BEACH DYNAMICS OF KERALA COAST IN RELATION TO LAND-SEA INTERACTION

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CERTIFICATE

This is to certify that this thesis is an authentic record of the work carried out by Shri. R. Sajeev, M.Sc., under my supervision and guidance in the Regional Centre of National Institute of Oceanography (Council of Scientific and Industrial Research), Cochin-18 and that no part thereof has been previously formed the basis of the award of any other degree in any University.

Cochin-682016,
December, 1993.

Dr.K.S.Neelakandan Nampoodiripad
(Supervising teacher)

CONTENTS

PREAMBLE

" What sight is more beautiful than a high energy beach facing lines of rolling white breakers?. What battle ground is more ferocious than where waves and sand meet? What environment could be more exciting to study than this sandy interface below land and sea? And yet how much do we know about sandy beaches?."

........McLachlan and Erasmus (1983)

Coastal zones are recently receiving increased attention of the scientific and engineering community. This interest is motivated from the thrust and pressure of the economic development which demands a better understanding and utilization of the coastal belt, as it accommodates more than sixty percent of the world's population. The expansion of world trade demands construction of a large number of harbors and terminals. The varied human interference on the coastal zone also includes exploitation of living and non living marine resources, recreation, navigation, waste disposal, etc..

The sandy portion of the coastal zone, the beach, is a complex and dynamic environment which is examined in detail in this thesis. The general configuration of a beach changes continuously, in response to the variations in the forcing functions like winds, waves, currents and tides etc. in addition to the man-made changes.

The beaches of Kerala coast undergo considerable topographic changes under the influence of the seasonally varying monsoonal forcing. At times, the beach sand containing valuable minerals is lost in large quantities due to erosion which are local and seasonal. It is in this context that studies on problems of the coastal and nearshore areas along the coast of Kerala received considerable impetus in recent years. There had been a number of studies in the past, concerning various aspects of beach/coastal dynamics along the different stretches of the coast of Kerala. However, efforts to study Kerala coast as a whole combining both the theoretical model and comprehensive field observation have been lacking. Hence the problem " Beach dynamics of Kerala coast in relation to land-sea interaction" has been taken up for this doctoral thesis. The result of this study could provide the basic information much needed for the planning of various developmental projects so as to achieve sustainable economic growth of the hinderland.

Due to variations in the nature and type of the beaches constituting the Kerala coast, the responses of the individual beaches are different, though the monsoonal forcing is more or less same. In view of this, 8 sites were selected at various locations with Kasargod in the north to Trivandrum in the south, along the entire stretch of the Kerala coast for the field observations, taking into account the morphological setting. The field observations consisted of detailed survey on waves, littoral currents and beach characteristics for a period of one year from March 1990 to February 1991.

The thesis is addressed in 5 chapters. The first chapter provides a general introduction to the topic, geomorphological settings of India and Kerala with factors affecting the stability of the coast. The locations of study, aim of the present work, research approach, and a review of literature on the various coastal processes are also included in this chapter.

Chapter two deals with the wave theories, wave climate along the region under study, wave transformation model used and the results of the model has been presented.

Third chapter highlights the results of the field studies on beach morphology and grain size composition of beach material. The results arrived at from the application of E.O.F analysis have also been presented in this chapter.

The results of the Littoral Environmental Observation (L.E.O) and the sediment transport estimations for the Kerala coast are discussed in the fourth chapter.

The last chapter synthesizes the results obtained in the earlier chapters to arrive at a comprehensive picture of the beach dynamics of the Kerala coast. It is followed by a list of references cited in the text. The computer program used for the construction of refraction diagram is given as Appendix-I.

CHAPTER 1

1. INTRODUCTION

The zone where land and sea meet is a complex environment. The coastal areas of the world are of extreme economic importance as approximately, two-thirds of the world's population live along the 4,48,000 km coastlines. In most of the highly developed countries, industrial, residential and recreational developments as well as large urban complexes occupy much of the coastal margin. The future expansion in many undeveloped maritime countries will also be concentrated on coastal areas. Inorder to utilize the coastal zone to the maximum of its capacity, and yet not plunder its resources, an extensive knowledge of this complex environment is necessary for geologists, engineers, oceanographers and coastal planners engaged in the coastal zone management. The general configuration of the beach (Fig. 1.1), changes continuously in response to the time varying forcing functions viz. winds, waves, currents, tides etc..

1.1. Coastal geomorphology of India

India has a long coastline of about 6500 km. The shelf has a gentle uniform gradient. Cliffs and offshore islands are comparatively scarce, while barriers and spits are common. The coastline of India is characterised by varieties of features like rocky headlands, coral reefs, reef-like structures, tidal inlets, estuaries, lagoons, barrier islands, bays, etc. The eastern coastline is essentially alluvial, gently indented and extensively

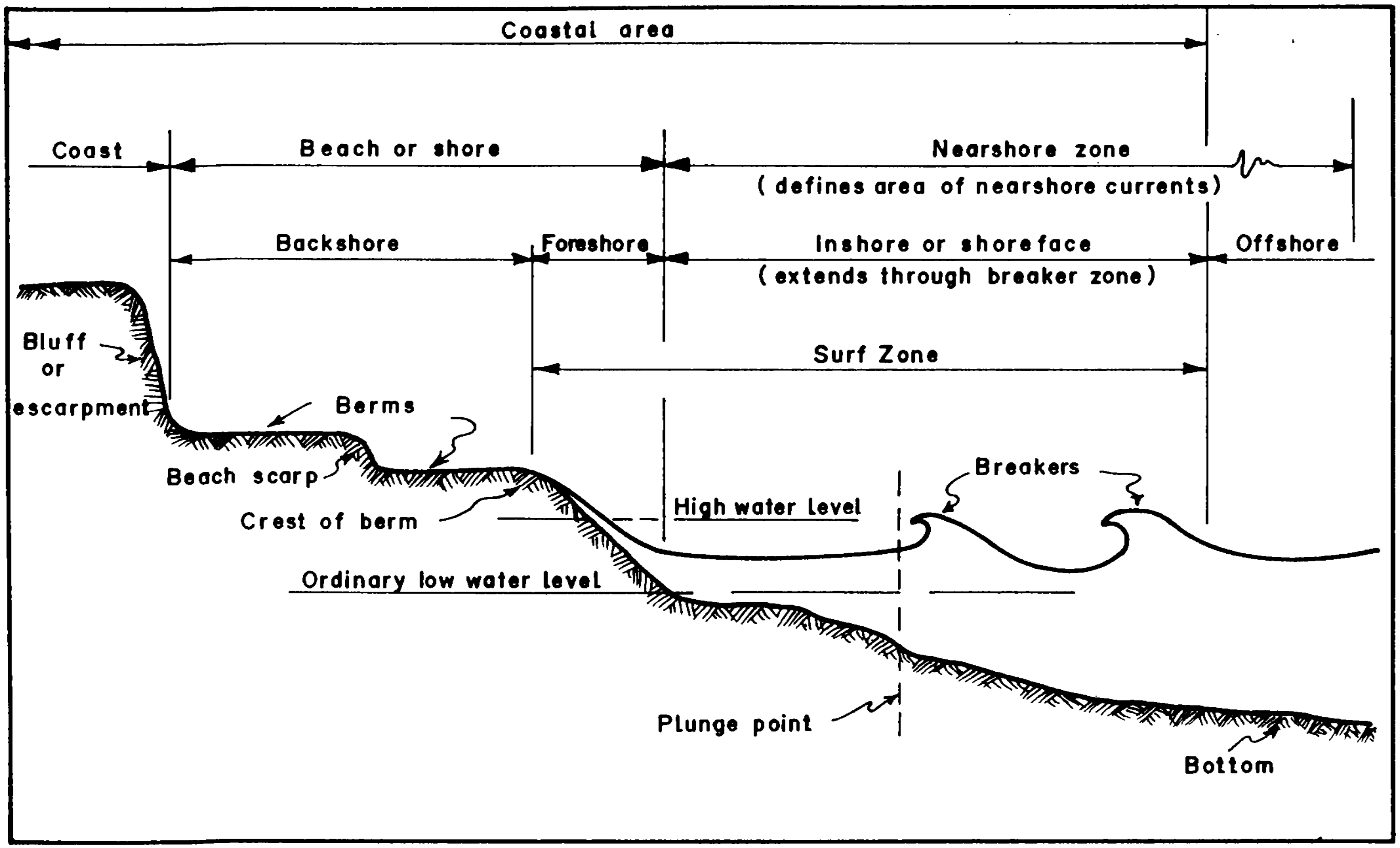


Fig. 1.1. Definition diagram for the Coastal Zone.

developed in contrast to the western coastline which has highly irregular, cliffed and wave eroded character. (Ahmad 1972). The backshore zone of the beach is commonly marked by the sand dunes or beach ridges. The foreshore is marked by tidal terraces. The plains of the west coast of India are confined to a narrow belt of about 10 to 25 km wide lying between the Arabian Sea and the western ghats extending from Gujarat to Kanya Kumari.

The shoreline of the west coast is one of the submergence attributed to rise in sea level against a stable coast. (Ahmad, 1972). According to him, about 55 % of the Indian coastline is fringed by beaches receding in the past few decades. The most remarkable feature of the west coast is the widespread presence of estuaries and lagoons. (Nair, 1987). Almost the entire stretch of the west coast possess relatively similar geological and climatological characteristics.

1.2. Description of the Kerala coast

Kerala coast is a 560 km long narrow strip of land bordering the Arabian Sea at the south western part of the penisular India extending from latitudes 8° 15' N to 12° 85' N and longitudes 74° 55'E to 77° 05' E and has a remarkable straight coastline oriented in NNW - SSE direction. It is believed to have originated as a result of faulting during the late Pliocene (Krishnan, 1968). Kerala plains are much wider and less hilly than the rest of the west coast. Recent observations indicate that the shoreline as a whole is dynamic and neotectonically active leading to considerable erosion and loss of surface area. Narrow stretches of sandy beaches are present all along the coastline except in areas of cliffs.

The elevation of the shoreline on the western side bordering Arabian sea ranges from 0 - 5 m. Intervening the ghats and the shoreline are exposures of tertiary formations such as the Miocene Warkalli at Varkala in south and Tellicherry-Cannanore in the north. North of Varkala for about 100 km there are coastal Tertiaries occupying the zone between the extremely narrow alluvial bars towards the shore and the edges of the gneisses and granites interior on the east. This consists of marine fossiliferous coralline limestones and sands and clays with bands of lignite. They are frequently capped by laterite. The present shoreline is straight for over a great part of the length from Calicut to Quilon, but in Cannanore, Trivandrum and Quilon districts, indentations, cliffs and protuberances are present.

The width of the continental shelf along the Kerala coast varies widely from south to north. Major contributions for the shelf deposits are the west flowing rivers. There are 44 rivers flowing west into the Arabian sea which originate from the hills of the western ghats and drain into the backwaters. The major rivers are Pamba, Periyar, Bharathapuzha and Chaliyar (Fig. 1.2) which together drain

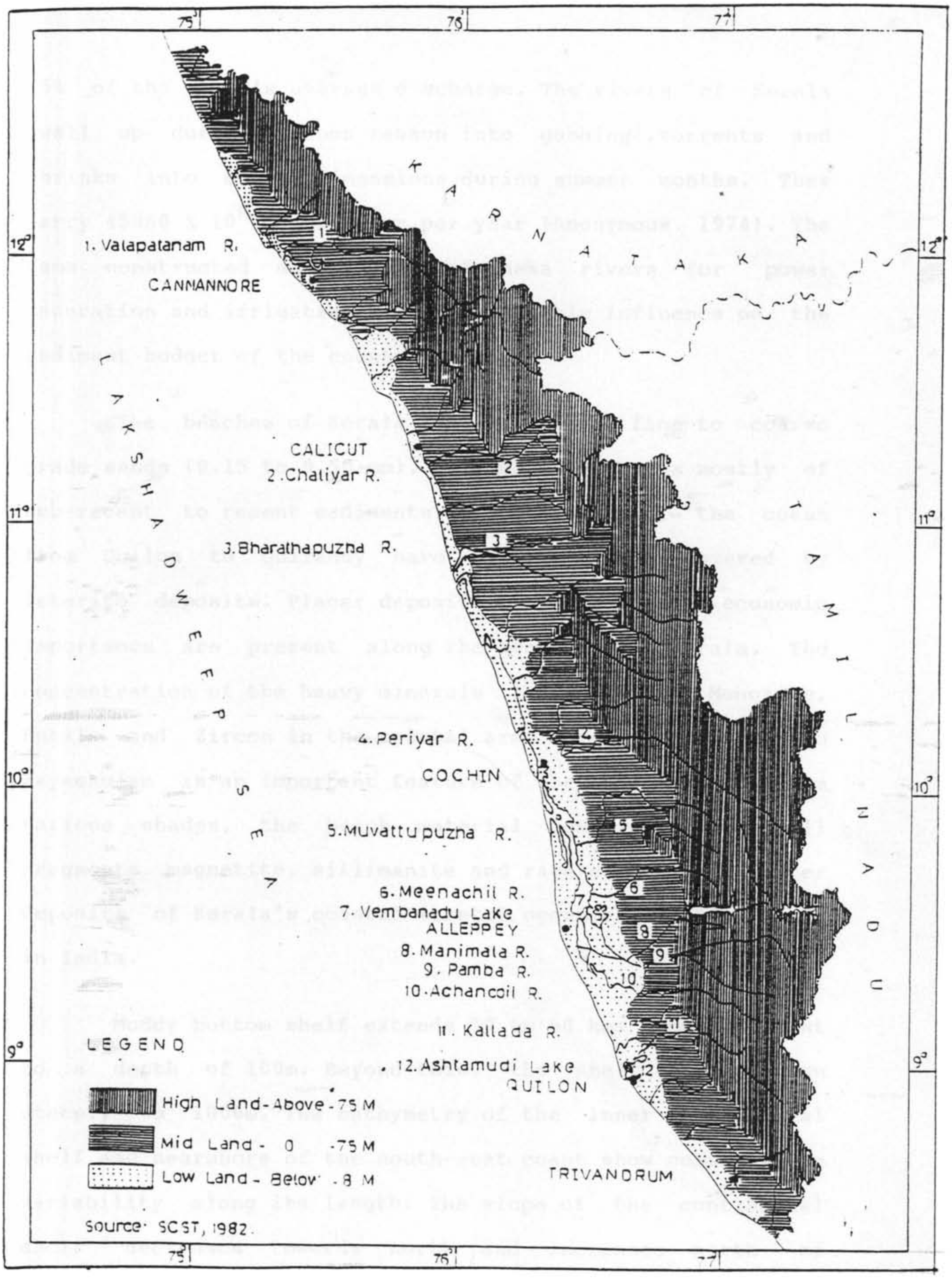


Fig. 1.2. Physiography and major rivers of Kerala

35% of the state's average discharge. The rivers of Kerala swell up during monsoon season into gushing torrents and shrinks into modest dimensions during summer months. They carry 45060 X 10^6 m^3 of water per year (Anonymous, 1974). The dams constructed across many of these rivers for power generation and irrigation have considerable influence on the sediment budget of the coastal zone.

The beaches of Kerala are composed of fine to coarse grade sands (0.15 to 0.50 mm). The coastal area is mostly of sub-recent to recent sediments. The structure of the coast from Quilon to Quilandy have alluvial belt covered by laterite deposits. Placer deposits of considerable economic importance are present along the beaches of Kerala. The concentration of the heavy minerals like Ilmenite, Monozite, Rutile and Zircon in the coastal area from Neendakara to Kayamkulam is an important feature of the coast. Apart from various shades, the beach material comprises of shell fragments, magnetite, sillimanite and rare earths. The placer deposits of Kerala's coastal stretch occupies a pride place in India.

Muddy bottom shelf extends 50 to 60 kms from the coast to a depth of 100m. Beyond this, the shelf slopes down steeply to 1000m. The bathymetry of the inner continental shelf and nearshore of the south-west coast show considerable variability along its length. The slope of the continental shelf decreases towards north and increases north of Cannanore. (Baba, 1988).

The coastal zone of Kerala is well known for its rich fisheries, placer mineral deposits, water resources, transport facilities, excellent backwater systems and above all a well literate and hard working population. It is also rich with wetlands having mangroves, industries, ports and harbors, tourism and recreational facilities.

1.2.1. Morphological features

Lagoons and estuaries

Along the Kerala coast, between Quilon and Kasargod, long and irregular lagoons are present behind the impressive coastal barriers. Many of the lagoons, locally known as Kayals, are bestowed with numerous islands of different sizes. There are 34 Kayals in this area. Among these lagoons, Vembanad lake is the largest (205 sq.km) followed by Ashtamudi Kayal further south. The Vembanad lake opens into the Arabian Sea at Cochin. Six major rivers, Periyar, Pamba, Manimala, Achankovil, Meenachil and Muvattupuzha discharge into this lake. Lagoons and estuaries play an important role in beach dynamics along this coast.

Bars, spits, headlands and barriers

The south-west coast, as a whole, is well known for most well-developed bars and lagoons. Low cliffs alternating with pocket beaches, promontories, head-lands and bays are present along the coast of Kerala. North of Ponnani, the shore consists of continuous formation of mainland beaches. North of Trivandrum, the coast is characterised by the presence of barrier beaches except at few places where rocky cliffs and head lands are present. Where the lagoons opens out into the sea across the bars, spits are present with or without submerged sand bars.

The principal influence of the lagoons in-so-far as beach studies are concerned is that they act as sediment traps. A well developed barrier is seen between Neeleswar and Cannanore. The Vypeen Island barrier, north of Cochin, is about 23 km long and 2 km wide. Several barriers are observed near Quilon. Remarkable features of the barriers are their alongated formation with small width.

1.2.2. Physical factors

Climatology of Kerala

Orographic influence on the monsoons plays an important role in the climate of Kerala. In the meteorological map of India, Kerala has a pre-eminent place. It is the gateway through which great rain-bearing south-west monsoon current gains access to the subcontinent year after year by the end of May or in early June and through which the monsoon make its lingering exit towards the end of the year after having dispersed its priceless bounty over the length and breadth of the country (Ananthakrishnan et al., 1979). Average annual rainfall in Kerala is nearly 300 cm, which is

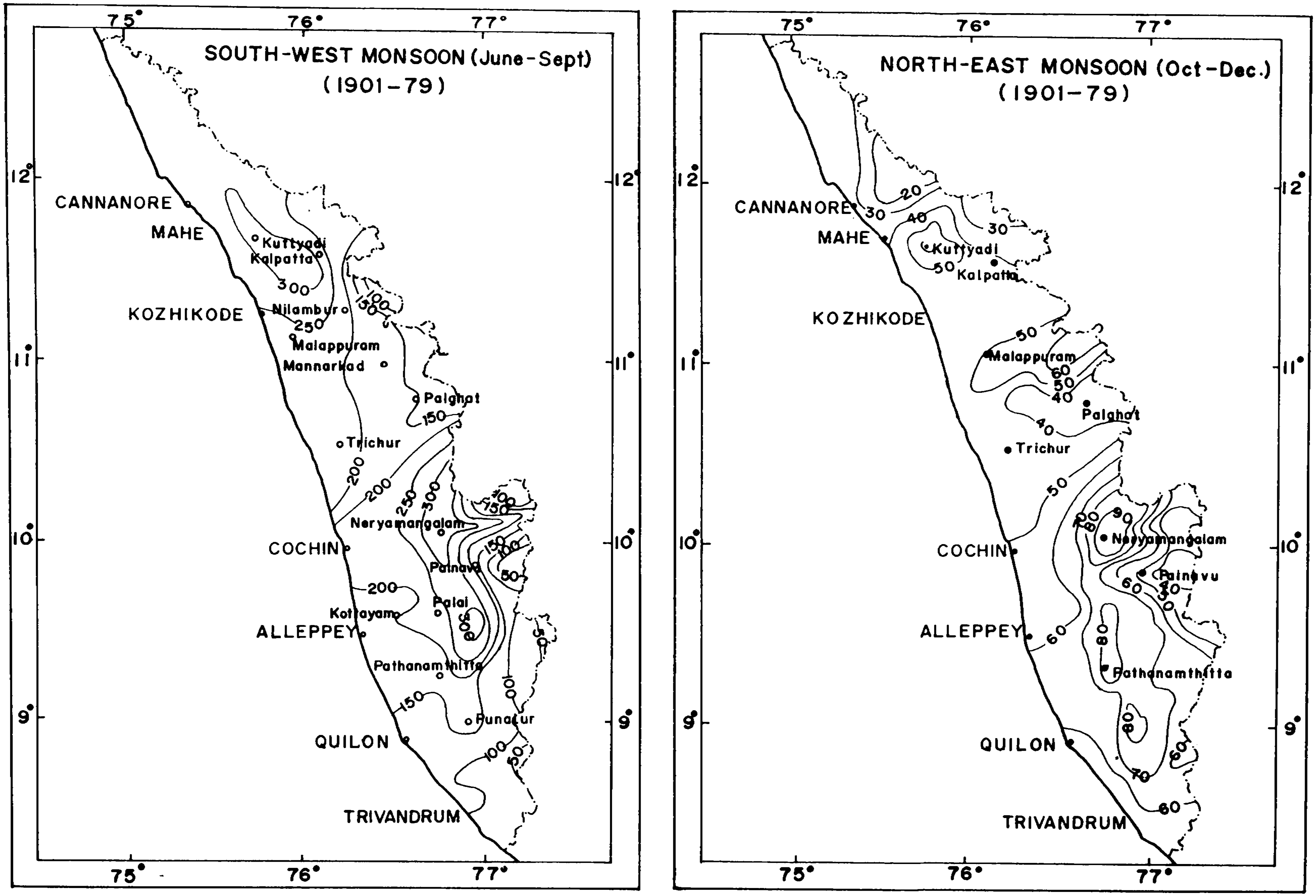


Fig. 1.3. Distribution of average rainfall (Cms) over Kerala

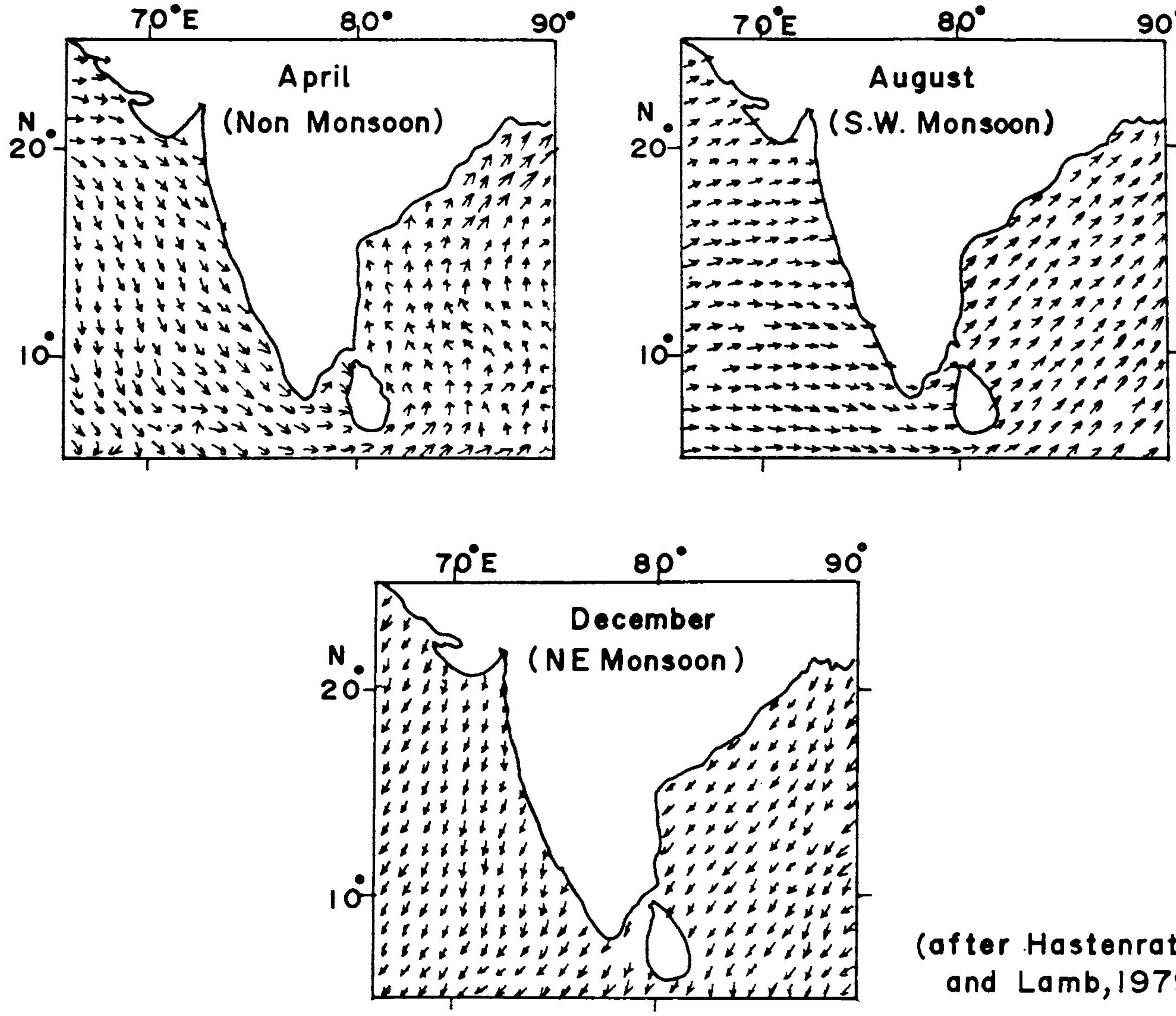
about three times the average annual rainfall of India. The distribution of average rainfall over Kerala state during the south-west monsoon (June-September) and north-east monsoon (October-December) are shown in Fig. 1.3.

Wind

The basic feature of wind distribution over Arabian Sea is the reversal of the wind systems during an year known as the monsoon. The reversals take place predominantly from south-west direction during May-September to north-east direction during December-March. Between these reversals are the transition periods during which weak and variable winds prevail. The typical wind pattern for different seasons (south-west monsoon, north-east monsoon and non-monsoon seasons) are shown in Fig. 1.4. The wind set up caused by wind pushing surface water against the shoreline results in a change of the existing equilibrium profile of the beach. The wind is also significant on a wide sandy beach as large quantities of sand can be blown from the beach.

Tides

The tide is an important factor influencing the beach dynamics. Tidal currents which are oscillatory in nature are particularly important in transporting sand in shoals and in the formation of sand waves on submerged bars around entrances to bays and estuaries, but have virtually no effect on uninterrupted straight shorelines, except in areas with



(after Hastenrath and Lamb, 1979)

Fig. 1·4· Seasonal Predominant wind pattern around Indian region.

very large tidal ranges. The tides of Kerala are mixed, semidiurnal in nature and occur within the microtidal range (<2m).

Nearshore waves

Most of the dynamic nature of the beach and nearshore zone is the direct or indirect result of wave action. Wave information is vital in design and construction of various coastal and offshore structures, ports, harbors and for various ocean engineering projects. For an understanding of long term variability of beaches, and for various developmental activities of the coastal region, wave data is very much essential. Energy mainly from wind, imparted to the water produces wave motion and are modified by the general configuration and contour of the near shelf. Waves are the most important cause of alteration and evolution of our coastlines. During south-west monsoon, due to the strong wind action, increase in wave activity with long swells and high breakers has been observed along the Kerala coast Considering the orientation of the coastline (NNE - SSW), wave directions varying between 180° - 340° are more significant in the shore processes. In the south-west monsoon season the predominant direction of waves fall between WSW and WNW.

Longshore currents and rip currents

One of the major effects of wave action in the shallow water is the generation of longshore current, which plays an important part in the longshore movement of material. As the waves arrive obliquely to a straight coastline and break at an angle to the beach, they generate longshore current flowing parallel to the shoreline. This wave induced current is confined to the nearshore, rapidly decreasing in velocity beyond the breaker zone. The nearshore currents varying in space and time are responsible for many of the beach processes.

Rip currents are the most noticeable of the exchange mechanisms between offshore and surfzone. Rip currents are strong and relatively narrow jets of seaward flowing currents. The rips are fed by a system of longshore currents. Bowen (1969) has shown that cell circulation with rip currents is produced by longshore variation in the wave breaker heights.

Littoral transport

The longshore current transports beach sediments for many kilometers in the longshore direction. Littoral transport of sand occurs in two modes. 1) parallel to the shoreline due mainly to the effect of longshore current, which is referred to as longshore transport and 2) perpendicular to the shoreline due to swash and backwash, referred to as the beach drift.

The direction of longshore transport varies from season to season, day to day or hour to hour depending upon the location and direction of the storm winds which generate waves. It results from the stirring-up of the sediments by breaking waves and movement of sediment by the longshore component of wave induced current. The beach drift occurs as a result of the stirring up of the bottom sediments in breaker zone which tend to be carried up the beach to the limit of swash of the breaking wave and back with back wash. The volume of the beach drift is determined primarily by wave steepness, sediment size and beach slope. Determination of the amount of sand that can be moved in the onshore-offshore mode is difficult and entails detailed profile surveys.

Mud banks

Mud bank is a phenomenon peculiar to the south-west coast of India. The occurrence of mud banks provides safe and smooth anchorage even during the rough wave conditions of the south-west monsoon. As many as 27 locations are identified where mud banks had appeared along the Kerala coast. This has been classified into three regions, viz. the southern strip (Thrikkunnapuzha - Alleppey), the central strip (Chellanum-Munambam) and the northern strip (Calicut pier-Muzhappilangadi) by Nair (1983). The mud banks are reported to be decisively affecting the equilibrium conditions thereby causing shoreline instability of the coast. They trap the littoral materials from either side thereby preventing it's downdrift, causing accretion within the mud banks and erosion on down drift sides.

1.2.3. Man made structures

Apart from natural phenomenon, the man-made structures along the coastline act as barriers to the material and energy balance, and produce adverse effects on the stability of the nearby coast. Kerala's maritime activity is mainly related to the major port at Cochin. There are 3 intermediate ports and 11 minor ports along this coast. Some of the man-made barriers are dredged channels, jetties, groins, sea walls and break waters. The structures constructed along these ports have triggered many environmental problems in addition to upsetting the sand balance in many locations of the coastal zone.

1.3. Scope of the present work

The sandy portion of the coastal zone is a complex and dynamic environment which is investigated in detail in this thesis. The general configuration of the beach changes continuously, in response to the variations in the forcing functions namely winds, waves, currents and tides on a similar time scale as these forcing mechanisms. The present work is aimed at a theoretical and field assessment of the physical processes involved in the shoreline development and beach stability along the entire stretch of the Kerala coast from Kasargod in the north to Trivandrum in the south.

Along the Kerala coast, the beaches are subjected to changes of varying degrees in response to seasonally varying monsoonal forcing. At times, the beach sand containing valuable minerals is lost due to erosion which may be local or seasonal. It is from this view point that studies on problems of the coastal and nearshore areas along the coast of Kerala received considerable impetus in recent years. There had been many studies in the past, concerning various aspects of beach/coastal dynamics along the different stretches of the coast of Kerala. However, studies along the entire stretch of the coast of Kerala combining both the theoretical model and field observations are practically lacking. It is in this background that the problem "Beach dynamics of Kerala coast in relation to land-sea interaction" has been taken up in this study. The present study aims at examining 1) the dynamic response and stability of different types of the beaches along the coast of Kerala, 2) the predictability of the beach changes along the entire stretch of the Kerala coast, both theoretically and empirically. The result of this study could provide the basic information required for various developmental as well as recreational purposes.

The objectives of the present study are achieved through following :

1) The application of a numerical wave transformation model for the Kerala coast to study the distribution of nearshore wave energy for the predominant deep water wave directions and periods.

2) The application of the Empirical Orthogonal Function (E.O.F) analysis to the beach morphology and grain size data to separate the temporal and spatial variations and thereby relate the E.O.F mode of beach morphology and grain size to the waves.

3) The study of the variations in grain size of beach sediments from Kasargod to Trivandrum and to bring out the physical factors controlling different environments of the beach.

4) The estimation of the longshore sediment transport based on the field observation. (LEO data - Littoral Environmental Observation data).

1.4. Area of Investigation

The field observations consist of a detailed survey on waves, littoral currents, beach sediment size and beach morphology for a period of one year along the Kerala coast from Kasargod (Lat. 12° 13'N and Long. 74° 58' 24''E) to Trivandrum (Lat. 08° 29' 11''N and Long. 76° 54' 12''E), consisting beaches of different morphologic types.

Due to the geographical variations of the nature and type of beaches constituting the Kerala coast, the responses of the individual type of beaches is different, though the monsoonal forcing is more or less same. Inview of this, 8 sites were selected along the entire stretch of the kerala coast (Fig. 1.5) for the field observation by taking into

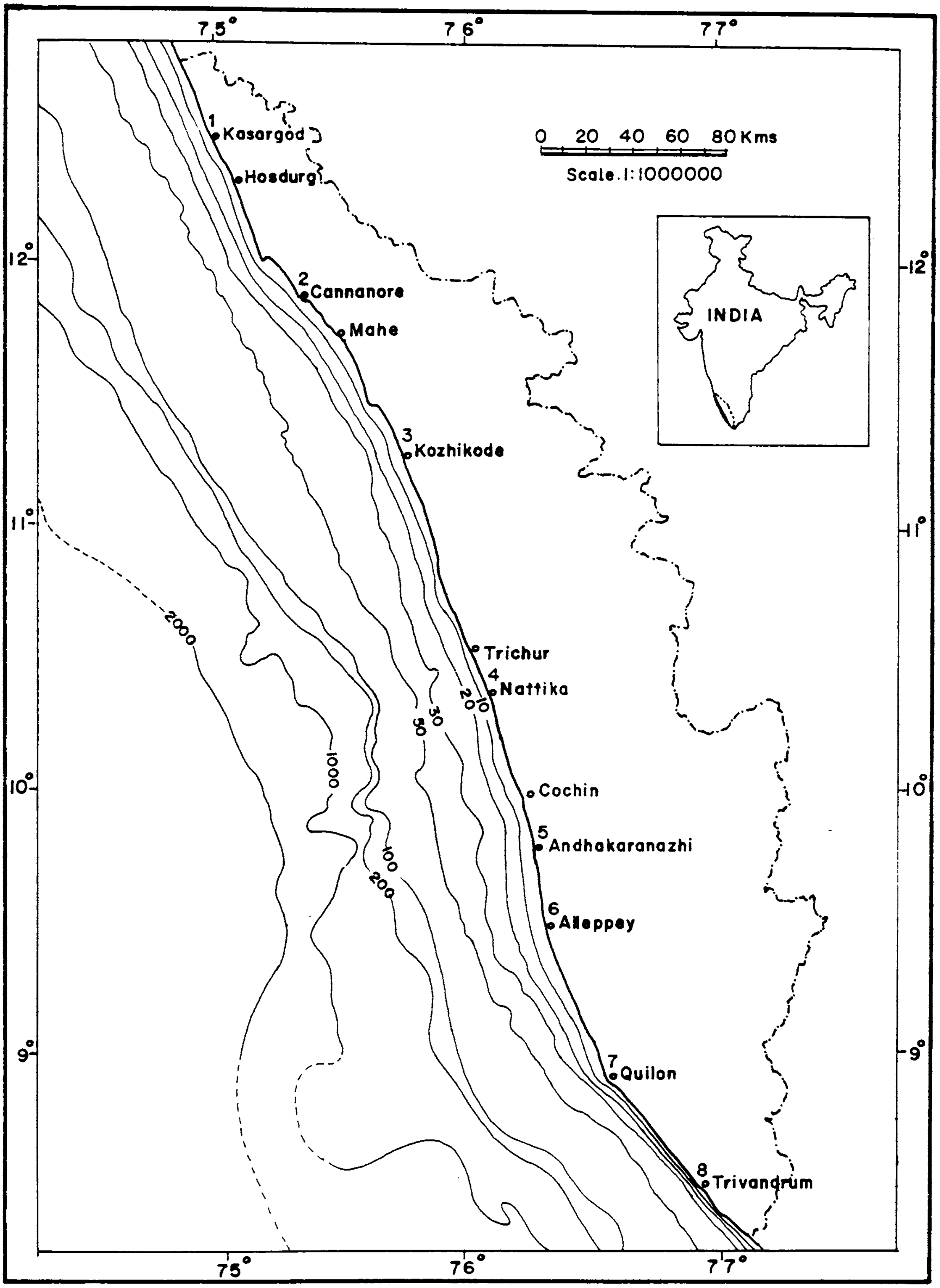


Fig. 1.5. Region under study showing the bathymetry and location of stations.

account the morphological settings. They have been chosen to represent headland beaches, barrier beaches, open coast beaches, beaches exposed to low and high energy environment and beaches in the vicinity of mud bank formation.

1.5. Previous Studies

Much work has been done in India and elsewhere on various types of coastal process phenomena.

A good deal of literature have been generated in regard to the general principles, beach set up, various processes and structure of the beaches (Bascom, 1954, 1980; Inman and Fratuschy, 1966; Ippen, 1966; Komar and Inman, 1970; King, 1972; Shepard, 1973; Komar, 1976; Goldsmith et al., 1977; Curt, 1990; Wiel, 1991). They have conducted various experimental as well as model studies on this subject. The Coastal Erosion Board (CEB), Army Crops and the CERC (Coastal Engineering Research Centre) of United States have made substantial contributions on beach processes and configuration. The stability of beaches in California and north Carolina have been extensively described by Dingler (1981) and Dolan (1965) respectively. Beach processes and erosion in various beaches of United states have been studied by Brunn (1954), Caldwell (1956), Giles and Pilkey (1965) and Ingle (1966).

The first attempt to quantify the longshore sediment transport of sand has been made by Scripp's Institution of

Oceanography. Many theories have been developed using the relationship between the wave forces and the transport of sediment (Krumbien, 1944; Savelle, 1950; Johnson, 1956; Galvin, 1972; Komar and Inman, 1970; Komar, 1976; Walton and Bruno, 1989). Extensive studies on nearshore currents have been made over the last several years. Several investigations have been made both in the field and laboratory to obtain a quantitative measure of the field of motion in relation to the breaker characteristics utilizing the concept of radiation stress. (Longuet-Higgins and Stewart, 1962). Many theories have been initiated to derive the nature of circulation in the surf zone (Bowen, 1969; Inman and Bagnold, 1963); Sonu, 1972; Noda, 1974). All these studies have shown the occurrence of descrete circulation cells for normal incidence of wave rays. Sediment drift estimations based on empirical relationship developed from quantitative estimates of littoral flows through wave refraction studies and field experiments have been made along various coastlines of the world. Pyokari and Lehtovaara (1993) have studied the beach material and its transport in accordance with the predominant wave directions on some shores in Northern Greece. Bagnold (1963) and Horikowa (1978) have conducted model experiments and explained the formation of beaches. Friedman (1967) has given a detailed picture of dynamic processes and statistical parameters and compared the size frequency distribution of beach and river sands. These studies, both experimental and theoretical, have brought out the importance of topography and radiation stress in the realistic derivation of the complicated field of motion within the surfzone.

Earlier studies of the morphology of sandy beaches, for example those reported by Eliot (1974), Wright et al. (1978, 1979), Chappel and Eliot (1979), Short (1979), Short and Wright (1981) and Frew et al. (1983) have described a variety of morphologic patterns and highlighted their susceptibility to changes. Previous statistical analyses of beach profile data have been stochastic in nature or have treated the changes in profile configuration as Markov processes (Sonu and Young, 1970; Sonu and Van Beek, 1971; Sonu and James, 1973). The E.O.F method has been applied for morphological studies of the beaches at Torrey Pines in United States (Winant et al., 1975; Aubrey, 1979; Aubrey et al., 1976), at Gorlestone and Great Yarmouth (Aranuvachapun and Johnson, 1979) and at Coledale (Clarke et al., 1984) and for prediction of beach changes at Torrey Pines (Aubrey, 1978).

Studies on different coastal processes relating to the east and west coasts of India are briefly reviewed in the following sections.

East coast of India :

Detailed coastal geomorphological studies have been carried out first by Andhra University (1954 and 1958), along the east coast of India. In addition, littoral processes along the east coast have been investigated by La Fond and Prasada Rao (1956), Sastry (1958), Subba Rao and Madhusudhana Rao (1970), Varadarajulu (1972), Reddy et al. (1979), Chandramohan et al. (1981), Vasudev (1982), Chandramohan and Narasimha Rao (1984), Chandramohan and Rao (1985) and Sundar and Sarma (1992). Wave refraction studies using graphical method has been carried out by Prasad et al. (1981) and Dhanalakshmi (1982). Sediment dynamics along the east coast has been studied at Kakinada Bay by Subba Rao (1967) and at Madras and Puri by Kanth (1984). Grain size trends in the Kakinada beach have been studied by Sathyaprasad et al. (1987). Other studies relate to analysis and hindcasting of wave data along the coast. (Sathe et al., 1979; Reddy et al., 1980; Mukherji and Sivaramakrishnan, 1982a, 1982b). Chandramohan et al. (1991) compared reported wave data with instrumentally measured waves at Kakinada coast.

West coast of India :

Since coastal processes along the west coast have been investigated by many researchers in relation to various aspects of the beach problems, they have been broadly classified subjectwise herein.

Geomorphology : Formation of the Kerala coast with it's net-work of lagoons and estuaries and rich and heavy mineral sands has been studied by Prabhakara Rao (1968). Studies on the origin and distribution of black sand concentration on the southern coast of India have been carried out by

Aswathanarayana (1964). Later, Jacob (1976) described the general geology of south Kerala including the structure, tectonics and erosion. Soman (1980), Thiagarajan (1980) have reviewed the earlier studies on geology and geomorphology of Kerala.

Studies on morphological changes at selected places along the west coast of India in relation to wave energy have been made by Veerayya (1972), Veerayya and Varadachari (1975) and Murty (1977). The coastal evolution of Kerala with special reference to coastal instability and erosion has been reviewed by Varadarajan and Balakrishnan (1980). Coastal geomorphology of Kerala has been described by Nair (1985). Report by Kerala Engineering Research Institute, KERI (1971) shows that 600 m wide belt of land has been lost during a period of 120 years from 1850 to 1970. Shoreline changes based on historical records have been investigated by Ravindran et al. (1971). A comprehensive report of the coastal geomorphology of this area is available in the text book by Ahmed (1972).

Comparative study of the maps of 1850 to 1966 by John and George (1980) suggested that a major part of Kerala coast has receded during this time. Shoreline changes on Kerala coast between Ponnani and Quilon for a period of 120 years have been studied by John and Verghese (1976) based on authentic maps and charts. However shoreline fluctuation studies over a time gap of 55 years (1910-1965) by Thrivikramji et al. (1983) using Survey of India toposheets have shown that the Kerala coast has gained 41 km^2 by accretion and lost 22 km^2 by erosion.

Nearshore waves: Studies to understand the wave climate were initiated in the fiftees mainly for understanding coastal processes (Varadachari, 1958; Sastry, 1958). The need for an in-depth study of the waves in the seas surrounding India was felt in the late sixties and early seventies. Some information on wave groupness along the south-west coast is available for Mangalore (Dattatri, 1973) and for Vizhinjam (Namboothiri, 1985). Non dimensional time series data on waves measured by wave rider buoys are available for limited locations and duration. (Dattatri, 1973; Baba, 1985; Nayak et al., 1990, Baba et al., 1991). The wave studies along the south-west coast have been conducted by many researchers (Swamy et al., 1979; Gopinathan et al., 1979; Murty and Varadachari, 1980; Varma et al., 1981; Baba et al., 1987; Joseph et al., 1984; Baba and Harish, 1986; Harish and Baba, 1986; Baba, 1987; Muraleedharan, 1991). Ship observed data, reported by I.M.D have been analysed by Srivastava and George (1976) and Thiruvengadathan (1984). Hindcasting studies also have been taken up for this period by Srivastava (1964), Dattatri and Renukaradhya (1971), Rao and Prasad (1982) and Joseph (1984). The ship reported waves around the Indian coasts have been compiled for the wave statistics of different regions and prepared in the form of atlases and charts. (Srivastava et al., 1968; NPOL, 1978; Varkey et al., 1982; Chandramohan et al., 1990).

The analysis of the wave data (Baba *et al*., 1985; Thomas and Baba, 1983) collected by CESS for five years have helped in understanding the wave climate and its year-wise variations at different locations of the Kerala coast. They have reported that the wave climate along the coast showed considerable variation, with highest wave activity at Trivandrum as compared to the northern beaches. The wave climate is evidently controlled by the meteorological conditions in the neighboring Arabian Sea and Indian Ocean. The highest wave activity has been observed with the occurrence of Southwest and Northeast monsoon winds. It has also been revealed that the wave power potential varied from place to place along the beaches of Kerala and Valiyathura (Trivandrum) recorded the highest wave power (4 - 25 Kw/m) throughout the year. (Baba *et al*., 1987).

