STUDIES ON THE DYNAMICS OF COCHIN ESTUARY

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JULY 1989

to my beloved parents

DECLARATION

I hereby declare that this thesis entitled "Studies on the Dynamics of Cochin Estuary" has not previously formed the basis of the award of any degree, diploma or associateship in any university.

COCHIN - 682 016,
July, 1989.

JOMON JOSEPH

CERTIFICATE

This is to certify that this thesis is an authentic record of research work carried out by Sri. Jomon Joseph, M.Sc., under my supervision and guidance in the School of Marine Sciences for the Ph.D Degree of the Cochin University of Science and Technology and no part of this has previously formed the basis for the award of any other degree in any university.

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C O N T E N T S

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PREFACE

Estuaries play important role in the commercial and industrial growth of nations. They also form natural breeding grounds for a variety of fishes and shrimps. Presently many of these highly productive ecosystems are under pressure, either as repositories for industrial effluents and domestic wastes or as prime sites for reclamation to create land for industry, agriculture or human settlement. These stresses can be reduced considerably by planning human interference on estuaries with sufficient knowledge of estuarine dynamics. In recent years, the Cochin estuary has been subjected to drastic environmental changes owing to the development of the Cochin harbour, shipyard and a large number of industries located near it.

A knowledge of the dynamics of this estuarine system is essential for understanding its physical, biological, chemical and geological aspects and engineering and developmental possibilities because the different types of physical conditions that may exist affect the transport, distribution and reaction phenomena in the estuary. The hydrodynamics of estuarine water bodies is complex as it is influenced by river flow, tide, wind, density factors and the estuarine geometry.

This thesis is addressed to an investigation on the tidal, seasonal and spatial variations of the hydrographic parameters, circulation and mixing processes of the Cochin estuary. The thesis is presented in five chapters with further subdivisions.

A comprehensive discussion on estuaries in general and the Cochin estuary in particular and a brief historical background of the Cochin harbour are given in Chapter 1. Different factors influencing the estuarine environment namely tides, sedimentation, pollution, climate, rainfall and freshet are also briefly discussed. The methodology used for collection and analysis of data, and a review of the earlier studies are also presented in this chapter.

Basic concept of tides, harmonic analysis and prediction of tides are discussed in chapter 2. Variations in range, duration and levels of tides, difference between predicted and observed tides and sea level anomalies at Cochin have also been computed and presented.

The third chapter deals with the seasonal and tidal variations of temperature and salinity in relation to different stages of spring and neap tides in the estuary. The dilution and flushing characteristics of the estuary are also presented in this chapter.

Circulation and stratification, tidal prism and rate of flow at the Cochin inlet at different stages of tides are computed and described in chapter 4. Classification of the estuary has been made using Stratification - Circulation diagram.

The summary of the results obtained and the conclusions emanating from the study are presented in chapter 5.

ABBREVIATIONS AND SYMBOLS

°C	:	Degree Centigrade
%		Percentage
‰		Parts per mille
μm		Micrometer
cm		Centimeter
m		Meter
km		Kilometer
sec		Second
min		Minute
h		Hour
Fig.		Figure
Sq km		Square kilometer
ha		Hectare
N		North
S		South
E		East
W		West
NE		North-East
SE		South-East
SW		South-West
NW		North-West
NNE		North-North-East
ENE		East-North-East
SSE		South-South-East
SSW		South-South-West
WSW		West-South-West
WNW		West-North-West
NNW		North-North-West

CHAPTER - I

1. INTRODUCTION

I. INTRODUCTION

Estuaries and their bordering marshes stand among the most productive and stressed systems on our planet. They provide rational sites for harbours and their role in transportation and industrial developments are great. The creeks and saltmarshes in estuaries are rich in nutrients and form excellent natural nursery grounds for a variety of fishes and shrimps. From very ancient times, estuaries have been the main centres of human progress and civilisation because of their fertile waters, sheltered anchorages and the navigational access they provide for a broad hinterland (Dyer, 1979). Many of the world's largest metropolitan areas developed in the vicinities of estuaries and as a result,these waters became adversely affected by human activities (Lauff, 1967). Now-a-days they are under pressure, either as repositories for the effluents of industrial processes and domestic wastes or as prime sites for reclamation to create land for industry or agriculture (Mc Lusky, 1981). These stresses can be reduced considerably by planning human interference on estuaries with sufficient knowledge on estuarine dynamics.

1.1 Definition and Classification of Estuaries

As far as most engineers and scientists are concerned, estuaries are areas of interaction between fresh and salt waters. It is difficult to devise a precise definition of an estuary which would satisfy workers in all of the wide variety of disciplines concerned with such regions. Essential elements in such a definition have been discussed by many of the contributors in a volume edited by Lauff (1967).

The word 'Estuary' is derived from the Latin word, 'Aestus', which means the tide (Ketchum, 1983). According to the Concise Oxford Dictionary, an estuary is a region of tidal mouth of a large river. Traditionally, the term 'Estuary' has been applied to the lower reaches of a river into which sea water intrudes and mixes with fresh water draining seaward from the land. The term has been extended to include bays, inlets, gulfs and sounds into which several rivers empty and in which the mixing of fresh and salt water occurs (Cameron and Pritchard, 1963; Officer, 1976). The definition given by Pritchard (1952, 1967) and by Cameron and Pritchard (1963) is the most accepted one. According to them, "An estuary is a semi-enclosed coastal body of water which has a free connection with the open sea and within which the sea water is measurably diluted with fresh water derived from land drainage."

Estuaries have been uncommon features during most of the earth's history which started geologically when the oldest rock now exposed at the surface originated (Russell, 1967). Essentially, all estuaries in existence today owe their origin to the fact that in the last 18,000 years sea level raised approximately by 130 m due to the melting of much of the major continental glaciers that covered portions of North America, Europe and Asia during the pleistocene epoch, more commonly referred to as the Ice Age (Thurman, 1983). An estuary may also be built by the river itself through the formation of a delta; sedimentation, together with erosion has often developed a system of typical estuaries in the lower part of the rivers (Caspers, 1967). Contrasts between different estuaries usually are caused by differences in local topography, geological structure, rock composition and structure, processes of erosional sculpture, or a similar group of elements associated with depositional land forms (Russell, 1967).

Estuaries constitute a small part of the area and an even smaller part of the volume of the total marine hydrosphere. Because of mixing of salt and fresh water, the distribution of salinity in an estuary varies in space and time (Perrels and Karelse, 1978). This makes one to consider that the estuary is confined to the area of brackish water. In nature, however, it is difficult to limit the estuarine region in this manner. The mixing is a result of the periodic restriction of fresh water outflow by the tides; all brackish water regions are limited to the mouth of the river. The lower limit of the estuary is fixed by geomorphological features (Caspers, 1967).

Estuaries may be classified by a variety of criteria, though no particular system of classification is universally used. Within given criteria, there are marginal cases, or cases where an estuary may change its classification depending upon the prevailing conditions.

The balance between fresh water inflow and loss due to evaporation provides the basis for one such classification. Where the fresh water inflow exceeds evaporation, the estuary is defined as 'positive estuary'; where evaporation exceeds the fresh water inflow, the estuary is defined as 'negative estuary'. In a 'neutral estuary', evaporation and fresh water inflow are in approximate equilibrium (Perkins, 1974).

From a geomorphological standpoint, Pritchard (1967) classified estuaries into four basic types. The first type is the 'drowned river valleys' also named 'coastal plain estuaries' which were formed during the Ice Age, when glaciers were thawing, subsequently causing the sea level to rise worldwide. As sea level rose, the flooding caused low lands to submerge and led to the formation of estuaries. 'Fjords' are generally U-shaped in cross section, quite deep, steep-walled and have a shallow sill. The inner waters below this sill depth often remain stagnant for most of the year. 'Bar-built estuaries' are formed when offshore barriers or sand spits build above sea level, and extend between headlands in a chain broken by one or more inlets. They are shallow and are often fed by more than one river. Water movements in bar-built estuaries may not be very vigorous, while wind-mixing is important. The fourth group of estuaries formed by 'tectonic processes' includes indentations produced in the coast by faulting, subsidence, etc. (Smith, 1977).

Dyer (1973) pointed out that the majority of estuaries that have been studied, fall within the coastal plain category and that, within this group, large differences occur in the circulation pattern, density stratification and mixing processes. He suggested that a better classification would be one based on the salinity distribution and flow characteristics within the estuary. In the 'highly stratified' or 'saltwedge type', the fresh water flows seawards over inflowing salt water. At the interface between the salt and fresh water, entrainment (mixing) occurs and salt water is mixed into the outflowing fresh water. Fjord is basically similar to the highly stratified estuaries. In a situation where the tidal movements are appreciable, a 'partially mixed estuary' developes. In these, there is continuous mixing between the sea and fresh water due to the efficient exchange of the water bodies, and the surface waters will be less saline than the bottom waters at any given point in the estuary (Mc Lusky, 1981). In the 'well mixed estuary', the tidal range is very large and the water column becomes vertically homogeneous. In this type of estuaries, there can be lateral variations in salinity and velocity with a well developed horizontal circulation (Dyer, 1979), and the salinity increases with distance along the estuary from head to mouth (Pickard and Emery, 1982).

Hansen and Rattray (1966) have presented a quantitative classification system for the description of estuarine conditions in which there are negligible lateral variations (Ketchum, 1983). This system is presented by the Stratification-Circulation diagram. In this diagram, the ordinate is the ratio of the difference in salinity between surface and bottom (δ_s) to the depth mean salinity (S_o), both averaged over a tidal cycle. The abscissa is the ratio of the surface velocity (U_s) averaged over a tidal cycle, to the discharge velocity (U_f), i.e., the rate of river discharge divided by the cross-sectional area. The three broad estuarine categories mentioned above and subdivisions of them, corresponding to distinctive areas in the Stratification-Circulation diagram (Bowden, 1978). This method is applied for the classification of Cochin estuary in the present study and is described in Chapter 4.

1.2 The Cochin Estuarine System:

The State of Kerala, a narrow segment in the south-western part of Peninsular India, extends north-south over a distance of 560 km, with a width varying from 15 to 120 km. The Lakshadweep sea on the west and a long range of mountains called Sahyadris (a part of Western Ghats) on the east are the boundaries of the State (Anon, 1984). The coastal area of Kerala extending north-south as a barrier strip of land includes a chain of lagoons and backwaters with connection to the sea at various points. This coastline is seriously affected by erosion of shore and tidal overflow, resulting in considerable damage and loss of dwellings and agricultural crops. Forty-one rivers, most of them of the type of mountain streams, flow from the Western Ghats into the backwaters and lagoons that skirt the coast. The coastal area of Kerala has as many as nine estuaries and twenty one backwaters extending from Nileshwar backwaters in the north to Akathuri lake in the south (Pylee, 1987; Moni, 1987).

The Vembanad lake which is the largest (205 Sq km) among the backwaters in this region runs almost parallel to the coast extending from Alleppey in the south to Munambam in the north between latitudes 9°28' and 10°10'N and longitudes 76°13' and 76°31'E. It has a length of about 113 km and the width varies between a few hundred metres to about 14.5 km (Josanto, 1971.a). In this lake, there are a number of small islands like the Willingdon Island, Pathiramanel, Vallarpadam etc. The major rivers Achankoil, Pampa, Manimala, Minachil, Muvattupuzha and Periyar originating from the Western Ghats and a number of canals debouch into this lake (Cheriyan, 1967). The Cochin harbour entrance is the major inlet connecting the lake with the Arabian sea, and another inlet at Azhikode is relatively shallow. A third opening near Thuravur is seasonal which remains closed except during monsoon season (Raju et al, 1979; Lakshmanan et al, 1982).

The Cochin Estuary which forms more or less a northward extension of the Vembanad lake has all the characteristics of a typical estuary. This positive tropical estuary (Varma et al, 1981; Lakshmanan et al, 1982) is well connected to the rivers and lagoons on one side and to the Lakshadweep sea on the other. Major perennial rivers which discharge fresh water directly into this estuarine system are Periyar and Muvattupuzha (Fig.1.1). A large number of industries located on the banks of Periyar discharge effluents into this river which flow into the estuary.

1.2.1 Cochin Harbour

The ports of Kerala have played vital role in shaping its history and perhaps no other port has played so crucial a role in Kerala's

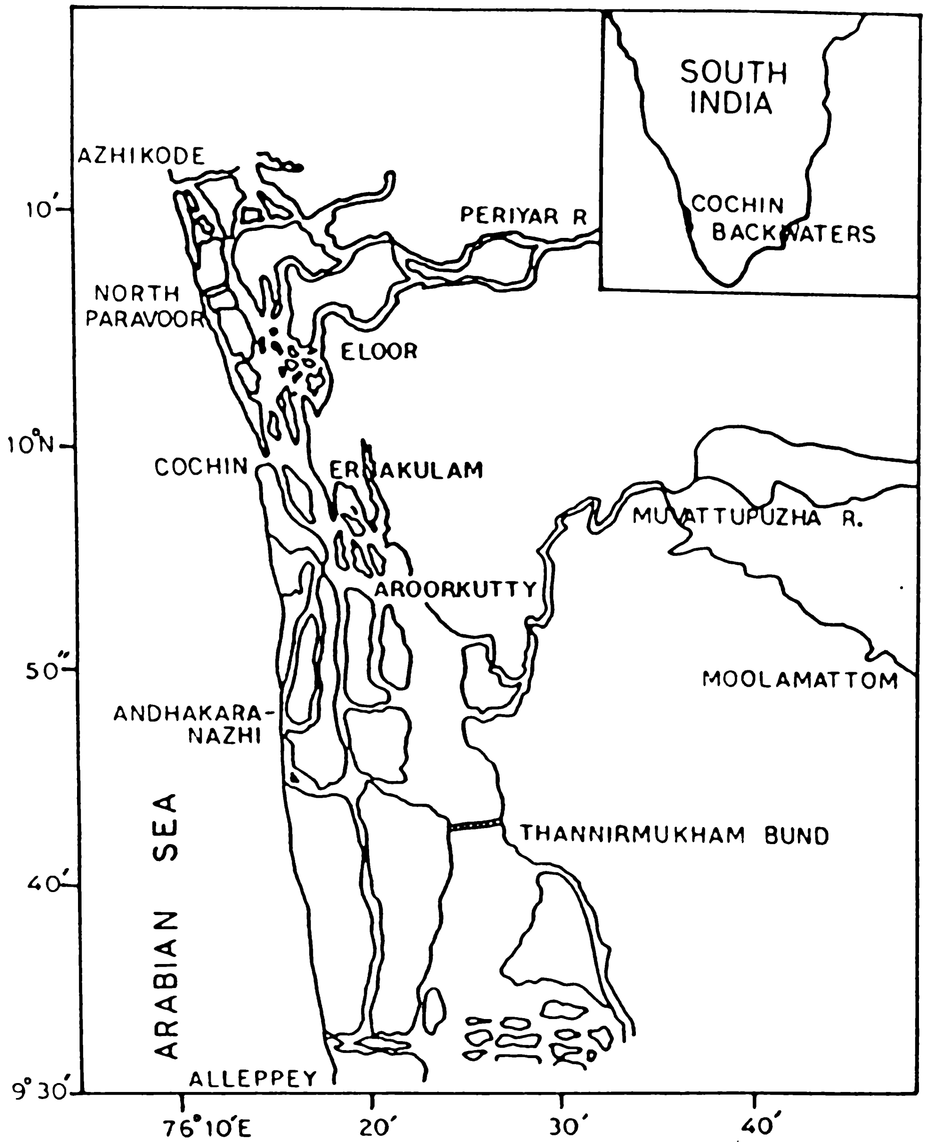


Fig.1.1 Map showing backwaters near Cochin

history as the port of 'Cochin'. It was during the British days, in 1870, that J.H. Aspinwall, a British merchant in Cochin, conceived the idea of developing a safe harbour in Cochin backwaters. Fifty years later, in 1920, Sir Robert Bristow came on the scene as Harbour Engineer-in-Chief to the Government of Madras Presidency. From 1936, he served as the Chief Executive of the new Major Port and was the architect of the present Cochin harbour. Using the dredged material, Willingdon Island, the present seat of Cochin Port, having an area of nearly 365 ha was reclaimed. Thereafter, there were no major reclamations till 1970s, when the fishery harbour having an area of 10.78 ha was reclaimed. This was followed by an integrated project for the development of Cochin Port, under which, Vallarpadam-Ramanthuruth-Candle island complex having an area of 141.7 ha had been reclaimed (Gopalan et al, 1987). The port is of considerable economical importance among the Indian harbours. It is on the direct route to Australia and the Far East.

The Cochin harbour hailed as the 'Queen of the Arabian sea', is one of the finest natural harbours of India and provides safe anchorage even during the roughest monsoon months. The navigational channels of Cochin harbour consist of an approach channel (which is about 8 km long, 200 m wide, with a dredged depth 12.8 m) and two inner channels, the Ernakulam channel (6 km long, 255 m wide, 11.6 m deep) and the Mattancherry channel (5 km long, 225 m wide, 9.75 m deep) on either side of the Willingdon Island (Fig.1.2). In recent years, considerable changes have been brought about in this waterbody as a

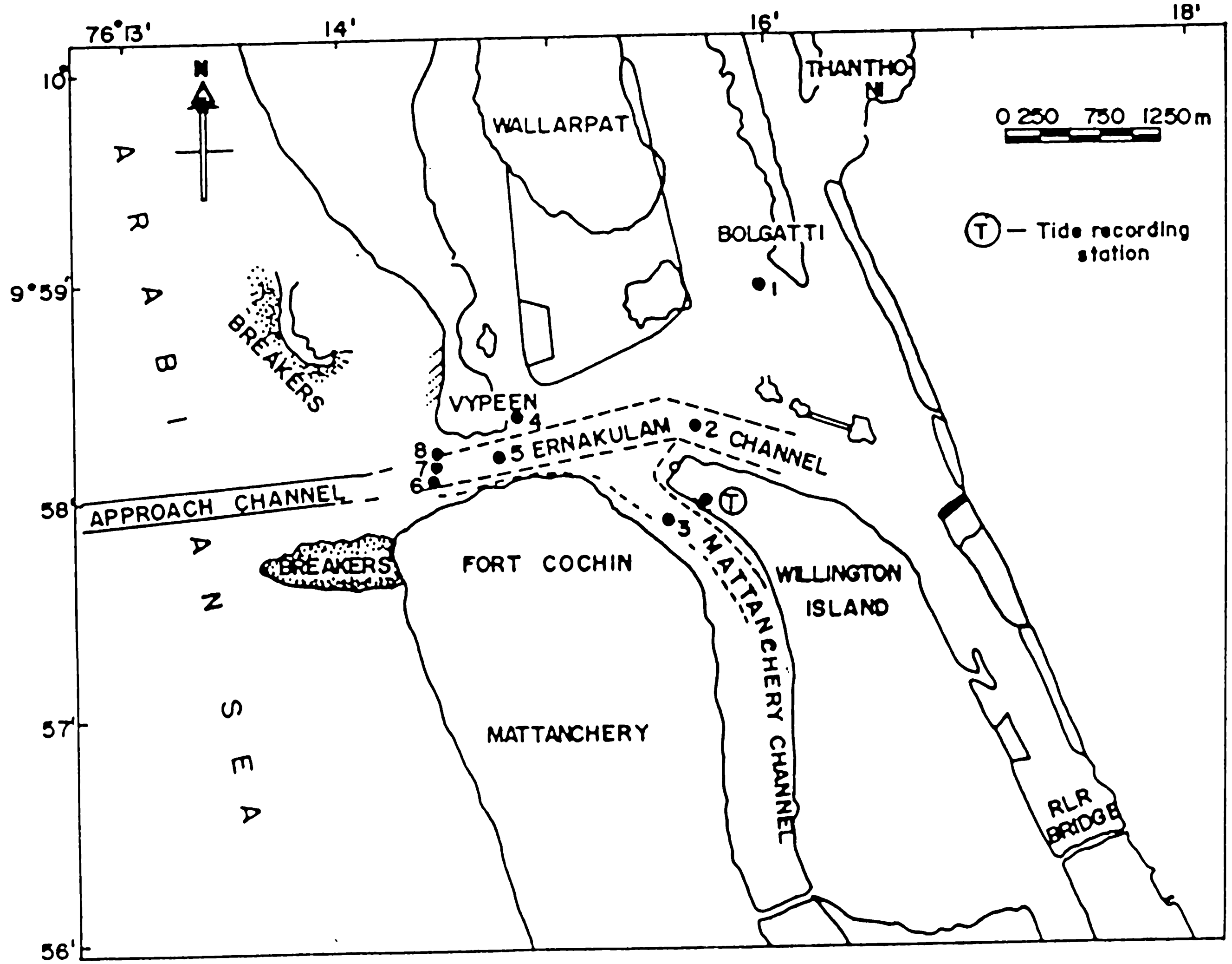


Fig.1.2 Map showing location of stations 1-8

result of urbanization, industrialisation and harbour development activities.

1.2.2 Tides

The gravitational pull of all celestial bodies, particularly the sun and moon induces rhythmic diurnal or semidiurnal rise and fall of sea level which are called the tides. These vertical displacements of the surface waters are accompanied by horizontal displacements of water, called tidal currents. The tidal motions in an estuary are generally caused by the ocean tide at the estuarine entrance and not by the tide generating forces acting on the estuarine waters. Tidal motions are dominant in shallow estuaries (Defant, 1961; Officer, 1976; Ketchum, 1983; Murakami, 1986).

The tidal currents constitute the most obvious water movements and are considered as primarily responsible factors that supply energy needed for the vertical and horizontal mixing in estuaries. The interaction between tidal oscillations and fresh water discharge is exhibited in the form of vertical, lateral and longitudinal velocity and salinity variations which change with time during each tidal cycle. The tidal level in an estuary is an important factor that influences the estuarine parameters. Tidal variations of water level in estuaries are generally greater than those in the open sea. There can also be such large variations within an estuary due to funnelling, slowing down of the tidal wave and frictional dissipation (Glen, 1979).

In Cochin estuary, the tides are mixed, predominantly semidiurnal with varying amplitudes. The average range of the tide is about 90 cm with the highest known tide of 1.75 m (Josanto, 1971.a). There is a marked difference in the mean sea level from season to season. The mean sea level is normally low during the monsoon season compared to winter and pre monsoon months (Varma et al, 1981). The lower mean sea level during monsoon season on the west coast of India is due to the upward flow of the cool dense water from deeper layers caused by the divergence of surface layers (Banse, 1968). The general flow pattern at the mouth of the estuary is characterised by an incursion of sea water during the flood tide and an excursion during the ebb tide. At the time of heavy monsoon rainfall, the intensity of tidal influx into the estuary is very much reduced due to the heavy efflux of fresh water. Hence, flood tides during the monsoon season cause sea water influx limited to the bottom layers. The observed and predicted tidal characteristics are studied in detail and presented in Chapter 2.

1.2.3 Sedimentation

The pattern of sediment distribution and movement depends on the type of estuary and the estuarine topography. The major part of different types of sediments introduced into the estuary is brought in by the rivers, by erosion of the banks and from the sea. In many estuaries, the movement of sediments is controlled by currents which include both the tidal and non-tidal circulations. Sediment transport by tidal streams can occur with or without accompanying the residual currents (Anto et al, 1977; Srinivasan, 1987).

Estuarine sediments range from fine granular sand common on most beaches to very fine colloidal materials in suspension (Ippen, 1966). The finer material ($< 2 \mu m$) moves in suspension and follows the residual waterflow, although there may be deposition and re-erosion during times of locally low velocities. The coarse-grained material ($> 2 \mu m$) which travels along the bed is mostly affected by high velocities and consequently, in estuarine areas, it normally tends to move in the direction of maximum current. The maximum turbidity zone is positioned in the upper estuary around the head of the salt intrusion and is associated with mud deposition.

The Cochin estuarine region is subjected to heavy siltation which necessitates continuous dredging to maintain channel depths. Deepening of estuary by dredging will increase estuary volume and alter the mixing processes and circulation patterns (Ippen, 1966). The estuary receives large quantities of sewage from Cochin and nearby areas. Industrial wastes are discharged into the estuary from the factories located upstream on the banks of rivers. The load of suspended material and rate of silting in this estuary vary considerably with the state of tides and seasons. Maximum load of suspended material occurs during the monsoon season and decreases progressively during the post monsoon periods (Gopinathan and Qasim, 1971). Generally, the suspended sediment load increases with depth (Raju et al, 1979) and the estuary has a muddy bottom (Qasim and Madhupratap, 1979). The movement of mud along sea bottom depends not only on the nature of the bottom but also on the distribution of currents (Kurup, 1971). Of the two channels encircling the Willingdon Island, the Mattancherry channel is subjected to a much greater silting than the Ernakulam channel (Gopinathan and Qasim, 1971). Cherian (1973) reported that the sediments of Ernakulam channel and northern part of the Mattancherry channel are mostly very fine sand and in the central part of Mattancherry channel, they are comparatively finer sediments. The coarsest sediments (medium sand) are observed south of Mattancherry channel. Josanto (1971.b) has presented the distribution of grain size of sediments in Cochin backwaters.

The tides in this area play an important role in the transportation of sediments. Raju et al (1979) pointed that the mean sediment load during flood tide is higher than during ebb tide, indicating that during an average tidal period of equal flood and ebb, more suspended sediment moves into the harbour with the flood current. Because of the marked differences in chemical properties of estuarine waters compared to the river waters, several processes such as flocculation of colloidal particles, leaching and subsequent release of adsorbed elements to sea water from fluvial sediments etc. can occur in the estuaries.

1.2.4 Pollution in Cochin Backwaters

Pollution of estuarine water is a serious problem in the Cochin backwater area. This is caused mainly from the direct or indirect discharge of sullage waters and municipal sewage from the urban area. The industries situated in Cochin area pollute these waters by the introduction of different combinations of fertilizers, chemicals, biocides, metals, catalysts, rubber products, milk and milk products, oil and petroleum products, pulps and related substances. The effluents in different concentrations reach the backwaters and seriously affect the productivity of the ecosystem. A decrease in volume of water due to sedimentation results in a limited exchange rate with the sea which may reduce the diluting capacity of the backwaters.

The major part of the effluents discharged into the backwaters is from various industries located upstream on the banks of the river Periyar. The industrial area at Eloor (Udyogamandal) extends to a distance of nearly 5 km from Varapuzha to Alwaye along the upper reaches of the backwaters. The urban wastes and other particulate matter reach the estuary through major canals, viz. Padiyathukulam canal, canal from Ernakulam market, Kalvathi canal from Fort Cochin, Rameswaram canal from Mattancherry, Pulimuttu canal from Palluruthy and Thevara Canal (Unnithan et al, 1975).

Oil pollution is another problem encountered in this estuarine area. Oil floats on water and does not easily mix with it. The main source of oil pollution is the oil tankers and other vessels engaged in transporting crude and refinery products. Coconut husk retting also causes contamination of Cochin backwaters. Unnithan et al (1977) and Venugopal et al(1980) have reported incidences of mass fish kills and the increased bacterial activity due to disposal of wastes.

Hydrographic features, water quality and characteristics of sediments of the Cochin backwater have been reported earlier by Vijayan et al (1976), Sarala Devi et al (1979) and Remani et al (1980). Presently, the rate of discharge of domestic effluents have increased to the level of 80 million litres/day (Gopalan et al, 1987).

Various inland waterbodies of Kerala are now threatened by the prolific spreading of the weed 'Salvinia auriculata' known as the 'African Payal'. They are believed to have reached the backwaters accidentally from Africa or South Central America (Qasim and Madhupratap, 1979) and resulted in the reduction of primary productivity and dissolved oxygen concentration. From the fresh water reservoirs, ponds and paddy fields, the weeds are carried to the estuaries by water currents during monsoon season. The differences in salinity at various parts of the estuary influence their growth and survival. During monsoon season, the plant grows well in the upper reaches of the estuary where the salinity is very low. But, during the late monsoon period, it undergoes decay in the lower reaches of the estuary where the salinity of water reaches above 7‰ (Samuel et al, 1975; Gopalan and Nair, 1975). This plant is a biological pollutant and covers the surface of water as thick mat-like formations, affecting water transport.

1.2.5 Climate, Winds and Waves

The Cochin estuary falls in the region of tropical monsoon climate.

On the basis of meteorological and hydrographical conditions, four seasons can be identified namely, pre monsoon or hot weather period (March-May), south-west monsoon (June-September), north-east monsoon (October-December) and winter (January-February). The south-west monsoon constitues the principal and primary season which gives 75% of the annual rainfall while north-east monsoon provides a secondary rainy season. The winter months are characterised by minimum clouds and rainfall, and the pre monsoon is a period of increasing thunderstorm activity (Ananthakrishnan _et al_, 1979). The atmospheric temperature is maximum (>32°C) during pre monsoon period and from June, it gradually comes down due to heavy rainfall. An increasing trend is noticed again during October - November, followed by lower temperature (<27°C) during December and January. The coastal areas are influenced by land and sea breezes and here the seasonal and diurnal variations of temperature are almost of the same range (5°C to 7°C) (Anon, 1984).

At Cochin, the wind is mainly from west and north-west. The winds are strongest during south-west monsoon season (> 30km/h), and during the other seasons, wind speeds generally lie between 5 and 20 km/h (Fig.1.3). Winds are, therefore, directed transverse to the length of the estuary which is elongated in the north-south direction. Winds from north-east and east prevail in the morning (0830h). while in the afternoon (1730h) they are from west and north-west. Easterlies or north easterlies during night time and westerlies or south westerlies during day time are indications of mesoscale circulation in Cochin (Viswanadham and Anil Kumar, 1985).

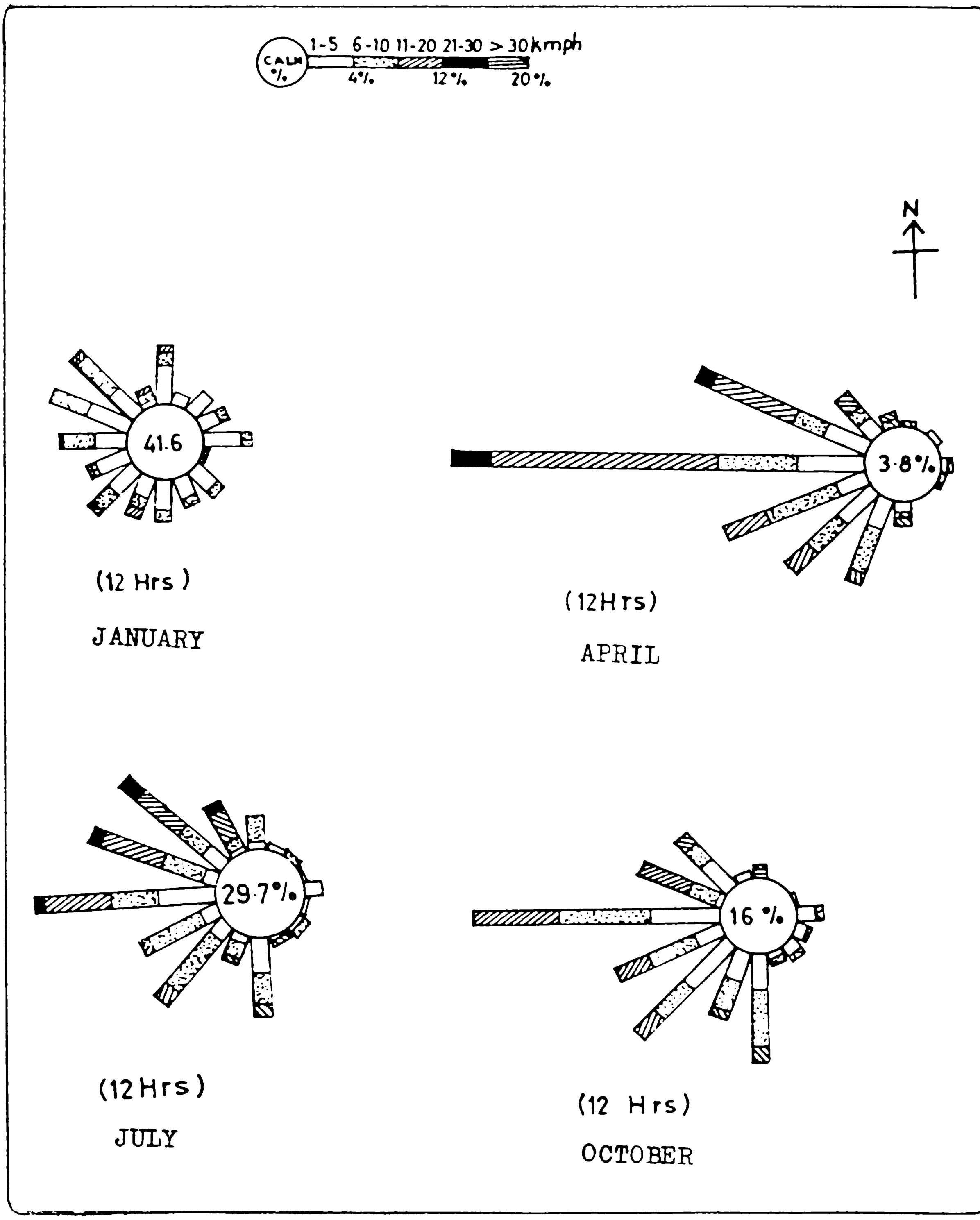


Fig.1.3 Wind roses at 1200 hrs during January(Winter), April(Pre monsoon), July(South-west monsoon) and October(North-east monsoon) (After Viswanadham and Anil Kumar,1985)

Character of waves in the estuary is determined by the interference between the waves entering from the coastal waters outside and the reflection from the banks or other structures in the estuary. Wind is the main factor for the generation of small waves or ripples in the estuary. The predominant periods of the swell waves approaching the Cochin coast are between 5 and 11 sec. The heights of the swells mostly range from 0.6 m to 2.4 m (Kurup, 1977). The waves approaching the estuarine mouth are northerly from November to February, north-westerly from April to July and westerly from August to October (Gopinathan and Qasim, 1971; Anto et al, 1977).

1.2.6 Rainfall and Freshet

The freshet depends on the intensity of rainfall in the region between the estuary and the mountain ranges, 50 km east of it. The annual rainfall in the Cochin area is about 320 cm with considerable variations from year to year. With the onset of monsoon, within the course of a few weeks,hydrographic conditions in the estuary undergo remarkable changes and the estuary becomes dominated by fresh water (Wyatt and Qasim, 1973) . During 1985, the total rainfall at Cochin was 289 cm, the highest monthly total being 106 cm in June. Most of the rainfall occurred in the months of May to August and thereafter the rainfall decreased.

The south-central part of the state of Kerala is characterised by the presence of the two large basins of Periyar and Muvattupuzha rivers, originating from Western Ghats. The catchment areas of

Periyar and Muvattupuzha are 5,284 sq km and 1,699 sq km and lengths 244 km and 121 km respectively. These rivers empty into Cochin backwaters (Fig.1.1) which is subjected to the tidal effects through the Cochin barmouth. Monthly average rate of discharge in Periyar was insignificant (<35 m^3/sec) during January to May, 1985, while that in Muvattupuzha was noticeable ($\approx$ 68 m^3/sec) (Fig.1.4). During the south-west monsoon season, large quantity of fresh water is discharged into the estuary due to heavy rainfall. While the rate of discharge in Muvattupuzha increased to 402 m^3/sec and 408 m^3/sec during June and July respectively, the discharge in Periyar was higher reaching 659 m^3/sec and 579 m^3/sec respectively in these two months. In August, discharge from Muvattupuzha suddenly decreased to 168 m^3/sec while Periyar maintained a discharge of 526 m^3/sec. The increase and decrease of flow was found to be seasonally systematic in Periyar. From a value of 5 m^3/sec in February 1985, the discharge rate rose to a very high value of 659 m^3/sec in June and decreased gradually to 25 m^3/sec in March 1986. In the Muvattupuzha river, on the otherhand,almost constant flow was maintained during non-monsoon months by the discharge of tail race water from Idukki hydroelectric station. The influence of this massive increase in fresh water run-off extends to a considerable distance beyond the estuarine mouth.

1.3 Materials and Methods

Estuaries experience considerable spatial variations and seasonal, semidiurnal and or diurnal oscillations in material concentrations, water level and flow velocity. The present programme of study is

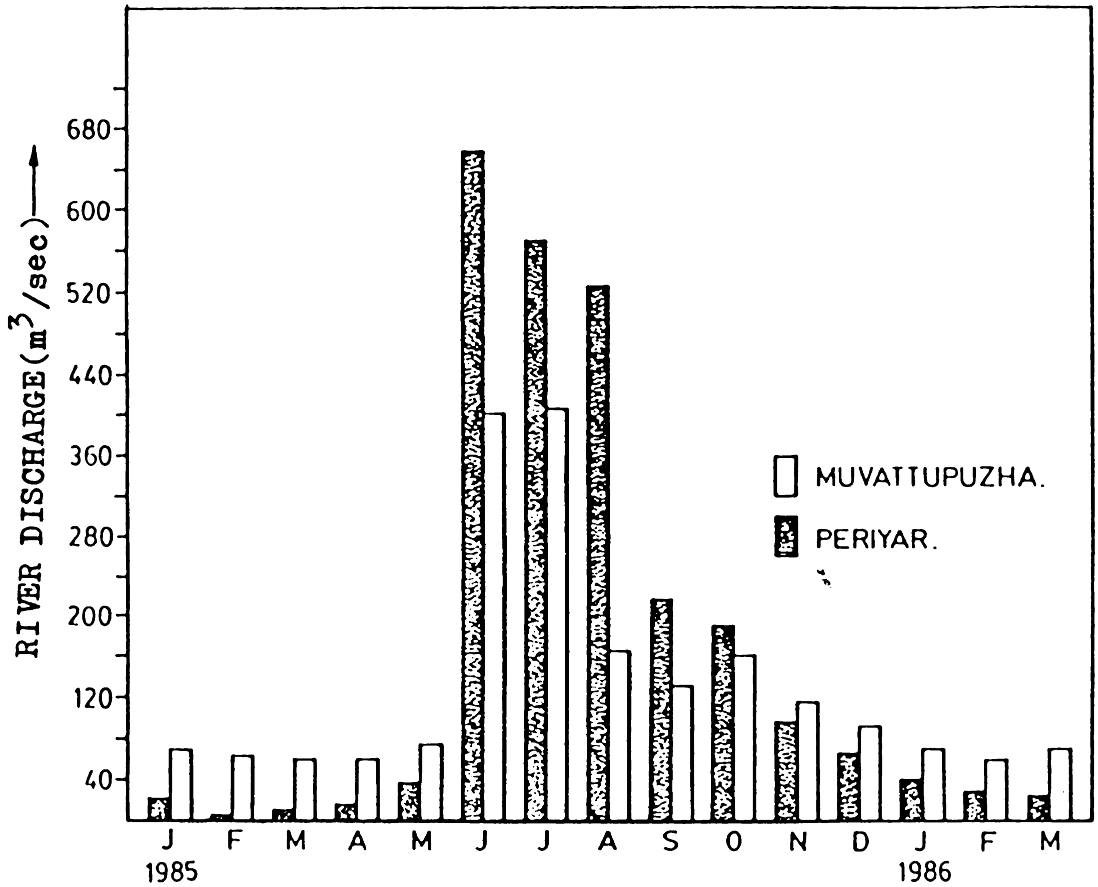


Fig.1.4 Average daily river discharge of Periyar and Muvattupuzha rivers during January 1985-March 1986

aimed at obtaining a comprehensive picture of the tidal characteristics, hydrography, circulation and mixing present in this estuarine system during different seasons. The studies have been carried out through field collection of data on salinity, temperature and water currents to get a picture of their spatial and temporal variations. The hydrographic data have been analysed in relation to tide, rainfall and river discharges.

