Studies on the Physical Aspects of the Mud Banks along the Kerala Coast

with special reference to the Purakad Mud Bank

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CONTENTS

PREFACE

This thesis presents the results of the studies carried out on the physical aspects of the mud banks along the Kerala coast with special reference to the mud bank at Purakad. The mud banks of the Kerala coast not only influence the socio-economic life of the fishermen community of Kerala, by way of providing them calm fishing grounds during the monsoon season, when the sea is otherwise rough and inaccessible of their frail crafts, but also decide the stability of Kerala's beaches. In the present work an attempt has been made to obtain a complete picture of the various physical processes at work in the mud bank formations.

In the first Chapter the mud bank formations at various localities along the Kerala coast have been discussed. A discussion on the general geomorphology of the Kerala coast and of the inshore sea bottom, a brief survey of the previous works and the scope of the present work are also presented in the same Chapter. Chapter II deals with the hydrography of the Purakad mud bank region. The distribution and seasonal variation of suspended matter in the Purakad mud bank during 1972-73 are presented in Chapter III. Chapter IV describes laboratory experiments conducted to determine the effect of salinity on the flocculation and settlement of suspended mud in the mud bank regions and discusses the influence of salinity on the stability and longevity of the mud banks. Chapter V deals with the characteristics of the sea bottom and the physical properties of the bottom mud of the mud bank region. The calmness of the mud banks and the wave refraction and alongshore currents in the region of the mud bank are discussed in Chapter VI. The summary and final conclusions are presented in Chapter VII.

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C E R T I F I C A T E

I hereby certify that this thesis is a bonafide record of work of Sri P. Gopalakrishna Kurup, M. Sc., carried out by him under my supervision in the Physical Oceanography Division of the National Institute of Oceanography and that no part thereof has been presented for any other degree.

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D E C L A R A T I O N

I hereby declare that the work described in this thesis has been carried out entirely by me in the Physical Oceanography Unit, Regional Centre of the National Institute of Oceanography (Council of Scientific and Industrial Research), Cochin during the period 1969 - 1973 and further that it has not been submitted either wholly or in part by me to any University or Institution for the award of any Degree or Diploma.

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CHAPTER I

INTRODUCTION

CHAPTER I

INTRODUCTION

1. The mud banks of the Kerala coast

The patches of calm, turbid water with high load of suspended sediment, appearing close to the shore along the Kerala coast during the south-west monsoon season, are known as mud banks. The mud bank formations not only influence the socio-economic life of the fishermen community of Kerala, by way of providing them calm fishing grounds during the monsoon season, when the sea is otherwise rough and inaccessible for their frail crafts, but also influence the shoreline changes along the coast. Acting as dampers to waves, the mud banks protect portions of the beach from erosion and also help in trapping sediments from either side facilitating the growth of the adjoining beach.

The formation of the mud banks at definite localities along the Kerala coast between Quilon and Cannanore, a distance of about 270 km, is an annual phenomenon. They appear, in general, during the south-west monsoon season, i.e., during the period June to September.

The mud bank is popularly known as the 'Chakara', literally meaning dead or quiet land. It is also called 'Kotta Vellam' in Malayalam meaning dirty or muddy waters. Mud banks have also been referred to as 'mud bays' or 'mud flats'. Navigators have often qualified the mud banks as 'calm water anchorages'.

The term 'mud bank' will be used in the present thesis. The word 'bank' has its secondary sense in this context, as "a shallow area consisting of shifting forms of silt, sand, mud, gravel, etc., to be used with a qualifying word such as 'sand bank', 'gravel bank', etc." (Baker, et al. 1966; Allen, 1972).

2. Early literature

The earliest known record of the existance of the mud banks on the Kerala coast, dates as far back as 1678, in an extract from Alexander Hamilton's account of the East Indies which is contained in Pinkerton's "Collections of Voyages and Travels", given in the Travancore Administration Report of 1860. "The mud bay" Hamilton wrote, "is a place that, I believe, few can parallel in the world. It lies on the shore of St. Andrea*, about half a league out in the sea, and is open to the wide

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* St. Andrea is situated about 6 miles south of Alleppey

ocean and has neither island nor bank to break off the force of the billows, which come rolling with great violence on all other parts of the coast, in the south-west monsoons, but on this bank, lose themselves in a moment, and ships lie on it, as secure as in the best harbour, without motion or disturbance".

"The History of Kerala" (Padmanabha Menon, 1924) contains extracts of some early records on the mud banks by the Dutch Admiral Stavorinus (1777) and Captain Heber Drury ("Notes on an Excursion along the Travancore Backwater", 1858). Captain Drury described the mud bank in these terms: "Undoubtedly the greatest advantage of Alleppey as an emporium arises from the singular natural backwater formed in the open roadstead, and which consists of a long and wide bank of mud, the effect of which is so completely to break the force of waves, that large vessels in the stormiest weather can securely anchor in the open roads, where the water is as calm as a mill pond".

Early records show descriptions of the Alleppey and Narakkal mud banks by the following persons among others: Captain Cope ("A New History of the East Indies", 1775), Maltby (1860), Crawford (1860), John Castor (1861), J. J. Franklin (1861), Francis Day (1864), J. Mitchell

(1864), W. King (1881), John Rhode (1886), Philip Lake (1890), J. E. Winckle (1892) and G. H. Davey (1928, 1937). The two volumes of "History of Mud Banks" published by R. C. Bristow in 1938 contain relevant portions from all these records. The articles are mostly qualitative descriptions of the mud banks and are only of historical interest now. They, nevertheless, brought forward some hypothesis about the formation of the mud banks which might have been helpful for future investigations. These volumes compiled by Bristow consolidated all the available informations on the mud banks upto 1938 and threw some light on the origin, movement and dissipation of the mud banks. Bristow also initiated the first scientific investigation on the problem of the mud bank formation. The results of these investigations are given in the report by Du Cane, et al (1938).

3. Recent Studies

Recent studies on the mud banks include the hydrographic investigations conducted by George (1953) and Seshappa and Jayaraman (1956) in the region of the mud bank at Calicut, the hydrographic studies of the coastal waters off the Malabar coast by Ramasastry and Myrland (1959), the studies on the Narakkal mud bank by Damodaran and Hridayanathan (1966) and the studies on the texture of the bottom sediments of the Narakkal mud bank by Dora, et al (1968). Seshappa (1953a, 1953b) has studied some of the chemical and biological aspects of the bottom mud of the mud banks. A critical review of the existing knowledge on the physical aspects of the mud banks was made by the author (Kurup, 1969) and since then, Varma and Kurup (1969) have made some studies on the formation of the mud banks, Reddy and Varadachari (1972) have studied the wave refraction in relation to sediment movement along the Kerala coast and Kurup (1972) has made some observations on the movement of the mud banks. Damodaran (1973) made a detailed study of the benthos of the mud banks.

4. Locations of mud banks

The mud banks have been reported to have appeared at different places along the west coast of Kerala between Cannanore and Quilon. There are about twenty places where, according to available records, mud banks have appeared some time or the other in the past. Of these the most famous and well-marked are the mud bank north of Cochin (the Narakkal mud bank) and the one south of Alleppey (the Purakad mud bank). These two mud banks have appeared almost every year. Reports are available regarding the formation of mud banks at the following places, since 1835, during the years noted against them:

Cannanore	...	1949, 50
Mahe	...	1949, 50, 51, 61
Pantalayani (Kollam)	...	1938, 49, 50, 61
Calicut	...	1937, 50, 51, 61, 62, 66, 67, 68
Beypore	...	1937
Veliyangod	...	1938, 67
Chetwai	...	1949, 50
Nattika	...	1968, 69, 70
Vadanappally	...	1951, 61
Cranganore (north of river mouth)	...	1949, 61, 62
Cranganore (south of river mouth)	...	1835, 65 1938, 49, 50
Narakkal	...	1939, 61, 62, 65, 66, 67, 68, 69, 70, 71, 72, 73
Cochin (south of estuarine mouth)	...	1966, 71, 72
Shertallai	...	1938, 49, 61
Alleppey	...	1885, 90, 1938, 49
Ambalapuzha	...	1961, 65, 66, 67, 68
Purakad	...	1949, 66, 69, 70, 71, 72, 73
Trikunnapuzha	...	1898, 1902, 61
Kayamkulam	...	1949

The locations of these mud banks during 1835 to 1973 are shown in Fig. 1.

