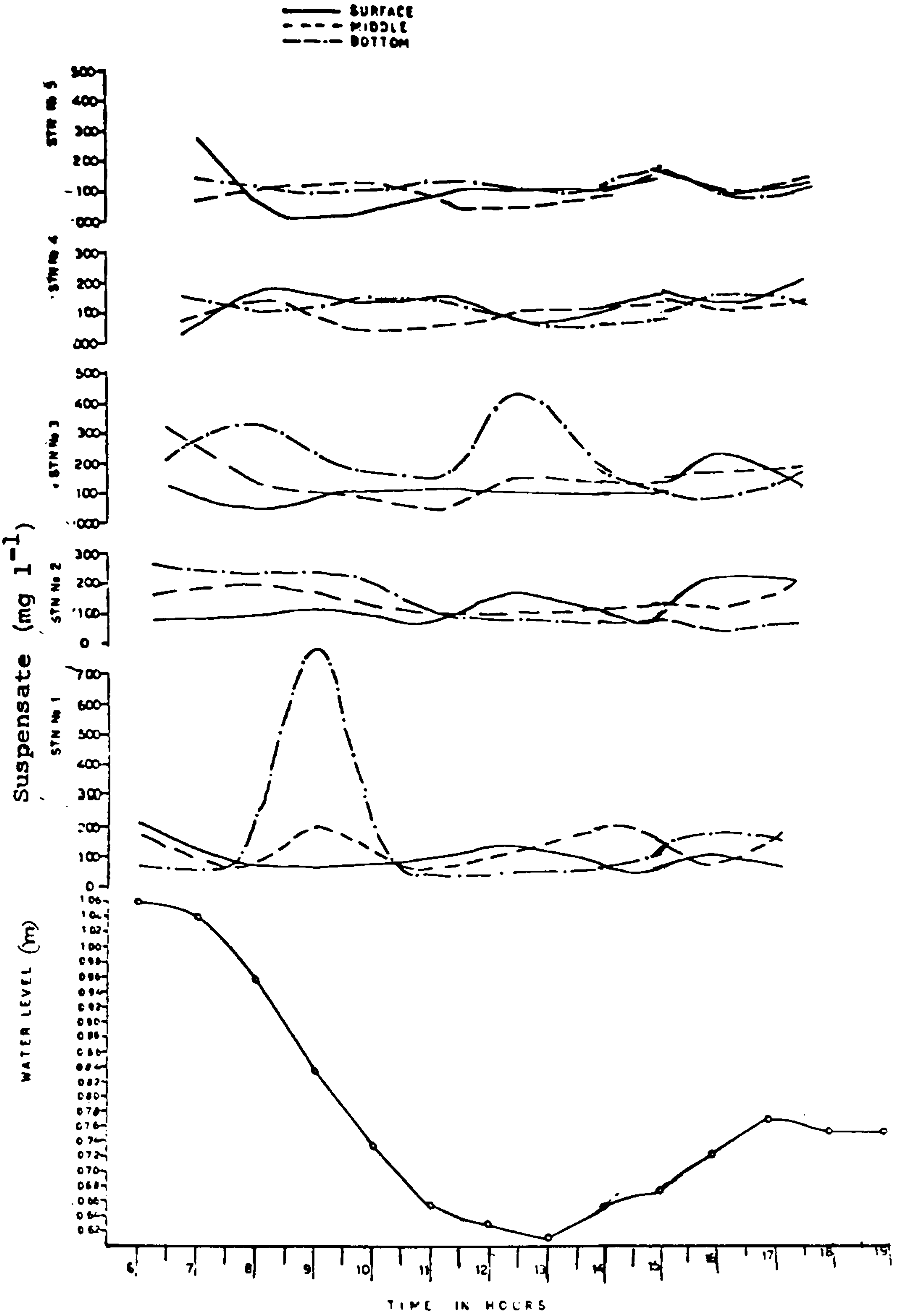


Fig. 47 . Variations in surface, middle and bottom water suspensate at Ernakulam (station 1), Mattancherry (station 2) channels and Cochin cut (stations 3,4 and 5) during neaptide.

more or less similar variations; hence when ebb flow was predominant at the cut during neaptide, the trends of suspensate variations were asymmetrical.

5.3.3. Sedimentary Environment of the Harbour Area

5.3.3.1. Textural Analysis

The textural percentage of surficial sediments in the Cochin harbour area are presented in the figures 48 - 51. Figure 48 describes the monthly distribution of sand-silt-clay contents during Oct. 84 to Sept. 85.

5.3.3.1.1. Ernakulam Channel

During postmonsoon months, fine sediment was present in the Ernakulam channel (stations 1 - 9, Fig. 49). The deeper stations (2, 5, 7 and 8) exhibited silty sediments from upper (> 95%) to lower reaches (> 97%) of the channel. Fine fractions are generally more in the deeper stations (Mavis et al. 1985). The sediment texture across the tanker berths showed considerable coarse fractions at station 4 and less coarse fraction at station 5 and more clay content on the eastern side (station 6). Silt with small amount of coarse fraction was observed near the oil terminal (station 9) and silt with small amounts of clay at the Ernakulam wharf (station 7). The coarse fraction at station 4 and 5 may be due to the water current on the western side of the channel, directed towards station 5. A decrease in size fraction may be indicative of the decrease in river discharge into estuarine parts (Ramanathan et al. 1988).

During the premonsoon months the deeper channel contained relatively more fine fractions (clay-silt) than other seasons (Fig. 49). The figure exhibits that the shallow stations showed identical textural pattern i.e. silt with small amounts of coarse fraction except at station 4 (where coarse fraction was slightly more, 25%). The presence of fine fraction is attributed due to the low fluvial discharge that facilitate the presence of more saline waters whose residence time is also more resulting in the flocculation of suspensate in the channel, acting as a depositional environment. The coarse fraction in the shallow stations is due to the increased bottom

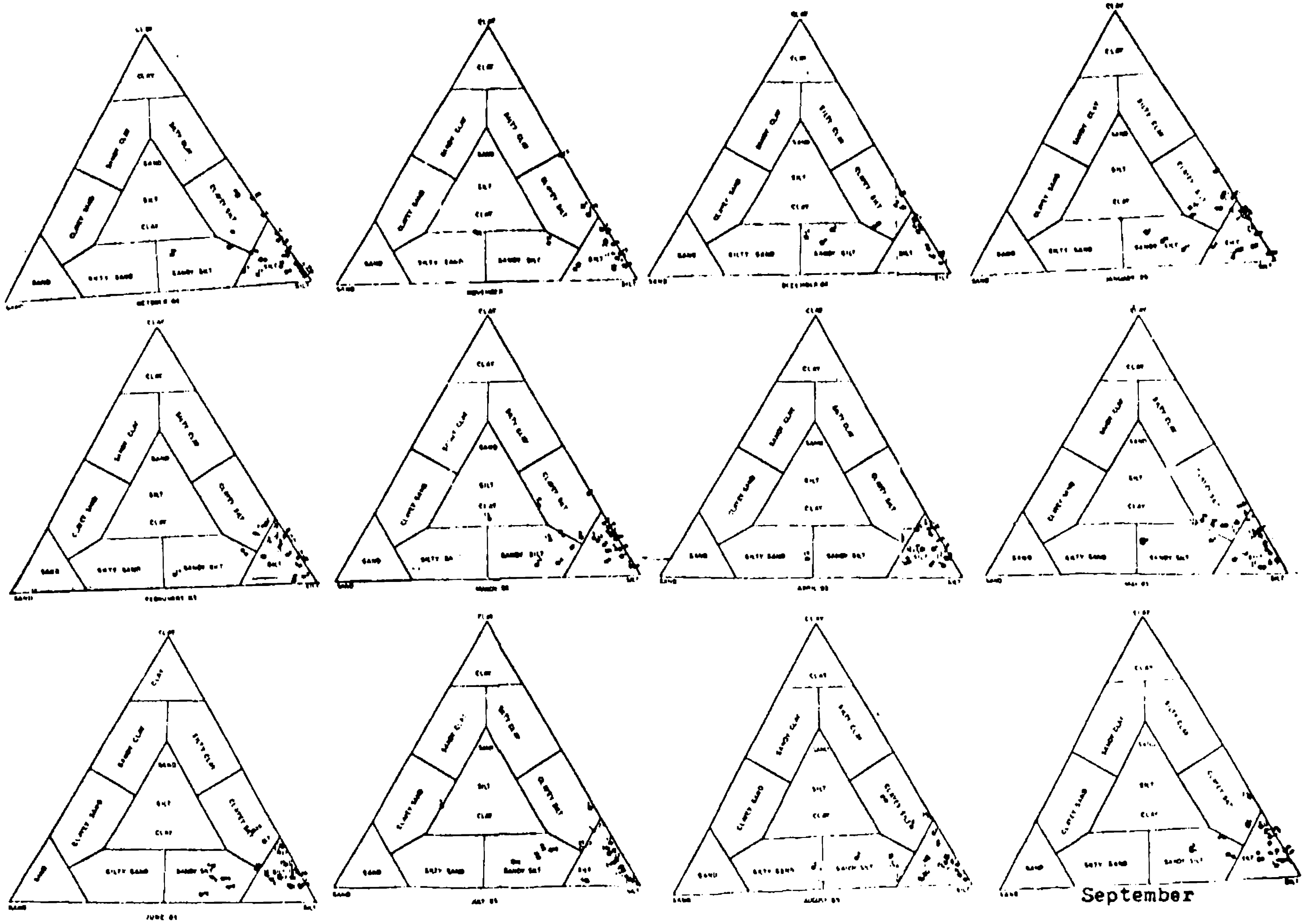


Fig. 48. Monthly distribution of sand-silt-clay contents in the surficial sediments of the Cochin harbour area during October 1984 to September 1985.