Eight stations were fixed (Fig.1.2) in the Cochin estuary for collection of data on temperature, salinity and water currents. The stations were fixed with the help of prominent land marks and channel marking buoys. Details of the hydrographic stations are given in Table 1.1. Using predicted tide table, the tide levels were plotted for each month. From these charts, the days of maximum and minimum tidal forcing, spring tides and neap tides, were chosen for conducting cruises during February 1985 - June 1986. The collections were carried out onboard RV/Sagitta, of the School of Marine Sciences, Cochin University of Science and Technology. This motor boat is 25 feet long and is well equipped for hydrographic data collection in the backwaters. Two consecutive days of spring and neap tides were chosen for the cruises so that the eight stations were covered in two consecutive days. Details of cruises conducted are given in Table 1.2. Hourly observations were made at three levels i.e.,0.5 m below the surface, middle and 0.5 m above the bottom of the estuary and at all these stations the boat was anchored for collection of data.

TABLE 1.1.

Details of Hydrographic Stations

(Ref. Fig.1.2)

Station 1:	Located north of the Ernakulam channel, 200 m east of Bolgatty jetty; mean depth 1.5 m.
Station 2:	Situated in the Ernakulam channel, 300 m from the Willingdon Island; mean depth 12 m.
Station 3:	Situated in the Mattancherry channel, 250 m from the Willingdon Island; mean depth 13 m.
Station 4:	At the northern side of the approach channel, 200 m off Vypeen jetty; mean depth 2.5 m.
Station 5:	At the middle of the approach channel between Fort Cochin and Vypeen, approximately 225 m from either side; mean depth 13m.
Station 6:	Located on the southern side of the estuarine mouth; mean depth 10 m.
Station 7:	At the middle of the approach channel outside the estuarine mouth; mean depth 14 m.
Station 8:	Located on the northern side of the estuarine mouth; mean depth 9 m.

TABLE 1.2

Details of Cruises Conducted

Date	State of tide	Predicted tide Duration(h)	Tide levels (m)
10.04.85	Spring flood	09 15 - 16 52	0.08 - 1.00
11.04.85	Spring flood	10 01 - 17 45	0.13 - 0.95
17.04.85	Neap ebb	11 39 - 16 54	0.76 - 0.46
18.04.85	Neap ebb	12 26 - 17 35	0.82 - 0.51
13.05.85	Neap ebb	07 11 - 12 24	0.61 - 0.45
14.05.85	Neap ebb	08 46 - 13 46	0.64 - 0.52
22.05.85	Spring flood	07 00 - 15 01	0.09 - 0.97
23.05.85	Spring flood	07 31 - 15 35	0.09 - 0.96
11.07.85	Neap ebb	07 24 - 11 24	0.66 - 0.60
12.07.85	Neap ebb	08 54 - 12 50	0.69 - 0.66
19.07.85	Spring flood	06 18 - 14 18	0.04 - 0.95
20.07.85	Spring flood	06 54 - 14 41	0.06 - 0.96
05.08.85	Neap flood	08 09 - 15 35	0.30 - 0.89
06.08.85	Neap flood	08 43 - 15 33	0.38 - 0.86
17.09.85	Spring flood	07 09 - 13 16	0.37 - 0.89
18.09.85	Spring flood	07 50 - 13 35	0.44 - 0.87
23.09.85	Neap ebb	08 01 - 13 31	0.77 - 0.61
24.09.85	Neap ebb	09 39 - 16 05	0.77 - 0.56
07.10.85	Neap flood	10 30 - 14 43	0.63 - 0.70
08.10.85	Neap flood	11 30 - 15 05	0.67 - 0.68
16.10.85	Spring flood	07 03 - 12 23	0.53 - 0.88
17.10.85	Spring flood	07 46 - 12 50	0.57 - 0.87
07.11.85	Neap ebb	07 22 - 14 00	0.86 - 0.61
08.11.85	Neap ebb	08 05 - 14 48	0.87 - 0.54
13.11.85	Spring ebb	11 05 - 18 00	0.91 - 0.07
14.11.85	Spring ebb	11 45 - 18 43	0.90 - 0.05

contd.....

Date	State of tide	Predicted tide Duration(h)	Tide levels (m)
06.12.85	Neap ebb	06 13 - 13 03	0.98 - 0.55
07.12.85	Neap ebb	06 48 - 13 52	0.97 - 0.46
12.12.85	Spring ebb	10 30 - 17 41	0.92 - 0.08
13.12.85	Spring ebb	11 37 - 18 28	0.91 - 0.09
15.01.86	Neap flood	10 11 - 15 50	0.51 - 0.85
16.01.86	Neap flood	10 50 - 17 05	0.47 - 0.84
28.01.86	Spring flood	08 35 - 13 26	0.62 - 0.88
29.01.86	Spring flood	09 05 - 14 15	0.57 - 0.91
13.03.86	Spring flood	08 07 - 14 56	0.32 - 0.95
14.03.86	Spring flood	08 35 - 15 37	0.29 - 0.95
18.03.86	Neap flood	10 37 - 18 33	0.28 - 0.83
09.03.86	Neap flood	11 15 - 19 58	0.30 - 0.81
11.06.86	Spring flood	07 33 - 15 43	0.11 - 0.94
12.06.86	Spring flood	08 05 - 16 11	0.14 - 0.94
16.06.86	Neap flood	11 11 - 18 11	0.47 - 0.89
17.06.86	Neap flood	12 26 - 18 43	0.47 - 0.89

Tide data from Cochin Port Trust, rainfall data from Indian Daily Weather Report and River discharge data from Southern Rivers Division of the Central Water Commission have been made use of in this study. The data on actual recorded tide levels at Cochin were obtained from records of the tide guage which is installed at Willingdon Island (Fig.1.2). The predicted tide levels were obtained from the Tide tables published by the Geodetic Research Branch, Survey of India, Dehradun.

The following instruments developed by the Central Institute of Fisheries Technology, Cochin were used for the field programmes.

1. Direct Reading Digital Current Meter

The velocity of water flow were measured by using a Direct Reading Digital Current Meter (Fig.1.5). It consists of an under water probe with a water axis rotor that keeps it in stabilised position. A tilting lever provides additional stability to the system and the vertical position of the rotor. The rotor is mounted onto stainless steel pins. The inductance changes due to rotation of an attached coil are sensed and transmitted to the onboard meter.

The current direction is sensed by means of an electromagnetic compass moulded inside the probe. The relative angular position of water flow is sensed with the help of a circular potentiometer attached to the compass, which makes electrical resistance variation proportional to the angular variation of water current. The onboard unit gives the speed of water current in cm/sec and the direction is displayed in an L.C.D meter in the range of 0-360 millivolt representing the directions 0-360°. The accuracy of water current speed and direction are ± 2 cm/sec and ± 5° respectively.

2. S.T.D. meter

Measurements of salinity, temperature and the depth of sampling were made using a Salinity - Temperature - Depth Meter (Fig.1.6). It measures salinity in the range of 0-38‰ (± 0.01‰), temperature in the range of 10-35°C (± 0.1°C) and depth in the range of 0-30 m (± 0.1 m). The under water probe consisting of the different sensors for salinity, temperature and depth are connected through copper

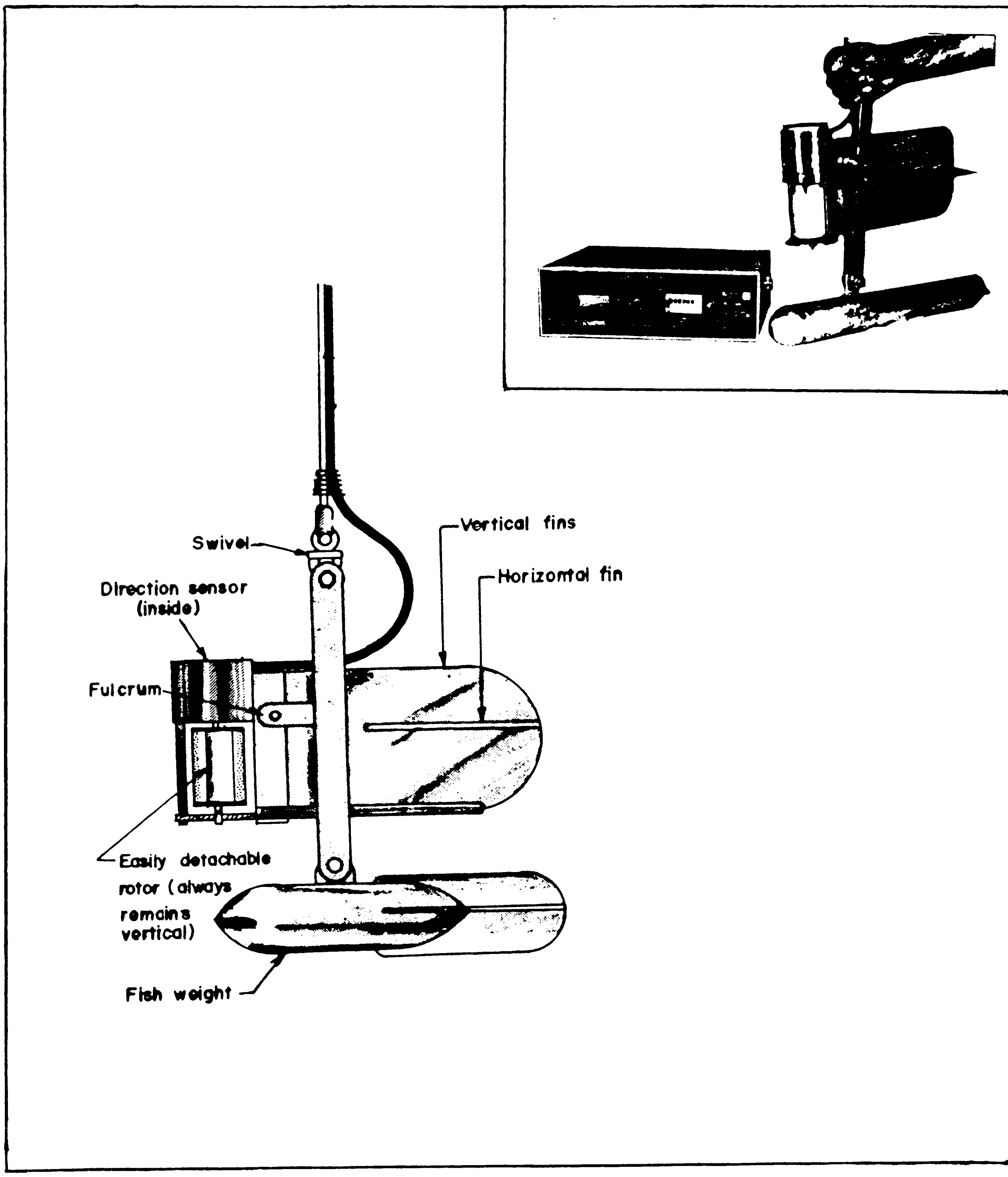


Fig.1.5 Direct Reading Digital Current Meter

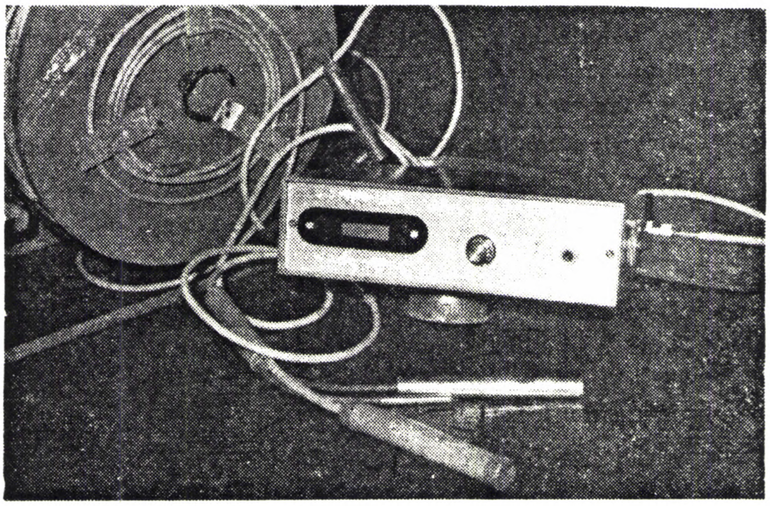


Fig.1.6 Salinity-Temperature-Depth Meter

cables with the onboard unit and the signals are displayed one by one separately. The salinity sensor is a platinum conducting cell making conductivity changes as a function of salinity of sea water. The temperature device makes use of voltage difference as a measure of temperature variations. The depth sensor consits of stainless steel bellows whose compression due to hydrostatic pressure is converted to electric induction for transmission to onboard unit.

1.4 Earlier Studies

A large number of studies have earlier been carried out on the biological aspects of this estuarine system, including productivity of plankton and fishes. Studies relating to physical aspects have, however, been limited. Bathymetry and water characteristics of the Cochin estuarine system have been discussed in some of the earlier publications by Qasim and Reddy (1967), Srivastava et al (1967 and 1968), Sankaranarayanan and Qasim (1969), Josanto (1971.a), Wyatt and Qasim (1973) and Qasim and Madhupratap (1979). Balakrishnan (1957), Ramamritham and Jayaraman (1963), George and Kartha (1963), Qasim and Reddy (1967), Cheriyan (1967), Qasim et al (1968 and 1969), Qasim and Gopinathan (1969), Sankaranarayanan and Qasim (1969), Josanto (1971. a), Haridas et al (1973), Wellershaus (1974) and Sreedharan and Salih (1974) have reported the distribution of various hydrographic parameters in space and time, their seasonal fluctuations and their relationship with the tides. Raju et al (1979) studied diurnal and seasonal variations (May 1975 to April 1976) of salinity at the inlet of the Cochin harbour.

Gopinathan and Qasim (1971), Wellershaus (1971 and 1974) and Varma et al (1981) have traced the seasons at Cochin into three, by considering meteorological and hydrographical conditions. Joseph (1974) and Balakrishnan and Shynamma (1976) showed that the hydrography of the backwater system depends mostly on fresh water discharge, particularly during the south-west monsoon period and on the tidal influence during all seasons. The flushing out of sea water from the harbour region by the efflux of fresh water has been reported by Cheriyan (1967). Wyatt and Qasim (1973) discussed the rate of flushing and the total discharge of the water through Cochin channel. Sankaranarayanan et al (1986) calculated the fresh water fraction at different stations in the estuary and noticed that the fresh water fraction was very large during the monsoon period.

George (1961) observed that the influence of the massive increase in fresh water run-off during monsoon season extends to a considerable distance beyond the estuarine mouth. Studying the seasonal distribution of temperature and salinity at surface and bottom, Lakshmanan et al (1982) have shown that the hydrological conditions of Cochin backwaters are greatly influenced by sea water intrusion and influx of river water.

George and Kartha (1963) attempted to understand the strength of tidal influence on the salinity of the backwater at various heights of the tide. A general picture of the outgoing and incoming tides in the backwaters has been presented by Qasim and Gopinathan (1969). Pillai et al (1973) studied the effect of tidal currents on the hydrography of the backwaters around Cochin barmouth during post and pre monsoon seasons. Generally, high velocities of current occur during ebb current of spring tide at the surface of the estuarine mouth (Raju et al, 1979). Varma et al (1981) presented the general distribution of currents in the channels around Wilingdon Island with respect to the tidal rhythm and its effect on the salinity changes. Joseph and Kurup (1987) carried out studies relating to tidal influence on salinity and current structure in the estuary during spring flood and neap ebb tides.

Josanto (1971.a) described the bottom salinity characteristics and the factors that influence the salt water penetration in the estuarine system. It was noticed by Balakrishnan (1957) and George (1958) that in the Ernakulam channel and the Narakkal bunder canal, the surface salinity varied from fresh to that of sea water. The surface salinity of the Cochin estuary in Ernakulam channel was studied for 5 years from 1956 to 1960 by George and Kartha (1963) who showed that tidal influence on the surface salinity in the channel was practically nil. The pre monsoon period is characterised by no salinity stratification whereas with the onset of monsoon (June), rapid build up of stratification is observed when surface waters show nearly fresh water conditions (Wellershaus, 1971; Raju et al, 1979 and Lakshmanan et al, 1982). Sankaranarayanan et al (1986) assessed the extent of salt water intrusion into the lower reaches of Periyar during different seasons and its effect on the flushing of pollutants introduced into the river by the industries.

Ramamirtham and Jayaraman (1963) studied the distribution of hydrographic parameters and the mixing processes around the Willingdon Island. Sankaranarayanan and Qasim (1969) stated that influx of fresh water into the estuarine system is not the sole factor influencing the water temperature in the estuary, but the influx of cold water from the sea may also be a significant factor. Wellershaus (1971) studied the stability characteristics of the Cochin backwater and showed that the stability was very high at the end of the monsoon season when the increased fresh water supply supports the stratification of the backwater into two layers. Ramamirtham and Jayaraman (1963) and Silas and Pillai (1975) reported that thermal stratification is absent in the estuary during the summer months.

Investigations by Du Cane et al (1938), Das et al (1966), Josanto (1971.b), Gopinathan and Qasim (1971), Kurup (1971), Cherian (1973), Anto et al (1977), Raju et al (1979), Mallik and Suchindan (1984) dealt with the distribution of suspended material and the sedimentation processes in the Cochin backwater system.

1.5 Scope of the Present Study

Owing to the very wide variations in water characteristics, both spatial and temporal, estuaries have always been found to be complex environment for scientific study. However, owing to the increasing importance of estuaries as man's interface with the sea, there has always been a need for closer scientific understanding of estuarine processes.

A knowledge of the dynamics of Cochin estuary will be of considerable help in the planning of the developmental programmes of the Cochin harbour and its hinterlands. The present studies were carried out with particular emphasis to the Cochin harbour area in view of commercial, developmental and environmental priorities. The shipping channels, tanker berths and a number of islands present in this estuarine region exert significant influence on the circulation pattern in this estuary. The passage of oil tankers and other large vessels in Cochin estuary necessitates the prediction of tides all round the year. The flow characteristics and the mixing processes of this estuary have great influence in fishing and in the transportation and disposal of waste materials. This estuary is the recipient of heavy load of industrial effluents. Ecological conditions in the estuary are greatly influenced by the tides and estuarine dynamics. The distribution of estuarine organisms depends mainly on temperature and salinity fluctuations. Better understanding of the estuarine hydrography and dynamics may contribute to optimal utilisation of the various aspects of this environment.

CHAPTER - II

2. TIDES

2. TIDES

2.1 Introduction

Among the many natural phenomena of the oceans, the occurrence of tides and their effects are of particular interest. Tidal effects are felt conspicuously in coastal areas where the periodic rise and fall of sea level alternately submerge and expose the shallow ocean bottom, influencing plant and animal life and their behaviour. In 1687, Sir Isaac Newton explained the occurrence of tides and the influence of celestial bodies in the generation of tides. He introduced the theory of equilibrium of tides. But, Newton's concept was qualitative and, therefore, unsuitable for practical application (Dronkers, 1964). In 1755, a French mathematician and astronomer, Laplace, propounded the dynamic theory of tides. More recently Darwin (1911), Doodson (1928, 1947, 1962), Harris and Pore (1961), Horn (1959) and Suthons (1959) added to the further development of the science of tides. Panikkar and Srinivasan (1971) made a search into the past on the concept of tides in ancient India and found that the Harappans were the first to utilize the phenomenon of tides effectively for berthing ships in the dockyard.

Tides result from the periodic rise and fall of the sea produced by the differential gravitational effect of the sun and the moon on the ocean. Tides are complex in nature as any tide can consist of a number of partial tides, each of which is related to the effect of the sun and the moon. Defant(1961), Darwin(1962), Dronkers(1964), Smith(1980), Dietrich et al(1980) and Pond and Pickard(1983) have dealt with different types of tides and their characteristics in detail. Tides are the longest waves known in the ocean, having a typical period of 12 h and 25 min and wave length, half the circumference of the earth. Tides occur in the world oceans as progressive or standing long waves, modified by reflection, the coriolis force and friction (Dietrich et al, 1980). The rise and fall of water level usually take place twice a day, and the difference in elevation between high water and low water is called the 'Range' of the tide. The rising tide is known as 'Flood tide' and falling as 'Ebb tide'. Range of tide at any location is not constant, but varies periodically from maximum to minimum values. Tides of the maximum ranges are known as Spring tides and the minimum are known as Neap tides. Spring tides generally occur when the moon is full or new while Neap tides occur with the moon in its quarters (Darwin, 1962; Mc Lellan, 1965; Perkins, 1974).

The tidal effects in estuaries are caused by the ocean tides rather than by the local direct action of the lunar and solar gravitational forces. The ebbing and flooding provide much of the energy for the mixing which takes place within estuaries. The other two major sources of energy are the river flow and the winds. The tide enters an estuary as a progressive wave and travels upstream. In many of the estuaries, the tide wave is damped by friction of the channel and opposing river flow. But in some estuaries, the tide wave reaches the end of the estuary and is reflected back to form standing waves (Gross, 1987).

When the estuary is wide and deep and is not unduly restricted, a pure standing wave can occur when the estuary length is equal to an odd number of quarter wave length of the tidal wave, when there is node with maximum range at the mouth. In this tidal regime, the tide rises and falls simultaneously in all parts of the estuary. Because of the tidal conditions in the neighbouring seas, estuaries do not normally have a node at their mouths, but form co-oscillating components of the offshore tidal system. They show most of the characteristics of a standing wave response, but with some modification caused by friction.

In most of the estuaries, there is an increase in tidal amplitudes towards the upper estuary because of convergence, but near the head of the estuary, where friction becomes important, the tidal range diminishes. The tide wave penetrating up the estuary is modified as a result of change of width and depth, increase in friction and of river flow seaward. If the estuary becomes narrower and shallower away from the sea, the tidal range will increase up the estuary. This is known as the funnelling effect (Pond and Pickard, 1983).

2.1.1 Harmonic Analysis

The harmonic analysis conceives the sum of the rise and fall of a number of simple tides provided by various forces at one place. The average wave is thus affected by many inequality values, which are found empirically, and predictions regarding height and time are corrected. These are known as harmonic components of the tide (Sharma and Vatal, 1980). The most important tide producing forces are those of nearly semidiurnal and nearly diurnal periods and so, the character of the tide in any locality depends mainly upon the relative heights and phase angles of the partial tides corresponding to the tide producing forces (Sverdrup _et al_, 1942). The constants in the harmonic development of the tide at any place are determined by the analysis of a long series of observations at that place. Knowing the values of these constants, it is possible to reconstruct or synthesise the tide for any past, present or future time.

The first 'almost' harmonic tidal analysis was developed by George Darwin in 1882, who allocated a series of symbols for each tidal component, with subscripts 0, 1 and 2 to indicate whether it was of long period, diurnal or semidiurnal (Anon, 1966). Doodson (1922), lists some 390 components of tide generating potential, of which about 100 are of long period, 160 diurnal, 115 semidiurnal and 14 one-third diurnal. To each, an exact period and amplitude can be assigned (Mc Lellan, 1965).

The seven most important component tides are M_2, S_2, N_2, K_2, K_1, O_1, and P_1, among which the two largest semidiurnal and diurnal tides M_2, S_2, and K_1, O_1, respectively stand out as the important ones (Defant, 1961). For locations with a semidiurnal tide, the phase of the M_2 tide (Principal lunar semidiurnal component) gives the mean arrival of high water after the moon passes through the meridian of that location, a value sometimes referred to as "time of transit" or "establishment of the port" (Dietrich _et al_, 1980). Table 2.1 presents the more important components with their basic values. The symbols by which they are designated are also indicated. The numerical coefficient of the largest components M_2 is taken as 100.

TABLE 2.1

Principal Tidal Components

Symbol	Name of partial tides	Argument deg/hr	Period in Solar Hrs. Hr. Min.	Coefficient Ratio M_2 = 100
	Semidiurnal components			
M_2	Principal lunar	28.98	12.25	100.00
N_2	Larger lunar eliptic	28.44	12.39	19.20
S_2	Principal solar	30.00	12.00	46.60
K_2	Luni-solar	30.08	11.58	12.70
	Diurnal components			
O_1	Principal lunar	13.94	25.49	41.50
P_1	Principal solar	14.96	24.04	19.40
K_1	Luni solar	15.04	23.56	58.40

In order to classify the tides of a locality, Van Der Stok (1897) adopted a method based on the ratio of the sum of the amplitudes of the diurnal components $K_1 + O_1$ to the sum of the amplitudes of the semidiurnal components $M_2 + S_2$. This ratio, $F = \frac{(K_1 + O_1)}{(M_2 + S_2)}$ is referred to as "Form Number" or "Formzahl" of the tides (Defant, 1961; Dietrich et al, 1980). Courtier (1938) has discussed the tides in detail and classified them using the Formzahl. If values 'F' lies between 0.25 and 1.25, the tide is mixed and predominantly semidiurnal; i.e., two high and two low waters occur daily with large inequalities in range and time, attain their maximum whenever the moon's declination passes its maximum value. The mean spring tide range is 2 (M_2 + S_2) (Defant, 1961; Dronkers, 1964; Anon, 1966; Dietrich et al, 1980). According to Dronkers (1964) the tides at Cochin are of mixed character and value of the Form Number is 0.9. Defant (1961) has given the following values of harmonic constants at Cochin.

Cochin	Amplitude & phase angle	M_2	S_2	K_1	O_1	$\frac{K_1+O_1}{M_2+S_2}$	$M_2+S_2+K_1+O_1$
9°58'N	H (cm)	22.2	8.0	18.0	9.4	0.91	57.6
76°15'E	X°	332	29	52	58		

2.1.2 Tide Levels and Prediction

Tidal variations in water level in estuaries are generally greater than those in the open sea (Glen, 1979). At many locations in the world, the two tides of the day may have unequal ranges. The higher of the two successive high tides is called 'Higher High Water'(HHW); the other is called 'Lower High Water' (LHW). There is a similar nomenclature for the low tides- Lower Low Water (LLW) and Higher Low Water (HLW) (Gross, 1987). There may also be recurring inequalities in 'tidal interval' or the time between successive high waters (Mc Lellan, 1965). Descriptions of the important terms used in connection with tides have been given by Defant (1961) and Dietrich et al (1980). The different tide levels mentioned above can be represented as in Fig. 2.1.

Because of the great importance of tidal phenomena in shipping, harbour engineering and fishing, it is necessary to predict tides and tidal currents for all locations of interest. The predicted elevations in tide tables are referred to a fixed level called the 'Low Water Datum'. Inshore navigation charts show depths of water below this Datum (Mc Lellan, 1965). For predicting the heights and times of occurrence of tides in a harbour, one must refer to the tidal observations made previously. It is possible to predict future tides from observational data of past tides, without any understanding of tidal theory at all. The predicted tide tables are based on long runs of information and the isolation of height and relative phase of each major components of tide are calculated in an accurate way. Since the effects of barometric pressure and wind are not easy to predict, it should generally be assumed that the errors of prediction are of the order of 20-30 cm. Large discrepancies of the order of 2-3 m from forecast heights can occur in storm conditions (Craig, 1973).

2.2 Tides in the Cochin Estuary

At Cochin Estuary, two high and two low water marks occur each day, with appreciable differences in range and time. The studies on tidal

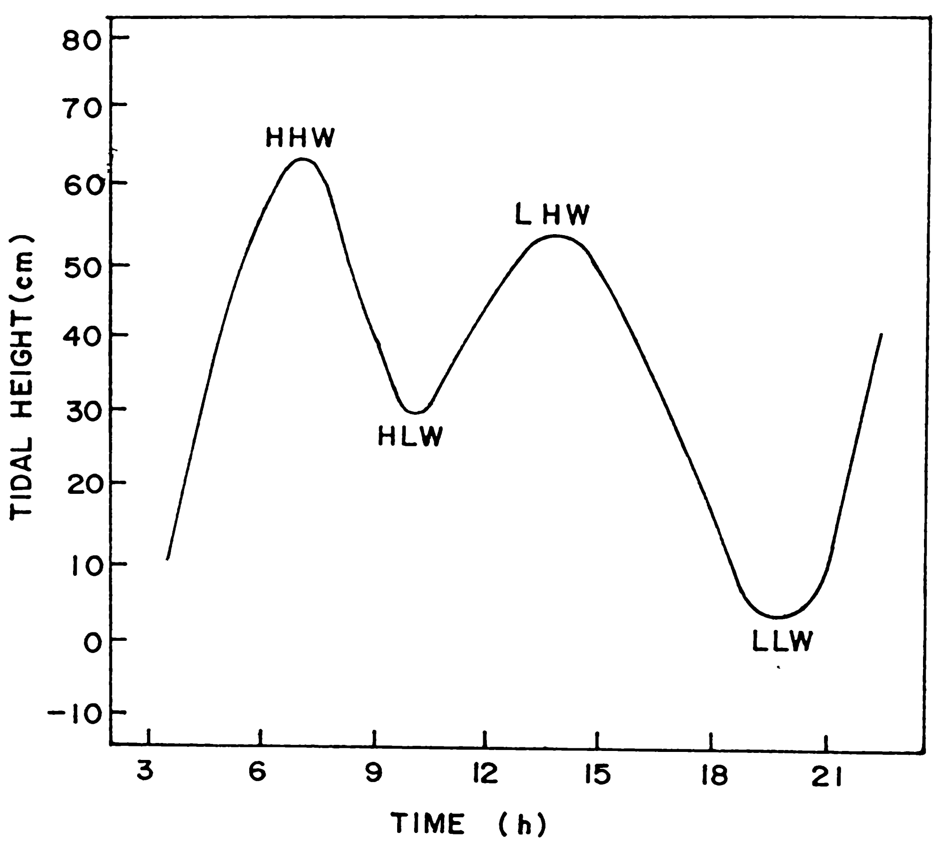


Fig.2.1 A semidiurnal tide curve showing the different levels

characteristics of this region show that the tides are of mixed, predominantly semidiurnal character having a maximum range of 1 m (Qasim and Gopinathan, 1969; Raju et al, 1979; Varma et al, 1981). A general picture of the outgoing and incoming tides in the backwaters has been presented earlier by Qasim and Gopinathan (1969).

Table 2.2 depicts different tidal measurements viz. Highest Higher High Water levels (HHHW) and Lowest Lower Low Water levels (LLLW), Highest ranges, mean sea levels and average tidal ranges during the months April, 1985 to March, 1986. The highest and lowest water levels usually occur at spring tides in all months. In May, the HHHW is recorded as +108 cm at neap (13.5.85) and spring (21.5.85) tides. This highest range associated with neap tide may be due to the local weather disturbances such as barometric pressure fluctuations. Considering all the months, the HHHW is recorded (+127 cm) in April and the LLLW is recorded (-22 cm) in May. The highest tidal range is recorded as 126 cm in November and December. Josanto (1971.a) also has noted that the high spring tides having ranges of 1.1 m and above were experienced at the estuarine entrance in November and December of the years 1969 and 1970. The lower tidal ranges are observed in August (107 cm) and September (97 cm). The higher mean sea levels are observed in November (72.7 cm) and December (74.9 cm) and the lower mean sea levels in August (51.7 cm) and September (53.4 cm). In general, the lower mean sea levels are observed during south-west monsoon period, which may be attributed to the upward flow of the cool dense water from deeper layers, due to the divergence of surface layers on the west coast of India (Banse,

TABLE 2.2

Tide levels and ranges in different months during the period April 1985 - March 1986

HHHW - Highest Higher High Water
LLLW - Lowest Lower Low Water (*)

Month	State of tide (cm) HHHW	State of tide (cm) LLLW	Highest range (cm)	Mean level (cm)	Average range (cm)
April 1985	+ 127 (08.04.85, Spring)	-5 (25.04.85, Spring)	118 (08.04.85)	64.5	52.3
May	+ 108 (13.05.85, Neap) (21.05.85, Spring)	-22 (07.05.85, Spring)	123 (07.05.85)	59.2	53.2
June	+ 111 (30.06.85, Spring)	-14 (04.06.85, Spring)	124 (04.06.85)	61.0	54.6
July	+ 119 (02.07.85, Spring)	-7 (17.07.85, Spring)	116 (02.07.85)	59.5	53.8
August	+ 99 (02.08.85, Spring)	-8 (02.08.85, Spring)	107 (02.08.85)	51.7	53.8
September	+ 93 (01.09.85, Spring)	-8 (19.09.85, Spring)	97 (18.09.85)	53.4	49.1
October	+ 109 (30.10.85, Spring)	-15 (17.10.85, Spring)	114 (16.10.85)	60.8	50.1

contd.....

Month	State of tide (cm) HHHW	LLLW	Highest range (cm)	Mean level (cm)	Average range (cm)
November	+ 118 (28.11.85, Spring)	-15 (14.11.85, Spring)	126 (14.11.85)	72.7	49.8
December	+ 124 (12.12.85, Spring) (14.12.85, Spring) (30.12.85, Spring)	-4 (14.12.85, Spring)	126 (12.12.85)	74.9	51.03
January 1986	+ 120 (01.01.86, Spring)	-3 (11.01.86, Spring)	118 (09.01.86)	67.1	52.6
February	+ 116 (28.02.86, Spring)	+3 (04.02.86, Spring)	101 (08.02.86)	67.5	53.5
March	+ 114 (01.03.86, Spring) (13.03.86, Spring)	+4 (29.03.86, Spring)	104 (29.03.86)	67.2	52.9

* Negative values represent the water level below the zero reference level.

1968; Varma et al, 1981). From the monthly average tidal ranges, it can be seen that the highest average range occurs in June (54.6 cm) and the lowest in September (49.1 cm). Varma et al (1981) observed that the average ranges of tide during the monsoon, post monsoon and pre monsoon seasons were 47.3, 43.1 and 46.08 cm respectively. From table 2.2 it can be seen that there is a marked monthly variation in the mean sea level, but there is no such variation in the tidal ranges. From the analysis of tidal range (Fig.2.2), it is seen that the maximum frequency (14.35%) is in the range of 60 to 70 cm and the lowest frequency (0.45%) in the range of 120 to 130 cm.

Tables 2.3 and 2.4 give the average range and duration of flood and ebb tides at spring and neap tides respectively. The averaging is done for two consecutive days of spring tide (usually higher ranges of spring tides occur closer to fullmoon and newmoon days). The state of tides are chosen so as to get the highest ranges of tides during spring and neap tide days. Hence, it can be noticed that during spring tide days in each month (Table 2.3), the highest ranges occur generally between LLW and HHW during flood tides and between LHW and LLW during ebb tides. But neap tides do not exhibit such regularity in the occurrence of the highest ranges (Table 2.4). It can be noted that there is no relationship between tidal range and duration, i.e., higher tidal range may not be related with higher duration. Duration for flood and ebb tides mainly depends on short term and seasonal weather conditions. Comparing the tidal ranges of spring and neap tides (Tables 2.3 & 2.4) during the period of observation, a general trend is observed that, when the tidal ranges increase for spring tides, there is a decrease of neap tide and vice versa.

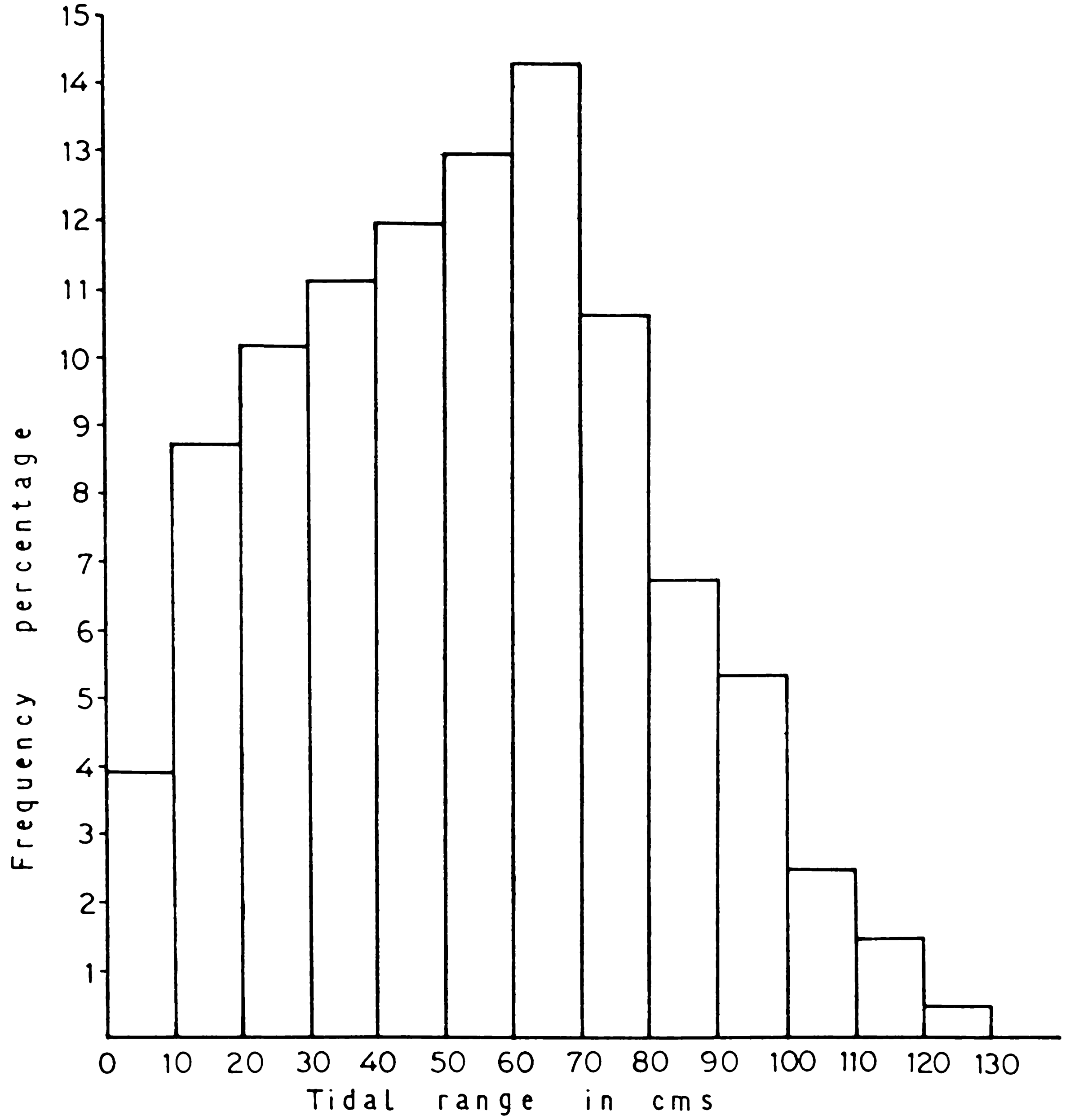


Fig.2.2 Percentage frequency of tidal range at Cochin during April 1985-March 1986

<u>TABLE 2.3</u>

Average range and duration of spring flood and spring ebb tides

Month	Spring tides Full moon(F)/ New moon(N)		State of tide levels	Averaging dates	Average range	Average duration
April 1985	F	Flood	LLW - HHW	8 - 9	110	8 h 2 min
		Ebb	LHW - LLW		98	6 h 27 min
	N	Flood	LLW - HHW	22 - 23	82	7 h 38 min
		Ebb	LHW - LLW		74	5 h 56 min
May	F	Flood	LLW - HHW	7 - 8	121	7 h 38 min
		Ebb	LHW - LLW		95	7 h 6 min
	N	Flood	LLW - HHW	20 - 21	99	7 h 59 min
		Ebb	LHW - LLW		74	6 h 58 min
June	F	Flood	LLW - HHW	4 - 5	121	8 h 5 min
		Ebb	LHW - LLW		91	6 h 50 min
	N	Flood	LLW - HHW	18 - 19	90	9 h 12 min
		Ebb	LHW - LLW		66	6 h 34 min
July	F	Flood	LLW - HHW	2 - 3	113	8 h 10 min
		Ebb	LHW - LLW		85	6 h 57 min
	N	Flood	LLW - HHW	17 - 18	97	7 h 40 min
		Ebb	LHW - LLW		69	7 h 31 min

contd.....