5. Physiography of the mud banks

The mud banks are found close to the shore and extend more or less in a semi-circular shape towards the sea. The seaward extent of the bank is usually the 6 fm line, at a distance of about 5 km from the shore. The alongshore stretch varies from about 3 km to 6 km. From the shore, the mud bank can easily be distinguished by the absence of waves while heavy rollers break upon the shore north and south of the bank. Separating the calm region of the mud bank from the wavy surface of the monsoon sea, is a transition zone where moderate swells can be observed. Damodaran and Hridayanathan (1966) reported the formation of two mud banks side by side at Purakad during June, 1966 which merged into one by August. Shepard (1973) is of the opinion that the formation of mud banks is a unique phenomenon on the Kerala coast.

Calmness and high turbidity are the apparent features of the mud banks. While W. King in 1881 (Bristow, 1938) attributed the damping of waves in the mud bank region to the presence of oil in the mud, Keen and Russel (Du Cane, et al. 1938) attributed the calming effect to the mud itself. The generally accepted view is that the mud, when in suspension, increases the ratio of the viscosity of the medium to its density and causes viscous damping of waves. As early as 1860, Leiutenant Taylor of the Royal Navy explained the calmness of the mud bank as due to "the soft mud at the bottom which when stirred up by the heavy swell from seaward, so deadens the activity of waves as to render the shoreline free from surf" (Records of the Geological Society, Vol. XVII, p. 21). During the monsoon months, when the wind force reaches 7 Beaufort or more, the mud bank regions remains very calm. The process of damping of waves in the mud bank region will be discussed in greater detail in Chapter VI.

6. The coast and the sea bed

The edge of the continental shelf on the western coast of India is remarkably straight and is believed to have originated as a result of faulting during late Pliocene (Krishnan, 1968). The coastline between Quilon and Cannanore is low and sandy, with some small rocky outcrops (Admiralty, 1961). The whole surface of this coastal belt is undulating and traversed from east to west by many rivers which near the coast, flow into numerous lagoons and backwaters. Artificial canals, in places, connect these backwaters and lagoons and form an inland line of water transport extending for about 130 km between Alleppey and Ponnani. This great backwater system is a striking feature of this part of the Kerala coast.

The width of this estuarine system, which runs parallel to the coast for about 130 km varies from about 15 km to a few hundred metres. Eight rivers - Kallada, Achencoil, Pampa, Manimala, Meenachil, Muvattupuzha, Periyar and Chalakudy rivers - rising from the Western Ghats flow into the backwater systems and the discharge increases considerably during the southwest monsoon season. The backwaters are separated from the sea by a narrow strip of land and open out into the sea at certain localities (Fig. 2).

The nearshore sea bottom of this region has sand upto several feet whereafter the substratum is composed of sand mixed with mud. These alluvial deposits continue till rock is reached at varying depths ranging between 400 and 600 m (Du Cane, et al. 1938).

On the landward side of the coast, there is a series of laterite rocks backed by alluvial deposits (King, 1882; Menon, 1974). Laterite is a claylike, soft, coloured rock and it contains alumina, iron, manganese and titanium. Laterites are the extreme end products of the weathering cycle of igneous and metamorphic rocks and are formed under oxidising conditions in areas of low or moderate topographic relief but with a minimum of erosion. The climate should be persistently warm or sub-tropical with temperatures above 25°C and rainfall exceeding evaporation (Hatch and Rastall, 1913). They are widely distributed throughout the humid tropics and subtropics. Well-known examples occur in Brazil, Jamaica, India and West Africa (Persons, 1970). On degeneration by water, laterite gives out a very soft mud in large quantities (Du Cane, et al. 1938).

Off the southern tip of India, the continental shelf is about 100 km wide and narrows to about 50 km at 11°N. Lat. The deposits of the shelf are alluvial. Between Tellicherry and Quilon, the sandy intertidal region is followed by muddy substratum just below the tidal belt. The mud itself is peculiar and not found elsewhere along the coast except in this belt. It is a very soft mud, derived from the laterites and brought down by the rivers and streams. It is this mud which, when churned up by the swells during the monsoon, comes into a soupy suspension in the mud banks (Hiranandani and Gole, 1959). The formation of the mud banks is discussed in detail elsewhere in this Chapter. Du Cane, et al (1938) states that upto 7 fm, the mud of the sea bed and that of the mud banks have common nature and origin. According to Coggin Brown (Du Cane, et al. 1938), the chemical compositions of the mud of the mud bank and of the laterite rocks are also similar. The proportions of $Si\ O_2 : Al_2O_3 : Fe_2O_3$ in the laterite and the mud of the mud banks are as given below:

Laterite	3.28 :	1.00 :	0.44
Mud	3.91 :	1.00 :	0.45

The bottom contours in this region show a wavy pattern at shallow depths and further offshore they are more or less parallel. The depth contours show a shallowing in the region of the mud banks which may probably be due to the deposition of the mud on the dissipation of the mud banks. During the southwest monsoon season when the mud bank is active, the bottom mud becomes loose and remains as a highly viscous, ooze-like suspension of mud.

The mud is dark greyish green in colour, and very soft and plastic to touch. The fineness of the mud gives it an oily appearance. Seshappa (1953b) has reported that both the interstitial and absorbed inorganic phosphate values of the mud are several hundred times higher than the inorganic phosphate values of the overlying water during the pre-monsoon months. During monsoon, when the bottom mud is disturbed, it releases large quantities of phosphates (and perhaps other nutrients also) to the overlying water. The physical properties of the bottom mud of mud banks will be discussed in Chapter V.

7. Climate, winds, waves, tides and currents

The climate in this region is controlled by the two monsoons. The southwest monsoon breaks over Kerala usually during the first week of June and continues till early September. During this period, the wind blows roughly from the southwest and cloudly conditions and frequent rains are experienced. During December and January, the general wind blow is from the north-easterly direction and there are occasional thunderstorms. During February the weather is fine and March, April and May are the months when summer conditions are experienced in this area. October and November form a transition period between the two monsoons.

Winds: Between March and May, the predominant wind direction over the sea in this region changes gradually from NE to NW and then to W (Anonymous, 1966). In June, the winds tend to blow from directions between SW and W and increase in strength. By July, the wind force reaches about Beaufort 5 to 7 or more. From June to August, three quarters of all winds blow from directions between SW and W with an average force of Beaufort 5 to 7. By the end of August, a reverse series of changes take place in the predominant wind direction. The wind force also decreases. During October and November, the direction of the wind is is between NW and ENE. The winds during the northeast monsoon season are light or moderate and very rarely reach Beaufort 7.

Land and sea breezes are also experienced almost throughout the year except during the southwest monsoon season. The land breeze is well developed during December and January and decreases in strength and duration during March.

Waves: The H. M. S. O. Publication (1949) and Hogben and Lumb (1967) contain some information on the deep water wave climate over the Arabian sea. Srivatsava, et al (1968) and Srivatsava and George (1971) have prepared compilations of the visual observations on waves published in the Daily Weather Reports of the India Meteorological Department.

The predominant periods of the swell waves approaching the coastline in the region of investigation are between 5 and 11 seconds and the directions are between 247° and 315° with a maximum frequency at 270°. The heights of the swells mostly range from 0.6 m to 2.4 m. During the southwest monsoon period, the direction of approach ov waves varies between WSW and WNW.

Tides and tidal currents: The tides are semi-diurnal and have a range less than 1 m. Tidal currents are not significant except near river mouths and estuaries.

On the open coast of the Nircunnam - Purakad region, appreciable tidal currents do not occur.

Coastal currents: The surface currents in the Arabian Sea are characterised by the seasonal reversal of circulation. In the open waters of the Arabian Sea, the general circulation of the surface waters is clockwise during the southwest monsoon season and anticlockwise during the northeast monsoon season. Correspondingly, the coastal currents also show a reversal of direction. Along the coast of Kerala, during November-January, the coastal currents flows northward and by the end of January, a southward flow is established. The northerly coastal current of the northeast monsoon season is not very strong, and it seldom reaches a speed of 1 knot. During the southwest monsoon season, the coastal currents are stronger and attain speeds upto 2 knots.