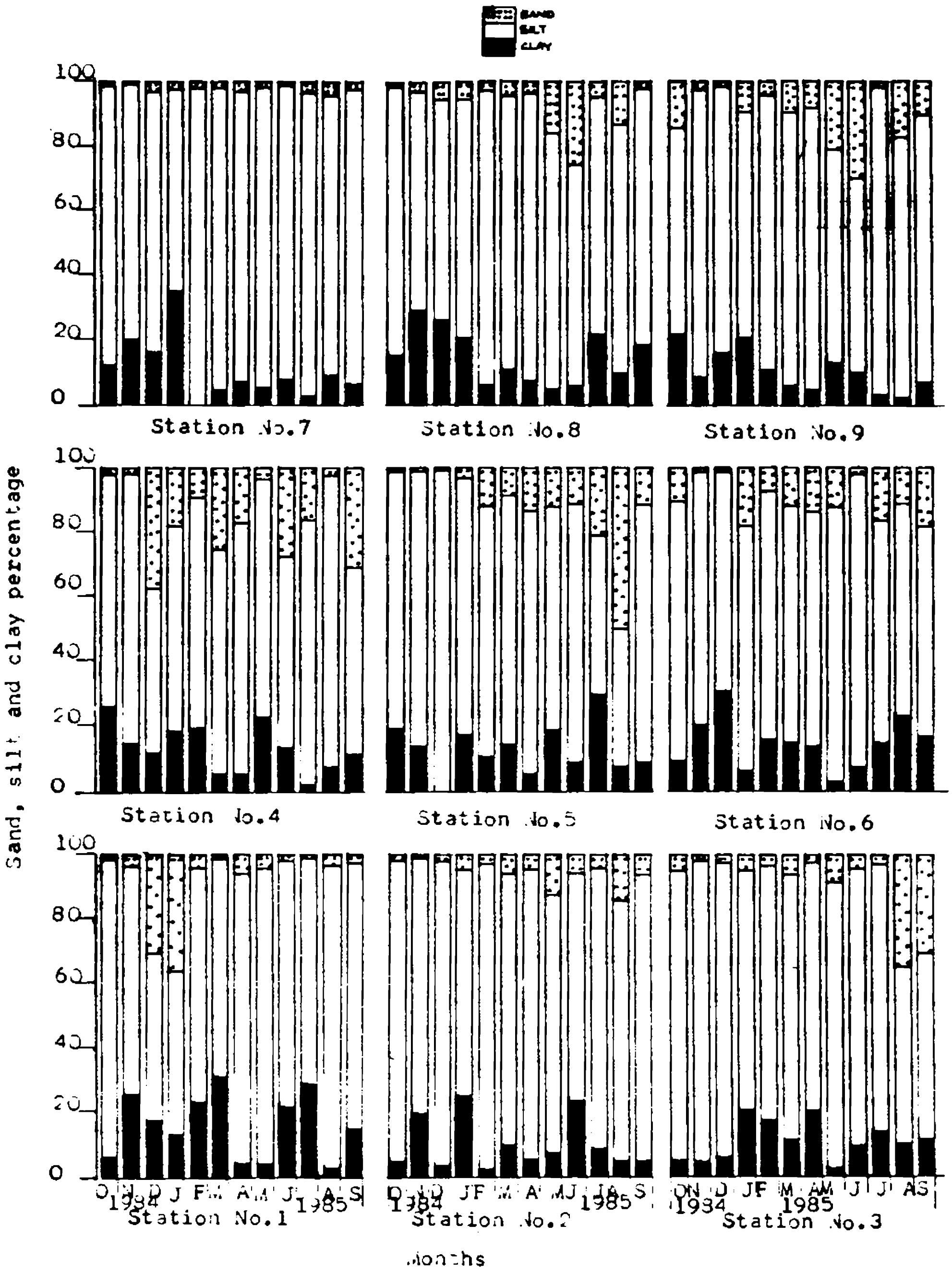


Fig. 49. Monthly variation in sand, silt and clay of surficial sediment of Ernakulam channel (stations 1 - 9).

currents that resuspend the fine material. Josanto (1971) also observed fine sediments in this region during premonsoon months.

In monsoon months, the shallow stations showed more coarse fraction (5 - 33%) than the deeper stations. The increased coarse content is surmised to be due to the sediment movement resulting from the fluvial discharge, since the coarse fraction was more at the upper reaches of the channel. Also, the strong water flow may resuspend the fine material, if any, in the shallow stations. However, the deeper station (5) exhibited high amount of coarse fraction (50%). This is presumably due to the transverse water flow towards the channel from the shallow stations and the salinity front retarding the fine sediment bed load transport. The fine fractions in this channel is attributed to the presence of persisting salt wedge in this area causing the settling and accumulation of suspended load, as explained by Guilcher (1967) in a partially mixed estuary.

5.3.3.1.2. Northern End of the Harbour

The textural percentage distribution of the surficial sediment at the northern end of the harbour (stations 10, 11 and 12) is shown in the figure 50.

During postmonsoon months, clay content was more between Bolghatty and Wallarpat islands. This may be due to the comparatively quite water at station 11, facilitating the settling of alluvial suspensate from Periyar river when introduced from brackish to marine conditions. The sediment at station 10 was dominantly silt with a small coarse fraction towards the end of postmonsoon months. Sandy silt sediments (≃15% sand) were present at station 10 in premonsoon months. Between Vypeen and Wallarpat islands coarse fraction was found in May. This may be due to the riverine material brought during the increased freshet as the monsoon begins. It was observed from the figure that station 10 i.e. between Bolghatty and Ernakulam mainland, may be a sheltered sedimentary environment during monsoon season with increasing silt content. The surficial sediments on the northern end were dominantly silt laden with small amounts of coarse fraction, revealing the influence of fluvial transport into this

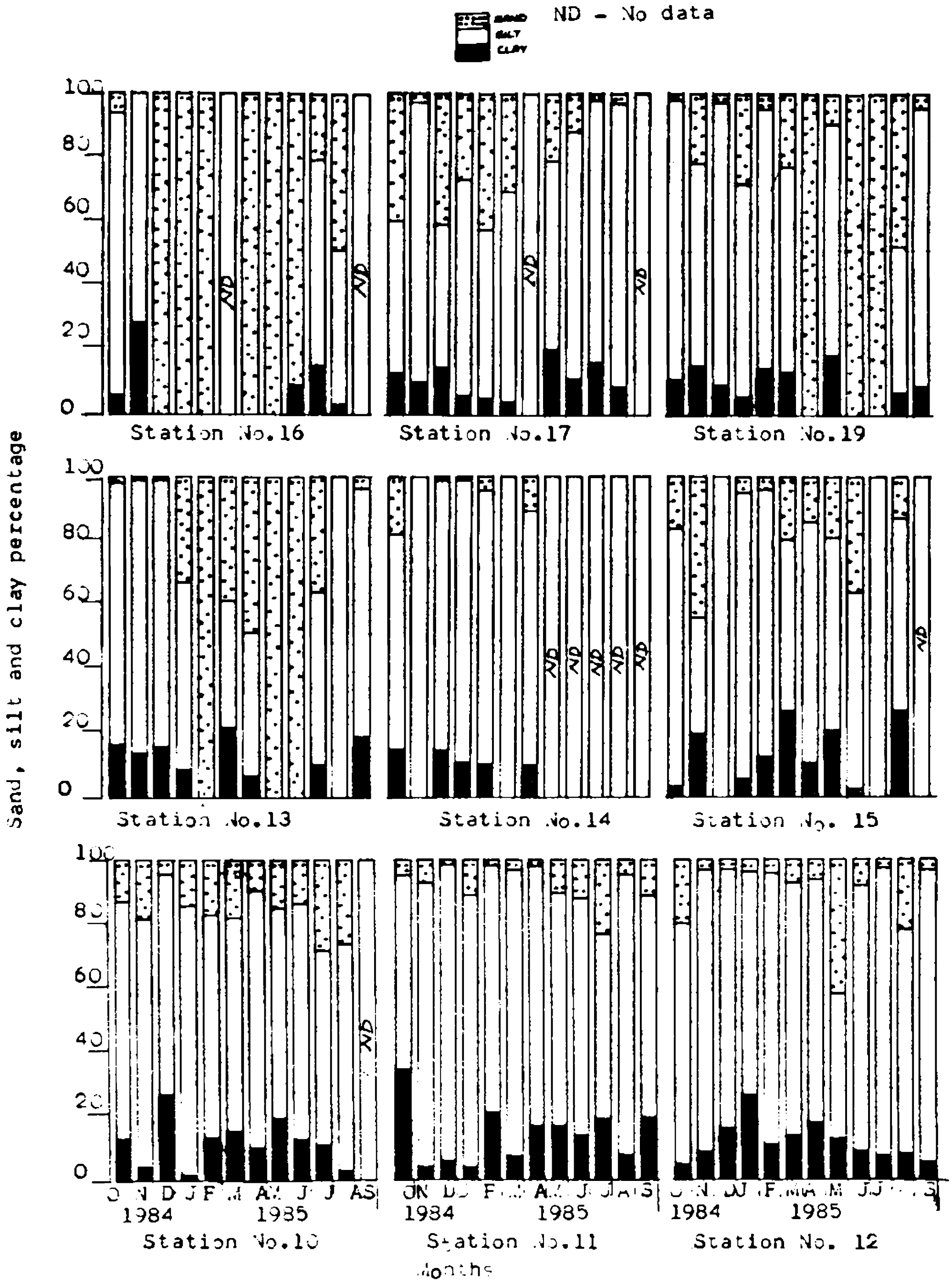


Fig. 50. Monthly variation in sand, silt and clay of surficial sediment of Northern part of Ernakulam channel (stations 10 - 12) and Approach channel (stations 13 - 19). No collection were made at station 18.

regime. The studies of Josanto (1971) during premonsoon months showed that silty-clay deposits were predominant around the Wallarpadom island which is again confirmed by this study. The gradually increasing presence of coarse fraction may be due to winnowing effect of the increased tidal inflow due to the deepening of the inner channels after 1980 and may also be due to retarded bed load movements around the Wallarpat island by the interplay of hydraulic forces present in this area.

5.3.3.1.3. Approach Channel

The sand, silt and clay percentages comprised in the surficial sediment at the Approach channel is also shown in figure 50.

During the beginning of postmonsoon months, clayey sediment were present at the cut region, while more silt was present at the south of the cut towards the end of this season. The clay content may be due to settlement of the seston in the monsoon months, which is retained as the postmonsoon begins. The south of the Approach channel showed silt with small amount of clay (station 16) while equal amount of sand and silt was present at the north.

During premonsoon months more coarse fraction ($\simeq$ 35%) was present at the cut. This is presumably due to the winnowing effect of the bottom current. Almost equal amounts of sand and silt were found at the south of the Approach channel (station 16) and silty sediment with moderate amounts of sand at the north of the Approach channel (station 17).

In monsoon months coarse fraction was more at the south of the cut and silty sediment on the north end (stations 16 and 17). The coarse fraction was due to the churning action of waves that transport material towards the Approach channel from the southwest direction. Towards the end of monsoon months, more silt was found in the mid-channel, due to the accumulation of the alluvial suspensate through the cut in this region where the circulation pattern facilitates more settlement of the suspensate.

The lower reaches of the Approach channel (seaward side) exhibited sandy sediments in all the months of observation which elucidated the nature of the marine environment of this region. Moderate to well sorted sediments confirm that this material was brought by the littoral mechanism.

5.3.3.1.4. Mattancherry Channel

The quantitative textural composition of surficial sediments in Mattancherry channel is exhibited in the figure 51.

In the lower reaches of the channel, silty sediment was found during postmonsoon months, with small amounts of clay fraction at station 20 on the western side of the channel and coarse fraction ($\simeq$16%) at station 22 (eastern side). This may be due to the channel orientation towards the eastern side and hence increasing winnowing effect of currents favouring the settling and deposition of material more on the western side of the channel. Large amounts of silty sediments (98%) were present across the transverse section at the Mattancherry wharf (stations 23, 24 and 25). In the upper reaches of the channel moderate amounts of coarse fraction were present during postmonsoon due to the alluvial supply from the extended monsoonal discharge. Towards the end of postmonsoon months, silt with clay (20%) was present in higher amounts.

During premonsoon months, silty sediment was present in the lower reaches of the channel and also, in the transverse section across the Mattancherry wharf (Fig. 51). The upper reaches of the channel showed silt with moderate amounts of clay (25%). The increased clay content showed that the settling of suspensate was more in the upper reaches of the channel. The decreased fluvial supply and the reduced water flow may facilitate this channel to behave as a depositional environment; hence the sedimentary material entering the marine environment gets flocculated and settles to the bottom.