Month	Spring tides Full moon(F)/ New moon(N)		State of tide levels	Averaging dates	Average range	Average duration
August	N	Flood	LLW - HHW	14 - 15	81	8 h 20 min
		Ebb	LHW - LLW		63	7 h 18 min
	F	Flood	LLW - HHW	29 - 30	82	6 h 50 min
		Ebb	LHW - LLW		61	5 h 32 min
September	N	Flood	LLW - HHW	18 - 19	96	7 h 23 min
		Ebb	LHW - LLW		90	7 h 19 min
	F	Flood	HLW - HHW	29 - 30	57	7 h 12 min
		Ebb	HHW - LLW		66	5 h 49 min
October	N	Flood	LLW - HHW	16 - 17	114	7 h 28 min
		Ebb	LHW - LLW		98	6 h 33 min
	F	Flood	LLW - HHW	29 - 30	80	7 h 32 min
		Ebb	LHW - LLW		68	5 h 51 min
November	N	Flood	LLW - HHW	14 - 15	124	7 h 44 min
		Ebb	LHW - LLW		100	7 h 26 min
	F	Flood	LLW - HHW	28 - 29	95	7 h 39 min
		Ebb	LHW - LLW		70	6 h 17 min

contd.....

Month	Spring tides Full moon(F)/ New moon(N)		State of tide levels	Averaging dates	Average range	Average duration
December	N	Flood	LLW - HHW	11 - 12	124	8 h 44 min
		Ebb	LHW - LLW		99	6 h 53 min
	F	Flood	LLW - HHW	27 - 28	98	8 h 3 min
		Ebb	LHW - LLW		69	7 h 6 min
January 1986	N	Flood	LLW - HHW	10 - 11	117	8 h 17 min
		Ebb	LHW - LLW		87	6 h 29 min
	F	Flood	LLW - HHW	25 - 26	93	8 h 10 min
		Ebb	LHW - LLW		64	6 h 21 min
February	N	Flood	LLW - HHW	7 - 8	100	9 h 6 min
		Ebb	LHW - LLW		77	6 h 15 min
	F	Flood	LLW - HHW	23 - 24	84	7 h 12 min
		Ebb	LHW - LLW		62	6 h 7 min
March	N	Flood	LLW - HHW	10 - 11	75	6 h 24 min
		Ebb	LHW - LLW		68	5 h 52 min
	F	Flood	LLW - HHW	26 - 27	97	7 h 45 min
		Ebb	HHW - LLW		92	7 h 5 min

TABLE 2.4

Average range and duration of neap flood and neap ebb tides

Month	Neap tides	State of tide levels	Averaging dates	Average range	Average duration
April 1985	Flood	LLW - HHW	2 - 3	66	6 h 48 min
	Ebb	LHW - LLW		45	6 h 21 min
	Flood	LLW - HHW	15 - 16	49	7 h 5 min
	Ebb	HHW - HLW		43	6 h 30 min
May	Flood	LLW - HHW	1 - 2	45	7 h 8 min
	Ebb	HHW - LLW		48	6 h 53 min
	Flood	LLW - HHW	14 - 15	39	6 h 26 min
	Ebb	HHW - LLW		58	6 h 13 min
	Flood	LLW - HHW	28 - 29	51	7 h 38 min
	Ebb	HHW - LLW		53	6 h 18 min
June	Flood	LLW - LHW	13 - 14	48	7 h 30 min
	Ebb	HHW - LLW		59	7 h 19 min
	Flood	LLW - HHW	27 - 28	74	7 h 1 min
	Ebb	HHW - LLW		82	7 h 36 min

contd.....

Month	Neap tides	State of tide levels	Averaging dates	Average range	Average duration
July	Flood	LLW - HHW	10 - 11	48	6 h 38 min
	Ebb	HHW - LLW		62	6 h 57 min
	Flood	LLW - LHW	25 - 26	66	7 h 12 min
	Ebb	HHW - LLW		75	7 h 58 min
August	Flood	LLW - LHW	8 - 9	52	7 h 49 min
	Ebb	HHW - LLW		66	6 h 35 min
	Flood	LLW - HHW	24 - 25	74	8 h 32 min
	Ebb	LHW - LLW		70	8 h 53 min
September	Flood	LLW - HHW	11 - 12	58	9 h 19 min
	Ebb	LHW - LLW		44	6 h 49 min
	Flood	LLW - HHW	24 - 25	56	7 h 48 min
	Ebb	LHW - LLW		43	6 h 1 min
October	Flood	LLW - HHW	10 - 11	48	7 h 2 min
	Ebb	HHW - HLW		38	6 h 56 min
		LHW - LLW		29	6 h 19 min
	Flood	LLW - HHW	23 - 24	48	7 h 36 min
	Ebb	HHW - HLW		43	6 h 37 min

contd.....

Month	Neap tides	State of tide levels	Averaging dates	Average range	Average duration
November	Flood	LLW - HHW	7 - 8	47	6 h 52 min
	Ebb	HHW - HLW		38	7 h 8 min
	Flood	LLW - LHW	21 - 22	41	6 h 26 min
	Ebb	HHW - LLW		57	7 h 16 min
December	Flood	LLW - HHW	5 - 6	53	7 h 20 min
	Ebb	HHW - LLW		49	6 h 54 min
	Flood	LLW - LHW	20 - 21	47	7 h 30 min
	Ebb	HHW - LLW		62	8 h 2 min
January 1986	Flood	LLW - LHW	3 - 4	46	5 h 49 min
	Ebb	HHW - LLW		61	7 h 11 min
	Flood	LLW - LHW	17 - 18	58	6 h 57 min
	Ebb	HHW - LLW		69	7 h 3 min
February	Flood	LLW - LHW	1 - 2	58	6 h 45 min
	Ebb	HHW - LLW		80	6 h 56 min
	Flood	LLW - LHW	15 - 16	57	6 h 59 min
	Ebb	HHW - LLW		69	7 h 37 min
March	Flood	LLW - HHW	4 - 5	78	8 h 34 min
	Ebb	LHW - LLW		72	8 h 45 min

It is observed that the range and duration of flood tide (Table 2.3) is greater than that of ebb in all months except September. In September, at spring tide (associated with fullmoon), the range of flood (HLW-HHW) is found to be 57 cm with duration 7 h 12 min, while that of ebb (HHW-LLW) is 66 cm with 5 h 49 min. From April 1985 to July 1985, it is observed that the ranges (both flood and ebb) of spring tides are higher at fullmoon than newmoon days. In August 1985, the corresponding tidal ranges at newmoon and fullmoon are the lowest and more or less equal (81 and 82 cm for flood and 63 and 61 cm for ebb). From September (1985) to February (1986), the tidal ranges are higher on newmoon days and again in March (1986), they are higher on fullmoon days. So, in general, it can be inferred that higher tidal range is associated with fullmoon for about six months (March/April-August/September) and with newmoon during the other six months (August/September - February/March). This alteration can be explained on the basis of the retardation of the high and low from one day to the next. Generally, the high and low waters are retarded from one day to the next by 50 min. This is related to the movement of the moon, which lags by 50 min each day, on its passage through the meridians (Defant, 1961).

Neap tides, however, do not exhibit conspicuous variations in higher tidal ranges for flood and ebb tides as in the case of spring tides (Table 2.4). Also, there is no particular state of tide levels regarding the higher tidal ranges associated with flood and ebb tides. The difference in duration is higher(generally more than 1 h) for spring flood than for spring ebb tides. But, in the case of neap tides, variation in duration between neap flood and neap ebb tides is considerably low (less than 40 min).

2.2.1 Predicted and Observed Tides

Figures 2.3 to 2.14 show the daily variations of observed and predicted tides during the period April 1985 to March 1986. During this period, the predicted tide levels are found to be above the zero reference level in all months except July 1985, while observed tide levels are found to lie below the zero reference level, especially during spring tides. But in April 1985, February 1986 and March 1986, both lower tidal levels of predicted and observed tides are found to lie above zero reference level. It may also be noted that the tidal ranges are higher for observed than predicted tides, and the difference even goes upto 30 cm. Generally, the lagging or priming between the observed and predicted tides varies from 0 to 30 min, but large variations, upto 65 min are also found to occur in certain cases.

In April 1985, it is seen that the predicted tidal heights are lower than the observed during the first fortnight and are higher during the second fortnight (Fig.2.3). In June 1985, generally higher tidal amplitudes are recorded at both spring and neap tides (Fig.2.5). In June, the tidal ranges during the days close to second neap tide (after newmoon) are generally higher and there is no conspicuous variation in higher high water levels between the days close to newmoon (spring) and after that (neap). This may be associated with the summer solstice (21 June), when the tidal ranges are higher (Anon. 1966). Also, large variations in tidal height between observed and predicted tides are seen towards the end of the month. These discrepancies observed towards the end of the month may be attributed to local weather conditions. Variations in barometric pressure and wind control the tides locally.

In August 1985, it is seen that the amplitudes of spring tides are comparatively smaller than those of previous months (Fig.2.7). Between the newmoon and fullmoon days, the ranges of tides lie between 75 cm and 88 cm, so that the smaller tidal ranges associated with neap tides are not conspicuous. This may be due to the local weather conditions as seen in the month of June. In August, the observed LLWs are generally lower than the predicted. The difference between observed and predicted LLWs ranges upto 20 cm. During September, the tides appear to have smaller amplitudes (Fig.2.8). The difference in LLW between predicted and observed tides are well marked and ranges up to 18 cm. Also, observed LLWs are lower than predicted in all the days, as in the case of August. The tidal pattern during October also appears similar to the previous months. The observations during the period April 1985 to March 1986 generally show that the tides are of semidiurnal type. However, on 10th September and 9th October, diurnal nature (one low and one high in a day) is observed, at neap tides. So at the Cochin estuary, the tides are characterised by mixed, predominantly semidiurnal behaviour.

In November 1985 (Fig.2.10), daily variations in observed higher water levels are found to be smaller (101 to 118 cm) than predicted, whereas, the lower water levels show larger variations (-15 to 63 cm). December is the month of winter solstice and usually the highest high and lowest low of tide levels occur during this month (Anon.1966). In association with the winter solstice (21 December) the tidal ranges of neap tide days (5-7) occurring before the newmoon are lower than those occurring after the newmoon (19-21) (Fig.2.11). In January 1986 (Fig.2.12), the variation of lower tidal levels between the predicted and observed are well reflected during the period from newmoon to fullmoon days. Generally, the tidal ranges of March 1986 are found to be smaller compared to other months (Fig.2.14). During the first fortnight, variation in tidal ranges between neap and spring tides is not well marked and ranges between 75 cm and 90 cm.

2.2.2 Slack Water Conditions

'Slack Water Condition' is an important characteristic of currents associated with tides. When the direction of tidal stream changes, there is a period of no horizontal movement due to tidal forces. This is called slack water (Mc Lellan, 1965). Occurrence of this closest to the time of high water is called 'High Water Slack' and that closest to low water is called 'Low Water Slack'.

From the tidal characteristics of the Cochin Estuary, in general, it is observed that slack water conditions exist for a duration of upto