8. Formation of the mud banks

The mechanisms of formation, maintenance, movement and dissipation of the mud banks are not clearly known. Various theories have been put forward to explain the formation of the mud banks. Rhode's hypothesis of 1886 (reported by Bristow, 1938) is the earliest in which the formation of the banks is attributed to a subterranean channel flow of mud from the backwaters to the sea, this flow being maintained by the hydrostatic pressure-head developed in the backwaters due to their higher water level during monsoon. Reports of 'mud volcanoes' or cones of mud and water appearing and bursting up at the surface of the mud bank at Alleppey are considered as evidence for the existence of the underground discharge of mud and water from the backwaters to the sea. Even roots and trunks of trees were reported to have been brought up by the mud volcanoes. It was argued that such subterranean mud flows must be existing at Narakkal also, but mud volcanoes do not appear there because the pressure of water in the Cochin backwater is less on account of a free opening at Cochin for the freshwater. The reliability of these reports are doubtful; the present writer has not observed any such features in any of the mud banks during the five years of his observation from 1969 to 1973.

The increase in pressure due to rise in water level in the backwaters during monsoon is insufficient to cause such an underground mud discharge. The strip of land separating the backwaters from the sea is a low-lying one and so, the maximum possible increase in water level in the lake is only about 5 ft, for, above this level water will overflow. A head of 5 ft of water will give a pressure of 2 lb/sq. inch, which is not sufficient to overcome the frictional resistances set up by solids in suspension. The water head has, therefore, little or no significance (Du Cane, et al. 1938).

Dr. Lake's analyses of the mud samples (Du Cane, et al. 1938) from the Narakkal and Alleppey mud banks and those from the backwaters have shown that the former is quite different from the latter. The mud of the mud banks is greyish, tenacious and miscible with water whereas the mud of the backwaters is black containing high percentage of carbon and full of vegetable debris. It does not mix well with water. Dr. Lake concluded that the mud of the mud banks might have been derived from an older source than the mud of the backwaters. Du Cane reported that upto the 7 fm line, the mud of the sea bottom and that of the mud banks have common nature and origin.

Borings conducted at Alleppey and Cochin also rule out the possibility of any underground discharge of mud and water in these regions (Du Cane, et al. 1938). The fact that in certain years mud banks have formed even before the onset of monsoon and increase in the water level in the backwaters also does not contribute to the above theory.

Du Cane, et al (1938) were the first to point out the role of waves in churning up the bottom mud and bringing it into suspension. They suggested that the high waves of the monsoon season feed energy continuously to keep the mud in suspension. They also emphasised the role of rivers in the supply of suspended sediments, as most of the mud banks are found within a moderate distance from river mouths. The lowering of salinity during monsoon season keeps the sediments in suspension for longer periods. However, it may be noted that mud banks have appeared at places for away from river mouths (see Figs. 1 and 2). Also, the bottom mud and the monsoon swells are there all along the entire coastline between Cannanore and Quilon. The theory of Du Cane and others failed to explain the formation of mud banks at definite localities along the coast.

Ramasastry and Myrland (1959) suggested that "upwelling and divergence near the bottom between 20-30 m along the coastline" produce vertical accelerations resulting in the lifting of the bottom waters. This water carries along with it the fine mud of the bottom, thus forming the mud banks. Even though upwelling can lift up bottom sediments as occurs in the Benguela upwelling region (Hart and Curie, 1960), it is doubtful whether an overturning of subsurface water as occurring along the Kerala coast can bring up so large a quantity of mud from the bottom and keep it in suspension for a long period. The mud flats of the Benguela region disappear in about 24 hours whereas the mud banks of Kerala coast remain for a period of over 3 months.

The author of this thesis (Kurup, 1969) reviewed the various theories on the formation of mud banks and showed how meagre was our knowledge on the physical aspects of the mud banks. He observed that Du Cane's suggestion that the pre-monsoon swells churn up and bring into suspension the fine mud of the bottom at shallow depths was sufficient to explain one phase of the problem and that none of the theories succeeded in explaining the occurrence of the mud banks at definite localities along the coast.

More recent studies reported by Varma and Kurup (1969) sought to explain the localised formation of the mud banks. They found from wave refraction studies and field observations that the region of the Purakad mud bank formed a zone of converging littoral currents for higher period waves. Hence for these waves, one can expect the formation of rip flows at this locality. These rip flows carry finer sediments offshore and prevent the onshore transport of sediments by waves. Thus localisation of suspended sediment takes place at the rip head. The high concentration of mud in suspension causes viscous damping of waves and the formation of calm zone. Varma and Kurup also suggested that the rip currents carry the low salinity nearshore water towards offshore, thereby diluting the waters of the mud bank. This dilution facilitates deflocculation of sediment in suspension, which accounts for the continued existence of the mud banks. With the increase in salinity during the post-monsoon season, the mud flocculates and settles down and thus the mud bank disappears. The details of flocculated settlement of suspended mud in the mud banks are discussed in Chapter IV.

Reddy and Varadachari (1972) have, from wave refraction studies, found evidence for such convergences and offshore flows at all the mud bank regions of the Kerala coast. The refraction of waves in the Purakad mud bank region will be discussed in Chapter VI.

9. Movements of the mud banks

The mud banks exhibit some movements alongshore, the year to year shift being more conspicuous than the movements within the year. Compiling all the available records, Du Cane, et al (1938) have prepared a series of charts showing the location of the Narakkal and Purakad mud banks during 1841 to 1937. Kurup (1972) has plotted the alongshore stretch and location of the Narakkal mud bank during 1861-1970. According to the available records, the Narakkal mud bank has moved southward at an average rate of 7 miles in 100 years with a partial return to the north in between. The average rate of southward movement of the Purakad mud bank is about 15 miles in 100 years, with no movement towards north. The movement of the Narakkal mud bank is restricted to a range of 12 miles from the Periyar river mouth to the estuarine mouth at Cochin and that of the Purakad mud bank to a range of 15 miles of coastline from about 2 miles south of Alleppey to Purakad. It is reported that after travelling to the southern-most point, the mud bank gradually disappears while another bank bursts out at the northern limit. The reliability of these reports on the movement of the mud banks is doubtful and also records are not available consecutively for all years till 1965. Since 1965, both the Narakkal and the Purakad mud banks have shown slight southward movement. The southern perifery of the Purakad mud bank was at Kakkazham during 1965, which reached Ambalapuzha by 1967. During 1968, 1969 and 1970, the southern limit of the bank was north of Karoor and by 1971 it had reached Karoor. In recent years, the Purakad mud bank is located approximately between Nircunnam on the north and Purakad on the south. The Narakkal mud bank appears approximately between Narakkal and Nayarambalam.

Du Cane, *et al* (1938) pointed out that excessive floods due to increased rainfall, which in turn increase the discharge of water from the rivers and the backwaters may be a causative factor in the movement of the mud banks. They believed that the excessive floods of 1934, the Bihar earthquake of 1934 and the unusually high rainfall of 1937 might all have worked in sequence to move the Narakkal mud bank far south so that its southern edge crossed the outer channel of Cochin harbour in 1937 and caused heavy silting in the channel. They also considered the coastal currents to be responsible for the southward drift of the mud banks. Along the southwest coast of India, the coastal currents are directed southward from February to October and are northerly during the rest of the year. October and January are the transition months.

According to Varma and Kurup (1969), the formation of the mud bank is the result of the interaction between the onshore and offshore transports of sediments in suspension, the former by waves and the latter by rip flows. This means that the location of a mud bank is decided by the location of converging littoral currents strong enough to cause an offshore transport of suspended sediments. Thus the shift in location of the mud bank can be considered to be caused by a shift in the location of the zone of convergence of littoral currents, which is determined by the wave refraction pattern. Narup (1972) suggested that the movements of a mud bank, both year to year and within a year, are the result of the changes in the wave refraction pattern due either to the changes in the bottom topography of the region (caused by the deposition of mud on the dissipation of the mud bank) or to the changes in the composition of the wave spectrum or both. This aspect will be discussed in detail in Chapter VI.

10. Present work

Panikkar and Jayaraman (1966) stated: "the mud bank formation and disappearance is the result of a series of events and it would be difficult to isolate a single factor and show it as the main causative factor". The present work aims at obtaining a complete picture of the various physical processes at work in the mud banks. The hydrography, suspended sediments, their suspension, flocculation and settlement, bottom sediments, waves and currents and the refraction of waves in the region of the mud bank at Purakad have been studied with the aim of elucidating the role of these parameters in the formation, maintenance, movements and dissipation of the mud banks.

The methods adopted to study each aspect are given separately while discussing the respective aspects. The studies have been made with particular reference to the mud bank at Purakad. The mud banks at Narakkal and Nattika were also visited periodically and the general observations have been kept in mind while discussing the observations at Purakad.