The lower reaches of the channel exhibited silty sediment with small amounts of coarse fraction (station 22, 22%) in rainy months. This feature results from sediment movement by the wave induced currents

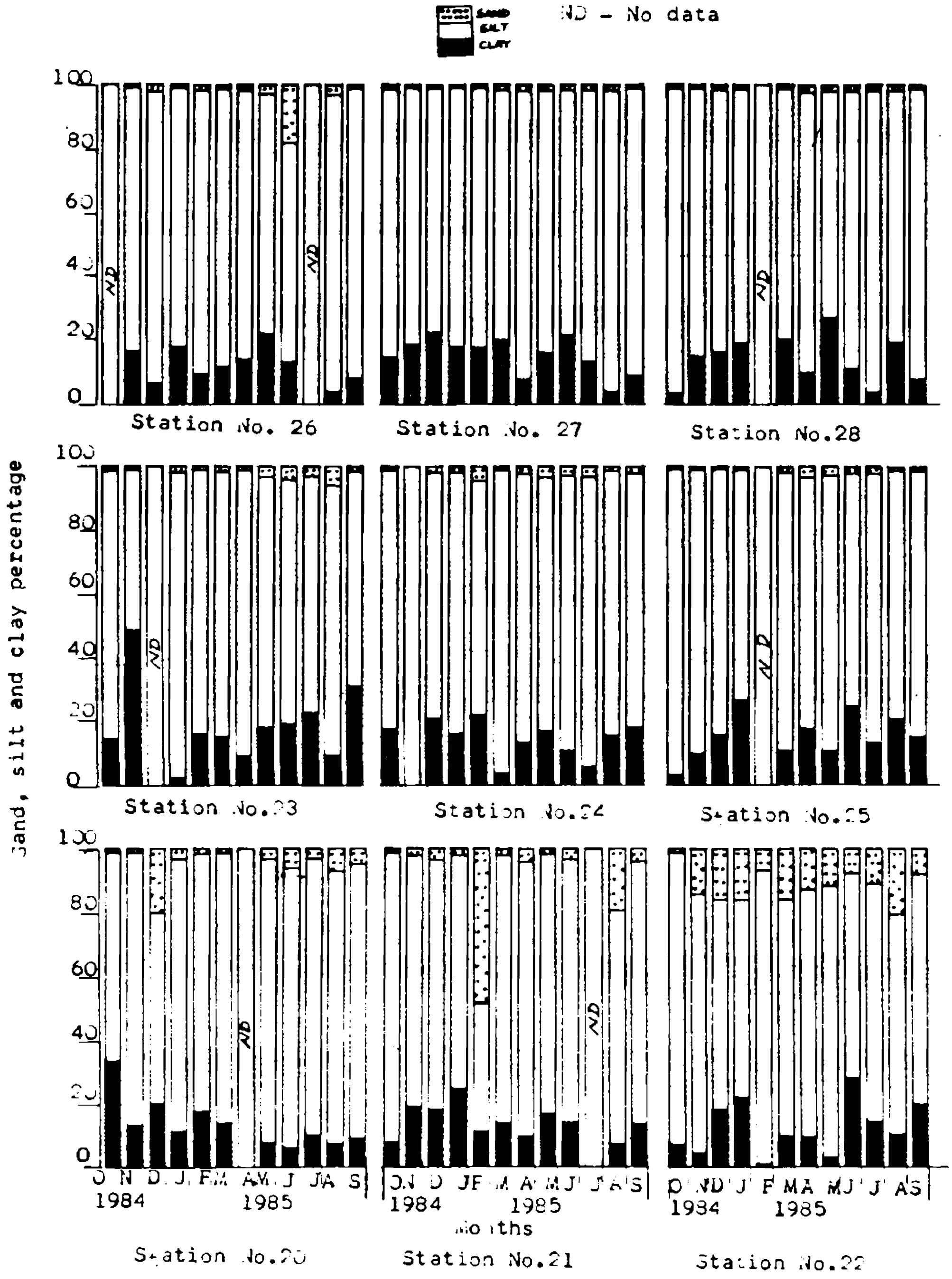


Fig. 51. Monthly variation in sand, silt and clay of surficial sediment of Mattancherry channel (stations 20 - 28).

in June and July due to the direct access of this segment of the channel with the cut. The transverse section across the Mattancherry wharf showed silty sediment with clay (20%) except in the Mattancherry wharf, where silt with coarse fractions ($\simeq$10%) was observed. The fine sediment is presumed to be due to the salt wedge present in the region which facilitates the accumulation of clay material. The upper reaches of the channel exhibits silty sediment with small amounts of coarse fraction and clay. The coarse material content at the upper reaches may be due to the sediment movement from the increased monsoonal fluvial discharge.

5.3.3.2. Distribution of Grain Size Parameters

5.3.3.2.1. phi Deviation Measure

The regional variation in the phi deviation measure values of sediments for the three seasons are shown in the figure 52 . The figure elucidates that very poorly sorted sediments were present in the inner channels and their content was more in the calm months (premonsoon and postmonsoon season) than the monsoon season. The sediments close to the Cochin cut in the Approach channel were moderately sorted in the post- and premonsoon months while moderately to well sorted in the monsoon months. Very well sorted to well sorted sediments were present towards the southwest side of the Approach channel (station 18) in all the seasons.

The scatter plot between phi median diameter and phi deviation measure (Fig. 52) indicates that the sediments with less than 3 Ø shows low standard deviation diameter values and falls within well to moderately sorted scale. During the monsoon months, the phi median diameter is 9 Ø to 11 Ø whereas in the calm months (premonsoon and postmonsoon months) is between 8 Ø and 11 Ø at higher values of phi deviation measure. The figure also indicates that the Cochin harbour area is predominantly estuarine with low sandy regions.

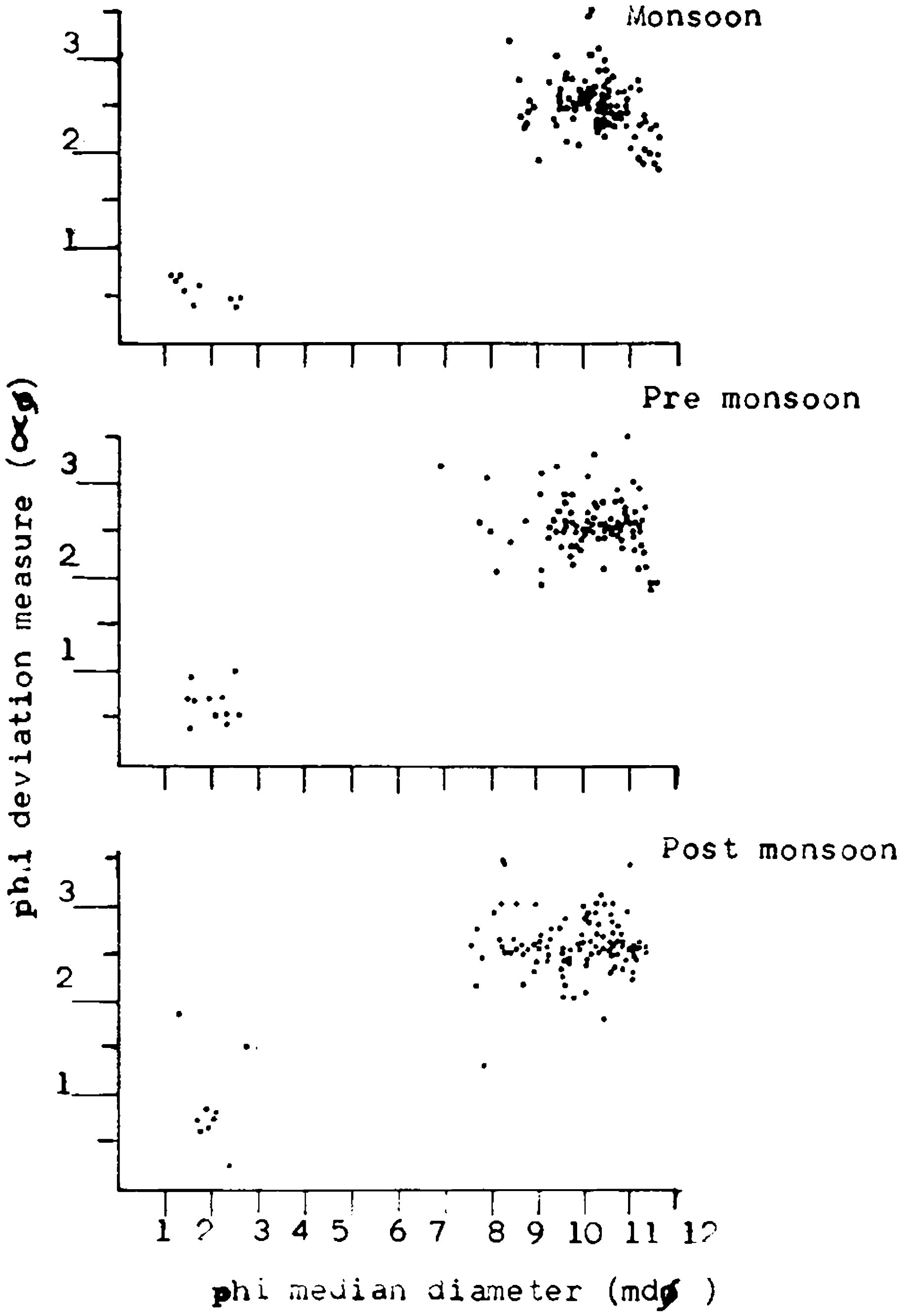


Fig. 52. Seasonal scatter plot between phi median diameter and phi deviation measure.

5.3.3.2.2. phi Skewness Measure

The skewness values reveal that the sediments of the Ernakulam channel, southwest end of the Approach channel, northern part of the harbour area and upper reaches of the channel were negatively skewed in the postmonsoon months. In premonsoon and postmonsoon months, the harbour area consisted of almost negatively skewed sediments.

The scatter plot between phi median diameter and phi skewness measure (Fig. 53) showed that the sediments were mainly composed of fine particle size, i.e. high phi median values and the negatively skewed sediment was more in the harbour area especially in the premonsoon and monsoon months. The sediments with median diameter in the fine sand range were less and well sorted and symmetrically distributed in all the seasons.

The scatter plot between phi deviation measure and phi skewness measure (Fig. 54) indicated that the sediments in the 2 to 3 standard deviation values were positively and negatively skewed and the positive skewness was less in the monsoon months within this range, than the other two seasons. The standard deviation slightly decreases for the high values of skewness.

The negative skewness is inferred as due to the marine material, (i.e. beach sediments) and also associated with continuous addition of fine material (Mason and Folk, 1958; Friedman, 1961; Chappell, 1967). The analyses of modern sediments show that the fine clay fraction is very sensitive to depositional processes (Selley, 1988).