Wave transformation and Refraction : Areas of erosion and accretion have been identified by the construction of refraction diagrams along the west coast of India by Das *et al*. (1966), Reddy (1970), Sastry and D' Souza (1973), Gouveia *et al*. (1976), Antony (1976), Varma and Varadachari (1977), Veerayya *et al*. (1981), Shenoi and Prasannakumar (1982) and Prasannakumar *et al*. (1983). The sediment characteristics, beach volume changes and the wave transformations have been studied by Reddy and Varadachari (1972), Murty and Varadachari (1980), Hameed *et al*. (1984), Prakash *et al*. (1984), Baba (1988a), Ramamurthy *et al*. (1986) and Mallik *et al*. (1987). Only limited studies have been reported on wave transformation using numerical models (Mahadevan and Renukaradhya, 1983; Kurian et al., 1985a). Kurian (1987) and Chandramohan (1988) have studied the wave transformation of deep water wave in shallow water using refraction models.

Beach erosion and stability : The impact of erosion on the socio-economic sphere has inspired the researchers to account for the processes that impart instability to the coast. Studies on various beach processes, stability and structure of the Kerala coast have been made by Narayanaswamy (1967), Nayak (1970), Dattatri and Ramesh (1972), Ahmed (1972), Kurup (1977), Shenoi and Prasannakumar (1982), Shenoi (1984), Prasannakumar (1985), Murty and Veerayya (1985), Suchindan et al. (1987) and Samusuddin and Suchindan (1987).

Beach erosion and geomorphology of the Kerala coast have been studied by Das et al. (1966), Varma and Varadachari (1977), Moni (1980), Sreenivasan et al. (1980) and Baba (1979b, 1981a & 1986). Chavadi and Bannur (1992) have studied the relationship between the changes in volume of the foreshore and its slope. A review of erosion and shore protection works along the Kerala coast has been provided by Achuthapanickar (1971).

Some insight into the management problems related to coastal erosion in Kerala has been provided by Kurup (1974), Baba (1979b) and Moni (1981). A critical appraisal of coastal erosion of Kerala has been done by Raju and Raju (1980).

Monsoon-induced seasonal variability of the beaches has been studied by Shenoi et al. (1987) and Kurian et al. (1985). Studies on beach profile conducted by Thrivikramji et al. (1983) during the pre-and post-monsoon showed that all along the coast from Cape Comorin to Mangalore, 30 million tons of sand were removed by waves from the shore face of Kerala while 11 million tons were added in different sectors. The effects of seawall constructed along the beach were discussed by Murty et al. (1980). Reddy et al. (1982) have made valuable contribution to the study of formation of beaches, its set up and the different processes responsible for causing drastic changes on the beach face. The beach cycles and the seasonal changes at Valiyathura, Trivandrum were recorded by Murty and Varadachari (1980) and along the Quilon beaches by Prakash and Aby Verghese (1985).

Discussions on the shore changes related to the mud banks of Kerala region have been given by Dora et al. (1968), Nair and Murty (1968), Varma and Kurup (1969), John and Padmanabhan (1971), Moni (1971), Gopinathan and Qasim (1974), Varadachari (1972), Kurup (1977), Sreenivasan et al. (1980) and Mac Pherson and Kurup (1981).

Only a very few studies have been made using E.O.F method for the Indian beaches. The responses of the barrier beaches of the south-west coast of India due to the monsoonal forcing have been studied using E.O.F analysis by Prasannakumar (1985) and Prasannakumar and Murty (1987) and the changes in profile configuration of the beaches along the west coast of India have been compared by means of E.O.F analysis by Shenoi et al. (1987) and Harish (1988).

Sediments and Grain sizes : Viswanathan (1949) has studied the physical and chemical characteristics of the beach sands of south Kerala coast for the first time. Nair and Pylee (1965) have given the grain size characteristics and Calcium carbonate content of the shelf sediments of the west coast of India. Studies on beach sediments have been carried out by Murty et al. (1966) and Nair et al. (1973).

Murty et al. (1966) have investigated the nature of the beach sand level changes during a tidal cycle on the beaches along the south-west coast of India. Varadachari and Murty (1966) studied the sedimentation pattern of the beaches along the south-west coast. A detailed study of geochemistry of sediments of the west coast of India has been made by Murty et al. (1970). Studies on movement of sediment using radioactive/ fluorescent tracers have been carried out by Nair et al. (1973). A comprehensive report on coastal geomorphology of recent shelf sediments has been given by Siddique and Mallik (1972).

Physical aspects of shoreline dynamics and the textural characteristics have been given in some detail by Murty (1977). The grain size characteristics have been utilized mainly to distinguish major depositional environments (Veerayya, 1972; Veerayya and Varadachari, 1975; Chaudhri et al., 1981; Prakash et al., 1984; Ramamurthy et al., 1986). A study on the graphic measures of the beach sand size distributions in the foreshore and breaker zone has been carried out by Samsuddin (1986). Textural and mineralogical variations of beach sands along the Kerala coast have been studied by Purandara et al. (1987) and Unnikrishnan and Dora (1987). Previous studies pertaining to the inter-relationship between wave-refraction, shoaling and ultimate effects on the transportation of sediments are numerous (Nair et al., 1973; Reddy and Varadachari, 1972; Varma, 1971; Murty and Varadachari, 1980; Shenoi et al., 1987). The seasonal variations in textural characteristics of the beach sediments in relation to beach profiles of northern Kerala, between Mahi and Talapadi have been studied by Suchindan et al. (1987). Sediment characteristics, processes and stability of the northern Kerala coast beaches have been presented by Samsuddin et al. (1991).

Longshore current : A number of studies have been conducted on longshore currents along the west coast (Chandramohan and Rao, 1984; Hameed et al., 1986; Krishnakumar et al., 1989). Structural aspects of the surfzone currents have been presented by Murty et al. (1975) and Murty and Veerayya (1985). The erosion/accretion pattern and the related longshore current variations have been studied in detail along the coastal stretch of the northern Kerala by Samsuddin and Suchindan (1987), Suchindan et al. (1987) and Samsuddin et al. (1991). Wave induced nearshore flow pattern has been studied by Prasannakumar et al. (1990).

Littoral transport : Many authors have summarised the littoral transport of beach sediments (Sastry, 1958; Nambiar and Moni, 1966). Along the west coast of India, quantifative determination of littoral flows have been made only at few localities. (Sastry and D'Souza, 1973; Antony, 1976; Lalithananda Prasad et al., 1981; Shenoi and Prasannakumar, 1982; Prasannakumar et al., 1983, 1990). Sediment transport along the west coast of India has been studied by Chandramohan et al. (1989) and Chandramohan and Nayak (1991). Sediment movement in relation to the wave refraction and beach erosion and accretion has been studied by Varma (1971), Nair et al. (1973), Reddy and Varadachari (1972), Murty and Varadachari (1980) and Baba (1985). The sediment movement on Aligagga beach has been studied by Hanamgond and Chavadi (1993) using E.O.F analysis and volume changes have been compared to better understand the on-offshore sediment movement.

CHAPTER 2

2. WAVES AND WAVE TRANSFORMATION

Wave action provides the primary source of energy available in the nearshore zone for various processes. Waves contribute to form beaches, assorting bottom sediments on the shoreface and transporting bottom materials onshore-offshore and alongshore. An adequate understanding of the fundamental physical processes in surface wave generation and propagation must precede any attempt to understand the complex water motion in nearshore areas. Inorder to provide the physical and mathematical understanding of wave motion, various theories have been used to describe wave generation and transformation. Waves which reach coastal regions expend a large part of their energy in the nearshore region. Since the actual water-wave phenomenon is difficult to describe mathematically because of non-linearities, three-dimensional characteristics and apparent random behaviour, many theoretical concepts have been evolved for describing the complex sea waves.

2.1. Wave climate

Information on wind waves is extremely important for projects related to coastal and offshore development and for the proper management of the coastal zone. Wave climate at a shoreline depends on the offshore wave climate, caused by the prevailing winds and storm, and on the bottom topography that modifies the waves as they propagate shoreward. Ocean waves are highly random in nature, and longer the duration of observation, more realistic would be the estimation of design parameters.

Compilation of ocean wave climate involves the long-term collection of wave data at many locations on an operational basis. Since a systematic collection of wave data for the seas around India is lacking, the information about the wave climate is limited. Under such circumstances, the following procedures are generally followed to obtain information on waves.

1. Visual information on sea and swell wave characteristics reported by ships passing in the seas around India pertain to deep water waves. This data are reported by the India Meteorological Department and form a major source of wave information till recently. The human error in the visual observation and the scarcity of data during rough weather seasons are some of the limitations in such wave information. Soares (1986) stresses that visual observations of wave height are still the main source of statistical informations available for the reasonable prediction of extreme wave conditions.

   The information on waves close to wave breaking zone is lacking due to the operational difficulties involved in making the measurement close to the shore. In many of the littoral environmental observation programs, still the visual observations are made to estimate the breaking wave parameters.

2. Wave hindcasting using meteorological conditions is another source to obtain the wave information. The estimation of nearshore wave climate from hindcasting is usually a time-consuming job and the estimate obtained may suffer in quality because of the inaccuracy of the meteorological data and the difficulty of assessing the effect of nearshore topography on wave characteristics. Computer based wave prediction models include deep water forecasts for commercial and military ship routing, nearshore forecasts for commercial and recreational interests and climatological forecasts of extreme wave conditions for ocean engineering applications such as offshore structural designs.

3. The direct source of wave climate information is the measurement of wave using instruments, which forms a more reliable one. Instrumentally measured wave data around the Indian coast are very limited. In India, wave measurements have been done using shore based stations, moored buoys, and shipborne wave recorders on board R.V. Gaveshani, O.R.V. Sagar Kanya and FOR V Sagar Sampada.

Since the wave measurements using instruments are very expensive both in manpower and facility, the ship reported data compiled for a longer periods have been advantageously used for various coastal engineering studies. In India, effective long term data collection using instrument is not yet systematic. The instrumental measurements at many places mostly cover the duration of only an year or less.

Waves in deep water can propagate for enormous distances without much attenuation. The coastal wave climate of any region is dependent on deep water waves and their complex transformation processes. Depending upon the location the breaker direction vary between 210° N to 300° N along the south-west coast of Kerala. (Baba, 1988).

In the light of the general wave climate data available (N.P.O.L, 1978; Varkey et al., 1982; Chandramohan et al., 1990), the deep water waves having directions 270°, 210° and 290° for south-west monsoon, north-east monsoon and fair-weather seasons respectively with periods 6 and 8 sec. were selected for the preparation of refraction diagrams along the Kerala coast.

2.2. Wave theories

Wave phenomenon is complex and difficult to describe mathematically. The wave theories put forward by Airy (1845) and Stokes (1880) predict the wave motion reasonably well in the region where the water depth is large compared to wave length. The higher order wave theories (Stokes, 1880) are found satisfactory under certain circumstances in describing the waves. For shallow water regions, cnoidal wave theory (Kortweq and DeVries, 1895) is generally used to predict the form and associated motion. At very shallow regions, the solitary wave theory (Russel, 1845; Boussinesq, 1872; Rayleigh, 1876; McCowan, 1891; Keulegan, 1948; Iwasa, 1955) can be used to describe the wave behaviour satisfactorily. The regions of validity of various wave theories are indicated by Le Mehaute (1969).

In shallow water region, particularly close to breaking zone, the use of higher order wave theories would provide more accuracy in the analysis. The appropriate wave theories for the different regions are classified according to the relative water depth as follows.

h/L	Wave theory
> 0.2	Stoke's III order
0.2 > = h/L> 0.05	Cnoidal
0.05 > = h/L > h_b/L	Solitary

where h is the water depth and L is the wave length.

2.2.1. Small amplitude wave theory

The elementary progressive wave theory referred to as the small amplitude wave theory was developed by Airy (1845). It is of fundamental importance because it is easy to apply and reliable over a large segment of the whole wave regime. While the exact wave theories are presented in series of terms., the one with only the first term is called the small amplitude wave theory. It assumes that the wave height (H) is so small that all higher order terms can be neglected. In this way, the free surface boundary condition is linearised and the resulting approximate equation is obtained. The small amplitude wave theory with the associated boundary conditions give the phase velocity (Svendsen and Jonsson, 1976),

$$C = \frac{gT}{2\pi} \tanh kh \qquad (2.1)$$

$$u = \frac{(agk)}{\sigma} \left| \frac{\cosh k(h+z)}{\cosh kh} \right| \sin(kx - \sigma t) \qquad (2.2)$$

where

$k = 2\pi/L$

c = wave celerity

u = Horizontal particle velocity

a = wave amplitude

σ = wave frequency = $2\pi / T$

2.2.2. Finite amplitude wave theory

Once the wave amplitude become larger compared to wave length the assumption of small amplitude wave theory is no longer valid and it is necessary to retain higher order terms to obtain an accurate representation of the wave motion. The finite amplitude wave theory takes into account the additional parameters H/h and H/L (where H is the wave height), but it rapidly grows complicated with increasing order of approximation.

2.2.3. Stoke's higher order wave theory

Stoke's (1880) presented the approach and subsequently many researchers extended the theory to various higher orders. Using the third order equations, Miche (1944) has given the following relationship for wave celerity.

$$C = gT / 2\pi \tanh kh \, (1+(\pi H/L)^2 K') \tag{2.3}$$

where $K' = (5 + 2 \cosh 2kh + 2 \cosh^2 2kh)/(8 \sinh^4 kh)$

2.2.4. Cnoidal wave theory

The existence of long finite amplitude waves of permanent form propagating in shallow water was first recognised by Boussinesq (1872) and the theory was developed by Korteweg and deVries (1895). The approximate range of validity of cnoidal wave theory is $0.2 > h / L > 0.05$ or the Ursell parameter $(U=HL^2/h^3)>25$ (Isobe, 1985). Wiegel (1960) and Masch (1961) presented the wave characteristics in tabular and graphical form to facilitate the application.

Svendsen (1974) presented the description of cnoidal waves solving the Korteweg and deVries (Kdv) equation. The solution of this equation is expressed by a Jacobian elliptic function c_n of two variables, θ and a parameter m ($\theta <= m < 1$)

$$\eta = \eta_{min} + H c_n^2 (\theta, m) \tag{2.4}$$

$$\eta_{min} = (1/m)((1-E/K)-1)H \tag{2.5}$$

where

η_{min} = distance of trough from the mean water level

K = K(m), complete elliptic integrals of the first kind

E = E(m), complete elliptic integrals of the second kind

The value of parameter m is the solution of the transcendental equation

$$U = H\,L^2/h^3 = (16/3)\;mK^2 \qquad (2.6)$$

If the wave motion is specified by H and L at depth h, equn. (2.6) has only one solution and hence for K and E. For practical purposes, Skovgaard et al. (1974) have tabulated m, K and E as functions of U. The cnoidal solution for wave celerity, c is given by,

$$C = (gh\;(1+A(m))\;H/h)^{0.5} \qquad (2.7)$$

where A(m) = (2/m)-1-(3/m)(E/K)

Often as the wave is specified by the wave period (T) in addition to height (H) and depth (h), using C = L/T in equn. (2.7),

$$L/h = T(g/h)^{0.5}\;(1 + A(H/h))^{0.5} \qquad (2.8)$$

Skovgard et al. (1974) have tabulated the solution of equn. (2.7) in terms of L/h with $T(g/h)^{0.5}$ and H/h as parameters.

2.2.5. Solitary wave theory

Russel (1844) first recognised the existence of a solitary wave. The original theoretical developments were made by Boussinesq (1872), Rayleigh (1878), McCowan (1891), Keulegan and Patterson (1940) and Iwasa (1955). A particular simple type of cnoidal wave is obtained when T tends to infinity in equn. (2.8), which implies that L and hence U tends to infinity. In equn. (2.6) this results in m ⟶ 1 and in equn. (2.4) $c_n(\Theta,m) \longrightarrow \text{sech}\ \Theta$. Hence the wave celerity in solitary wave becomes,

$$c = (g\ h\ (\ 1 + H/h))^{0.5} \qquad (2.9)$$

In this study, the Stoke's third order, Cnoidal and Solitary wave theories have been used according to the depth of wave propagation.

2.3. Wave transformation

As waves propagate in to shallow water, they get modified due to wave shoaling, refraction, bottom friction, sea bed percolation, non-rigidity of the bottom and diffraction. As the phase velocity is a function of water depth, when the wave propagates over the bottom of variable bathymetry, it bends and tries to align to the bottom contours. This is known as refraction of water waves. In wave shoaling, the wave height changes because of change in the velocity of propagation.

The roughness of the seabed and the adjoining turbulent boundary layer retard the wave motion due to bottom friction. If the seabed is permeable, the percolation of water into the sea bed further retards the wave motion. The viscosity of water causes the wave energy to dissipate termed as viscous dissipation. The presence of barriers would cause the wave to diffract leeside.

In the present study, the effect of wave refraction and wave shoaling are considered. Assumption made in estimating the nearshore wave transformation are,

(1) The wave energy transmitted between adjacent wave orthogonals remain constant. The lateral dispersion of wave energy along the wave front, reflection of energy from the sloping bottom and the loss of energy by other processes are negligible.

(2) Waves are long crested and of constant period.

(3) Curvature of the wave front is small so that it has negligible effect on the velocity of propagation.

(4) Effect of wind, current and reflection from beaches are negligible.

(5) Changes in bottom topography is gradual.

(6) No crest breaking during propagation.

2.3.1. Shoaling

The wave power transmitted forward between two orthogonals in deep water

$$P_o = 1/2\ b_o E_o C_o \qquad (2.10)$$

where b_o is the distance between the selected orthogonals in deep water, E_o is the energy transmitted between two orthogonals in deep water and C_o is the phase velocity in deep water.

The power equated to the energy transmitted forward between the same two orthogonals in shallow water

$$P = n\ b\ E \qquad (2.11)$$

where b is the spacing between the orthogonals in shallow water, E is the energy transmitted between two orthogonals in shallow water and $n = 0.5(1 + (2kh/ \sinh 2kh))$

$$1/2\ b_o E_o C_o = n\ b\ E$$

$$E = 1/8\ \rho g H^2$$

$$E_o = 1/8\ \rho g H_o^2$$

where H_o is the wave height in deep water

$$\frac{E}{E_o} = \sqrt{\frac{1}{2}\frac{1}{n}\frac{b_o}{b}\frac{C_o}{C}}$$

$$\frac{H}{H_o} = \sqrt{\frac{E}{E_o}}$$

$$\frac{H}{H_o} = \sqrt{\frac{1}{2}\frac{1}{n}\frac{b_o}{b}\frac{C_o}{c}}$$

$$\sqrt{\frac{1}{2}\frac{1}{n}\frac{C_o}{c}} = K_s \text{ is the Shoaling coefficient} \qquad (2.12)$$

$$\sqrt{\frac{b_o}{b}} = K_r \text{ is the Refraction coefficient} \qquad (2.13)$$

2.3.2. Refraction

Since the phase velocity is a function of depth in shallow water, when the wave front propagates over the bottom of variable bathymetry, it bends and tries to get aligned to the bottom contours. The reduction in phase velocity in shallow water causes refraction in a process analogous to Snell's law in geometrical optics. Then the change in direction of orthogonal as it passes over relatively simple bathymetry may be approximated by,

$$\sin\alpha_2 = C_2/C_1 \sin\alpha_1$$

α_1 = angle of wave crest make with the bottom contour

α_2 = angle of wave crest for the next bottom contour

C_1 = wave velocity at a depth of first contour

C_2 = wave velocity for the next contour.

The spacing between orthogonals indicate the amount of concentration or dispersion of energy. Wave rays are normal to the crests and are therefore in the direction of wave advance and energy propagation. The wave power is conserved between adjacent rays, so that a convergence of rays implies a focusing of the wave energy leading to greater wave heights and progressive separation of rays represents defocussing. For straight and parallel contours, the orthogonals would be parallel and the horizontal distance is constant between two adjacent orthogonals. Therefore,

$$b_o/ \cos\alpha_o = b/ \cos\alpha$$

$$b_o/b = \cos\alpha_o/ \cos\alpha$$

$$Kr = (b_o/b)^{0.5} = (\cos\alpha_o /\cos\alpha)^{0.5} \qquad (2.5)$$

where α is the angle between two orthogonals in shallow water and α_o is the angle between two orthogonals in deep water.

For a given topography and deep water wave characteristics, the refracted orthogonals can be plotted by geometrical procedure (Anonymous, 1975). The graphical method of wave refraction analysis by Arthur et al. (1952), has been widely used till recently for computation of wave refraction. Studies using graphical method are many for the Kerala coast as well as other part of the country, which have been reviewed earlier (Chapter I). Many refinements have been made relating to the direct construction of refraction diagrams based on the wave crest method (Johnson, 1947) and orthogonal method. Recently computer based numerical methods for determining refraction characteristics have been used (Griswold, 1963; Harrison and Wilson, 1964; Wilson, 1966; Dobson, 1967). While these computer methods are undergoing considerable refinement, they are operational and may result in significant time saving in refraction computations over a relatively large area.

Refraction studies based on the numerical models are scanty for the Kerala coast. A study of the wave transformation using a numerical model along the Kerala coast by making synchronized measurements of deep and shallow water waves has been done by Kurian (1987). For a given bathymetry and deep water characteristics, numerical wave transformation models incorporating shoaling and refraction have been developed by many researchers. (Skovgaard et al., 1975; Griswold, 1963; Harrison and Wilson , 1964; Orr and Herbich, 1969; Jen, 1969). Most of the numerical refraction model have used the linear wave theory and a few have attempted using finite amplitude wave theories.

2.3.3. Numerical wave refraction

Fig. 2.1 shows the adjacent orthogonals O1, O2 and two consecutive wave fronts F1, F2 separated by time interval dt (Skovgaard *et al*., 1975). At point A, the infinitesimal distance between orthogonals and fronts are Df and Ds respectively, where,

$$Ds = c\ dt \tag{2.16}$$

The distance s is taken as positive in the direction of wave propagation and the positive direction of f is such that Ds and Df form a right hand coordinate system. Φ is the angle between the x axis and the orthogonal, positive in anticlockwise direction.

From the triangles BCE and CDF,

$$\text{Curvature of wave orthogonal} = D\Phi/Ds = -(1/c)\ (Dc/Df) \tag{2.17}$$

$$\text{Curvature of wave front} = D\Phi/Df = (1/Df)\ (D(Df)/Ds) \tag{2.18}$$

Defining the following operators as

$$D/Ds = \cos \Phi\ (d/dx) + \sin \Phi\ (d/dy) \tag{2.19}$$

$$D/Df = \sin \Phi\ (d/dx) + \cos \Phi\ (d/dy) \tag{2.20}$$

and using equns. (2.16) and (2.17),

$$d\Phi/dt = -\ (Dc/Df) \tag{2.21}$$

Using equns. (2.17), (2.18), (2.19), (2.20) and (2.21), the basic equations for the wave orthogonals become,

$$dx/dt = c \cos \Phi \tag{2.22}$$

$$dy/dt = c \sin \Phi \tag{2.23}$$

$$d\Phi/dt = (dc/dx) \sin \Phi - (dc/dy) \cos \Phi \tag{2.24}$$

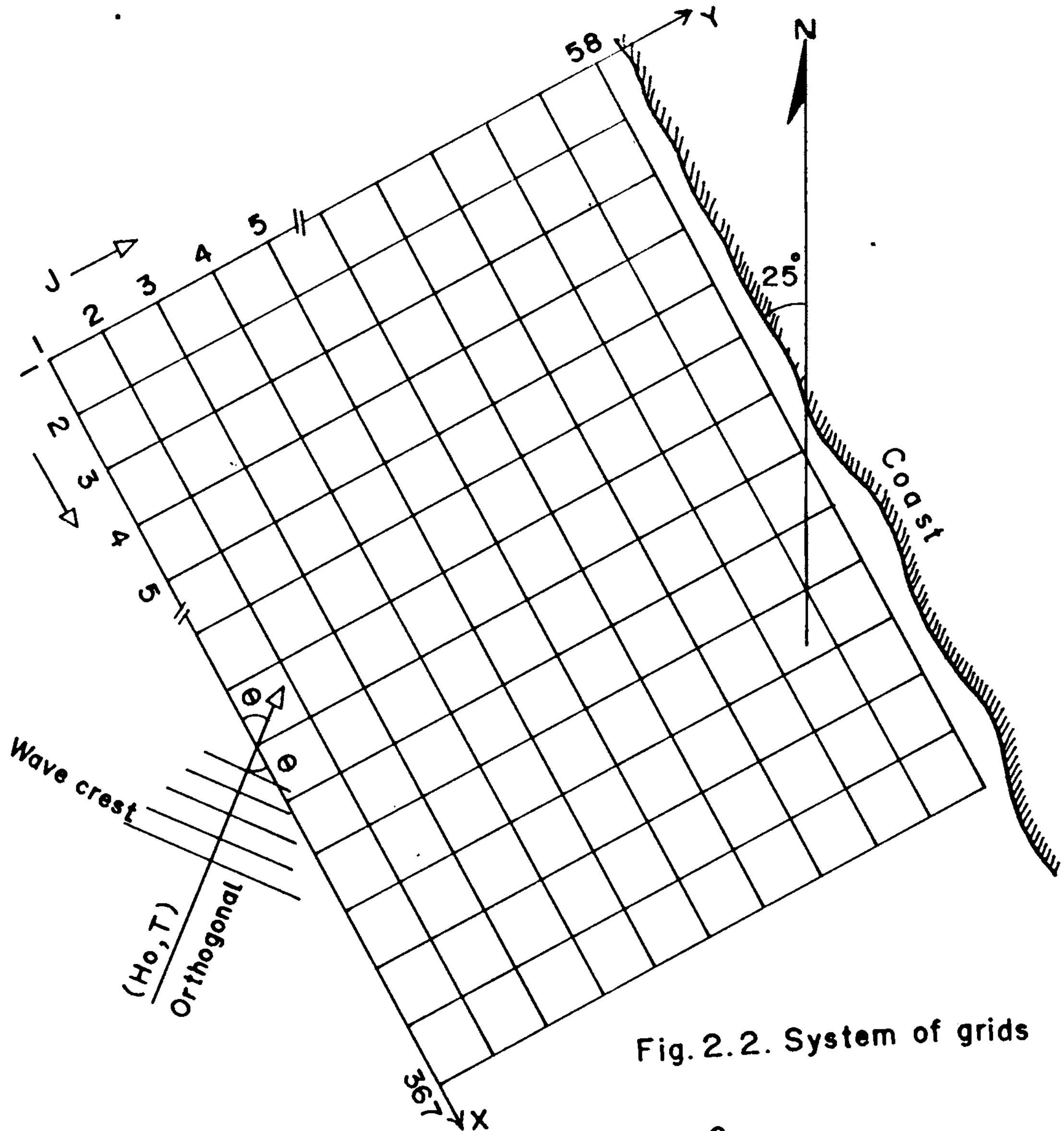


Fig. 2.2. System of grids

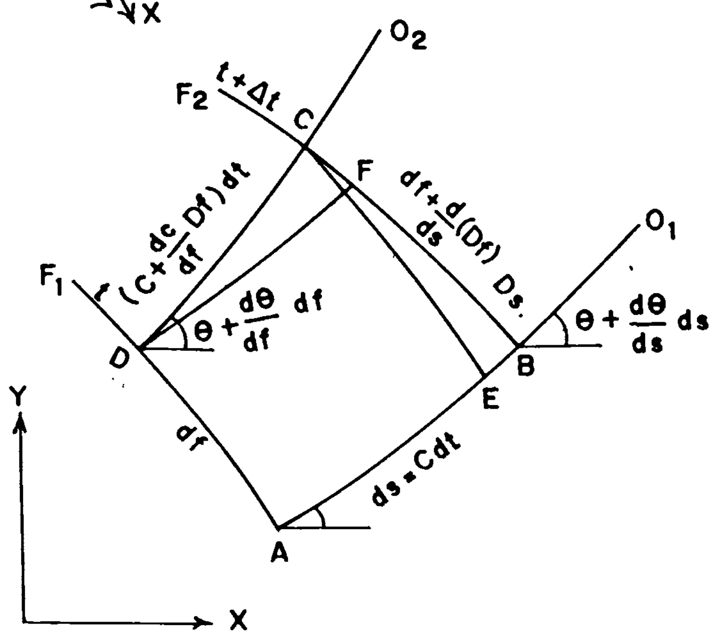


Fig. 2.1. System of wave orthogonals and fronts

For the calculation of wave heights along the orthogonal, Munk and Arthur (1952) have derived a second order homogeneous ordinary differential equation for the orthogonal separation factor (β) with distance (s) along the orthogonal as,

$$(d^2 \beta / ds^2) + p(s)\,(d\beta/ds) + q(s)\beta = 0 \qquad (2.25)$$

Using equn. (2.16), equn. (2.25) can be rewritten as function of time (t) hence the use of variable t has the advantage of giving the phase of wave motion with self adjusting wave length,

$$(d^2 \beta/dt^2) + p(t)\,(d\beta/dt) + q(t)\,\beta = 0 \qquad (2.26)$$

where, $p(t) = -2(\cos \Phi\, dc/dx - \sin \Phi\, dc/dy)$ (2.27)

$$q(t) = c((\sin^2 \Phi d^2c/dx^2) - (\sin 2\Phi d^2c/dxdy) + (\cos^2 \Phi d^2c/dy^2)) \qquad (2.28)$$

$$\beta = Df/Dfst = Kr^{-2} \qquad (2.29)$$

Equns. (2.22), (2.23), (2.24) and (2.26) with (2.27) and (2.28) can be solved numerically with proper initial boundary conditions.

2.4. Construction of refraction diagram

The numerical wave transformation model explained in Chandramohan (1988) has been used for studying the wave refraction pattern for the entire Kerala coast and to identify the regions of convergence and divergence of waves.

Referring to the section 2.2, based on the wave climate of Kerala coast the three predominant wave directions, 270° for south-west monsoon period (June-September), 210° for north-east monsoon period (October-January) and 290° for fair-weather period (February-May) were selected for the construction of wave refraction diagrams. Reflection and diffraction were not considered for this coast which is straight and open.

The grid system was prepared as shown in (Fig. 2.2) with X-axis parallel to the coastline and Y-axis perpendicular to it. The Naval Hydrographic Chart Nos. 217, 218, 219, 220 and 221 were used for estimating the contour depths. Computation starts when the origin for the specified wave direction and the wave orthogonal is plotted for each successive grid points. The orientation of the grid has been made according to the orientation of the coast. (Fig. 2.2).

The wave refraction diagrams for each wave direction have been constructed for the predominant wave periods of 6 and 8 seconds from the 100 m contour line. The program listing is given in Appendix - I and the flow chart of the model used is shown in Fig. 2.3.

2.4.1. Input for the model

1. Number of grids in X direction = IXEND
2. Number of grids in Y direction = JYEND
3. Depth at nodal points = D(IXEND, JYEND)

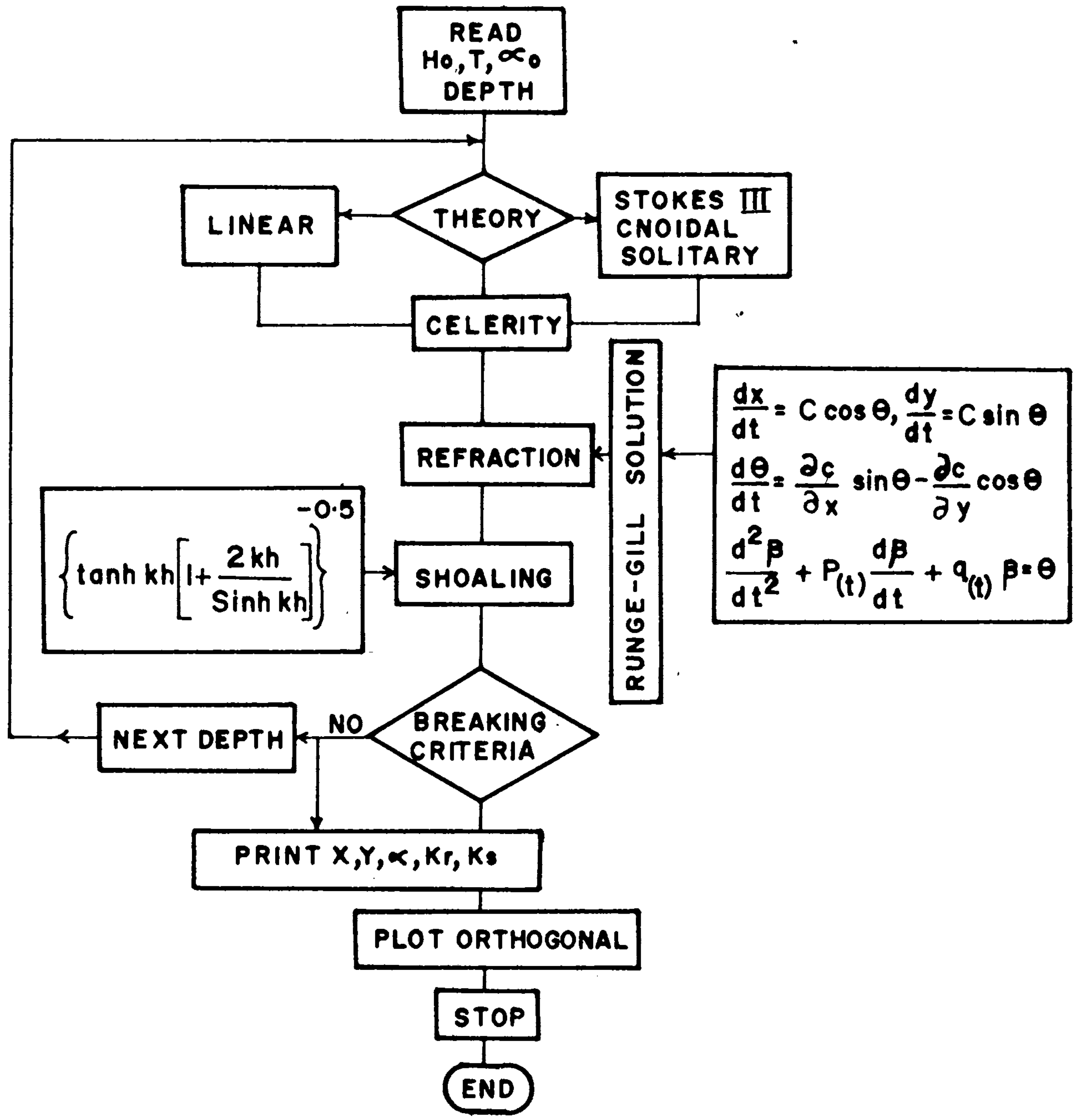


Fig. 2.3. Flow chart of Nearshore wave transformation model.

4. Distance between the grids (metres) = SCA
5. Slope of the seabed = SLOPE
6. Starting point of wave orthogonal in X direction = X
7. Starting point of wave orthogonal in Y direction = Y
8. Deep water wave height (m) = H
9. Wave period (s) = T
10. Direction of wave crest with X axis (deg) = THETA (wave crest to X axis anticlockwise positive)
11. Wave theory = LINEAR/HIGHER
12. Time step = T
13. Stop computation at = BREAKING/GIVEN DEPTH

Computation stops at one of the following condition:

1. Wave steepness : $H/L = 0.172 \tanh kh$
2. breaking depth : $d_b = 1.28\ H_b$
3. orthogonal reaches the sides/shore/required depth.

Output : Output of the model consists of grid locations of the orthogonals at different time, deformed wave crest direction, shoaling and refraction coefficients and the net wave breaker heights.

2.5. Results

The numerical wave refraction study was undertaken to find out the distribution of wave energy along the Kerala coast. The refraction diagrams for different incoming wave directions and different wave periods are presented in (Figs. 2.4a & 2.4b), (Figs. 2.5a & 2.5b) and (Figs. 2.6a &

2.6b). The pattern of wave refraction according to the different seasons are described below.

South-west monsoon period (Wave direction : 270^{o}, Wave period : 6 S and 8 S)

The refraction diagram for the predominant wave periods 6 S and 8 S for the wave direction 270^{o} with respect to north are presented in (Fig. 2.4a) and Fig. (2.4b) respectively.

(Fig. 2.4a) shows convergence of wave orthogonals only at Vypin, north of Cochin. The divergence of wave orthogonals is observed south of Ezhimala, south of Cannanore, at Quilandi, Quilon, Varkallai and Puvar. The remaining stretch of the coast experiences nearly uniform wave energy for this direction of wave approach and wave period.

Waves approaching from 270^{o} with respect to north and with 8 S period, show more convergence of energy along the coast than waves of 6 S period (Fig. 2.4b). Convergence of wave energy is observed at Kasargod, south of Cannanore, North of Quilandi, south of Beypore, at Ponnani, Vypin, north of Alleppey, north of Karunagappalli and at Neendakara. The divergence of wave orthogonals is seen south of Ezhimala, Andhakaranazhi and Quilon. Along the rest of the coastal stretch, it is seen that the wave energy is uniformly distributed.

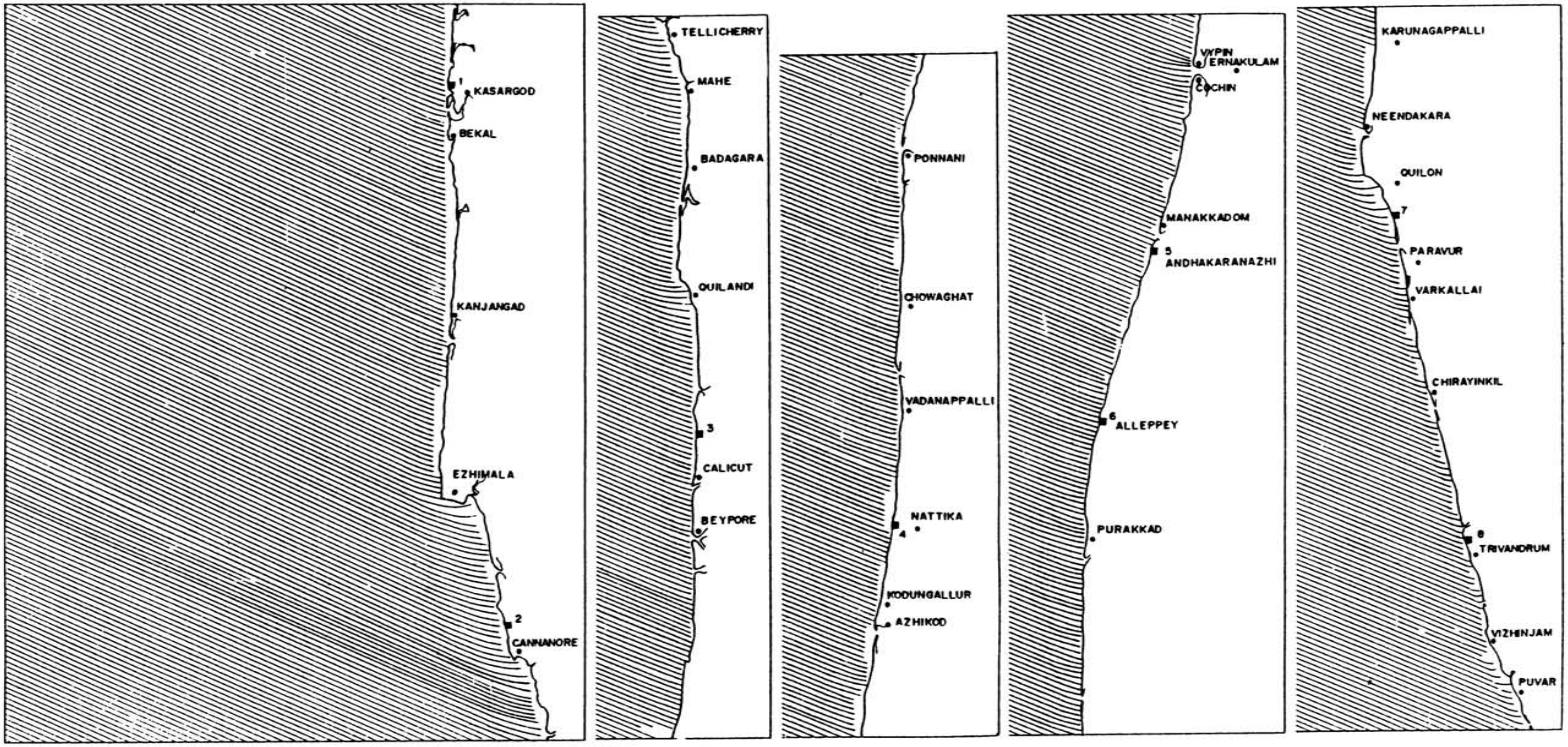


Fig. 2.4a. Wave refraction diagram for Kerala coast - Direction : 270°, Period : 6 S

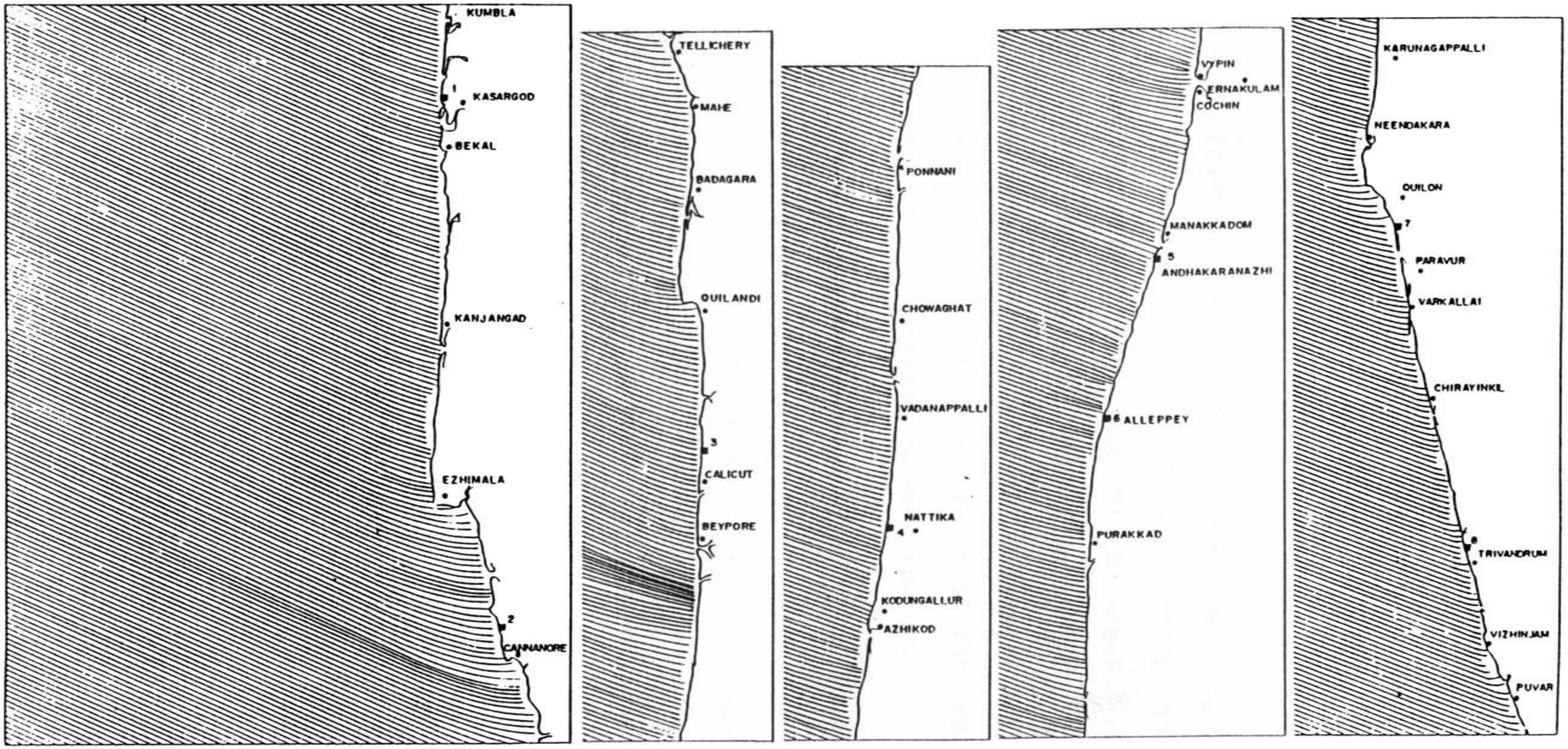


Fig. 2.4b. Wave refraction diagram for Kerala coast - Direction : 270°, Period : 8 S

North-east monsoon period (Wave direction : 210°, Wave period : 6 S and 8 S)

The wave orthogonals approaching the coast at 210° with respect to north for the wave periods 6 S and 8 S are presented in (Fig. 2.5a) and (Fig. 2.5b) respectively.

The refraction diagram for the wave period of 6 S (Fig. 2.5a), shows convergence of wave energy north of Kanjangad, at Vypin and at Purakkad. The divergence of wave orthogonals is seen along the coast south of Ezhimala, between Cannanore and Mahe, Quilandi and further south and Quilon. It is seen that remaining stretch of the coast is subjected to uniform distribution of wave energy.

(Fig. 2.5b), for the 8 S waves shows, convergence of wave energy along south of Kasargod, Kanjangad, north of Ponnani, Azhikod, Vypin, north of Alleppey, Purakkad and Neendakara and divergence of wave orthogonals near Cannanore upto Badagara, Mahe, south of Nattika, Andhakaranazhi and north of Karunagappalli. The wave energy is uniformly distributed along the other parts of the stretch of this coast.