11. Region of investigation

An inshore water area of about 90 sq km adjacent to the Nircunnam-Purakad beach has been investigated (Fig. 3). The beach along this part of the Kerala coast is oriented in the north northwest direction and has varying width from place to place. South of the mud bank region the beach width is negligible and towards north of this point the width of the beach increases. The coastline is thickly fringed with coconut trees. Nircunnam and Purakad are two fishing villages at a distance of about 5.5 km. A small town, Ambalapusha, is situated mid-way between them. Ambalapusha, has a wide beach due to the consistent formation of the mud bank in this locality during the past few years. The National Highway passes through this region at distance of not more than 1 km from the shore. At Purakad, the Highway is only 200 m from the shoreline. At Thottapally, about 15 km south of Purakad, there is a controlled outlet for the backwater into the sea through a canal across which a Spillway has been constructed.

The width of the continental shelf in the region of investigation is about 50 km. The bottom contours are characterised by several small undulations approximately upto the 10 fathom line and the deeper contours are relatively more uniform. Very near the shore, the bottom consists of sand and shells and beyond this, it is composed of soft mud upto about 24 fathoms. Beyond this mud belt sand is again present.

CHAPTER II

HYDROGRAPHY

CHAPTER II

HYDROGRAPHY OF THE MUD BANK REGION

1. Introduction

Extensive studies have been made by various authors on the hydrographic conditions of the continental shelf waters of the south-eastern Arabian Sea (Chidambaram and Menon, 1945; Menon, 1945; Banse, 1959; Rama Sastry, 1959; Rama Sastry and Myrland, 1959; Subrahmanyam, 1959; Ramamirtham and Jayaraman, 1960; Ramamirtham and Nair, 1964; Darbyshire, 1967 and Banse, 1968). Most of these studies are based on data pertaining to stations beyond the 10 fathom line and very little is known about the hydrography of the coastal and nearshore waters of Kerala. Seshappa (1953a), George (1953) and Seshappa and Jayaraman (1956) have reported the hydrographic conditions of the inshore waters at Calicut and Damodaran and Hridayanathan (1966) and Damodaran (1973) have studied some of the hydrographic features of the Narakkal mud bank region. Nearshore hydrography changes with season and it is influenced by freshwater influx and run off and hence varies considerably along the same coastline.

This chapter deals with the hydrographic conditions in and around the mud bank region at Purakad. Hydrographic conditions of the mud bank region exert great influence on the stability and longevity of the mud bank inasmuch as the suspension of mud in sea water is governed by the salinity and density conditions of the water.

2. Material and Methods

The area of study and the locations of the hydrographic stations are shown in Fig. 3. Hydrographic surveys were conducted at the Purakad area during April, June, July, September and December, 1972 and February/March 1973. Monthly sampling was done from a station very near the shore during 1971. Surface samples were collected using plastic buckets and subsurface samples using Hytech Bottles. The temperatures were noted immediately after collection and salinities were estimated in the laboratory by titration. A temperature-salinity probe was also employed for hydrographic surveys during 1972. All the surveys were carried out using country boats and no sophisticated instruments could be operated because of the limitations of these frail crafts. Stations nearer to the coast were fixed by taking land bearings with the help of a sextant and the distant stations were fixed by a dead-reckoning. The position, depth and distance from the shore of the stations are given in Table I.

3. Results

Fig. 4 shows the monthly variations of salinity of the nearshore waters at Station N, near Ninrumam during

T A B L E I

LOCATION OF HYDROGRAPHIC STATIONS

Station Number	Station position: Latitude	Station position: Longitude	Depth (m)	Distance from shore (km)
N	9° 24.6'N	76° 21.5'E	<1.0	-
22	9° 23.4'N	76° 21.6'E	3.0	0.5
23	9° 23.3'N	76° 21.4'E	5.0	1.0
24	9° 23.2'N	76° 21.0'E	7.0	2.0
25	9° 23.0'N	76° 20.6'E	9.0	3.0
26	9° 22.8'N	76° 20.2'E	10.0	4.5
27	9° 22.4'N	76° 19.2'E	11.0	6.0
28	9° 21.9'N	76° 17.7'E	13.0	8.0
29	9° 21.4'N	76° 16.3'E	18.0	10.0
2	9° 25.7'N	76° 19.1'E	10.0	4.5
47	9° 20.2'N	76° 21.3'E	10.0	4.5

1971 and the average daily rainfall during the same year at Alleppey. Fig. 5 shows the seasonal variation of surface salinity during April 1972 to February/March 1973 at Station No. 26 in the mud bank region and the average daily rainfall reported at Alleppey during this period. In Fig. 6 are shown the seasonal variation of surface salinity and temperature at eight stations (22-29) in a line perpendicular to the shoreline in the mud bank region. Fig. 7 gives the seasonal variation of surface, mid-depth and bottom (1.0 m above the bottom) salinities at 3 stations in a line parallel to the shoreline (stations 2, 26 and 47 shown in Fig. 3) at Purakad.

The variations of nearshore salinity shows a close relationship with the rainfall. It falls from 33.5 ‰ during the last week of May to 8 ‰ during the middle of June (Fig. 4). There was heavy rainfall (24 to 75 mm/day) from the last week of May 1971 onwards which caused a dilution amounting to a lowering of salinity by 25.7 ‰ in the nearshore waters. Damodaran and Hridayanathan (1966) have reported a fall of 27.47 ‰ in the nearshore salinity at the Narakkal mud bank region between May and August, 1966. During the season when the mud bank was active at Purakad during

1971, the salinity of the nearshore water was always below 18 $^{o}/oo$.

Further offshore at station No. 26, the variations of surface salinity does not show so close response to rainfall as at the nearshore station (Fig. 5). Even though there was heavy rainfall during the second week of May, 1972 (22 to 97 mm/day), this did not cause considerable dilution of surface water at this station located at 4.5 km off the shore. These showers were followed by a period of about 4 weeks with only light showers till the last week of June, 1972, whereafter the rainfall increased suddenly. All the while the salinity of the surface water at station No. 26 kept on decreasing gradually. The lowest salinity of 13.6 $^{o}/oo$ was reached during mid-July. After this the rainfall decreased and the salinity increased correspondingly.

Fig. 6 shows the seasonal and spatial variations of surface salinity and temperature during 1972/73 at eight stations along a section across the mud bank region. During April the salinity is above 34 $^{o}/oo$ at all the stations with a slight increase towards the offshore areas. The surface temperature also increases towards offshore, from 30.8°C near the shore to 31.4°C at station No. 28, 8 km offshore. During June, the salinity remains more or less constant and at its minimum over a distance of 1 km from the shore whereafter it shows a sharp increase from 8.4 ‰ to 15.7 ‰ over a distance of about 3.5 km. Beyond this distance, the surface salinity increases only slightly. During this month, the surface temperature increases gradually with distance from the shore.

During July, the increase in surface salinity towards offshore is sharp beyond Station No. 23. Stations 22 and 23 show uniform salinity. The temperature of surface water remains more or less uniform at all stations. During September, surface salinity remains uniform at the first 5 stations and it shows a gradual increase further offshore. More or less uniform salinity is encountered during December. Surface temperature remains almost uniform during these months.

In February, the surface salinity increases upto a distance of about 4.5 km offshore beyond which it remains more or less uniform. The surface temperature remains uniform during this month also.

Station No. 26 is located in the mud bank region at a distance of about 4.5 km offshore and stations 2 and 47 are located north and south respectively of the mud bank region at the same distance from the shore. These three stations have depths around 10 metres. As can be seen from Fig. 7, the salinity condition and the general trend of its seasonal variation at the surface, mid-depth and bottom at these 3 stations are identical. On closer examination, it can be seen that during June, July and September, the surface and mid-depth salinities are slightly lower at the station in the mud bank than at the stations outside the mud bank. The difference is more during July and less during June and September. Also, the difference is more at the surface and less at mid-depths. Bottom salinities are uniform at all the three stations. During February/March, April and December, these three stations show identical salinity variations with depth. During April, salinity slightly decreases with depth while the other observations during the year show increase of salinity with depth.

4. Discussions

The influence of the monsoons on the hydrography of the Kerala inshore waters is immediately reflected very near the shore and to a lesser degree offshore. The monthly distribution of average daily rainfall during 1972/73 suggests that the hydrographic observations of February and April may, with some reservations, be considered to be representing the conditions during early and late summer; those of June and July representing the southwest monsoon season; September representing the post-monsoon season and December representing the north-east monsoon season. February and April observations as depicted in Figures 4 and 5 indicate waters of relatively higher salinity with uniform seasonal heating. During December, the salinity of the waters at the surface, mid-depth and bottom remains uniform over the area while it increases considerably from surface to bottom. By September, the excess dilution by the southwest monsoon rains disappears. June and July recorded increasing salinity towards offshore which is a feature brought about by the dilution due to land drainage.