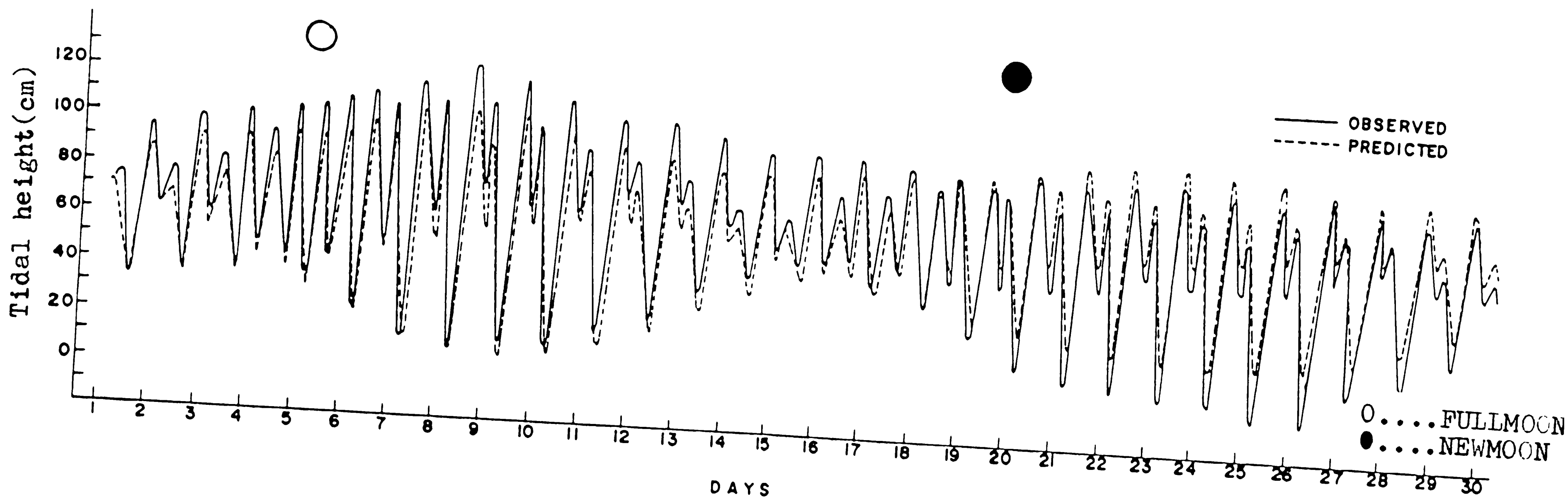


Fig.2.3 Daily variations of observed and predicted tides during April 1985

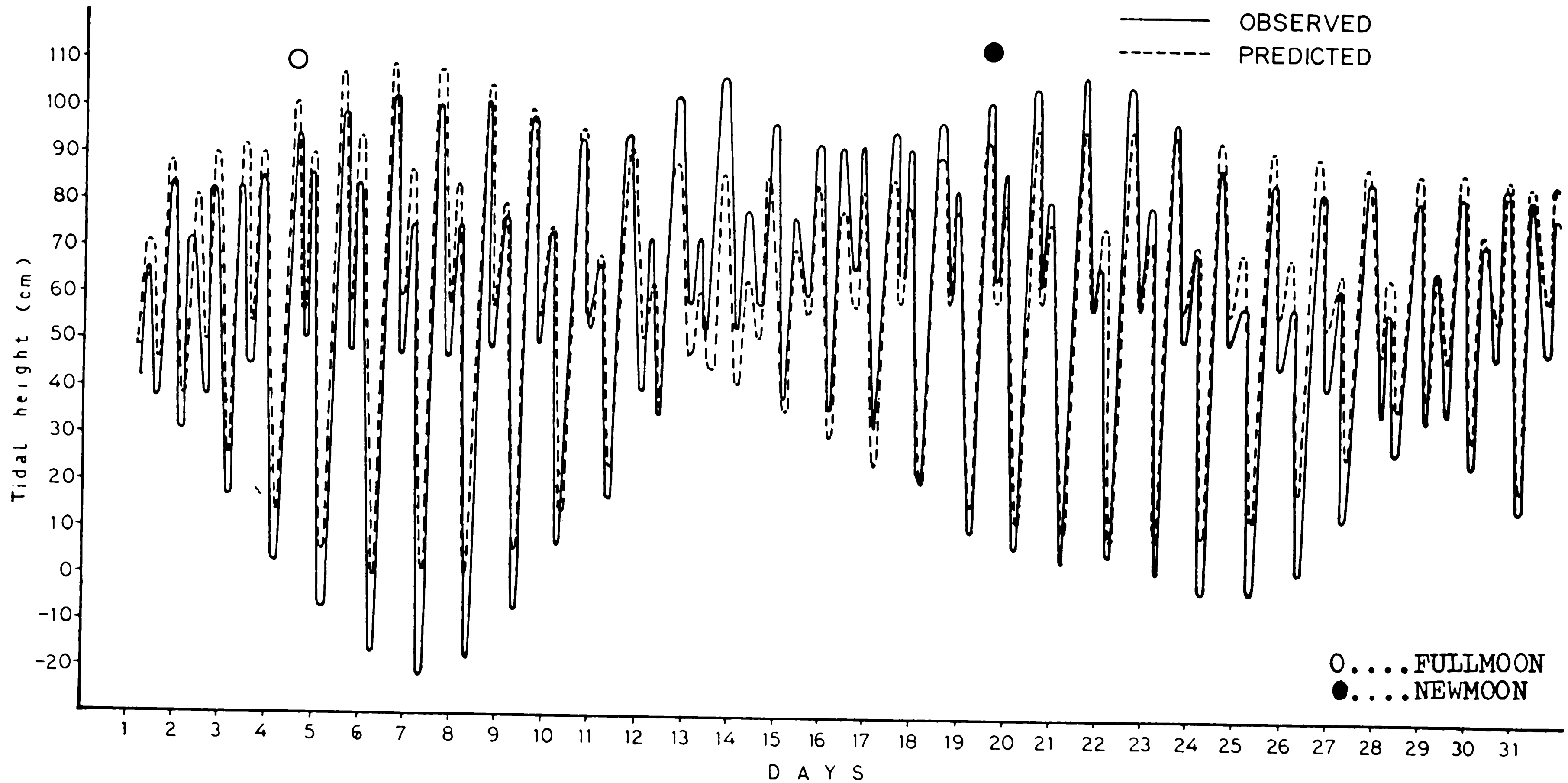


Fig.2.4 Daily variations of **observed** and predicted tides during May 1985

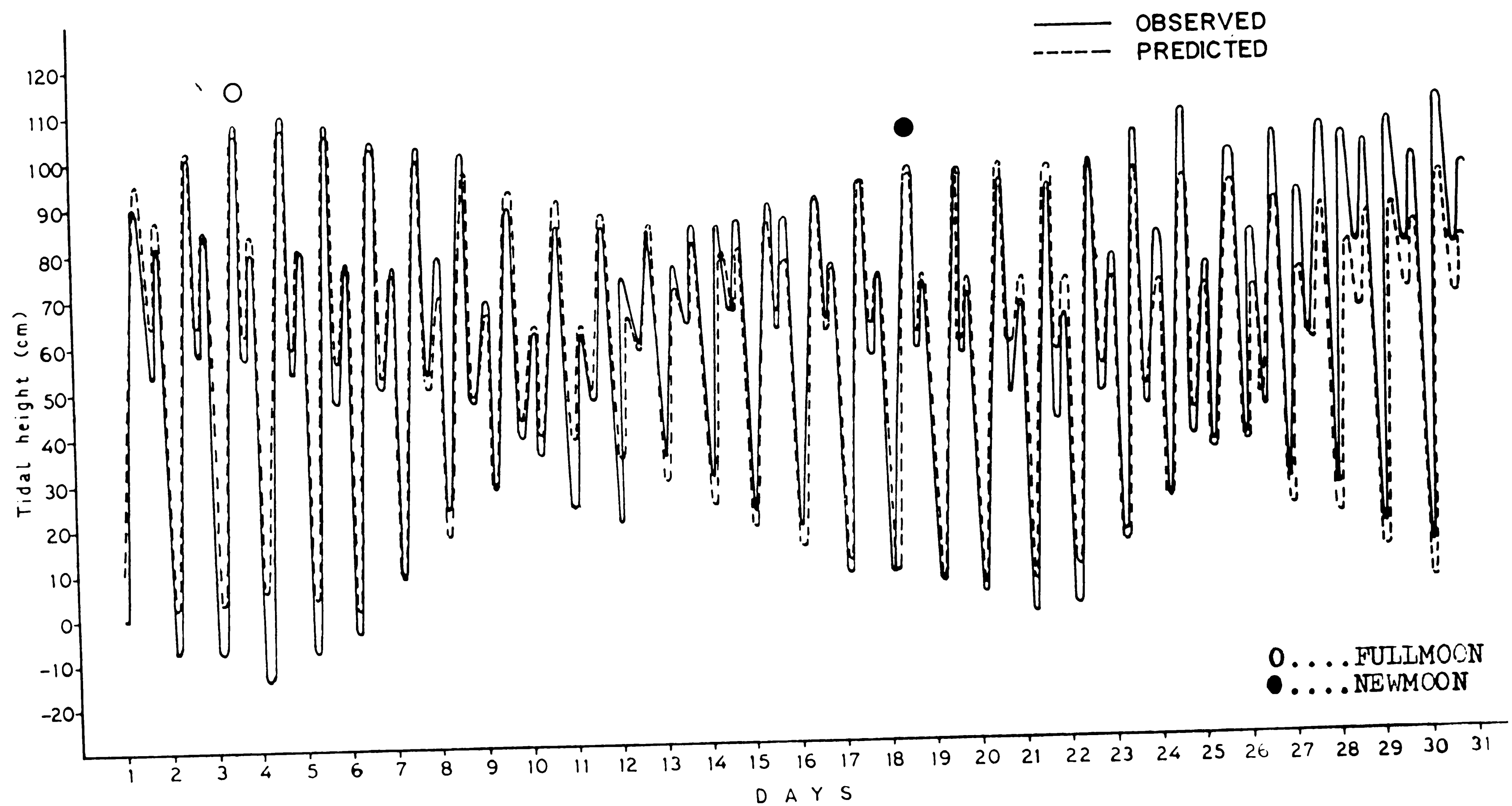


Fig.2.5 Daily variations of observed and predicted tides during June 1985

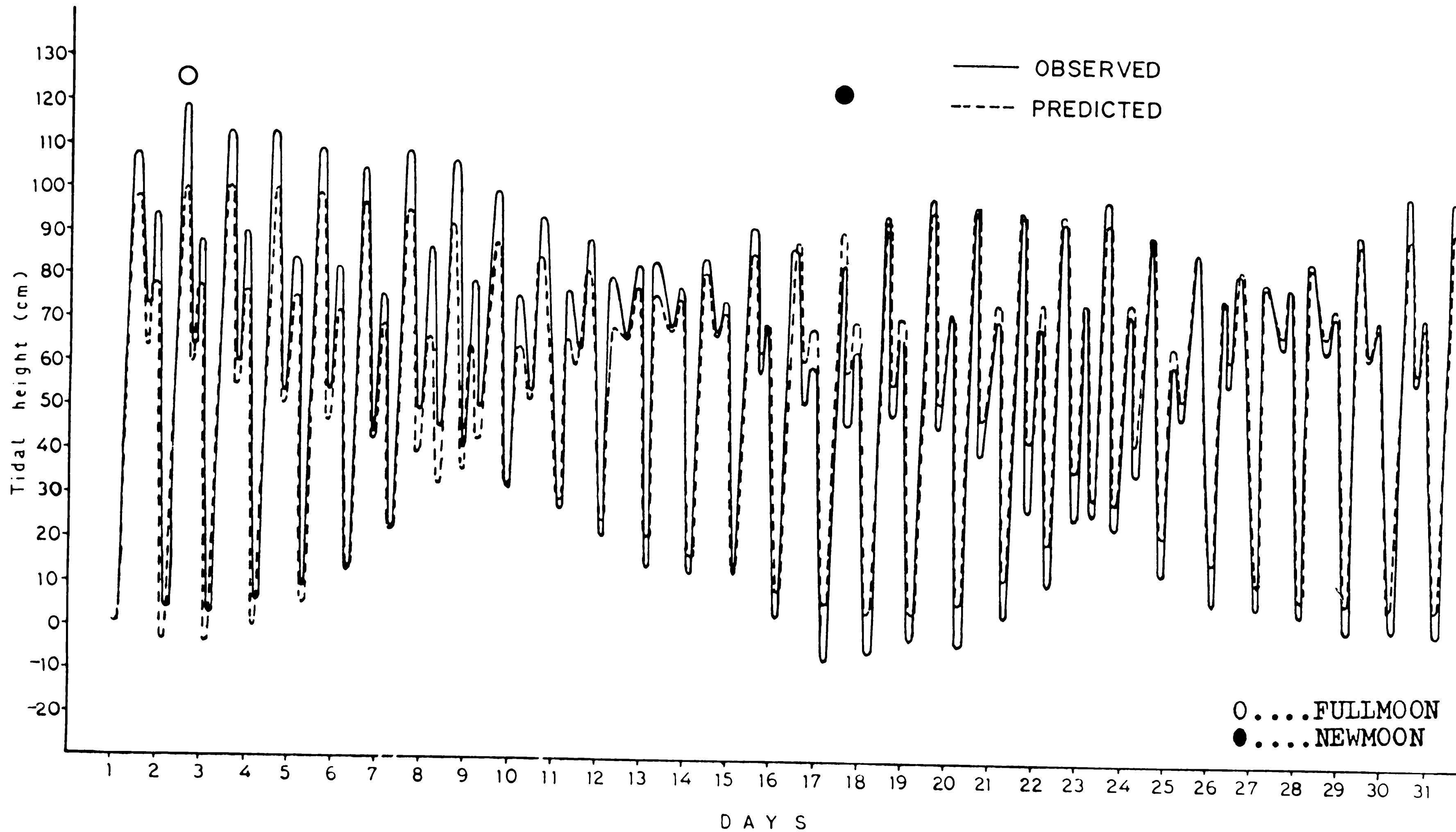


Fig.2.6 Daily variations of observed and predicted tides during July 1985

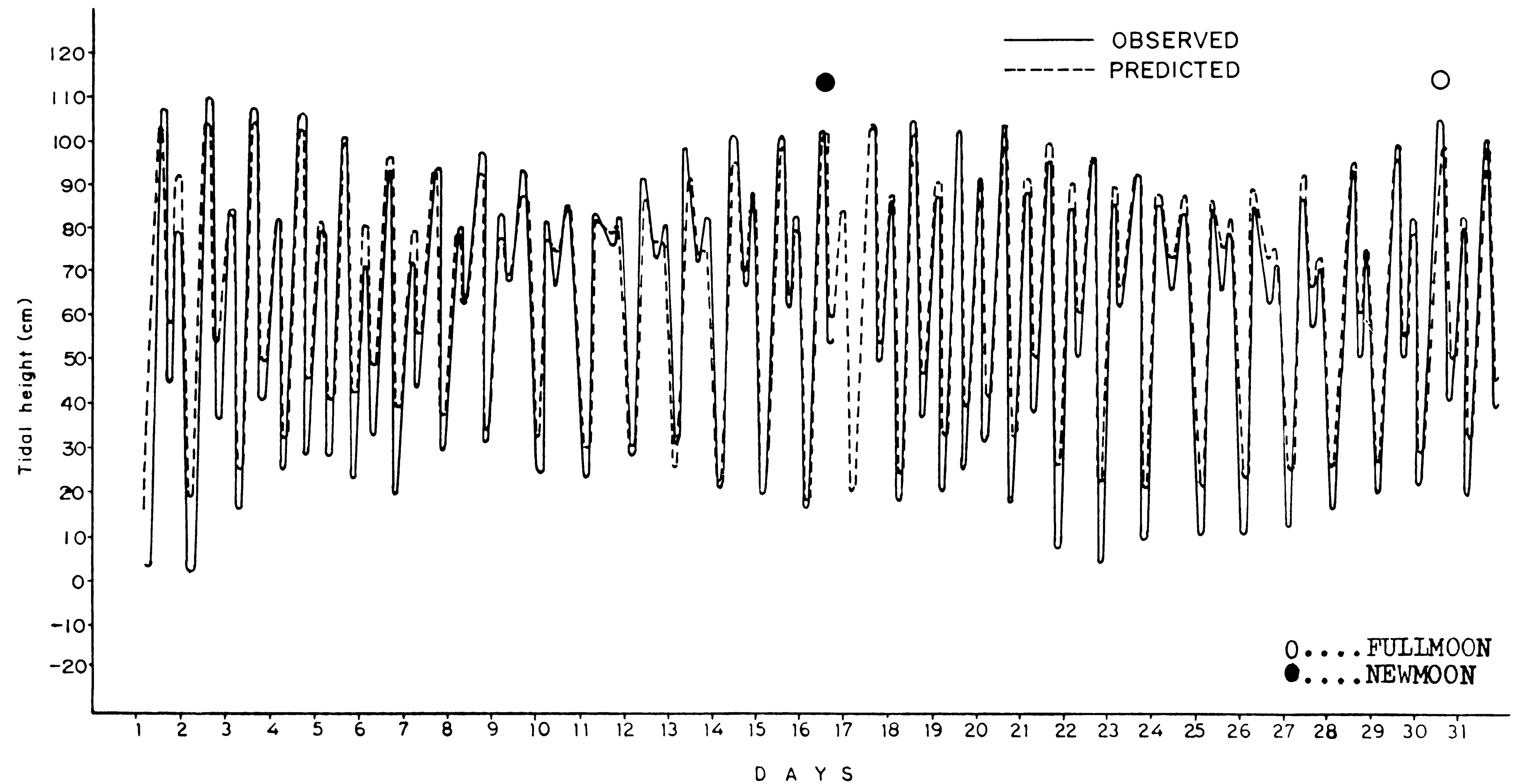


Fig.2.7 Daily variations of observed and predicted tides during August 1985

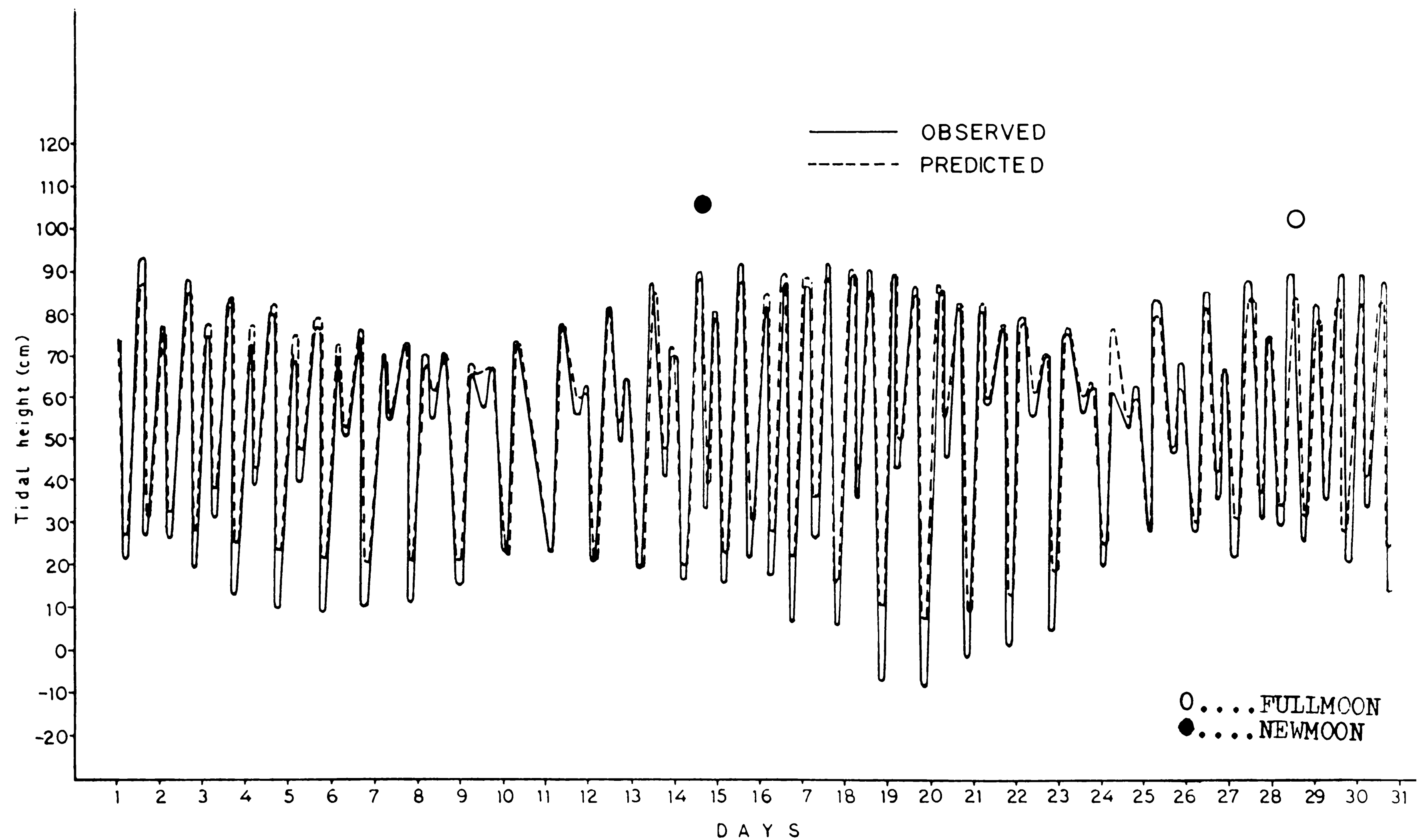


Fig.2.8 Daily variations of observed and predicted tides during September 1985

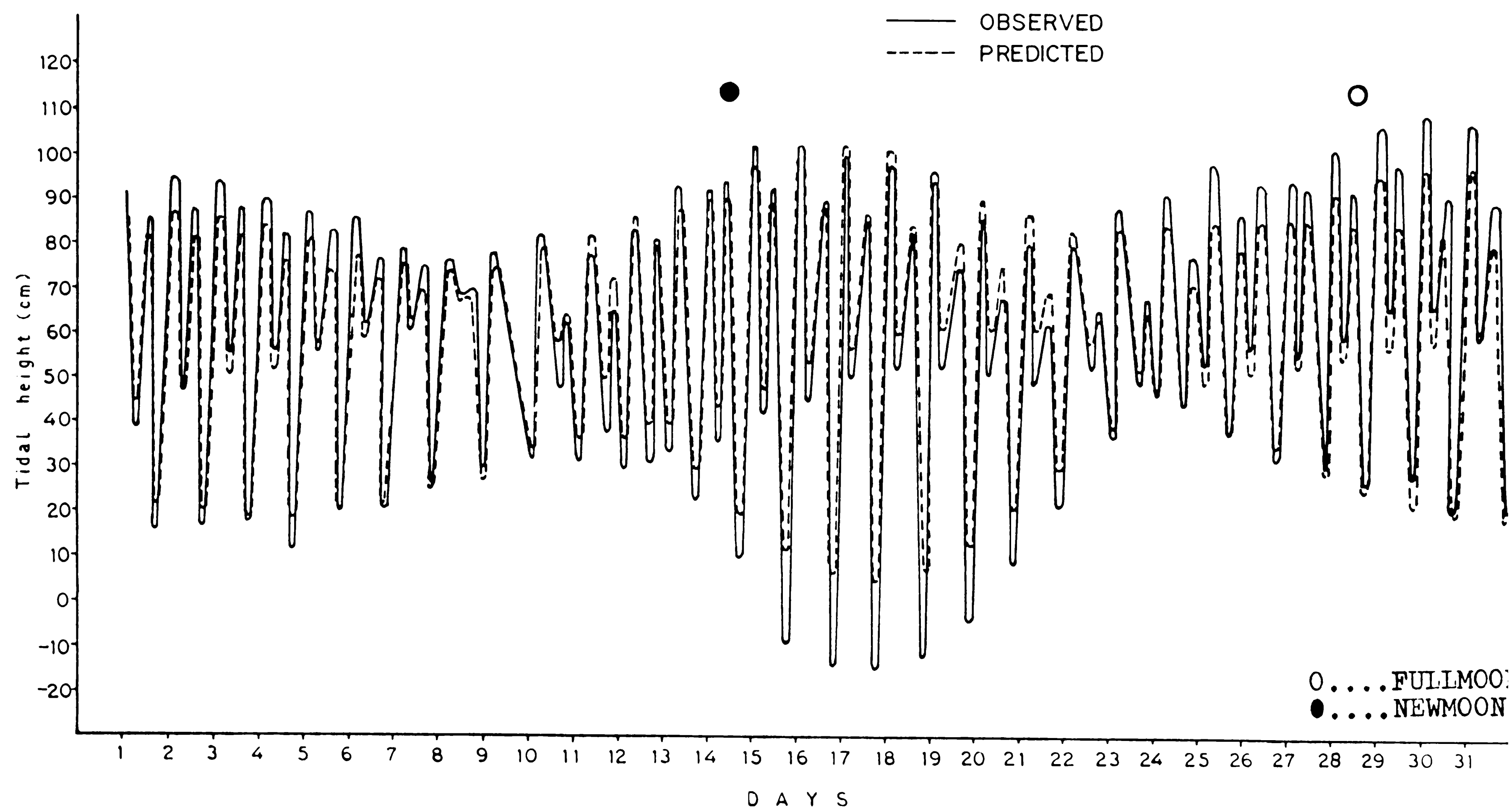


Fig.2.9 Daily variations of observed and predicted tides during October 1985

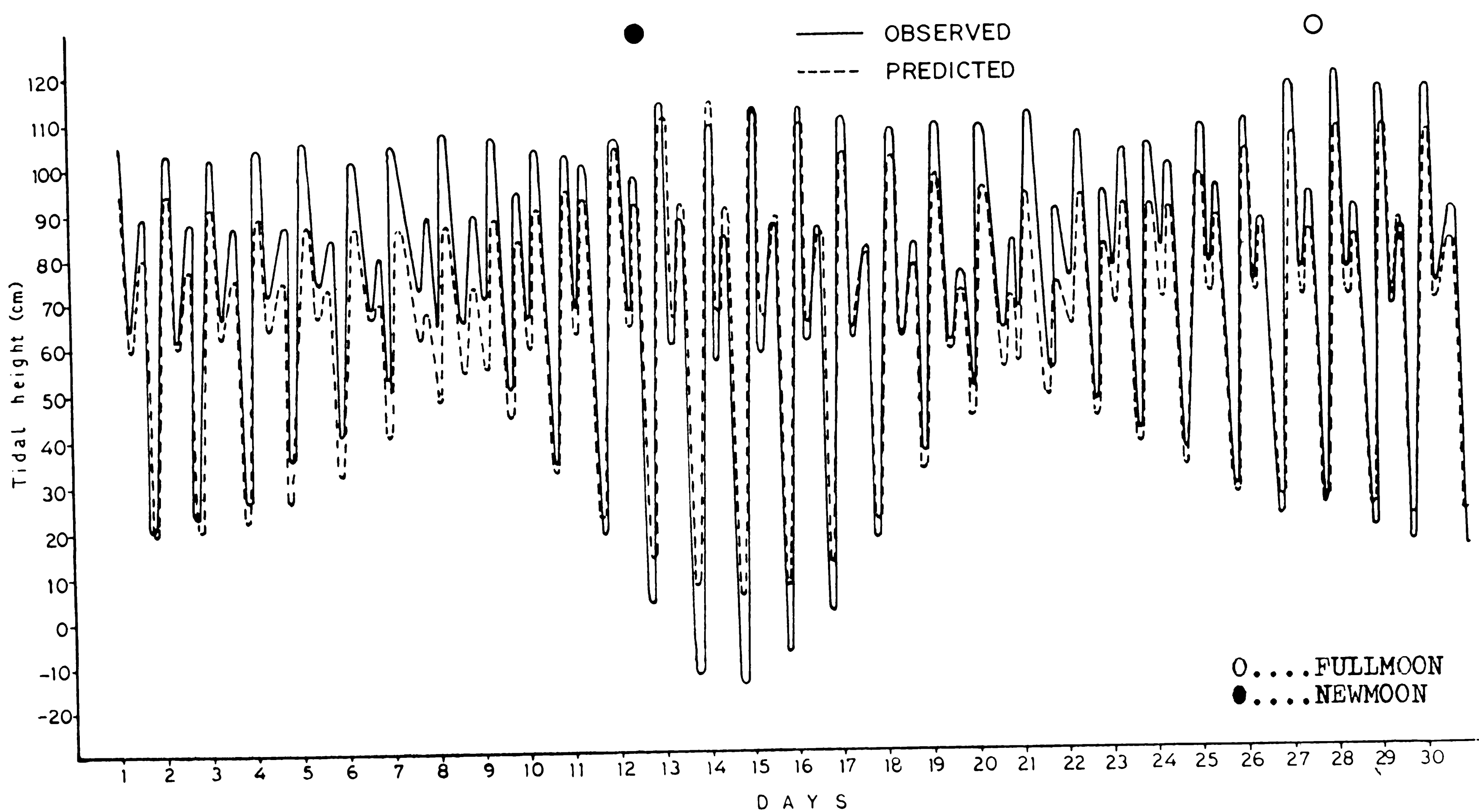


Fig.2.10 Daily variations of observed and predicted tides during November 1985

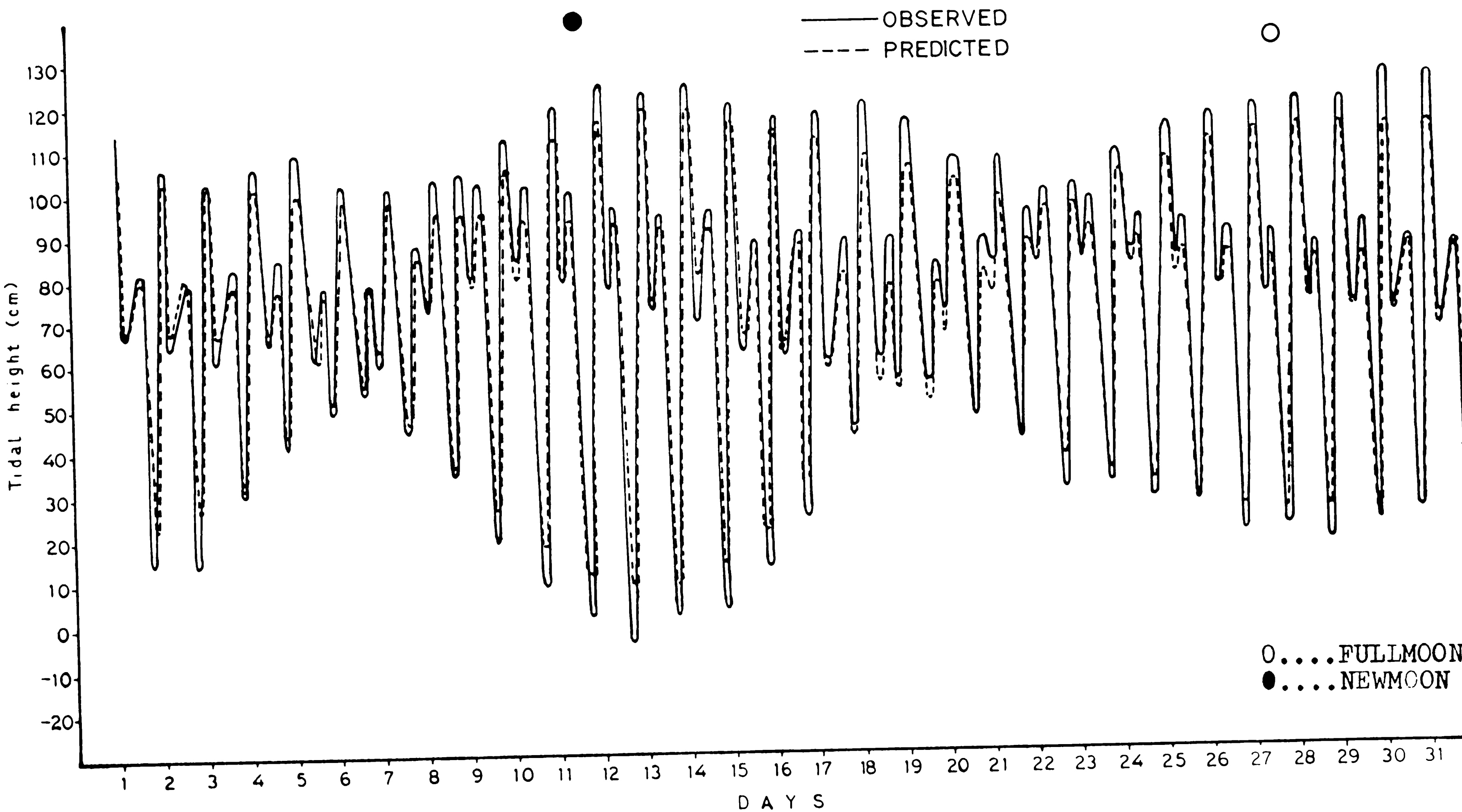


Fig.2.11 Daily variations of observed and predicted tides during December 1985

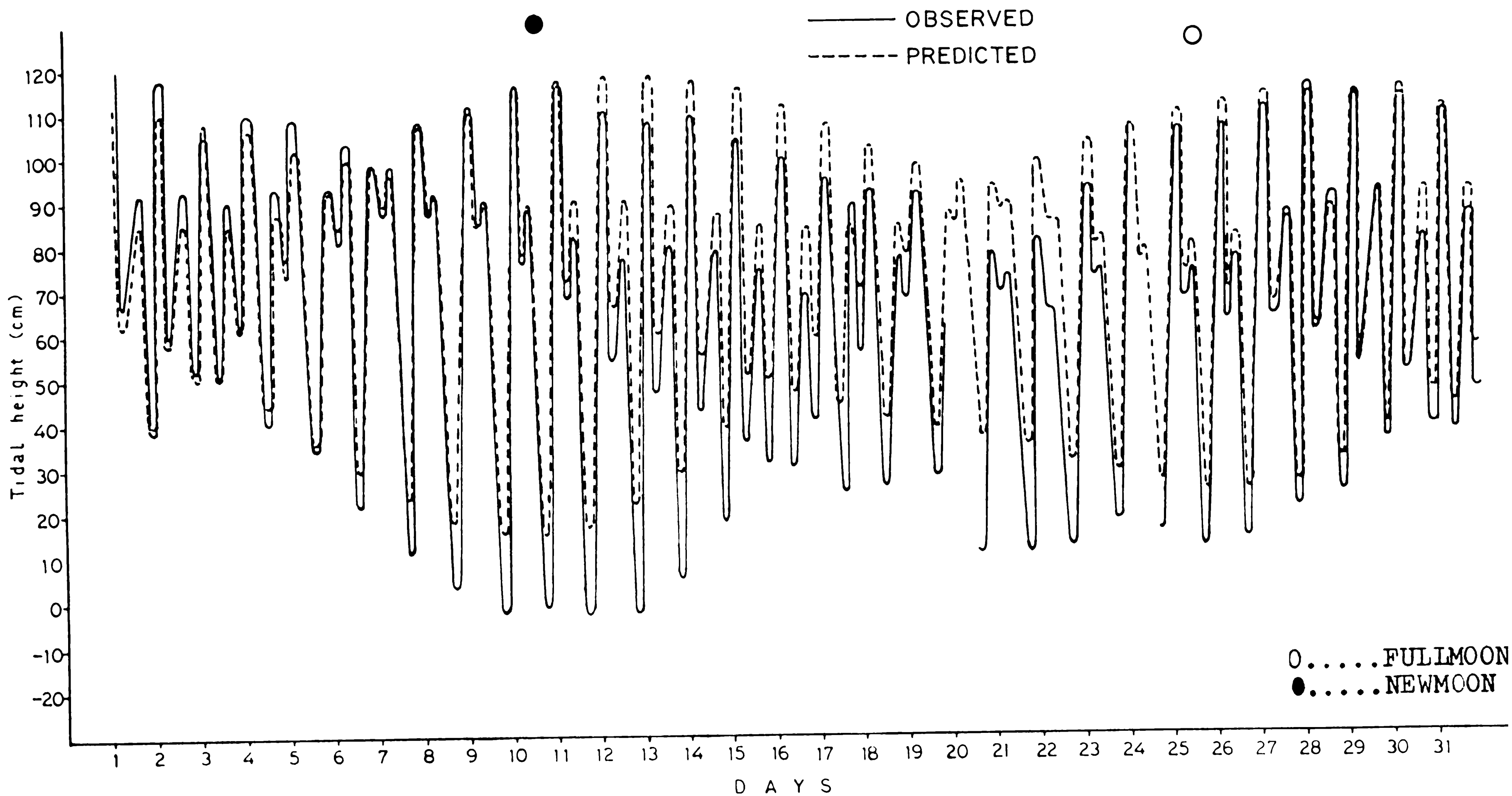


Fig.2.12 Daily variations of observed and predicted tides during January 1986

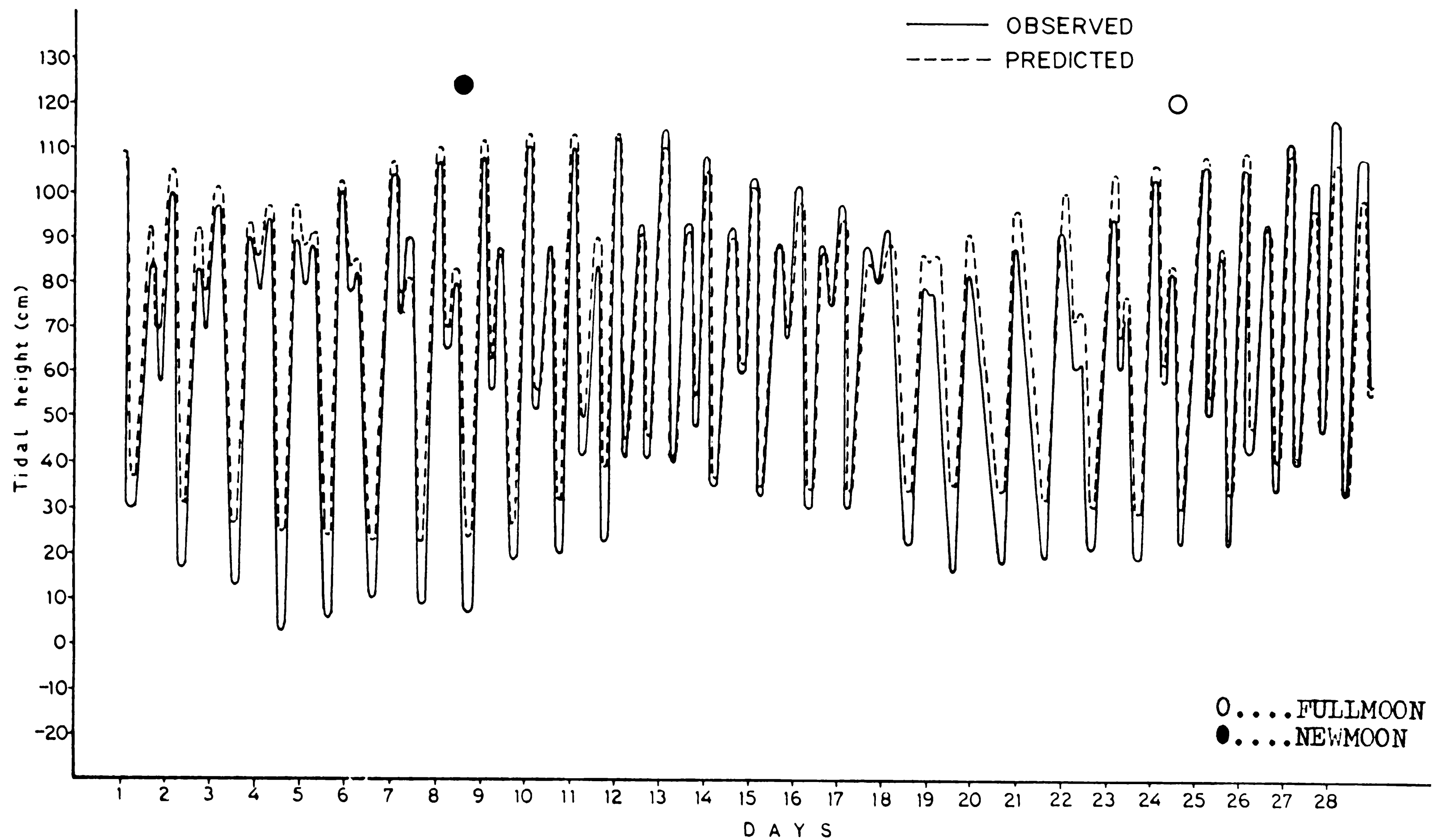


Fig.2.13 Daily variations of observed and predicted tides during February 1986

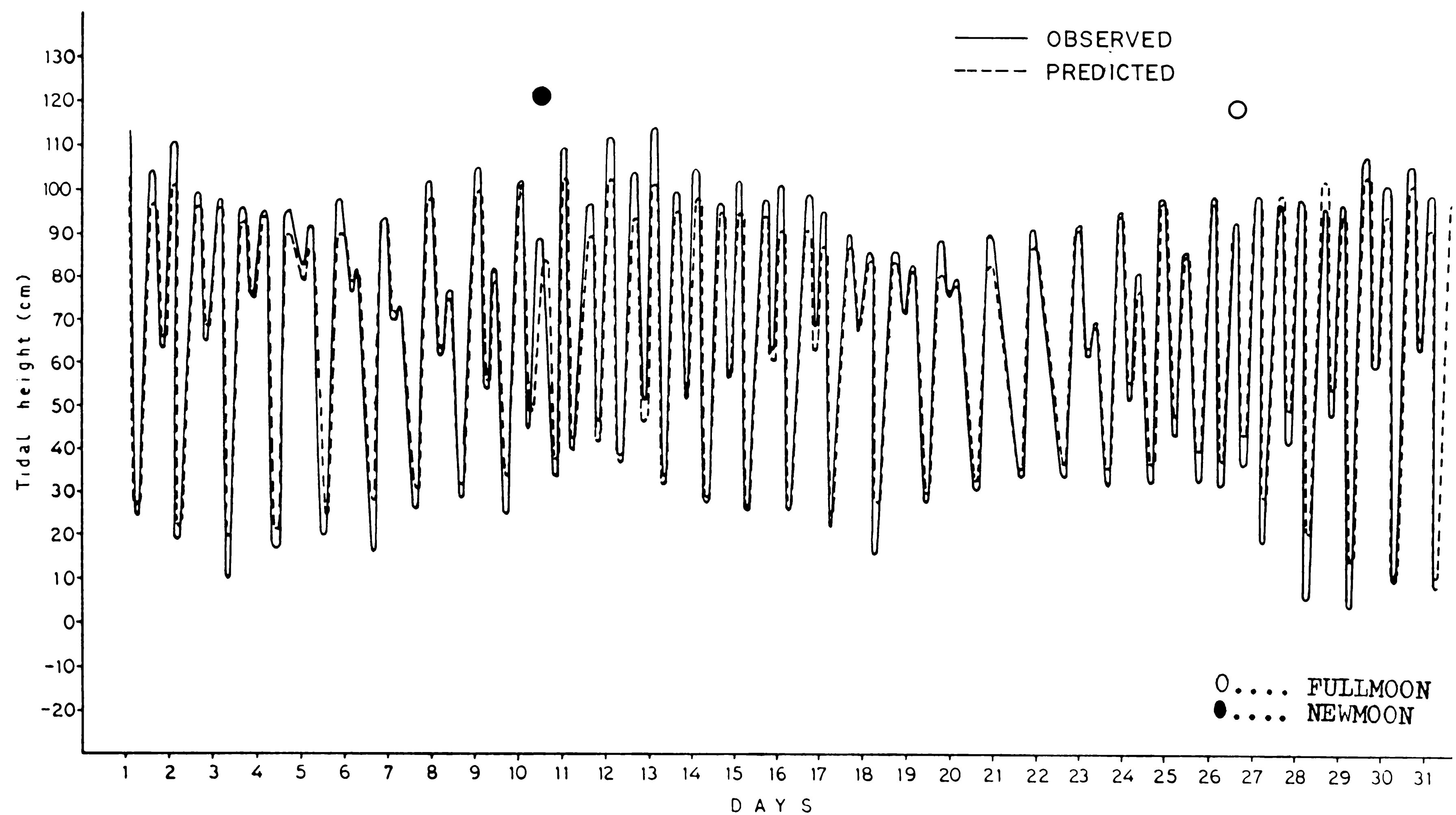


Fig.2.14 Daily variations of observed and predicted tides during March 1986

20 min. But on very few occasions, higher durations are also observed. A particular case is observed on 19th February 1986, when for a high water slack condition at 78 cm, high water level lasted for a duration of 3 h 58 min. There is no plausible explanation for this, that perhaps this may be due to local disturbances affecting the tide gauge readings.

2.2.3 Sea Level Anomalies

The study of variations of sea water level has assumed considerable importance in recent years, since it affects the operation schedule of any commercial port. The differences between the actual recorded sea levels and the predicted sea levels at high water and low water are known as sea level anomalies which can be postitive (observed — predicted) or negative (predicted — observed). The predicted sea levels are composed of the components related to astronomical influences and weather elements on a monthly basis (Varadarajulu and Dhanalakshmi, 1987).

The magnitudes of high water anomalies and low water anomalies during April 1985 - March 1986 are shown in Fig.2.15. Distinct variations between high water and low water anomalies can be observed during this period. The low water anomalies (total 341) consist mostly of negative anomalies (270) while high water anomalies (total 343) consist mostly of positive anomalies (242). The highest negative anomaly (-26 cm) is recorded in January 1986 and the highest positive anomaly (+20 cm) is recorded in November 1985 and January 1986 for low water. The highest positive anomaly

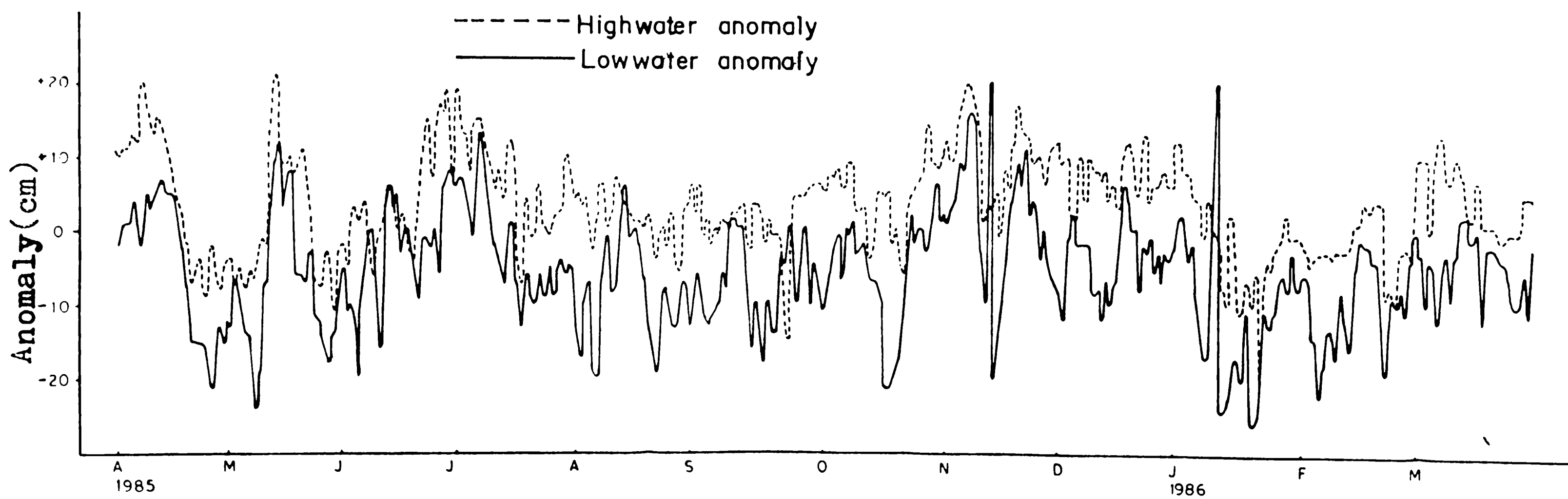


Fig.2.15 Magnitudes of high water and low water anomalies during April 1985-March 1986

(+22 cm) for high water is recorded in March 1985 and negative anomaly (-20 cm) in January 1986. Higher ranges of fluctuations are distinct between two consecutive low water anomalies observed in November 1985 and January 1986, when the corresponding values are 40 cm. (-20 to + 20) and 44 cm (-24 to +20) respectively. In February 1986, all the low water anomalies are negative and in December 1985 all the high water anomalies are positive. In general, the distribution of anomalies during this period shows that the influences of local weather elements such as wind, rainfall and pressure are considerably small.

CHAPTER - III

3. HYDROGRAPHY

3. HYDROGRAPHY

3.1 Introduction

Hydrographical conditions in an estuarine system experience considerable spatial and temporal variations associated with the seasonal, semidiurnal and/or diurnal oscillations in material concentrations, water level and flow velocity. The primary factors responsible for these variations are a combination of tidal influences, fresh water discharge rates, meteorological forcings and the constraints imposed by the configurations and geometry of the estuary. Variations in the thermohaline properties do not, in general, influence the dynamics of estuaries considerably.

From the ecological point of view, salinity and temperature distributions are important, as they govern the migration of marine and fresh water organisms into the estuary. It has been found that the ranges of temperature tolerance by different species depend on the size of the individuals and the salinity of the medium, (Kuttyamma, 1981). In the case of sedimentation in the estuary, the settlement velocity of particles is influenced by density and viscosity of the medium through which they settle. Because an increased temperature increases the settlement velocity, sediments are transported more readily in winter than in summer (Perkins, 1974). Also, flocculated settlement increases with increasing salinity. Large scale changes in temperature and salinity occur in estuaries and in shallow, partially isolated coastal waters and these changes are far more greater than the variations observed in the open ocean.

Generally, the density of water depends on salinity and temperature, but in the case estuaries, the latter is less important in determining density (Dyer, 1973).

3.2 Temperature

Temperature is a conservative property that affects the internal structure of water and its properties. It alters the viscosity of water and consequently water flows faster at higher temperature and carries less silt (Mitchell, 1974). Surface water temperatures are the highest in the afternoon and the lowest at dawn. It is considered that estuarine water temperatures are controlled fundamentally by the temperatures of the sea water and run-off water from land and by solar radiation. Temperature fluctuations in the estuarine system tend to be greater than those in either offshore waters or the open ocean, since inflowing river water tends to be colder than sea water during winter and warmer during summer.

The present study attempts to understand the influence of river inputs, tides and solar radiation on the variations of water temperature at the Cochin estuary. For this purpose, the studies related to temperature distribution are made both on seasonal and on tidal basis. Average monthly variations of temperature at surface, mid-depth and bottom at the selected stations(1-8) have been studied. The average values are obtained from the hourly observations of temperature on the days of observations in each month during 1985-86. Eventhough the averaging of temperature is not fully justifiable, it has been found satisfactory in the interpretations of monthly variations. To study the tidal influence on temperature variations with the combined affect of sea water incursion, fresh water discharge and incoming solar radiation, three representative stations (1, 2 & 7) are chosen. The hourly variation of temperature is studied at these stations in relation to flood and ebb tides in different months.

3.2.1 Annual Variation of Temperature

The ambient temperature of estuarine system depends mainly on climate and varies with seasons. The seasonal variations of temperature are well reflected at all stations in the Cochin estuarine system (Fig.3.1). From the figure, it can be seen that the estuarine water temperature reaches its maximum during the dry pre monsoon period. During this season, the temperatures are comparatively higher at all depths in the entire estuary (Balakrishnan & Shynamma, 1976). The surface temperatures are found to be high throughout the season ranging between 29°C and 33°C. The vertical thermal gradients are found to be very weak, indicating strong vertical mixing. During February - April (1985) and February - March (1986), the difference between surface and bottom layers are less than 0.7°C. The temperature gradually decreases with depth. But in March (1986), temperature slightly higher than that of the surface is found to occur in the bottom layers at station 8 in certain occasions. Haridas et al (1973) reported the presence of cells of higher temperature in the bottom layers at stations near the mouth during the pre monsoon period. At station 1, which is very

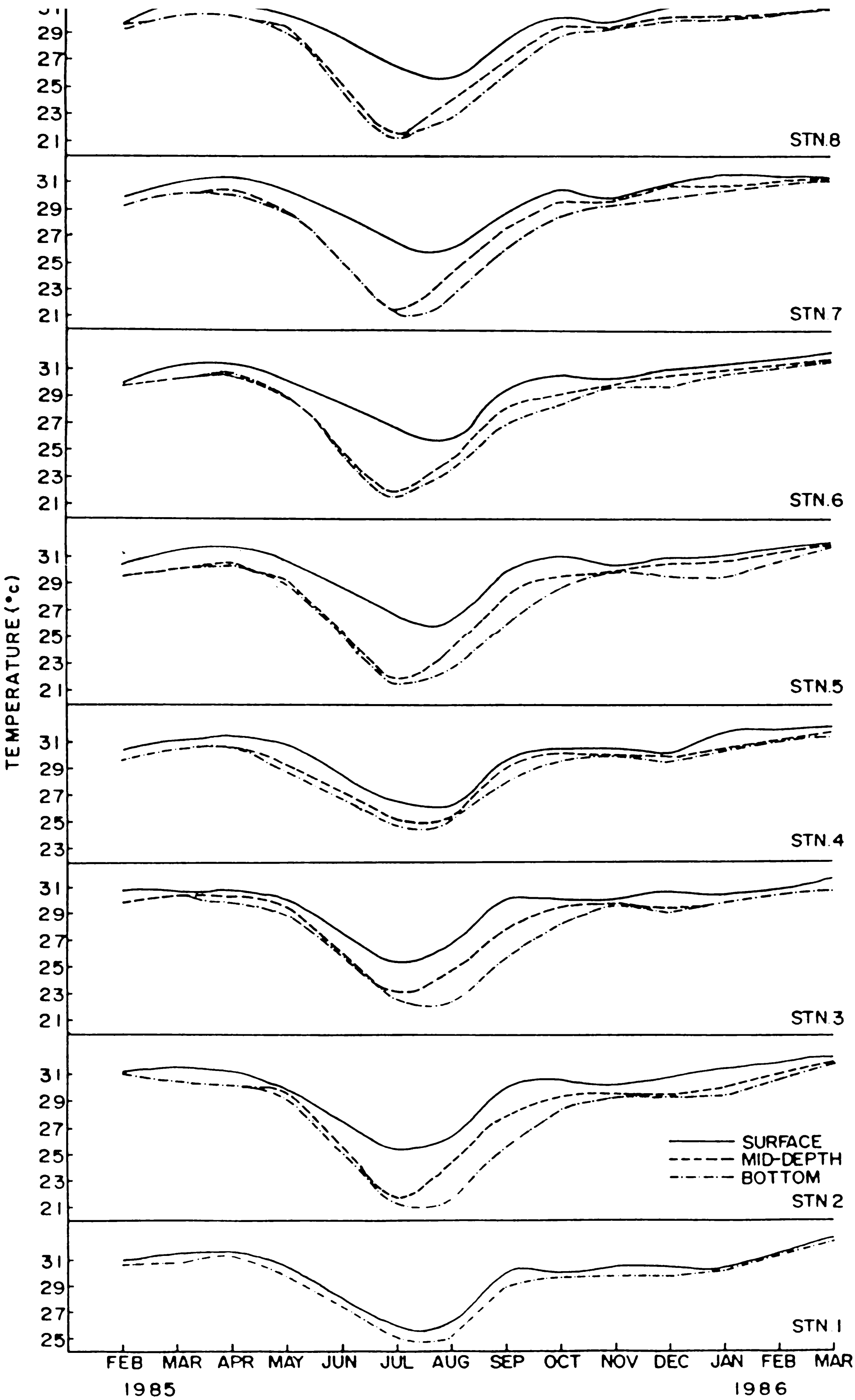


Fig.3.1 Seasonal variation of temperature at stations 1-8 during 1985-1986

shallow (about 1.5 m deep), the temperature showed only very small variation ($< 0.5°C$) in the water column throughout the year. Almost similar conditions are observed at station 4 (about 2.5 m deep) also.

A sudden fall in temperature is observed with the onset of south-west monsoon. Banse (1959) and Darbyshire (1967) reported that the surface temperature during the monsoon months is very low due to upwelling along the south-west coast of India. Raju et al (1979) suggested the coincidence of lowest annual temperature of the Cochin backwaters during the monsoon with the temperature of the coastal waters. In July, the surface temperatures are slightly lower (between 25°C and 26°C) at stations 1-3, which are located away from the estuarine mouth, than at stations 4-8 which are located near the mouth (26°C-27°C). In August, the reverse conditions are observed at stations 4 to 8, when the surface temperature falls between 25°C and 26°C and at stations 1 to 3 between 26°C and 27°C. This shows that in July, temperature of the fresh water discharged is less than that of sea water and in August, sea water is colder than the freshet. But at most of the stations, the temperature of bottom layers is found to be the least (between 21°C and 22°C) in July. At station 4 (Mattancherry channel), the temperature at bottom layers is the least in August, contrary to the observations at other stations. Temperature of the bottom layers is comparatively higher (about 25°C) at shallow stations (1 and 4) during this season. The vertical thermal gradient in the estuary is found to be steep, with a difference of about 5°C between surface and bottom temperatures. The distribution of temperature at bottom layers in the estuary during south-west monsoon season furnishes important indications as to the extent of mixing with the waters of the Arabian sea (Ramamirtham and Jayaraman, 1963).

As the season progresses, there is an increase in temperature by September in the water column. The surface temperature at stations 1 to 3 are close to 30.2°C and that at stations 4 to 8 is between 28.4°C and 30.0°C. This shows that surface temperatures are slightly higher at stations away from the estuarine mouth during August-September. During north-east monsoon season (October-December), there is a slight decline in surface temperature which is more pronounced at stations located near the mouth of the estuary. The temperature at bottom layers varies between 28.0°C and 30.0°C during this period. Again, a slight increasing trend is observed during the period January-February (1986) (winter) when thermal gradients are very weak in the entire estuary. The highest temperatures (31.0°C-32.7°C) during the period of observations are recorded in March (1986).

3.2.2 Tidal Variations of Temperature

Tidal variations of temperature in estuaries and coastal waters are larger than in the oceans. Generally, it is considered that, with the progress of flood tide, temperature tends to decrease as water is drawn from the cooler sea and increasing temperature is associated with the progress of ebb, when warmer water from the rivers and upper reaches of the estuary is brought in (Qasim and Gopinathan, 1969; Raju et al, 1979). In the Cochin backwaters the surface temperature more or less follow a typical diurnal pattern and the tidal circulation is found to have little or no influence on the variations observed in the temperature structure in the vertical plane (Pillai et al, 1973). At station I, the tidal changes in temperature are conspicuous on 7.10.85 and 16.1.86 during neap flood tides (Fig.3.2). During these tidal periods, the temperature falls by about 2.5°C in the water column. On 11.4.85 and 6.8.85, the temperature curves indicate that the temperature variations are affected by the coupling of tide and solar radiation. The other flood tidal observations did not show such a variation. Generally, the vertical thermal gradients are weak during flood tides.

Diurnal variations of temperature are predominant during ebb tides, when the heating of water by solar radiation greatly overshadows the small changes in temperature induced by the tides. On 24.9.85 (neap ebb) significant variations in temperature (1 to 2.5°C) are observed between surface and bottom waters. Though the surface temperature is normally higher than bottom temperature, reverse conditions have also been recorded occasionally in the morning (before 11 a.m). This may be related to local topographic and hydrological influences including mixing, circulation and wind effects.

The temperature distribution at station 2 (Ernakulam channel) shows pronounced tidal influence during flood tides (Fig. 3.3). The flood tides are characterised by the flow of colder sea water, whose

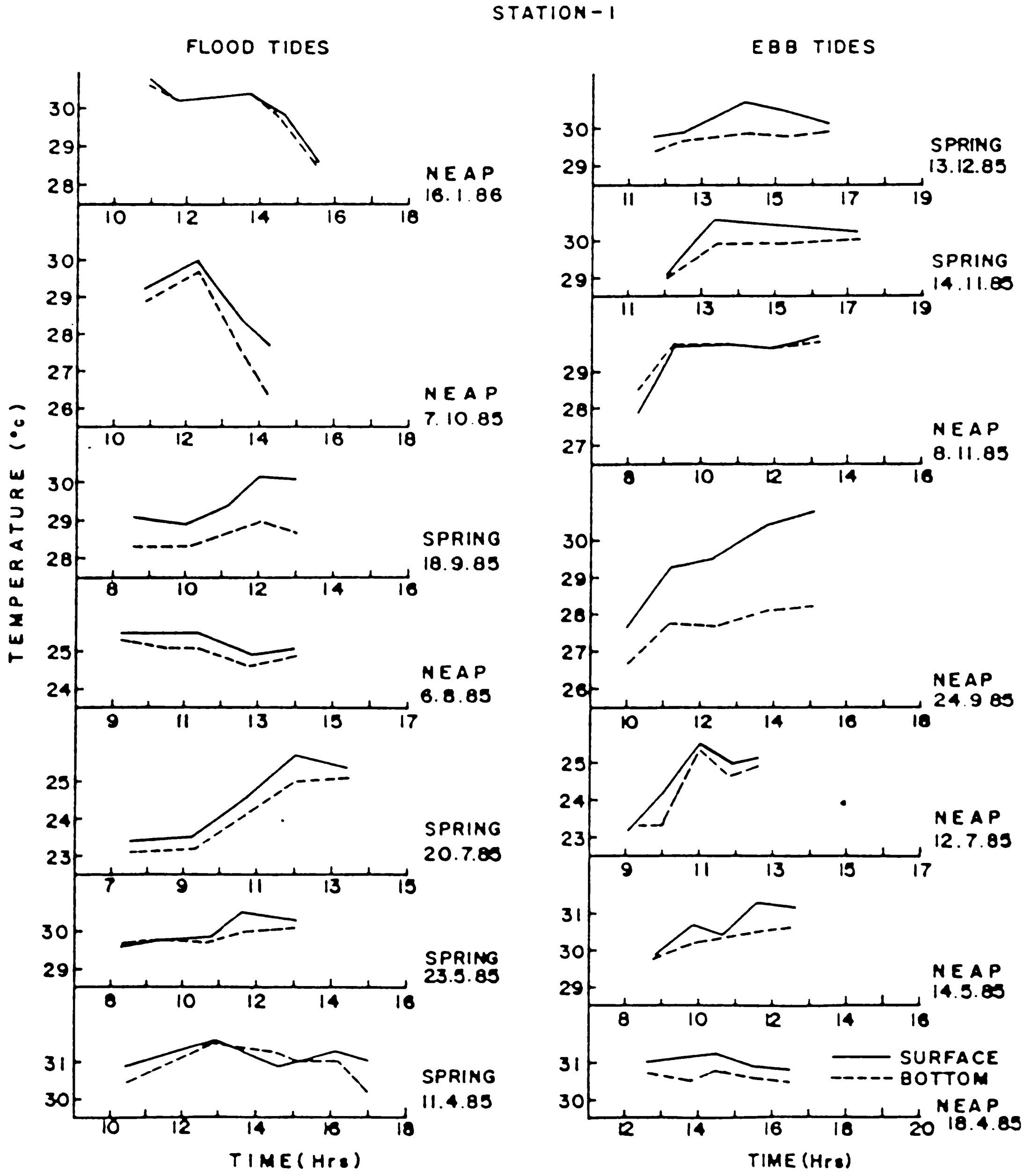


Fig.3.2 Tidal variations in temperature at station 1

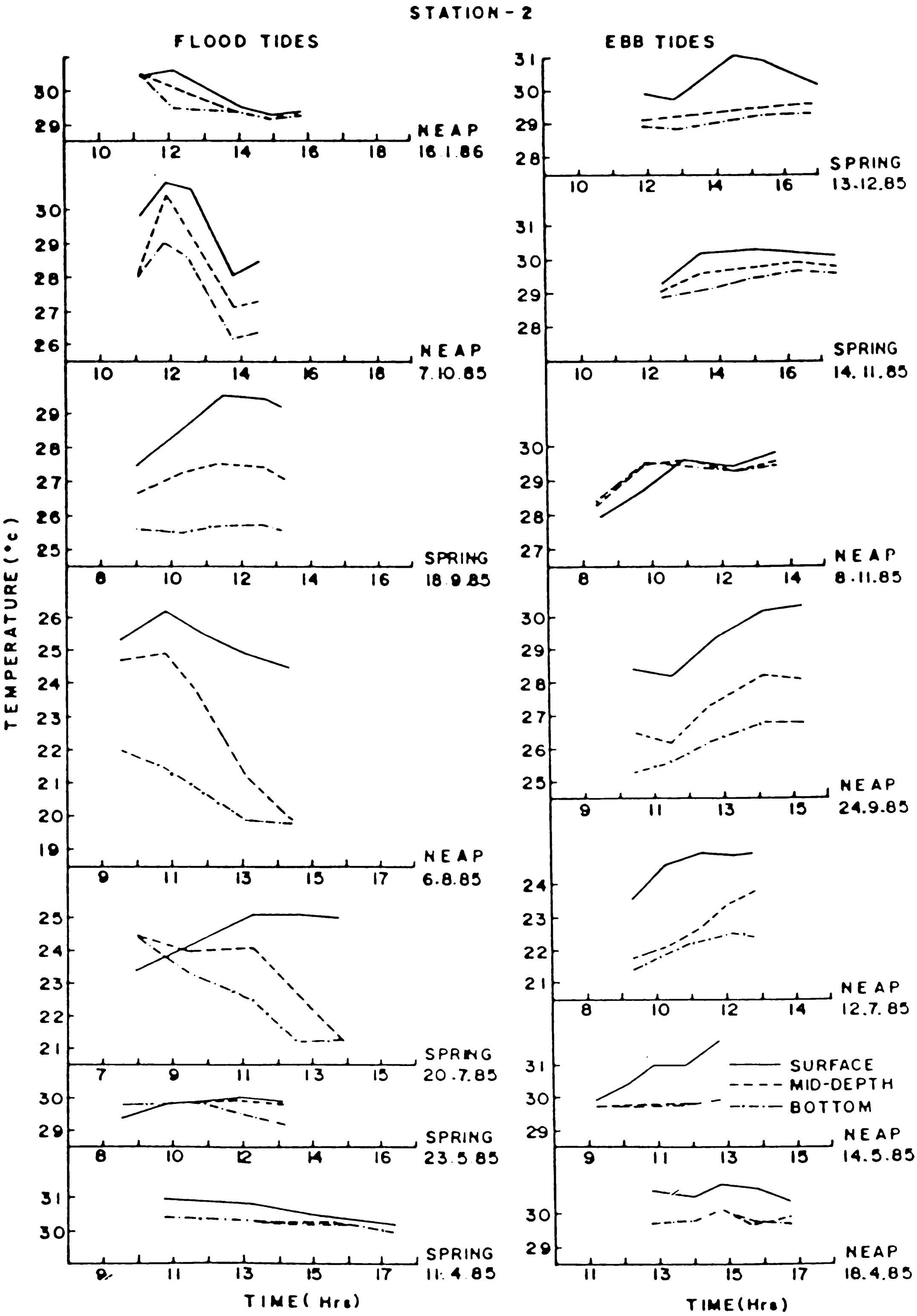


Fig.3.3 Tidal variations in temperature at station 2

intrusion into estuary lowers the temperature of estuarine waters. During the first few hours of flood tides, cooling caused by the penetration of colder sea water in the esuary is not noticed. The surface temperature increases by about 2°C in the first few hours in all months. The surface temperature thereafter decreases. On 23.5.85 and 20.7.85, the temperature recorded in the morning (before 10 a.m) at bottom layers is higher than the surface temperature. On 11.4.85 and 23.5.85, the variation of temperature during spring flood is very small ($<$ 1°C) in the entire water column, whereas, in general, flood tide periods are associated with significant variations in temperature (between 1.5°C and 5°C). The highest variation is recorded on 6.8.85 at mid-depth level where temperature decreases from 24.9 to 19.9°C during neap tide.