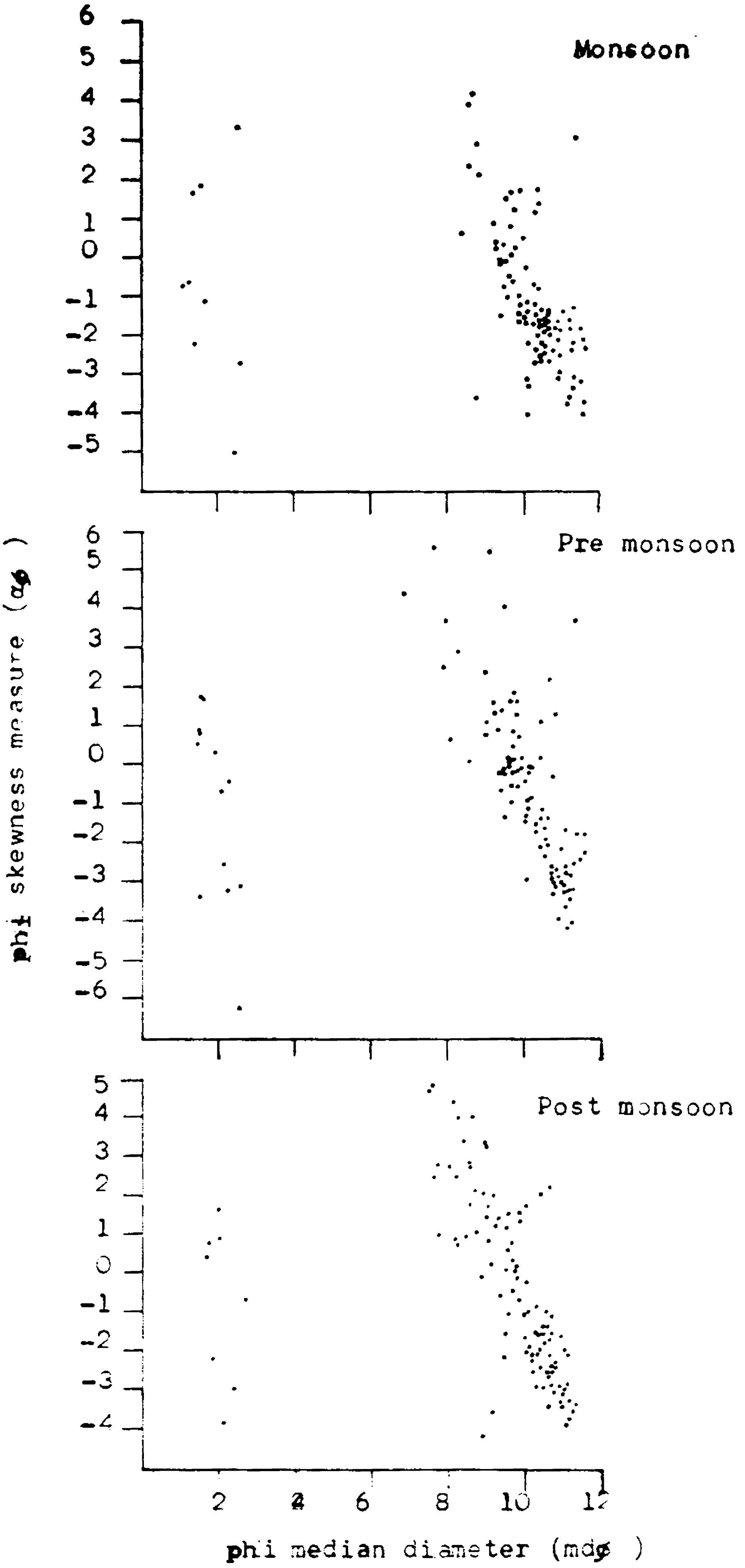


Fig. 53. Seasonal scatter plot between phi median diameter and phi skewness measure.

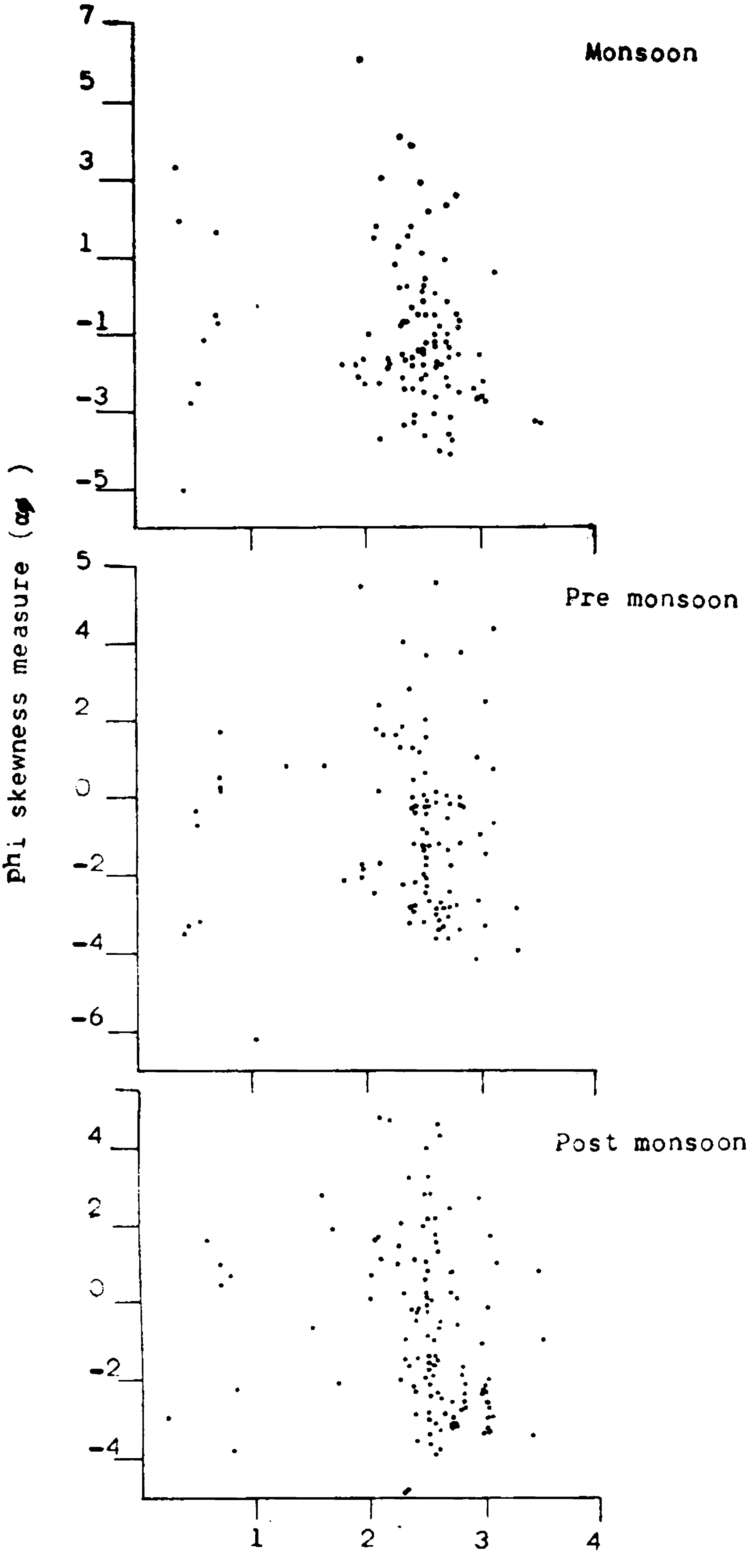


Fig. 54. Seasonal scatter plot between phi deviation measure and phi skewness measure.

CHAPTER 6

CONCLUSION

The significance of particle dynamics in controlling the siltation processes is brought out from a detailed study of the Cochin harbour area. The source of suspensate, its transport and cycling mechanism within the estuarine region before its eventual removal into the coastal plains have been investigated in detail and these studies helped to elucidate the depositional behaviour of the suspended particles and also highlighted the influence of forces, tractive or otherwise, causing deposition/erosion within the harbour area. In the light of recorded and present observations and conclusions drawn therefrom some effective remedial measures have been suggested to improve harbour navigation facilities.

Siltation in this harbour area is mainly controlled by the interaction of various physical processes viz. winds, tides, water currents, salinity, freshwater supply and the sedimentary features of the regime itself. The interplay of various factors influencing siltation is a very complex process and is not amenable to any direct experimentation. The results of studies carried out on the behaviour of particle dynamics associated with siltation in the Cochin harbour area (viz. Ernakulam channel, Approach channel and Mattancherry channel) are summarised hereunder.

The hydrography of the Cochin backwaters is mainly influenced by the freshwater flow from the Periyar and Muvattupuzha rivers and the tidal currents acting through the barmouth. The temperature as well as salinity values in this estuary are much affected by the seasonal climatic changes. It has been noted that the hydrographic conditions had varied over the years, especially since 1976, due to the commissioning of Thanneermukkam bund (modifying the hydrography of the southern parts) and the inter basin transfer of water (consequent to commissioning of Idukki hydroelectric project). Consequently, the sedimentary environment of this region has been exhibiting varying characteristics. The studies on temperature have helped the author to deduce information on the incursion of upwelled coastal waters into the lower reaches of this estuary.

Maximum temperature values were recorded in March and April months of 1985 in Ernakulam channel, preceeding a secondary maximum observed in November 1984. The Approach channel in the outer harbour area indicated higher variability in temperature than the two inner channels. The flushing characteristics of Cochin estuary as evidenced by salinity distribution brought out certain significant results with regard to the sedimentary features. The Ernakulam channel of the harbour was observed to be much affected by the fresh water discharges from the Muvattupuzha river, throughout the year. However, during periods of flood tide, high saline waters intruded through the bottom layers of this ship channel. During active monsoon period , convergent frontal phenomena, driven by the gravity discharge of freshwater were prominently observed. The reduced freshet during premonsoon months brought about more or less homogeneous conditions within this channel whereas the monsoon period was characterised by highly stratified conditions. The study revealed the presence of turbulent vertical mixing in this channel during monsoon season conditionally caused by external disturbances of waves and winds and internal shear due to density gradients.

The Approach channel exhibited high turbulent conditions due to geographical features as well as due to influences from outer sea. As such, the distribution of salinity in pre-, post- and monsoon months had their own specific characteristic features. The premonsoon water column was well mixed; the monsoon water column exhibited stratification, the postmonsoon remained partially mixed. On the other hand, the Mattancherry channel was more susceptible to salinity intrusion due to its proximity to the cut region and also due to orientation of the channel. During both the spring and neap tides the three channels exhibited salinity changes differing in time lag. Studies on dilution of seawater within the estuary indicated seasonal variations, especially under the spells of monsoon rainfall. At times, the freshwater fraction at surface was as high as 93 - 100% during monsoon months; while the bottom waters exhibited the presence of diluted seawater (20 - 30 x 10^{-3}).

The intensity of currents determines the nature of mixing at various levels as well as influences the silting/scouring behaviour of particulates. Synoptically, currents in Cochin harbour area were randomly distributed. Meaningful interpretation could be made by segmenting the results in each of the channel, which helped to bring out significant features as concluded below. In Ernakulam channel, interference of tidal and reduced fluvial supply caused currents of translatory nature giving rise to secondary circulation. Many-a-time a two-layer flow was recorded in this channel as well as in other places of the harbour to substantiate the contention on a partially mixed estuarine behaviour of the Cochin harbour area. Presence of gyral circulation, which might have profound effects on sediment transport, was recorded in the two inner channels. The monsoonal run-off gave rise to stronger water currents and depending on the phase of the tide, the value was as high as 125 cm sec^{-1}, in the barmouth region. A noteworthy phenomenon of principal currents in this estuary was the presence of flow in opposite directions in the transverse section. This might well give rise to secondary circulation within the port area. It was also noted that the Approach channel was characterised by currents that were much affected by outer sea disturbances. Semidiurnal studies on current variability at surface and subsurface waters in this estuary revealed tidal asymmetry. The cut region exhibited rhythmic tidal fluctuations in speed and direction within each vertical section, with the changing phase of tide. Observations also pointed out higher tidal current speeds along the two sides of the barmouth than along the middle, lagging by about 90^{o}.

Semidiurnal characteristics of Cochin harbour area were elucidated by studying the distribution of suspended solids within the lower estuary and by correlating these results with the hydrographical features of the estuary. Factors influencing the distribution of suspended solids were summarised by understanding the nature of fluvial suspensate loads, landward transport of marine particulates and by following the hydrodynamically introduced changes. As for Cochin harbour area, capital dredging has played an important part in modifying the existing conditions.

The postmonsoon period, transitional in behaviour, showed tidal scouring and dislocation of sedimented material. Resuspension of fine sediments during wedging of saltwater, especially in the Ernakulam channel, paved way towards the presence of concentrated mud patches along the bottom layers. During the monsoon season, the water column in the Ernakulam channel contained high amount of suspensate ($>$350 mg l^{-1}); the presence of higher amounts towards the upper reaches of channel was associated with increased fluvial discharge of heavy seston load during the onset of monsoon. The hydrological modifications by way of construction of Thanneermukkam bund as well as the interbasin transfer of water might have influenced changes in the transport of suspended solids into Cochin backwaters. In effect, regulating the water flow had resulted in tidal energy convergence on bottom sediments to resuspend and relocate the fine sediment material.