These features can be expected to be uniformly present in the inshore waters all along the Kerala coast except at river mouths and at places where the backwaters open out into the sea. Purakad is an open coast with no influx of freshwater except land drainage. The only canal emptying freshwater into the sea in this region is located at Thottappally, about 15 km south of

Purakad. This freshwater influx which is a controlled one through the Thottappally Spillway seems to have no influence on the hydrography of the inshore waters at Purakad. Station No. 47 does not show any excess dilution compared to the stations north of it. Under the influence of the coastal current system which is directed towards south during the southwest monsoon season (Varadachari and Sharma, 1967), the freshwater let out at Thottappally probably flows mostly southwards.

Though the general patterns of distribution and seasonal variation of salinity are identical both inside and outside the mud bank region, the comparatively low surface and mid-depth salinities found in the mud bank region during the south-west monsoon season deserve special consideration. Observations during June, July and September indicate that the surface and subsurface waters of the mud bank are slightly more diluted than those outside the mud bank. The dilution decreases from surface to mid-depths and disappears at the bottom. Varma and Kurup (1969) reported from wave refraction studies the possibility of the existence of rip currents in the Purakad mud bank region and suggested that the rip flows carry low salinity water from near the shore thereby diluting the offshore waters. Reddy and

Varadachari (1972) based on wave refraction studies have found corroborative evidence for such convergences and offshore flows at all the mud bank regions of the Kerala coast. The observations on currents in the mud bank region are reported in Chapter VI. The present observations on salinity within and outside the mud bank region show that during the southwest monsoon season, there is a possibility of a flow directed offshore in the mud bank region which is probably responsible for the comparatively lower salinity of the waters of the mud bank.

CHAPTER III

SUSPENDED MATTER

CHAPTER III

SUSPENDED MATTER OF THE MUD BANK

1. Introduction

Distribution of suspended matter in different parts of the oceans has extensively been studied by various authors (Armstrong and Atkins, 1950; Atkins, et al. 1954; Burt, 1955; Nishizawa and Inoue, 1958; Jerlov, 1958; Sasaki, et al. 1962; Hobson, 1967; Otto, 1967; Sheldon, et al. 1967; Sheldon and Parsons, 1967a; Schubel, 1968; Sheldon, 1968; Sheldon, 1969; Beardsley, et al. 1970; Manheim, et al. 1970; Wageman, et al. 1970; Carder, et al. 1971; Darke, 1971; Parke, et al. 1971; Buss and Rodolfo, 1972; Ettreim and Ewing, 1972; Manheim, et al. 1972; Reiswig, 1972; Sheldon, et al. 1972; Bornhold, et al. 1973; Heathershaw and Simpson, 1974; Gibbs, 1974; etc.). Most of these studies deal mainly with the distribution of concentration of suspended matter in the surface waters of the shelf regions wherein the order of magnitude of the concentration varies from 10-100 mg/l nearshore to 0.1 - 1.0 mg/l over the outer shelf. There have been no attempts to study the concentration and distribution of suspended mud in any of the mud banks of the Kerala coast. A knowledge of the distribution of the suspended load in the mud bank is essential to understand the surface and subsurface build-up of the bank and its shape, structure and movement. The distribution of suspended matter and its seasonal variation in the Purakad mud bank region wherein the concentrations of the suspended material are of the order of 10^3mg/l, have therefore been studied in detail and the results are discussed in this Chapter.

2. Method

Concentration of suspended matter can be studied by various techniques including ultramicroscopical counting (Freundlich, 1922; Schubel and Schiemer, 1969), filtration (Schubel, 1967; Sheldon, 1972) and optical measurements (Jerlov, 1968; Glover, et al, 1969). Other methods include use of the Coulter Counter (Sheldon and Parsons, 1967b; Lee and Folkard, 1969) and space photography (Webber, 1967). In the present study the concentration of suspended matter was determined by filtering the water samples and weighing the residue. Secchi disc observations were also made in the field but they failed to give any comparable results probably due to the overcast sky of the monsoon months and the very high concentrations of suspended matter in the mud bank. Hence the Secchi disc data have not been presented in this write-up.

Optical observations on the suspended mud of the mud bank are presented in Chapter IV.

The area of investigation and the location of the sampling stations are shown in Fig. 8. Water samples were collected from the surface, mid-depth and bottom (1.0 m above the bottom) from 8 stations (Stations 22-29) in a line perpendicular to the shoreline in the mud bank region. These samplings were done during the hydrographic surveys conducted from April, 1972 to March, 1973. In order to obtain a detailed picture of the mud bank formations, surface, mid-depth and bottom (1.0 m above bottom) water samples were collected from 50 stations (Stations 1-50) in an area of about 90 sq.km in the inshore region at Purakad during June, July and September, 1972. The details of the station positions are given in Table II.

At stations very near the shore, where the depth is only 3 m, only surface and near bottom samples were collected. At all the other stations water samples were collected from surface, mid-depth and near bottom (1.0 m above the bottom) levels. Surface samples were collected using buckets and subsurface samples using Hytech bottles.

TABLE II

LOCATIONS OF SESTON STATIONS

Station No.	Station Position		Depth (m)
	Latitude	Longitude	
1	9° 26.2'N	76° 20.2'E	4
2	9° 25.7'N	76° 19.1'E	10
3	9° 25.2'N	76° 17.8'E	11
4	9° 24.7'N	76° 16.7'E	13
5	9° 24.2'N	76° 15.5'E	16
6	9° 24.7'N	76° 21.1'E	3
7	9° 24.6'N	76° 20.7'E	5
8	9° 24.4'N	76° 20.3'E	7
9	9° 24.2'N	76° 19.6'E	9
10	9° 23.8'N	76° 18.8'E	11
11	9° 23.4'N	76° 17.6'E	12
12	9° 23.0'N	76° 16.6'E	15
13	9° 22.6'N	76° 15.5'E	18
14	9° 24.2'N	76° 21.3'E	3
15	9° 24.1'N	76° 21.1'E	5
16	9° 23.7'N	76° 20.6'E	7
17	9° 23.5'N	76° 20.0'E	10
18	9° 23.3'N	76° 19.3'E	11
19	9° 22.7'N	76° 18.2'E	13
20	9° 22.4'N	76° 17.1'E	16

TABLE II (CONTD..)

Station No.	Station Position		Depth (m)
	Latitude	Longitude	
21	9° 21.8'N	76° 15.9'E	18
22	9° 23.4'N	76° 21.6'E	3
23	9° 23.3'N	76° 21.4'E	5
24	9° 23.2'N	76° 21.0'E	7
25	9° 23.0'N	76° 20.6'E	9
26	9° 22.8'N	76° 20.2'E	10
27	9° 22.4'N	76° 19.2'E	11
28	9° 21.9'N	76° 17.7'E	13
29	9° 21.4'N	76° 16.3'E	18
30	9° 22.7'N	76° 21.9'E	3
31	9° 22.6'N	76° 21.6'E	5
32	9° 22.4'N	76° 21.3'E	8
33	9° 22.2'N	76° 20.5'E	10
34	9° 21.8'N	76° 19.7'E	11
35	9° 21.4'N	76° 18.6'E	13
36	9° 21.0'N	76° 17.6'E	16
37	9° 20.7'N	76° 16.4'E	18
38	9° 22.0'N	76° 22.2'E	3
39	9° 21.9'N	76° 22.0'E	6
40	9° 21.7'N	76° 21.5'E	8

TABLE II (CONTD..)

Station No.	Station Position		Depth (m)
	Latitude	Longitude	
41	9° 21.4'N	76° 20.7'E	9
42	9° 21.2'N	76° 20.0'E	10
43	9° 20.7'N	76° 18.8'E	13
44	9° 20.3'N	76° 17.7'E	16
45	9° 19.9'N	76° 16.6'E	18
46	9° 20.5'N	76° 22.5'E	6
47	9° 20.2'N	76° 21.3'E	10
48	9° 19.6'N	76° 20.2'E	11
49	9° 19.1'N	76° 19.0'E	15
50	9° 18.5'N	76° 17.8'E	18

One litre of the water sample was filtered through a previously weighed Whatman filter paper No. 42 with the help of a vacuum pump. When the concentration of the suspended mud is very high, it was found necessary to change the filter paper 3 or 4 times to facilitate a quick filtering. The final weights were determined after drying the filter paper with the residue in a desiccator. The APD (average pore diameter) of the filter papers used is 1.1 μ and so all suspended particles of sizes smaller than this may not be retained in the filter. However, it is known that filters retain a significant amount of material with sizes less than the APD of the filter (Sheldon and Sutcliffe, 1969) and so the results of the present investigation may be considered to be realistically representing the total suspended matter. The residue includes both organic and inorganic matter in suspension--the seston.