Fair-weather season (Wave direction : 290°, Wave period : 6 S and 8 S)

The refraction of wave orthogonals for the direction 290° with respect to north for wave periods 6 S and 8 S are presented in (Fig. 2.6a) and (Fig. 2.6b).

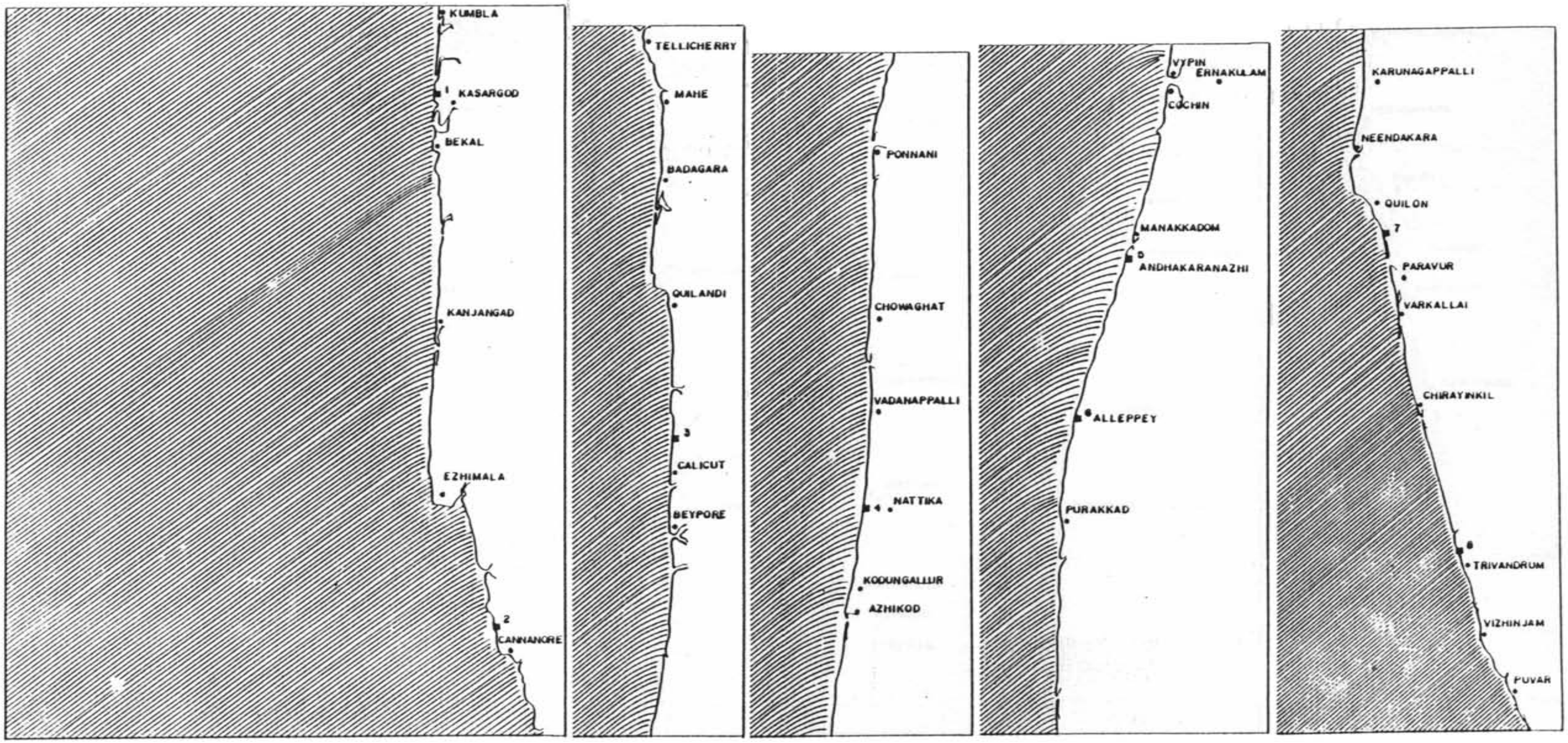


Fig. 2.5a. Wave refraction diagram for Kerala coast - Direction : 210°, Period : 6 S

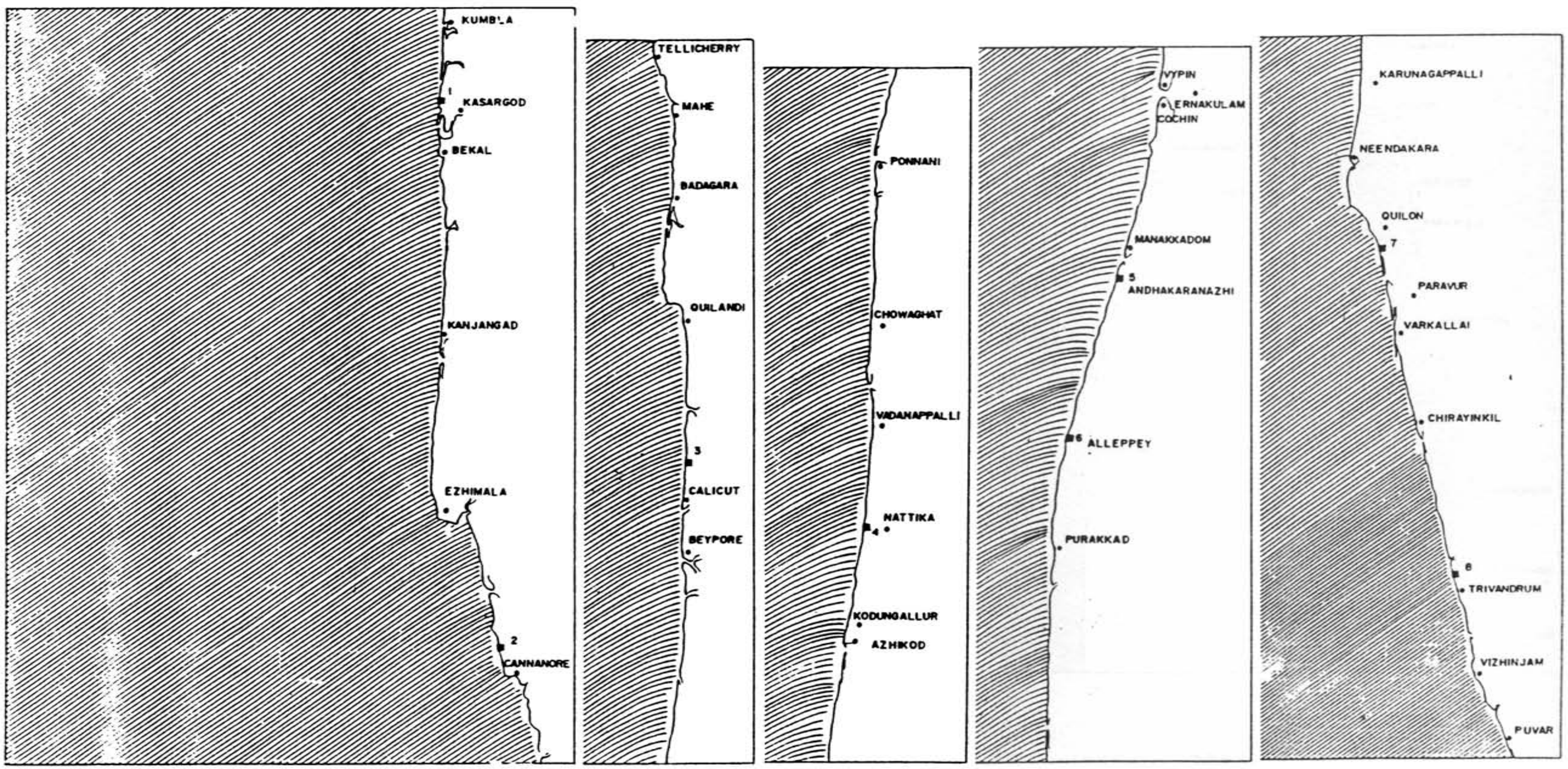


Fig. 2.5b. Wave refraction diagram for Kerala coast - Direction : 210°, Period : 8 S

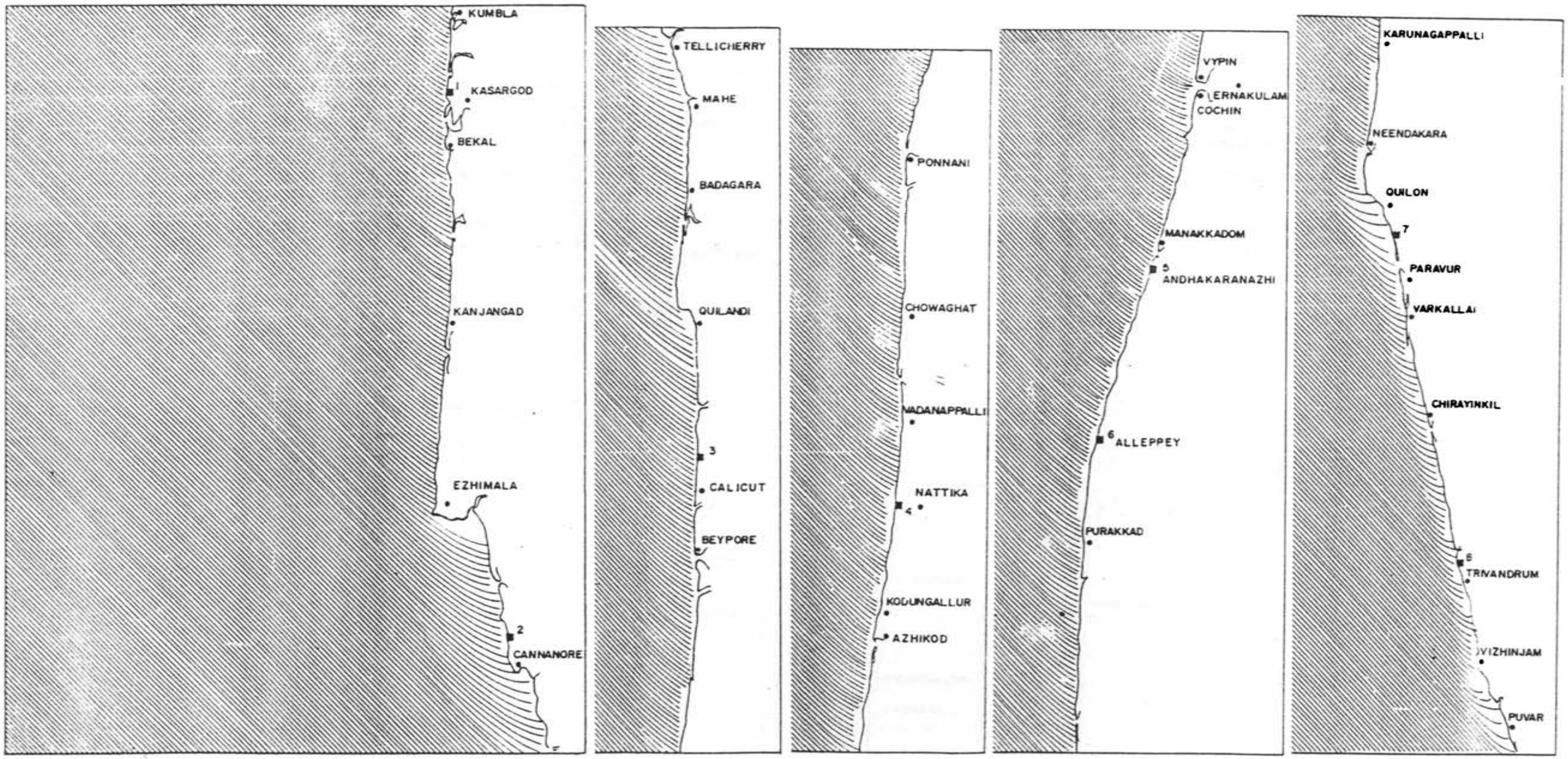


Fig. 2.6a. Wave refraction diagram for Kerala coast - Direction : 290°, Period : 6 S

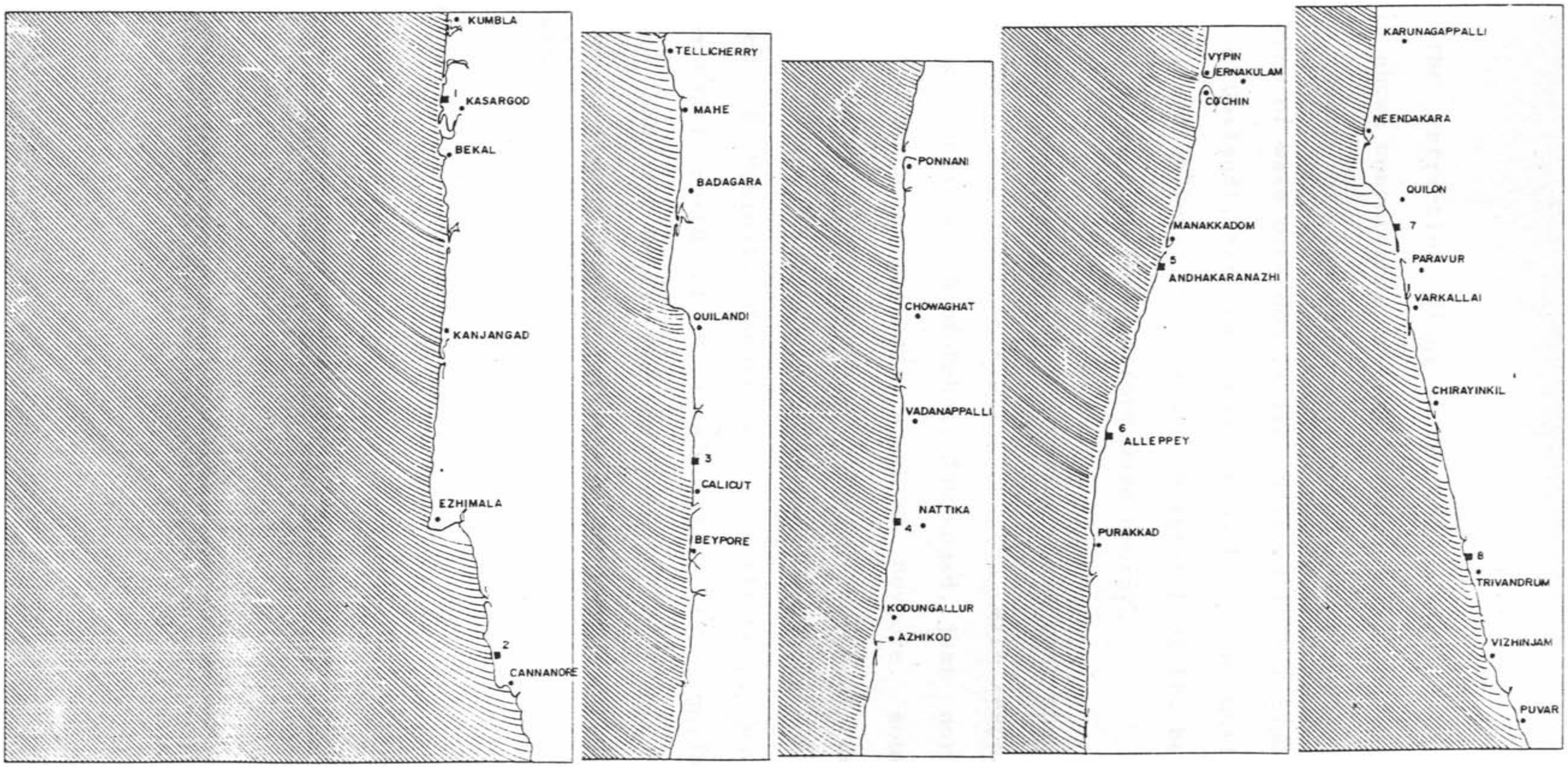


Fig. 2.6b. Wave refraction diagram for Kerala coast - Direction : 290°, Period : 8 S

The refraction diagram for wave period 6 S (Fig. 2.6a), shows convergence of wave orthogonals along north of Bekal, south of Ponnani, at Vypin and Purakkad. The divergence of wave orthogonals are observed from Ezhimala to Mahe, at Quilandi, Nattika, Andhakaranazhi, from Quilon to Varkallai and at Puvar. The remaining stretch of the beach is subjected to more or less uniform wave energy.

(Fig. 2.6b), for the 8 S period shows that the waves approaching the coast with a direction 290^{o} with respect to north converge at south of Bekal, Kanjangad, just north of Cannanore, south of Quilandi, south of Beypore, south of Ponnani, Azhikod, Vypin, north of Alleppey, north of Purakkad and at Neendakara. Divergence of the wave energy is observed at North of Ezhimala, Cannanore to Tellichery, Nattika, Andhakaranazhi north of Karunagappalli, along Quilon to Varkallai and at Puvar. The remaining part of the coast experiences direct attack of waves without appreciable refraction.

2.5.1. Variation of breaker parameters

Based on the numerical wave refraction study, the shoaling coefficient (Ks), refraction coefficient (Kr) just before wave breaking, and the variation of breaker height (H_b) for the entire Kerala coast were estimated and presented in (Figs. 2.7a & 2.7b), (Figs. 2.8a & 2.8B) and (Figs. 2.9a & 2.9b).

South-west monsoon period (Wave direction : 270°, Wave period : 6 S and 8 S)

The shoaling coefficient (Ks) for 6 S waves approaching from 270°, (Fig. 2.7a), shows relatively large values (>0.95) at Ezhimala, Cannanore, Quilandi, Cochin and between Quilon and Trivandrum. Ks shows values around 0.9 at all the other places.

For 8 S waves approaching from 270° (Fig. 2.7b), the value of the shoaling coefficients (Ks) is less than 1 at most of the places. But in some places it shows values greater than 1 (Ezhimala, Cannanore, Mahe, Quilandi, Nattika, Vypin and at South of Alleppey).

The value of the refraction coefficient (Kr) is very important because the wave energy distribution along the beach depends on Kr. From (Fig. 2.7a) it is clear that for waves approaching the coast from this predominant directions of 270° with period 6 S, the Kr values at the breaking point are greater than 1 north of Ezhimala, at Vypin, Andhakaranazhi, Alleppey and north of Quilon. The Kr value is very low along south of Ezhimala and along south of Quilon.

The refraction coefficient (Kr) presented in (Fig. 2.7b), for 8 S period waves, shows values greater than 1 north and south of Ezhimala, Kanjangad, south of Beypore, south of Bekal, between Vypin and south of Alleppey and Quilon. Kr values are low around 0.6 north of Quilon and at Varkallai. The lowest value of 0.5 is observed near Puvar.

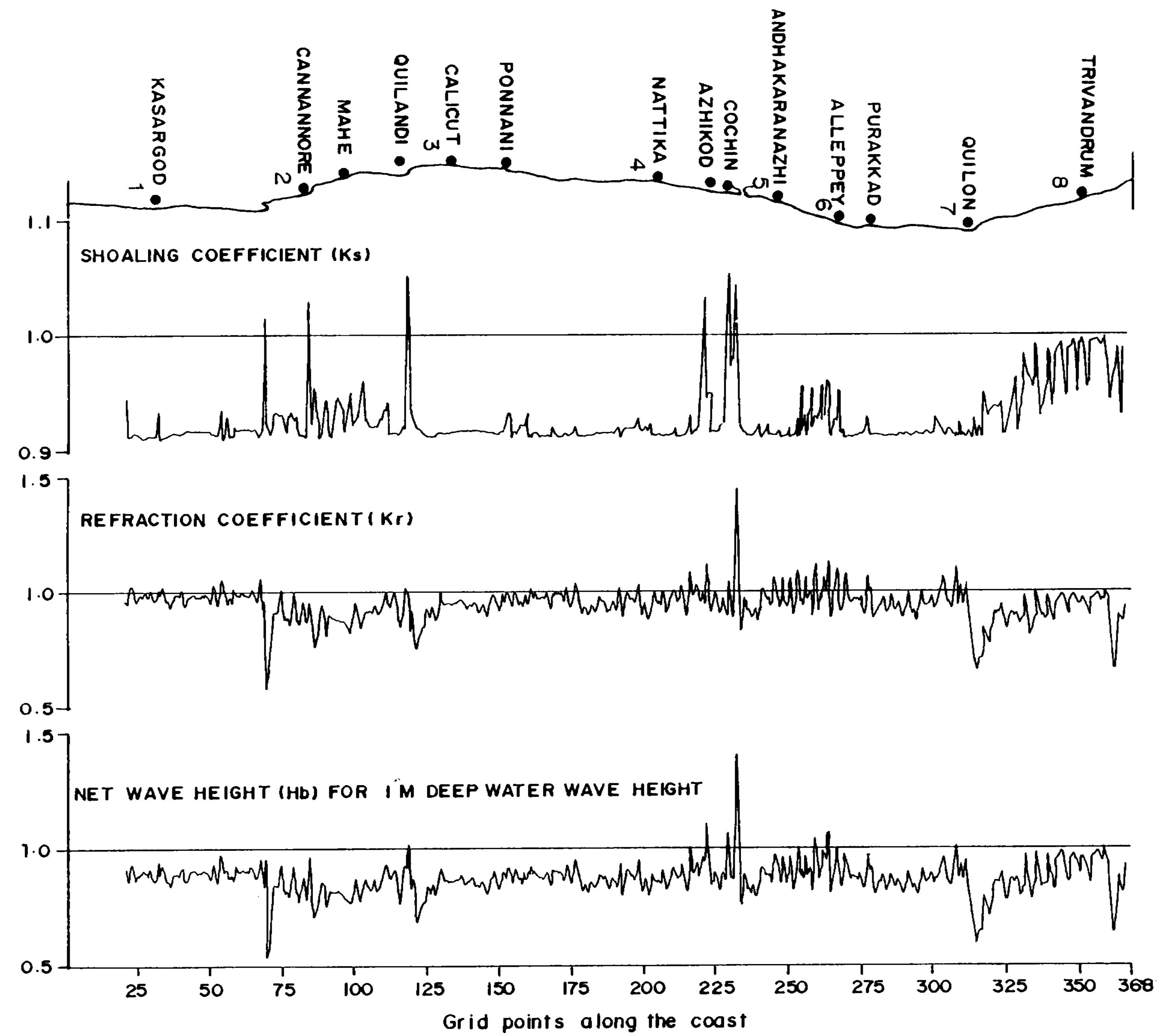


FIG.2.7a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 270° WAVE PERIOD = 6 SEC.

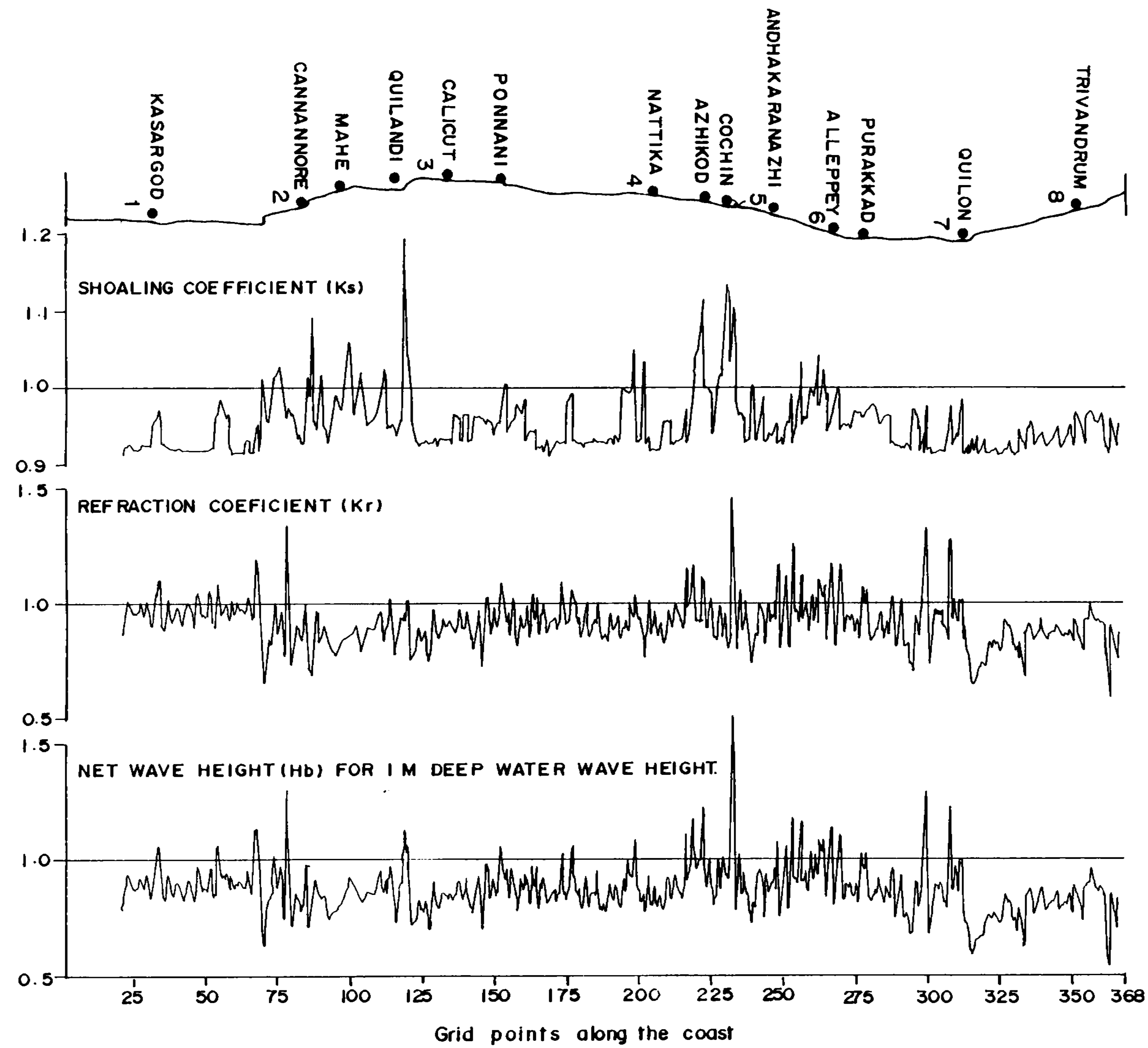


FIG. 2.7b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT. WAVE DIRECTION = 270° WAVE PERIOD = 8 SEC.

The breaking wave heights (H_b) along the Kerala coast, evaluated from Ks and Kr for unit deep water height for 6 S waves are presented in (Fig. 2.7a). Increase in net wave height (>1 m) is observed at Quilandi, Vypin, North of Alleppey and Quilon. The highest breaker height of 1.5 m is observed near Vypin. Breaker height is around 0.8 m along the remaining stretch of the Kerala coast. Low breaker height is observed at Calicut beach.

The breaker height distribution (H_b) for 8 S period waves (Fig. 2.7b) shows that the breaker heights are more than the deep water wave height at Kasargod, Kanjangad, north of Ezhimala, south of Bekal, Quilandi, south of Beypore, Ponnani, Nattika, Vypin, Andhakaranazhi, Alleppey and Quilon. Along the rest of the coast, the breaker heights are less than (0.6 m - 0.9 m times) the deep water wave height. Lowest breaker height is observed near Puvar.

North-east monsoon season (Wave direction : 210°, Wave period : 6 S and 8 S)

(Fig. 2.8a), shows that for waves approaching from 210° with respect to north with period 6 S, the shoaling coefficient (Ks) is greater than 1 at Quilandi, north of Nattika, Vypin and at Alleppey. At all the other places it is around 0.95.

The shoaling coefficient values (Ks), for the 8 S waves (Fig. 2.8b), are greater than unity at Cannanore,

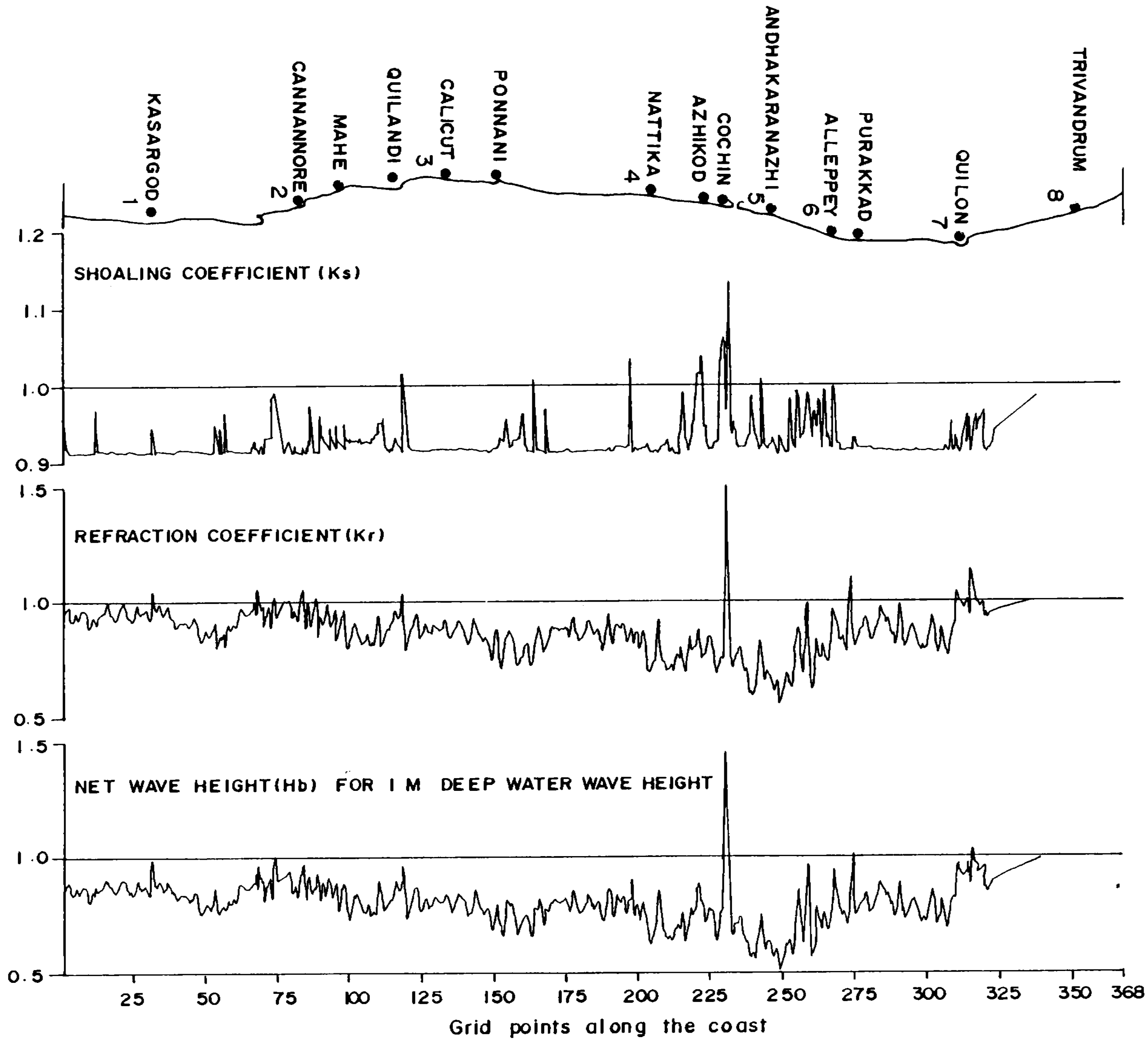


FIG.2.8a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT. WAVE DIRECTION = 210° WAVE PERIOD = 6 SEC.

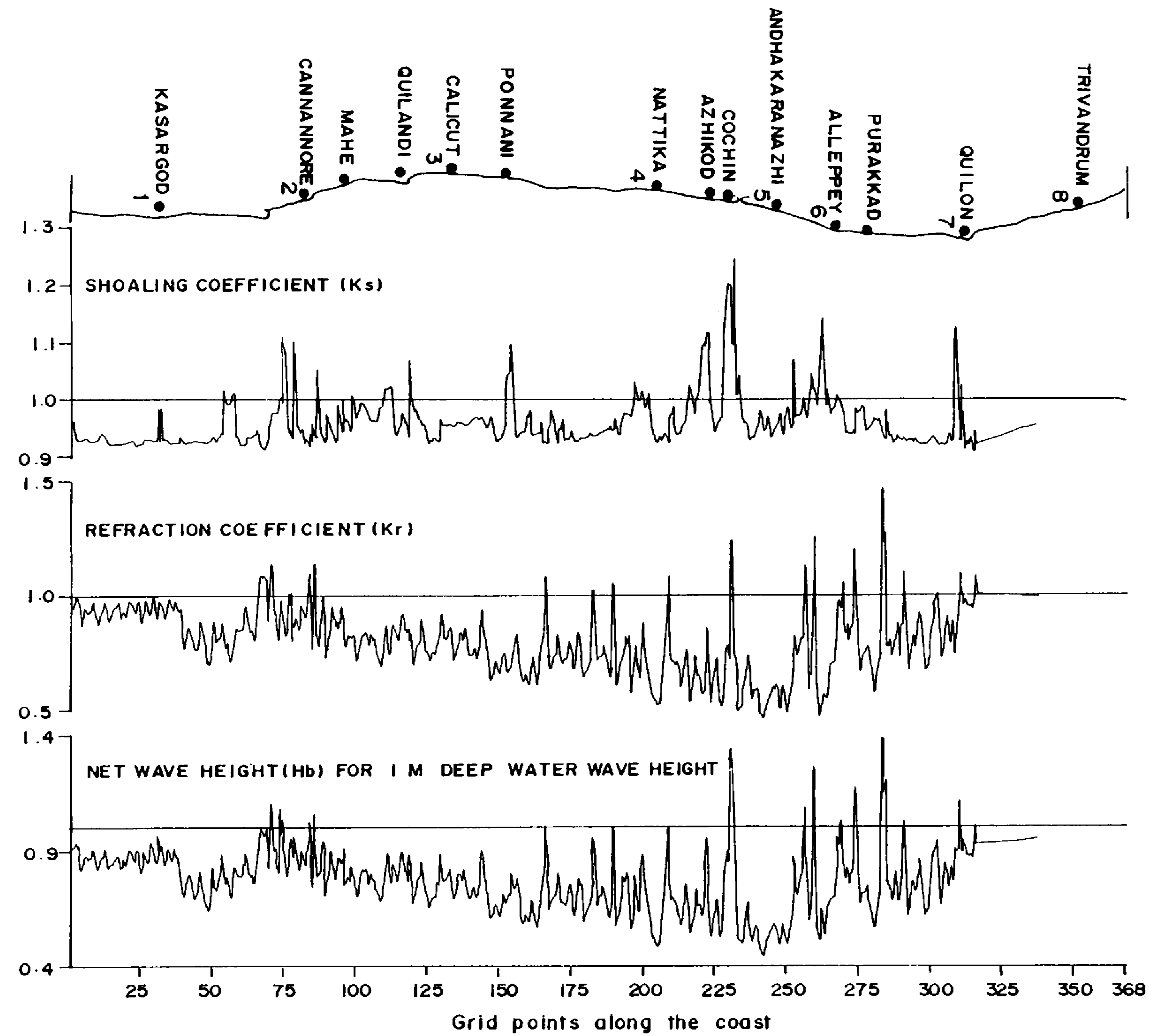


FIG. 2.8 b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT
WAVE DIRECTION = 210° WAVE PERIOD = 8 SEC.

Quilandi, Ponnani, north of Nattika, Vypin, north of Alleppey, and north of Quilon. Along the remaining stretch of the coast, the values are around 0.95.

The refraction coefficient (Kr) for 6 S period waves shows values greater than 1 at Kasargod, Ezhimala, Cannanore, Quilandi, Vypin, south of Alleppey and Quilon. All the other places, it ranges between 0.5 to 0.9.

The refraction coefficient (Kr) estimated for 8 S period waves shows that the values are greater than 1 at Ezhimala, Cannanore, south of Chawaghat, North of Nattika, Vypin, north of Alleppey, Purakkad and Quilon.

The breaker height parameter (H_b) computed for the waves approaching from 210° with 6 S period, indicates high values at Vypin and Quilon. Between Andhakaranazhi and Alleppey, the values show a minimum breaker height for this period and direction (0.6m). At other places, it is 0.75 of the deep water wave height. The highest breaker height of 1.4 m is observed north of Cochin.

For the direction of approach of 210°, waves with period 8 S show net breaker height (H_b) greater than 1 at Ezhimala, Cannanore, Vypin, north of Alleppey, Purakkad and north of Quilon. At Vypin, the wave breaker heights get amplified and show values around 1.3m for the deep water wave of 1m. At places between Nattika and Andhakaranazhi, H_b shows values around 0.5m while at Kasargod it is 0.9 m.

Fair-weather period (Wave direction : 290°, Wave period : 6 S and 8 S)

The refraction coefficients and the breaker heights estimated for the predominant wave approaching from 290° with 6 S period are presented in (Fig. 2.9a). The shoaling coefficient shows high values (>1) at Ezhimala, north of Nattika, Cochin and Quilon. Along the remaining stretch of the beach, the value is around 0.94.

From (Fig. 2.9b), for 8 S period waves, it is seen that the shoaling coefficient (Ks) is greater than 1 at Ezhimala, Cannanore, Mahe, Quilandi, Ponnani, north of Nattika, Azhikode, Cochin, Andhakaranazhi and Alleppey. At all other locations, it is around 0.95.

The refraction coefficient (Kr) for 6 S period shows low values along the entire stretch of the Kerala coast with an average value of about 0.75. High values of refraction coefficient (0.9) are observed south of Kasargod, Quilandi, Alleppey and a maximum value of 1.1 at Quilon.

The variation of refraction coefficient (Kr) estimated for 8 S period waves shows values higher than those for 6 S period waves. Kr shows high values (>1), at Cochin, south of Andhakaranazhi, south of Alleppey (Purakkad), Karunagappalli and at Neendakara. The maximum value of Kr (1.4) is observed near Neendakara and low value (0.5) near Ezhimala. Along the remaining stretch of the coast, the value is around 0.9.

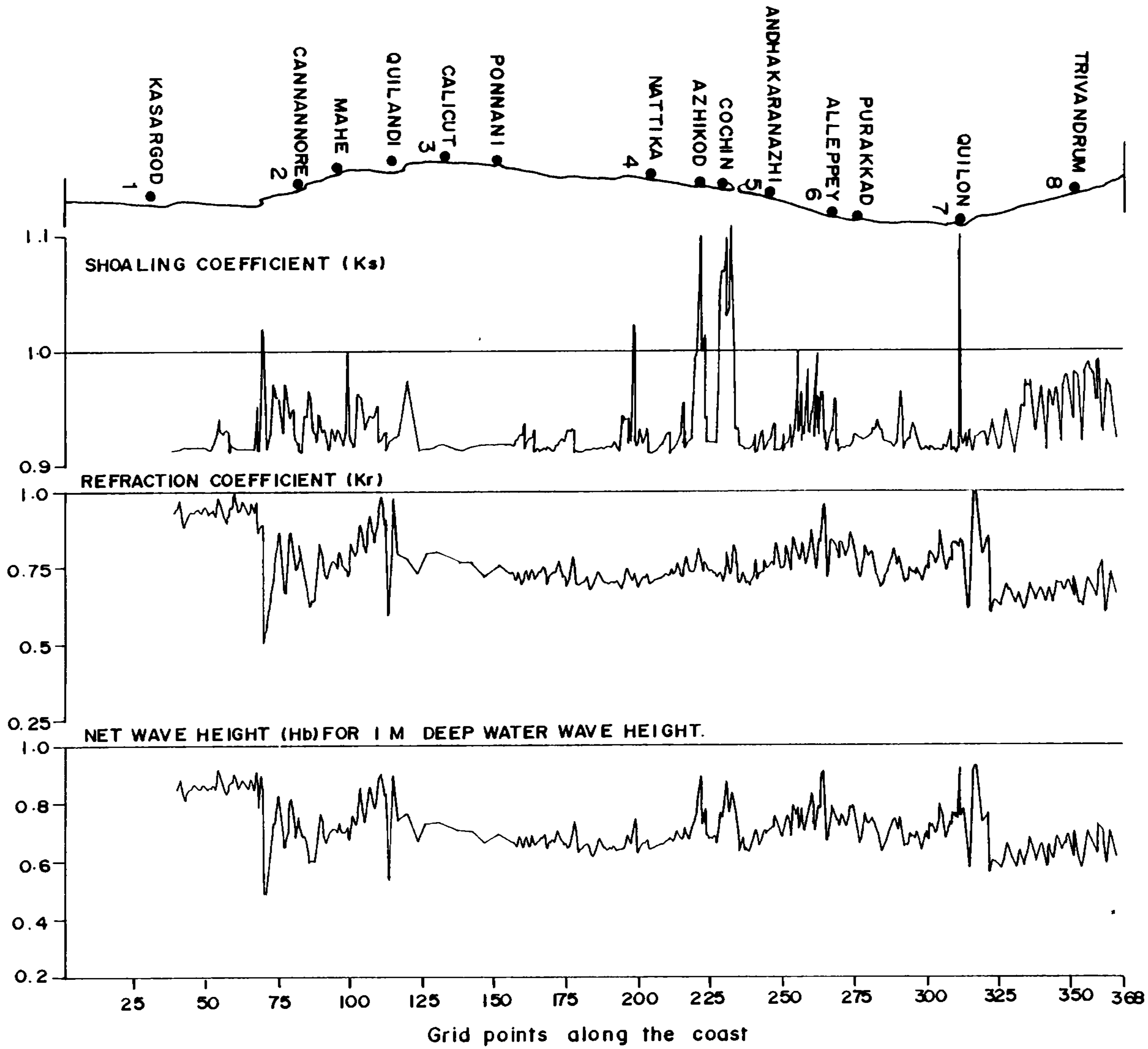


FIG. 2.9a. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 290° WAVE PERIOD = 6 SEC.

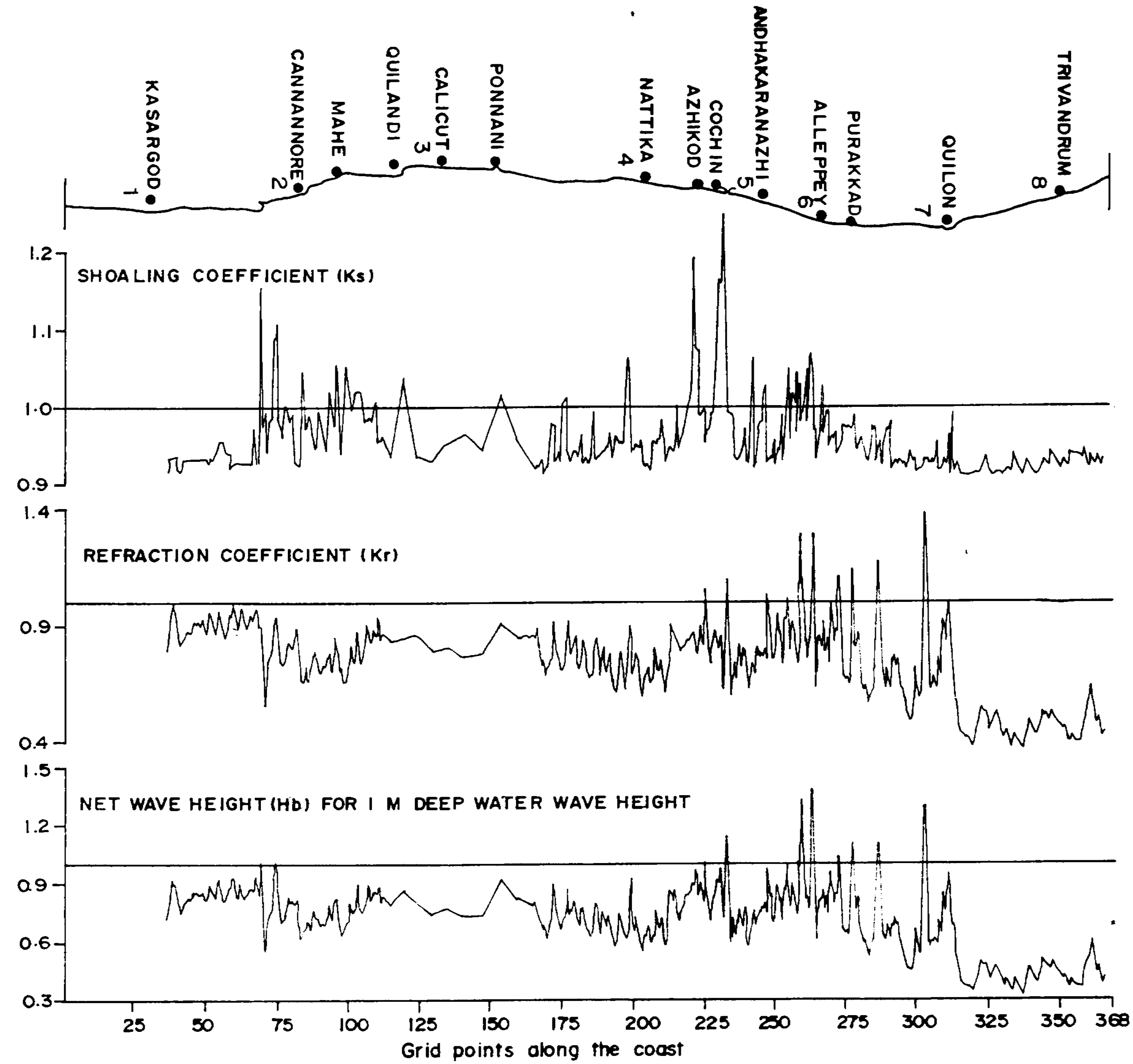


FIG. 2.9b. VARIATION OF SHOALING COEFFICIENT, REFRACTION COEFFICIENT AND NET WAVE HEIGHT.
WAVE DIRECTION = 290° WAVE PERIOD = 8 SEC.