The Approach channel indicated a peculiar pattern in water flow namely the funnelling action during the flood and jetting effects during the ebb tides. Additionally, the translatory action caused by the littoral coastal currents resulted in the deposition of the material in the Approach channel itself. The high energy environment sorted coarse grained material in the entire stretch of the Approach channel during the months March to May and August to September, when deposition was a minimum. This was due to the oscillatory motion of waves which throw the material into suspension while tidal currents provided the necessary transporting power. The continued circulation of sediments permitted sorting; while the finer grains were winnowed away in suspension, the coarser sands and gravels were restricted to deep channel parts. Bruun (1978) also reported similar phenomenon in studies on stability of tidal inlets. This explains why the south side of the confluence and the entire southern side of the Approach channel exhibited minimum deposition of finer sediments. Considerably high proportion of silty sediment and more amount of suspensate were present on the northern side of the channel. This might be due to the entry of dredged material dumped on the northern parts of the outer harbour. Tidal streams, dispersed the spoil containing appreciable amounts of silt and clay over considerable distances causing higher suspended solids concentration in the months of October to February and June to July. Thus, the net effect of interaction of estuarine flow with wave induced littoral sand-drift system acted as a depocentre for suspensate at the Cochin barmouth area.

During the months June to February, the southern parts of the turning basin in Ernakulam channel was observed to silt considerably. In Ernakulam channel, in these months, the river inflow maintained longitudinal and vertical salinity gradients which in turn, imparted a unique estuarine circulation pattern for dispersal of sediment. At the south of the turning basin, the water stream often encountered the freshwater - saltwater transition zone near the bottom; it converged with landward flowing seawater (velocity approaching zero) arresting the seaward transport of sediments. The suspended loads were higher in the subsurface waters than the surface waters in this channel. This was due to the flocculation owing to the inter-mixing of saltwater with freshwater having high seston content. Presence of higher seston concentration in bottom flood currents caused the bed material to travel up the estuary and later to silt at slack time; the weak ebb currents did not retrieve the material downstream. Often in this channel, the seaward river flow and landward tidal flow converged to give rise to 'turbidity maximum' zones. Though the exact effect of this phenomenon is not well understood in this part of the channel, this physical feature is likely to influence localised silting.

Silt in Mattancherry channel was mainly contributed by the freshwater seston transported downstream in June to August months. The flood tidal currents brought suspended material during October to April into this channel as revealed from data on suspensate (Chapter 5). During late May, seston accumulation was found to be more towards north of the turning basin of the Mattancherry channel due to the seaward transition of the freshwater-saltwater front permitting higher sedimentation. As the transition zone shifted more seaward, so too did the current convergence zone, (or null zone). Therefore, the zone of turbidity maximum of high suspended loads shifted seaward in response to river flow, as revealed by the results of study on suspended solids distribution. Of the two inner harbour channels the Mattancherry channel was subjected to a much greater silting. The fine material brought inside the cut, by the flood tide was mostly deposited in the Mattancherry channel due to the orientation of the channel as well as proximity to the barmouth.

During flood tides incursion of bottom saline waters caused synoptically characterized turbidity maximum zones. Hence the findings of higher turbidity in the cut region associated with flood-tide conditions lead to postulate the landward transport of suspended material that may eventually settle within the harbour region. Further, the investigations on the variations of suspended solids content with tide indicated that the circulation of sestons did not respond in unison with the changing tidal conditions. Summarising, the suspended solids distribution was highly dynamic, true to the features of this environment and was much affected by varying physical factors. The present study on particle dynamics bring out the influencing factors such as: (a) seasonality variations, (b) hydrological changes, (c) fluctuation within the harbour due to tidal currents, (d) quasi-chemical reactions such as flocculation and precipitation and (e) geographical modification. The Cochin backwaters contained relatively low suspensate in the monsoon months. Except for the initial transport of weathered/ eroded suspended solids in alluvial discharges, wherein the amount of suspensate drastically increased (which partially settled in the lower reaches of the estuary before eventually being transferred to offshore regions), this tropical waterway was resolved to dissisipate energy in relocating sediments and generating quasi-stability conditions super-imposed on hydrodynamical equilibria. Transverse dislocation was often encountered in the cut region permitting to rely on the results of randomly distributed suspended solids content.

An attempt was made to systematise the principles of uniqueness, sensitivity and the logical structure of the situation by studying the inter-relationship between depth and water current (Fig. 55) and water

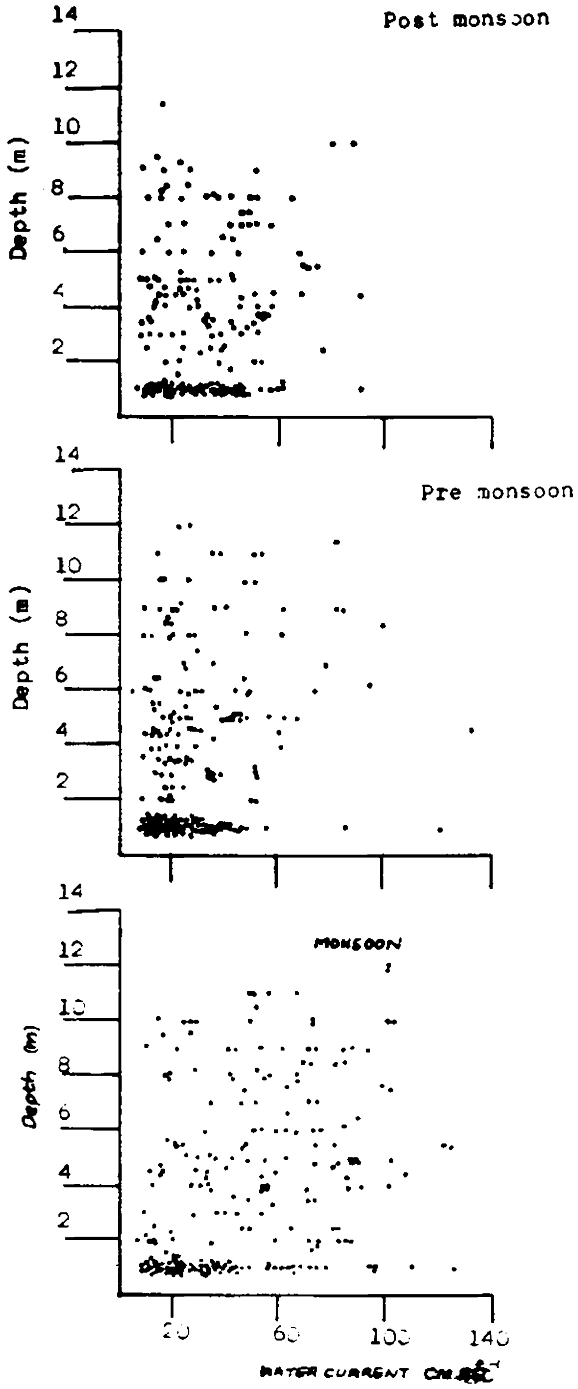


Fig. 55. Inter relationship between water current and depth in Cochin harbour area during postmonsoon, premonsoon and monsoon.

current and suspensate (Fig. 56) by the regime approach. From among a number of methods developed and applied to natural streams (Kennedy, 1977), the characteristic two dimensional diagrams relating depth-velocity and suspensate-velocity can be plotted to describe the hydraulic system (Southard, 1971). The wide applicability of such plots had been demonstrated by Southard (1975) and Middleton and Southard (1978). Many of the formulations reviewed by Kennedy (1977) have fallen far short of explaining many of the physical features but complex hydraulic relations may be better resolved by applying studies on inter-parametric relations (Dawdy, 1961). As different combinations of depth-velocity and suspensate-velocity exist, these figures may be used to describe a specific condition characterising of the stream under study. The information contained in figure 55 relates to the inter relationship between water current and depth in the Cochin harbour area during postmonsoon, premonsoon and monsoon. The large scatter of values observed during monsoon related to the distribution of current vectors even at the deeper regions of the navigational channels. It can be inferred that the harbour area may be deprived of build-up in suspended solids or in other words, sediment transport mechanisms function effectively during this season. The current variability with depth was restricted to low magnitudes during the pre- and postmonsoon months. The more frequently observed water currents were in the range 10 - 50 cm sec^{-1} at near surface levels in these seasons whereas the mid-water currents were relatively non-clustered. The pattern of the current distribution with depth during premonsoon and postmonsoon helps to reason the prolonged persistence of suspensate in selected regions of the channels.

Figure 56 presents the seasonal inter-relationship between the water current and suspensate in Cochin harbour area. The characteristic features were: (1) low suspensate content ($<$ 300 mg l^{-1}) widely distributed in the current range 10 - 110 cm sec^{-1} during monsoon period indicative of dispersive mechanisms; (2) in the postmonsoon months, data points clustered within the current velocity range 10 - 60 cm sec^{-1} and seston concentration 30 - 400 mg l^{-1}; this feature points out to a transitional period where the suspended solids distribution

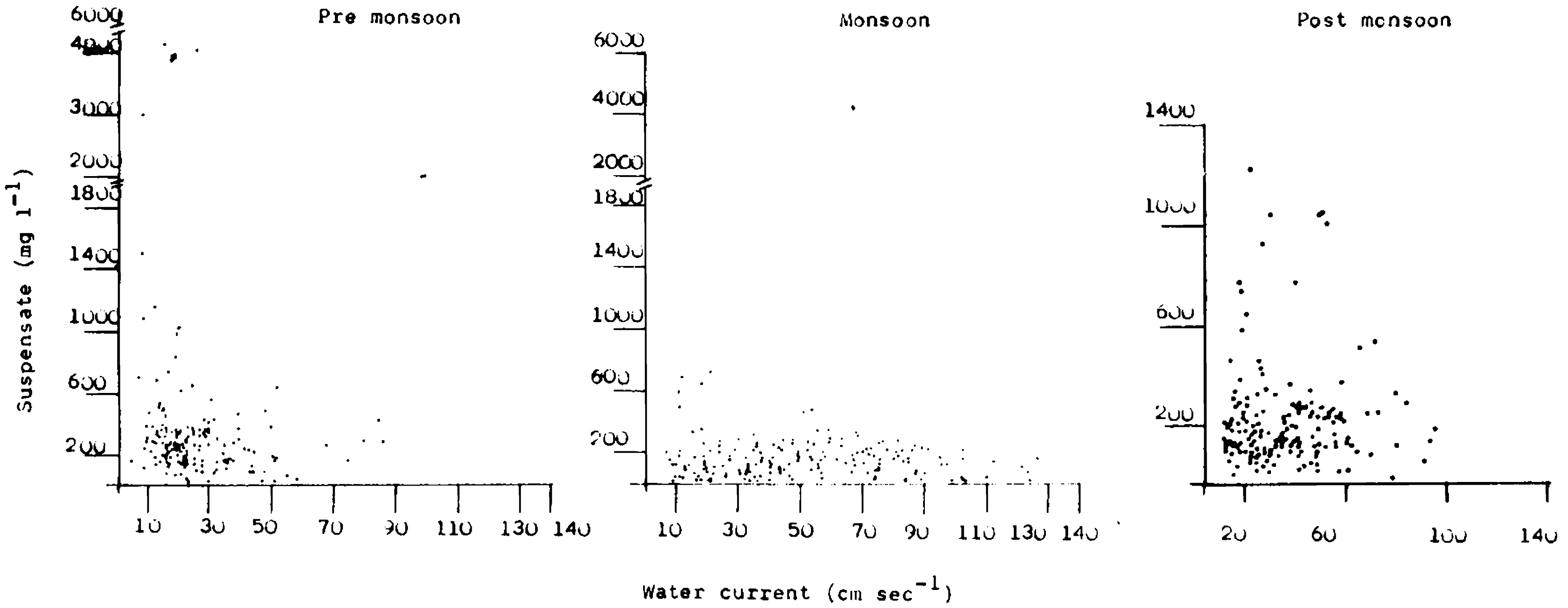


Fig. 56. Inter relationship between water current and suspensate in Cochin harbour area during postmonsoon, premonsoon and monsoon.

is influenced by low magnitude currents and (3) small magnitude currents dispense energy to cause high water turbidity during premonsoon; this aspect in the figure was indicated by the values of suspensate concentration as high as 4000 mg l^{-1} at currents of magnitude 20 cm sec^{-1}. The above two figures highlights the various aspects of particle dynamics of seasonal variability.