3. <u>Results</u>

Figures 9-14 show the vertical distribution of suspended sediment (mg/l) in a section (Stations 22-29) across the mud bank region extending upto a distance of about 10 km from the shore. Figures 15-23 show the horizontal distribution of the suspended load in the surface, mid-depth and near-bottom waters during June, July and September 1972.

During April (Fig. 9) the vertical section shows suspension concentrations varying between 100 mg/l and 250 mg/l between surface and 1 m above the bottom. The concentration decreases from near the shore upto a distance of about 1.5 km whereafter it increases in the seaward direction upto Station 24 located at a distance of about 2 km from the shore. Beyond this station, the concentration gradually decreases in the offshore direction. From surface to bottom, the concentration shows a gradual increase except at 2 stations (22 and 23) near the shore.

During June (Fig.10) the concentrations of suspended matter show comparatively higher values than during April. From near the shore, the surface concentration shows a slight decrease upto a distance of 1 km from the shore whereafter it increases from about 150 mg/l to about 300 mg/l at a distance of 3.5 km from the shore. Between 3.5 km and 8 km from the shore, the surface waters have somewhat uniform concentration of suspended matter (> 300 mg/l). Beyond a distance of 8 km from the shore, there is a sharp decrease of concentration at the surface in the seaward direction. In the region of maximum concentration (6 km from the shore) the concentration increases from 340 mg/l at the surface to 550 mg/l at levels 1 m above the bottom.

During July (Fig. 11) the concentration of suspended matter at the surface decreases from 1300 mg/l near the shore to 1200 mg/l at a distance of about 1 km from the shore. Beyond 1 km from the shore, the concentration increases from 1200 mg/l to 1300 mg/l at a distance of about 3.5 km from the shore. From 3.5 km to 8 km from the shore, the concentration at the surface shows gradual decrease (1300 mg/l - 1000 mg/l) whereafter it decreases with sharp gradients in the offshore direction. Between surface and 1 m above the bottom, the concentration of suspended matter increases from 1300 mg/l to 1500 mg/l at a distance of 3.5 km from the shore and from 1100 mg/l to about 1600 mg/l at a distance of 6 km from the shore.

During September (Fig. 12) the surface waters show uniform concentrations of over 900 mg/l upto a distance of about 6 km from the shore. From 6 km to 8 km from the shore, the concentration decreases from 900 mg/l to 800 mg/l and beyond 8 km the seaward decrease has sharp gradients. In the region of maximum concentration (4.5 km from the shore), the concentration increases from 950 mg/l at the surface to over 1300 mg/l at levels 1 m above the bottom. Though the concentrations at all depths are slightly lesser than during July, in the region upto a distance of about 8 km from the shore, the horizontal isolines of concentration indicate a 'stratification' which is more stable than during July.

By December (Fig. 13) the concentration of suspended matter has fallen considerably and also the horizontal isolines have almost diappeared. At the surface, the concentration decreases in the offshore direction gradually from 590 mg/l near the shore to about 100 mg/l at a distance of 10 km from the shore. Near the bottom, the highest concentration is encountered at station No. 25 located at a distance of about 3 km from the shore.

During February (Fig. 14) the surface concentration decreases from 200 mg/l near the shore to about 180 mg/l at a distance of 1 km from the shore whereafter it increases to 250 mg/l at a distance of about 3.5 km from the shore. Beyond 3.5 km from the shore, the surface concentration shows gradual decrease in the offshore direction. Near the bottom, the highest concentration occurs at Station No. 27 located at a distance of about 6 km from the shore.

Figures 15-17 show the horizontal distribution of suspended matter in the mud bank area in the surface, mid-depth and near-bottom waters during the second week of June. Figures 18-20 show the horizontal distribution at these three levels during the third week of July and Figures 21-23 during the first week of September.

During June, at the surface (Fig. 15), the concentration varies between 100 mg/l and 350 mg/l in the region covered in this study. The highest concentration (350 mg/l) is encountered at Station No. 34 located at a distance of 5.5 km from the shore , about 1 km north of Purakad. The contours of equal concentration extend in a semi-circular (more correctly, semi-elliptical) shape from the shore. Along the shore, the concentration in the surface water varies between 250 mg/l and 300 mg/l, the highest values being near Hirovunnam.

At mid-depths, during this month (Fig. 16), the concentration of suspended sediment varies between 150 mg/l and 400 mg/l. The region of high concentration in the mid-depth is directly below the region of high concentration in the surface water. Near the shore, high value is found in the vicinity of Station No. 30 which is located midway between Nirounnam and Purakad.

Near the bottom (Fig. 17) the contours are more elongated towards offshore with the result that the contours are almost perpendicular to the shoreline. The concentrations at this level vary between 150 mg/l and 550 mg/l. The region of high concentration is directly below the region of high concentration at the surface and mid-depth levels.

During July, at the surface (Fig. 18), the concentration varies between 100 mg/l and 1300 mg/l in the region covered in this study. The region of highest concentration is in the vicinity of station No. 25, located at a distance of about 3 km from the shore, about 3.5 km north of Purakad. Along the shore, the concentration varies between 800 mg/l and 1300 mg/l and the highest concentration along the shore is found in the vicinity of Station No. 22 which is about 4 km north of Purakad. The isolines are more elongated towards offshore than during June.

At the mid-depths, during July (Fig. 19), the suspension concentration in the area of investigation varies between 200 mg/l and 1300 mg/l. The region of the highest concentration is slightly to the south-west of the region of the highest concentration at the surface. The contours have the same shape as at the surface.

At near-bottom levels during this month (Fig.20), the suspended sediment concentration varies between 200 mg/l and 1500 mg/l over the area. The region of the highest concentration is almost directly below the region of highest concentration at the mid-depth levels. The contours are more elongated towards offshore and also they are almost normal to the shoreline. Along the shore, the variation of suspension concentration is between 800 mg/l and 1400 mg/l, the maximum being in the vicinity of Station No. 30, located mid-way between Purakad and Nircunnam.

During September (Fig. 21), the surface concentration varies between 100 mg/l and 900 mg/l in this horizontal section. The region of highest concentration coincides with the region of highest concentration during July. The isolines are almost normal to the shoreline on the southern side of the mud bank. The horizontal gradient is very sharp on the southern side compared to the northern side.

At mid-depth levels, during September (Fig. 22), the concentration varies between 200 mg/l and 1200 mg/l. The isolines have more or less similar shape as at the surface. They are normal to the shoreline on either side of the mud bank. The region of high concentration at this level is almost below the region of high concentration at the surface.

At near-bottom levels (Fig. 23) during September, the concentration of suspended sediments varies between 100 mg/l and 1300 mg/l. The region of the high concentration is almost below the regions of high concentration both at the surface and mid-depths. The horizontal gradient is very sharp on either side of the mud bank and the contours are almost normal to the shoreline.

4. <u>Discussions</u>

As can be seen from the diagrams showing the vertical and horizontal distributions, enormous quantity of mud comes into suspension in the mud bank region during the period June-September as compared to the other months. This is illustrated by the integrated total concentration of suspended matter between the surface and 9 m depth at station No. 26 which has a depth of 10 m, which varies as follows: 16 April: 1780 mg/l; 11th June: 3823 mg/l; 17th July: 12292 mg/l; 5th September: 10854 mg/l; 10th December: 5209 mg/l; 28th February: 3312 mg/l. The mud cannot remain indefinitely in suspension, especially in sea water where it will flocculate and settle down. This means that there is a continuous supply of suspended mud to the mud bank area during the months when the mud bank is active, which compensates for the settlement of mud.

Figures 15-23 help to delineate the shape of the mud bank during the season when it is active. The mud bank rises above the bottom in the shape of a ridged, irregular, solid cone with a flat top. The shape as well as the location of the 'centre' of the mud bank (the region of highest concentration of suspended matter) undergo slight changes within the period of its activity during a year. The contour of a particular concentration covers a larger areas at mid-depth than at the surface and also at the bottom than at the mid-depth. That is, the area covered by the contour of a particular concentration increases from surface to subsurface levels. The isolines of concentration widen alongshore and also get elongated towards offshore as we proceed from surface to bottom.