Generally, the ebb tides are characterised by warming of water column due to the excursion of warmer fresh water. Higher variations of temperatures (between 1.1°C and 2.2°C) are observed on 12.7.85 and 24.9.85 and vertical thermal gradients are pronounced during these ebb tides. Vertical thermal gradients are generally prominent during flood tides in monsoon months. This is due to the incursion of colder sea water through bottom layers and the excursion of warmer fresh water over it. On few occasions, the temperature at mid-depth and bottom waters are found to be the same, probably due to mixing.

Station 7 is located at estuarine mouth where tidal influence on the temperature distribution is considerable. During flood tides, due to the intrusion of colder sea water, the decreasing tendency of temperature is strongly marked here (Fig.3.4). The diurnal variation of surface temperature is found to be less than 1.3°C in all the flood tide observations. The diurnal variation is weak (< 1°C) in the entire water column during nonmonsoon flood tide days. This uniformity suggests that the influence of flood tides on temperature is significant only during the monsoon period. The vertical temperature gradient (about 0.36°C/m) is the highest on 19.7.85 and the tidal variation of temperature is the highest (2.6°C) on 5.8.85 at bottom layers. At this station also inversion of temperature is observed occasionally during flood and ebb tides, in the morning (before 11 a.m). The vertical thermal gradients are more clearly observed during flood tides than ebb tides in monsoon period as at station 2.

In general, the influence of flood tides on temperature distribution and the variation of temperature are more clearly observed at estuarine mouth. The highest diurnal temperature usually occurs between 1300 h and 1500 h during ebb tides, and the temperature variation largely depends on diurnal solar heating.

3.3 Salinity

Salinity is usually considered as the most characteristic aspect of the estuarine environment. Salinity refers to the degree of saltiness of water, or more specifically, the concentration of dissolved solids in water. It is a good indicator of estuarine

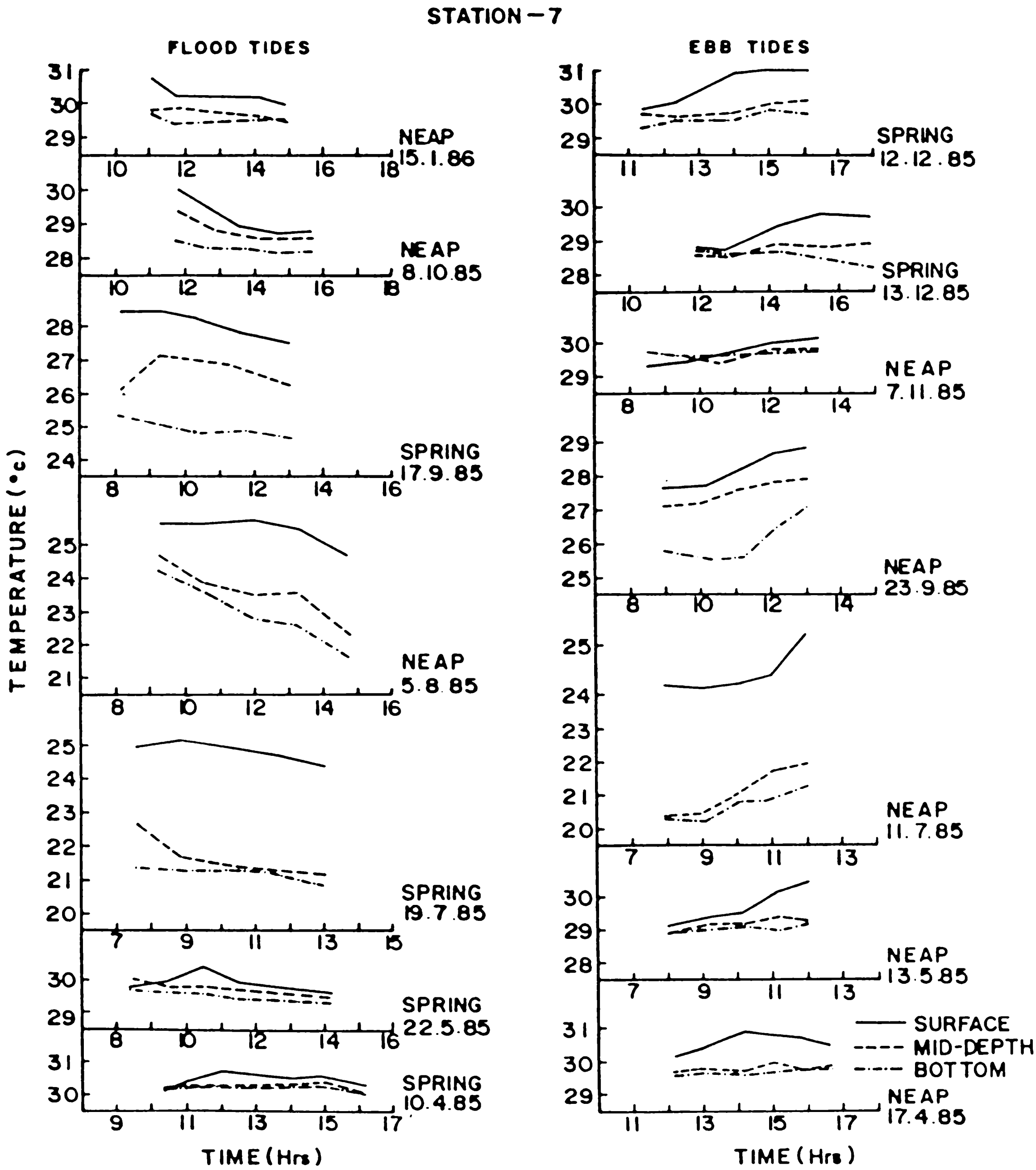


Fig.3.4 Tidal variations in temperature at station 7

mixing and the patterns of water circulation. The salinity distribution depends upon the combined action of water movements induced by freshet and tidal action. The mixing processes are of immense importance in an estuarine system. One of the important characteristics of an estuary is the short period fluctuations in salinity. In an estuary, variations in salinity occur vertically, horizontally and with time. Salinity of the water may vary vertically by several parts per thousand and large variations may occur as the tide ebbs and floods (Ketchum, 1983). The salinity differences create density differences and result in horizontal pressure gradients. Fresh water inflows are highly transient and are important in establishing salinity gradients.

The seasonal and tidal variations of salinity distribution in the Cochin estuary are discussed in this section. Spatial and temporal variations of salinity at surface, mid-depth and bottom waters in this estuarine area during various months are discussed. For each month, variations in salinity in relation to tidal ranges, during different phases of spring and neap tides, are presented. Figures 3.5 to 3.15 show the tidal variations of the surface, mid-depth and bottom salinity at stations 1-8 under different phases of tides during the period April 1985 to March 1986. During certain months (June, 1985 and February, 1986) observations could not be carried out due to constraints in instruments/boats. However, observations repeated during June 1986 have been reported.

3.3.1 Monthly and Tidal Variations of Salinity

APRIL (1985): Spring flood, Neap ebb

The observations in April, indicating the summer (Pre monsoon) conditions are presented in Fig.3.5. The figure gives the tidal variations of the surface, mid-depth and bottom salinity at stations 1-8 under spring flood and neap ebb tides of this month. The diurnal variations in salinity are found to be in phase with the tides, with increase in salinity during flood tide and decrease in salinity during ebb tide. The average duration (7 h 54 min) and range (96 cm) during spring flood are found to be higher than those during neap ebb (4 h 32 min and 32 cm). It may be noted that salinity values at mid-depth are more closer to bottom salinity than the surface salinity during both spring flood and neap ebb tides. In general, the salinity during this month is between 19.3‰ and 32.3‰ considering the entire estuarine water during both the flood and ebb tides.

The influence of tides decreases with distance from the estuarine mouth. Station 1, which is farthermost from the inlet shows the lowest salinity values during both spring flood (20.3‰ - 30‰) and neap ebb (19.3‰ - 26.9‰). At stations 2 and 3, salinity varies between 21.6‰ and 31.8‰ during spring flood and between 21.9‰ and 29.8‰ during neap ebb. At stations near the estuarine mouth, salinity varies between 23.2‰ and 32.3‰ during spring flood and between 23.9‰ and 32.2‰ during neap ebb. At station 4 (2.5 m deep), salinity varies between 20.3‰ and 30.3‰ during spring flood and between 19.3‰ and 26.9‰ during neap ebb. At

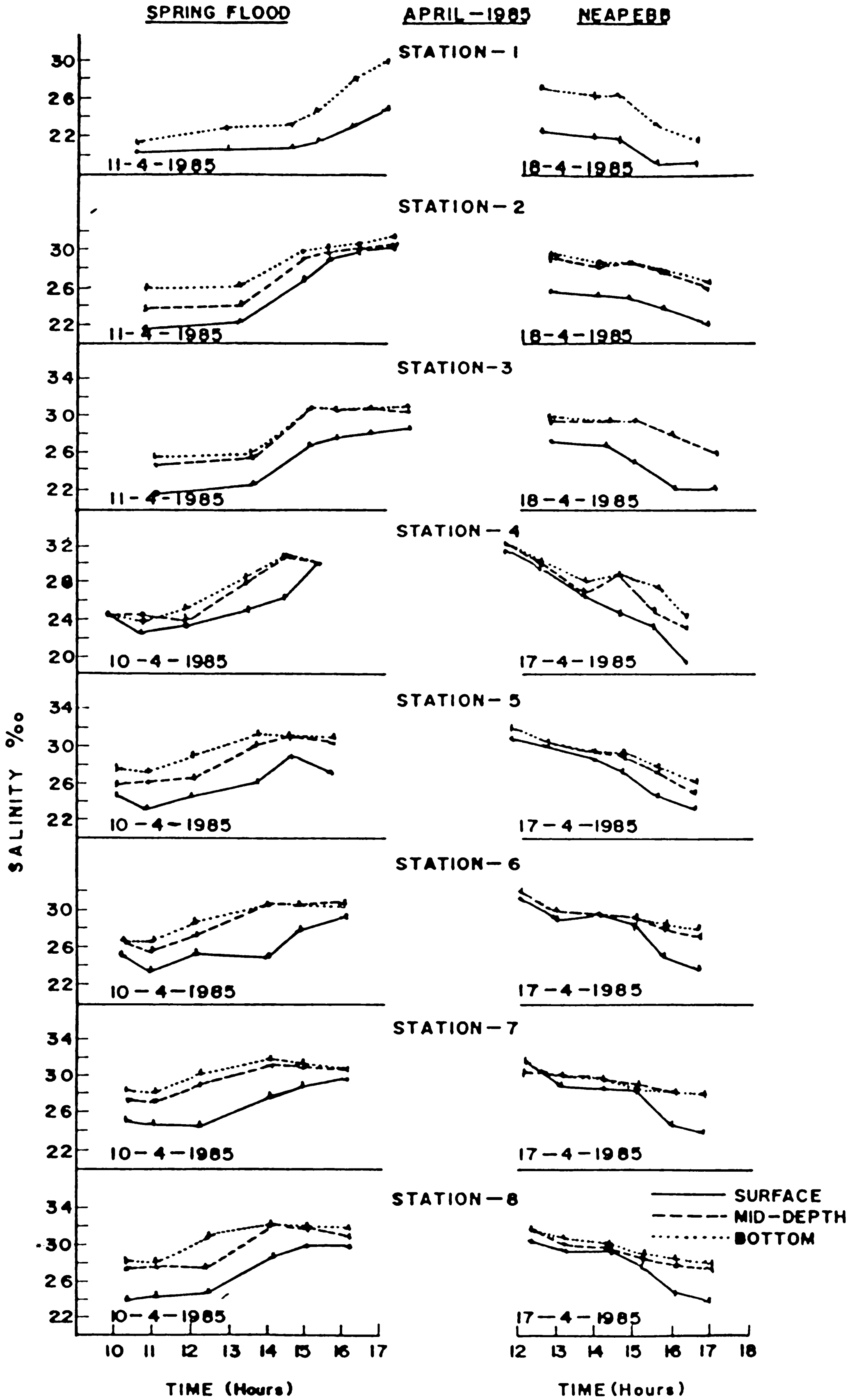


Fig.3.5 Tidal variations in salinity at stations 1-8 during spring flood and neap ebb in April 1985

stations 1-3, which are away from the estuarine mouth, slightly higher salinity variations are noticed during spring flood than during neap ebb, perhaps related to the higher range and duration of spring flood. Such distinct variations are not observed at the stations located near the estuarine mouth.

The difference in salinity between the bottom and surface waters is more at stations 5-8, located near the estuarine mouth (5.2‰ - 5.9‰) during flood tide, than at stations 2 and located away from the estuarine mouth (4.1‰ - 4.7‰) during ebb tide. Unlike other stations, at station 1, the maximum difference in salinity (5.1‰) between the bottom and surface waters occurs at spring high. At all other stations, the mixing starts after mid flood and continues till the high tide. The mixed water flows out during ebb tide and the water regains stratification by the time the low tide is reached.

MAY (1985): Neap ebb, Spring flood

Fig.3.6 gives the tidal variations in salinity during neap ebb and spring flood of May 1985. These observations were carried out before the onset of monsoon and therefore represent the summer conditions. During neap ebb, duration and range of observed tide are about 4 h 30 min and 20 cm respectively. Both at the surface and the bottom, the salinity decreases from neap high to neap low. This decrease is more reflected at surface layers, especially at the estuarine mouth, where the surface salinity decreases by 3.1‰ from neap high to neap low. At mid-depth and bottom layers, the variation is comparatively

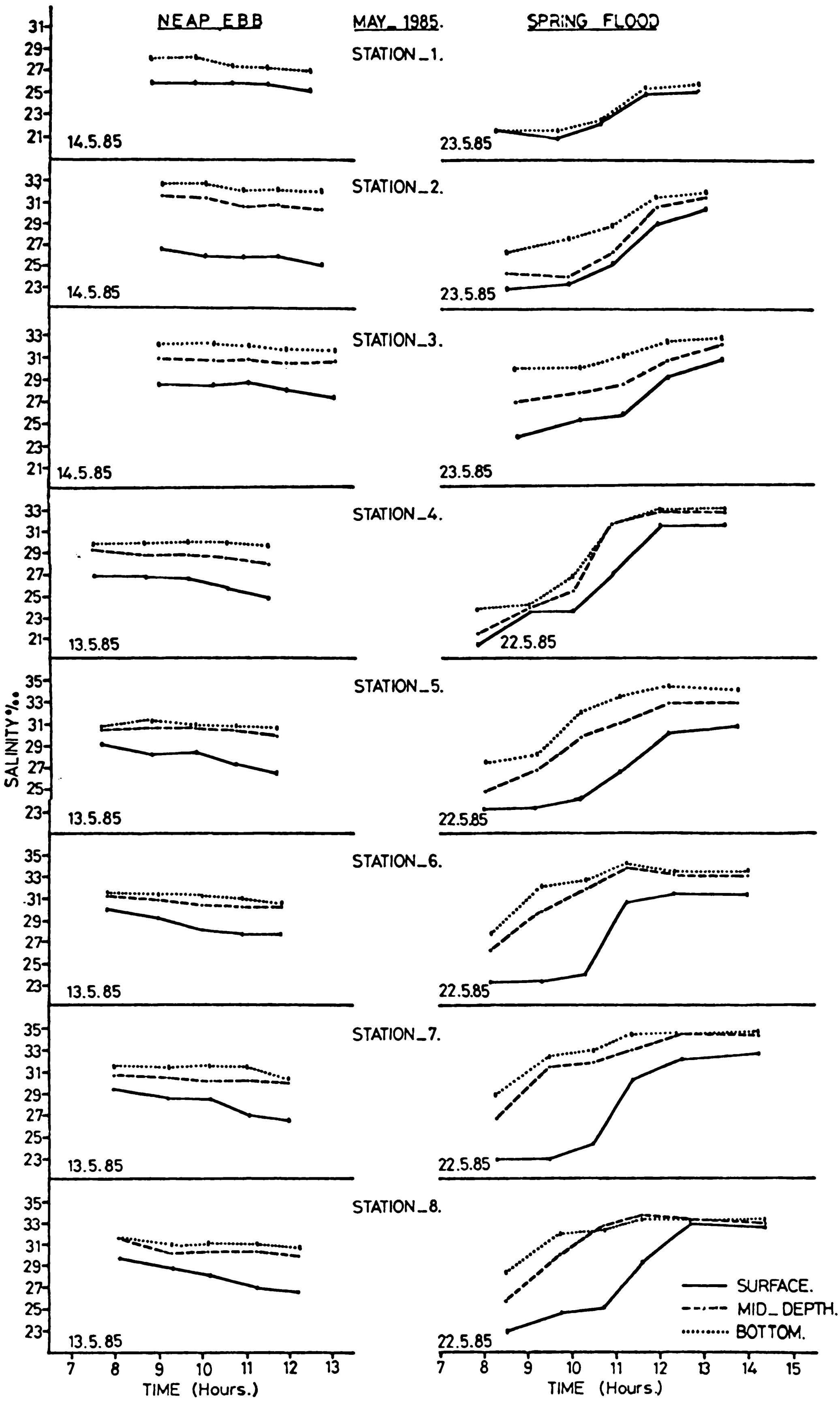


Fig.3.6 Tidal variations in salinity at stations 1-8 during neap ebb and spring flood in May 1985

low (< 1.4‰). At stations 4-8, the vertical variation in salinity, in general, increases from neap high to neap low. Stations 1-3, which are located away from the estuarine mouth, exhibit large vertical variations in salinity. Considering the entire area under study, the salinity varies between 24.8‰(neap low) and 32.7‰ (neap high) during this month. The maximum variation in salinity at the surface is about 12.3‰ (20.4‰ - 32.7‰) at the surface and about 12.8‰ (21.8‰ - 34.6‰) at the bottom in the area studied.

The tidal variations in salinity are marked during the flooding phase of spring tide which has a duration of about 7 h 35 min and range of about 97 cm. Salinity increases from spring low to spring high. At station 4, the variation in salinity in the entire water column is found to be higher than that of other stations (20.4‰ - 31.0‰ at surface, 21.4‰ - 32.5‰ at middle and 23.5‰ - 32.8‰ at bottom). Between spring low and mid flood, the salinity gradient between bottom and surface is higher (about 6.5‰ within 10 m depth) at stations 5-8 near the mouth of the estuary compared to the other stations. At spring high, salinity values at surface, middle and bottom show lower gradients, indicating partial mixing. At all the stations, the waters are more stratified before the mid flood stage and becomes less stratified afterwards.

The mixing of water is observed at spring high and neap high and mixed water flows outside during ebbing. The water regains stratification by the time the low tide is reached, as in the case of previous month. The highest value of salinity (34.6‰) is observed at the bottom at station 7 during spring flood. The duration and range of tides are comparatively short at neap ebb than at spring flood. The salinity variations are also influenced by the tide level.

JULY (1985): Neap ebb, spring flood

July represents an active monsoon month when large quantities of fresh water enter the estuary (Sec. 1.2.6) resulting in the formation of low saline water at the surface and denser, more saline water at the bottom. The average duration and range of neap ebb are found to be 4 h 20 min and 14 cm respectively. The salinity variations at the bottom layers, in general, show slight decrease during neap ebb and comparatively higher increase during spring flood (Fig.3.7).

The surface waters of the estuary exhibit nearly fresh water conditions during the neap ebb tide. The difference in salinity between middle and bottom layers is small at neap low, showing partial mixing and is large at neap high, indicating weakly stratified conditions, except at stations 1 and 4 which are very shallow ($<$ 3 m). At station 1, salinity is zero in the entire water column throughout the neap ebb tide, indicating minimal tidal effect. At station 4 also, the influence of fresh water efflux is more than that of tidal influx. This station is located in an area sheltered in between two islands (See Fig.1.2). The salinity of the mid depth and bottom waters varies between 12.2‰ and 21.5‰ at stations 2-3 and 5-8 during the neap ebb tide.

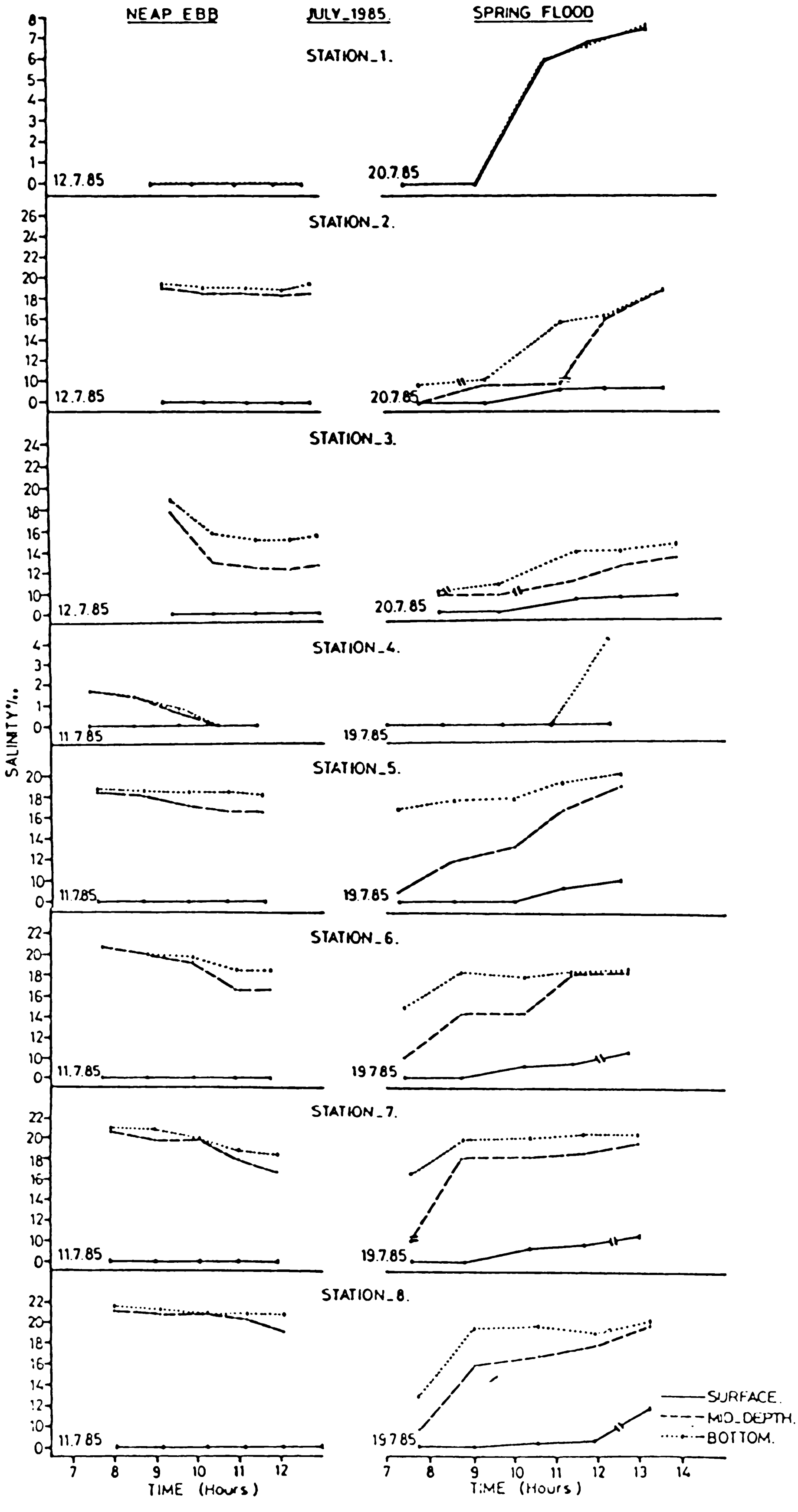


Fig.3.7 Tidal variations in salinity at stations 1-8 during neap ebb and spring flood in July 1985

The average duration (7 h 10 min) and range (100 cm) of spring flood are much larger than neap ebb and hence the variation in salinity is considerably high. At station 1, where the tidal influence is the least, mixing takes place (7.7‰) only about 2 h after the commencement of flooding. Highly stratified conditions are observed at mid-depth and bottom levels at stations having depth greater than 10 m and the stratification decreases towards spring high. The highest salinity is recorded as 20.4‰ at the bottom at station 7. The surface water remains fresh in the initial stage of flooding whereafter it is mixed to acquire a salinity of about 11.8‰ at spring high.

During neap ebb, the surface waters exhibiting nearly fresh water conditions override the more saline bottom waters. Almost constant salinity at bottom throughout the neap ebb indicates the presence of the saline wedge (Raju et al, 1979). Under spring flood, the gradient decreases towards spring high as a result of mixing at the interface. After mid flood, the tidal force begins to weaken and the surface salinity increases due to entrainment. In the entrainment process, the surface layer flowing towards the sea with a sufficiently high velocity creates interfacial waves in the halocline. These waves eject parcels of salt water into the fresher surface layer to mix with, but no fresh water is mixed downwards so that the salinity within the saltwedge remains almost constant (Dyer, 1979).

AUGUST (1985): Neap flood

During August, the salinity values could be recorded only during one phase of the tide (neap flood). The average duration and range of neap flood are found to be 7 h 8 min and 56 cm respectively. Stratification, as observed during July, is found to persist during this month also. Salinity is found to be higher than the previous month (Fig. 3.8).

Stations 5-8 located at the estuarine mouth exhibit higher salinity (20.0‰ - 25.8‰) at the bottom layers. At stations 2 and 3 the salinity of the bottom water varies between 17.3‰ and 22.1‰ during the neap flood. At shallow regions the salinity is very low ($<$ 3.0‰ at station 1 and $<$ 12.0‰ at station 4) in the entire water column as seen during the previous month. Highly stratified conditions are observed at stations located in the channels ($>$10 m depth). The vertical salinity gradient is maximum at neap low and decreases towards neap high, indicating slight mixing at neap high. But at stations 1 and 4, which are shallow, the vertical gradient is higher at neap high, contrary to the other stations. During neap flood, the salinity variations are considerably higher in the middle layers indicating mixing, but, the variations in the bottom layers are very low.

At surface, before mid flood, the salinity is negligible ($<$ 3.0‰) in the entire estuary but after mid flood, sharp increase (from 3.0‰ to 13.0‰) is observed at estuarine mouth. As the tide floods in, the stations near the estuarine mouth show slight decrease in the

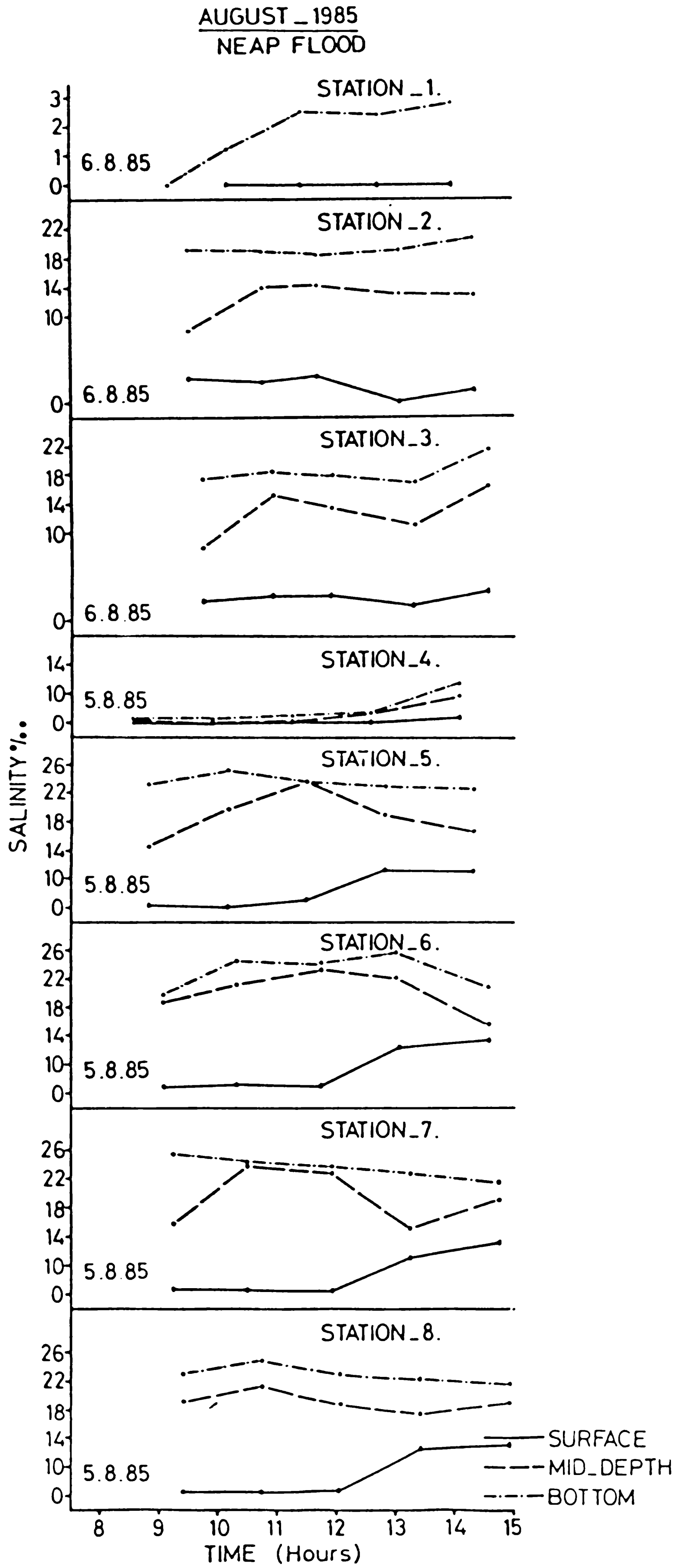


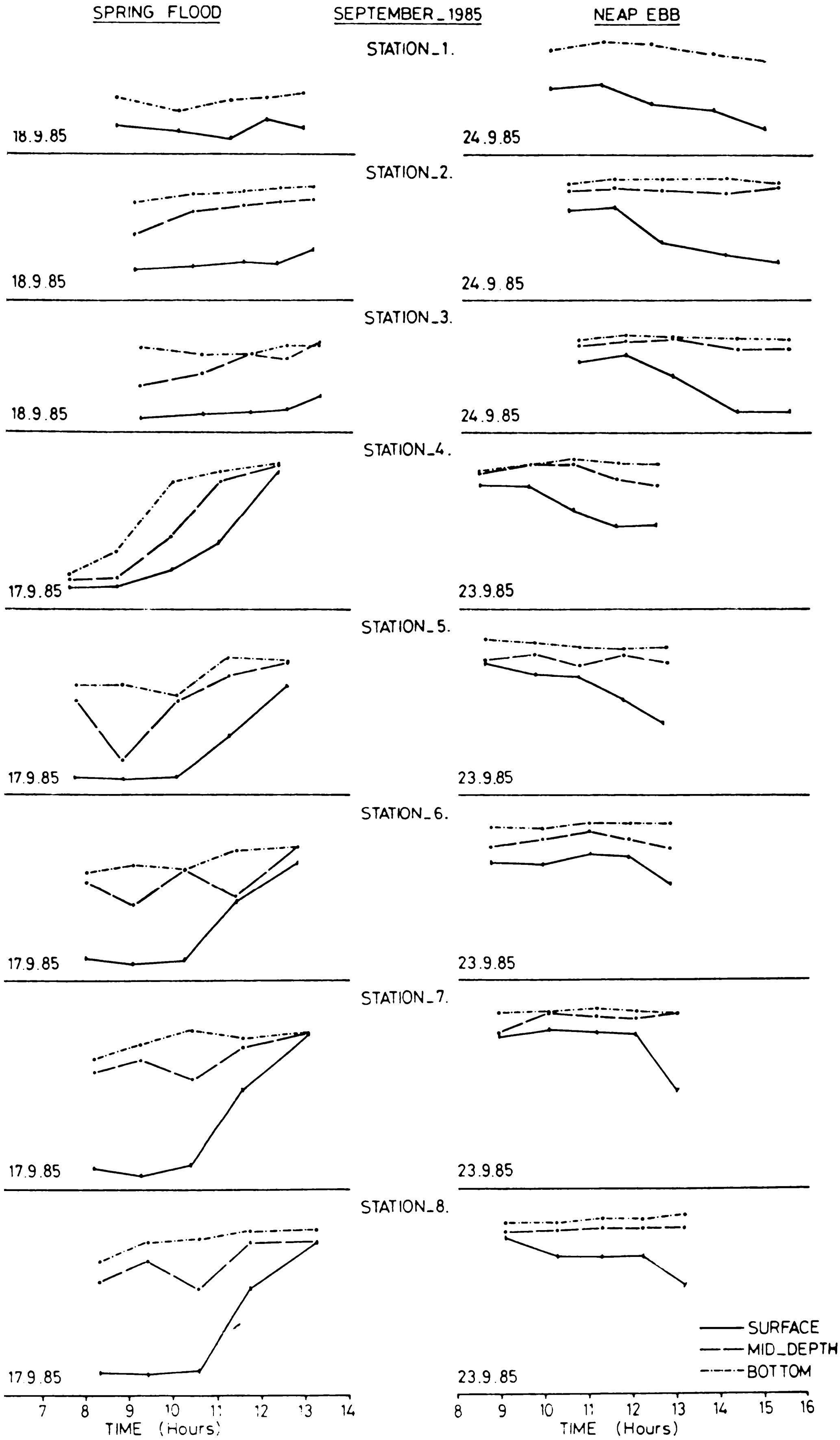
Fig.3.8 Tidal variations in salinity at stations 1-8 during neap flood in August 1985

salinity at bottom layers and at surface layers it is found to increase, leading to decrease in the vertical gradient after mid flood.

SEPTEMBER (1985): Spring flood, Neap ebb

As the season progresses, the estuary becomes more and more saline due to the decrease in monsoonal fresh water supply. The variation of salinity is well marked during spring flood, which has an average duration of 6 h 14 min and a range of 62 cm; but such significant variation is not indicated during the neap ebb which has average duration of 6 h 28 min and range of 19 cm. The reduced fresh water efflux leads to higher saline and weakly stratified conditions during neap ebb (Fig.3.9). In this month, the characteristic features of the saline wedge are absent during both phases of tides.

At stations 4-8, highly stratified conditions are observed during spring flood. At the estuarine mouth, large variations in salinity are observed at surface (11.0‰ to 30.0‰). The vertical gradient in salinity is higher (about 18.0‰ in 10 m depth) at this region before mid flood. The highest variation is observed at station 4 from spring low to spring high (4.0‰ to 28.6‰ at surface and 9.0% to 30.0‰ at bottom). Variations in salinity at bottom layers are small (vary between 30.0‰ and 32.6‰) at all stations during neap ebb when the tidal range is small (about 19cm). However, the neap ebb tide causes considerable variations in salinity of surface waters in the entire estuary. Neap low provides stratified



.3.9 Tidal variations in salinity at stations 1-8 during spring flood and neap ebb in September 1985 conditions in the entire water body.

OCTOBER (1985): Neap flood, Spring flood

October can be considered to indicate the distribution of salinity during the north-east monsoon season. During this month, observations have been carried out during the flooding stage of the neap and spring tides. The observed durations and levels of neap flood tides during the two consecutive days are as follows: 7.10.85:- 0915-1420 h, 61-75 cm; 8.10.85:- 1120-1500 h, 68-70 cm. The salinity distribution is found to show good response to the tidal variations (Fig.3.10). However, at stations 5-8, located in the ship channels, salinity does not show pronounced response to the tide due to the negligible tidal range (2 cm). At stations 2 and 3, middle and bottom waters show significant increase in salinity from neap low to neap high. At all stations, the surface salinity varies between 2.0% and 5.0% during the neap flood. At stations 5-8, located near the estuarine mouth, it may be noted that salinity values at mid-depth are more closer to bottom (30.0‰ and 32.0‰) than the surface during neap flood. At station 1, which is very shallow, salinity ($<$ 7.0‰) is not found to be affected by tide during the period of observations. Highly stratified conditions are observed at the estuarine mouth, with an average vertical difference of about 25.0% within 10 m depth.

The spring flood has an average duration of 6 h 42 min and a range of 39 cm on the days of observation. At all stations, the variation in salinity is conspicuous during the flooding phase of the spring

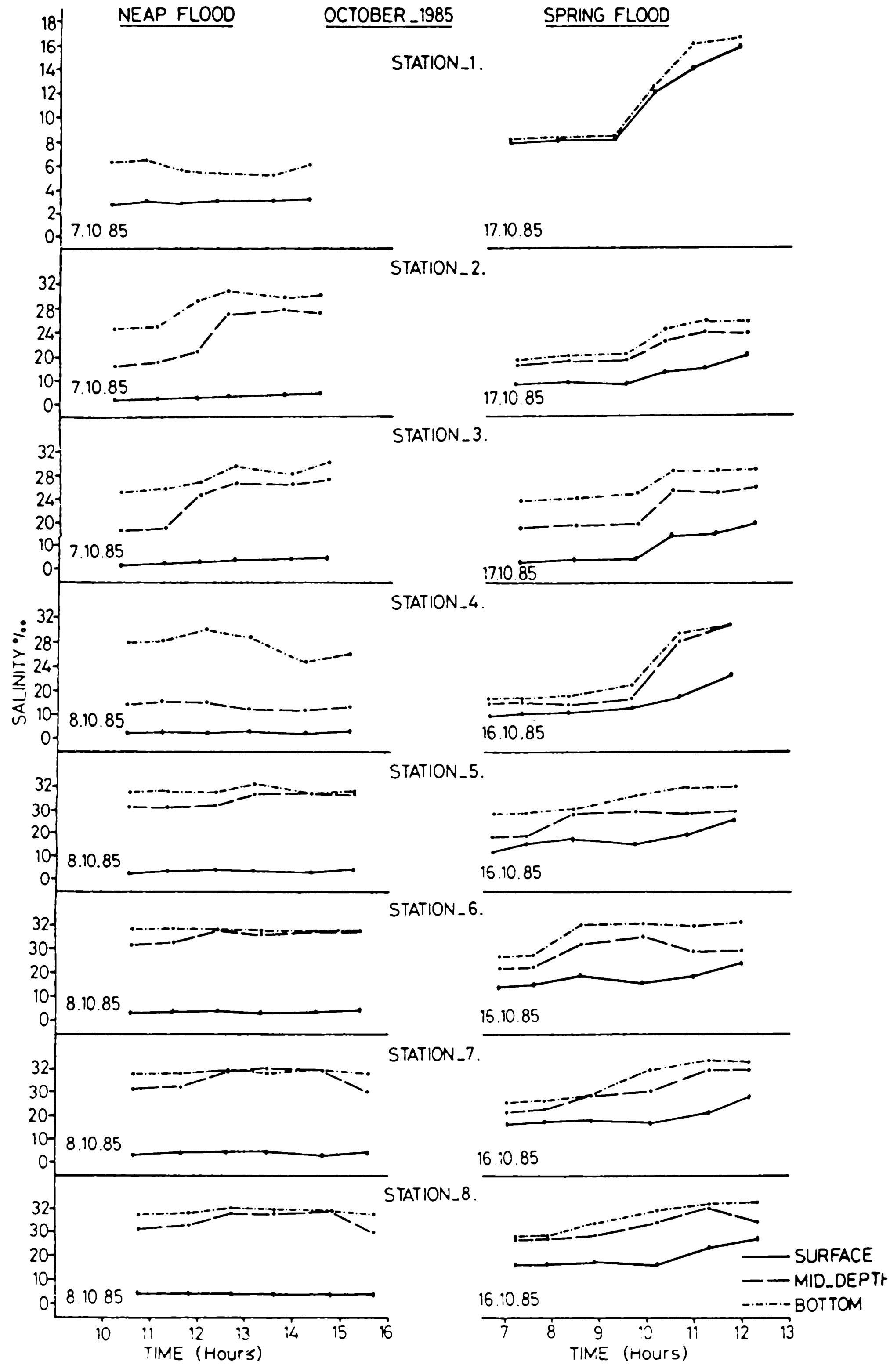


Fig.3.10 Tidal variations in salinity at stations 1-8 during neap flood and spring flood in October 1985

tide. The salinity of surface waters is found to be higher during spring flood than during neap flood. At estuarine mouth (stations 4-8), the highest salinity at bottom layers is found to lie between 30.0‰ and 32.8‰ and at stations away from the estuarine mouth (2 and 3), it is between 28.5‰ and 30.8‰. The mixing occurring at spring high is not prominent as in the previous months. This may be due to the short tidal range.