The textural studies had revealed the predominant nature of sediment size distribution, categorised seasonally in the three reaches of the navigational channels. Whereas, the Ernakulam and Mattancherry channels exhibited silt-clay fractions (low energy environment), the Approach channel had more coarse fraction.

A record on the quantum of harbour dredging operations is maintained at the Cochin Port Trust based on dredging and sounding data. The records provide data on the amount of material dredged every year alongwith the variations in estimations (a brief account of these aspects is given as Annexure I). Earlier studies (using radio-tracers) had pointed out return of large amount of sediments, once disposed in offshore regions. The report pointed out to the fact that major part of the dredging operations were conducted in the Approach channel. No conclusive results are yet available as to whether the dredged spoil finds its way back into the inner channels too. Based on the direction of the turbid currents flowing into the barmouth region even during monsoon season as well as more strongly during flood tides, it is postulated that re-entry of spoil takes place into the harbour area.

A discussion on harbour siltation and suspensate distribution is incomplete unless sediment control techniques and remedial measures to alleviate the problems are not presented. The increasing demand for expanding facilities at Cochin harbour area involves extensive dredging operations; this will necessarily create varied environmental consequences. Practical applications of this research study lie in the interpretation of results on estuarine circulation, suspensate distribution vis-a-vis knowledge on siltation processes. Consequences of dredging on estuarine hydrodynamics and sedimentation has been well documented by Kirby and Parker (1977)and Nichols (1988). Two aspects of estuarine hydrodynamics are directly affected by change in geometry caused by dredging; they are (1) tidal hydraulics, including landward propagation of tides, tidal discharge and channel stability and (2) the residual density flow or estuarine circulation. The situation before and after dredging at Delaware river near Philadelphia has been well documented (Pillsbury, 1955). Dredging in Ems estuary, Netherlands reportedly changed the tidal propagation resulting in new current patterns, locally altered morphology and an increase in turbidity throughout the estuary (Harleman and Lee, 1969; De Jonge, 1983). A direct consequence of deepening tidal channels is the increase in flood velocities over ebb velocities causing a strong landward dominance of sediment transport (Inglis and Kestner, 1958). Other aspects of tidal currents include amplitude modification, energy convergence, standing wave effects and implications on channel stability (Wright et al., 1973; O'Brien, 1976 and Allen et al., 1980). Illustrative case histories on expanded dredging operations include increased sedimentation in Delaware estuary (Army Corps, 1973), massive siltation extending seaward from the estuary head in Lune estuary, U.K. (Inglis and Kestner, 1958) and large scale geometry changes within Seine estuary, France with offshore mud-zone formation (Avoine et al., 1981). Long-term effects include the changed role of estuaries from a sink for fluvial and marine sediments to a source of fluvial sediment for the shelf, particularly noted for the Seine estuary. Effects on estuarine circulation extends from changes in mixing rate, salinity stratification and formation of turbidity maximum at null zones (Pritchard, 1955). The Savannah harbour (U.S.A.) exhibited overall increased sedimentation on deepening; locus of maximum sedimentation shifted (19 km) landward, and density circulation developed to such a degree to trap most of the potential sediments (Simmons and Herrmann, 1972). Dredging in South pass and Southwest Pass of the Mississippi river caused new bars to form at the landward tip of the saltwedge, far upstream of the entrance (Simmons and Herrmann, 1972). In conclusion, dredging work at lower regions of estuaries can produce changes in the dynamic behaviour of an estuary and create an imbalance between erosion and sedimentation (Nichols, 1978). As a system deviates more from its natural equilibrium, great is its imbalance — as channels are dredged deeper, the potential for entrapment of sediment is increased — more the sedimentation, more dredging will be required and therefore, dredging is self-perpetuating (Price and Kendrick, 1967).

Properties and distribution of sediments, effect of dredging on redeposition etc. were considered in order to reduce the cost of dredging at Rotterdam-Europort (Parker and Kirby, 1982). The above study suggested the in-situ determination of density to guide dredging operations. The survey had a number of specific advantages - a regular monitoring of density allowed the rapid incursion of material to be monitored necessitating dredging only on consolidation. The study further suggested the dredging of that material for the purpose of navigation or defining sea traffic routes along sea beds of navigability without dredging. An alternate procedure utilized was to dig a silt trap (10^6 m^3 size) to trap material following the sediment transport or silting mechanisms (van Oostrum et al., 1980). This procedure has been adopted in some U.K. ports, Hamburg (Germany), Zeebrugge (Belgium), Bordeause (France) and in several ports of United States of America.

The Chinese experience is not different from other places - the techniques used in controlling sedimentation includes hydraulic sluicing, agitation dredging and tidal flushing (Luozhaosen and Gu Peiyu, 1982). Each of these methods are specific in applicability subject to conditions at each Chinese location - sluicing by means of a gate controlling river flow was applied to Sayang river (Don Duoren, 1963); agitation dredging by resuspending deposited sediments to be carried away in ebb current was practised at estuaries located in Jiangsu and Heber provinces (Duguoren, 1980) and finally tidal flushing by enlarged tidal prism in Liangdu river (Luozhaosen and Gu Peiyu, 1980). In United States of America, four methods of controlling sediments in estuaries have been tested (Hoffman, 1982). These are (1) water jets (single and arrays), (2) silt curtains, (3) eductors and (4) agitation dredging. Use of jets to flush berths are practised at More Island Shipyard at the appropriate tidal stage. Also the use of silt curtains made of hypalon fabric was tested at More Island Naval Yard and at Rotterdam Port, Holland (Jenkins et al., 1981). Eductors, working basically on the principle of the venturic tube, was tested on Virginia beach port with varying success (Hoffman, 1977). Adalph (1982) summarises the advantage and disadvantages of different dredging types and compares merits of river training and dredging operations.

Dredging operations at Madras port have been reviewed by Prasad and Reddy (1988); the authors report rapidly varying bottom contours with seasonal fluctuations owing to extensive dredging. A study on nearshore profiles off Paradip port (Orissa) presents estimates on shore erosion and deposition and discusses the effectiveness of sand pumping and hoppering into the offshore area in safeguarding the beaches and port within (Sharma and Sundar, 1988).

Sedimentation process confront the development of Cochin harbour with several distinct problems. Dredging has been the only practised solution to all of the problems since the birth of this harbour. This cannot be afforded indefinitely due to the intrinsic high rates of energy consumption, equipment breakdown and every growing costs. It is observed that dredged spoil is a continuing source of seston to the Cochin harbour area and as such, dredging cannot be a final solution to siltation. Control of sedimentation in harbours, apart from dredging, involves trapping/diverting the sediments from critical areas (navigational channels, jetties or berths), blocking the sediments before they reach these critical areas or resuspending the sediments and eventually removing them (Adalph, 1982; Hoffman, 1982; William, 1982). In principle, this means application of any one or a combination of source control, transport control or field control over the amount of suspensates. Hydraulic sluicing combined with silt curtains at upper estuarine regions and agitation dredging at port area may be the techniques most effective for this harbour area. The duration of ebb flow facilitates the operation of the second method in this tropical estuary. During post- and premonsoon (October to May) silt curtains appear to be an effective trap for suspended solids at the landward tip of Cochin estuary. Nevertheless, a detailed investigation is called for to look into the re-entry of the dredged spoil in the Approach channel and further landwards into the lower reaches of the two inner channels. It is also necessary to adopt continuous monitoring of the density (suspensate concentration) in the port area, to ascertain the optimum level of dredging.

Assessment of future trade prospects and marine terminal requirements of the Cochin Port has been projected by the Engineers India (1986). The major engineering measures planned are deepening side channels along Wallarpat and Bolghatty islands to 7 m depth, supply base for offshore exploration, ship breaking yard, fisheries harbour etc. The extensive dredging of the channel at the northern end of the harbour will change the salinity distribution conditions; higher salinity may be encountered in the upstream directions. As the navigational channels are deepened, the freshwater stream becomes more saline and the salinity of water may affect the industries on the sides of the Periyar, adversely. Since the dredging is away from the Cochin cut, the water influx at the Mattancherry channel is least affected; and therefore the circulation pattern may remain more or less the same allowing continued sedimentation in this channel. The extend to which saltwater penetrates into the estuary is a function of depth; hence a part of the tidal influx may flow towards the north of the harbour. This may reduce the quantity of flooding through the Ernakulam channel and consequently the freshwater - saltwater interface will shift further northwards of the channel causing sedimentation. The increased sediment movement may thus relocate silt necessitating more dredging work. The qualitative consequences of the above engineering measures in the harbour area may now be rationally considered in the planning and design. The schemes are, therefore, to be adjusted to minimise the incidental damages or to circumvent them altogether. It is absolutely necessary to study the port area in better details, especially the northern side of the harbour before the implementation of the above developmental programmes.

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ANALYTICAL COMPILATION OF SOUNDING AND DREDGING DATA FROM COCHIN PORT TRUST.

The higher degree of siltation in the Approach and Inner channels of Cochin harbour area than other parts of the backwaters necessitates annual maintenance dredging. Marine Survey Division of the Cochin Port Trust conducts monthly bathymetric surveys in the harbour area of this estuary in order to determine the dredging requirements. For the purpose of dredging, the navigational channels are divided into various compartments. A systematic record of dredging, giving break up of spoil lifted from individual compartments on a monthly basis together with monthly sounding charts provide a good basis for extended interpretation of siltation processes. As on record, outside the cut region, the maintenance dredging is undertaken only during the calm months of September to May. The Approach channel is dredged to 11.6 m and Mattancherry channel to 9.75 m around the year (Manoharan, 1987).

A few studies on the bed profile and the quantity of material dredged from the Cochin harbour area, based on the data compiled by the Cochin Port Trust, were carried out by earlier workers. Central Water Power Research Station (1969) studied the variations in the amount of dredged material from the Inner and Approach channels and showed that the quantity of dredged material was more from the Approach channel than those from the two Inner channels. Gopinathan and Qasim (1971) pointed out that the quantity of material removed from the channel is $2 \times 10^6 \ m^3 \ yr^{-1}$, nearly 70% of the material being from the Approach channel, 28% from the Mattancherry channel and the rest (2%) from the Ernakulam channel; they also studied the monthly (August 1965 to September 1966) bathymetry of an area of 0.26 km^2 in the backwaters. Their studies showed that unless dredging was continued, siltation would take place with varying degrees in the harbour area. Anto et al. (1977) studied siltation processes in the Approach channel from the sounding data along with the quantity of material dredged for a period of six years (1967 - 1972). This study revealed that the settling of silt near the narrow barmouth of the channel was minimal and that considerable amount of sedimentation occurred off 1800 m from the harbour mouth with decreasing tendencies beyond 6000 m distance.