The breaker height estimated for the predominant wave direction of 290° with period 6 S, shows that the wave height ia getting reduced and the breaker height never exceeded the deep water wave height of 1 m. It shows an average value of about 0.8 m along the stretch of the Kerala coast with low values at Ezhimala (0.5 m) and Quilandi (0.6 m). Low values of about 0.7m have been observed between Calicut and Nattika and shows a maximum value of 0.9 m at Quilon.

The breaker height distribution (H_b) for 8 S period waves shows higher values for the stretch of the coast from Cochin to Quilon. Hb is greater than 1m at Cochin, Alleppey, Purakkad and Neendakara. It shows high values north of Alleppey (1.4 times the deep water wave height) and at Quilon (1.3 times). At the southern end of the Kerala coast, Hb is only 0.4 times the initial deep water wave height for this wave direction and period.

CHAPTER 3

3. BEACH DYNAMICS

3.1. Beach morphology

Beach is the most dynamic zone of the coastal environment which is subjected to a wide range of variations. The changes in beach profile are caused, to a large extend, by the variations in the incident wave energy and fluctuation in the position of the mean water level induced by tidal oscillations. Seasonal changes of the beaches constitute an important aspect of the coastal environment and hence data on beach profiles along with constituent sediment provide vital information on the energy levels to which this environment is subjected to. Though our understanding of such changes improved qualitatively over the past few decades, quantification of these changes still needs attention. In view of this, the dynamics of the beaches bordering the Kerala coast, which falls under different environmental settings, has been addressed through a comprehensive field measurement program initiated during March 1990 - February 1991.

3.1.1. Materials and methods

Beach profiling

Beach profile measurements were taken at 5m interval, from backshore to seaward during low tide using dumpy level, metric staff and a measuring tape at 8 locations (Fig. 1.5, Table 3.1). The profiles were taken over a period of 13 months at monthly intervals during spring low water level when the maximum beach emerged above the waterline. The seaward end of the profiles were terminated near the low water point as estimated from tide table. This data were then reduced with reference to the bench mark.

Empirical Orthogonal Function Analysis

The beach profile data is further subjected to Empirical Orthogonal Function (E.O.F) analysis to delineate the spatio-temporal variations of the beach, at each of the location.

E.O.F analysis is a statistical technique for effectively representing variability in an array of geo-physical data. It facilitates representation of a large quantity of data in terms of small number of orthogonal components which accounts for a large fraction of total variance in the original data. Conceptually the objective of the analysis is to separate the temporal and spatial dependence of the data so that it can be represented as a linear combination of corresponding functions of time and space which best accounts for the variability in the original data. E.O.F analysis has been applied to beach profile data by many researchers to bring out the variability and seasonality of the beaches (Winant and Aubrey, 1976; Aubrey, 1978; Winant et al., 1975).

Table 3.1. Description of beach profile location and bench marks.

Stn.No.	Location	Survey Interval	Bench mark Description	Width of the beach from bench mark (m)	Remarks
1	Kasargod beach	Monthly	Yellow painted concrete stone	85 - 100	South of Kasargod light house. Relatively wide beach. No sea wall.
2	Cannannore (Payyambalam beach)	Monthly	Concrete stone	55 - 75	North of Payyambalam crematorium. Mostly all the 7 km beach is protected by sea wall. South of Ezhimala promontory.
3	Calicut (Konad beach)	Monthly	Concrete mile stone	145 - 150	Long and wide beach, no sea wall. A fresh water channel was present in the early stage of the study and subsequently disappeared.
4	Nattika beach	Monthly	Marking on the back wall of a cemeteri	60 - 85	Moderatley wide beach with fishing activity. Sea wall exist well behind the backshore. Beach built up considerably. Surrounded by many casurina trees.
5	Andhakaranazhi beach	Monthly	Marking on a vertical cocunut tree surrounded by many cocunut trees, in front of the church	65 - 90	Short beach with sea wall, fishing gap of about 50-75m is present. Coast is protected by seawall. A small seasonal opening is present north of this station (SW monsoon).
6	Alleppey beach	Monthly	Yellow painted concrete mile stone.	110 - 125	Wide and long beach north of the pier, no sea wall.
7	Quilon (Eravipuram beach)	Monthly	Marking on a vertical cocunut tree in front of the ice factory	55 - 80	Short beach backed by continous seawall.
8	Trivandrum (Sankumukham beach)	Monthly	Marking on the backside of the bus shelter	55 - 60	Wave dominted sandy beach, north of the pier, steep foreshore and free from sea wall.

The beach profile data obtained at each location were set into a data matrix H, with row containing a time series of the beach elevation / depression at a particular station along the profile and column containing beach profiles at a particular time. The variability of the data matrix H could be explained in terms of few simple eigen functions of the matrix H. These eigen functions were obtained by normalizing and decomposing the data matrix H using Singular Value Decomposition (SVD) technique.

$$X_{mxn} = H/\ (mxn)^{1/2} = U_{mxr}\ \Gamma_{rxr}\ V^{T}_{rxn} \qquad (3.1)$$

where m and n are the number of rows and columns of the data matrix respectively and T indicates the transpose of the matrix. The column vectors of U and V are orthogonal, ie. $U^TU = I$ $V^TV = I$ and Γ is a diagonal matrix with diagonal elements called the singular values of H, and $r(r \leqslant min(m,n))$ is the rank of the matrix H.

U, Γ and V satisfying equn. (3.1) are obtained by solving the the eigen value problem

$$(B - \lambda I)\ V = 0 \qquad (3.2)$$

$$(A - \lambda I)\ U = 0 \qquad (3.3)$$

where $B = X^TX$ and $A = XX^T$. Values of λ is obtained by solving the characteristic of equn. (3.2), ie. $|B - \lambda I| = 0$ and its substitution in equn. (3.2) leads to a system of equations which are solved following the standard Gaussian elimination method (McCormick and Salvadori, 1968) to obtain values of V.

Knowing V and λ , U is determined from equn. (3.3).

The ratio between the sum of the squares of the elements of the factor model and that of the data matrix is considered as the measure of closeness of the model data

Measure of closeness = $\sum_{i=1}^{K} \lambda i / \sum_{i=1}^{r} \lambda i$ where K is the number of factors and r is the rank of the data matrix.

The eigen functions are ranked according to the percentage of mean square value of the data they explain. These percentages as accounted by each function, enable evaluation of the relative importance of each function in explaining the observed beach variability.

Beach volume computation

To quantitatively estimate the beach volume changes associated with each of the beaches under study, the relative changes in volume of the sediments per unit length of the beach (storage volume) at each location were computed in cubic metres using an arbitrary defined base line.

3.1.2. Results

In this chapter, the seasonal changes of the beach morphology inferred from monthly profile data, E.O.F analysis and storage volume changes at 8 selected beaches are presented. The storage volume calculated for different months and different locations are given in Figs. 3.2a & 3.2b.

Kasargod beach

The beach located south of Kasargod light house is a moderately wide beach backed by cassurina trees. It is free from any protective structures like sea wall. Three minor rivers drain into Arabian sea north of this beach. One Major river Chandragiri having a total annual run-off (3118.6 X 10^6 m^3 (Anonymous, 1974), debouches into the sea within 2 Km south of the study region. Beach vegetation like casuarina trees are present on the back shore. This beach falls in the category of straight open coast beach. The beach has a wide backshore and a gently sloping foreshore. The width of the beach varies between 85-100 m, having a berm present at a distance of 50 -60 m from the bench mark (Fig. 3.1a). The beach shows maximum variability in the foreshore and it is almost stable in the backshore region. The beach responds to the monsoonal forcing with seasonal episodes of erosion and accretion.

The E.O.F analysis of the profile data shows that, at Kasargod the first eigen function accounts for 97.5 % of the mean square value while the second and third accounts 1.5 % and 0.4 % respectively (Table 3.2). In general, the contribution from the higher order function is insignificant. Since most of the variations in the profile are accounted by the first three eigen functions corresponding to largest eigen values, in the following discussions only the first three eigen functions are considered.

Table 3.2. % Variance explained/contained by each eigen functions.

STATION NO.S	FUNCTIONS			
	1	2	3	4
1	97.5	1.5	0.4	0.3
2	99.5	0.2	0.1	0.1
3	99.2	0.4	0.2	0.1
4	96.3	2.8	0.5	0.2
5	98.2	1.3	0.3	0.1
6	98.1	1.1	0.6	0.1
7	98.6	0.8	0.4	0.1
8	96.5	2.7	0.6	0.1
MEAN GRAIN SIZE	92.1	3.9	1.6	1.1

The first eigen function (U1), representing the mean beach profile (Winant et al., 1975) shows a wide backshore and a berm located between 50-60m from the bench mark with moderately sloping foreshore (Fig. 3.1c). The associated temporal function (V1), shows the erosional tendency of the beach during the period of study.

The spatial configuration of the second function (U2) indicates the locations of the beach subjected to maximum variabilities. In the present case, the maximum variability occured at about 70 m from the bench mark, as could be inferred from the peak of the curve. A lesser variability is seen at about 55 m from the bench mark, coinciding with the berm crest. In other words, the foreshore region of the beach undergoes greater changes while the berm is subjected to lesser variability. The distribution of the second temporal eigen function (V2) shows the erosional/accretional episodes to which the beach is subjected. The beach at Kasargod experiences a slight accretion from March to April followed by an erosion till September. The erosion has three phases: an initial rapid rate from April to May, a slow rate from May to August and then again a rapid erosion from August to September. Then the beach started rapid accretion from September to December indicating that the beach has regained some of the material lost due to erosion. Once again, the beach shows a slight erosion from December to February followed by an accretional phase towards the end of the survey.

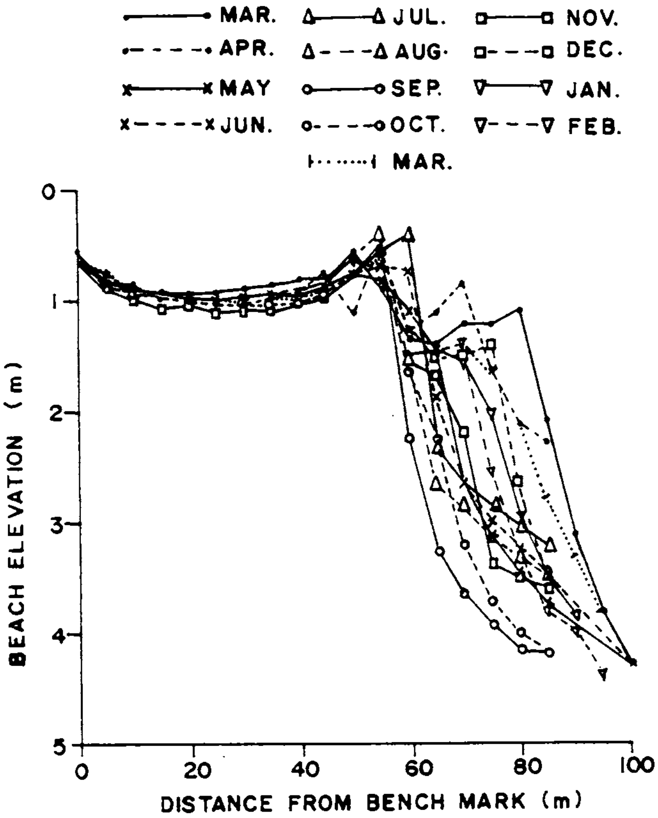


Fig.3.1a. Beach profiles at station - 1 (Kasargod)

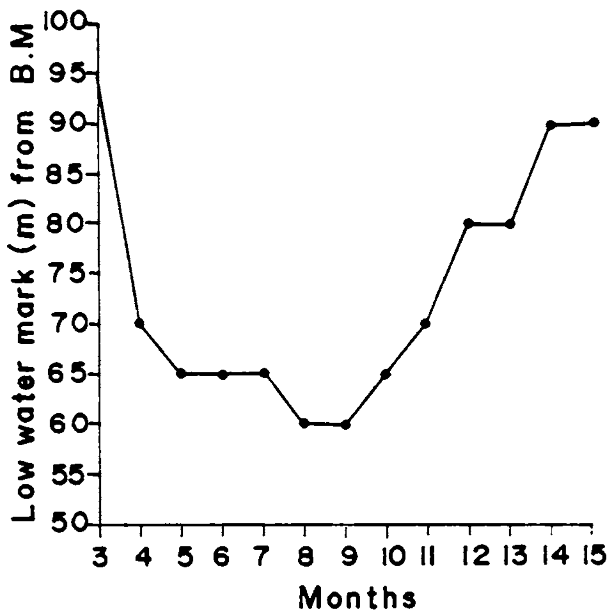


Fig.3.1b. Monthly variation of Low water mark from benchmark (m)

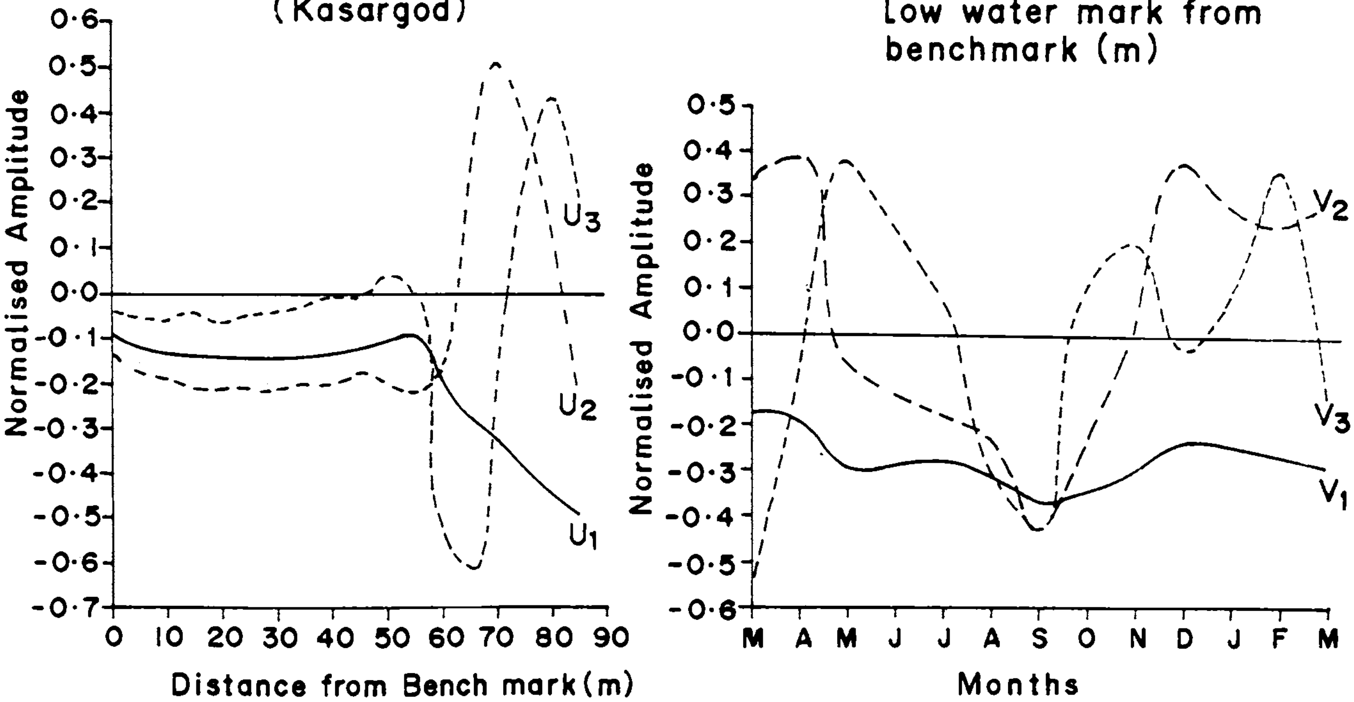


Fig.3.1c. Spatial and temporal distribution of eigen functions at station - 1 (Kasargod)

The third function (U3), shows a more complex nature of distribution with a broad maxima around 60-65 m from the bench mark. This coincides with the mean low water mark encountered during the period of one year. In order to understand the temporal distribution of the third eigen function (V3), the position of the mean low water line from the bench mark during each survey has been presented in Fig. 3.1b. A close examination of this figure with the distribution of V3 shows that, V3 depicts the temporal fluctuations of the low water line. Further, the lowest positive peak in the distribution of V3 occurs during October which coincides with the minimum distance of the position of the low water line which is at about 60 m from the bench mark. Similarly the lowest value occurs during March, coinciding with the maximum distance (95 m) of the position of mean water line from the bench mark.

The storage volume of beach material per metre length of the beach calculated for different months are presented in Fig. 3.2a. The beach has a maximum storage volume during March which decreases till May. During June to August the volume changes are marginal. The storage volume decreases from July onwards and the beach attains a minimum storage volume during September which is 704 m^3/m. From September onwards the storage volume indicates a build up. The pre and post monsoon periods indicate a maximum accreted phases.

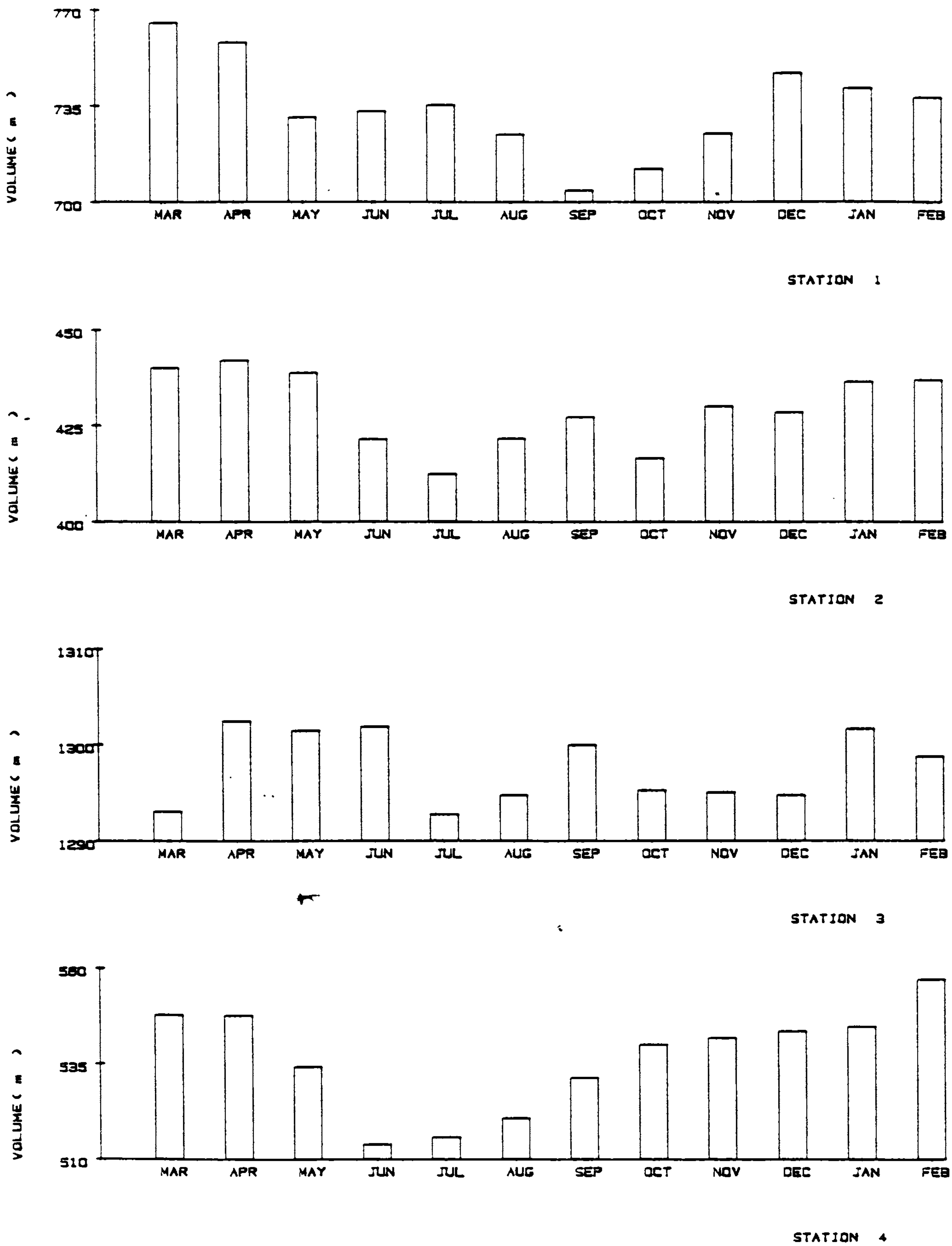


FIG.3.2a. VOLUME OF BEACH SEDIMENT/METRE LENGTH

PAYYAMBALAM BEACH

The Payyambalam beach at Cannanore is situated about 5 km south of Ezhimala promontory. Valapattanam river with an annual run off of 2764.9 X 10^6 m^3 drains in to the sea about 10 km north of this beach . It is a short beach (7 km), protected by sea wall. The upper backshore is covered by beach grass. The beach has a moderately steep foreshore and gentle backshore with a total width of 55-75 m. From the profiles (Fig. 3.3a), it is clear that the beach has a stable backshore while the foreshore is subjected to changes seasonally.

The mean beach function (U1) shows a narrow backshore with a well developed berm and a moderately sloping foreshore with a step like feature at 20 - 30 m from the bench mark. (Fig. 3.3b). The corresponding temporal eigen function (V1) shows almost stable nature of the beach during the study period. The second function U2 indicates maximum variability in the upper foreshore where the step-like feature is noticed. The distribution of the second temporal function (V2) shows that the beach is subjected to continuous erosion from March till July with a high rate of erosion during June-July. Thereafter the beach starts building up rapidly, regaining its lost material till December. Once again the beach undergoes erosion from December to till the end of the survey. The third spatial function (U3) shows a maximum around 40-45m from the bench mark. The lowest positive peak associated with the third temporal function occurs during

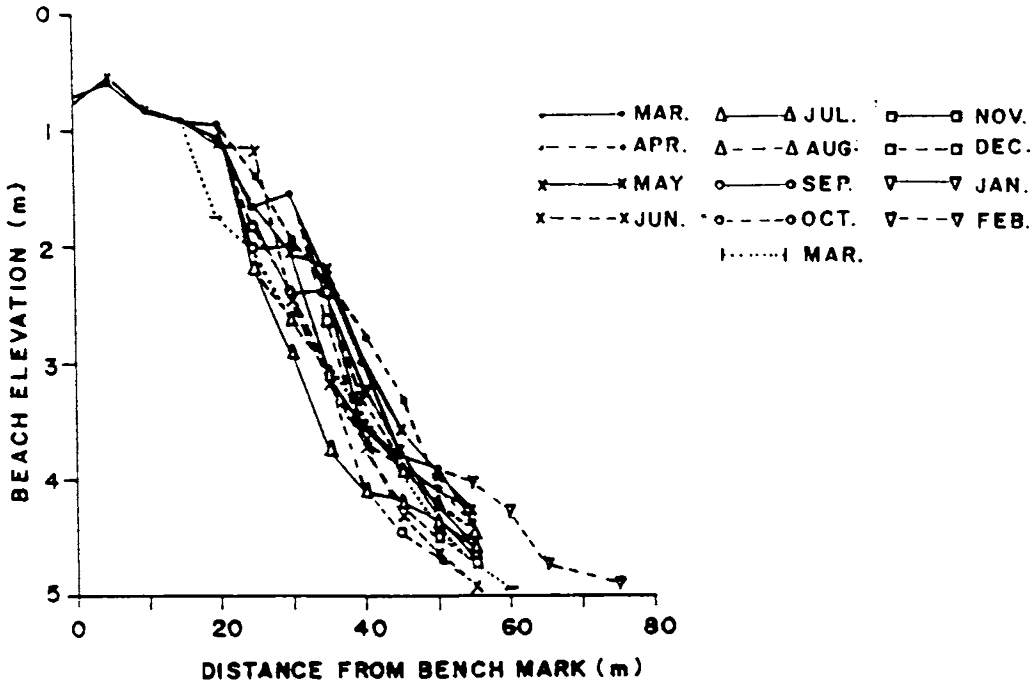


Fig. 3.3a. Beach profiles at station-2 (Cannanore)

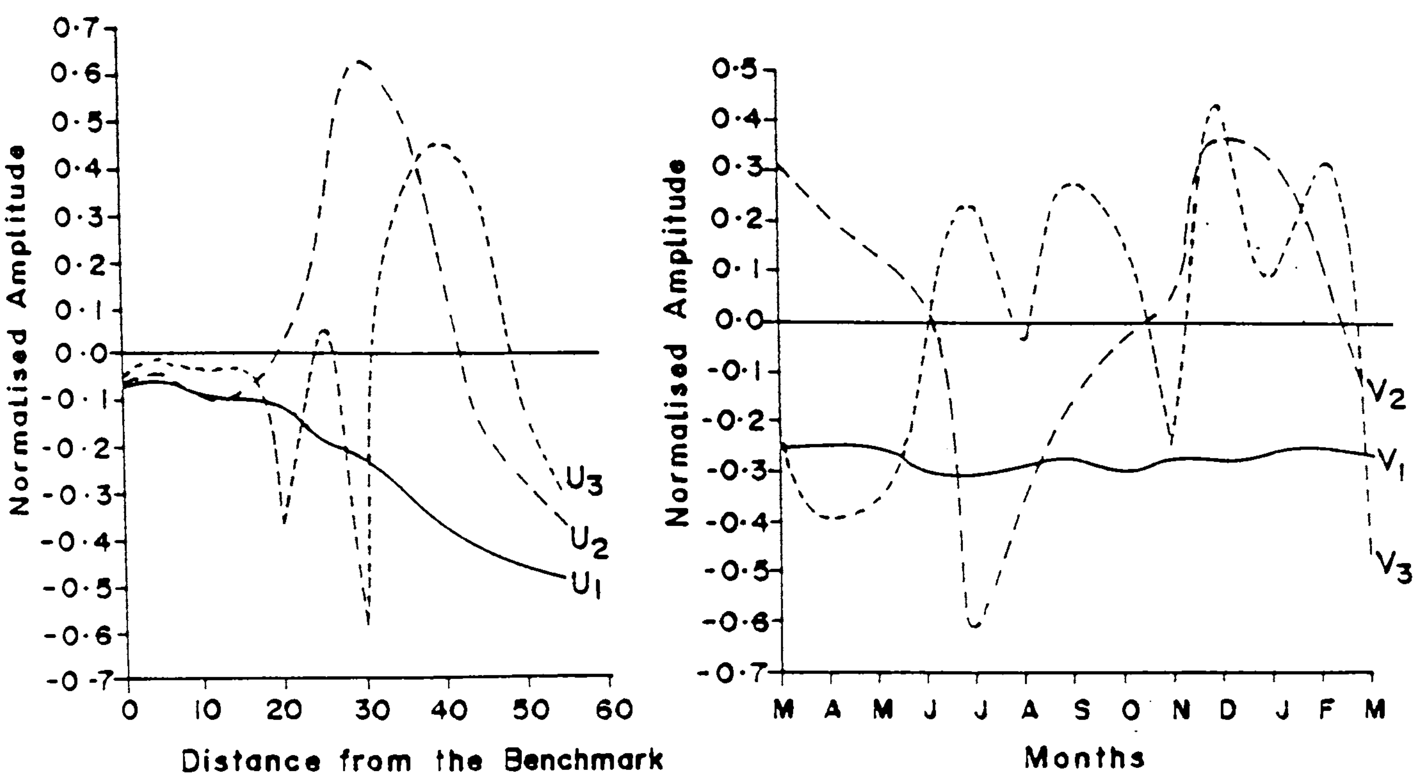


Fig.3.3b. Spatial and temporal distribution of eigen functions at station-2 (Cannanore)

July coinciding with the nearest position of the low water mark at about 35 m from the bench mark. The lowest value during March-April coincides with the farthest position of mean water line which is 55 m from the bench mark during March.

The storage volume of beach material for this location (Fig. 3.2a), indicates that the beach does not undergo much changes from March to May while during July to October, it gains material. The lowest storage volume level of the beach is during July (412 m^3/m). From July end to September beach experiences accretion and receives some part of the lost material. From September end, the beach once again passes through a state of erosion till the end of October and again shows a building up tendency. In general the storage volume shows that the beach loses material during monsoon months of June-July and regains the materials during the rest of the year except an erosional tendency during October (416.6m^3/m).

KONAD BEACH

Konad beach at Calicut is a long and very wide sandy beach free from any protective structures like sea walls. A fresh water channel was present in the early stage of the study which has been subsequently disappeared. There are two small rivers, on either side of the beach, Elattur river on the south and Kallai river on the north. The beach width varies between 145-150 m from the bench mark. From the beach profiles (Fig. 3.4a), it is clear that the beach profile variations are the least for this beach as compared to the other 8 locations.

The first spatial function (U1) shows that the beach has a very wide gently sloping backshore and a moderately steep foreshore (Fig. 3.4b). The backshore contain two berms, one at 30-40 m which is a permanent berm while the other at 120-130 m is a seasonal one. The almost straight line of the distribution of the temporal function (V1) associated with the first eigen function, shows the stable nature of the beach during the period of study. The spatial configuration of the second function (U2) shows the maximum variability associated with the second berm and lesser variability at 100-110 m from the bench mark. The second temporal eigen function (V2) shows that the beach undergoes an initial slow accretional phase during March-April followed by an eroding phase till the end of June. From July onwards the beach started building up at a very slow rate till January. The maximum value associated with the third spatial function (U3) around 140 m from the bench mark indicates the position of low water mark. Its corresponding temporal function (V3) shows lowest positive peak during January-February at 145 m which indicated the farthest position of the low water line while the lowest value at 30-35 m during November-December indicates the closest position of the mean low water line from the bench mark.

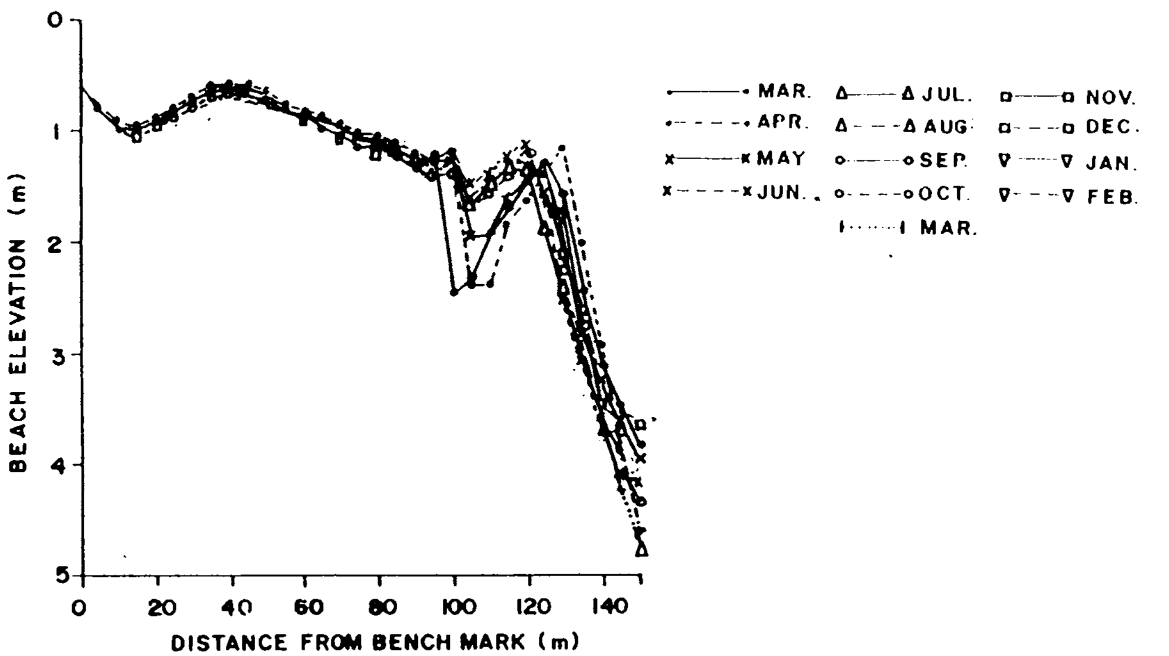


Fig.3.4a Beach profiles at station-3 (Calicut)

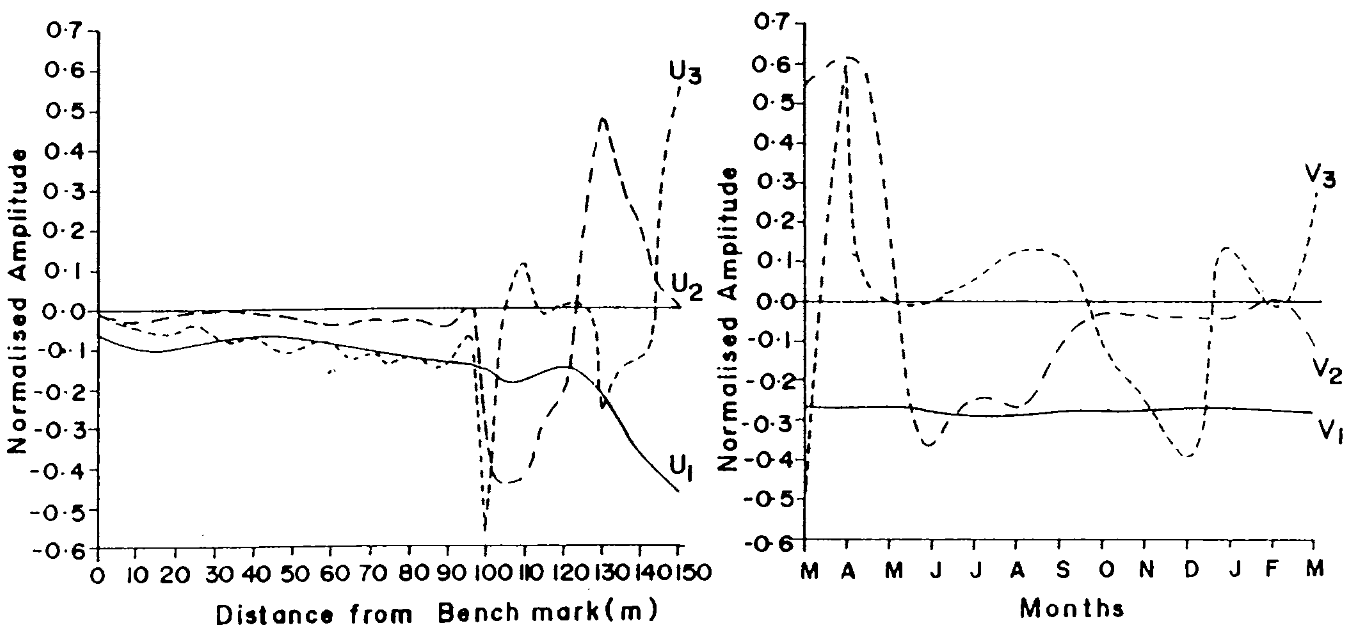


Fig.3.4b. Spatial and temporal distribution of eigen functions at station-3 (Calicut)

The variations in storage volume along this beach is minimal (of the order of 10 m^3/m) (Fig. 3.2a). The beach shows the highest storage volume in March-April and lowest storage volume in June-July. There is a gradual increase of storage volume towards September and a decrease in the north-east monsoon period followed again by an increasing tendency.

NATTIKA BEACH

Nattika beach is a straight beach with comparatively wide back shore and a gently sloping foreshore. This beach with considerable fishing activity is backed by casuarina plantations. There are no rivers in the near proximity of this beach. An old sea wall exists well behind the backshore indicating that the beach has built during the past years. The width of this barrier beach varies between 60-85 m from the bench mark. The beach is composed of fine sand mixed with silt. The profiles shows the presence of a seasonal berm in the foreshore (Fig. 3.5a).

The first spatial eigen function (U1), shows the presence of a berm situated at 5m from the bench mark (Fig. 3.5b). It shows a wide, gently sloping foreshore. From the distribution of the associated temporal eigen function (V1), it is seen that the beach shows slight accreding tendency. The second eigen function (U2) shows that the maximum variability of the beach occurs in the upper foreshore. The second temporal function (V2) shows that the beach undergoes slight accretion initially (March-April) and a rapid erosion

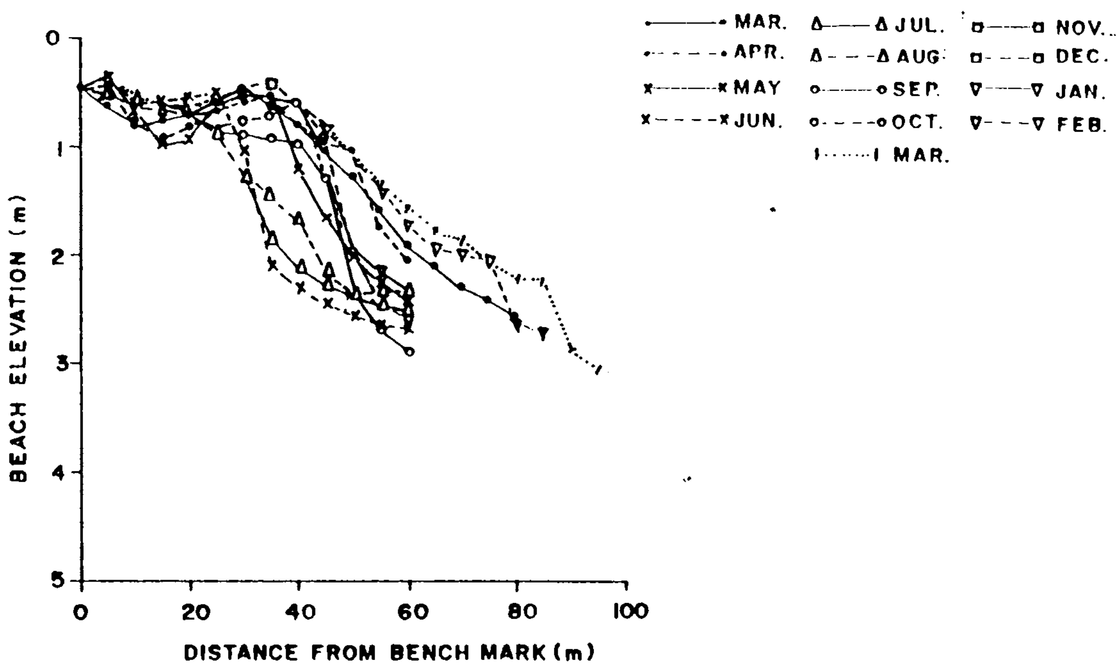


Fig.3.5a.Beach profiles at station-4 (Nattika)

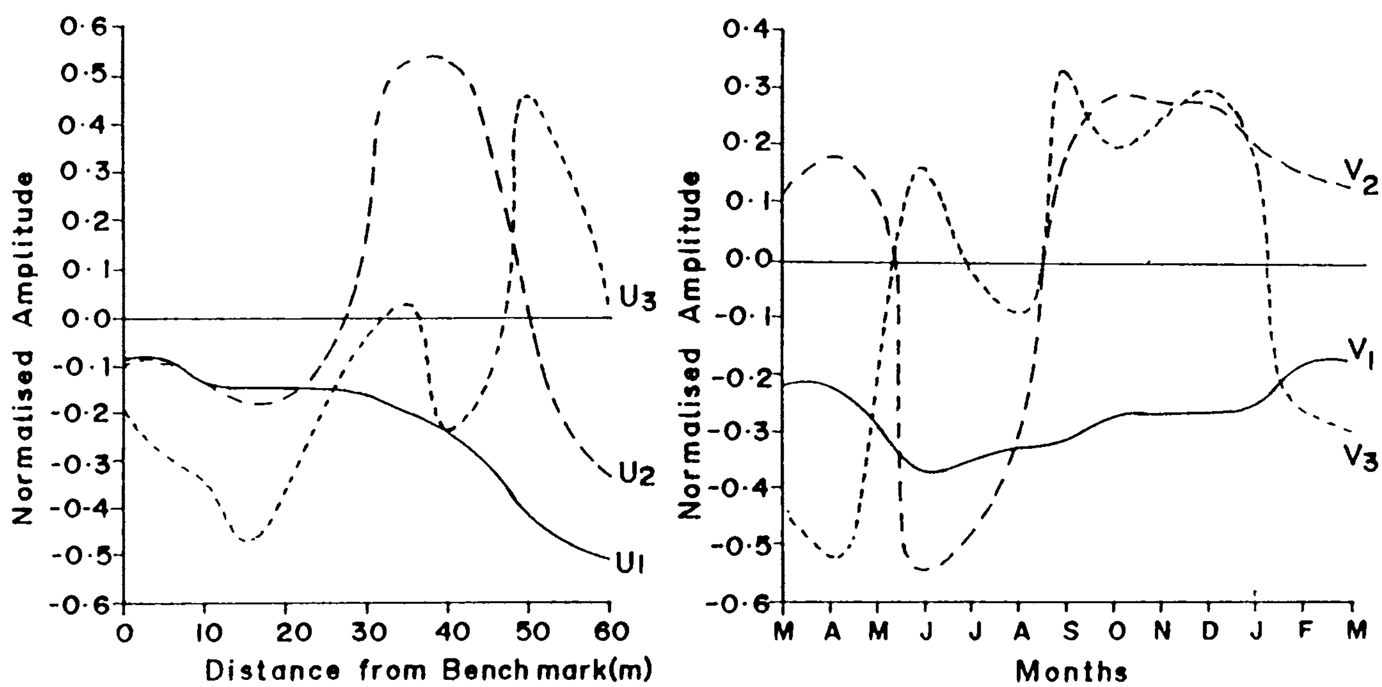


Fig.3.5b. Spatial and temporal distribution of eigen functions at station-4 (Nattika)

till June. This is succeeded by a fast rate of accretion till October and then a gradual tendency of erosion. The third spatial eigen function (U3) shows a maxima at about 50 m from the bench mark, which coincides with the mean water level. The corresponding temporal function V3 shows that during June the low water level is closest (30 m), while during February-March it is farthest (80 m).

The storage volume of the beach material (Fig. 3.2a), shows that the beach undergoes gradual erosion from March (547 m^3/m) reaching the minimum storage volume in June (514 m^3/m). Afterwards the beach gradually build up regaining all the lost material by the end of February (557 m^3/m).

ANDHAKARANAZHI BEACH

Andhakaranazhi beach is a short and narrow barrier beach protected by sea wall with a fishing gap of 50-75 m width. A small seasonal opening to the sea is present north of the station during the south-west monsoon season. The beach has a narrow backshore and a moderately steep foreshore. The beach width varies in between 65-90 m. A seasonal berm is present in the foreshore and a permanent berm in backshore (Fig. 3.6a). The sand size is in the range of fine to coarse sand.

The first eigen function (U1), representing the mean beach profile (Fig. 3.6b), shows that the beach is very narrow with two berms at 10 m and 25 m from the bench mark.