NOVEMBER (1985): Neap ebb, Spring ebb

Consequent to the decrease in river discharge, a gradual increase in salinity is noticed in the entire water column at all stations during November (Fig.3.11). The average durations of neap ebb (7 h 10 min) and spring ebb (7 h 25 min) are found to be more or less equal while the tidal ranges are 37 cm and 100 cm respectively.

Distribution of surface salinity shows distinct horizontal variations under both spring and neap tide conditions. Higher surface salinity (26.0‰-32.8‰) is observed at stations 6-8, located near the estuarine mouth and comparatively lower surface salinity (4.4‰-16.1‰) is observed at stations 1-3, located away from the estuarine mouth during both neap ebb and spring ebb tides. The stratification is clearly observable between surface and mid-depth at stations 1-5 and increases from high to low during both neap and spring tides. At stations 6-8, the stratification decreases, leading to partially mixed conditions during both neap and spring tides. In general, the mid-depth and bottom salinity values are found to be closer. Even-

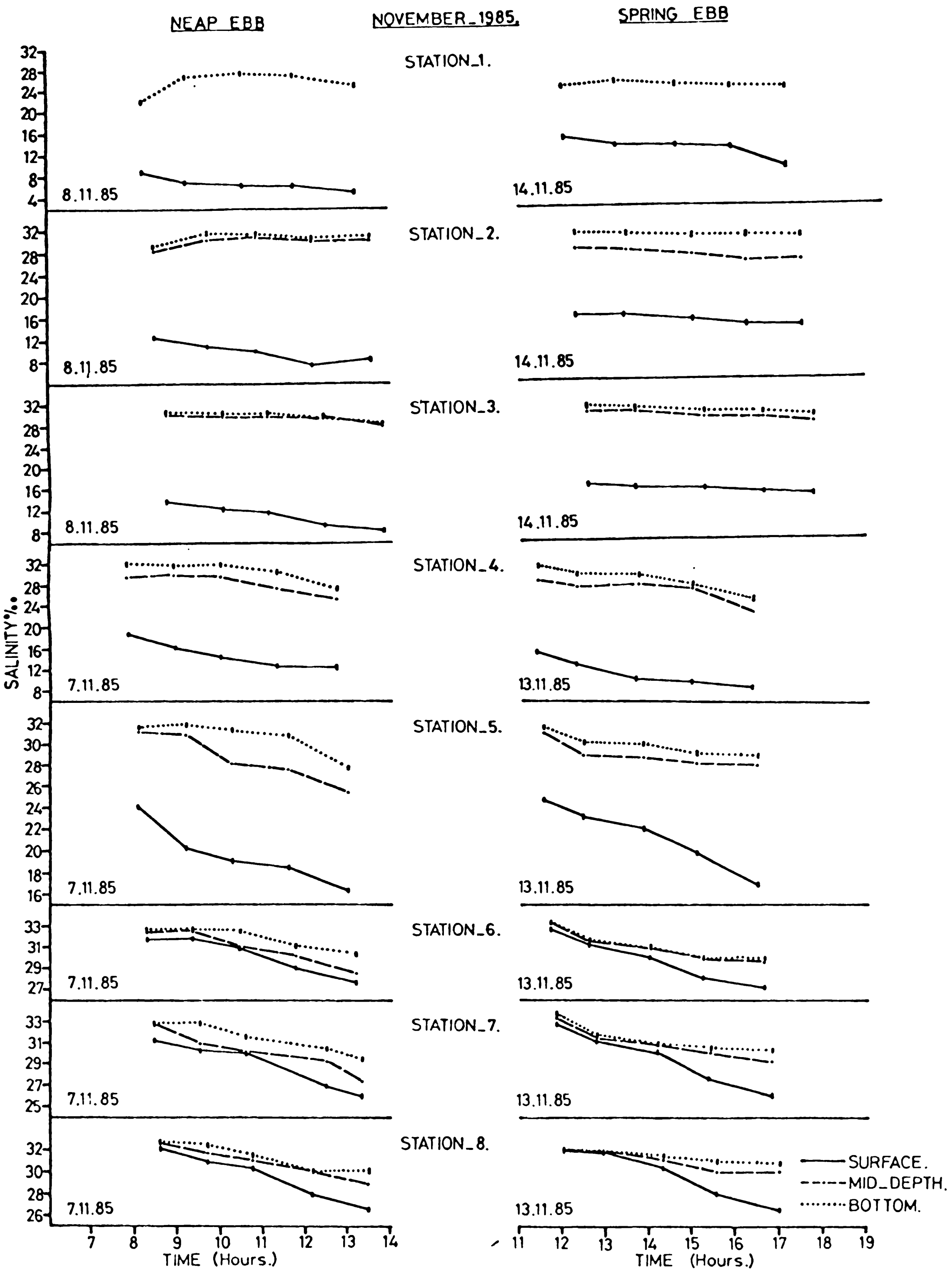


Fig.3.11 Tidal variations in salinity at stations 1-8 during neap ebb and spring ebb in November 1985

though station 1 is very shallow highly stratified conditions are observed between surface and bottom where, in 2 m depth, salinity increases by 10.1‰ during neap ebb and by 6.2‰ during spring ebb. Also, the variation of salinity during both neap ebb and spring ebb tides is low at stations 1-5 away from the estuarine mouth, and high at stations 6-8, located at the estuarine mouth.

DECEMBER (1985): Neap ebb, Spring ebb

With the cessation of monsoon rainfall, partially mixed conditions are found to develop during December. The average duration and range (7 h 20 min and 98 cm) during spring ebb are found to be higher than those during neap ebb (6 h 52 min and 53 cm). Generally, the vertical gradient and variation in salinity are found to be higher during neap ebb than during spring ebb (Fig.3.12).

At shallow regions (stations 1 and 4), the stratification is observed to be higher compared to the other stations during both phases of tides. At station 1, during ebbing phases of both neap and spring tides, the difference in salinity between surface and bottom waters are found to be nearly 9.0‰. During the previous months, the observations indicated mixed conditions at high tide and stratified conditions at low tide. This feature is not well pronounced during spring ebb, when almost constant salinity (variation $<$ 1.0‰) is observed at bottom and middle waters. The difference in salinity between mid-depth and bottom during both spring ebb and neap ebb is small (30.0‰ to 33.0‰ at stations 4-8, 27.0‰ to 30.5‰ at stations 2-3 and 24.9‰ to 27.0‰ at station 1). The lowest salinity

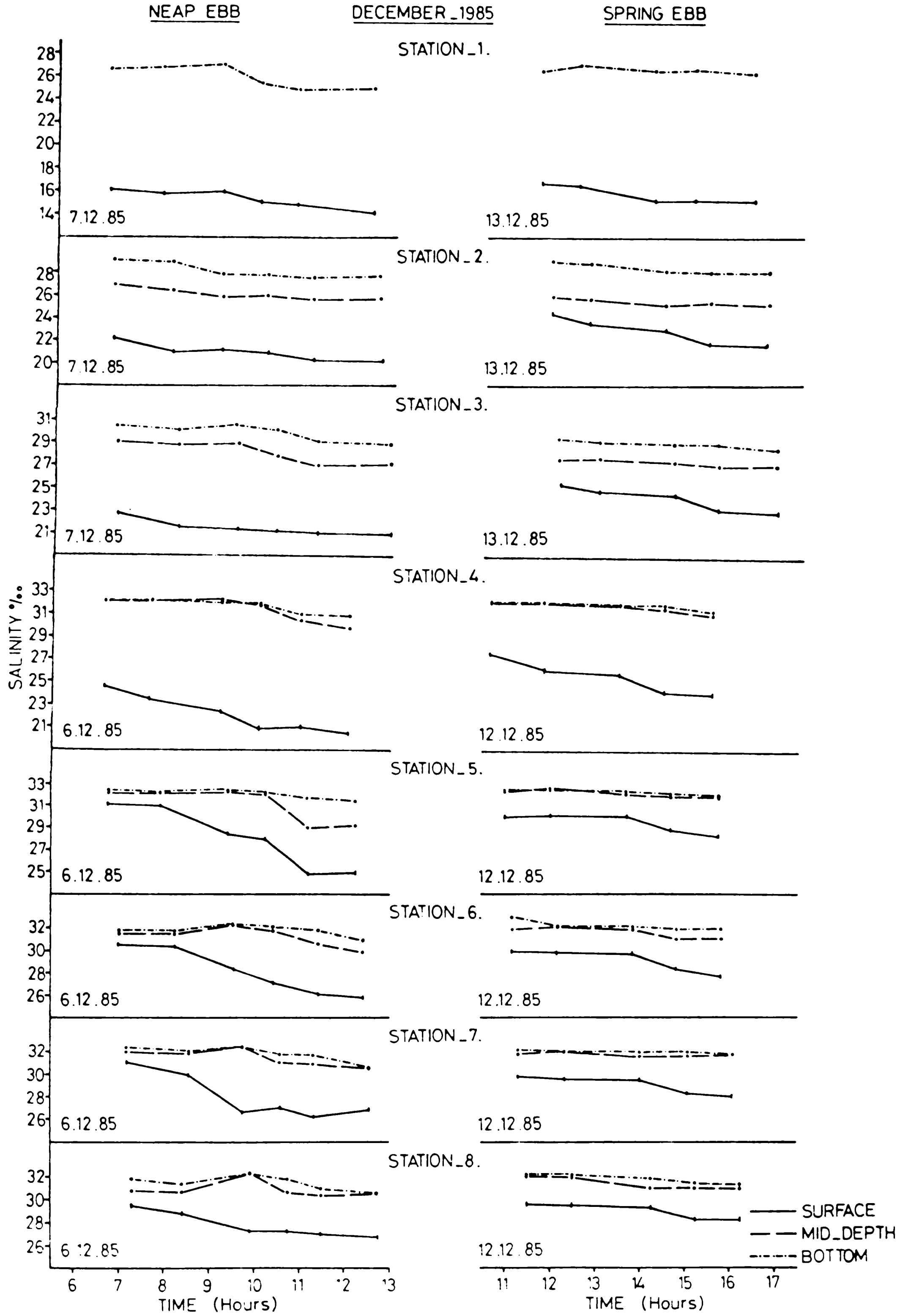


Fig.3.12 Tidal variations in salinity at stations 1-8 during neap ebb and spring ebb in December 1985

(14.1‰ to 16.8‰) is observed at the surface (station 1) during the period of observation. The variation in salinity at surface is slightly higher during neap ebb (24.9‰-31.1‰ at stations 5-8 and 20.5‰-24.5‰ at station 4) than during spring ebb. However, a weak horizontal salinity gradient always exists, with increasing salinity values towards the mouth.

JANUARY (1986): Neap flood, Spring flood

The salinity distribution during neap flood and spring flood of January (1986) shows that partially mixed conditions that existed during the previous month continues through January. Average tidal duration and range are 6 h 10 min and 39 cm respectively during neap flood while the corresponding values are 5 h and 34 cm during spring flood.

Higher salinity values are noticed during spring flood than during neap flood, but the range of variation is higher during neap flood (Fig.3.13). This is more prominent at stations 5-8. This feature can be explained by considering the tidal ranges during the neap flood and spring flood tides. While the duration and range are higher during neap flood, the low and high water levels are higher (0.58 m, 0.92 m) during spring flood. At station 4, surface salinity is the lowest (19.5‰) at neap low and increases sharply by about 4.0‰ in 2 m. In general, the salinity curves tend to converge towards the last stages of the flood tides, indicating that mixed conditions develop at high tides, as was observed in the previous months.

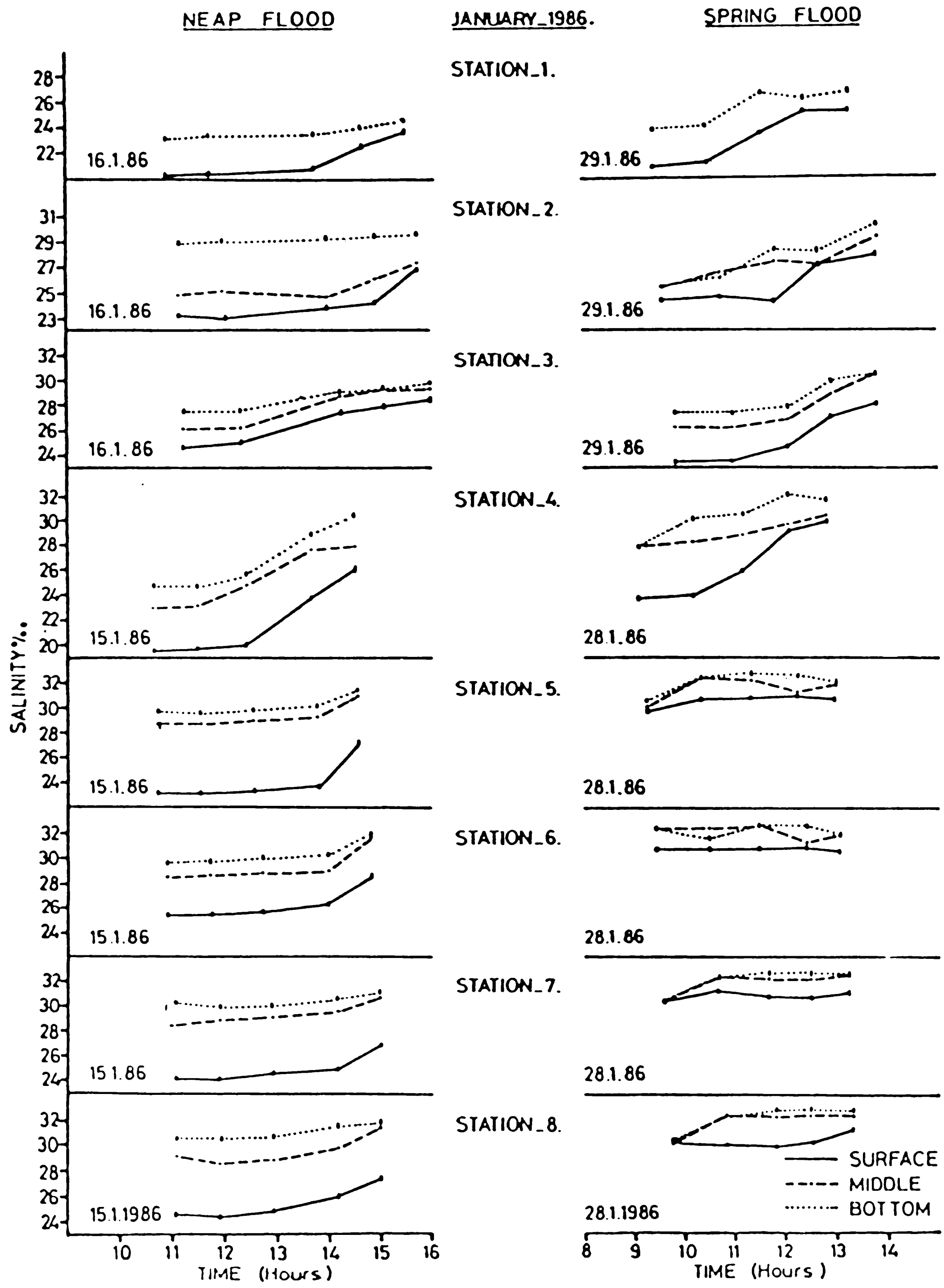


Fig.3.13 Tidal variations in salinity at stations 1-8 during neap flood and spring flood in January 1986

MARCH (1986): Spring flood, Neap flood

Almost homogeneously mixed conditions are observed during March (1986) (Pre monsoon season). During this month, the estuarine water shows higher salinity and the vertical gradients are very weak. The average duration (8 h 20 min) during neap flood is found to be higher than that during spring flood (6 h 55 min) while average ranges are almost equal (about 66 cm).

Higher salinity is observed at surface during spring flood than during neap flood (Fig.3.14). During neap flood, the variations in salinity are larger, especially at stations near the estuarine mouth. This may be due to the longer duration of neap flood. The vertical salinity gradients are weaker during spring flood than during neap flood, indicating higher mixing during spring flood. At spring high the vertical salinity gradient is negligible at almost all stations. The vertical salinity gradients are, in general, higher before mid flood during both spring and neap tides. During spring flood, the bottom salinity varies between 30.0‰ and 32.8‰ at the estuarine mouth. The least salinity observed at the bottom of station 1 varies between 25.0‰ and 30.4‰. The salinity at the surface during neap flood is found to be lower than 30.0‰ in the entire estuary. At stations 1-3, which are away from the estuarine mouth, the variation in salinity at the bottom is less than 1.5‰ during neap flood. Higher salinity (33.0‰) is reached at bottom at station 7 (neap high). At station 5, the salinity of the bottom layers is found to decrease from neap low to mid flood and increases

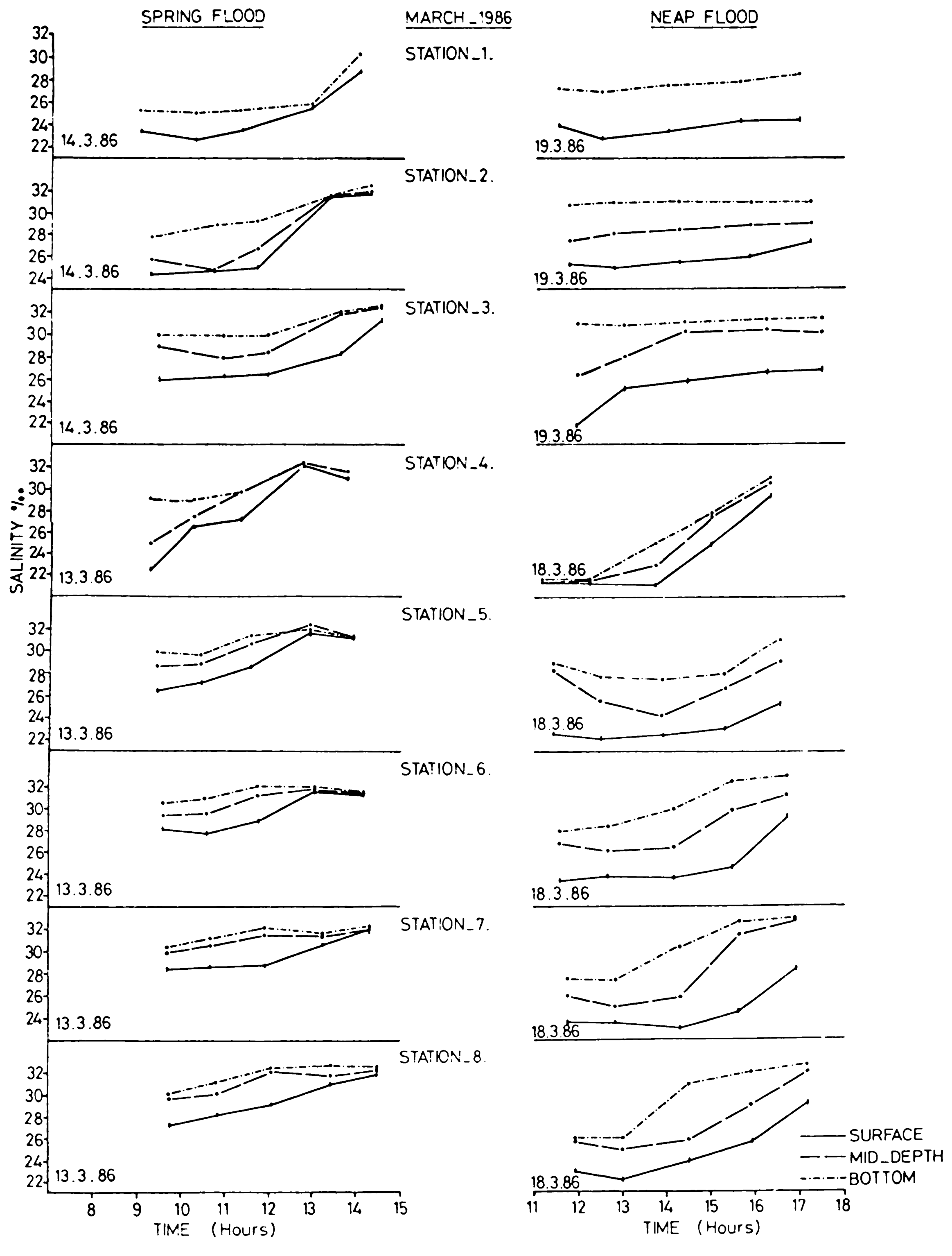


Fig.3.14 Tidal variations in salinity at stations 1-8 during spring flood and neap flood in March 1986

towards neap high. At neap high, the mixing is not well pronounced compared to the previous observations.

JUNE (1986): Spring flood, Neap flood

The salinity in the estuary is found to decrease considerably by the time the neap flood observations are taken (16-17 June 86), indicating considerable dilution by rain water and freshet. Generally, during active monsoon period, the tidal influence on salinity distribution is less significant. But the present observations on 11-12 June 86 during spring flood (average duration 8 h 8 min and range 81 cm) indicate that the tides influenced the salinity distribution considerably (Fig.3.15). The tidal influence decreased considerably by 16th June 86.

At the estuarine mouth the surface salinity increases from 22.2‰ (at spring low) to 32.4‰ (at spring high) and in regions away from the estuarine mouth, the increase is from 20.2‰ to 30.2‰. At all stations other than the shallow stations 1 and 4, stratified conditions are observed at spring low (the approximate vertical salinity gradient is found to be 8.0‰ within 10 m depth) and the mixed conditions are observed at spring high. The highest salinity (33.8‰) is observed at bottom of the estuarine mouth at spring high. During neap flood, the variation in salinity and salinity values are very low compared to spring flood. This may be due to the lower tidal range and duration and also increased fresh water discharge. During neap flood, the surface salinity varies between

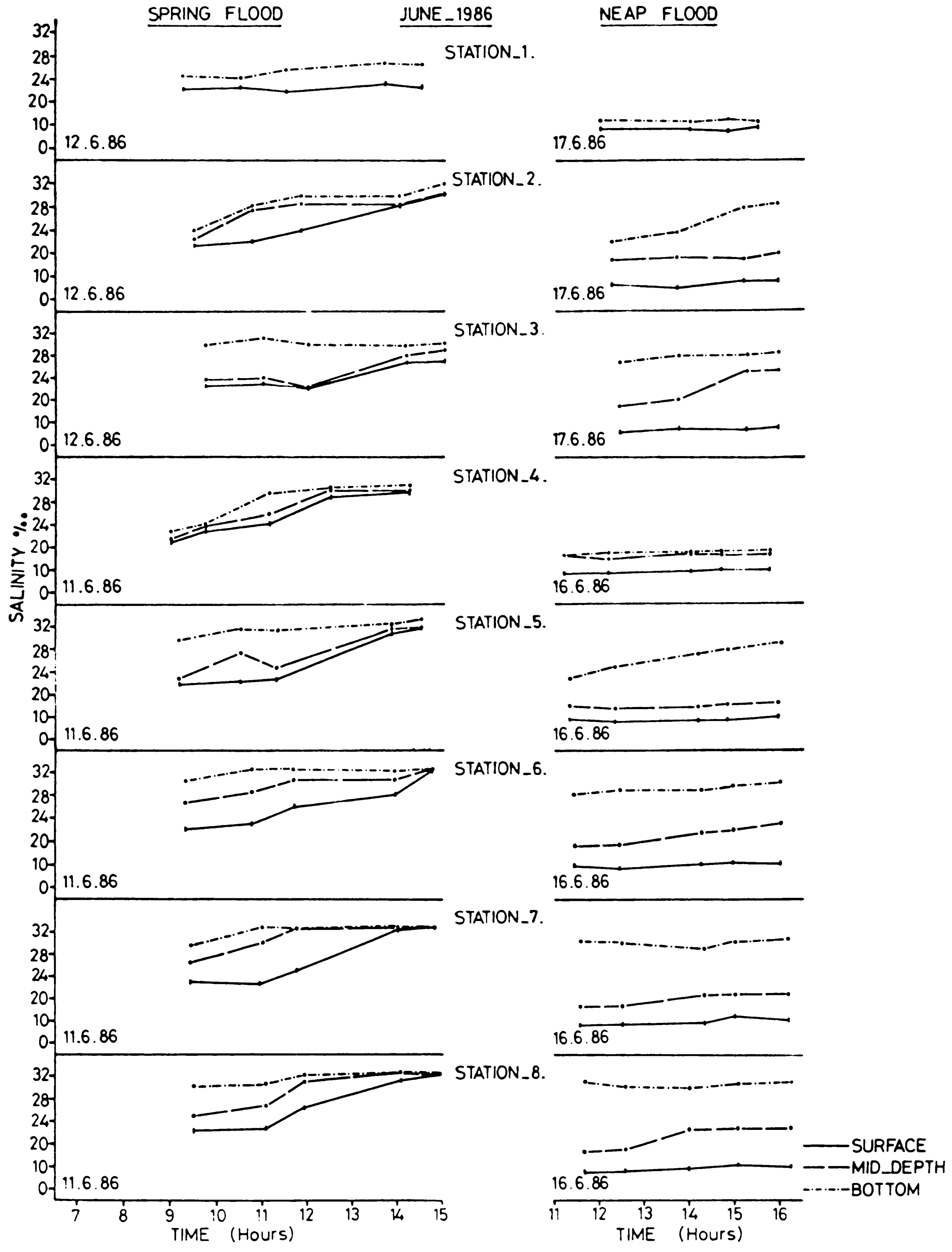


Fig.3.15 Tidal variations in salinity at stations 1-8 during spring flood and neap flood in June 1986

5.0‰ to 13.0‰ and the highest salinity is recorded as 31.2‰ at the bottom at station 7. Mixing causes higher variations in salinity at mid-depth layers during neap flood.

3.3.2 Estuarine Dilution and Flushing

River discharges into the estuary vary seasonally, sometimes quite drastically, and this is reflected in flushing of effluents within the estuary and in the salinity distribution. The amount of fresh water contained at any given location in the estuary can be calculated in terms of salinity at the same location using the equation

$$F = \frac{So - Sn}{So}$$

Where 'F' is the fraction of fresh water, 'Sn' is the salinity at any location inside the estuary and 'So' is the salinity of the 'Source' water (Ketchum, 1969; Officer, 1976). Using this method, Qasim and Sen Gupta (1981) studied dilution and flushing characteristics of the Mandovi - Zuari estuarine system, Sankaranarayanan et al (1986) at lower reaches of river Periyar and Zingde et al (1987) at Purna river estuary (Gujarat).

For the salinity of the 'Source' water the values at a station about 8 km away from the mouth of the estuary are taken. The average monthly fresh water fractions at different stations representing different areas of the estuary are calculated. Table 3.1 gives the fresh water fractions (F) and dilution factors (R) at different stations during the period of observations (1985-1986). It is seen that the fresh water content is the least at station 7 and the

TABLE 3.1

Fresh water fractions (F) and Dilution factors (R) at different stations during 1985-1986

Month		1985 APR.	MAY	JUL.	AUG.	SEP.	OCT.	NOV.	DEC.	1986 JAN.	MAR.	JUN.
Sea	(S‰)	36.21	36.43	32.35	32.43	34.45	34.57	35.13	35.68	36.21	36.09	33.48
	S‰	25.05	25.16	2.20	2.88	18.35	8.40	17.05	20.70	23.81	25.80	16.89
STN:1	F	0.31	0.31	0.93	0.91	0.47	0.76	0.51	0.42	0.34	0.29	0.50
	R	3.23	3.23	1.08	1.10	2.13	1.32	1.96	2.38	2.94	3.45	2.00
	S‰	27.15	27.75	12.20	12.60	26.05	19.20	23.80	25.31	27.00	28.31	21.83
STN:2	F	0.25	0.24	0.62	0.61	0.24	0.44	0.32	0.29	0.25	0.21	0.35
	R	4.00	4.17	1.61	1.63	4.17	2.27	3.13	3.45	4.00	4.76	2.86
	S‰	27.35	28.85	12.30	12.90	26.34	20.10	24.09	26.42	27.92	29.23	22.01
STN:3	F	0.24	0.26	0.61	0.60	0.23	0.42	0.31	0.26	0.23	0.19	0.34
	R	4.17	3.85	1.62	1.67	4.35	2.38	3.23	3.85	4.35	5.26	2.94
	S‰	27.30	28.40	6.33	8.40	23.55	18.90	22.40	28.60	26.50	28.21	20.59
STN:4	F	0.25	0.22	0.80	0.74	0.32	0.45	0.36	0.20	0.27	0.22	0.38
	R	4.00	4.55	1.25	1.35	3.13	2.22	2.28	5.00	3.70	4.55	2.63
	S‰	29.00	30.35	13.50	15.90	27.90	24.20	30.40	30.60	30.30	29.40	24.80
STN:7	F	0.20	0.17	0.58	0.51	0.19	0.30	0.15	0.14	0.17	0.19	0.26
	R	5.00	5.88	1.72	1.96	5.26	3.33	6.67	7.14	5.88	5.26	3.85
Average	$\bar{F}$	0.25	0.24	0.71	0.67	0.29	0.47	0.33	0.26	0.25	0.22	0.37
Average	$\bar{R}$	4.00	4.17	1.41	1.49	3.45	2.13	3.03	3.85	4.00	4.55	2.70

highest at station 1 during all months. Also, fresh water content is slightly higher at Ernakulam channel (station 2) than at Mattancherry channel (station 3), showing that the influence of fresh water discharge from rivers and land areas is more in the Ernakulam channel.

Some longitudinal variations in salinity may, however, exist, but it is assumed that they may not be very significant in the Cochin estuary, as the estuary is tide-dominated and remains almost homogeneous for a greater part of the year. Therefore, the salinity values at all the stations during different months are averaged and used as an approximation for the general conditions. Fig.3.16 shows the variations of fresh water fractions corresponding to dilution factors in different months during the period 1985-1986. It can be seen that the fresh water fraction is very large (0.71 in July 1985) during south-west monsoon period and the least (0.22 in March 1986) during pre monsoon period. The fresh water content increases from September (0.29) to October (0.47) and decreases afterwards. Higher values of dilution facator (4.00 to 4.55), inverse of the fresh water fraction, occur during pre monsoon season when the fresh water flow is negligible. Any pollutant, therefore, released to the estuarine system during this season will be diluted more than 4 times by the sea water before it finally reaches the open sea. During south-west monsoon season, dilution by sea water is minimum.

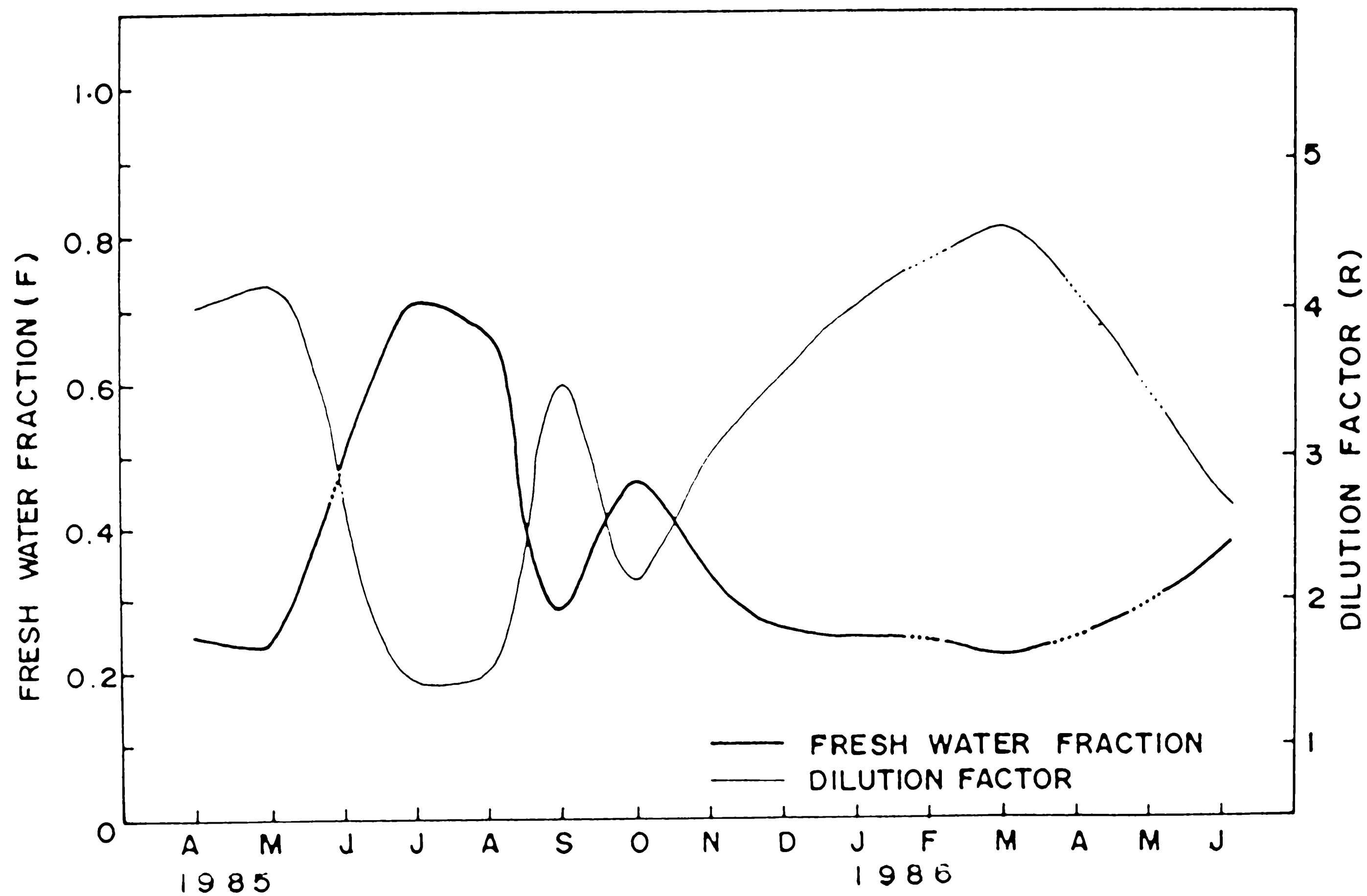


Fig.3.16 Monthly variation of fresh water fraction and dilution factor during 1985-'86.

CHAPTER - IV

4. CIRCULATION AND STRATIFICATION

4.1 Introduction

4.2 Estuarine Circulation

4.3 Volume Transport across Cochin Inlet

4.4 Stratification and Circulation Parameters

4. CIRCULATION AND STRATIFICATION

4.1 Introduction

The prediction and understanding of tide-induced currents in estuaries and inland water bodies are practical tasks of importance. These currents are especially significant in the vicinity of tidal inlets and estuarine mouths where they influence navigation, intrusion of salt water and morphological changes (Ozsoy and Unluata, 1982). The importance of estuarine circulation is obvious in problems related to discharge of effluents.

It is well known that tidal currents in channels may be asymmetric, i.e., in some channels the ebb is stronger than the flood, while in others, the reverse is true. The asymmetry between flood and ebb currents influences the residual tidal stress at the bed (Huthnance, 1973; Uncles, 1981). However, the law of conservation of volume requires that transport through the upstream section must equal the transport through the downstream section. In estuaries, changes in direction of tidal currents occur over relatively short periods of time (Swenson and Chuang, 1983). At the Bombay harbour, tidal currents are of translatory type and change from flood to ebb quickly, within about 1½ h (John and Pai, 1982). Pillai et al (1973) observed that at Cochin barmouth the tidal flow did not follow the predicted ebb and flood periods.

The circulation of water within an estuary is governed mainly by strong tidal oscillations on which residual water circulations are superimposed. These residual circulations may be generated by non-linear interactions between the tidal flow and estuarine topography, density gradients, wind stress and the mass input due to fresh water discharge into the estuary (Uncles and Jordan, 1979; Bowden, 1984). Tidal currents generate turbulence which causes vertical mixing that reduces the stability and influences the density circulation. When the mixing is not significant, the circulation approximates to two distinct layers in which the upper less saline layer moves seaward and the lower more saline layer moves up the estuary (Pritchard, 1952, 1954; Inglis and Allen, 1957). Fischer (1972) and Murakami (1986) are of opinion that the transverse circulation is more important than the vertical circulation with respect to longitudinal mass transport. The constant flow, such as the tidal circulation, density-induced flow or wind driven flow, is more important than the oscillatory (tidal) flow so far as material transport during long periods (a few months or longer) is concerned (Kunishi and Unoki, 1977; Murakami et al, 1985). The efficiency of tidal mixing and hence the importance of the relationship between the tides and wind-driven circulation is obviously dependent on the strength of the density stratification (Provis and Lenon, 1983).

For the Cochin estuary, detailed information is not available on the intensity of the currents and the associated exchange and mixing of the estuarine water with the coastal waters. Results of investigations aimed at obtaining a comprehensive picture of the circulation pattern during different phases of the tides are presented in this chapter. Volume transport across the harbour entrance is also investigated. Within the estuary, the fresh water flow is constantly pushed back and forth by tidal currents and therefore, a knowledge of the instantaneous current distribution is important. The monthly flow patterns at different tidal phases during 1985-86 are presented as vector diagrams in Fig.4.1 to 4.11. The monthly and tidal variations in the velocity field are discussed in the following section.

4.2 Estuarine Circulation

APRIL (1985): Spring flood, Neap ebb

During April, the flow variations show close relation with the tidal conditions, due to the reduced river discharge. Fig.4.1 shows the tidal variations of surface, middle and bottom currents at stations 3-8. Stations 1 and 2 do not show any consistent tidal variations in the velocity field. At these stations, the vectors indicate that disturbances due to shallowness and proximity of islands are by far greater than the tidal influences.