In this context, it may be kept in mind that the mid-depth and near-bottom sections are not exactly horizontal; instead, they are parallel to the bottom.

Experience shows that there is erosion of the beach on both the periferies of the mud bank and accretion of material on the beach adjoining the mud bank. (Erattupuzha and Raman, 1971; Moni, 1971; Padmanabhan and Pillai, 1971; Kurup, 1974). It is possible that the waves are refracted in this region in such a way that there is a strong component of the wave energy directed towards north on the southern side of the mud bank and towards south on the northern side of the mud bank. The wave conditions, wave refraction and nearshore currents of the region will be discussed in Chapter VI. Wave refraction diagrams drawn for this region (Thirupad, 1971) show that "Hircunnan is a nodal zone for the majority of the waves studied and deposition of coarser sediment takes place on the beach and finer sediments are transported offshore". Varma and Narup (1969) also reported that this region formed a zone of converging littoral currents for higher period waves. Wave refraction studies reported by Reddy and Varadachari (1972) have also shown that "for waves approaching from WSW and with 10 second period, which is the most probable direction and predominant period during SW monsoon season, converging littoral currents form at several places along the Kerala coast from Quilon to Cannanore........ Mud banks were reported some time or other in the past at all these places" (Fig. 24). The horizontal distribution of suspended matter in the mud bank region discussed above also suggests supply of suspended mud from both sides of the mud bank into the mud bank. The sharp gradients in concentration seen on the southern side of the mud bank at the surface during September indicate excess of settlement over nourishment in this region during September.

The existence of plumes of high concentration of suspended sediment, extending across the shelf in other parts of the world has been reported by various authors. Usually these are associated with major deltas, e. g., the Mississippi (Scruton and Moore, 1953), the Amazon (Nota, 1958), the Irrawaddy (Rodolfo, 1969) and the Po (Jerlov, 1958; Nelson, 1970). Plumes of heavy load of suspended mud also occur where there is convergence of coastal currents, resulting in a current across the shelf (Mc Cave, 1972). This phenomenon of plume formation by converging residual currents has been found to take place in the southern North Sea (Joseph, 1953; Lee and Ramster, 1968) and in the western Gulf of Mexico (Curray, 1960; van Andel, 1960). Another plume is indicated southeast of Port Arthur, Texas by space photographs (Webber, 1967). A plume extending south-east of Cape Hatteras has been identified by Emery (1969) and Buss and Rodolfo (1972). It seems likely that the mud banks of the Kerala coast are plume formations of a larger scale associated with convergence of littoral currents and the resulting offshore (rip) flows.

CHAPTER IV

FLOCCULATION

CHAPTER IV

FLOCCULATION OF SUSPENDED MUD IN THE MUD BANKS

1. Introduction

In the foregoing chapters the distribution and seasonal variations of the hydrographic parameters and the suspended sediment load in the mud bank were discussed. It is known that particles in suspension in sea water may either be deflocculated or flocculated depending on whether the salinity is low or high. Flocculation is the electrolytic coagulation process by which suspended particles of colloidal or semi-colloidal dimensions conglomerate to form larger units in an electrolytic medium. The process is reversible and, flocculation and deflocculation under the influence of changes in salinity, exert great influence on the settlement of suspended mud especially in coastal waters. In the deflocculated state, the mud will remain indefinitely in suspension subject only to slow sinking at a rate depending on the particle diameter whereas, in the flocculated state, the flocs will settle at a rapid rate. Flocculation plays an important role in processes like coastal shoaling, bar formation, harbour silting and mud bank formation.

Though the process of marine flocculation has been subject of study both through observations of natural samples (Welder, 1959; Committee on Tidal Hydraulics, 1960; Berthois, 1961; Demerara Coastal Investigation, 1962; Krone, 1972) and through laboratory experiments (Whitehouse and Jeffrey, 1955; Whitehouse and Mc Carter, 1958; Whitehouse, et al. 1960; Krone, 1962; Kranck, 1973), the exact mechanism of floc formation in sea water is not well understood. The electrolytic content (anionic) of the sea water decreases the electrolytic potential (cationic) of the suspended particles thereby increasing the possibility of union of clay particles approaching each other by the Brownian movement. The concentration and mineralogy of the clay particles and the turbulence, temperature and salinity of sea water are regarded as factors controlling the stability of a mud suspension in sea water (Postma, 1967). A detailed account of the rheological properties of mud suspensions has been given by Olphen (1963).

Flocculation plays an important role in the sedimentation characteristics of the mud banks of the

Kerala coast. The suspended mud in the mud bank regions is mostly in a colloidal state when the mud bank is active and as the salinity of the inshore waters increases during the postmonsoon period, the suspended mud flocculates and settles down. There has been no attempt to determine the effect of salinity on flocculation and settlement of the fine mud of the mud banks except that by Du Cane, et al (1938) who, by observing the volume of mud deposited in jar experiments under various NaCl concentrations in water, found that the mud of the mud banks "remained completely deflocculated if the NaCl concentration was below 2.5 ‰ and complete flocculation occurred with brine concentrations above 20 ‰. Between these two ranges, the mud is partially flocculated i.e., part of the mud settles as floccs and the rest remain in suspension". A report in Mahasagar (Anonymous, 1968) refers to a similar experiment with suspension concentration of 5 gm of mud/litre in water of different concentrations of NaCl, 3, 10, 20 and 30 ‰. The height of sediment deposited at fixed intervals of time was measured and the results revealed that "in water of low content of NaCl, 3 ‰, the flocculation was relatively slow requiring about 8 hours for complete settlement, whereas in water of high concentration of NaCl, 20 to 30 ‰, the flocculation and the corresponding settlement requiring only about 6 hours".

This chapter explains some optical experiments conducted by the author to determine quantitatively the effect of salt concentration on flocculation and settlement of suspended mud of the mud bank at Purakad. Some observations on the floccules of the mud bank are also presented.

2. Method of study

Suspension concentrations can be studied by wet ashing, direct microscopy or by optical measurements. Photometric determination of suspension concentration has successfully been made by Atkins, et al (1954), Joseph (1955), Burt (1958) and Glover, et al (1969).

The present experiment employs photometric determination of attenuation of tungsten light in the mud suspension to determine the flocculated settlement of the mud of the mud bank under different concentrations of NaCl in water. A series of experiments were conducted using glass jars with optically plane surfaces filled with tap water with varying salt concentrations in which mud from the top-most layer of the bottom at the mud bank region has been uniformly suspended. The experimental set-up is schematically shown in Fig. 25. A parallel beam of light from a tungsten filament lamp was employed and the scattered light coming out of the suspension after travelling horizontally through the suspension, was measured using a photometer at various time intervals after stirring the suspension uniformly without entrapping air bubbles. Following the suggestion of Shibata (1958), an opal glass diffuser was employed so that the fraction of the scattered light which reaches the photocell is increased and the photometer 'sees' mostly diffused light. The attenuance* of the suspension relative to that of pure water in the same glass jars was determined at fixed timings upto about 9 hours. The experiments were repeated for different salt concentrations from 0 to 35 °/oo and with three different mud samples. In all cases, the concentration of the mud suspensions was kept as 1 gm/litre. The experiments were conducted at room temperature.

The three mud samples were collected from depths of 16 m (Sample A), 10 m (Sample B) and 5 m

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* Attenuance is the ratio of the radiant flux lost from a beam by means of absorption and scattering to the incident flux.

(Sample C) in the mud bank region at Purakad (Fig. 26) during September, 1972 when the mud bank had started disappearing as indicated by decrease in turbidity and increase in wave action. The grain size composition of the samples as determined by the combined method of wet sieving and pipette analysis (Krumbein and Pettijohn, 1938) is shown below:

	Sample A	Sample B	Sample C
Sand (> 62 μ)%	0.95	0.00	3.00
Silt (4μ–62 μ)%	39.31	28.46	42.90
Clay (< 4 μ)%	59.74	71.54	54.10

All the three samples contain mostly silt and clay. Of the three, sample B is finer than sample A and, sample A is finer than sample C.