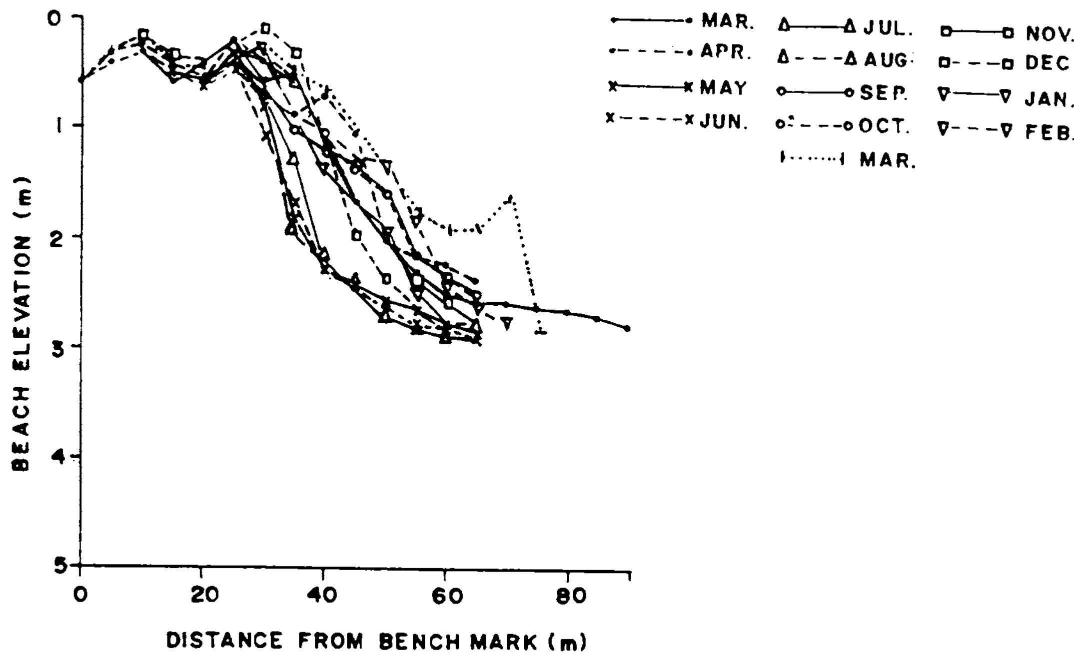


Fig.3.6a.Beach profiles at station-5 (Andhakaranazhi)

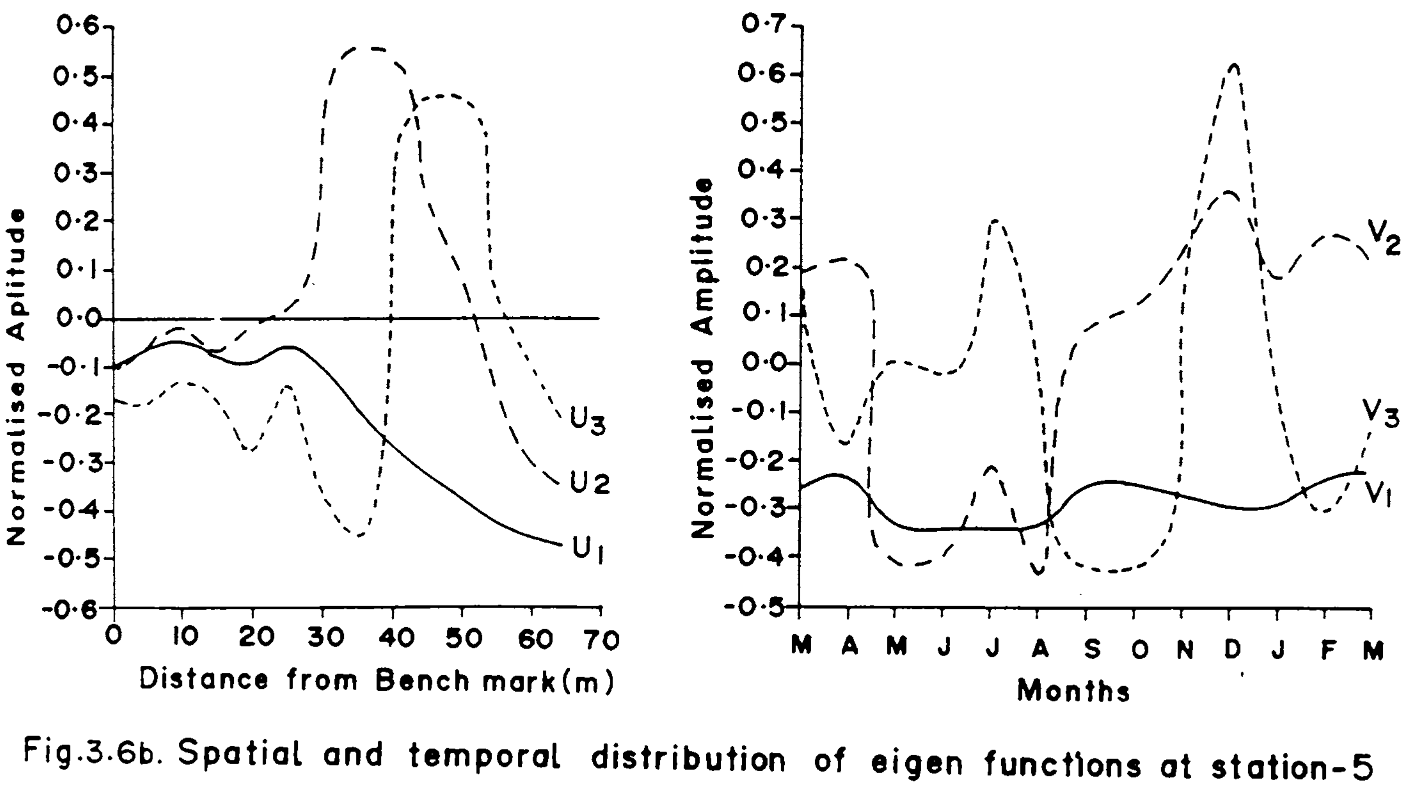


Fig.3.6b. Spatial and temporal distribution of eigen functions at station-5 (Andhakaranazhi)

The temporal function (V1) shows the near-stable conditions of the beach during the period of study. The second spatial function (U2) shows a broad maximum at around 35 m, clearly identifying the location where the beach profile experienced maximum variation. The distribution of the corresponding temporal function V2 shows that the beach is subjected to rapid erosion during April and May followed by slight accretion during June-July. Once again the beach is eroded till August. From August to September, the beach builds up rapidly followed by a slow rate of accretion till December. The beach undergoes another cycle of erosion and accretion, at a much lesser rate till the end of March. The third spatial function (U3) shows maximum variability in the lower foreshore. From the distribution of the third temporal function (V3), it is clear that low water mark is at about 30m which is closest during May and farthest during October (55 m).

The storage volume computed from the monthly beach profile (Fig. 3.2b), shows that from March there is a little increase in volume reaching maximum of 587 m^3/m during April, but suddenly there is a drop in volume as monsoon intensified and the storage volume reaches a minimum in June (551.6m^3/m). Subsequently there is a rapid increase in volume during September followed by a gradual decrease till January. After that it again shows a depositional tendency and the beach almost regains its lost material back by the end of February (588 m^3/m).

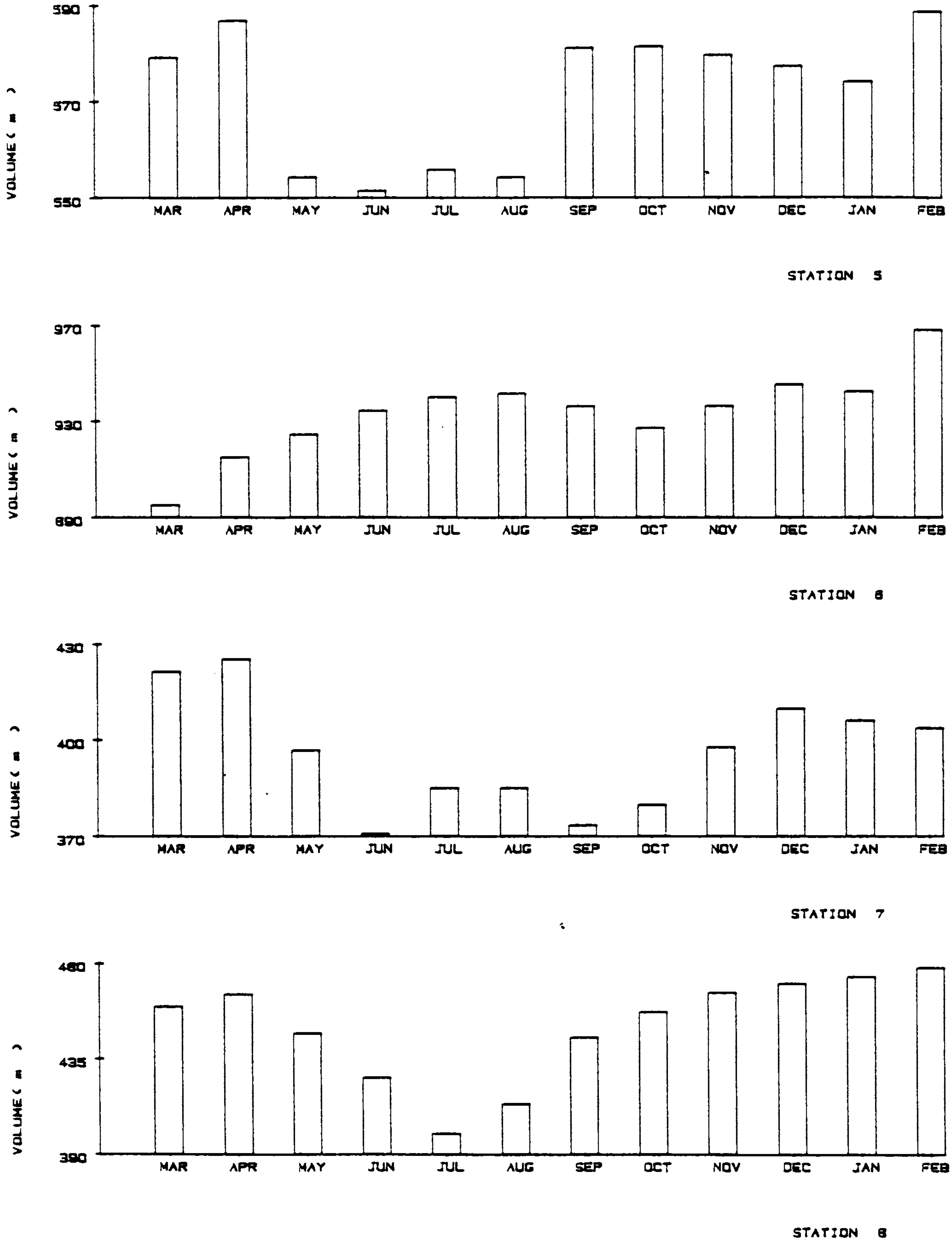


FIG.3.2b. VOLUME OF BEACH SEDIMENT/METRE LENGTH

ALLEPPEY BEACH

The beach at Alleppey is a wide and long barrier beach situated south of Alleppey pier and is free from any protective structures. There are no rivers in the proximity of this beach. The width of the beach ranges between 110-125 m. The beach is composed of fine size sands. The profiles (Fig. 3.7a), show a stable backshore and a foreshore which gets built up even during the peak monsoon months. The mud bank occurring in this region during the south-west monsoon season (Kurup, 1977; Kurian et al., 1984, 1985) dampens the high monsoonal waves and makes this nearshore region very calm. The observed accretion of the beach during the monsoon months is brought in by the presence of the mud bank.

The distribution of mean beach function (U1) shows the presence of a very wide backshore and a gently sloping foreshore (Fig. 3.7 b). A seasonal berm is situated at 80 m from the bench mark. The associated temporal function (V1) shows an overall accretional tendency of the beach. The second spatial function (U2), shows a maximum near the lower foreshore where the beach undergoes large variations. The temporal function (V2) shows that the beach is subjected to accretion throughout the period of study except during May-June, September-October and February-March. The distribution of the third spatial function (U3), shows the position of mean low water mark at 90 m from the bench mark. The third temporal function (V3) shows that the mean water line fluctuates between 90 m during May and 110 m during November.

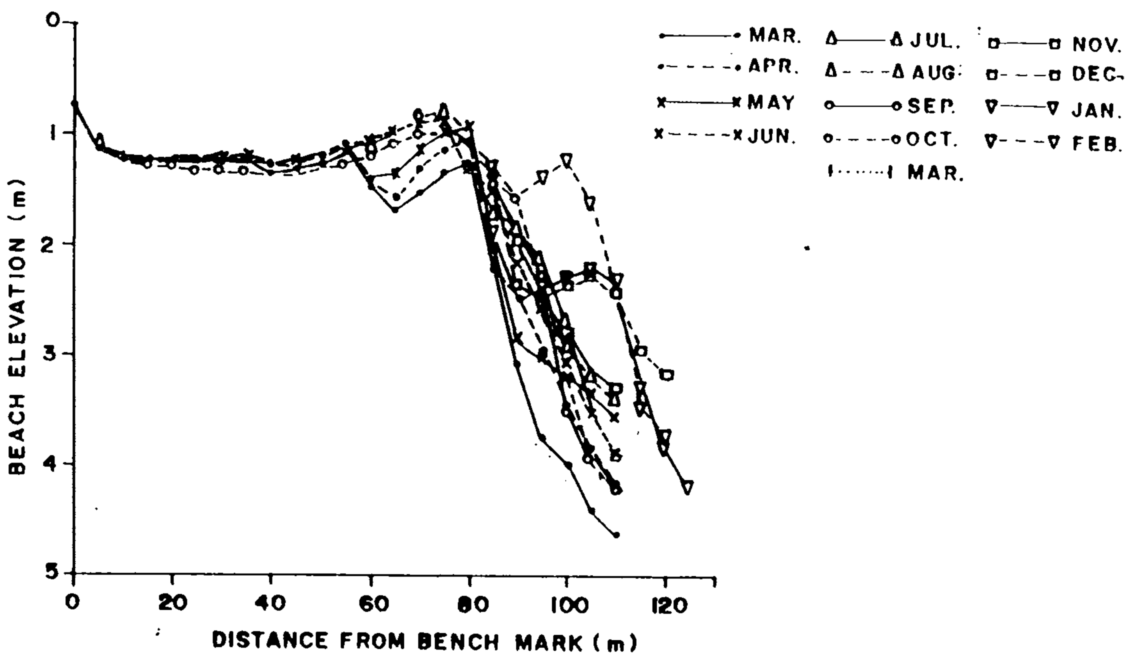


Fig.3.7a. Beach profiles at station - 6 (Alleppey)

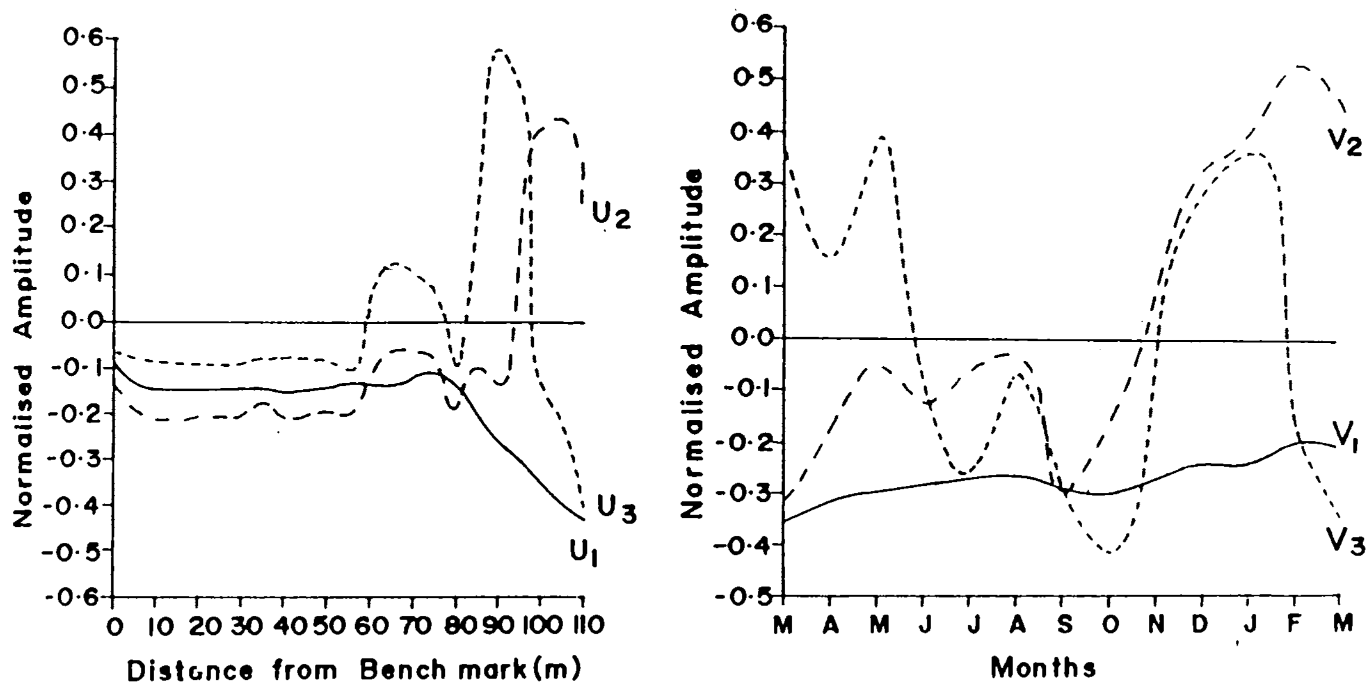


Fig. 3.7b. Spatial and temporal distribution of eigen functions at station - 6 (Alleppey)

The storage volume shows (Fig. 3.2b), that the beach continues its building up tendency rapidly till August when it attained a storage volume of about 940 m^3./m, followed by a slight erosion during September and October reaching a minimum storage volume at the end of October (927 m^3/m). Then the beach again shows an accretional tendency till the end of February (964.6 m^3/m).

ERAVIPURAM BEACH

Eravipuram beach at Quilon is a narrow curved beach south of Thankassery headland. The entire stretch of the beach is protected by sea walls. Ithikkara river falls south of this beach and a fresh water lake (Ashtamudi Lake) is present on the north. The beach width ranges between 55-80 m with a gently sloping backshore covered beach vegetation and a foreshore with maximum seasonal variations (Fig. 3.8a). The beach sediment is composed of coarse sand.

The first spatial eigen function (U1) shows a well defined berm in the backshore and a moderately sloping foreshore (Fig. 3.8b). The temporal function associated with the mean beach function (V1) shows an overall erosional tendency of the beach during the period of study. The second spatial function (U2) indicates maximum variability in the upper foreshore and a secondary maximum in the lower foreshore. The distribution of the second temporal function (V2) shows that the beach undergoes rapid erosion during April to June followed by a slow accretion till July and

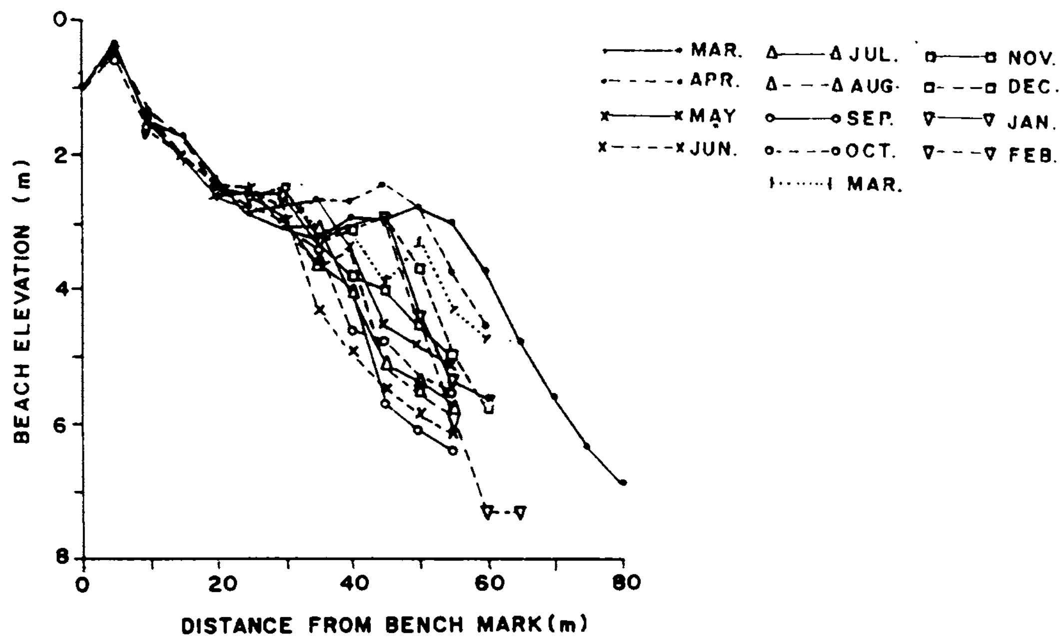


Fig.3.8a. Beach profiles at station-7 (Quilon)

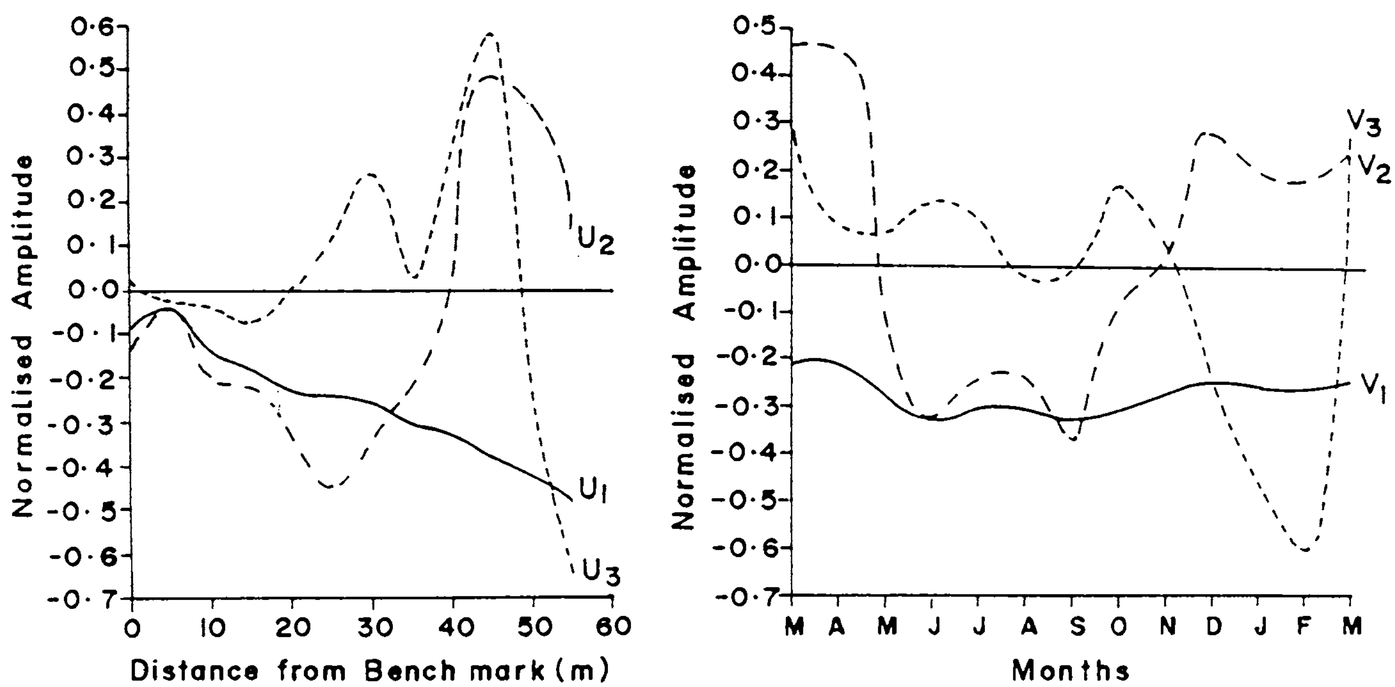


Fig. 3.8b Spatial and temporal distribution of eigen functions at station -7 (Quilon)

erosion during August to September. Subsequently the beach builds till December and shows an erosional trend during December-January. The third spatial eigen function (U3) shows the position of the low water mark at 60 m. The corresponding third temporal function (V3) indicates the closest water mark at 30 m during June and farthest at 60 m during February.

The storage volume shows that the beach has a maximum storage volume in April (425.4 m^3/m), (Fig. 3.2b) and a minimum storage volume in June (371 m^3/m) followed by a slight building up during July-August and erosion during September (373.6 m^3/m). This is followed by an accretional trend during October-December. In general, the beach loses material over a period of the year.

SHANKUMUKHAM BEACH

Shankumukham beach at Trivandrum situated north of the Valiyathura pier is a sandy beach with comparatively wide backshore and is devoid of any beach vegetation. Among all the beaches studied, this beach is exposed to higher wave energy throughout the year and undergoes maximum profile changes (Fig. 3.9a). The beach has a gently sloping backshore and a very steep foreshore during the rough weather season. The beach has a width of 55-60 m and is composed of coarse sized sand.

The distribution of the mean beach function (U1) shows a berm at 20 m from the bench mark and a moderately sloping

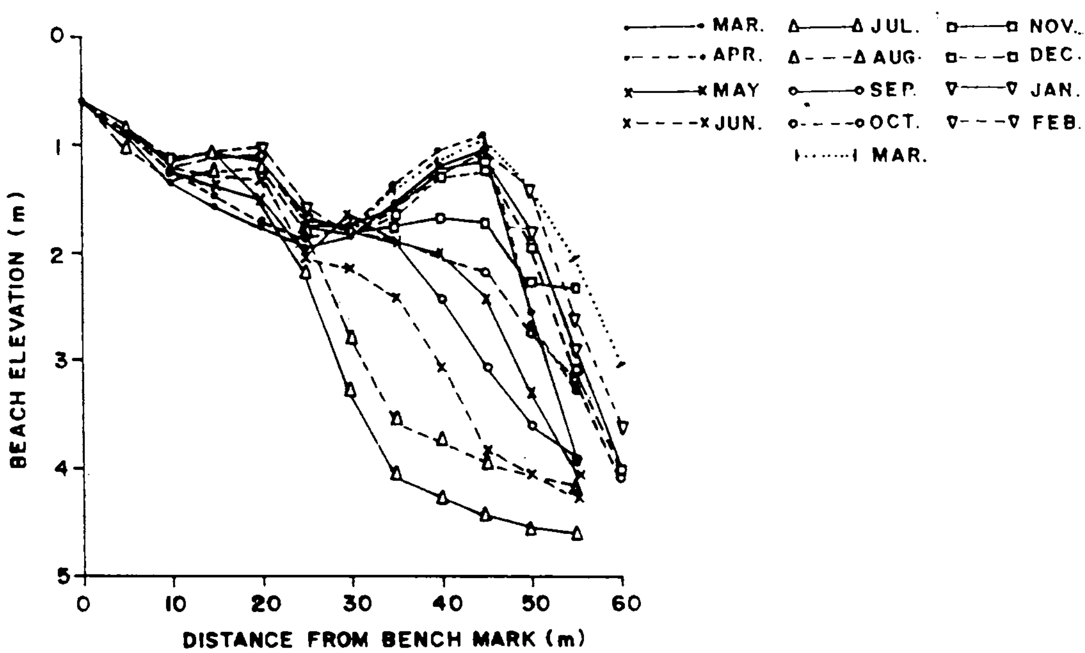


Fig.3·9a.Beach profiles at station - 8
(Trivandrum)

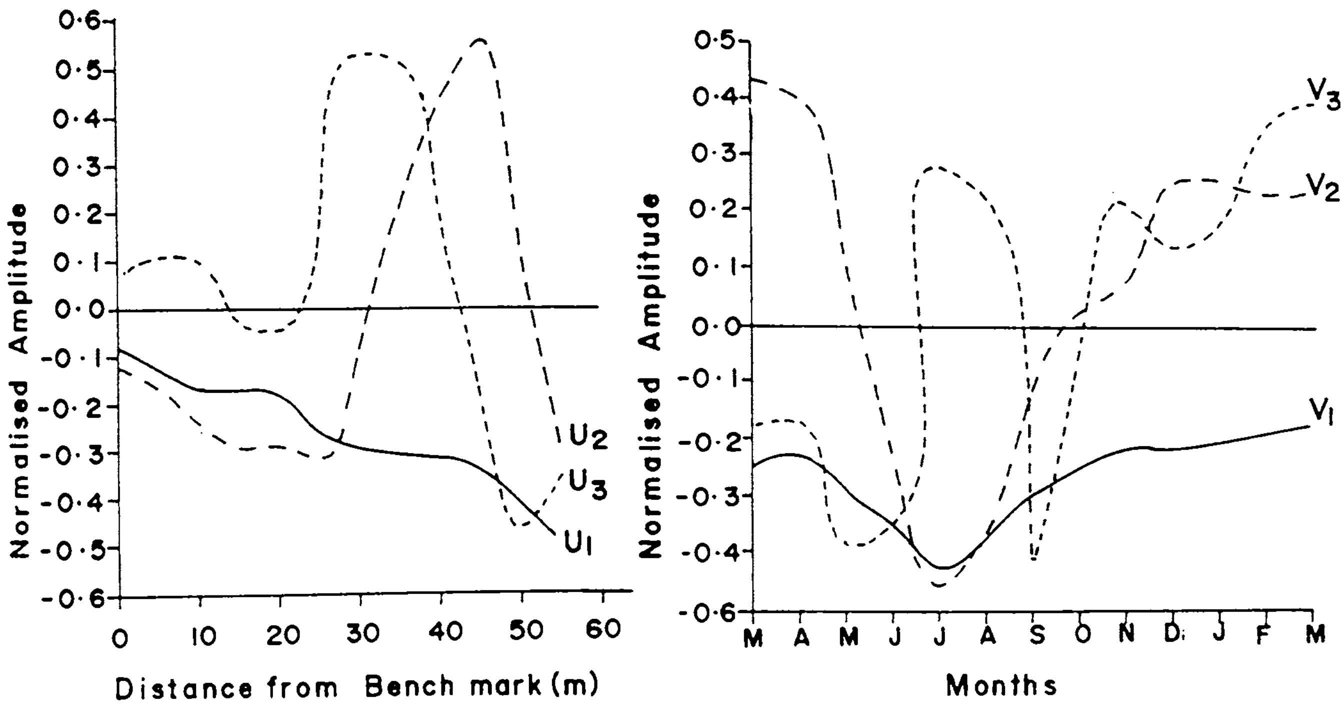


Fig. 3.9b. Spatial temporal distribution of eigen functions at station - 8
(Trivandrum)

foreshore (Fig. 3.9b). The corresponding time dependent factor, (V1) indicates an annual accretional trend. The spatial configuration of the second eigen function (U2) shows maximum variability in the lower foreshore and lesser variability near the berm. The second temporal function (V2) shows rapid erosion from April to July followed by rapid accretion till October. The accretional trend continues till December at a much reduced rate. However from December till the end of February, the beach does not undergo much variations. The distribution of the third spatial function (U3) indicates that the position of the low water level is around 35-40 m from bench mark where maximum erosion occurs. Its corresponding temporal function (V3) shows that the closest position of mean low water level occurs during July (30 m) and is farthest during September (55 m).

The storage volume computed for this beach (Fig.3.2b) shows that the beach loses material from April reaching a minimum storage level in July (400 m^3/m). Subsequently the beach experiences gradual accretion leading to a considerable deposition till the end of February when the beach gets built up considerably. The response of this beach depicts the typical monsoonal response of an open coast beach undergoing rapid erosion under monsoonal high waves taking away the beach material at a faster rate and regaining the material over longer period through the fair weather period.

3.2. Beach sediments

The beach is made up of unconsolidated sediments which range from very fine sands to pebbles. Wind, waves and tides are the important factors responsible for the movement of material on the beach and the resultant sediment distribution (Komar, 1976). The difference in wave energy and the period of the ocean swell are important factors that determine the nature and distribution of the foreshore sediments. The variation in grain size for any type of beach is primarily a function of variation in wave height and to a lesser degree, the wave period. (Write et al., 1985). On a beach, sediment is mainly exposed to two forces of unequal strength acting in opposite directions - the incoming waves and the outgoing wash. This is the primary mechanism by which sediment get sorted. The textural parameters, in addition to the degree of sorting, also reflect the mode of transportation and the energy levels of transportation media.

The aim of the present investigation is to determine statistically the significant variations in grain size distribution of the beach sediments along different beaches under study. In order to get a comprehensive picture about the seasonal changes in the size characteristics of the sediments along all the beaches, average moment measure statistics viz. mean, standard deviation and skewness were computed. The analysis has been done only for the samples collected from the low waterline.

3.2.1. Materials and methods

Monthly beach sediment samples were collected over a period of 12 months from each station, close to the water line during spring low water level when the beach exposure was maximum above the water line. A total of 104 samples were collected and used for the present study. The samples represent top 5 cm as on the day of sampling. Sieve analysis was carried out to study the grain size distribution.

Grain size analysis

Beach samples were subjected to size analysis by the simple sieving method. The samples were collected by scoop sampling. Approximately 1 kg in weight was washed free of salt, silt and clay and finally oven dried. From that 100 gm was separated by the conning and quartering method. Shells and shell fragments, if any present in the samples were separated by hand-picking method, as the presence of this would distort the trend of analysis. The samples were then sieved for 15 minutes in a semi automatic, motor driven mechanical Ro-Tap sieve shaker using a set of standard ASTM sieves (mesh nos. 18, 25, 35, 45, 60, 80, 120, 170 and 230). The weight of each fraction representing a particular grain size was measured using an electronic balance. The graphic mean, median, standard deviation and skewness were calculated based on the formula of Folk and Ward (1957).

E.O.F of grain size data

Mean grain size data of each of the samples were further subjected to E.O.F analysis to understand the spatio-temporal variability of the sediments in different environments. The size distribution of all the 104 samples were represented in the form of a matrix, $L(X,\phi)$ of discrete size class with X as the location and ϕ, the grain size class. The matrix was converted to a normalized data matrix, $X(X,\phi)$ and the eigen functions were obtained as described in section 3.1.2.

3.2.2. Results

The monthly variation of graphic mean, standard deviation and skewness calculated for the samples from different location are presented in Figs. 3.10a & 3.10b for mean size, Figs. 3.11a & 3.11b for standard deviation and Fig. 3.12a & 3.12b for skewness.

At Kasargod (Fig. 3.10a), the mean size of the beach sands fluctuated generally between 0.22 mm to 0.94 mm which corresponds fine to coarser grade. During the south-west monsoon period (June to September), the sediment is mostly in the coarser sand class. Fine and medium grade sands are present during the other months. On an average, the mean grain size of the beach is of the medium sand size. The standard deviation values (Fig. 3.11a), reveal that majority of the water line samples are moderately sorted and display

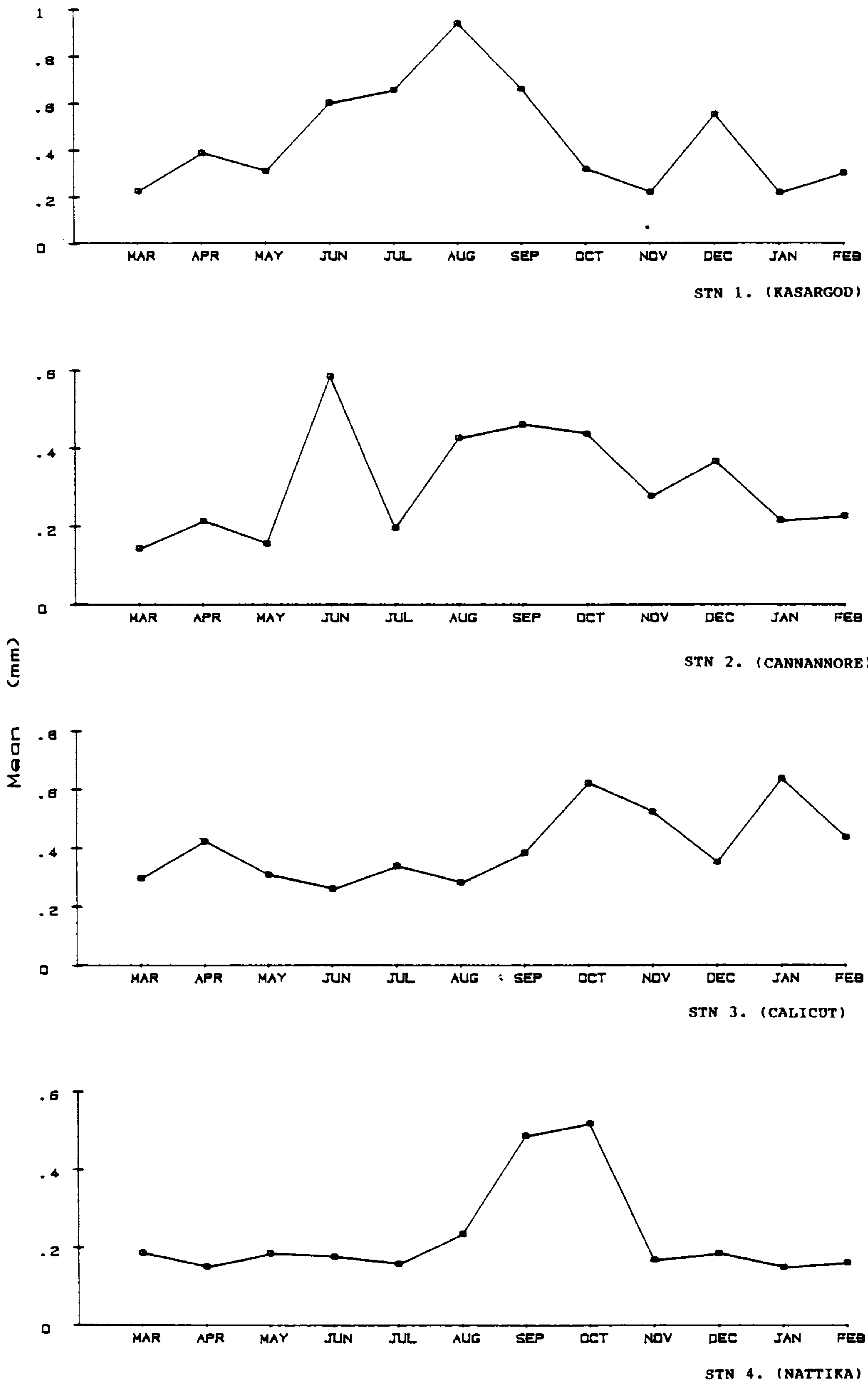


FIG.3.10a. MONTHLY VARIATION OF MEAN SIZE

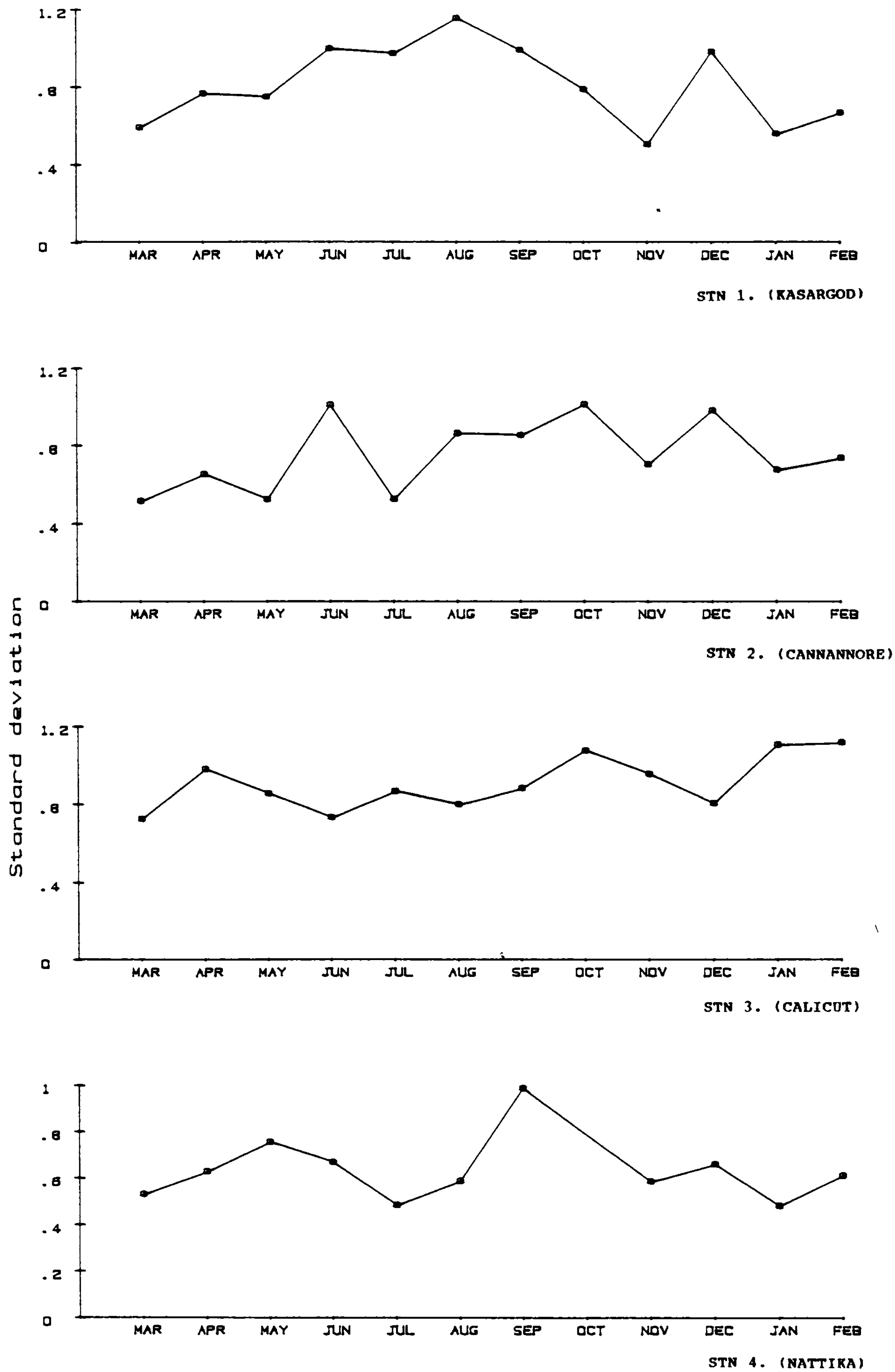


FIG.3.11a. MONTHLY VARIATION OF STANDARD DEVIATION

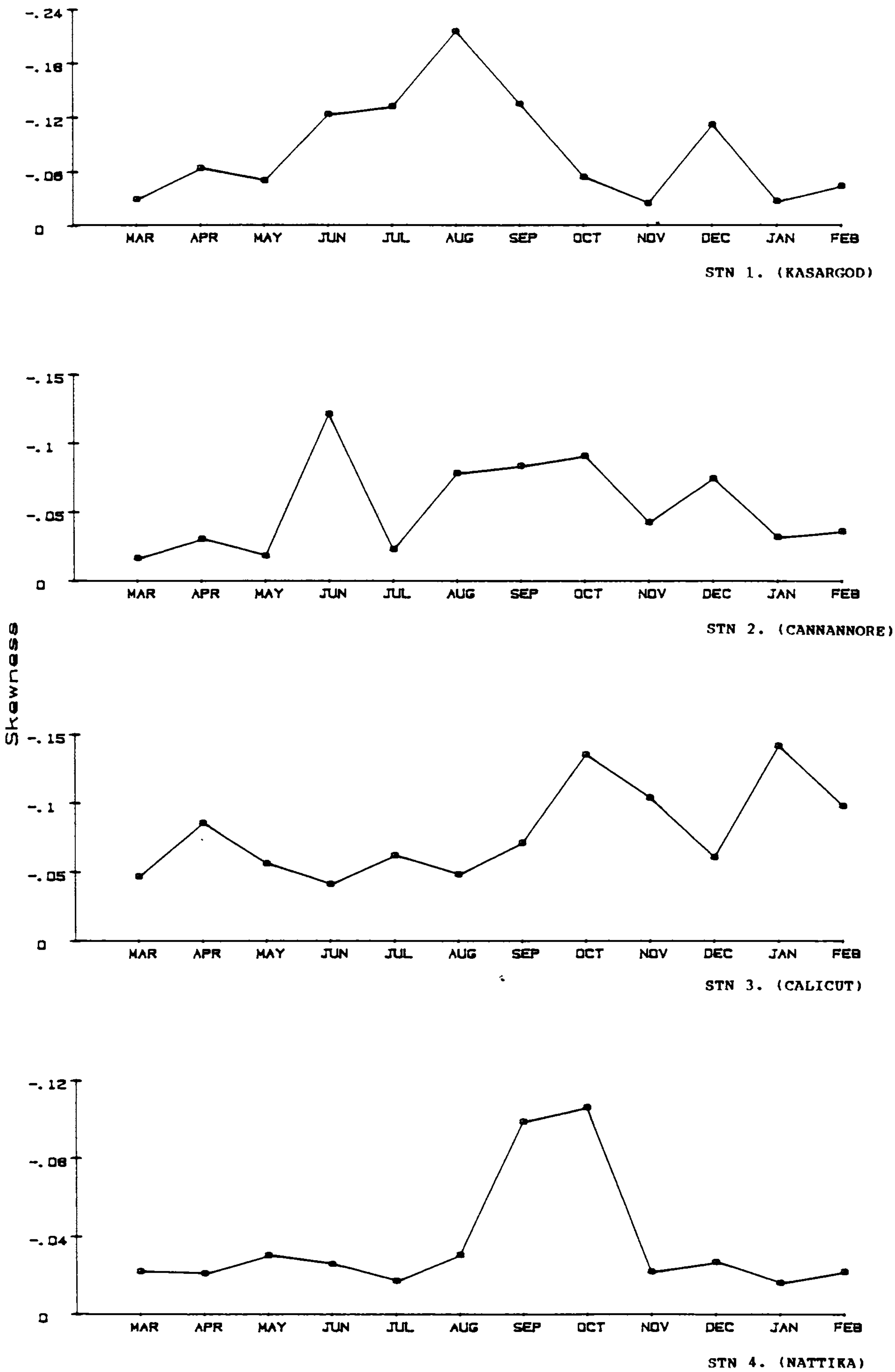


FIG.3.12a. MONTHLY VARIATION OF SKEWNESS

best sorting with an average value of 0.82 ϕ. In August, the sorting value is maximum (1.15 ϕ) and the mean grain size is coarsest (0.93 mm). This indicates that erosion is active till August. The samples are negatively skewed to nearly symmetrical with most of the values clustered around -0.02, -0.11 and -0.21 (Fig. 3.12a). However, during the rest of the months, it is symmetrically skewed with values around -0.21. The negative skewness indicates the erosional phase of the beach from June to September while the symmetrical skewness, the stable nature of the beach.