The earlier studies were done for a short period in a limited area. Within the scope of this study, monthly sounding and dredging data from the various compartments for a period of six years (1979-1985) and amount of annually dredged material for a period of fifty six years (from 1929-30 onwards) from the harbour area are analysed and presented. Attempts are made to elucidate the functional relationship between the amount of dredged material and soundings, significance of variations in volume of dredged material and the long term trends using appropriate statistical tools.

MATERIALS AND METHODS

The whole harbour area has been divided into twelve compartments by Cochin Port Trust for the purpose of dredging and related activities. Hence the monthly data on dredged quantities together with sounding charts were available separately for these twelve compartments for the years from 1979-80 to 1984-85. The above data were used for studying the seasonal variations in dredging and to analyse the relationship between the quantity of material removed and deposited.

Assuming that the vertical distance (depth) and spoil deposit were inversely proportional, the relationship between the vertical distance and quantity dredged were studied using the product moment correlation coefficients (Shukla and Gulshan, 1975). Also the horizontal distance between the contours were correlated with dredged quantity. Here it was assumed that more the deposited material, the higher the horizontal distance and hence more the dredging. Since the channels were of different measurements, the quantity of material dredged from unit area was calculated. These correlation analysis could be done only for the compartments of the inner channels, since the monthly contours for the Approach channel were not available. The correlation values were tested for their significance and results are given in table 1.

le 1. Correlation Coefficients

partments	Correlation coefficient between					
	Average horizontal distance and quantity of dredged material	Sample size (n)	Average depth and quantity of dredged material	Sample size (n)	Average horizontal distance and average depth	Sample size (n)
tancherry channel	0.3402	30	-0.4461*	29	-0.4968*	33
tancherry channel turning basin	-0.5991	3	0.7097	3	-0.1392	34
tancherry wharf and SCB	0.2323	32	0.1608	32	-0.0180	34
eam mooring western side	0.0372	15	0.1748	16	0.1180	33
eam mooring eastern side	-0.1982	13	-0.4904*	13	-0.5968*	34
tancherry channel (Total)	0.0068	34	-0.1482	35	-0.4564*	34
akulam turning basin opposite tanker berth	-0.4239	4	-0.0238	4	0.4332*	32
akulam wharf	-0.1713	20	-0.0718	20	0.0543	32
l tanker berths	-0.0777	12	-0.1660	11	0.1710	31
nakulam channel					0.3946*	30
nakulam channel (Total)					0.4504*	33

ndicate significant correlation

Three positions were fixed on the bathymetry chart; one position was in the middle of each compartment and the others at equal distances from them. The average horizontal distance between the contours of 0.5 m interval for each compartment was calculated. The average depth (vertical distance) for the above compartment was also determined. The correlation coefficient between the quantity of material removed per unit area and the average vertical distance and also with the horizontal distance was calculated using Pearson's product moment correlation coefficient formula.

The monthly data on dredged material was analysed for studying the seasonality pattern. Twelve-month centred moving-average was used in order to estimate the seasonality indices (Croxton et al. 1975) and the results are tabulated (Table 2). Also the quarterly pattern of variation was studied using three-month moving-average method (Table 3). Annual figures of amount of dredged material for twenty five years (1960-1985) from the twelve compartments of the Cochin harbour area and the annual dredging data for 56 years (1929-30 onwards) for the Inner channels and the Approach channel were analysed for long-term trends.

RESULTS AND DISCUSSION

The amount of annual dredged material per unit area for the years 1929-30 to 1984-85 from the inner channels, Approach channel and also for the harbour area are represented graphically in figure 1. The figure reveals an increasing trend in the amount of dredged material in the Approach channel with marginal fluctuations. This indicates that more deposition was taking place in the Approach channel which is in agreement with the findings of C.W.P.R.S.*(1969). Using the twelve month centred moving-average method, the seasonality indices were calculated (Table 2). The monthly indices indicate that more dredging was being conducted during the months March to May, which is the premonsoon period. This is further established from the values obtained by computing seasonality indices using quarterly centred moving-average method. The amount of suspensate in the water samples collected during these months, clearly indicates higher amount of

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*Central Water Power Research Station

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Table 2. Seasonality indices obtained by using twelve-month centred moving average method

Sl. No.	January	February	March	April	May	June	July	August	September	October	November	December
1.	78.8	132.4	423.4	190.0	202.4	91.8	106.9	105.0	100.3	154.9	158.4	128.3
2.	62.9	70.4	232.0	176.1	201.2	91.7	98.7	69.9	91.1	92.6	142.1	125.2
3.	59.9	56.1	161.0	172.5	112.0	82.3	60.2	61.0	82.5	75.7	133.1	92.3
4.	57.3	29.5	135.2	162.4	103.8	69.3	50.4	53.8	62.3	58.8	71.9	74.7
5.	46.3	14.4	9.5	111.4	83.2	44.3	7.8	24.6	61.1	58.45	61.4	54.3

Table 3. Seasonal indices obtained by using quarterly centered moving average method.

Sl. No.	December-February	March - May	June - August	September-November
1	107.4	218.3	98.0	113.70
2	80.9	175.30	87.34	96.0
3	68.70	162.50	57.3	83.5
4	55.8	142.0	56.0	81.5
5	49.10	117.5	38.21	-

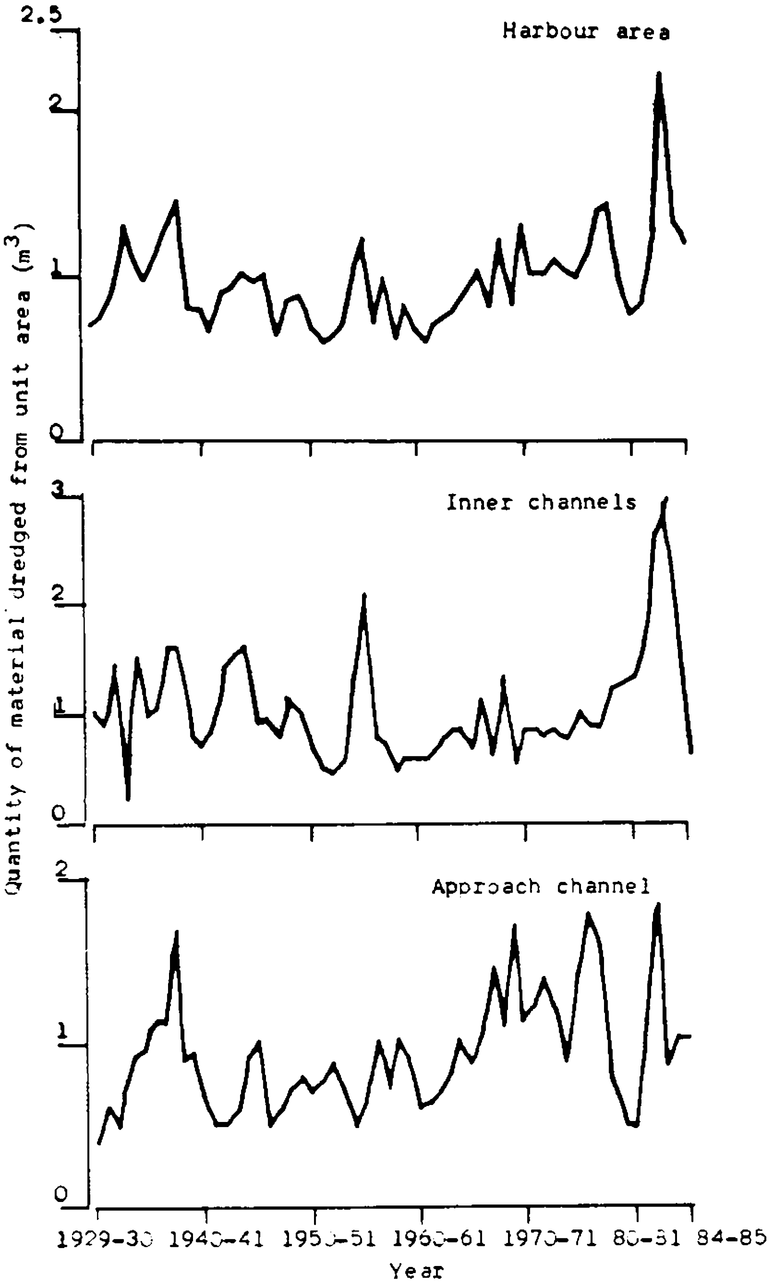

Fig. 1. Quantity of material dredged per unit area since 1929-30 - 1984-85 in the Approach channel, Inner channels and Harbour area (Data of harbour area is integrated of inner and Approach channels).

concentration compared to other months as already pointed out in the chapter detailing the suspensate and surficial sediment study. Evidently the high concentration of suspended material calls for higher rate of removal of spoil, hence the high indices during the above months.

Generally, before dredging, monthly sounding data are being collected. The data givesthe vertical distance from the water level (bench mark) to the bottom bed. Based on these vertical distances an attempt is made to find the correlation between the average depth and the dredged material per unit area. These are worked out for different compartments wherever measurements were available and tabulated in table 1. Out of the nine compartments available, five of them showed negative correlation. These correlation values indicate that less the depth, more quantity is to be dredged, which is in tune with the expected situation.

When higher rate of deposition is taking place, the distances between the depth contours were expected to be more. This is verified by studying the correlation between the average horizontal distances between the depth contours and the quantity of dredged material per unit area. These values give a positive relationship except for three compartments. However, the correlation values were not significant in all the cases. This may be due to the topographical differences of the channel which influence the horizontal distance between the depth contours. This is further established when the correlation between the average horizontal distance and average depth was studied and found negative. These negative values are to be expected since lesser the depth greater the horizontal distance. But the observations give both negative and positive values for the correlation, as explained above.

Annual variations in the total volume of material dredged from the Ernakulam channel is presented in figure 2. The Ernakulam wharf shows increase in amount of dredged material from 1960 to 1980. Since 1980, the sharp increase in the amount of material dredged out from this channel, especially from the wharf and Ernakulam channel compartments