The speed of currents is, in general, higher during spring flood than during neap ebb at stations 4-8. At station 3, the highest velocities are recorded as 50 cm/sec at bottom during flood tide and 77 cm/sec at surface during ebb tide. The velocity of flow increases after the mid tides. During mid flood, at station 4, the flow is directed inwards to the north. The highest speed (99 cm/sec) is recorded at mid-depth during flood tide. During ebb tide the currents flow seawards, changing from NNW to SSW.

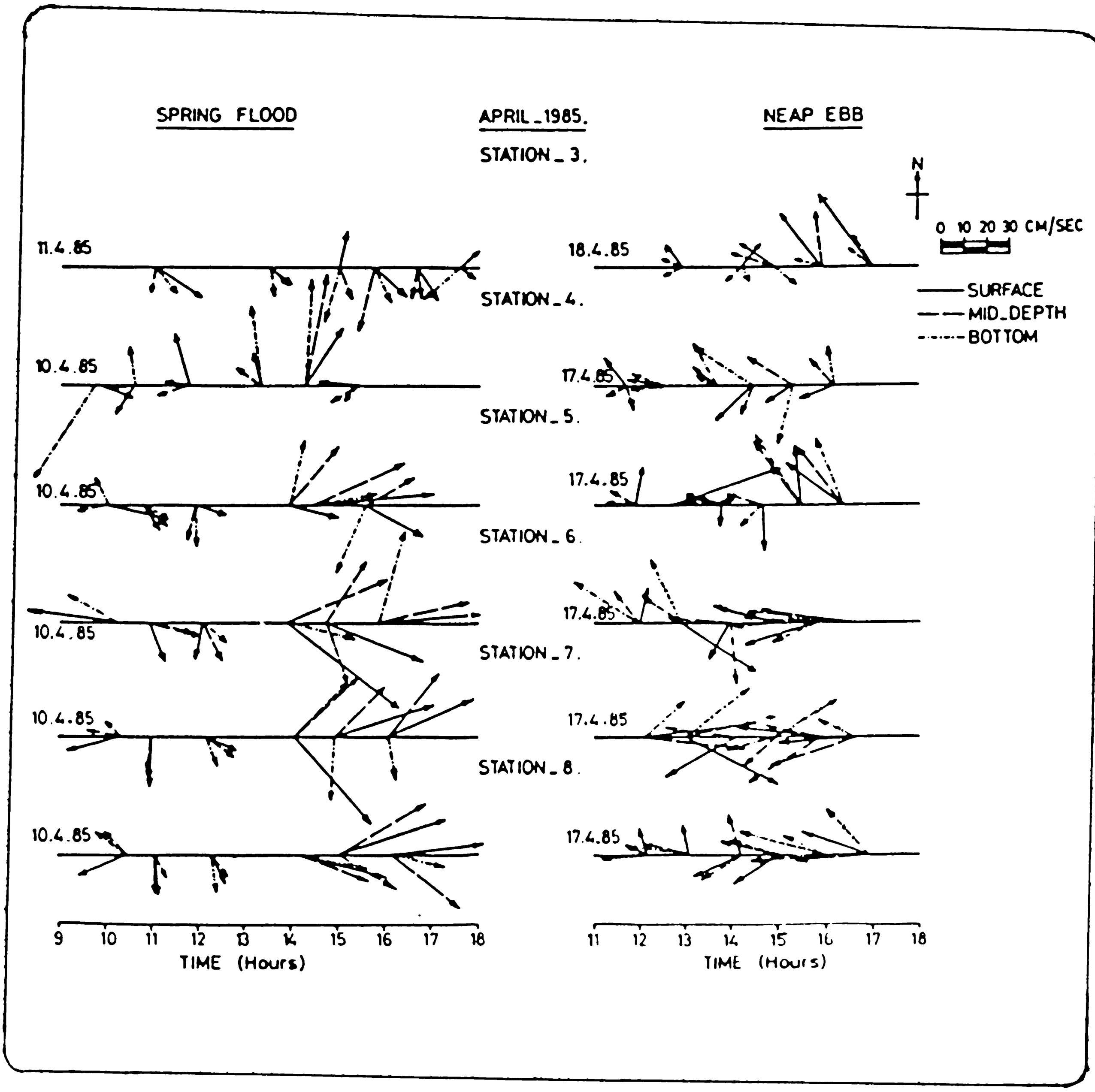


Fig.4.1 Tidal variations in currents at stations 3-8 during spring flood and neap ebb in April 1985

Almost identical pattern is observed at stations 5 to 8 during flood tide with the inflow starting before the mid flood stage of the tide. During flooding, the flow is generally directed between NNE and SSW and during ebbing the currents are directed between NNW and S. The highest current velocities are recorded as 125 cm/sec (at surface) at station 6 and 98 cm/sec (at surface) at station 7 during flood and ebb tides respectively. Flood currents are faster and lasts for about 3 h 40 min while ebb currents are comparatively slower and lasts for over 3 h 55 min. Higher speeds are observed at mid tide, but during the neap tide higher velocities are also recorded at the end of the ebb.

MAY (1985): Neap ebb, Spring flood

The flow velocities show large dependence on the tidal range during May (Pre monsoon). Higher velocities are associated with the higher tidal range of flood (about 85 cm) than ebb (about 17 cm). The higher velocities are observed at stations 2 and 5 during ebb tide (56 cm/sec) and at station 5 during flood tide (124 cm/sec) at the surface (Fig.4.2). At station 4, very weak currents ($<$10 cm/sec) are recorded at initial stage of flood tide. On some occasions the flow is inconsistent in direction due to local disturbances. Generally, higher velocities are recorded at the surface during both flood and ebb tides.

At station 1, which is very shallow (about 1.5 m deep), the currents are weak, showing no consistent directions during both flood and ebb tides. At stations 5-8, during the initial stage of flood tide, weak

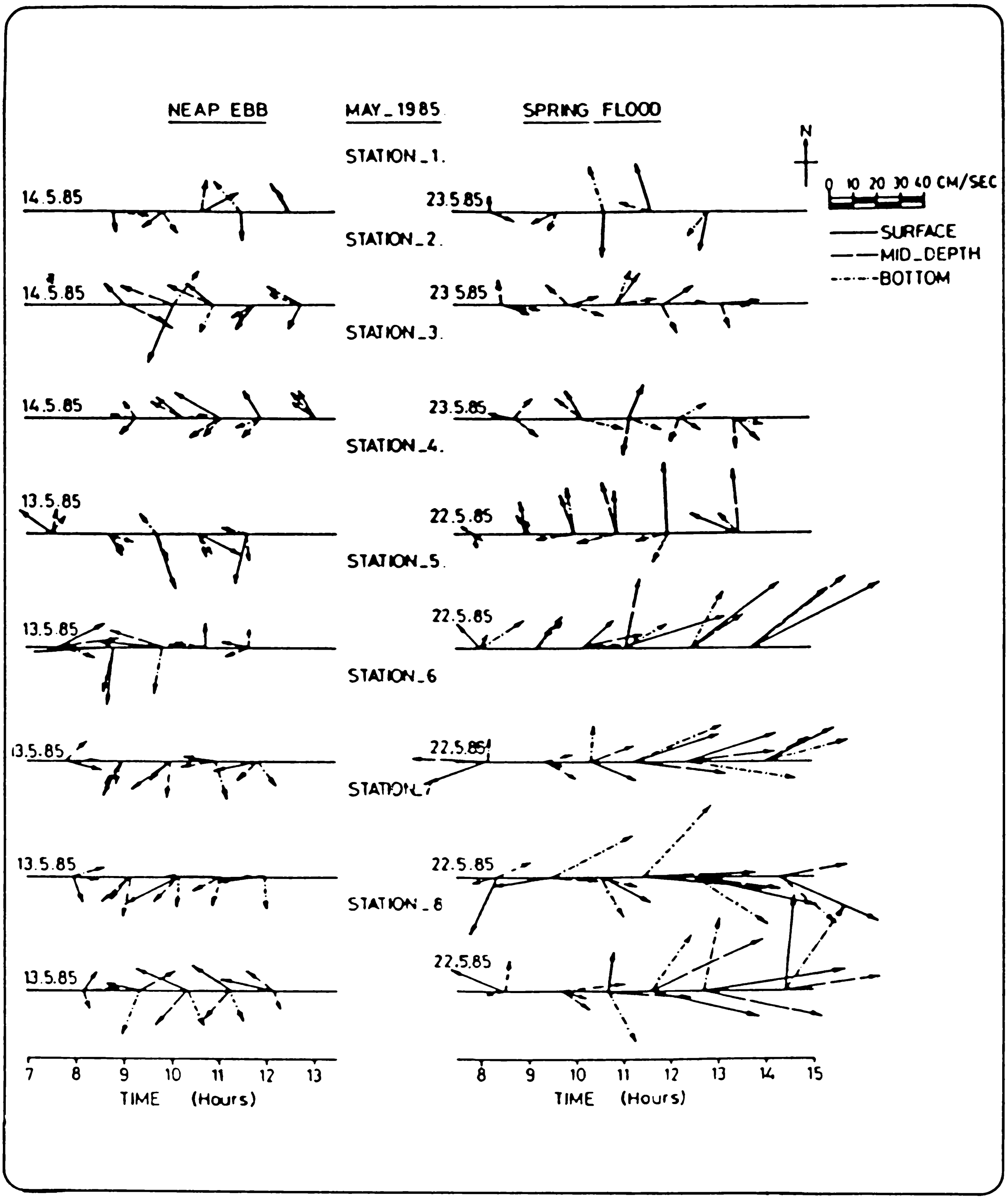


Fig.4.2 Tidal variations in currents at stations 1-8 during neap ebb and spring flood in May 1985

outward flows directed between NE and SE are observed. The ebb currents start earlier at stations 2-3, located away from the estuarine mouth than at stations 5-8, which are located near the estuarine mouth. At the estuarine mouth, the general flow is directed between WNW and SSW during ebb tide. Within the short ebb tide range, no marked variations are observed in the magnitude of ebb currents at all stations. At all the stations the current speeds frequent in the range 20 cm/sec-50 cm/sec.

At stations 5-8, the flood currents exhibit a time lag of about 2 h with the tide. At the estuarine mouth (stations 6-8), the currents are directed generally between SE and NE while at station 5, they are between NNE and ENE. At station 4, the flood tide is directed between NNW and WSW. An increase in speed is noticed after mid flood at stations 5-8. The magnitude of flood currents is more or less equal at both Mattancherry and Ernakulam channels during this month.

JULY (1985): Neap ebb, Spring flood

The estuarine circulation is greatly influenced by the increased discharge of fresh water during July. The flow pattern during neap ebb (average tidal range: 4 cm, average duration: 4 h) appears inconsistent and complicated (Fig.4.3). In Combarjua canal connecting Mandovi and Zuari estuaries, Das et al (1972) observed that the irregularities in the current pattern are prominent when the tidal range is very low. In the Cochin estuary, it is also seen that the magnitude of flood currents is weaker than that of ebb currents

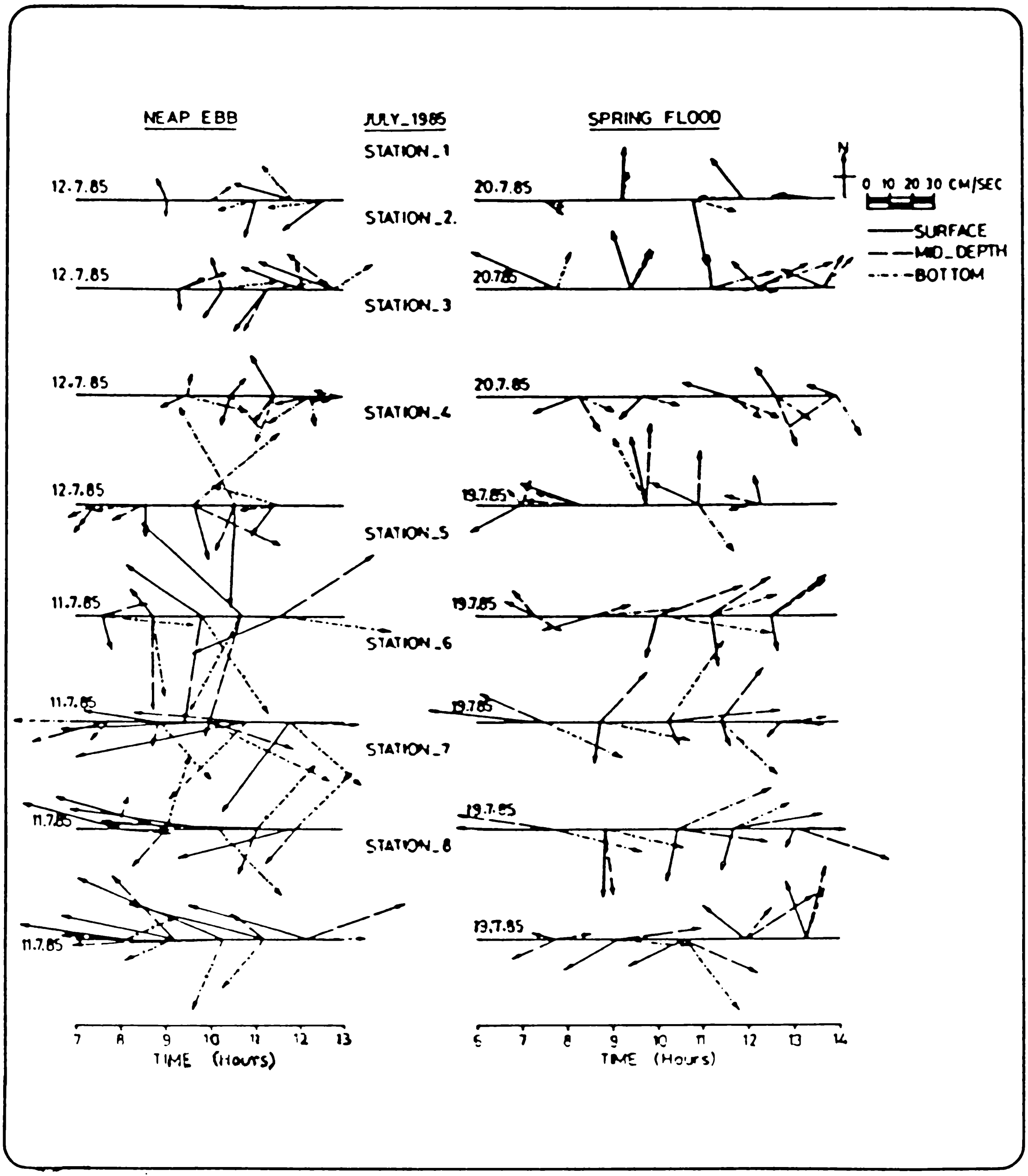


Fig.4.3 Tidal variations in currents at stations 1-8 during neap ebb and spring flood in July 1985

eventhough the tidal range (90 cm) and duration (7 h 50 min) are higher for flood tides.

In spite of weak currents related to the short tidal range and duration of neap ebb, the magnitudes of outflowing ebb currents are generally high at the estuarine mouth. This brings out the contribution by the fresh water discharge on the estuarine circulation, especially during south-west monsoon season. There is no consistency in direction of mid-depth and bottom currents during the ebb period. Ernakulam channel shows stronger ebb currents (highest velocity is 64 cm/sec at surface) than Mattancherry channel (highest velocity is 58 cm/sec at bottom). At the estuarine mouth, the outflowing surface currents are directed between WSW and NW and the highest velocity (158 cm/sec at surface) is recorded at station 6.

During spring flood, two layer flows are observed with weak surface currents flowing outwards. Negative shear is observed at the estuarine mouth during flood tide. The flood currents at surface layers flow against the fresh water discharge, giving rise to a weaker surface flow. The two layer flow exists prominently only for the first few hours. Highest current velocity (104 cm/sec at bottom) is recorded at mid flood at station 5, flowing towards ESE. During spring flood, the flood currents are first noticed at the bottom which gradually reaches the surface (Varma et al, 1981). Higher magnitudes of currents are observed at the estuarine mouth during both ebb and flood tides.

AUGUST (1985): Neap flood

The flow of flood currents is well marked during neap flood which has period of 7 h 10 min and range of 55 cm. As in July, negative shear flow is observed which is conspicuous at station 4. In the Mattancherry channel (station 3), slack water conditions are observed at bottom during the first few hours (marked as $\oplus$ in Fig.4.4), and bottom currents are found to be directed between SE and SSE after mid flood. Stronger flood currents are observed in the Mattancherry channel than in the Ernakulam channel. This may be due to the higher fresh water discharges in the Ernakulam channel, providing opposing force to the flood tide.

At the estuarine mouth (Stations 6-8) almost uniform flow pattern is maintained throughout the flood tide. At these stations, the currents are directed between SSW and SSE in the initial stage of the flood tide and between ENE and ESE thereafter. Higher magnitudes of currents are recorded at mid flood at almost all stations and the highest current is recorded (129 cm/sec at mid-depth) at station 6. Weaker currents are recorded at stations 1-4, where the magnitude of currents varies from 27 to 85 cm/sec during the entire flood tide. At estuarine mouth (stations 6-8) the currents are stronger, varying between 42 cm/sec and 129 cm/sec.

SEPTEMBER (1985) : Spring flood, Neap ebb

Stronger currents are observed at stations 5-8 during flood tide and at stations 2-3 during ebb tide. Weak reverse currents are also

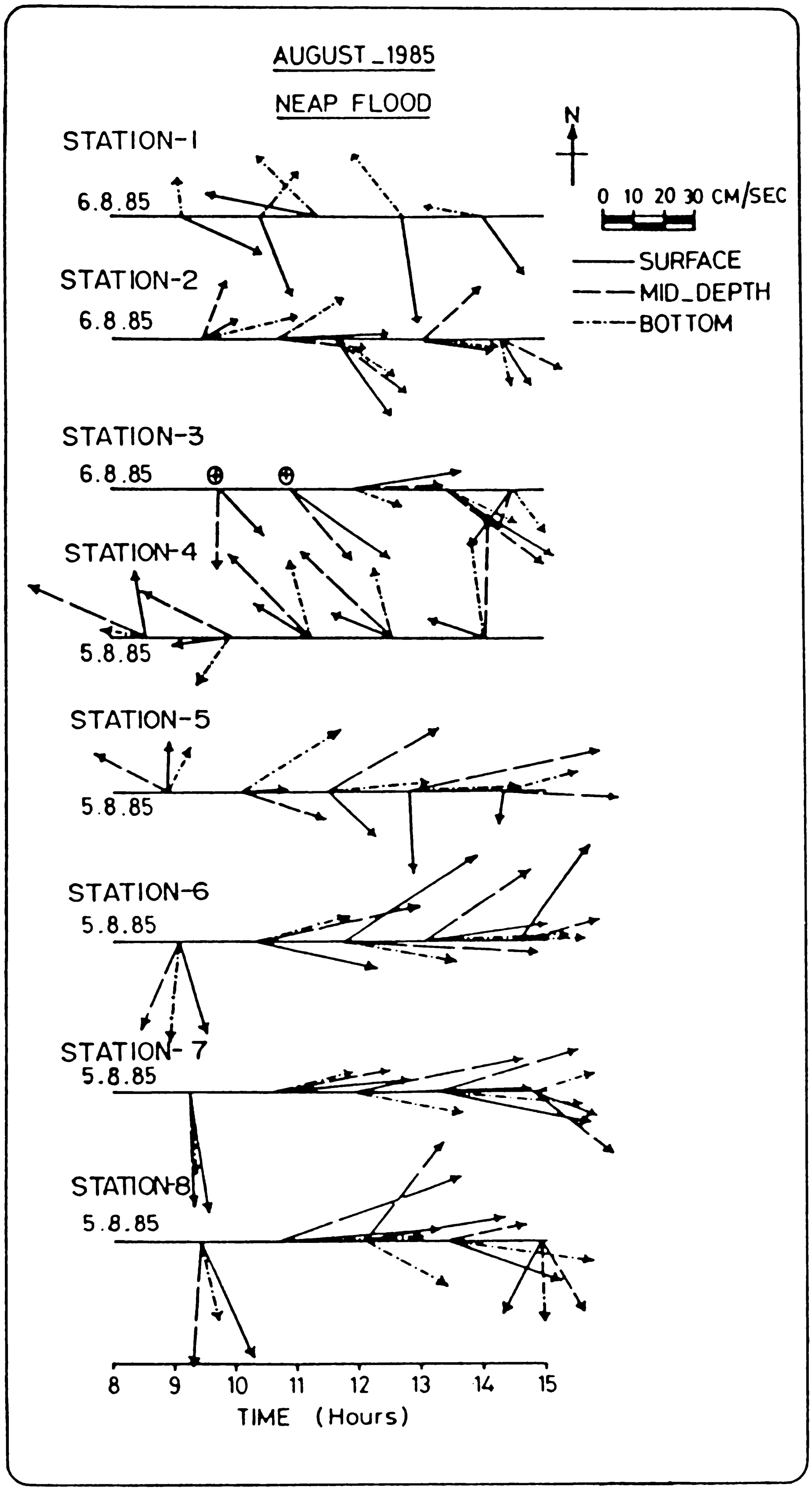


Fig.4.4 Tidal variations in currents at stations 1-8 during neap flood in August 1985

observed during both flood and ebb tides, caused probably by local disturbances. At station 1, relatively stronger currents are recorded during neap ebb, eventhough the tidal range is shorter than during the flood tide (Fig.4.5). The currents are directed almost in the same direction (predominantly ENE and NNE) during both spring flood and neap ebb tides indicating that the flow pattern is not primarily controlled by the tides at this station.

There are no marked variations in magnitude of currents at the Mattancherry and Ernakulam channels during both phases of the tides. At station 3, the currents at the three depths flow between ENE and NNE throughout the ebb period. The highest magnitude of currents during spring flood (121 cm/sec at surface) is recorded at station 7 and during neap ebb (101 cm/sec at surface) at station 3. At stations 1-4, the magnitude of currents varies between 21 cm/sec and 75 cm/sec and at stations 5-8, between 82 cm/sec and 121 cm/sec during spring flood. The corresponding values for neap ebb are 28 cm/sec-101 cm/sec (stations 1-4) and 23 cm/sec - 96 cm/sec (stations 5-8). Generally, higher magnitudes of currents are observed during mid tide at regions away from the estuarine mouth, but at the estuarine mouth stronger flows are encountered also towards the last stage of the tides during both flood and ebb tides. This may be because of the time lag in the reversal of currents.

<u>OCTOBER (1985): Neap flood, Spring flood</u>

During October, observations have been carried out during the flooding stages of both neap and spring tides (Fig.4.6). The irregu-

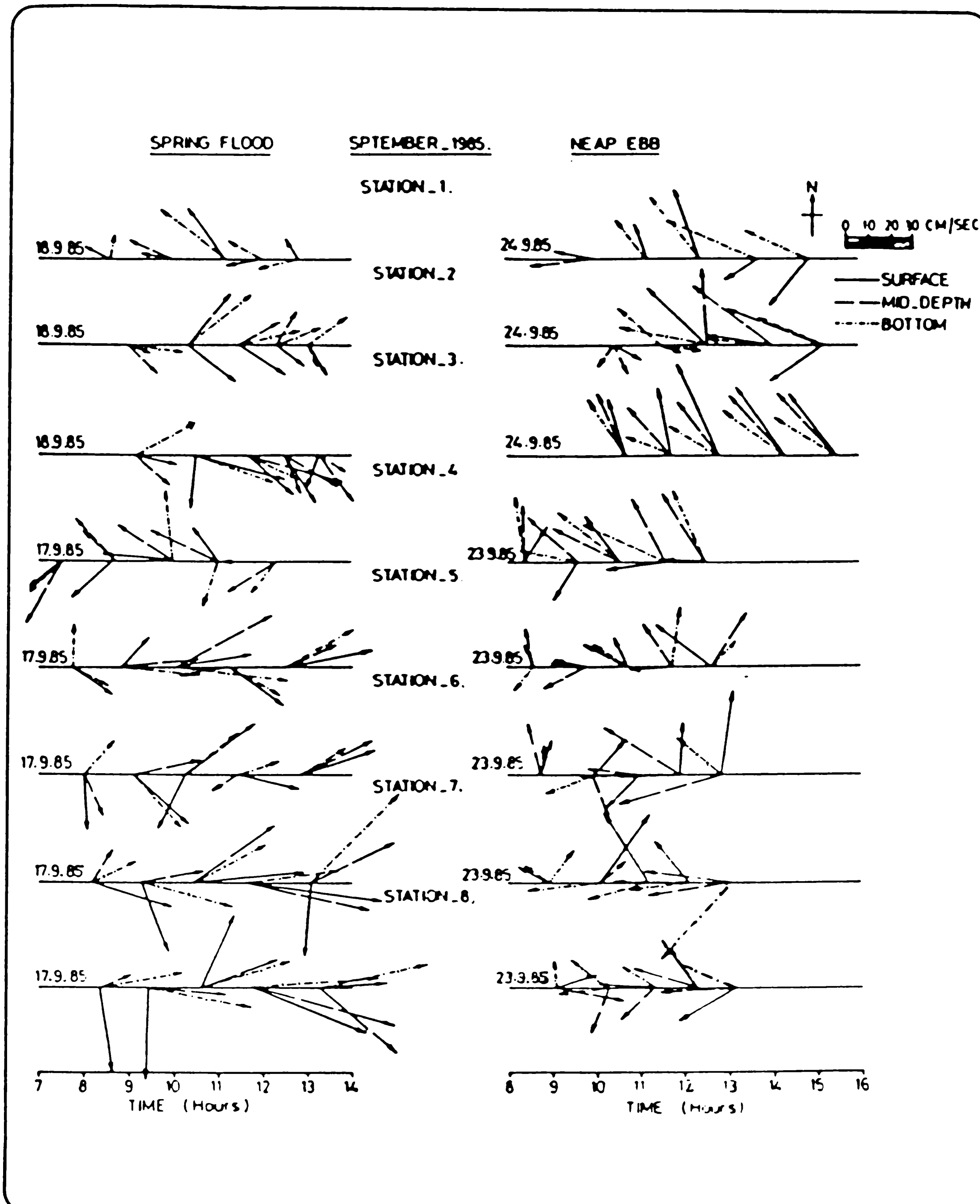


Fig.4.5 Tidal variations in currents at stations 1-8 during spring flood and neap ebb in September 1985

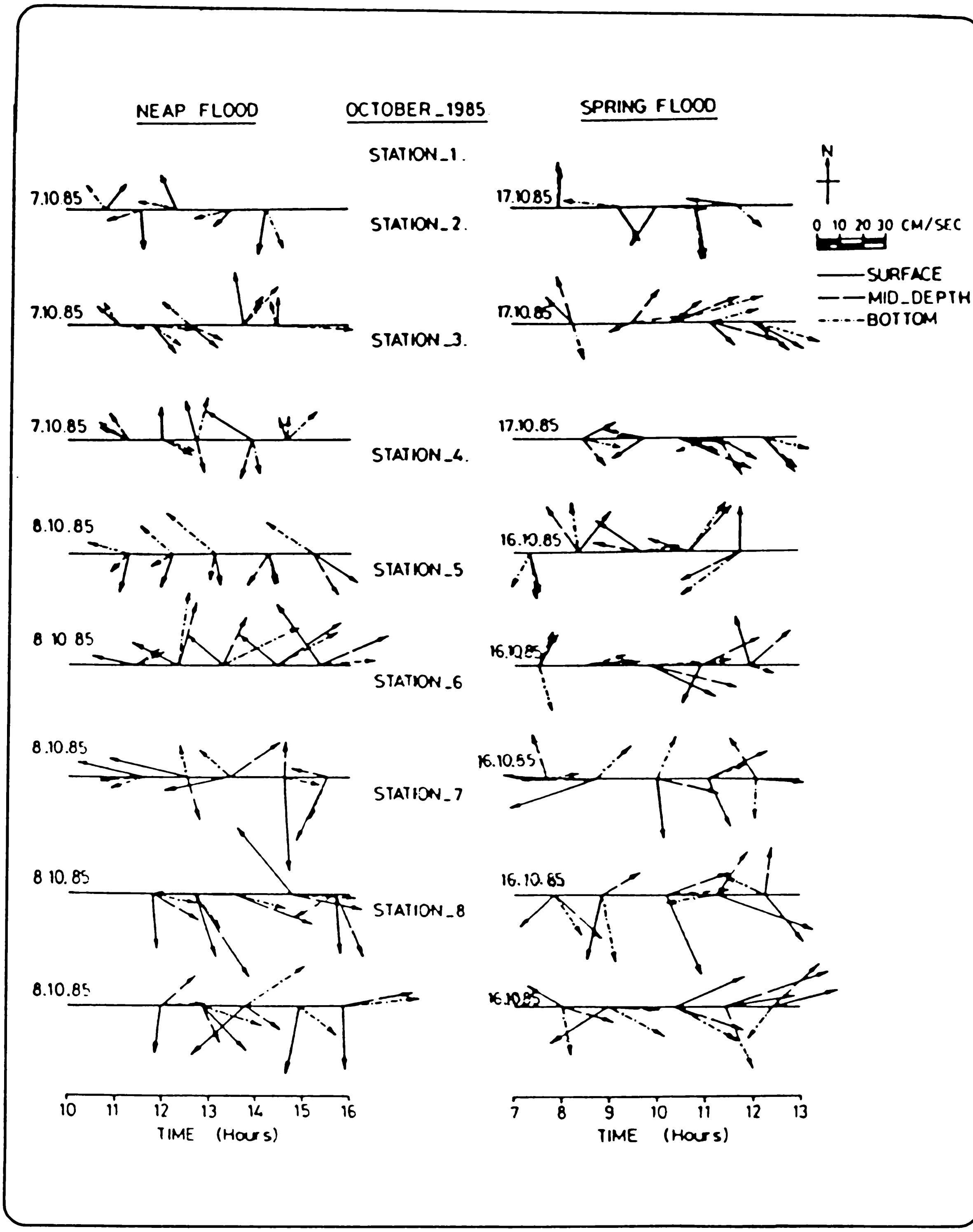


Fig.4.6 Tidal variations in currents at stations 1-8 during neap flood and spring flood in October 1985

larities in the flow related with very short tidal range ($<$ 8 cm) of neap flood are well marked. During this period, direction of flow shows no consistency at stations other than 4 and 5. At station 4, bottom currents are generally directed between NW and WNW and surface and mid-depth currents are directed between WSW and SE throughout the tide. At station 5, inflow is observed at bottom and mid-depth layers and outflow is recorded at surface layers throughout the period. There are no marked variations in the magnitude of currents at stations 2-4, but little higher values are recorded at stations 5-8. The magnitude of currents at stations 1-4 varies between 20 cm/sec and 46 cm/sec and at stations 5-8, between 25 cm/sec and 81 cm/sec.

The tidal range of spring flood is short (about 35 cm) and the flooding becomes prominent after the first few hours. At most of the stations, almost opposing directions of flow occur, especially at the surface, within 2 h. In general, negative shear flows (highest current velocity is 81 cm/sec at bottom; station 2) are observed at stations away from the estuarine mouth and positive shear flows (highest current velocity is 86 cm/sec at surface; station 7) at stations near the estuarine mouth. At stations 1-4, the magnitude of currents varies between 20 cm/sec and 81 cm/sec and at stations 5-8, between 18 cm/sec and 86 cm/sec.

NOVEMBER 1985): Neap ebb, Spring ebb

During November, the ebb currents are more disturbed during neap ebb than during spring ebb, especially during the initial stages

(Fig.4.7). The influence of higher tidal range of spring ebb is well reflected in the magnitude of currents. At station 1, however, higher magnitudes of currents are recorded during neap ebb with a negative shear flow. During neap ebb, at this station, the bottom currents vary between 32 cm/sec and 61 cm/sec, while surface currents vary between 26 cm/sec and 42 cm/sec. Higher magnitudes of currents are observed, in general,at mid tide of both neap ebb and spring ebb. Slightly higher magnitudes of currents are observed at Ernakulam channel during both ebb tides. Almost smooth outward flows are observed at stations 5-8 during spring ebb. During both the ebb tides, the surface layers are found to flow faster than bottom and middle layers. Higher speeds are observed at stations near the estuarine mouth.

Two-layer flows exist at station 3, after the first few hours of the spring ebb when the flows in the surface and intermediate layers are directed between NW and WNW, and in the bottom layers they are directed SE. On certain occasions, the current values at the intermediate level are higher than at the surface and bottom. The highest current velocities recorded are 80 cm/sec (at surface, station 7) during neap ebb and 112 cm/sec (at surface, station 7) during spring ebb. The speed of currents at stations 2-4 varies from 22 cm/sec to 57 cm/sec and at stations 5-8 from 25 cm/sec to 80 cm/sec during neap ebb. Similarly, during spring ebb, at stations 2-4, the currents vary between 23 cm/sec and 62 cm/sec and at stations 5-8, between 20 cm/sec and 112 cm/sec.

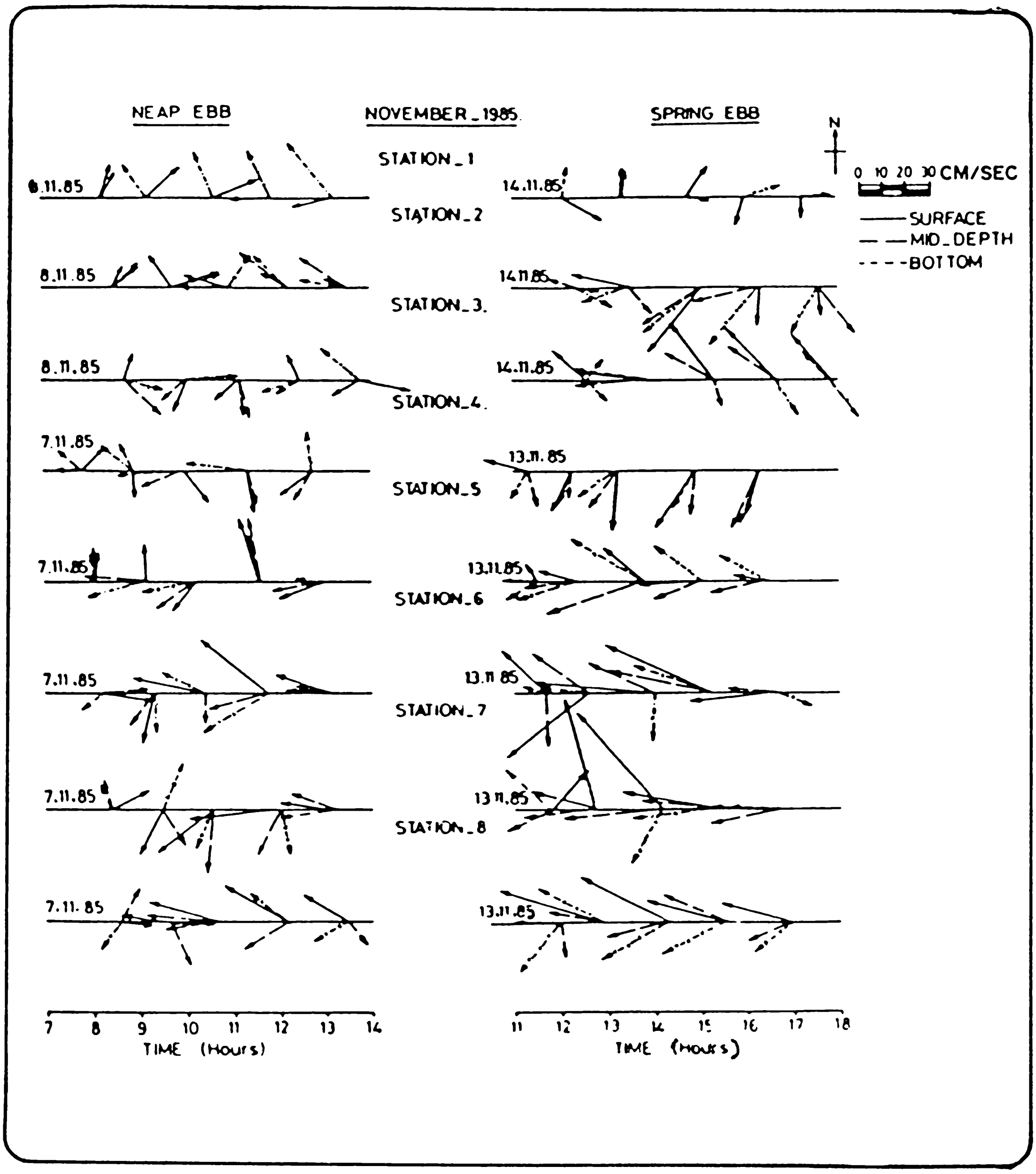


Fig.4.7 Tidal variations in currents at stations 1-8 during neap ebb and spring ebb in November 1985

DECEMBER (1985) : Neap ebb, Spring ebb

The flow patterns during neap ebb and spring ebb of December are more or less similar to the patterns during corresponding tidal phases of November. Associated with the higher tidal range, strong outward flowing tidal currents are observed during spring ebb (Fig.4.8). During neap ebb, weak inward flowing currents appear at few stations. At station 1, the flow pattern shows negative shear during neap ebb and positive shear during spring ebb.

Higher magnitudes of currents are, in general, recorded during mid tide. At stations 5-8, during spring ebb, the ebbing currents are directed between SW and SSW. At stations 1-4, during neap ebb, the magnitude of currents varies between 13 cm/sec and 67 cm/sec and at stations 5-8, the corresponding range of variation is between 19 cm/sec and 68 cm/sec. Also, the lowest current speed (13 cm/sec, at bottom) is recorded at Mattancherry channel (station 3) and highest (68 cm/sec, at surface) at the estuarine mouth (station 8). During spring ebb, the currents vary between 16 cm/sec and 103 cm/sec at stations 1-4 and between 17 cm/sec and 112 cm/sec at stations 5-8. The highest current speed is recorded (112 cm/sec, at surface) at station 5. During spring ebb, the currents frequently flow with speeds ranging between 70 cm/sec and 100 cm/sec.