At Cannanore (Fig. 3.10a), the average mean size of the beach sand is 0.29 mm which belongs to medium grade sand size. Coarsest size sand is observed in June (0.58 mm) coinciding with high energy environment under the influence of south-west monsoon. In August and October the sediments shows poorly sorting nature (Fig. 3.11a), while during the rest of the year they are moderately well sorted to moderately sorted. In general, throughout the period of study, the sediments show a moderately sorted trend. The skewness parameter (Fig. 3.12a), shows that during monsoon months the sediment is negatively skewed while during the rest of the period it was symmetrically skewed indicating an erosion during June.

The beach at Calicut (Fig. 3.10a), is composed of medium grade sand (0.26 mm to 0.40 mm) with moderate sorting and symmetrical skewness except during October, November and January, when coarse material is present. During January

(0.64 mm) the material is coarsest. The coarser size class during October and November along with high sorted (Fig. 3.11a) and negatively skewed nature (Fig. 3.12a) shows that the beach undergoes erosion during these months.

At Nattika (Fig. 3.10a), the average beach grain size shows fine sand class (0.15 mm to 0.26 mm) except during September when it is medium sand class (0.48 mm) and during October when coarser sands (0.52 mm) are present. The sorting values (Fig. 3.11a), show well sorted class during monsoon and moderately sorted trend during the other seasons. The negatively skewed trend in October (post-monsoon period)(Fig. 3.12a) and symmetrically skewed nature during the other seasons indicates the erosional and accretional behavior of the beach in terms of its constituent sediment.

At Andhakaranazhi (Fig. 3.10b), the average grain size shows medium grade sand size class. During monsoon period, fine (0.16 mm - 0.22 mm) to medium sand classes (0.30 mm) are observed and maximum medium grade sand class (0.44 mm) is present in October. The sediments are well sorted (Fig. 3.11b) in July and September and poorly sorted in October They are negatively skewed in October and symmetrically skewed during the other seasons (Fig. 3.12b).

At Alleppey, the mean grain size (Fig. 3.10b), does not show much significant changes till October when it belongs to the medium sand size class (0.27 mm - 0.46 mm) indicating almost stable nature of the beach during the

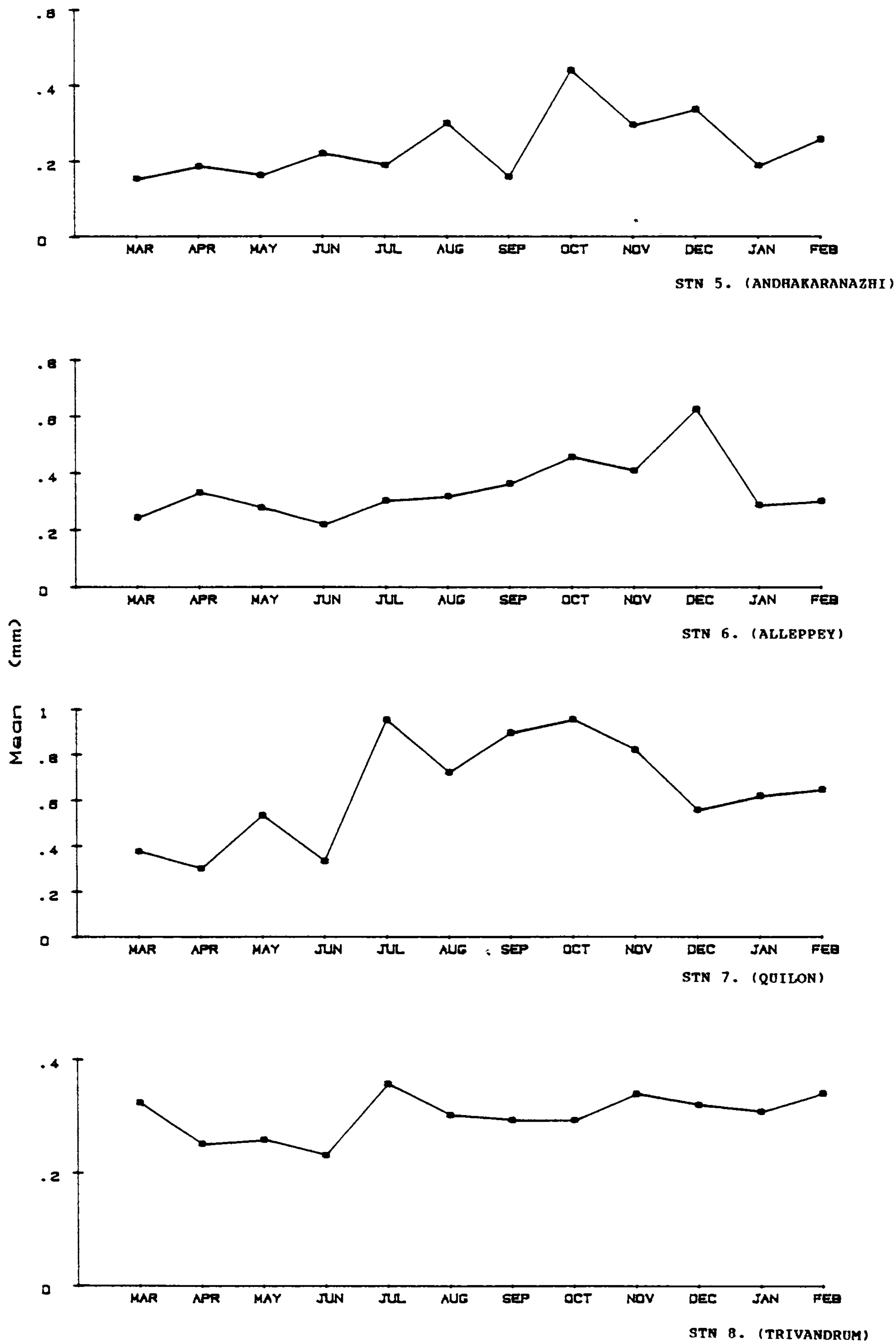


FIG.3.10b. MONTHLY VARIATION OF MEAN SIZE

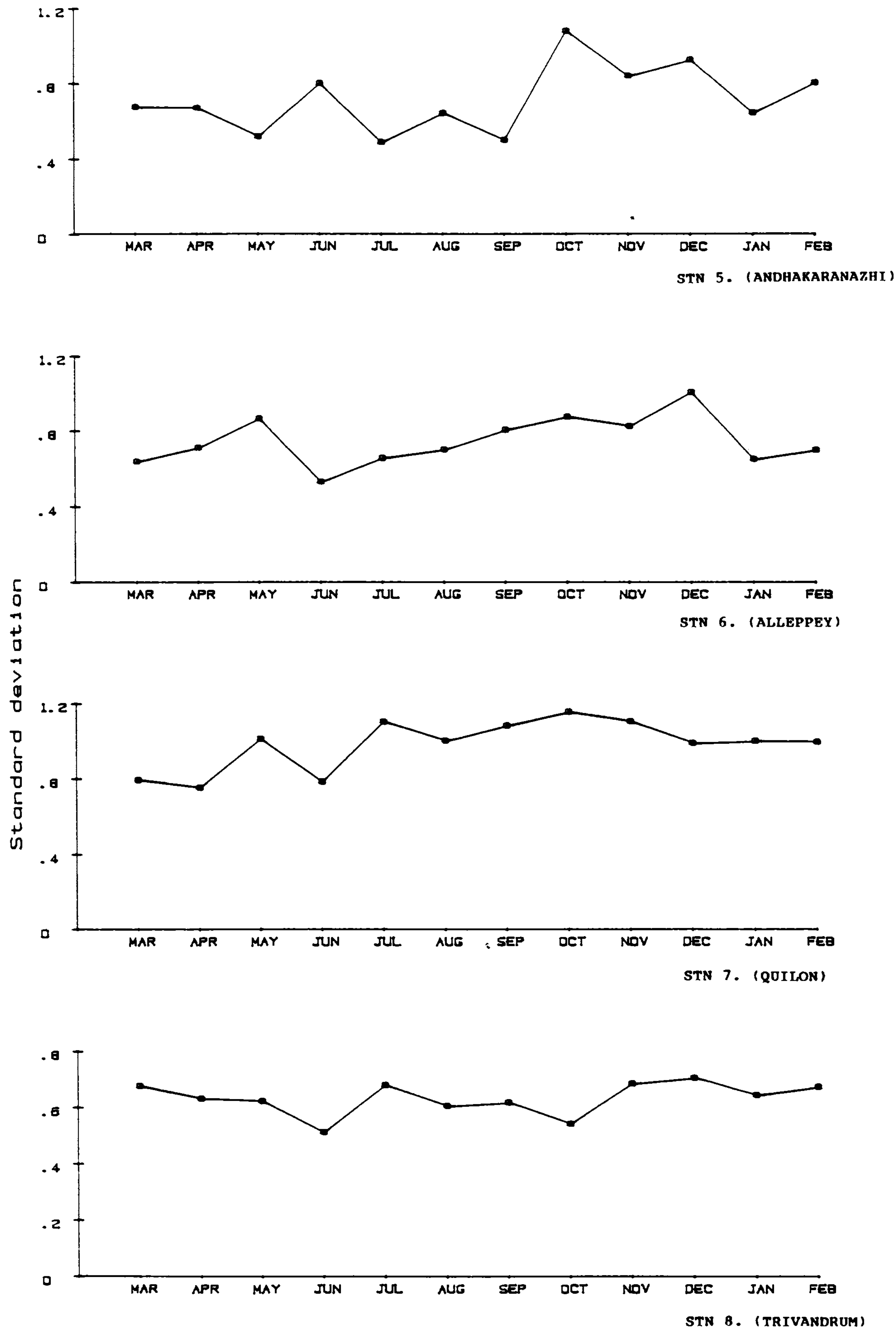


FIG. 3.11 b. MONTHLY VARIATION OF STANDARD DEVIATION

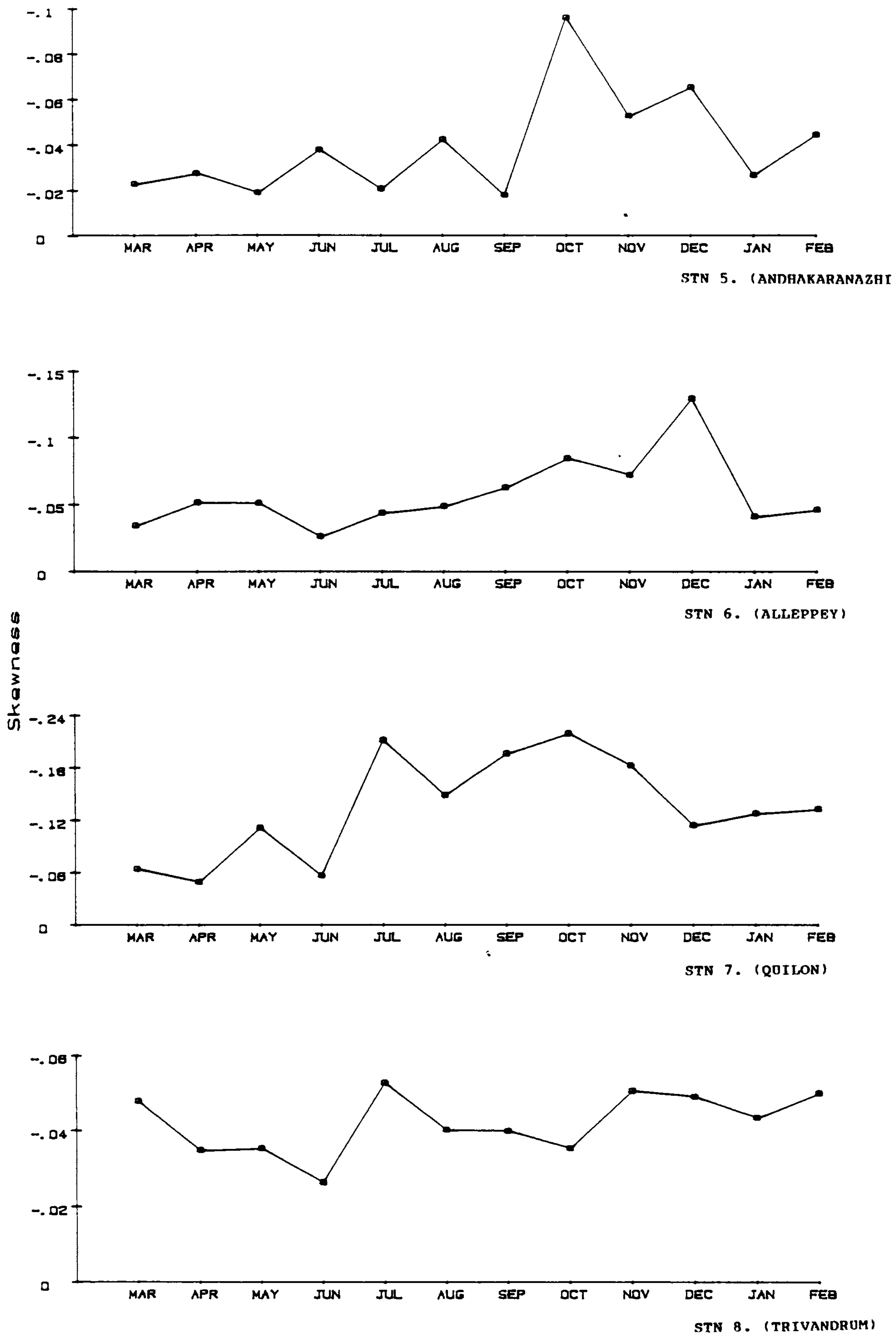


FIG. 3.12b. MONTHLY VARIATION OF SKEWNESS

south-west monsoon. During the north-east monsoon season, there is a decrease in size values from 0.46 mm (October) to 0.41 mm (November). However, during December, the sediments become coarser (0.62 mm). During June, the sediments belong to fine sand class (0.22 mm) indicating the depositional phase of the beach. It is moderately well sorted (Fig. 3.11b) during the south west monsoon season, poorly sorted and negatively skewed in December and symmetrically skewed in the other seasons (Fig. 3.12b). At Alleppey, the presence of mud bank during south-west monsoon is congenial to the accretion of the beach adjacent to it due to the wave dampening by the unconsolidated mud suspension. As a result, changes in sediment size, sorting value, skewness and beach volume changes are not seen at this location during this period. However, the changes in wave climate associated with north-east monsoon, though to a much less dynamic as compared to the south-west monsoon, are felt much more here than in any other locations. The results corroborate the earlier studies done in this beach (Hameed, 1988).

At Quilon, the average grain size, (Fig. 3.10b) shows the presence of coarse sand (>5 mm). From March to June, the sand size shows medium sand size class (0.30 mm - 0.38 mm) except in May (0.53 mm). Two peaks of coarser grain size are present, one during the south-west monsoon season and another during the north-east monsoon season with size class 0.95 mm during July and 0.96 mm during October. Medium sand is present in the other seasons. During July to August, the sorting value shows a poorly sorted tendency (Fig. 3.11b). The samples show negatively skewed nature (Fig. 3.12b) during most of the period except during April and June when they are symmetrical. This shows that the beach in general undergoes erosion during the period of study.

At Trivandrum, the average value of the mean grain size (Fig. 3.10b) shows the presence of medium size sand (0.25 mm - 0.36 mm) except in June where fine sand class is present (0.23 mm). The maximum grain size in July shows the severe erosion during this month. The sorting values (Fig. 3.11b) show moderately well sorted to moderately sorted nature during south-west monsoon. And was symmetrically skewed (Fig. 3.12b) through the entire period of study indicating the dynamically stable nature of the beach.

The E.O.F analysis of the mean grain size data shows that the first function accounted for 92.1% of the mean square value while the second and third functions accounted for 3.9% and 1.6% respectively (Table 3.2).

The first spatial eigen function (U1) of the mean grain size (Fig. 3.13) shows that, of all the beaches under study, the beaches at Kasargod and Quilon have the highest mean grain size whereas the beaches at Nattika and Trivandrum have the least grain size values. In general, the sediments are in the medium sand class except at Kasargod and Quilon where they are coarse sized.

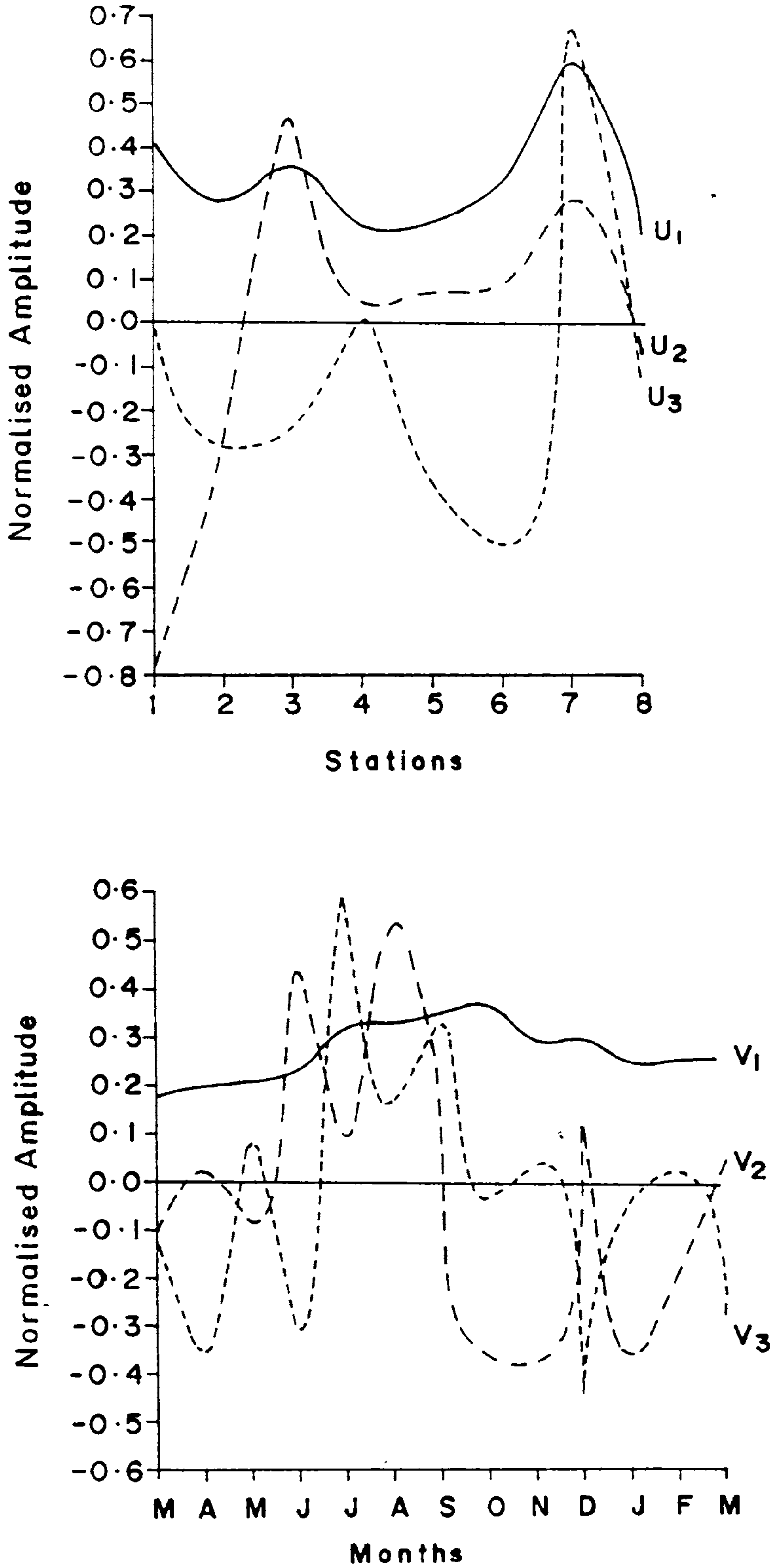


Fig. 3.13. Spatial and temporal distribution of eigen functions for mean grain size.

The second spatial eigen function (U2) of the mean grain size reflects the deviation in the grain size at a given station from the mean. It also follows a similar trend as that of the first eigen function indicating that the maximum variability of the mean grain size is seen at Kasargod and Quilon while at Nattika, Andhakaranazhi, Alleppey and Trivandrum it shows least variability.

The corresponding temporal functions V1 and V2 also indicate a similar profile variations as discussed under section 3.1.3. Since the third functions, both the spatial and temporal, does not depict any behavioral pattern that can be related to the physical phenomena, it has not been considered for the present study.

CHAPTER 4

4. SEDIMENT TRANSPORT

4.1. Littoral Environmental Observations

The surf zone is of primary importance in forming the final pattern of sediment movement and thereby shaping the coasts. The Littoral Environmental Observation (LEO) programme provides data on wave period, breaker height, angle of breaking waves to shoreline, breaking type, width of surf zone and longshore current speed and direction. The data collection in this zone using gauges or other instruments is difficult due to cost and inaccessibility. In the present study, visual observations were carried out once in a day, for a period of one year at 8 selected stations using regular measurement techniques.

4.1.1. Materials and methods

Breaker wave characteristics

Heights of 10 consecutive breakers were estimated and the average was noted as the significant wave height. The wave period was measured using a stop watch by observing the time required for 10 consecutive wave crests to pass a fixed point and taking the average. The breaking wave angle with respect to the coastline was measured using a surveyor's magnetic compass. Most of the observations were made between 0600 & 0900 hrs irrespective of the tidal phase.

Longshore current

Longshore current velocity and direction were measured by releasing neutrally buoyant floats in the surf zone and the distance traveled by the floats in 2 minutes was recorded and represented in m/s. The measurement was repeated twice and the average is noted. The approximate width of the surf zone was visually estimated.

4.1.2. Results

Littoral Environmental characteristics

Monthly average variations of surfzone width, breaking wave height, breaking period, breaking angle and longshore current velocity and direction at stations 1 to 8 are presented in (Figs. 4.1 to 4.8). Surfzone is seen to be wider during the monsoon and post-monsoon seasons. It shows a seasonal tendency in most of the study locations except at stations 4 (Nattika) and at station 8 (Trivandrum). At Nattika, the surfzone width is >10m during most of the time irrespective of season due to gently sloping foreshore of this beach. At Alleppey beach, the surfzone width is more during the pre-monsoon period and post monsoon season than during the monsoon season when it was <6m. The formation mud bank during the south-west monsoon period of the year 1990, (Joseph, 1992) provides calm conditions in the nearshore sea and causes the low value of the surf zone width .

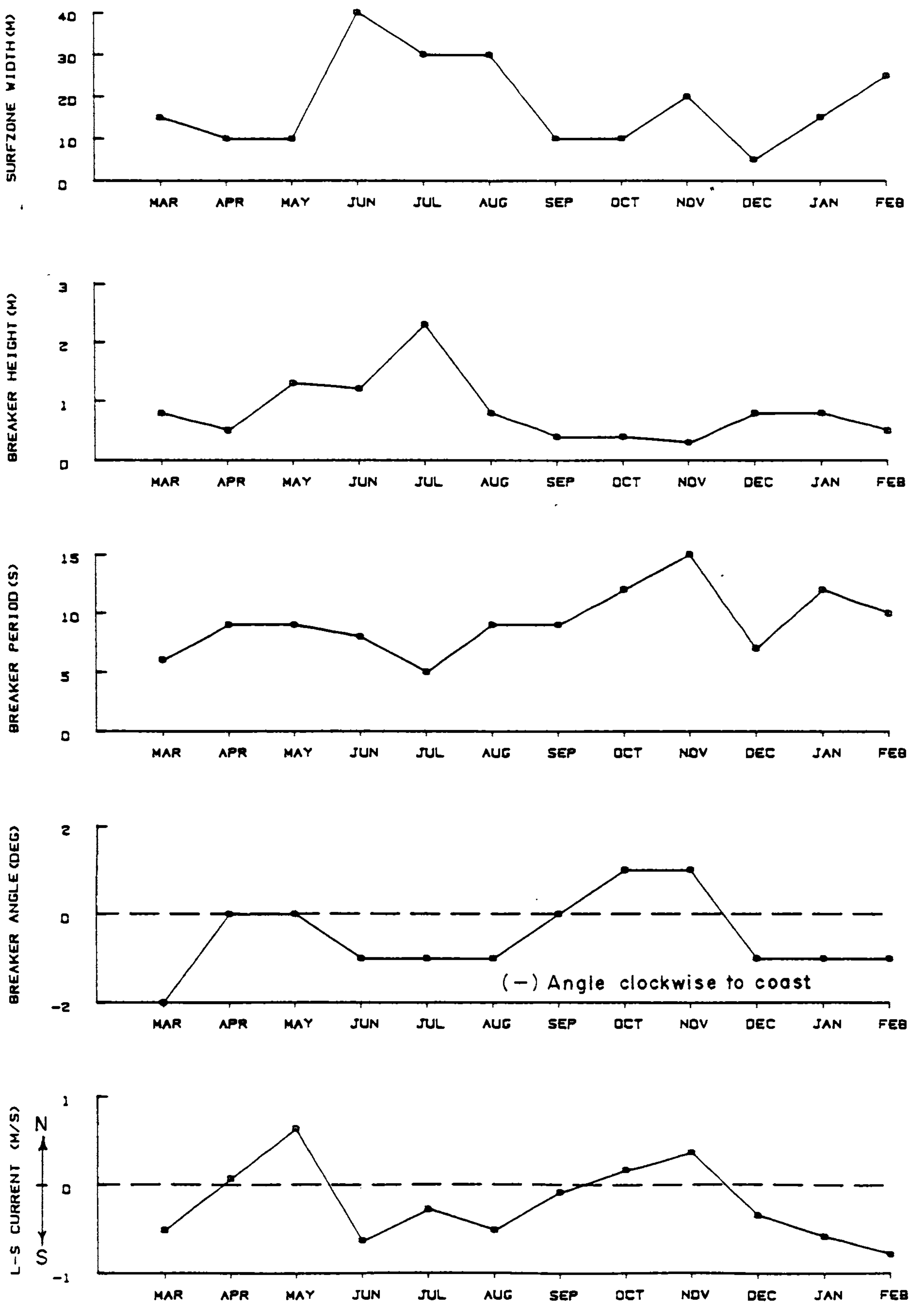


Fig. 4.1. Monthly littoral environmental parameters at Stn. 1 (Kasargod)

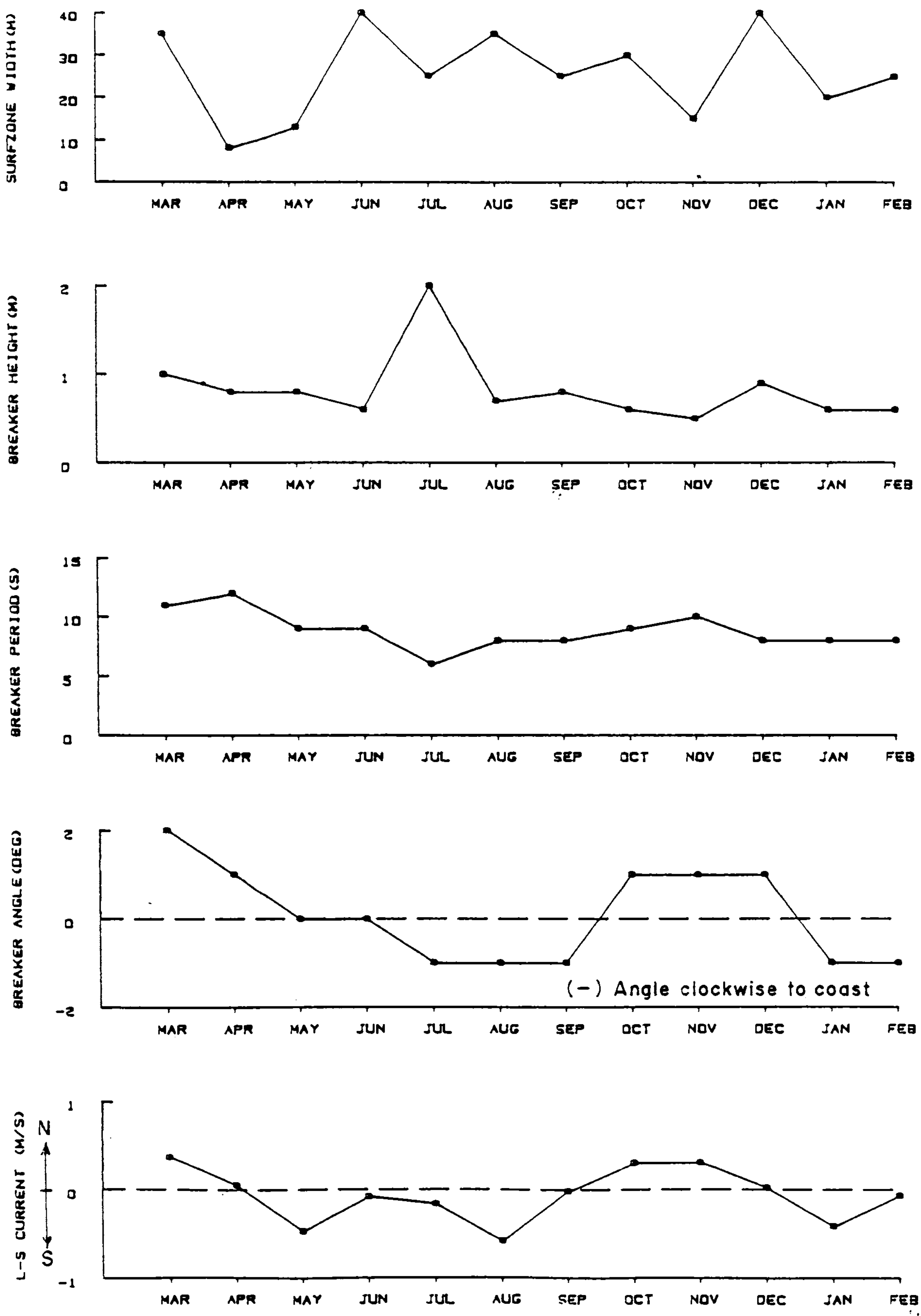


Fig. 4.2. Monthly littoral environmental parameters at Stn. 2 (Cannannore)

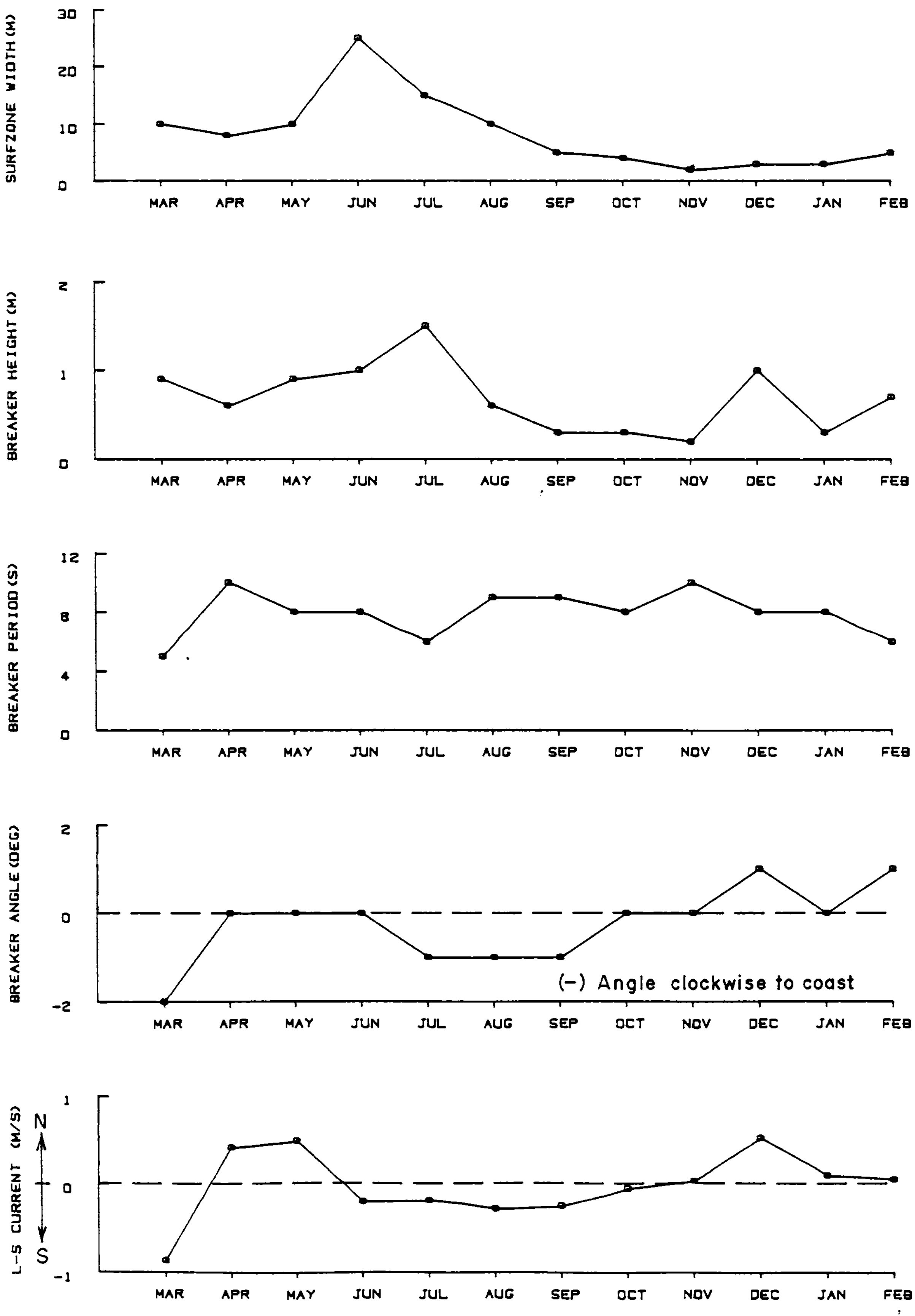


Fig. 4.3. Monthly littoral environmental parameters at Stn. 3 (Calicut)

Breaker height is maximum in the monsoon months and gradually decreases towards the other seasons with a secondary peak of comparatively lesser magnitude during the post-monsoon season except at stations 6 (Andhakaranazhi). The average breaker height shows a progressive increase from fair weather season to south-west monsoon season for all the eight stations. Maximum breaker height is observed during July at stations 1,2,3 and 6 and during June at the other stations (4,5,7 and 8). Trivandrum shows higher breaker heights (>0.6 m) throughout the year. Kasargod shows breaker heights >0.6 m except during the post monsoon.

The breaker period varies between 5 sec. and 15 sec. during an year at all stations. Frequency of breakers shows increase towards the south-west and north-east monsoons and decrease towards the other seasons. The breakers are mostly plunging or surging type and sometimes characterized the collapsing nature.

The breaker angle also shows a seasonal change in the direction of approach. It is reported that, depending upon the locations, the breaking direction are found to vary between 210° to 300° N along the Kerala coast (Baba, 1988). At stations 2,4,5,6 and 8, breaker direction is from north-north-west to westerly during the fair weather period and it gets reversed during south-west monsoon season to south-south-west and again shifts to north-north-west after the cessation of the south-west monsoon. The longshore current measurements are spot observations representing the average

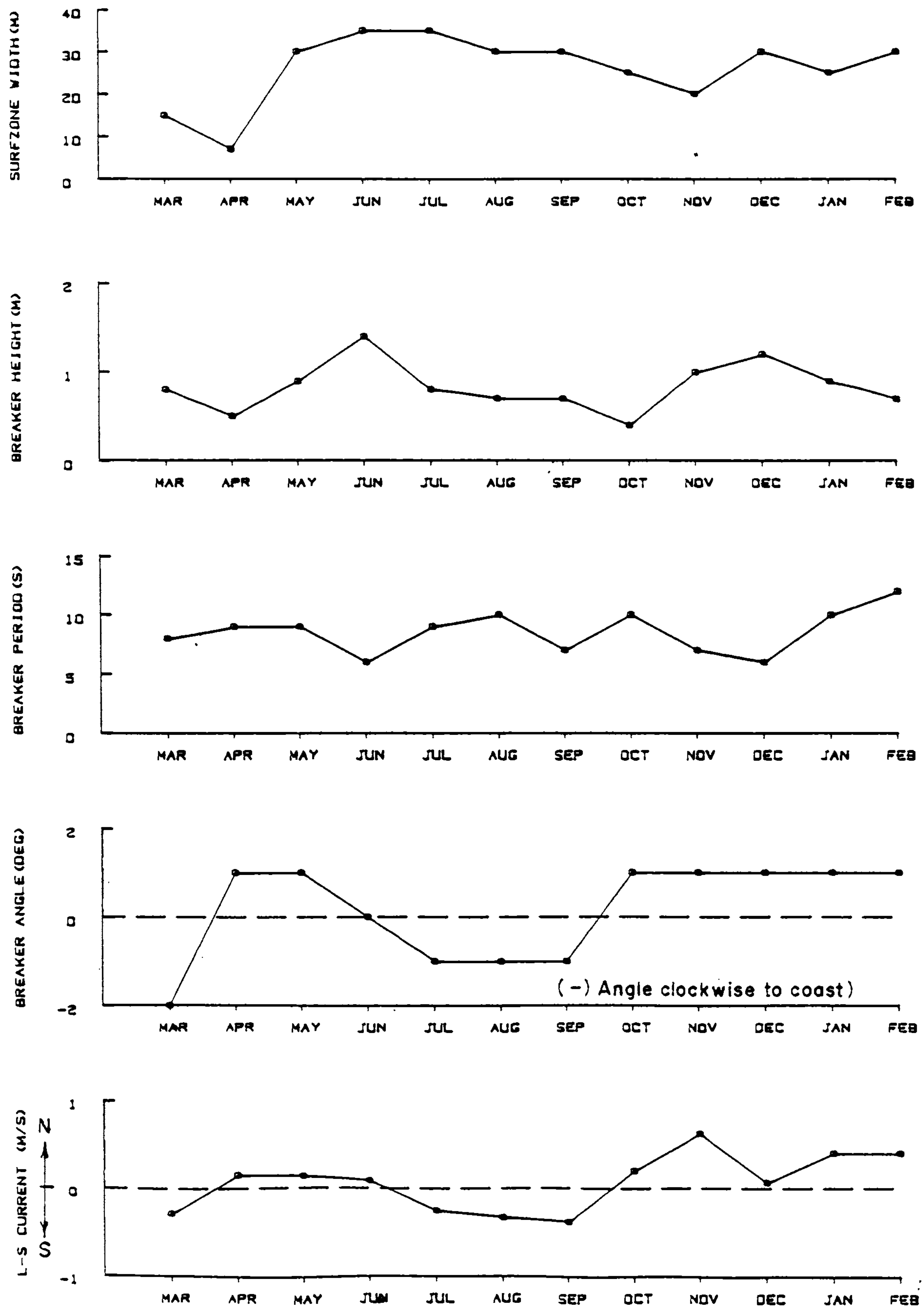


Fig. 4.4. Monthly littoral environmental parameters at Stn. 4 (Nattika)

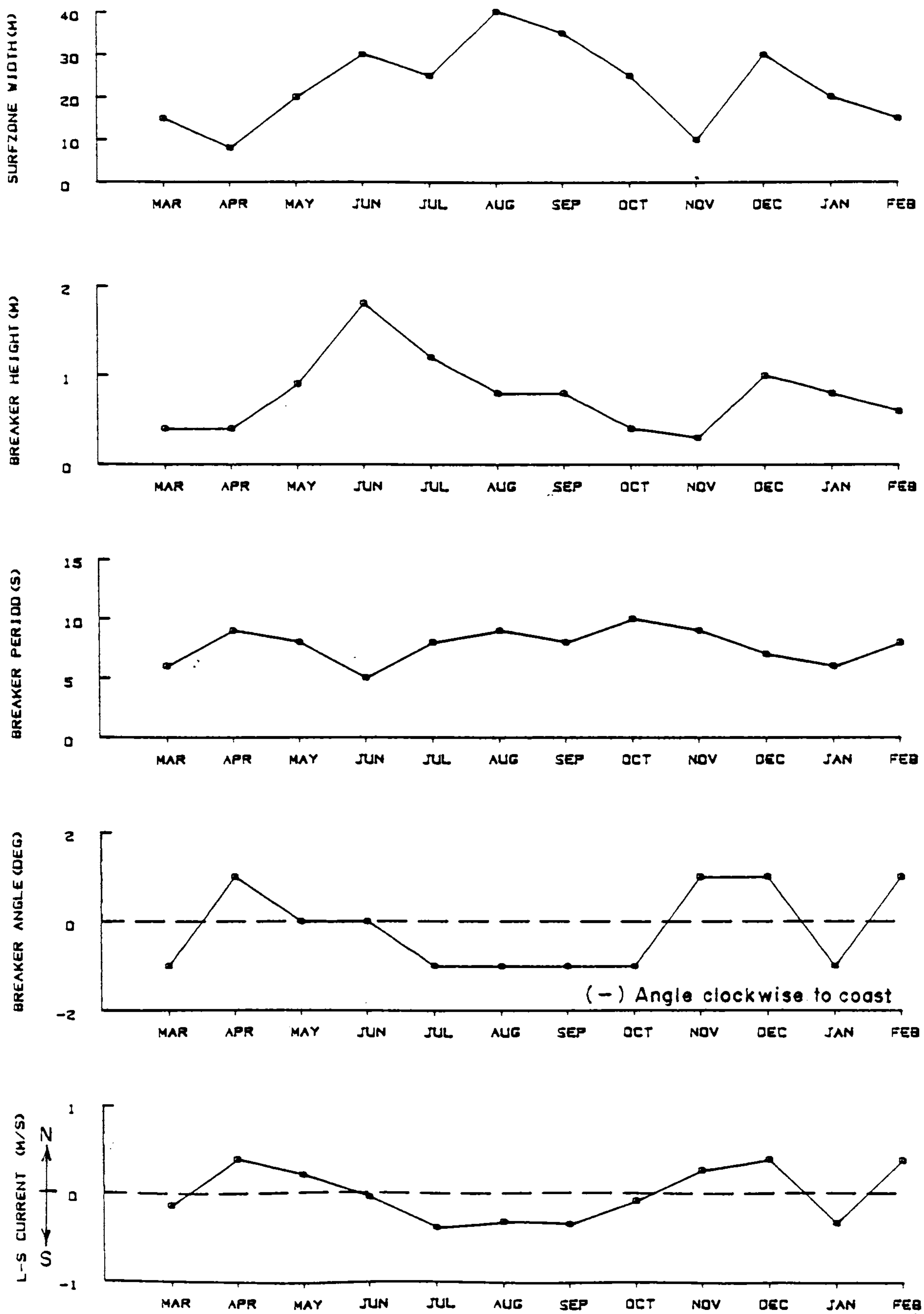


Fig. 4.5. Monthly littoral environmental parameters at Stn. 5 (Andhakaranazhi)

conditions persisting across the surf zone. The field observations on longshore currents at selected locations along Kerala coast spanning over a period of one year reveals high variability in their direction and speed. The wave induced longshore current values show significant temporal and spatial variations along the beaches under study The longshore current directions vary in response to the changes in wave direction both in time and space. The sudden changes in wind direction sometimes generate short period waves, which break on the beach at an angle larger than the long period waves causing strong longshore currents (Anonymous, 1975).

During the onset of south-west monsoon, a prominent reversal of longshore current direction towards south is noted in most of the stations with an increase in speed. It shows that during south-west monsoon, the longshore current shifts its direction towards south. (June-September). Changes in wind direction during the onset of monsoon cause the change in wave direction which results in the reversal of longshore current direction in most part of the Kerala coast. The obliquely approaching swell waves generate intense southerly longshore currents during the monsoon season causing southerly littoral drift along the beaches of Kerala.