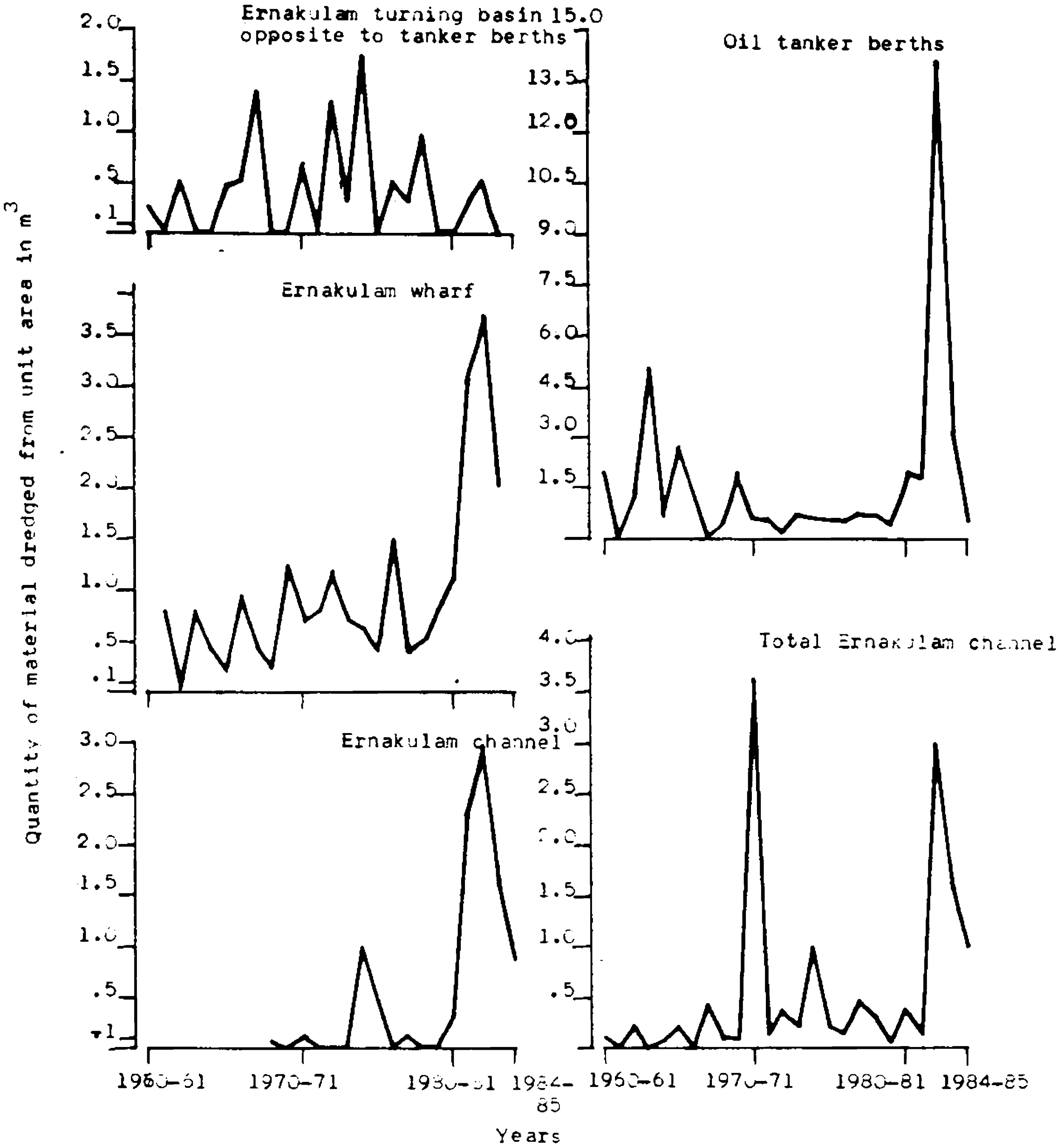

Fig. 2. Quantity of material dredged per unit area in the years 1960-61 - 1984-85 at different compartments in Ernakulam channel.

may be due to the capital dredging as a part of the Integrated Port Development Scheme. Amount of dredged material was noted to be highly varying in the compartment, Ernakulam channel turning basin; this may be due to the non-periodicity of dredging in this channel due to relatively low seston deposits. The amount of dredged material was again lower in the oil tanker-berths upto 1980-81. The increased dredged spoil in this channel from 1965 to 1967 was the after effect of December 1965 storm which deposited a large amount of silt along the coast (Anto et al. 1977). The figure elucidate that the amount of dredged material was more towards the northern end of the channel, especially in the Ernakulam wharf region.

The amount of dredged material from the various compartments of Mattancherry channel is shown in figure 3. Amount of dredged material was highly fluctuating in the Mattancherry channel turning basin. Mattancherry wharf and Mattancherry channel compartments exhibit increase in the amount of dredged material throughout the period under report, indicating that the deposition was continuously increasing in this region. Maximum dredged spoil in this channel was from the Mattancherry wharf and south berth subjected to higher deposition; this finding is also held true in the light of discussions in the chapter on suspensate and surficial sediments.

The figure 4 exhibits that the amount of dredged spoil was comparatively more in the Approach channel than Inner channels. The increased amounts of spoil in the Approach channel, east of turning point was the after effect of December 1965 storm which deposited a large amount of clay close to the coast just north of the Approach channel (Gopinathan and Qasim, 1971). After the storm in December 1965, the clay deposit was washed offshore during the subsequent monsoon months as revealed by the ecograms of November-December months of 1966 (Anto et al. 1977). The Approach channel, west of the turning point, indicates a location of higher amounts of dredged material than those in the east, annually. The suspensate concentration was also more in this region as shown in chapter 5. Evidently, the analysis of data from Port also indicate that the amount of dredged spoil was maximum in the Approach channel. Seasonality indices reveal that the conduct

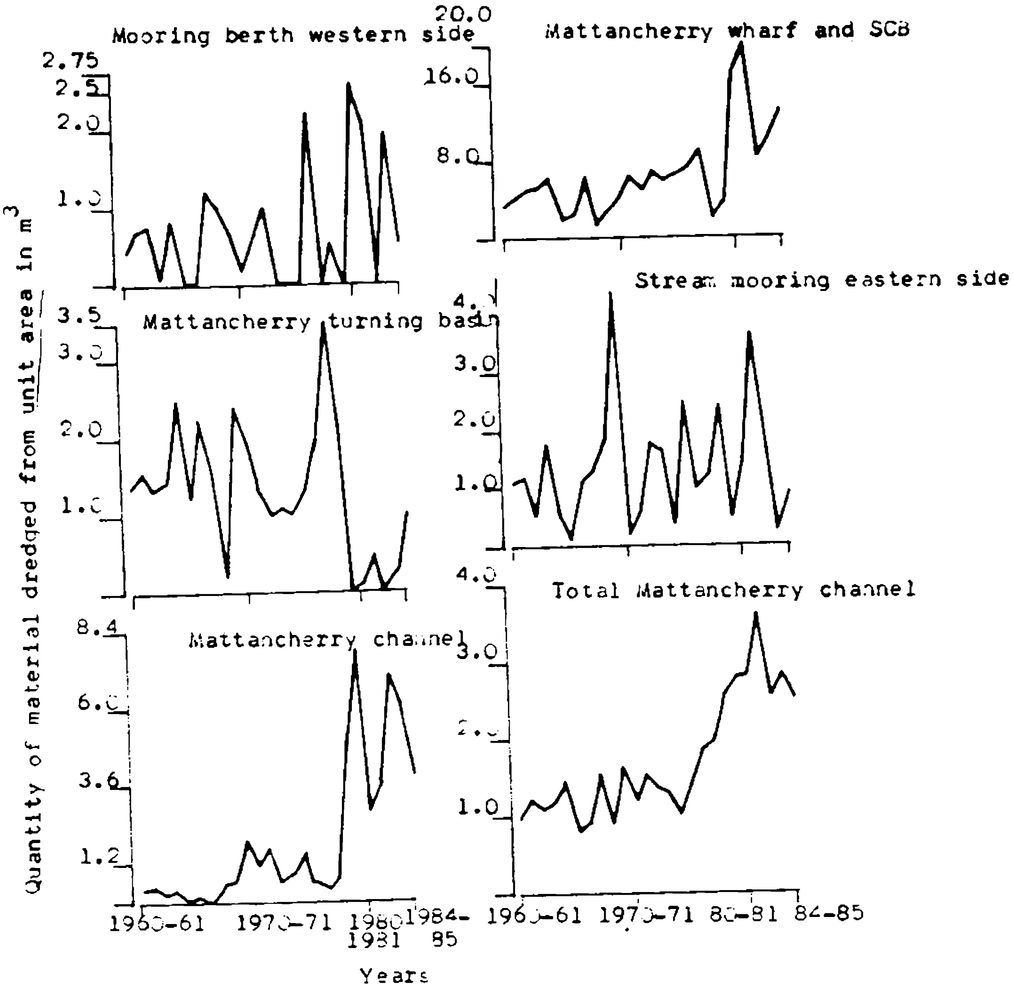

Fig. 3. Quantity of material dredged per unit area in the years 1960-61 - 1984-85 at different compartments in Mattancherry channel.

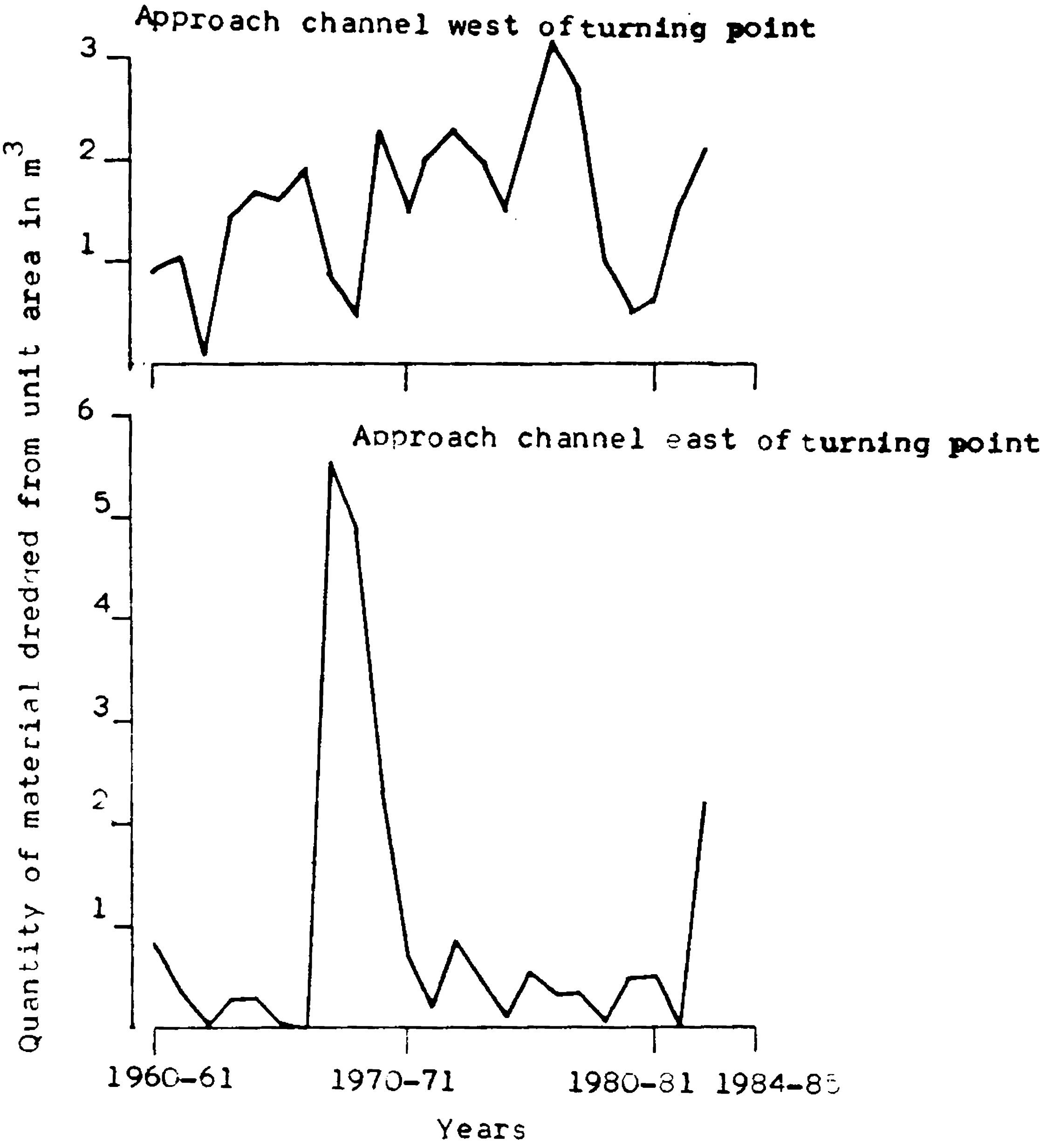

Fig. 4. Quantity of material dredged per unit area in the years 1960-61 - 1984-85 at east and west of turning point in Approach channel.

of dredging was held mainly during the premonsoon months (February - May). Inner harbour channels are however subjected to an increase in dredging operations since the last few years.

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