JANUARY (1986) : Neap flood, Spring flood

The observations during the two flooding stages of neap and spring tides of January also show that higher current speeds are, in

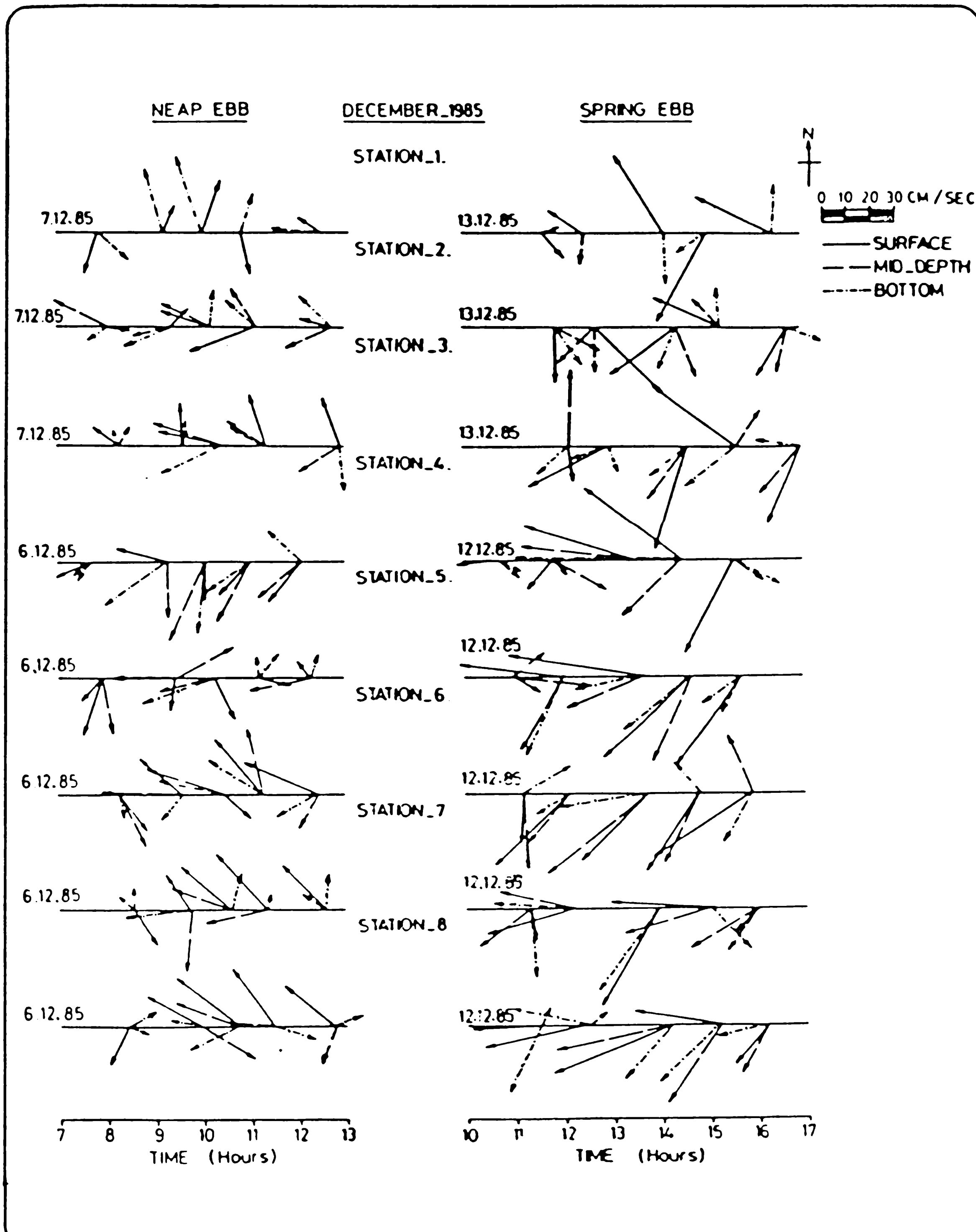


Fig.4.8 Tidal variations in currents at stations 1-8 during neap ebb and spring ebb in December 1985

general, associated with higher tidal ranges. During this month, spring flood had short tidal range (HLW to LHW) and neap flood had comparatively higher tidal range (LLW to HHW). There are no distinct variations in magnitude of currents at stations 2-3 and at stations 6-8, during both the flooding stages of tides (Fig.4.9). Stronger currents are recorded during neap flood than during spring flood. Generally, the current speed at the surface is found to be higher in the estuarine system. Weak currents are noted (10 cm/sec-40 cm/sec) at station 4, during both the flood tides.

During neap flood, the flooding currents are strong at Mattancherry channel than at Ernakulam channel, and the highest speed is recorded at station 7 (100 cm/sec, at surface). Generally, the flooding currents during spring flood are weak, disturbed and directionally inconsistent. But at shallow stations 1 and 4, almost uniform direction of flow is observed, though the magnitude is weak. The highest velocity (81 cm/sec, at surface) is recorded at Mattancherry channel and current speeds are frequent in the range 15 to 45 cm/sec during spring flood.

<u>MARCH (1986) : Spring flood, Neap flood</u>

During both the spring flood and neap flood stages, the general features of distribution of currents are almost identical during March (Fig.4.10). The flows are subjected to rapid variations in magnitude and direction. During spring flood, currents at the surface show greater speeds than at the middle and bottom levels in the entire estuary. The highest velocity (113 cm/sec) is recorded at

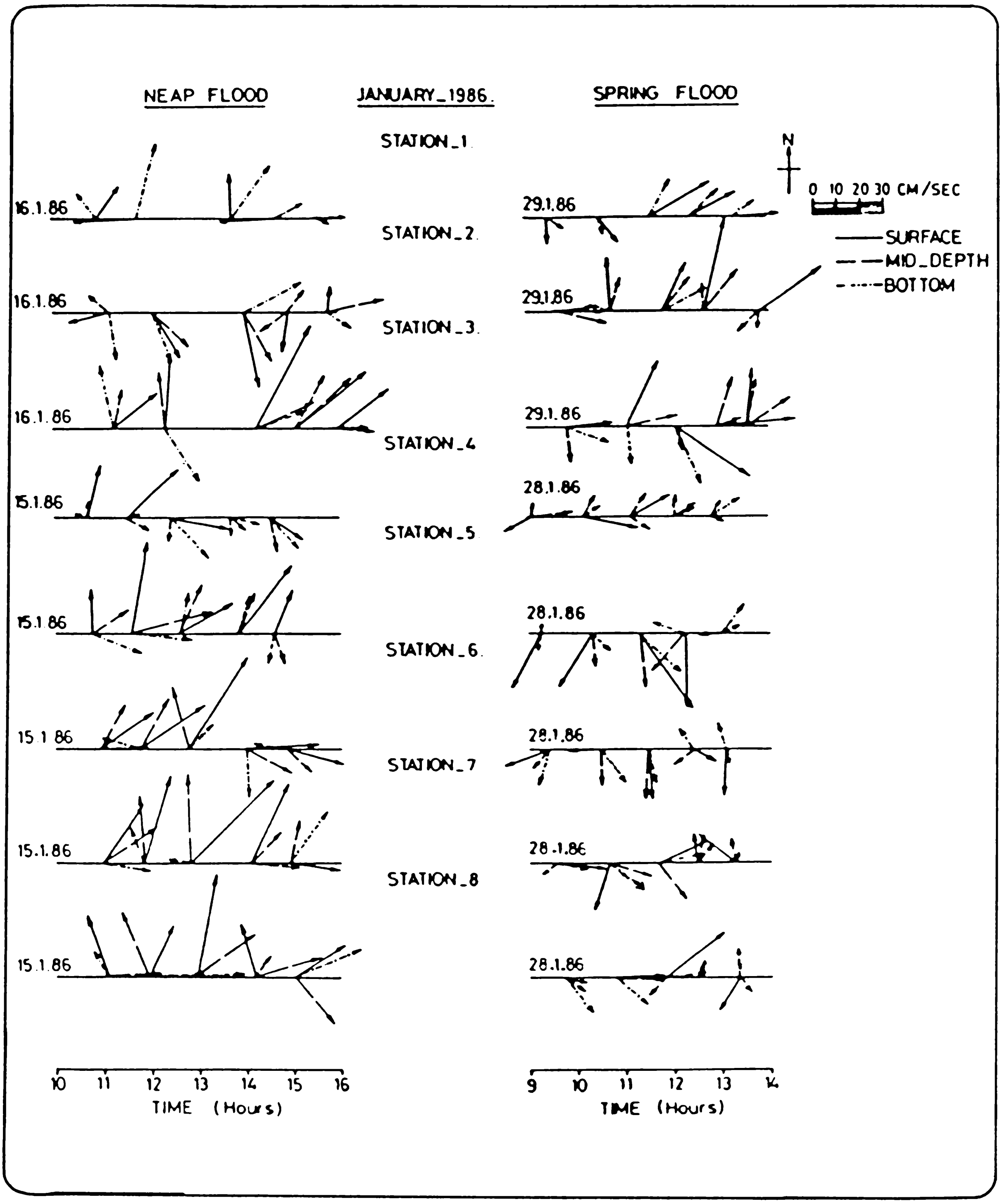


Fig.4.9 Tidal variations in currents at stations 1-8 during neap flood and spring flood in January 1986

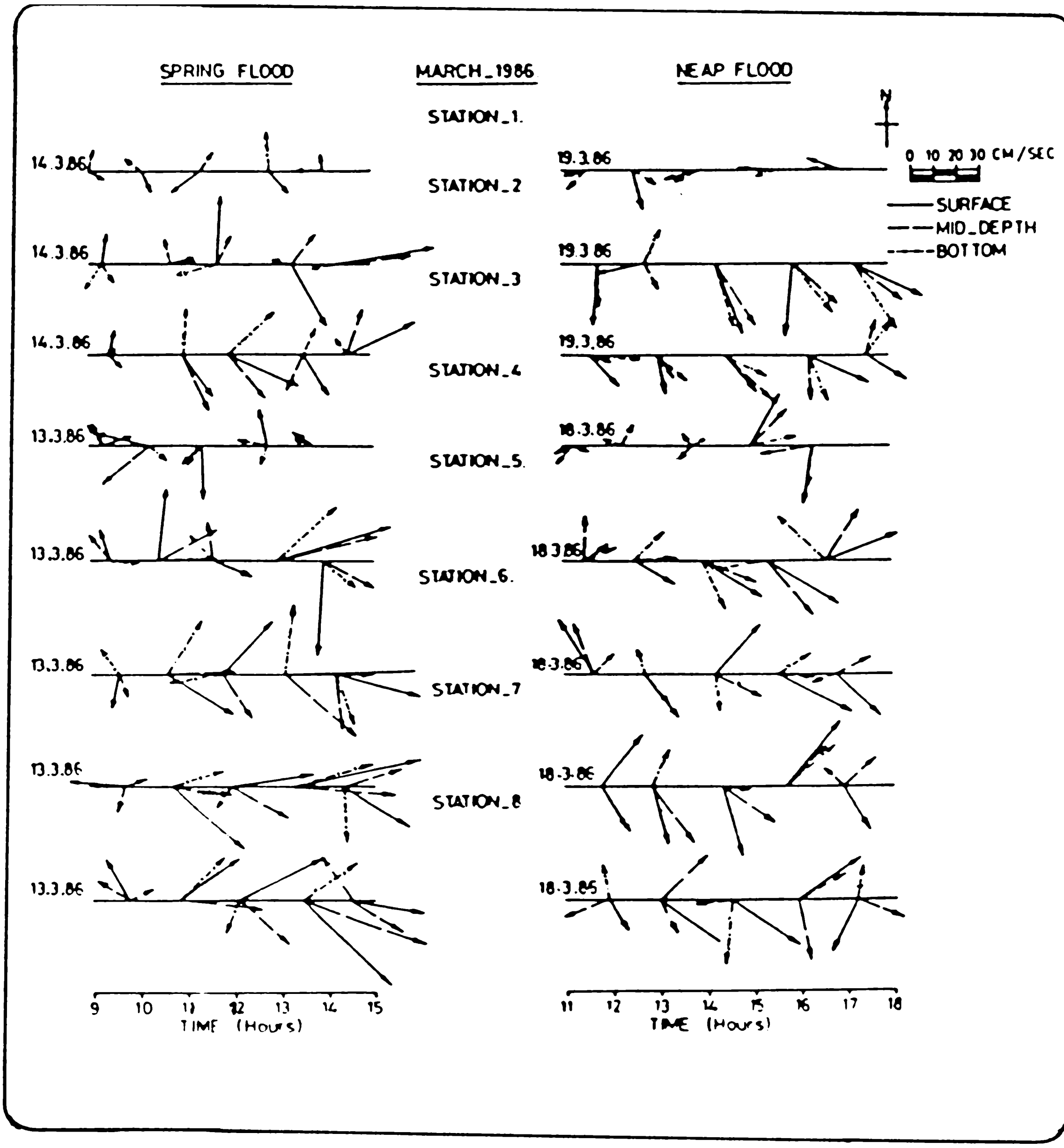


Fig.4.10 Tidal variations in currents at stations 1-8 during spring flood and neap flood in March 1986

station 7. In the Ernakulam channel, the circulation shows disturbed conditions throughout the spring flood. Increase in magnitude of currents is observed after mid flood but the inward flooding currents are comparatively weak.

During neap flood, the circulation indicates predominance of inflow in the entire estuary. Almost uniform direction of flow (between SE and S) is noted at stations 2 and 3. The magnitude of currents is more or less equal (frequently in the range 40 cm/sec-70 cm/sec) at all stations in the estuary, except at stations 1 and 4. At station 1, weak currents (16 cm/sec-38 cm/sec) flow predominantly towards the west, while at station 4, a rapid increase in magnitude (from 13 cm/sec-18 cm/sec to 40 cm/sec-53 cm/sec) is observed at mid tide. The highest current speed (72 cm/sec at surface) is recorded at station 8 at mid tide of the spring flood. Generally, the magnitude of currents is less compared to that during the previous months during the flooding phases of both spring and neap tides.

JUNE (1986) : Spring flood, Neap flood

In June (south-west monsoon period), the flow pattern is the resultant of tidal influx and the increased fresh water efflux. Distinct layers of flow exist during this season. From Fig.4.11 it can be seen that the magnitude of surface current is, in general, lower than that at intermediate and bottom layers. At the initial stage of spring flood the surface currents at stations 2-8 are directed partially outwards. Similar condition exists at certain stations

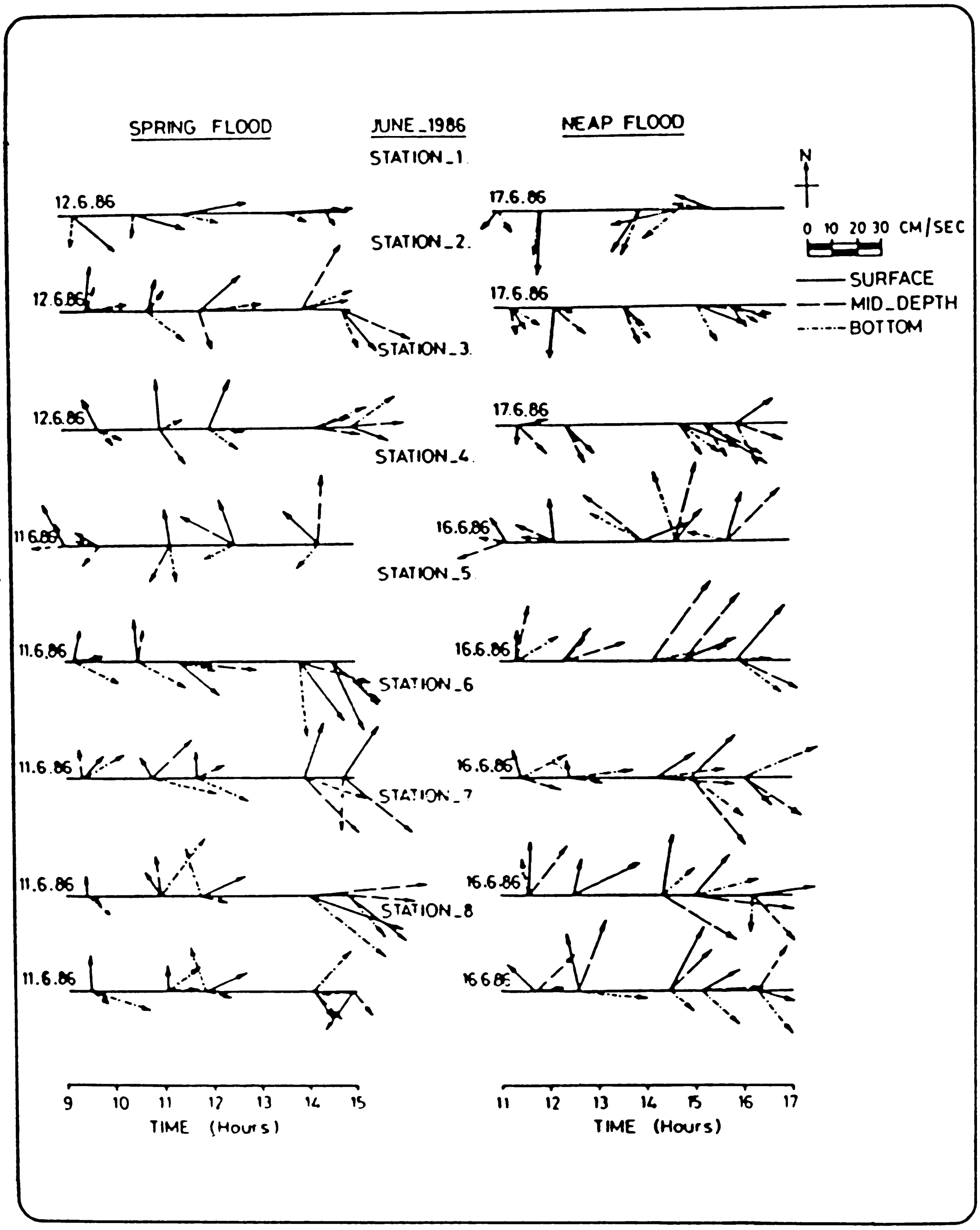


Fig.4.11 Tidal variations in currents at stations 1-8 during spring flood and neap flood in June 1986

during neap flood also. This may be due to the effect of fresh water discharge, as seen in July (1985). The inflow increases considerably after the mid flood. Eventhough higher magnitudes of flow are associated with higher tidal ranges during spring flood, lower tidal ranges of neap flood are not associated with lower speeds of flow.

Comparatively stronger currents (50 cm/sec-100 cm/sec) are observed at stations 5-7, after the mid tide of spring flood. There is no distinct difference in speed of currents between Ernakulam and Mattancherry channels during spring flood. However, after mid flood (neap), slightly faster flows are recorded at Mattancherry channel. The highest speed of current is observed at station 7 (100 cm/sec at mid-depth) during spring flood and at station 5 (82 cm/sec at mid-depth) during neap flood.

4.3 Volume Transport across Cochin Inlet

According to the law of conservation of volume, transport of water through the upstream section must equal the transport through the downstream section of the estuary (Swenson and Chuang, 1983). The accurate value of net water transport can be found out from continuous observations for a fortnight period. Since such continuous observations are of great practical difficulties, the present study is limited to estimation of the volume transport of water at different phases of tides across the Cochin inlet.

The net volume of water exchanged across the inlet can be calculated using the average current velocities at the cross sectional area.

The cross-sectional area of Cochin inlet (4805.5 m^2) was determined by obtaining the bottom profile using lead sounding corrected to mean sea level (Fig.4.12). Raju _et al_ (1979) calculated the tidal prism values at Cochin inlet at spring tide in different seasons and obtained the average tidal prism for the spring tide in the pre monsoon to be 31.5 x 10^6 m^3 (35.3 x 10^6 for flood and 27.7 x 10^6 for ebb). During pre monsoon season, the effect of fresh water discharge on the tidal prism is least but during monsoon and post monsoon season it is very significant. During monsoon and post monsoon season the tidal prism values range between 9.5 x 10^6 m^3 and 83 x 10^6 m^3 for flood and 27.7 x 10^6 m^3 and 132.6 x 10^6 m^3 for ebb tides.

Table 4.1 gives the values of volume transport at Cochin inlet at different phases of tides during 1985-1986. The highest magnitude (68.37 x 10^6 m^3) of volume transport is found during spring ebb in November and the lowest (6.25 x 10^6 m^3) during neap flood in October. The magnitude of these values depends on several factors viz. tidal range and duration, quantity of fresh water discharge, intrusion of saline water, etc. The volume transport during flood tide in monsoon season is comparatively lower than that during other seasons, for tides of almost equal duration and range. On the pre monsoon days (eg: 10.4.85 and 22.5.85), the volume transports during spring floods are found to be 54.73 x 10^6 m^3 and 66.62 x 10^6 m^3 respectively, while on monsoon days (eg:19.7.85) the value is 44.82 x 10^6 m^3 with more or less equal tidal range (about 101 cm) and duration (about 8 h). The volume transport is comparatively higher at ebb tides during monsoon season, eg. 30.41 x 10^6 m^3 on 11.7.85,

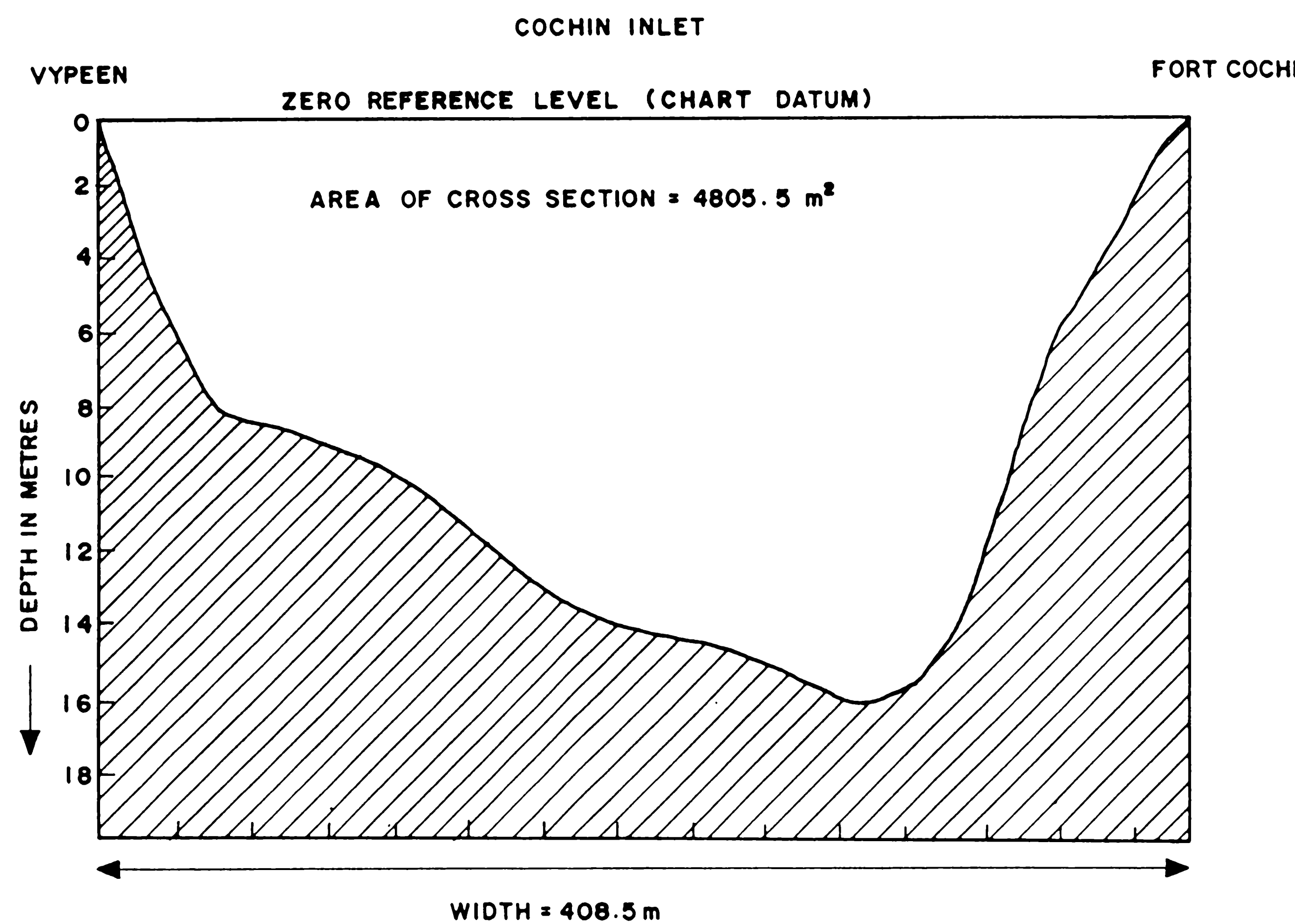


Fig.4.12 Cross sectional area of Cochin inlet

TABLE 4.1

Volume transports for ebb and flood periods across Cochin inlet

Date	Phase of the tides	Tide levels (cm)	Duration (h)	Average cross sectional area (m^2)	Volume transports ($\times 10^6$ m^3)
10.04.85	Spring Flood	011 - 114	0825-1631	5038.41	54.73
17.04.85	Neap Ebb	081 - 049	1156-1604	5071.03	20.56
13.05.85	Neap Ebb	073 - 054	0715-1150	5062.86	10.54
22.05.85	Spring Flood	006 - 106	0708-1502	5054.69	66.62
11.07.85	Neap Ebb	078 - 064	0717-1205	5095.54	30.41
19.07.85	Spring Flood	-(002)- 099	0612-1400	5017.80	44.82
05.08.85	Neap Flood	018 - 090	0755-1520	5026.01	43.08
17.09.85	Spring Flood	028 - 092	0718-1335	5050.60	51.83
23.09.85	Neap Ebb	076 - 057	0730-1328	5075.11	24.80
08.10.85	Neap Flood	068 - 070	1120-1500	5087.37	06.25
16.10.85	Spring Flood	045 - 089	0640-1352	5079.19	18.92
07.11.85	Neap Ebb	104 - 072	0700-1420	5164.98	31.60
13.11.85	Spring Ebb	088 - -(013)	1022-1730	5013.84	68.37
06.12.85	Neap Ebb	102 - 053	0550-1244	5124.13	25.59
12.12.85	Spring Ebb	096 - -(004)	0947-1710	5009.80	64.01
15.01.86	Neap Flood	036 - 075	0950-1510	5034.20	19.26
28.01.86	Spring Flood	060 - 091	0810-1300	5115.96	13.40
13.03.86	Spring Flood	034 - 100	0800-1420	5079.19	44.41
18.03.86	Neap Flood	016 - 086	1018-1820	5013.80	34.11
11.06.86	Spring Flood	011 - 094	0733-1543	5022.01	43.17
16.06.86	Neap Flood	047 - 089	1111-1811	5083.28	31.79

when the tidal range was only 14 cm.

4.4 Stratification and Circulation Parameters

Hansen and Rattray (1966) used the dimensionless theoretical parameters $\frac{\delta s}{S_o}$ and $\frac{U_s}{U_f}$ for the classification of estuaries, where $\frac{\delta s}{S_o}$ is the stratification parameter, defined as the ratio of the surface to bottom difference in salinity (δs) to the mean cross-sectional salinity (S_o), and $\frac{U_s}{U_f}$ is the circulation parameter which is the ratio of the net surface current to the mean cross sectional velocity (Chapter 1). All the above parameters are tidally averaged. The values of these parameters calculated at Cochin inlet for each month are presented in Table.4.2. Higher values of stratification and circulation parameters are, in general, found during monsoon months. The highest value of stratification parameter (1.692) is found in July (1985) and the lowest (0.0754) in November (1985). Similarly, the highest value of circulation parameter (2.27) is found in July (1985) and the lowest (0.82) in May (1985).

In the Stratification-Circulation diagram of Hansen and Rattray (1965, 1966), seven types of estuaries are delineated. Type 1, represents well mixed estuary in which the net flow does not reverse with depth and the upstream salt transfer is by diffusion. Type 1a represents laterally homogeneous, well mixed estuary whereas 1b shows appreciable stratification. For Type 2, the net flow reverses with depth, and both advection and diffusion contribute to the net upstream salt flux. Type 2a and 2b have the same stratification boundary as Type 1. Type 3 estuaries are differentiated by salt

TABLE 4.2

Circulation and Stratification Parameters at Cochin Inlet

Months	δ_s	S_o	$\frac{\delta_s}{S_o}$	Us	Uf	Us/Uf
1985						
APRIL	2.13	27.57	0.077	25.78	22.61	1.14
MAY	2.68	28.95	0.093	28.86	35.09	0.82
JUNE	-	-	-	-	-	-
JULY	15.4	9.1	1.692	82.13	36.20	2.27
AUGUST	18.04	12.38	1.457	46.53	28.10	1.66
SEPTEMBER	9.74	25.23	0.386	34.50	33.19	1.04
OCTOBER	18.95	22.47	0.843	64.87	42.03	1.54
NOVEMBER	2.19	29.04	0.0754	39.46	27.95	1.41
DECEMBER	3.16	29.72	0.106	51.49	39.44	1.32
1986						
JANUARY	3.20	29.05	0.110	34.23	30.11	1.14
FEBRUARY	-	-	-	-	-	-
MARCH	2.68	28.41	0.097	27.10	28.73	0.96
APRIL	-	-	-	-	-	-
MAY	-	-	-	-	-	-
JUNE	13.09	23.73	0.556	43.08	28.45	1.92

transfer that is primarily advective. In Type 3a, the lower layer is so deep that circulation does not extend to the bottom (eg: Fjords). Type 4 estuaries are characterised by saltwedge type (arrested saltwedge) (Dyer and Ramamoorthy, 1969; Dyer, 1973; Murray, 1975 and Officer, 1983).

At the Cochin inlet, the estuarine features vary from month to month (Fig.4.13). In July and August, the estuary is characterised as almost saltwedge type; in June, September, October, December and January with appreciable stratification and during the rest of the months the estuary shows almost well mixed nature.

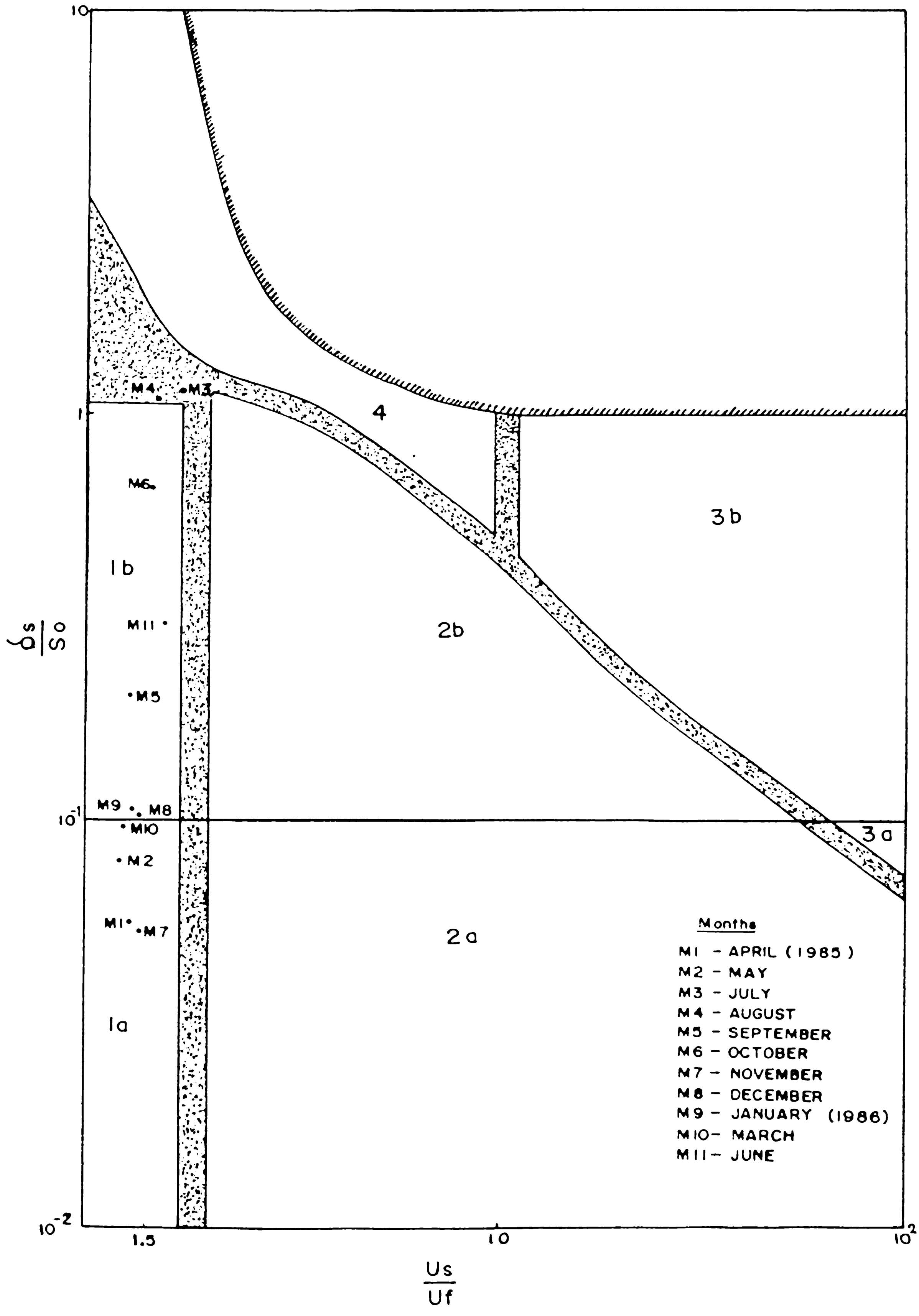


Fig.4.13 Stratification-Circulation diagram at Cochin inlet

CHAPTER - V

5. SUMMARY AND CONCLUSIONS

Knowledge of dynamics of estuarine waters is of great importance in estuarine developmental activities including navigation, harbour engineering, dredging and disposal of effluents. The present thesis is an outcome of the investigations carried out at Cochin estuary to study the spatial and temporal variations in its hydrography and dynamics.

The ebb and flood currents generated by the tides provide the primary mechanism of mixing of fresh and salt waters and of flushing of effluents. In the Cochin estuary, the tides are of mixed, predominantly semidiurnal character. The highest and lowest water levels occur at spring tides in all months. Lower mean sea levels are observed during south-west monsoon period. This may be attributed to upwelling of the cool, dense water from deeper layers due to the divergence of surface layers on the west coast of India during this period.

Higher mean sea levels are observed in November and in December. The maximum frequency (14.35%) occurs in the tidal range of 60 to 70 cm and the minimum (0.45%) in the range of 120 to 130 cm. Range and duration of flood and ebb tides are not found to be always mutually dependent. Higher tidal ranges are associated with fullmoon for about six months (March/April-August/September) and with newmoon during other six months (August/September-February/March). This alteration is caused by the retardation of the high and low from one day to the next.

The tidal ranges are higher for observed tides than predicted tides. The difference goes upto 30 cm. Generally, the lagging or priming between the observed and predicted tides varies from 0 to 30 min, but larger variations, upto 65 min are also found to occur in certain cases. These fluctuations are caused by local weather conditions and variations in barometric pressure and effect of local wind drifting.

It is seen that slack water conditions exist for a duration ranging upto 20 min. The differences between the actual recorded sea levels and the predicted sea levels at high water and low water are known as sea level anomalies which can be positive (observed — predicted) or negative (predicted — observed). Distinct variations between high water and low water anomalies have been observed during the period of study. The low water anomalies (total 341) consist mostly of negative anomalies (270) while high water anomalies (total 343) consist mostly of positive anomalies (242). In general, the distribution of anomalies shows that the influence of local weather elements such as rainfall, wind and pressure is comparatively small on the tides in this estuary.

The estuarine water temperatures are controlled mainly by the temperatures of the sea water, of the run-off water from land and by solar radiation. Seasonal variations are well reflected in water temperature in Cochin estuary, where the temperature reaches its maximum during the dry pre monsoon period with very weak thermal gradients indicating strong vertical mixing. Cells of higher temperature are found in the bottom layers at stations near the estuarine mouth during this period. In shallow regions, the temperature does not exhibit much variation in the water column.

During south-west monsoon season, the surface temperature is low and the vertical thermal gradients are found to be quite steep with a difference of about 5°C between the surface and bottom temperatures. The distribution of temperature at bottom layers in the estuary during monsoon season is indicative of mixing with the waters of the Arabian sea. In July, temperature of the fresh water discharged is less than that of sea water and in August sea water is colder than the freshet. The surface temperature more or less follows a typical diurnal pattern and the tidal circulation is found to have little or no influence on the variations observed in the temperature structure in the vertical plane.

The distribution of salinity depends mainly on the combined action of water movements induced by freshet and tidal action. Variations in salinity occur vertically, horizontally and with time. The variation of salinity is closely related to tidal range and duration, where higher variation in salinity is associated with higher tidal range and longer duration. Also, the estuarine water is found to have higher saline conditions at higher tidal levels. The diurnal variations in salinity are found to be in phase with the tides with an increase in salinity during flood tide and a decrease during ebb tide.

Generally, salinity values at mid-depth levels are more closer to the bottom salinity than the surface salinity. During pre monsoon period, salinity varies between 19.3‰ and 34.6‰ in the entire estuary. The difference in salinity between the bottom and surface ranges upto 6.0‰. Mixing progresses after mid flood tide and the mixed water flows out during ebbing. The water regains stratification by the time the next low tide is reached.

During active monsoon period, large quantities of fresh water enter the estuary, resulting in the formation of low saline water at the surface and denser, more saline water at the bottom. During July, the highest salinity is recorded as 20.4‰ near the bottom at the barmouth. The presence of saline wedge is observed during neap ebb in this month. Under spring flood, the tidal force begins to weaken after mid flood and the surface salinity increases due to entrainment. As the season progresses, the estuary becomes more and more saline due to reduced monsoonal influence.

With the cessation of monsoon rainfall, partially mixed conditions develop in December and January, when the salinity ranges upto 31.9‰. Almost homogeneously mixed conditions are observed in March. Higher salinity (33.0‰) is reached near bottom at the barmouth.

River discharge into the estuary varies seasonally, sometimes quite drastically and this is reflected in the flushing and salinity

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distributions. It is seen that the fresh water content is the least at mouth bar (station 7) and the highest near Bolgatti (station 1), during all months. Also, fresh water content is slighly higher in the Ernakulam channel (station 2) than in the Mattancherry channel (station 3) due to the influence of the higher fresh water discharges from rivers and land areas in the Ernakulam channel. Higher values of dilution factor (4.00 to 4.55) occur during pre monsoon season when the fresh water flow is negligible. Any pollutant therefore released to the estuarine system during this season will be diluted more than four times by sea water before it finally reaches the open sea.

The circulation of water within an estuary is governed mainly by strong tidal oscillations on which residual water circulations are superimposed. These residual circulations may be generated by nonlinear interactions between the tidal flow and estuarine topography, density gradients, wind stress and the mass input due to fresh water discharge into the estuary. In the Cochin estuary, during pre monsoon period, the flow pattern depends mainly on the tidal conditions, due to reduced river discharges. The velocities show large dependence on the tidal range during this period when higher velocities are associated with higher tidal ranges. The circulation during south-west monsoon season is mainly the resultant of the tidal influence and freshet. In July (1985), the flood currents are weaker than ebb currents eventhough the tidal range (90 cm) and duration (7 h 50 min) are higher for flood tides. In spite of short tidal range and duration of neap ebb, the magnitude of outflowing ebb currents recorded are generally high at estuarine mouth. This brings out the influence of fresh water discharge on the estuarine circulation, especially during this season. At Ernakulam channel, stronger ebb currents are observed than at the Mattancherry channel. During spring flood, weak surface currents are found to flow outwards in July. Slack water conditions are observed at bottom during the first few hours of neap flood in August. The stronger flood currents observed in the Mattancherry channel may be due to the higher fresh water discharges in the Ernakulam channel, providing opposing force to the flood tide.

Higher magnitudes of currents are observed, in general, at the mid tide stage. But, on certain occasions, higher currents are also recorded towards the last stages of the tides. This may be due to the time lag of tides for their reversal. In November and December, slightly higher magnitudes of currents are recorded at Mattancherry channel than at Ernakulam channel. Generally, the flood currents are stronger at Mattancherry channel than at Ernakulam channel. Negative and positive shear flows are noticed at different stations during the period of observations, indicating the resultant effect of tidal incursion, fresh water excursion, bottom friction and transient influences of wind.

The volume transport of water depends on several facators viz. tidal range and duration, quantity of fresh water discharge, intrusion of saline water etc.. At Cochin inlet, the volume transport during flood tide during monsoon season is comparatively lower than that during other seasons, for tides of almost equal duration and range. The volume transport is comparatively higher at ebb tides during monsoon season. From the Stratification-Circulation diagram it is seen that at the Cochin inlet, the estuarine features vary annually. During July and August, the estuary is characterised as almost saltwedge type; during June, September, October, December and January it shows appreciable stratification, and during the rest of the months the estuary shows almost well mixed nature.

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