A reversal in longshore current direction (towards north) with high magnitude is observed during north-east monsoon season. The longshore current direction is seen to be

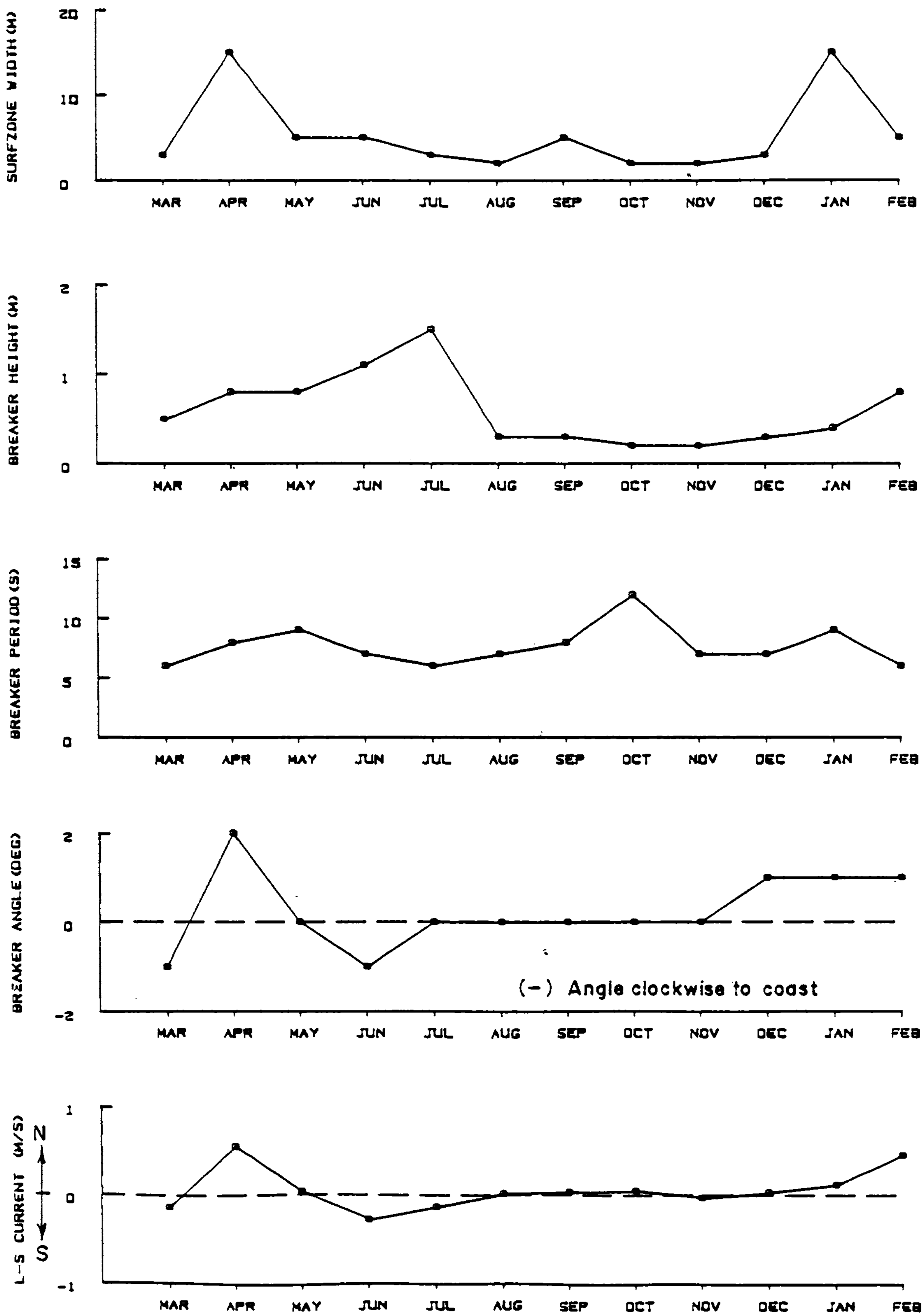


Fig. 4.6. Monthly littoral environmental parameters at Stn. 6 (Alleppey)

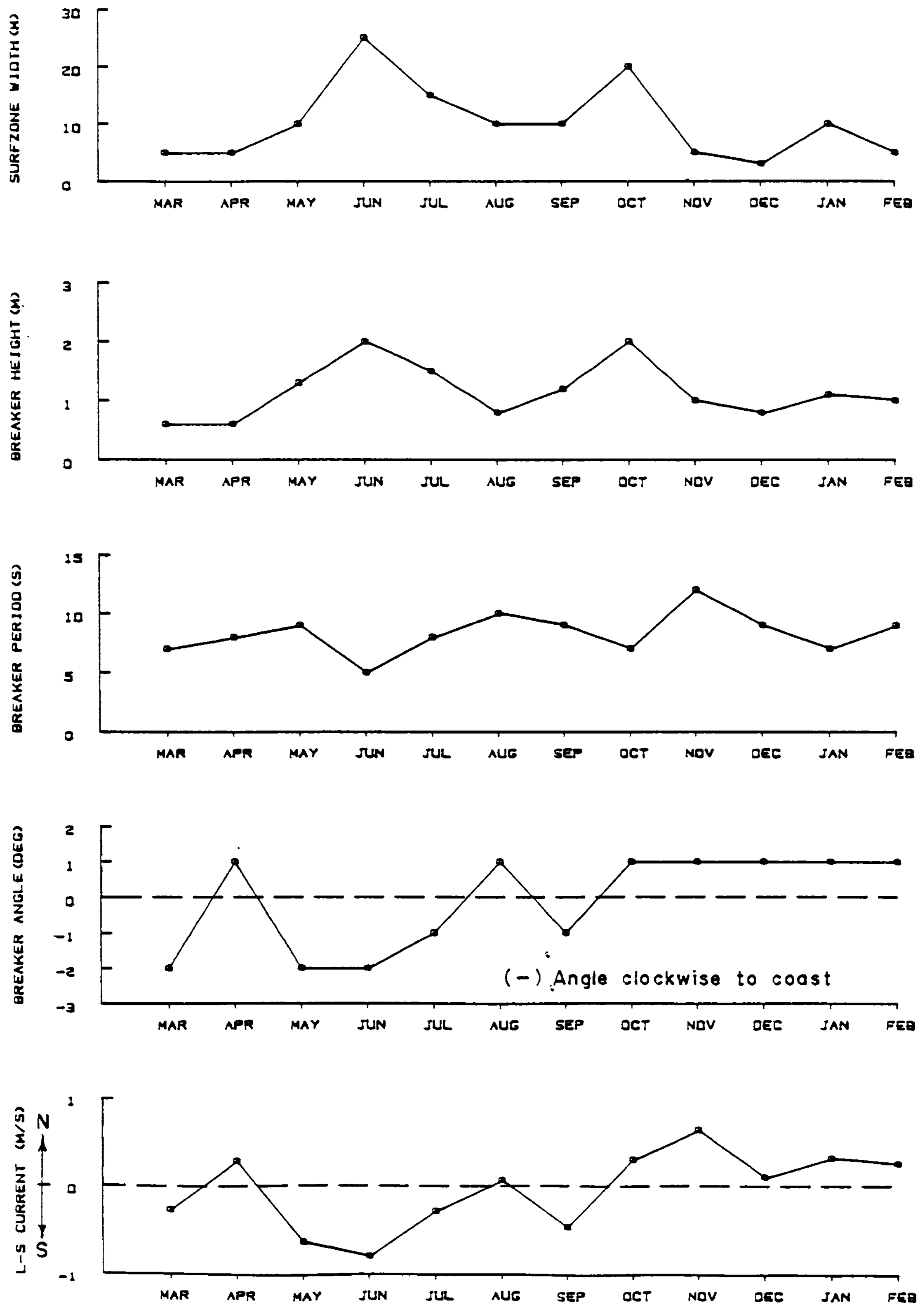


Fig. 4.7. Monthly littoral environmental parameters at Stn. 7 (Quilon)

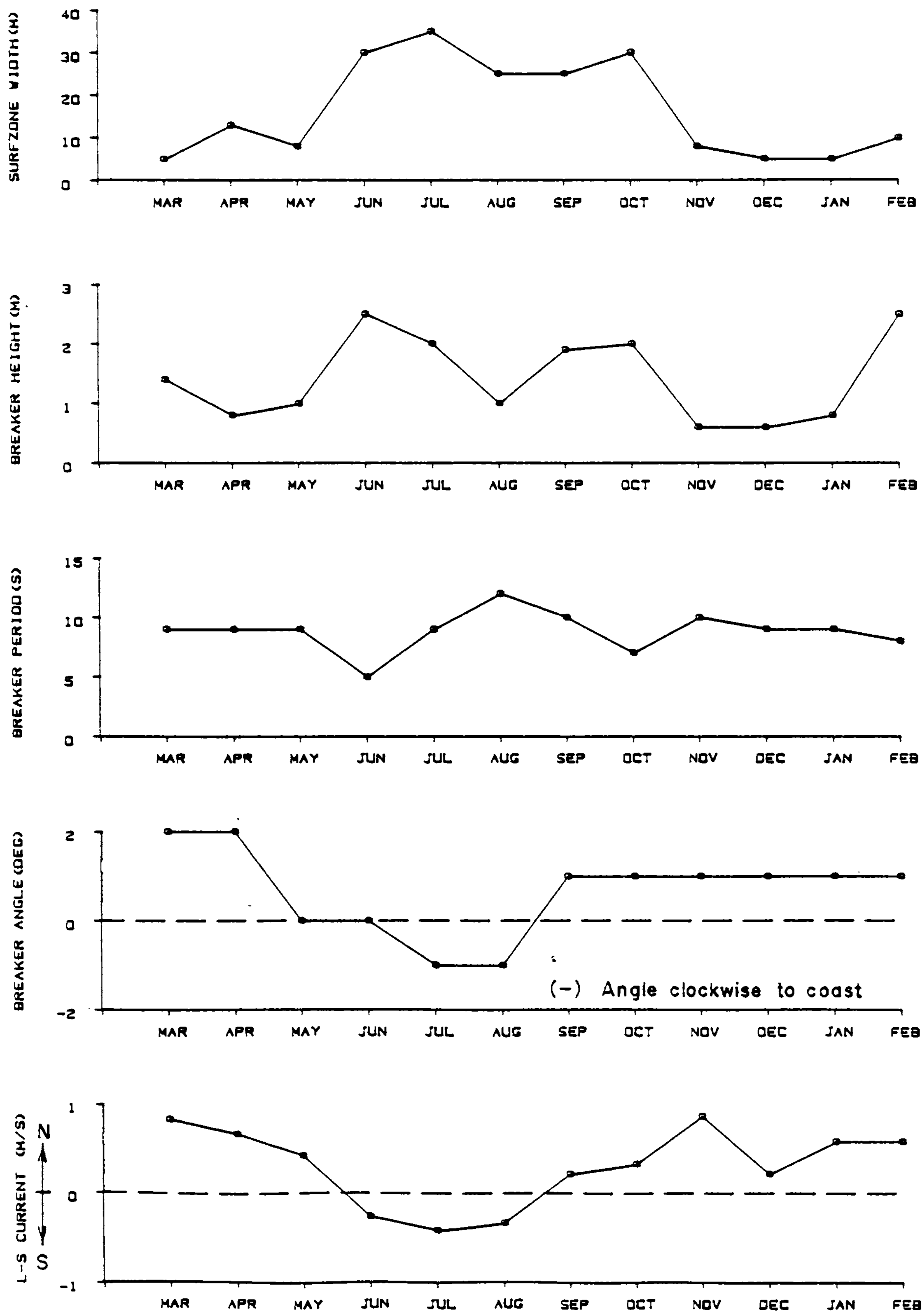


Fig. 4.8. Monthly littoral environmental parameters at Stn. 8 (Trivandrum)

transitional and inconsistent during March, December and January. A progressive increase in current velocity occurs from November through January and February along the studied locations. Current speed upto 0.88 m/sec is observed in the Trivandrum beach during November, which is highest among the recorded values on the beaches studied along the Kerala coast during this period. Current speeds of 0.2 - 0.6 m/sec. are frequently recorded at many locations. Negligible current velocity (0.02 to 0.05 m/sec.) values are also recorded at stations 3 and 6, ie. at Calicut and Alleppey, frequently during the period of study.

4.2. Longshore sediment transport

The longshore movement of beach sand poses a potential littoral problem. The important factor governing the beach erosion is the longshore sediment transport which is controlled predominantly by waves and nearshore topography. An understanding of sediment transport on beaches is also necessary for the analysis of formation of the geomorphic features such as sand spits and barrier islands, to examine the tidal inlet processes and to understand the irregularities in the shoreline. Interruptions of these natural movements of sands by man made barriers like groins, breakwaters, jetties etc. result in sediment deposition on the updrift side and removal of sediments on the downdrift side. This results in the necessity to study the longshore sediment transport around inshore coastal areas, which is of fundamental interest to coastal engineers in the planning of structures, dredging activities of ports and spoil disposal. A proper understanding of the seasonal littoral transport trend is important for the efficient management and development of coasts. Beach erosion problems along this coast have been the initial motivation for this study on sand transport by estimating the rate of sand movement.

Since estimation of the rate of littoral sand drift is one of the essential items necessary for the field investigation in regard to beach protection and sedimentation problems, much effort has been made in establishing a method of estimation by coastal engineers for a long time. The dynamics of sediment movement in the littoral zone is governed primarily by the wave induced currents. Specific knowledge of these currents and associated circulation patterns are helpful in better utilization of the coastal environment.

In the nearshore area, waves arriving from offshore continuously bring in momentum, energy and mass. Since the shoreline provides a fixed boundary, the momentum and energy fluxes are dissipated in the surfzone. Most of the energy is converted to turbulence in the breaker zone but enough is left to drive a nearshore current system and move loose bed material. The momentum brought in by the waves will drive the littoral current system and cause a local set-up or set-down of the mean water level.

The dynamics of sediment movement in the littoral zone depends mainly on four factors: the nature of the material available for transport, orientation and other geomorphic features of the shore, the angle of wave approach and the wave induced currents. Waves arriving at the shore are the primary cause of sediment transport in the littoral zone. Higher waves break further offshore, widening the surfzone and setting more sand in motion. Changes in wave period or height result in moving sands onshore or offshore. The knowledge about the wave climate - the combined distribution of wave height, period and direction during different seasons - is required for an adequate understanding of movement of sand in any specific area. The cellular circulation patterns in the surfzone depend on the longshore gradient in wave set-up. Because of the turbulence due to breaking and surging of waves, large volumes of sediments are placed in suspension or rolled along the bed in the surfzone.

4.2.1. Materials and methods

There have been many investigations in the littoral zone for the quantitative and qualitative estimation of sediment drift, making use of the relationship between wave forces and transport of sediment. Many studies have been carried out on the theoretical estimation of the longshore sediment transport using laboratory and field experiments. Longshore sediment transport is generally estimated by using empirical equations which relate the longshore energy flux in the breaker zone to the longshore transport rate. (Graff and Overeem, 1979; Willis, 1980). Empirical equations, using results of the wave refraction studies and progressive changes in grain size distribution have also been used to indicate sediment transport direction. Some analyses are more sophisticated by taking into account the frictional factors and bed permeability. These also assume for convenience, a constant mean sediment size. It has been shown later that these assumptions were far from reality during the short periods when the bulk of the littoral drift takesplace.

Komar (1976) presented graphically, various data indicating relationships between the longshore transport rate and the longshore component of wave energy flux. Komar and Inman (1970) made extensive field measurements and proposed an approach of longshore transport with the immersed weight of longshore transport of sand proportional to the longshore component of wave energy flux. Shore Protection Manual (Anonymous, 1975), presents different equations for estimating the longshore transport using the relationship between longshore energy flux factor (Pls) and the longshore transport rate (Q).

Almost all studies have attempted to relate, the longshore sediment transport with longshore energy flux in the form,

$$Q = K. Pls \qquad (4.1)$$

where Q = volume rate of longshore sediment transport.

K = dimensional constant

P_{ls} = longshore component of wave power at breaking

= $P \cos\alpha_b \sin\alpha_b$ where

P = wave power at breaking = $(E\,C_n)_b$

α_b = breaking angle

E = wave energy

C_n = group celerity and suffix b denotes at breaker zone

Using the value of Pls in equn. (4.1)

$$Q = K\,(E\,C_n)\cos\alpha_b \sin\alpha_b \qquad (4.2)$$

Walton (1980) established a computing technique for longshore energy flux factor (Pls) using the longshore current and breaking wave height.

By radiation stress principle, the longshore current is given by the relation (Longuet-Higgins, 1970)

$$V_b = 5\,\pi/8\,(k_a\,\beta/\,C_f)\,(gd_b)^{0.5}\,m \sin\alpha_b \cos\alpha_b \qquad (4.3)$$

where

V_b = longshore current velocity at breaker zone

β = a mixing parameter

d_b = breaking depth

C_f = bottom friction factor

m = beach slope

K_a = breaking wave amplitude/water depth

Using the relationship ($2K_a = H_b/d_b$) in equn. (4.3)

$$V_b = 5\,\pi/16\;k_a\,\beta/\,C_f\;(1/2k_a)^{0.5}\;m\;(gd_b)^{0.5}\sin 2\alpha_b \qquad (4.4)$$

The longshore current velocity at any point in the surf zone can be defined as

$$V = V_b\,(V_o/V_b)\,(V/V_o) \qquad (4.5)$$

where

V = longshore current velocity within the surfzone

V_o = theoretical Longshore current velocity at breaking (no mixing)

using (4.3) and (4.4)

$$V = (V/V_0)(5\pi/16)(k_a/C_f)(1/2\ k_a)^{0.5}\ m\ (gd_b)^{0.5} \sin 2\alpha_b \quad (4.6)$$

The relationship for longshore energy flux factor at surface is given by

$$Pls = \rho H_b^2/16\ (b \sin 2\alpha_b) \quad (4.7)$$

For breaking zone, substituting $C_b = (g\ d_b)^{0.5}$ in equn. (4.8)

$$Pls = \rho H_b^2/16\ (d_b/H_b)^{0.5}\ (g\ H_b)^{0.5} \sin 2\alpha_b \quad (4.9)$$

Using equn. (4.7) and assuming $m = d_b/W$

$$Pls = \frac{\rho\ H_b\ W\ V\ C_f}{0.78\ (5\ \pi/2)\ (V/V_o)} \quad (4.10)$$

Equn. (4.1) become

$$Q = K\ Pls$$

$$\text{ie}\quad Q = \frac{K\ \rho\ g\ H_b\ W\ V\ C_f}{0.78\ (5\ \pi/2)\ (V/V_o)} \quad (4.11)$$

where Q is the annual longshore sediment transport rate in m^3/yr and the value $K = 1288$ is a dimensional constant.

ρ = 1025 kg/m^3

g = 9.81 m/s^2

Cf = 0.01 = frictional coefficient dependent on bottom excursion and bottom roughness.

H_b = breaking wave height in m

W = surfzone width in m

V = longshore current velocity

$\frac{V}{V_o}$ = theoretical dimensionless longshore current velocity, (Longuet-Higgins, 1970), assumed mixing parameter p = 0.4 and is dependent on the parameter X/W.

For the estimation of sediment transport rate using the daily data of LEO, only Walton's equation can be well suited, as it takes into consideration the measured values of longshore current. Chandramohan et al. (1993) have used this equation for the estimation of longshore sediment transport along the south Maharashtra coast. The primary concern for such studies is to make estimations on breaker height, breaker period and longshore current direction and speed. Monthly averages of the daily LEO data for one year made at each station have been used in equation (4.11). The net transport (difference between the amount of littoral drift transported to the north and south across the surfzone for a given period) has been calculated.

4.2.2. Results

Monthly longshore sediment transport rates were estimated using Walton's equation (4.11) from the littoral environmental parameters on breaker height, surfzone width and longshore current direction and speed at all 8 stations. (Figs. 4.9 to 4.16 and Table. 4.1). The negative sign in the table indicate the drift towards south and the positive sign towards north. Annual net transport for each location is presented in Fig. 4.17.

Table 4.1. Monthly drift values at different stations (X 10^5 m^3)

Months	Stations							
	1	2	3	4	5	6	7	8
March	-0.60998	1.26592	-0.76541	0.32845	-0.07624	-0.01906	-0.07918	0.56795
April	0.03421	0.03128	0.19238	0.05132	0.11887	0.12903	0.08211	0.68115
May	0.80061	-0.47782	0.35191	0.34311	0.35191	0.01173	-0.80060	0.32845
June	-2.95609	-0.18768	-0.48877	0.38319	-0.26393	-0.15054	-3.91017	-1.97952
July	-1.88861	-0.83091	-0.39590	-0.68428	-1.11440	-0.05718	-0.61585	-2.87398
August	-1.21997	-1.38909	-0.16422	-0.67743	-1.00100	0.00117	0.05474	-0.80647
September	-0.03128	-0.01955	-0.03665	-0.78008	-0.95799	0.00439	-0.53960	1.02153
October	0.06256	0.52787	-0.00586	-0.19550	-0.07820	0.00195	1.17305	1.93553
November	0.21115	0.21994	0.00117	1.21215	0.07624	-0.00117	0.30792	0.40822
December	-0.13685	0.07038	0.15249	0.24634	1.11440	0.00264	0.02346	0.06451
January	-0.68037	0.49268	0.00879	0.87978	-0.51614	0.07038	0.34409	0.22679
February	-0.95310	0.10264	0.00342	0.82113	0.32552	0.17595	0.12219	1.41743

+ Northerly   - Southerly

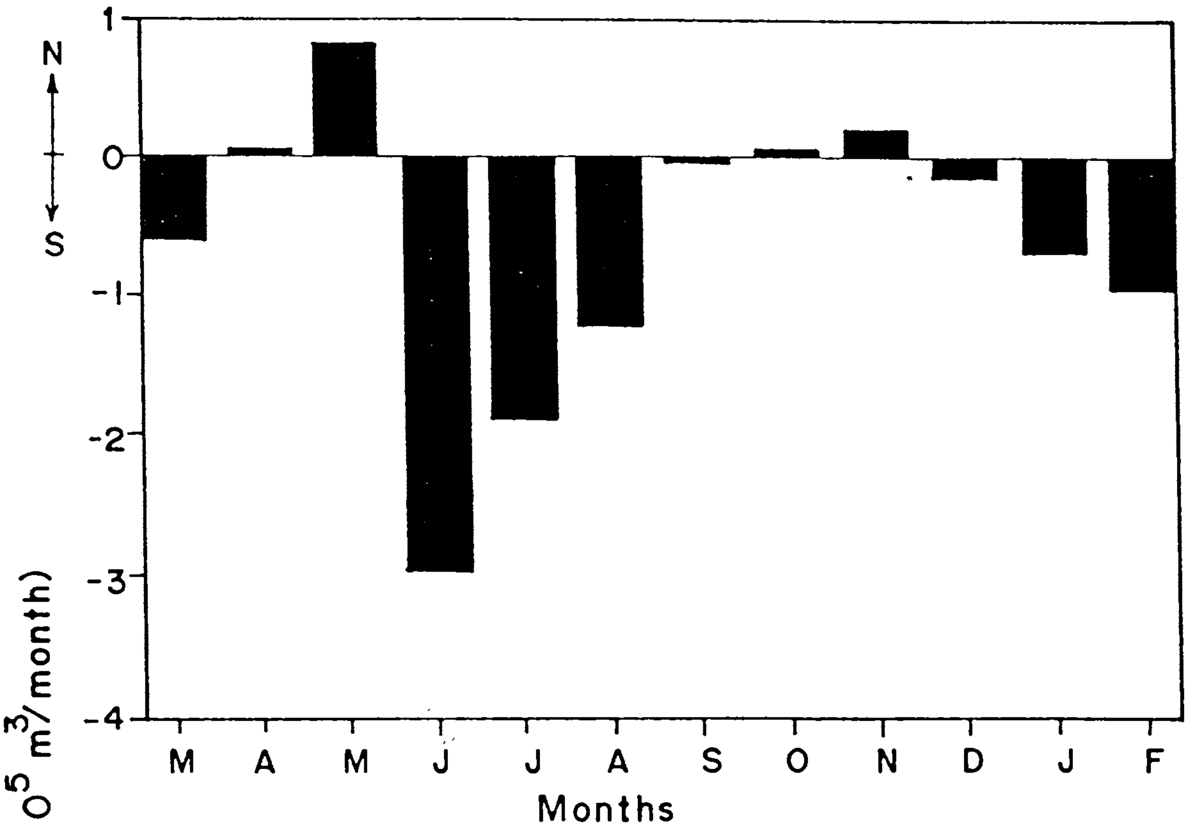


Fig. 4.9. Monthly surfzone drift at Kasargod

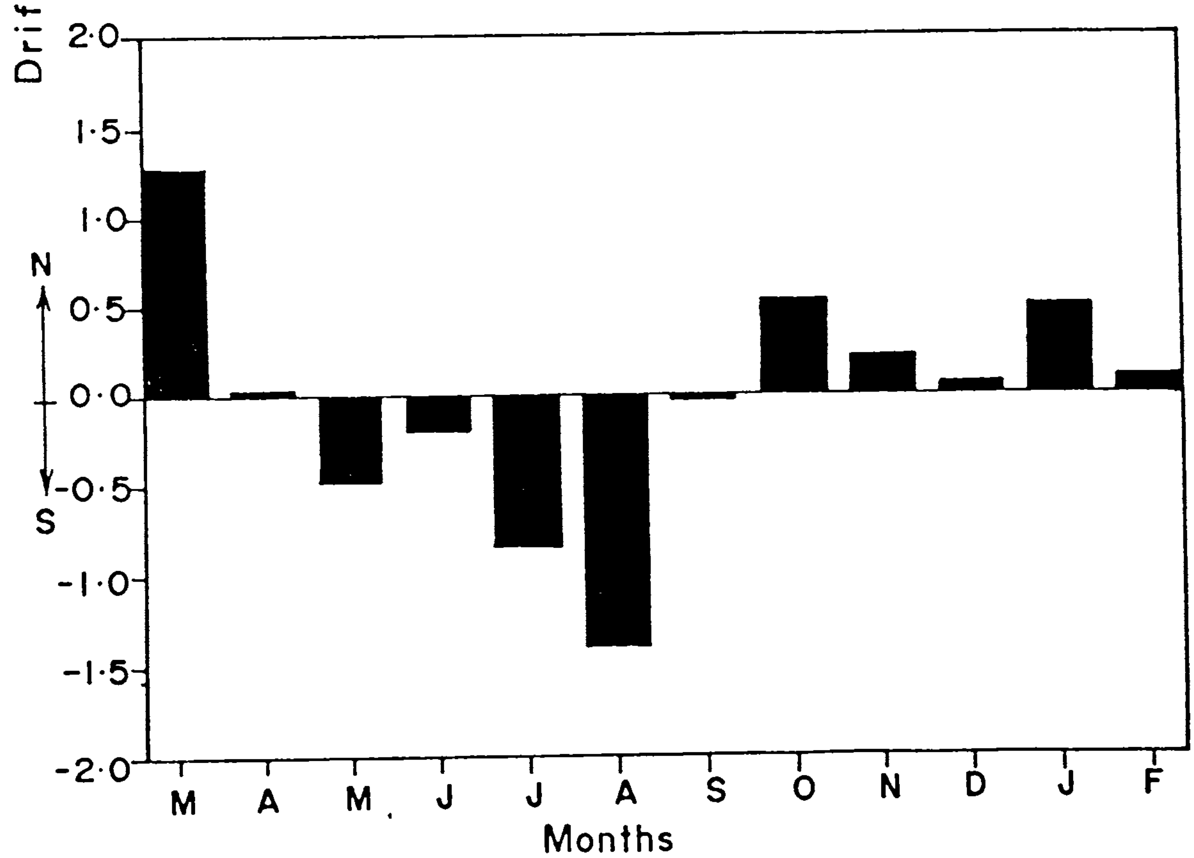


Fig. 4.10. Monthly surfzone drift at Cannanore

Along Kasargod beach (Fig. 4.9), the littoral drift shows higher values compared to all other beaches. In the pre-monsoon season southerly drift is observed during March and northerly drift during April-May. During May, the drift magnitude amounts to $0.8 \times 10^{5}\ m^{3}$. With the onset of south-west monsoon, a shift to southerly direction is observed in June and continues in the same direction till the end of south-west monsoon. Maximum southerly drift is observed in June ($2.95 \times 10^{5}\ m^{3}$). During post-monsoon season, the drift is low and inconsistent in direction. During January to March the drift is southerly. The annual net transport shows a southerly drift of $0.73 \times 10^{6}\ m^{3}$ which is the highest compared to the other locations. The higher drift magnitude along this beach is due to the high energy conditions prevailing along this beach. (Chapter 4, Section 4.1.2).

Along Cannanore section (Fig. 4.10), it is seen that, during pre-monsoon period the drift is northerly with a maximum value of $1.26 \times 10^{5}\ m^{3}$ in March. The beach shows southerly littoral drift during May - September and it is northerly during the other months. A decrease in magnitude is observed during June ($0.19 \times 10^{5}\ m^{3}$) followed by an increase towards August ($1.38 \times 10^{5}\ m^{3}$). From September onwards the drift is consistently directed towards north. The annual net drift is southerly with a magnitude of $0.019 \times 10^{6}\ m^{3}$.

Along the Calicut beach (Fig. 4.11), the littoral drift values show lesser magnitude compared to the locations on the north. The monthly drift is southerly during March

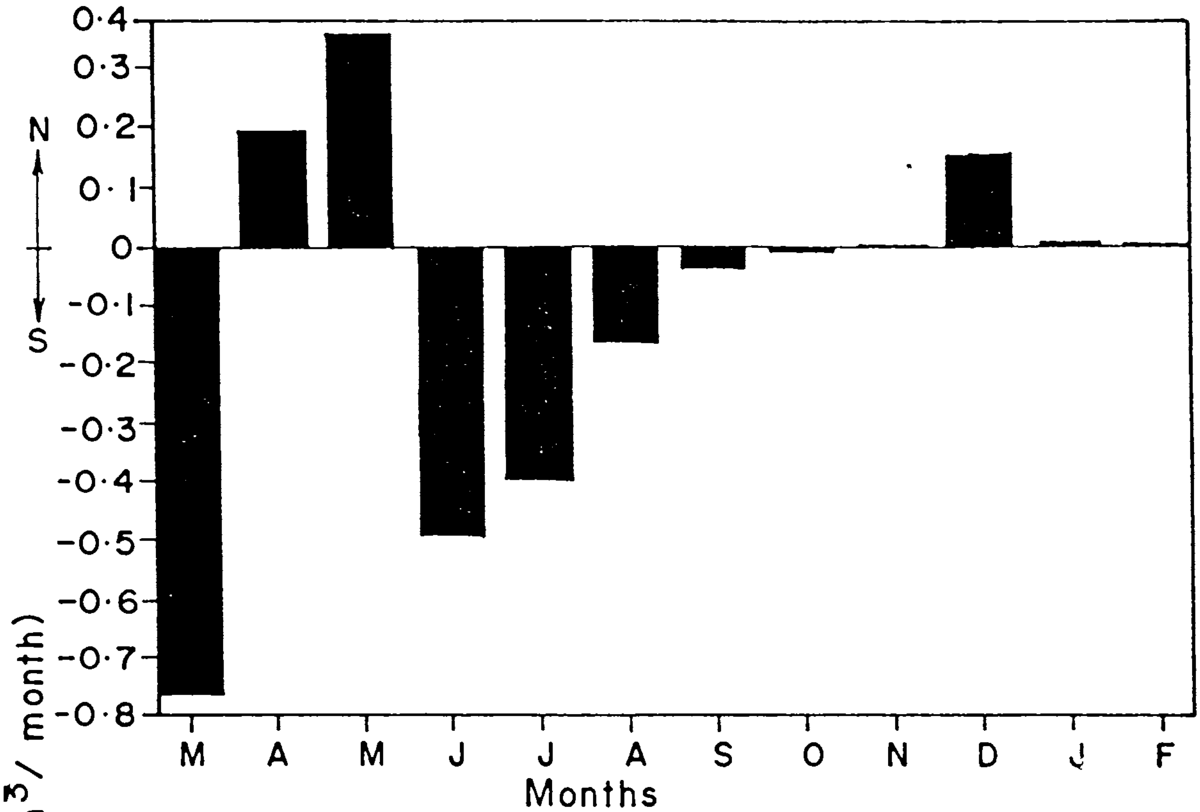


Fig. 4.14. Monthly surfzone drift at Calicut

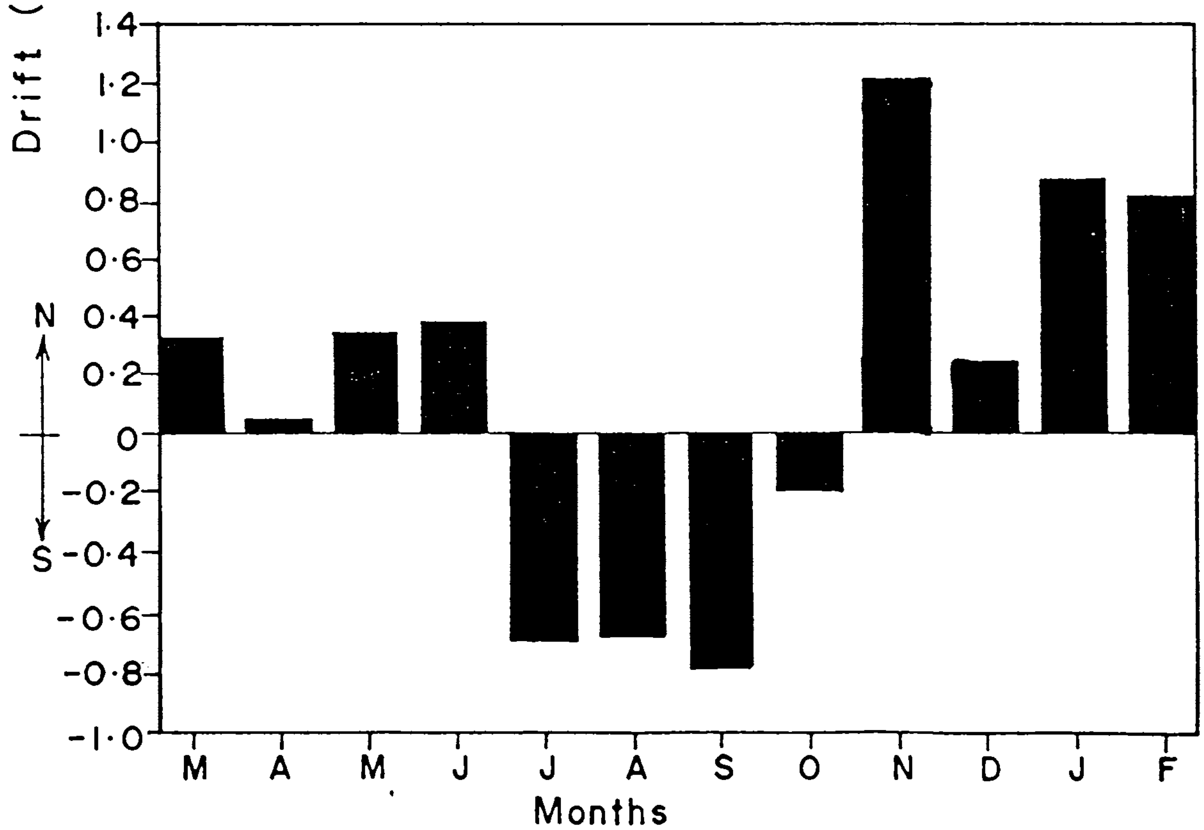


Fig. 4.12. Monthly surfzone drift at Nattika

with the highest value of 0.76 X 10^5 m^3. The drift is northerly during April-May. During the south-west monsoon season the drift is southerly with comparatively lower values contributed by the occurrence of mud bank in this region. The littoral drift shows a decrease during the post monsoon season reaching a minimum value of 0.001 X 10^5 m^3 in November. From the beach profile studies (Chapter 3, Section 3.1.2), this beach is seen to be a stable beach among the beaches studied along the northern coast of Kerala. This region represents a case in which the interaction between wave, current and the topography have reached a state of dynamic equilibrium. The annual net drift is southerly with very small magnitude (0.11 X 10^6 m^3).

Along Nattika beach (Fig. 4.12), the magnitudes of the monthly littoral drift show slightly larger values compared to Calicut beach. This could be related to the increase in width of the surf zone due to the sloping nature of the beach. Here the drift direction shows a typical monsoonal trend, ie. southerly during south-west monsoon and northerly during the other seasons. Along this beach, maximum southerly drift is observed during September with a magnitude of 0.78 X 10^5 m^3 and maximum northerly drift of 1.21 X 10^5 during the north-east monsoon (November). Annual net transport along the beach is towards north with a magnitude 0.19 X 10^6 m^3.

At Andhakaranazhi beach, (Fig. 4.13), the monthly transport shows southerly drift during south-west monsoon months with a maximum of 1.11 X 10^5 m^3 in July. Subsequently

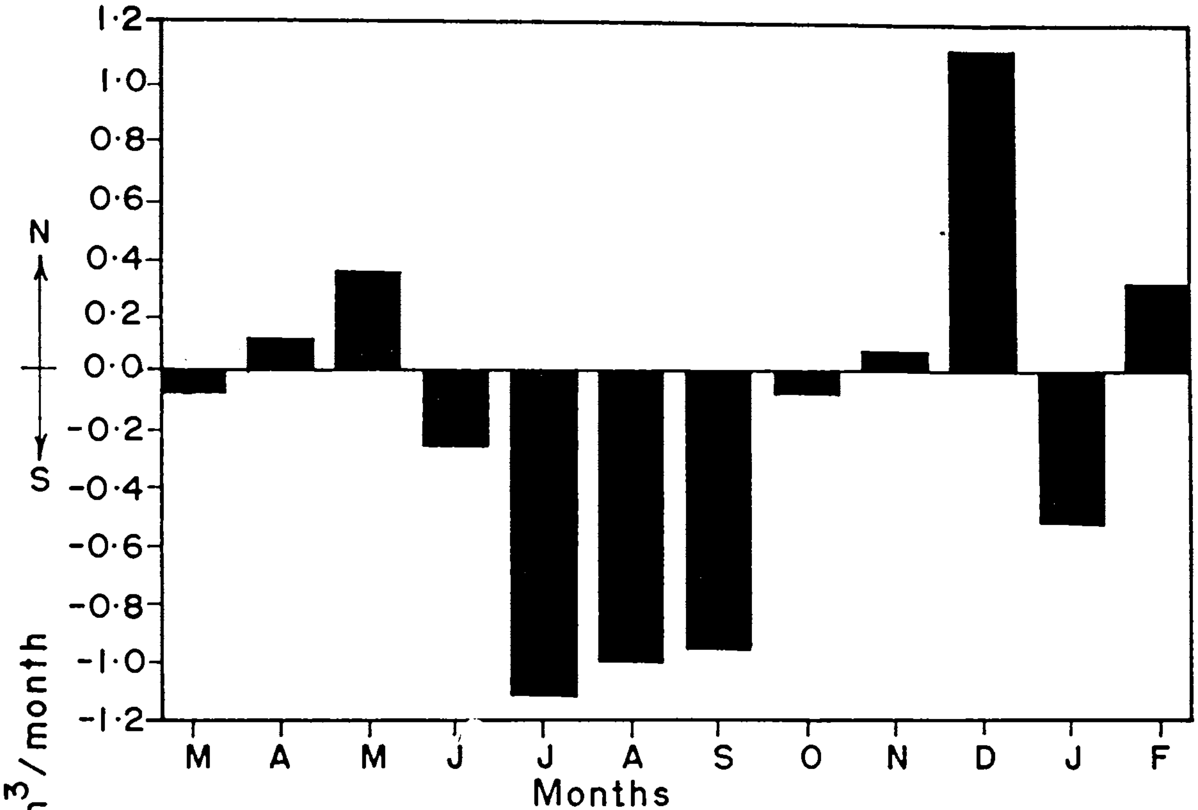


Fig. 4.13. Monthly surfzone drift at Andhakaranazhi

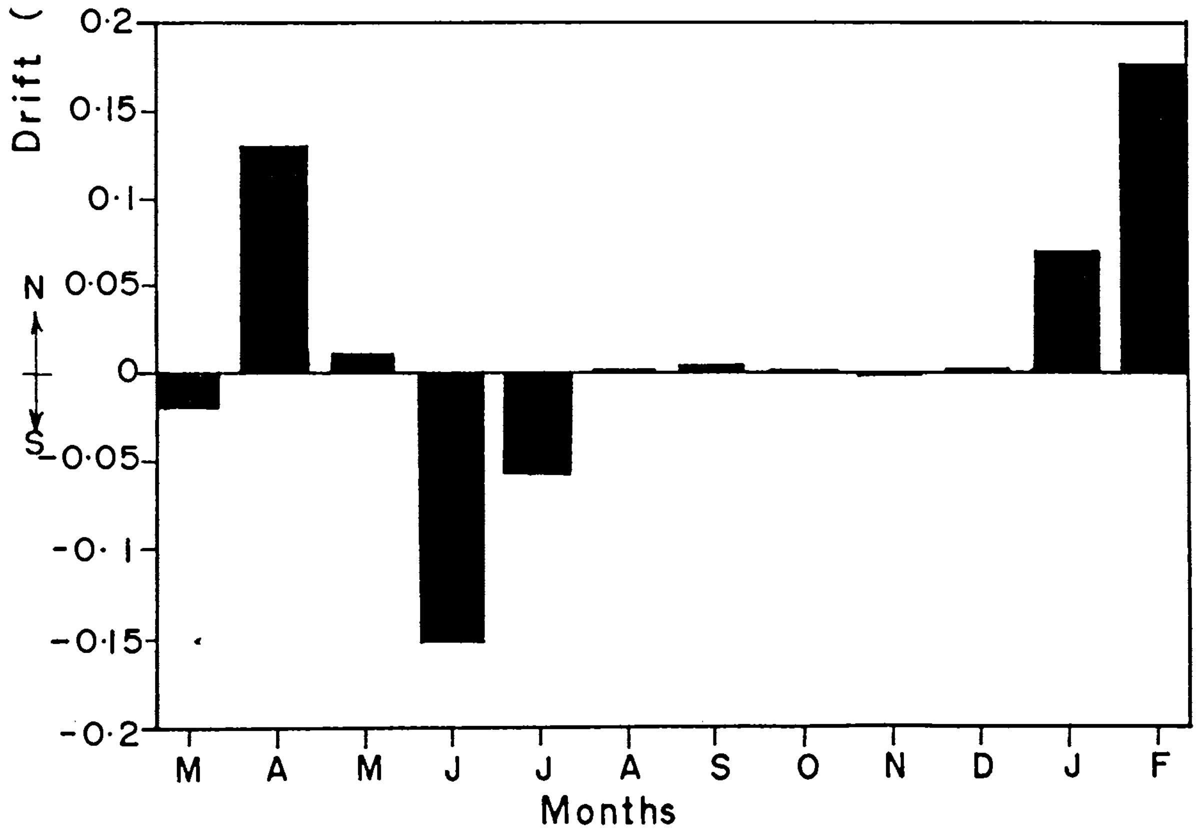


Fig. 4.11. Monthly surfzone drift at Alleppey

the magnitude decreases towards October. In all the other months except March and January the drift is seen towards north. Another peak value of the drift towards north is observed during the north-east monsoon season (December). Results of the earlier investigations showed similar features in this region. (Prasannakumar, 1985). The annual net drift along this stretch of the beach is southerly with magnitude of 0.2 X 10^6 m^3.

Monthly drift values estimated for the Alleppey beach (Fig. 4.14), show southerly drift with low magnitudes during south-west monsoon season. These low values may be due to the occurrence of the mud bank off this location which brings out calm conditions in this region. In all other months except March, the drift is northerly. A maximum northerly drift of 0.13 X 10^5 m^3 occurs in April and is followed by a reversal in direction towards south in the beginning of south-west monsoon season. The drift values are negligible during August to December (<0.005 X 10^5 m^3/month). The annual net drift value shows a northerly drift (0.016 X 10^6 m^3) which is least compared to the other beaches examined. The beach profiles (Chapter 3, Section. 3.1.2), also show the stable nature of the beach during the entire period of study.

At Quilon (Fig. 4.15), the estimated monthly drift values are higher in magnitude than the Alleppey beach. During pre and post-monsoon months, the monthly drift shows northerly trend, while during monsoon it is southerly with a

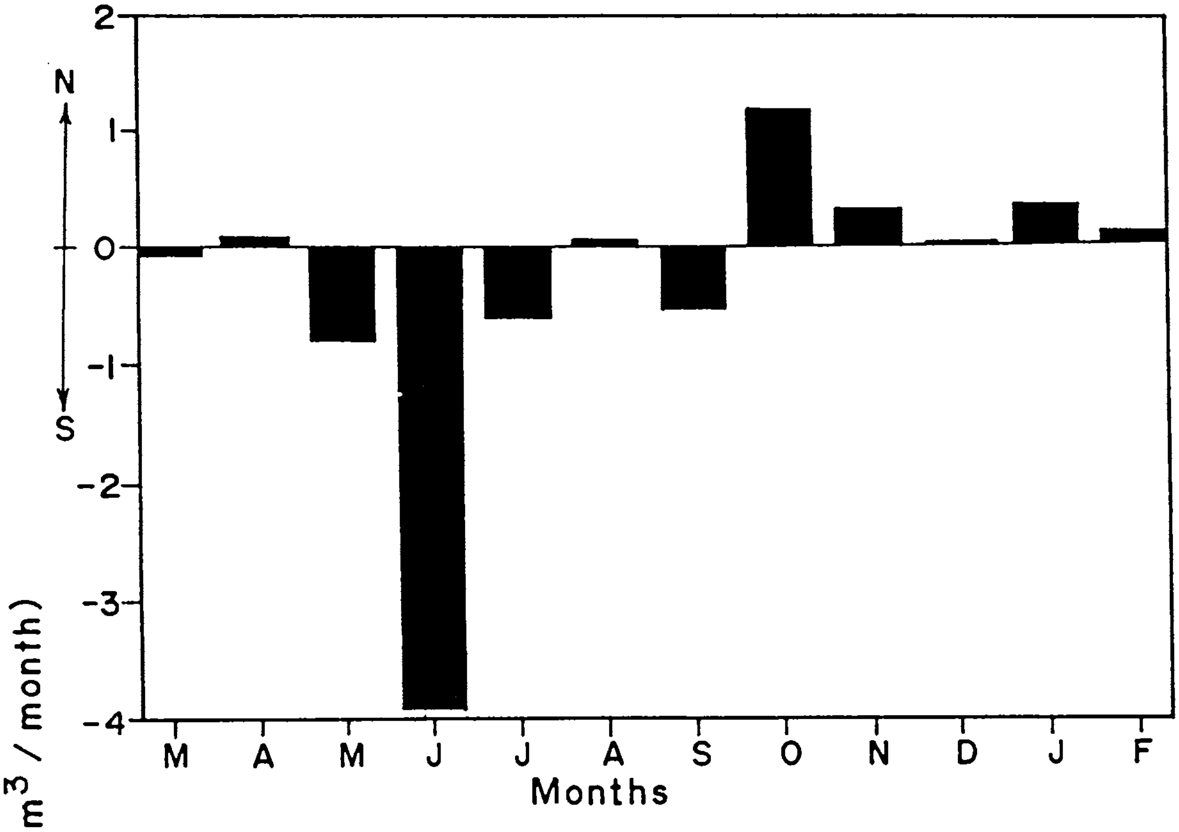


Fig. 4.15. Monthly surfzone drift at Quilon

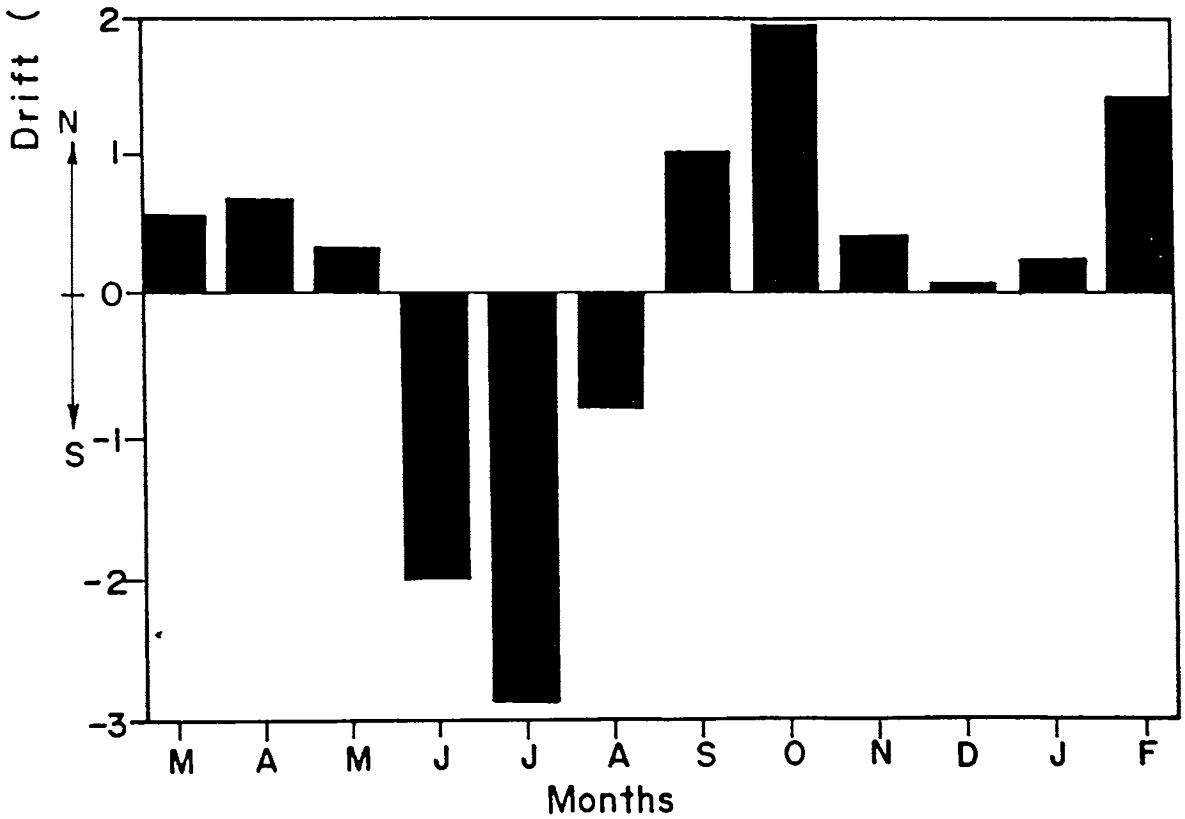


Fig. 4.16. Monthly surfzone drift at Trivandrum

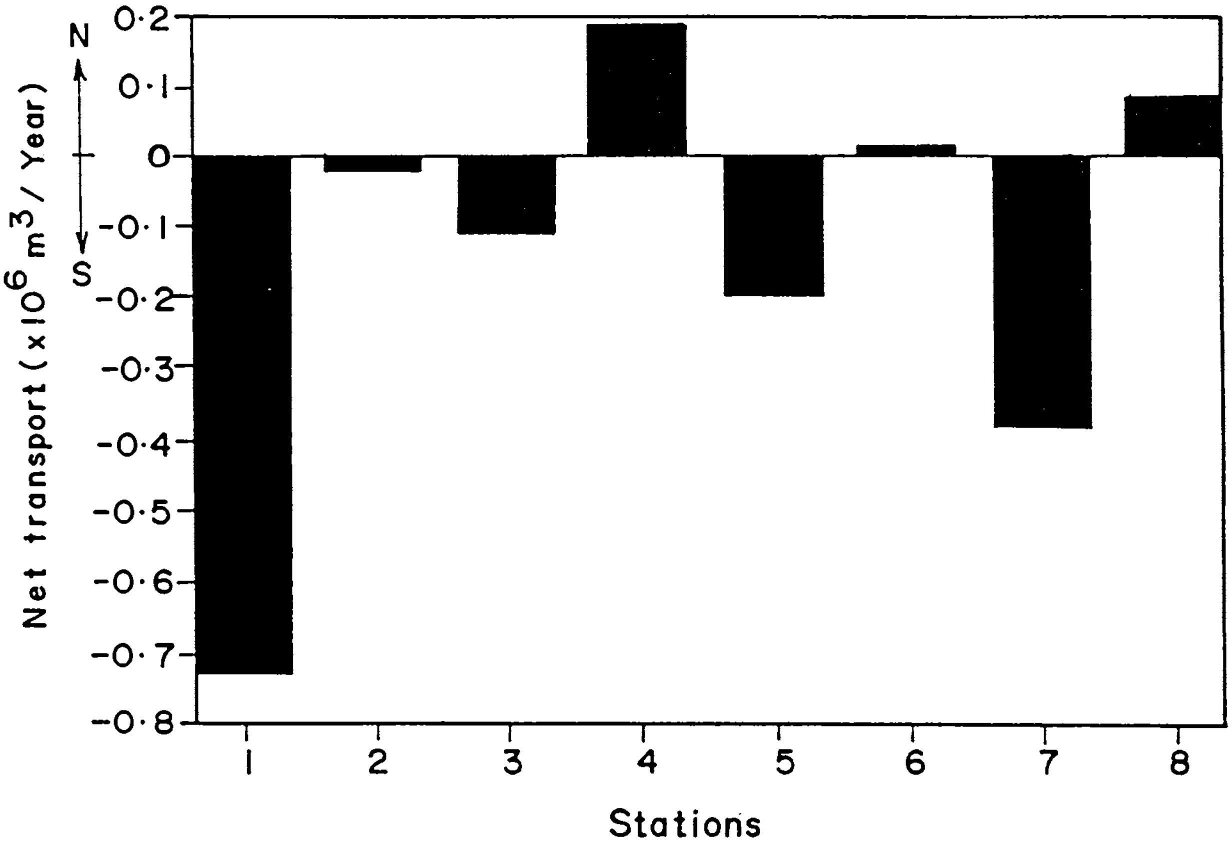


Fig. 4.17. Annual net transport for different locations

maximum value of 3.91 X 10^5 m^3 in June. The magnitude of drift values shows a decreasing trend towards September followed by a shift in direction. The lowest northerly drift value of 0.023 X 10^5 m^3 is observed during December. The annual net transport is towards south with a magnitude of 0.38 X 10^6 m^3.

The estimated value of the monthly drift for the Trivandrum beach (Fig. 4.16), shows higher magnitude than at Quilon beach. The drift is southerly only during the south-west monsoon period (May-September) and northerly in other months. The higher magnitude of the drift values along this beach is due to the high energy conditions prevailing along this beach. From the monthly and daily wave breaker height analysis (Chapter 4, Section 4.1.2), it is evident that this beach has all typical characteristics of a high energy beach. With the onset of monsoon, an increase in southerly drift value is observed and shows a maximum value in July (2.87 X 10^5 m^3). As reported from earlier studies, during the onset of south-west monsoon season, breaker directions mostly vary between 230° - 240° causing a southerly longshore current and a southerly drift. During post-monsoon months an increase in drift value is observed with a maximum of 1.93 X 10^5 m^3 in October and is northerly. The reversal in drift direction is very conspicuous in this beach. Annual net drift along this beach is towards north with a low value of 0.09 X 10^6 m^3.

CHAPTER 5

5. SUMMARY AND CONCLUSIONS

A coastline represents a dynamic, fragile physical and biological environment that is constantly changing in response to natural processes as well as human activities. It holds great attraction for man as it provides him with a variety of resources for food, construction, recreation, transportation and aesthetics. It also provides a natural protective barrier for inland areas against violent storms as well as daily or seasonal attacks by wind and waves. For many years, studies of coastal processes and landforms were attempted to gain a better understanding of the complex interaction between land, air and water.

The nature and behavior of a coastal system depend on the character, frequency and intensity of the input energy and on the configuration and composition of the subaquous and subaerial boundaries. Regional and local scale variations in coastal dynamic regimes and resultant morphologies reflect the complex mutual interactions between these energy inputs and boundary configurations.

Beach dynamics of the Kerala coast has been studied to delineate the physical processes along the different types of beaches representing the open coast beaches, beaches with headlands, barrier types, beaches exposed to high and low energy environments and beaches protected by the occurrence of mudbanks. Each type has been viewed as a representative entity for estimating different coastal processes.

The high energy beach at Kasargod, shows maximum variability in the foreshore region. The E.O.F analysis as well as the beach volume changes show that the beach exhibits cyclic episodes of erosion and accretion in response to the monsoon and fair weather seasons. The storage volume of the beach is maximum (765 m^3/m) at the beginning of the study, during March 1990 and shows the least storage volume (704 m^3/m) in September 1990 when it is subjected to maximum erosion. However the erosion to which the beach is subjected to, occurs in three phases. After the cessation of south-west monsoon, the beach builds up gradually. By the end of the study period (February 1991), the beach regains to only 738 m^3/m in storage volume. The mean grain size of the sediment sample, collected from the low water line sample of Kasargod beach, shows that it belongs to coarser grade sand size class, moderately sorted and negatively skewed. Coarsest material occurs during August, coinciding with the erosion during the south-west monsoon period. The skewness is directly related to the erosional/accretional pattern of the beach (King, 1972). The negative skewness values observed most of the time, indicates the erosional phase of the beach. The symmetrical skewness seen during September to November indicates the accretional phase of the beach. Monthly littoral drift values show that the drift values are maximum compared to the other locations and are oscillatory in nature. The maximum southerly drift is about 2.95 X 10^5 m^3 during June. Incidentally, this is the time when the beach starts eroding considerably. This maximum drift is brought about by the prevailing high wave energy at this location associated with the south-west monsoon which is also evident from the LEO data discussed in (Section 4.1.2). The magnitude of the annual net drift is 0.73 X 10^6 m^3 and is towards north.

The Payyambalam beach at Cannanore in the vicinity of Ezhimala promontory is a straight long beach with seawall at the backshore. The beach exhibits typical monsoon response by way of erosion during both south-west (June-July) and north-east (October) monsoons. Maximum erosion occurs during July when the storage volume is least (412.5 m^3/m). Over the period of one year the beach almost regained its initial storage volume of 442 m^3/m by March 1990. In general, though the beach has undergone seasonal erosion during monsoon, it receives its lost material thereby maintaining an equilibrium state. For most of the time, the beach sediment is in the medium sand class. The moderately well sorted sediments with negatively skewed occurring during the south-west monsoon indicates the erosion and the symmetrical skewness with poor sorting during the fair weather season indicates building up. The monthly littoral drift values show a maximum southerly direction during August (1.38 X 10^5 m^3) when it is southerly. Annual net littoral drift is towards south with a magnitude of 0.019 X 10^6 m^3.

Konad beach at Calicut, sheltered by the mud bank is wide and sandy with least variability compared to the rest of the beaches. This beach also responds, though to a lesser degree, to the south-west and north-east monsoons undergoing erosion both during July and October. Accordingly the changes in storage volume also are minimal to the tune of 10 m^3/m during the south-west monsoon and 5 m^3/m during the north-east monsoon. The beach regains it's initial storage volume of 1302 m^3/m (April 1990) by the end of January 1991. The stable nature of the beach is very clearly depicted in the E.O.F analysis also. The mean size of the beach sediment belongs to medium sand class without much variations over this period showing the low energy environment. Coarser grain size class, which is highly sorted and negatively skewed shows the erosional behavior of the beach during the north-east monsoon. The low values of the medium grain size during south-west monsoon along with small volume changes are caused by the calm conditions provided by the dampening of waves under the influence of the Calicut mud bank. The breaker height distribution also confirms the results. The monthly drift at this location shows that the magnitude of the littoral drift is low compared to the other northern locations. The maximum drift occurs during March (0.76×10^5 m^3) and is southerly. The low values observed during the south west monsoon is due to the occurrence of mud bank. The minimum monthly drift value of 0.11×10^5 m^3 is observed during the north-east monsoon season (November). The annual net drift is southerly with a magnitude of 0.011×10^6 m^3 indicating the stable nature of the beach. The supply of sediments from the rivers on either side of the beach also provides stability to the beach.

The Nattika beach is an open straight beach backed by seawall well inside the backshore. The storage volume shows that the beach has maximum material in the beginning of March 1990 (548 m^3/m) with a rapid erosion during the onset of the south-west monsoon. The beach loses about 34 m^3/m of the material within two months of south-west monsoon (June and July). It takes about six months for the beach to recover its lost material reaching 544.7 m^3/m by January 1991. Then onwards the beach continues to accrede to a storage volume of 557.0 m^3/m in February 1991. In contrast to the other beaches, this beach does not show any erosion during north-east monsoon. Thus, in general, the beach shows an accretional trend over the period of study. The existence of an old seawall well behind the backshore is a good indication of the building up nature of the beach during the past years. The mean grain size shows that the beach material belongs to fine sand class during most part of the year with some exceptions during September-October when it shows medium sand. The sediment shows well sorted to moderately sorted nature with symmetrical skewness indicating the accretional trend of the beach. The monthly drift at this beach shows a southerly direction during the monsoon months with the maximum drift occurring during September (0.78×10^5 m^3/month). This beach depicts the typical monsoon sediment drift pattern. However, during November to February, the drift is towards north. In general, the monthly drift values at this beach are higher than at the Calicut beach. This may be due to the wide surf zone which causes to set more sand in motion. Annual net drift shows a northerly drift with values of 0.19×10^6 m^3.

Andhakaranazhi beach is a barrier type short beach. The storage volume shows that before the onset of south-west monsoon, the beach has a storage volume of 587 m^3/m (April) which rapidly decreases to 35 m^3/m during June under the action of high monsoonal waves. The accretion is also rapid and the beach regains its material by the end of October 1991 (582 m^3/m). The influence of the north-east monsoon also is seen in the beach volume during November-December which shows a loss of material to the tune of 7 m^3/m. However, the beach regains this material by the end of February. Thus the storage volume as well as the results of the E.O.F analysis shows the near-stable nature of the beach during this period. The average grain size shows the presence of medium grade sand. Beach shows fine sand class till the end of July. The presence of medium sand during north-east monsoon indicates the eroding phase of the beach. The sediments show a well sorted nature during the south-west monsoon period and poorly sorted nature during north-east monsoon. The symmetrically skewed nature of the sediment during most of the time shows almost stable nature of the beach. The monthly littoral drift values along this beach also shows a monsoon trend of southerly drift with a maximum value of 1.11×10^5 m^3 in

June. In all the other months, except during March and January and monsoon months, the drift is towards north. Annual net drift shows a southerly drift with a magnitude $0.2 \times 10^6 \ m^3$.

The Alleppey beach is a wide and long beach with the sheltering provided by the mud bank during the south-west monsoon period. During the period of survey Alleppey mud bank was active with calm waters and heavy load of mud in suspension. (Joseph, 1992). The storage volume shows that the beach continuously builds from it's March level of 895 m^3/m to 942 m^3/m during August. Thus about 47 m^3/m of material is accreded during these six months. The north-east monsoon effect is seen during October when the beach volume reduces by about 15 m^3/m. The occurrence of mud bank in this region during the south-west monsoon dampens the high monsoonal waves and makes this nearshore very calm. The southerly drift from the beaches north of Alleppey gets trapped by the mud bank leading to the observed accretion. The E.O.F analysis and grain size composition also show the accretional nature of the beach. The poorly sorted distribution along with negative skewness during the north-east monsoon indicates an erosional trend. However the symmetrical skewness during the rest of the period indicates accretional nature of the beach. The monthly littoral drift shows lesser values even during the peak monsoon months substanciating the results obtained from beach volume and grain size studies. It shows the low energy environment prevailing over this location brought in by the mud bank. The maximum northerly drift of 0.13 X 10^5 m^3 is observed during April. Subsequently the drift shows southerly direction during the south-west monsoon season. During the north-east monsoon season the drift becomes negligible with a value of 0.0011 X 10^5 m^3/month during November. The annual net littoral drift (0.016 X 10^6 m^3/year) is the least and is directed northerly.

The Quilon beach, south of Thankasseri headland, is a narrow beach. During the south-west monsoon, the beach erodes rapidly loosing about 54 m^3/m of the beach material from it's initial storage volume of 425 m^3/m in April 1990. By the end of the survey the beach has only 404 m^3/m of storage volume, indicating a net deficiency of about 21 m^3/m of the material. Thus the beach at Quilon undergoes erosion as also evident from the E.O.F analysis. The mean grain size shows the presence of coarser sand most of the time. It shows coarsest sediment during the south west and north-east monsoon seasons with poor sorting. The intensive sand mining activity, for black sand, along this stretch of the beach could be a factor affecting the long-term equilibrium of this beach. The littoral drift shows higher values compared to Alleppey beach with a maximum drift of 3.91 X 10^5 m^3 towards south in June. It shows a typical monsoonal character with southerly drift during south-west monsoon period and northerly drift during rest of the year. The annual net drift is southerly with a magnitude of 0.38 X 10^6 m^3.

Shankhumukham beach at Trivandrum is an open beach exposed to high wave energy. This beach shows typical monsoon response by way of erosion during June-July. From the storage volume, it is seen that the beach loses 67 m^3/m of the material during monsoon period when the beach is subjected to very high wave energy environment. The erosion is rapid while the accretion is gradual and steady taking about 4 to 5 months to recover the material lost during the south-west monsoon. By the end of the survey the beach shows considerable building up (478 m^3/m) compared to its initial volume of 466 m^3/m before the onset of monsoon. The average grain size shows the presence of medium grade sand during the entire study period. Sorting value shows moderately well sorted material to moderately sorted during south-west monsoon. The sediment is symmetrically skewed throughout the entire period which shows that the beach accretes during the survey period. The monthly littoral drift values show comparatively higher magnitudes compared to the beaches at central part, which is due to the prevailing high energy environment at this location. The beach show monsoonal behaviour of southerly drift with a maximum value of 2.87×10^5 m^3 in July. Annual net drift along this beach was northerly with a magnitude of 0.09×10^6 m^3. The the volume changes as obtained from the storage volume studies also indicate this.

It is observed that the wave heights are high at some locations and lower at other locations along the coastline of

Kerala. This kind of wave height distribution is associated with the formation of zones of convergence of wave energy at locations with higher waves and zones of divergence of wave energy at locations with lower wave heights.

It is interesting to note that the wave convergence at Vypin is a permanent feature which occurs for waves from all directions.

The divergence of wave energy seen south of Ezhimala promontory for 270^{o} and 8 S. The divergence at Cannanore, Badagara and Mahe is caused by the presence of Ezhimala promontory The divergence at Quilon and Varkallai for wave direction 290^{o} and period 8 S is due to the presence of headland at Thankasseri .

The presentation of refraction coefficient and net wave height graphs can be used as monograms for evaluating the wave height for different deep water wave heights along the Kerala coast.

The Kasargod beach, shows an eroding nature over the period of study and indicates the monsoon response of erosion during both the monsoons. The Payyambalam beach at Cannanore, in the vicinity of the Ezhimala promontory shows an overall stable nature. The presence of promontory seems to modify any waves approaching the coast from north and protect the beach. This beach responds to both the monsoons with erosion and with accretion during the other months. The erosion seen at Kasargod may be in part due to the effect of promontory which prevents the northerly drift. Hence the beach at Kasargod gets only sediments which bypass the promontory. The high littoral drift value at Kasargod is indicative of larger sediment supply brought in by the high wave energy and the influx of sediments owing to the existence of rivers draining along this coast. The Konad beach at Calicut shows the least variability during the period of study. The drift values are also very low here, showing minimum variability. This beach shows monsoonal responses to a very lesser degree. Nattika beach shows monsoonal erosion during south-west monsoon and accretion during north-east monsoon. Andhakaranazhi beach shows stable nature and it shows erosion only during south-west monsoon and an accretional trend during the north-east monsoon. Alleppey beach shows accreding trend even during the south west monsoon with slight erosion during north-east monsoon season. This beach shows a typical mud bank response with accretion during the south-west monsoon season and a slight erosion during the north-east monsoon. Quilon beach shows typical monsoonal erosion during both the monsoons. Trivandrum beach, exposed to high energy environment shows high variability of beach volume. The beach responds well with erosion during south-west monsoon and during the north-east monsoon it shows a strong accretional trend.

The beach variability of the northern and southern beaches are maximum as compared to the central beaches because the former are exposed to high wave energy and the latter are either protected by mud banks or are low energy beaches. The northern beaches show northerly net drift while the central beaches show southerly drift. The southerly beaches show an oscillatory type drift characteristics.

The temporal distribution of the third eigen function depicts the temporal fluctuations of the positions of the low water mark. The lowest positive peak of the V3 curve coincides with the minimum proximity of the position of the low water line from the bench mark and the lowest negative value coincided with the maximum distance of the low water line from bench mark, which reflects the erosional and depositional phases respectively. This temporal variability may be attributed to the spatial variability of the interplay between locally generated winds, waves, tides, currents and the bottom topography.

Four different types of relations were tested for the monthly data sets of storage volume against the corresponding drift values.

1. $Y = -126.459075\ X + 736.228955$ (r=0.29,Variability=0.08)
2. $Y = -71.30008\ \mathrm{LOG}(X) + 550.64295$ (r=0.45,Variability=0.20)
3. $Y = 676.65959\ e^{-0.175061\ X}$ (r=0.30,Variability=0.09)
4. $Y = 525.140731\ X^{-.096641}$ (r=0.46,Variability=0.21)

Of these, $Y = 525.140731\ X^{-.096641}$ (Fig. 5.1), explains comparatively a better amount of variability. A major part of the variability remains unexplained which requires detailed investigations as suggested below.

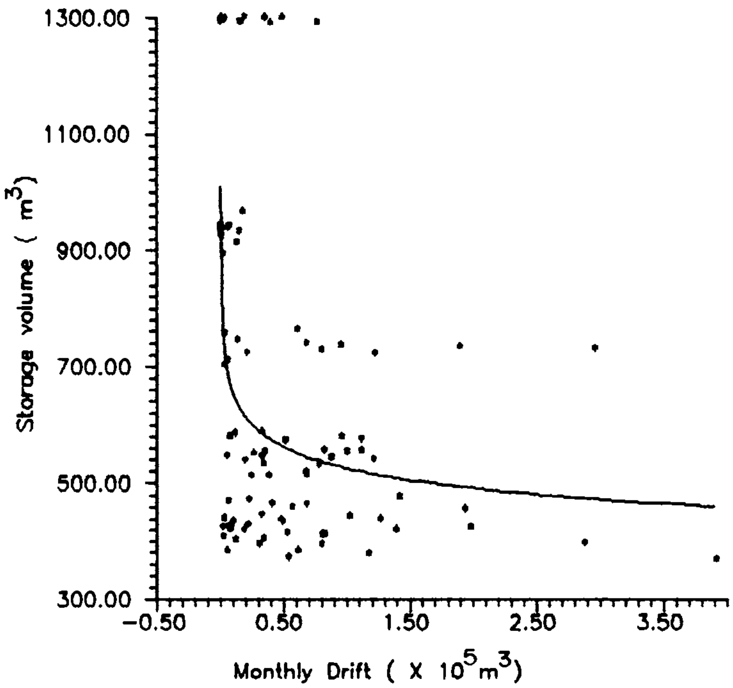


Fig. 5.1. Relation between monthly drift and storage volume

5.1. Scope for future study

Though the studies on the beach changes along this coast have been conducted, it is still necessary to monitor the beaches in this region continuously over an extended period of time with an increased number of close study locations, in order to establish a more reliable quantitative predictive model for the Kerala coast. The environmental and economical significance of an improved quantitative predictive model justifies the improvement of substantial future field programs. Further studies are needed to establish the estimation of effective nearshore transport of sediments using Littoral Environmental Observation (L.E.O), under varying environmental conditions.

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APPENDIX - I

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*     NEARSHORE  WAVE  TRASFORMATION  MODEL
*     SHOALING,REFRACTION
*     LINEAR  OR  THIRD ORDER, CNOIDAL  &  SOLITARY  WAVE  THEORY.
*---------------------------------------------------------------------
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE,SX
*---------------------------------------------------------------------
      CHARACTER ANS*3,THEORY*6
*---------------------------------------------------------------------
      DO 90 K=1,500
      DO 90 L=1,400
      H(K,L)=0
   90 C(K,L)=0
      DO 95 M=1,7
   95 DI(M)=0
      IFIRST=0
*-----VALUE OF CONSTANTS
      PI=3.141592653589793
      G=9.81
*-----USER INTERACTIVE INPUTS
      OPEN(30,FILE='KER:DATA',ACCESS='SEQUENTIAL')
      OPEN(15,FILE='CELIRITY:SIX',ACCESS='SEQUENTIAL')
*-----COMPUTING TIME INTERVAL IN SECONDS
      READ(30,*)DT
*-----GIVE SLOPE WHEN PARALLEL CONTOURS ARE ASSUMED
      READ (30,*)SLOPE
      SLOPE=1/SLOPE
*-----ENTER SCALE OF THE MAP AS 1 METRE IS HOW MANY METRES
      READ (30,*)SCALE
*-----TOTAL GRID POINTS IN X & Y AXIS
      READ (30,*)IXEND
      XEND=IXEND
      READ (30,*)JYEND
      YEND=JYEND
*-----SELECT DESIRED WAVE THEORY
      READ (30,*)THEORY
      IF(THEORY.EQ.'LINEAR')JTHERY=1
      IF(THEORY.EQ.'HIGHER')JTHERY=2
*-----OPT AT WHICH DEPTH THE COMPUTATION TO STOP
      READ (30,*)ANS
      IF(ANS.EQ.'Y')THEN
      READ(30,*)DEPINT
      ENDIF
      IF(ANS.EQ.'N')THEN
      READ(30,*)DEPINT
      ENDIF
*-----ENTER H,T & CREST ANGLE
100   READ (30,*)HT
      WRITE(1,170)HT
```

```
      IF(HT.LE.0.OR.HT.GT.10)THEN
      WRITE(30,*)'  WAVE HEIGHT IS  <0  OR  >10 METRES. REENTER.'
      GOTO 100
      END IF
110   READ (30,*)T
      IF(T.LE.0.OR.T.GT.25)THEN
      WRITE(1,*)'     WAVE PERIOD IS  <5  OR  >15 SEC.REENTER '
      GOTO 110
      END IF
*-----ENTER CREST ANGLE WRT X AXIS AS ANTICLOCKWISE
120   READ (30,*)THE
*-----CONVERSION OF CREST ANGLE TO ORTHOGONAL ANGLE
      THE=90.-THE
      IF(THE.LE.0.OR.THE.GT.360)THEN
      WRITE(1,*)'     DIRECTION IS  <0  OR  >360 DEG.REENTER '
      GOTO 120
      END IF
      THE=THE*PI/180.
      TTHE=THE
*-----READING DEPTH AND COMPUTING CELERITY --------------------------
      CALL CONTUR
      CALL  CELITY
*-----USER INTERACTIVE INPUT FOR INITIAL POSITION OF ORTHOGONAL
      READ (30,*)X
      SX=X
      READ (30,*)Y
      SY=Y
*-----COMPUTING SHIFTING OF ORTHOGONAL------------------------------
      READ(30,*)XSTOP
135   SX=X
      CALL SHIFT
*-----FOR REPEATING ORTHOGONAL COMPUTATION--------------------------
      IF(SX.LT.XSTOP)THEN
      IFIRST=0
      X=SX+0.5
      Y=SY
      THE=TTHE
      GOTO 135
      ENDIF
105   CONTINUE
*-------------------------------------------------------------------
 140  FORMAT('$ TOTAL NO OF I VALUES IN X AXIS =',I5)
 150  FORMAT('$ TOTAL NO OF J VALUES IN Y AXIS =',I5)
 160  FORMAT('$      WAVE THEORY(LINEAR/HIGHER)=',6A1)
 170  FORMAT('$                    WAVE HEIGHT =',F10.4)
 180  FORMAT('$                    WAVE PERIOD =',F10.4)
 190  FORMAT('       WAVE DIRECTION IN DEGREES ')
 191  FORMAT('$(    ANGLE OF CREST WITH X AXIS)=')
 200  FORMAT(//,'$    PLOTTING ANOTHER RAY (Y/N)? =')
 230  FORMAT('$ CALCULATING AT BREAKING POINT (Y/N)=')
 240  FORMAT('$ DEPTH OF INTEREST =')
 250  FORMAT('1   ',2F8.3)
 260  FORMAT('$          SCALE IN X AXIS (1metre=',F10.2,'metres)=')
 270  FORMAT('$          SCALE IN Y AXIS (1metre= ? metres)=')
```

```
 280  FORMAT('$         SLOPE OF SEABED ( 1:',F10.2,')=')
*---------------------------------------------------------------------
      STOP
      END
*************************
      SUBROUTINE CONTUR
*************************
*-----READING CONTOUR INPUT DATA
*------
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE,SX
*------
      CHARACTER ANS*3
*------
      OPEN(10,FILE='CONTOUR:DATA',ACCESS='SEQUENTIAL')
      OPEN(20,FILE='PANREF:RES',ACCESS='SEQUENTIAL')
      READ(10,*)((H(I,J),J=1,JYEND),I=1,IXEND)
305   FORMAT(20F5.0)
      CLOSE(10)
      READ(30,*)ANS
      IF(ANS.EQ.'Y')WRITE(20,350)((H(I,J),J=1,JYEND),I=1,IXEND)
350   FORMAT(20F5.0)
      RETURN
      END

************************
      SUBROUTINE CELITY
************************

*-----COMPUTES CELERITY AT EACH POINT
*-----USING RESPECTIVE WAVE THEORIES
*------
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE,SX
*------
      DO 350 I=1,IXEND
      DO 350 J=1,JYEND
      HDEP=H(I,J)
      IF(HDEP.LT.0.1)HDEP=0.1
*------------------
      CALL VELOCITY
*------------------
      C(I,J)=CEL
350   CONTINUE
      RETURN
      END

************************
      SUBROUTINE SHIFT
************************
*-----CALCULATION OF SHIFTING OF ORTHOGONALS
```

```
*-----IN X & Y DIRECTIONS
*-----CALLING ALL SUB ROUTINES & WRITTING RESULTS OVER
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE,SX
*------
*-----CONDITION FOR STOP FOR RAY TOUCHING THE SIDES
400   IF(X.LE.1.OR.X.GE.XEND)GOTO 440
      IF(Y.LE.1.OR.Y.GE.YEND)GOTO 440
*--------------
      CALL NUDI
*--------------
*-----OPTION FOR REDUCING TIME INTERVAL IN LOWER DEPTHS
      IF(DI(1).LT.2)DT=1.
      IF(DI(1).LT.5)DT=5.
      IF(DI(1).LT.10)DT=10.
*-----CONDITION TO STOP IF RAY REACES SPECIFIED DEPTH OR ZERO DEPTH
      IF(DI(1).LT.DEPINT)GOTO 440
      IF(DI(1).LT.0.2)GOTO 440
*-----SHIFT IN X,Y & THETA(ORTHOGONAL ANGLE)
      DX=DI(2)*COS(THE)*DT
      X=X+(DX/SCALE)
      DY=DI(2)*SIN(THE)*DT
      Y=Y+(DY/SCALE)
      DTHE=(DI(3)*SIN(THE)-DI(4)*COS(THE))*DT
      THE=THE+DTHE
      HDEP=DI(1)
*------------------
      CALL VELOCITY
*------------------
      SC1=(4*PI*HL1)/SINH(4*PI*HL1)
      SC2=TANH(2*PI*HL1)*(1+SC1)
      SC=1/SC2**0.5
*----------------
      CALL RUNGIL
*----------------
*-----CONDITION TO STOP FOR BREAKING
      STEEP=HT*HL1/HDEP
      CRITER=0.142*TANH(2*PI*HL1)
      IF(STEEP.GE.CRITER)GOTO 440
      IF(HDASH.GE.(0.78*HDEP))GOTO 440
      GOTO 400
440   CONTINUE
      RETURN
      END
****************************
      SUBROUTINE RUNGIL
****************************
*-----COMPUTES REFRACTION BY RUNGE-GILL METHOD
*-----
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE,SX
```

```
*------
      DIMENSION A(4),B(4),CE(4),Q(0:4),YBET(0:4)
      REAL KCONS(4)
      DATA A/.5,.29289322,1.7071068,.16666667/
      DATA B/2,1,1,2/
      DATA CE/.5,.29289322,1.7071068,.5/
*-----CALCULATION OF COEFFICIENTS  PT & QT IN DIFFERENTIAL EQUATION
      P1=DI(3)*COS(THE)
      P2=DI(4)*SIN(THE)
      PT=-2*(P1+P2)
      Q1=DI(5)*SIN(THE)*SIN(THE)
      Q2=DI(7)*SIN(2*THE)
      Q3=DI(6)*COS(THE)*COS(THE)
      QT=CEL*(Q1-Q2+Q3)
 17   FORMAT(8F10.4)
*-----SOLUTION STARTS
      IF(IFIRST.GT.1) GOTO 500
      YBET(0)=0
      BETA=1
      Q(0)=0
*-----ITERATION FOR K1,K2,K3 &K4 CONSTANTS IN GILL METHOD
500   DO 510 J=1,4
      KCONS(J)=-PT*YBET(J-1)-QT*BETA
      BRAC=A(J)*(KCONS(J)-B(J)*Q(J-1))
      YBET(J)=YBET(J-1)+DT*BRAC
      Q(J)=Q(J-1)+3*BRAC-CE(J)*KCONS(J)
510   CONTINUE
      YBET(0)=YBET(4)
      Q(0)=Q(4)
      BETA=YBET(4)*DT+BETA
*-------------------------REFRACTION
      RC=1/(BETA**0.5)
      ANGTHE=90-(THE*(180/PI))
*-------------------------
      IFIRST=IFIRST+1
*-----TOTAL TRANFORMATION AND NET WAVE HEIGHT
      ALLC=SC*RC
      HDASH=HT*ALLC
      HLNOT=HDEP/(1.56*T*T)
*-----WRITTING FINAL OUTPUT
      IF(DI(1).LT.DEPINT)GOTO 440
      IF(X.LE.1.OR.X.GE.XEND)GOTO 440
      IF(Y.LE.1.OR.Y.GE.YEND)GOTO 440
      STEEP=HT*HL1/HDEP
      CRITER=0.142*TANH(2*PI*HL1)
      IF(STEEP.GE.CRITER)GOTO 440
      IF(HDASH.GE.(0.78*HDEP))GOTO 440
      GOTO 400
410   WRITE(20,*)'----------RAY REACHED THE SIDE-------------'
      GOTO 440
420   WRITE(20,*)'----------RAY REACHED THE SHORE------------'
      GOTO 440
430   WRITE(20,450)HDEP
450   FORMAT('DEPTH= ',F6.3,'M   ',
     +       '---RAY STOPS AS THE WAVE STEEPENS & BREAKS--')
```

```
440   WRITE(1,520)SX,X,Y,ANGTHE,SC,RC,ALLC,HDASH
460   WRITE(20,*)'----------WAVE BREAKES  ------------'
440   WRITE(20,520)SX,X,Y,ANGTHE,SC,RC,ALLC,HDASH
520   FORMAT(3F8.3,F6.1,2F8.4,F7.3)
400   CONTINUE
      RETURN
      END

      SUBROUTINE NUDI
*-----INTERPOLATION OF DEPTH FOR A POINT INSIDE THE GRID
*-----FINITE DIFFERENTIATION OF CELERITY IN X AND Y
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE,SCALE
      COR=0.0000001
      I=X+COR
      J=Y+COR
*-----DEPTH INTERPOLATION
      HA=H(I,J)
      HB=H(I+1,J)
      HC=H(I,J+1)
      HD=H(I+1,J+1)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(1)=HG
*-----CELERITY INTERPOLATION
      HA=C(I,J)
      HB=C(I+1,J)
      HC=C(I,J+1)
      HD=C(I+1,J+1)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(2)=HG
*-----DIFFERENTIAN OF CELERITY---------------------------------------
*-----DC/DX
      IF(J.EQ.1)THEN
      HA=0
      HB=0
      ELSE
      HA=(C(I+1,J)-C(I-1,J))/(2*SCALE)
      HB=(C(I+2,J)-C(I,J))/(2*SCALE)
      END IF
      HC=(C(I+1,J+1)-C(I-1,J+1))/(2*SCALE)
      HD=(C(I+2,J+1)-C(I,J+1))/(2*SCALE)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(3)=HG
*-----DC/DY
      IF(J.EQ.1)THEN
      HA=(C(I,2)-C(I,1))/SCALE
      HB=(C(I+1,2)-C(I+1,1))/SCALE
```

```
      ELSE
      HA=(C(I,J+1)-C(I,J-1))/(2*SCALE)
      HB=(C(I+1,J+1)-C(I+1,J-1))/(2*SCALE)
      END IF
      HC=(C(I,J+2)-C(I,J))/(2*SCALE)
      HD=(C(I+1,J+2)-C(I+1,J))/(2*SCALE)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(4)=HG
*-----D2C/DX2--SECOND ORDER DIFFERENTIATION
      IF(J.EQ.1)THEN
      HA=0
      HB=0
      ELSE
      HA=(C(I+1,J)-2*C(I,J)+C(I-1,J))/(SCALE*SCALE)
      HB=(C(I+2,J)-2*C(I+1,J)+C(I,J))/(SCALE*SCALE)
      END IF
      HC=(C(I+1,J+1)-2*C(I,J+1)+C(I-1,J+1))/(SCALE*SCALE)
      HD=(C(I+2,J+1)-2*C(I+1,J+1)+C(I,J+1))/(SCALE*SCALE)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(5)=HG
*-----D2C/DY2--SECOND ORDER DIFFERENTIATION
      IF(J.EQ.1)THEN
      HA=(C(I,2)-C(I,1))/SCALE
      HB=(C(I+1,2)-C(I+1,1))/SCALE
      ELSE
      HA=(C(I,J+1)-2*C(I,J)+C(I,J-1))/(SCALE*SCALE)
      HB=(C(I+1,J+1)-2*C(I+1,J)+C(I+1,J-1))/(SCALE*SCALE)
      END IF
      HC=(C(I,J+2)-2*C(I,J+1)+C(I,J))/(SCALE*SCALE)
      HD=(C(I+1,J+2)-2*C(I+1,J+1)+C(I+1,J))/(SCALE*SCALE)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(6)=HG
*-----D2C/DXDY--SECOND ORDER DIFFERENTIATION
      IF(J.EQ.1)THEN
      HA=(C(I+1,2)-C(I-1,2))/(4*SCALE*SCALE)
      HB=(C(I+1,2)-C(I,2))/(4*SCALE*SCALE)
      ELSE
      HA=(C(I+1,J+1)+C(I-1,J-1)-C(I-1,J+1)-C(I+1,J-1))/(4*SCALE*SCALE)
      HB=(C(I+2,J+1)+C(I,J-1)-C(I,J+1)-C(I+2,J-1))/(4*SCALE*SCALE)
      END IF
      HC=(C(I+1,J+2)+C(I-1,J)-C(I-1,J+2)-C(I+1,J))/(4*SCALE*SCALE)
      HD=(C(I+2,J+2)+C(I,J)-C(I,J+2)-C(I+2,J))/(4*SCALE*SCALE)
      HE=HA+(HB-HA)*(X-I)
      HF=HC+(HD-HC)*(X-I)
      HG=HE+(HF-HE)*(Y-J)
      DI(7)=HG
      RETURN
      END
```

```
****************************
      SUBROUTINE VELOCITY
****************************

*-----COMPUTES THE CELERITY AT A POINT USING DESIRED.WAVE THEORY
*------
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
      COMMON IFIRST,DEPINT,SLOPE.SCALE
      REAL KH,KHBYH
*------
      ELNOT=1.56*T*T
      CNOT=1.56*T
      HLNOT=HDEP/ELNOT
*-----LINEAR WAVE THEORY---------------------------------------------
      HL1=HLNOT
600   HL=HLNOT*(COSH(2*PI*HL1)/SINH(2*PI*HL1))
      HLDIF=ABS(HL1-HL)
      HL1=HL
      IF(HLDIF.GT.0.00001) GOTO 600
      KH=2*PI*HL1
      KHBYH=KH/HDEP
      CEL=CNOT*TANH(KH)
      IF(JTHERY.EQ.1)GOTO 610
      IF(JTHERY.EQ.2.AND.HLNOT.GT.0.5)GOTO 610
*-----STOKES THIRD ORDER THEORY (SPM)--------------------------------
      IF(JTHERY.EQ.2.AND.HLNOT.LT.0.5.AND.HLNOT.GT.0.2)THEN
      CEL1=((KHBYH/2)*HT)**2
      CEL2=5+2*COSH(2*KH)+2*COSH(2*KH)*COSH(2*KH)
      CEL3=8*SINH(KH)**4
      CEL4=CEL2/CEL3
      CEL5=1+CEL1*CEL4
      CEL=CEL*CEL5
      GOTO 610
      END IF
*-----CNOIDAL WAVE THEORY (SVENDSEN)---------------------------------
      IF(JTHERY.EQ.2.AND.HLNOT.LE.0.2.AND.HLNOT.GT.0.02)THEN
      CALL CNODAL
      GOTO 610
      END IF
*-----SOLITARY WAVE THEORY (SVENDSEN)--------------------------------
      IF(JTHERY.EQ.2.AND.HLNOT.LE.0.02)CEL=(G*(HT+HDEP))**0.5
 610  CONTINUE
      RETURN
      END

******************************
      SUBROUTINE CNODAL
******************************
*-----CALCULATION OF WAVE CHARACTERISTICS BY CNOIDAL WAVE THEORY
*------
      COMMON H(500,400),C(500,400),DI(7),THE,DT,HDEP,HL1,SC
      COMMON CEL,PI,G,T,X,Y,XEND,YEND,IXEND,JYEND
      COMMON HT,BETA,ELNOT,F,JTHERY,HDASH
```

```
      COMMON IFIRST,DEPINT,SLOPE,SCALE
*------
      DIMENSION ELH(0:4,17)
      DATA ((ELH(I,J),I=0,4),J=1,17)/
     +6.7,6.8,7.1,7.6,8.2,9.2,9.3,9.8,10.4,11.2,
     +11.4,11.6,12.3,13.1,14,13.5,13.9,14.7,15.7,16.7,
     +15.6,16.1,17.1,18.3,19.5,17.6,18.3,19.5,20.9,22.2,
     +19.7,20.5,21.9,23.4,24.9,21.7,22.7,24.3,26,27.6,
     +23.7,24.9,26.7,28.5,30.3,25.7,27.1,29.1,31.1,33,
     +27.8,29.3,31.4,33.6,35.7,29.8,31.5,33.8,36.1,38.4,
     +31.8,33.7,36.2,38.7,41.1,33.8,35.9,38.6,41.2,43.8,
     +35.8,38.1,40.9,43.8,46.5,37.8,40.3,43.3,46.3,49.2,
     +39.9,42.5,45.7,48.8,51.9/
*------
      HTH=HT/HDEP
      TGH=T*((G/HDEP)**0.5)
      IF(HTH.GT.0.8.OR.TGH.LT.8.OR.TGH.GT.40)GOTO 700
      XX=HTH/0.2
      YY=(TGH/2)-3
      I=XX
      J=YY
      HA=ELH(I,J)
      HB=ELH(I+1,J)
      HC=ELH(I,J+1)
      HD=ELH(I+1,J+1)
      HE=HA+(HB-HA)*(XX-I)
      HF=HC+(HD-HC)*(XX-I)
      HG=HE+(HF-HE)*(YY-J)
      ELBYH=HG
      HL1=1/ELBYH
      CEL=ELBYH*HDEP/T
700   CONTINUE
      RETURN
      END
```

— G5305 —