3. Results

Figures 27–29 show the variation of the relative attenuance under different NaCl concentration of the medium for the three mud samples. The variations in the transmittance of the suspension system due to changes in the size of the floccs are not separated from those due to settlement of mud. The experiment thus measures the combined effect due to flocculation and settlement. The flocculation and settlement increase with time and with increase in the salt content of the medium. Both increases are more or less gradual. For suspension A, with salt concentrations 10 ‰, 20 ‰ and 35 ‰, complete settlement of the suspended load (relative attenuance unity) occurs in about 8 hours 15 minutes, 3 hours 40 minutes and 2 hours respectively. In the case of suspension B, when the salt concentration is 10 ‰, complete settlement occurs beyond the duration of the experiment and at 20 ‰ and 35 ‰, it occurs in about 8 hours 40 minutes and 3 hours 50 minutes respectively. For suspension C, complete settlement of the suspended mud occurs in about 8 hours 25 minutes, 2 hours 20 minutes and 1 hour 20 minutes at NaCl concentrations of 10 ‰, 20 ‰ and 35 ‰ respectively. At lower salt concentrations, complete settlement occurs only beyond the duration of the experiment.

It is known that for a given type of particulate matter, the attenuation is proportional to the particle concentration in suspension, expressed as mass per unit volume (Jones and Wills, 1956; Oshakovsky, 1966; Jerome 1968). Using this proportionality, Fig. 30 is prepared showing the time required for 25%, 50% and 75% of the suspended load to settle at various salt concentrations.

The proportionality may not be strictly holding good at all the salinities because of the changes in the size of the floccules at higher salinities. Nevertheless, the curves show that the decrease in the time required for settlement with increase of salt concentration is in a continuous and well-defined manner. At all brine concentrations the settlement rates are different with respect to the three mud samples, sample B being the slowest and sample C being the fastest.

4. Discussions

The processes of flocculation and settlement as occurs in the natural environment may be different from those taking place in the settling jars. Addition of NaCl in freshwater does not exactly simulate salinity conditions of sea water. The results can, however, be applied to natural conditions with slight modifications except in cases where large quantities of organic matter is dissolved in the sea water in which case flocculation occurs at enhanced rates. When examined under microscope, the floccules in both the natural samples and the artificial suspensions appear identical. They are nearly-rounded masses of varying dimensions. Each clump contains grains of various sizes. At higher salt concentrations, the individual floccules are bigger than at lower salt concentrations. This was found to be so in the natural samples also.

That the addition of salt to make up various concentrations does not cause a change in the attenuance has been shown by Clark and James (1939), who found no appreciable difference between the attenuance of distilled water and that of filtered sea water. Corroboratory results have been obtained by Sullivan (1963) by comparing the absorption of distilled water with that of artificial sea water. In the present study also the attenuance before any flocculation takes place (time 0) is found to be more or less same under all brine concentrations.

As can be seen from Fig. 30, flocculated settlement starts even at 1 °/oo salt concentration and the increase in the rate of settlement continues even beyond 35 °/oo, whereas Du Cane, et al (1938) suggested completely deflocculated state below 2.5 °/oo and completely flocculated state above 20 °/oo. Observations under microscope show that at 35 °/oo there are lesser individual particles than at 20 °/oo which became part of a floccule at higher salinities. The higher the salinity the lesser is the number of individual particles and bigger is the size of the flocculus. The minimum salinity at which complete flocculation occurs is certainly above 35 °/oo.

The mud of the mud bank responds very quickly to salinity changes of the medium upto 5 °/oo and at higher salinities the response is comparatively slower. In the jar experiment any tangential forces like those due to winds and currents or vertical forces other than gravity and buoyancy are absent whereas in the ocean, the tangential forces and the turbulence of water may delay flocculated settlement. Hence the very low salinities may not be so effective in forming flocs in the sea as in the jar experiment. But in the mud bank region, the waters are free of wave disturbances owing to the damping that waves undergo in the turbid water. The southwest monsoon and the heavy freshwater run-off during that season cause considerable dilution of the inshore waters of the Kerala coast. The distribution and seasonal variations of salinity in the region of the mud bank at Purakad have been discussed in Chapter II. The seasonal variations in salinity show that the monsoon season provides conditions favourable for increased deflocculation in the mud bank region and the post-monsoon conditions facilitate flocculation and settlement. However, even during monsoon, the salinity is never below 8 $^{o}/oo$ at a station very near the shore. Further offshore, it is always above 13 $^{o}/oo$ (Chapter II). As the results of the present study indicate, even at these low salinities, flocc lated settlement prevails and it is evident that there is a continuous supply of suspended sediment to the water column so that the mud bank continues to exist for a period of 2 to 3 months.

CHAPTER V

BOTTOM SEDIMENTS

CHAPTER V

BOTTOM SEDIMENTS OF THE MUD BANKS

1. Introduction

As can be seen from the foregoing discussions, the bottom sediments play an important role in the formation of the mud banks. The general zonation of the bottom sediments in the continental shelf off the southwest coast of India has coastal sand bordered seaward by muds and then limesands (Shepard, 1973). Nurian (1969) has identified four zones of bottom deposits in the shelf region off this coast. These are: (i) sandy deposit in the nearshore region upto a depth of 3.5 m. (ii) muddy deposit with small quantities of sand beyond 3.5 m depth and extending upto 18 m line. (iii) Sandy zone extending from the 18 m line to a depth of 100 or 120 m, in which the quantity of mud decreases and that of sand increases progressively towards higher depths. (iv) hard bottom zone beginning from 100 or 120 m line and extending upto 260 m depth, with deposits of grey or black and white sand mixed with fine shell fragments and very small percentage of silt. The textural and petrographical properties of the sediments of the south-eastern continental shelf of the Arabian Sea have been studied in detail by Stackelberg (1972) and Mattiat, et al (1973). Stackelberg (1972) has reported that from the coastline down to approximately 50 m depth, the sediments become progressively finer and on the outer shelf they are again considerably coarser. Mattiat, et al (1973) have distinguished the following five different facies zones which run more or less parallel to the coast: (1) coastal sand, (2) mud poor in lime, (3) calcarious sand, (4) sandy mud rich in lime and (5) mud rich in lime. Along the portions of the Kerala coast where the mud banks appear, mud occurs just below the low water line. The general characteristics of this mud as reported by Keen and Russel (in Du Cane, et al, 1938), Dora, et al (1968) and Damodaran (1973) have been discussed in Chapter I. The observations of the author on the bottom sediments of the Purakad mud bank region are presented and discussed in this Chapter.

2. Materials and Methods

48 bottom sediment samples were collected from 8 stations (Stations 22-29; See Fig. 3; Table I) in a line perpendicular to the shore at Purakad during the period April 1972 to February 1973. The samples were collected using a Van Veen grab and subjected to

size analysis by wet sieving and pipette analysis as described by Krumbein and Pettijohn (1938). Known quantities of the dried sediments were dispersed in 0.025 N solution of sodium hexametaphosphate and the sand fraction was separated by sieving through a 230 mesh sieve. The sand fraction retained in the sieve was dried and weighed. The finer fractions were analysed by the method of pipette analysis.

3. Results and Discussions

(a) Texture

In general, the mud bank sediments are very soft and plastic to touch and yellowish-brown to dark greyish-green in colour. During the season when the mud bank is active, the bottom sediments are in a highly unconsolidated state so that the bottom is not clearly demarked. Very often during this season, it is found that the grab fails to close as it does not hit a hard bottom.

Table III gives the weight percentages of sand (> 62 μ), silt (4 μ - 62 μ) and clay (< 4 μ) in the bottom sediments at stations 22-29 during different months. Figure 31 shows the cumulative weight percentages of these size fractions at the above stations during different months.

TABLE III

SAND, SILT AND CLAY CONTENT (%) OF THE BOTTOM SEDIMENTS

Station No.		22	23	24	25	26	27	28	29
16 April '72	Sand	3.21	1.72	2.41	1.82	2.53	5.03	2.33	4.81
	Silt	28.90	32.41	29.30	32.52	35.02	36.00	42.91	41.23
	Clay	67.89	65.87	68.29	65.66	62.45	58.97	54.66	53.96
11 June '72	Sand	6.80	3.51	4.98	3.45	3.41	5.10	10.22	6.83
	Silt	43.15	47.63	44.42	49.76	49.33	46.76	46.13	46.81
	Clay	50.05	48.86	50.60	46.79	47.26	48.14	43.65	46.36
17 July '72	Sand	4.72	3.43	3.12	3.16	1.91	3.47	7.12	10.17
	Silt	42.57	40.45	43.36	46.98	47.45	42.97	44.53	43.68
	Clay	52.71	56.12	53.52	49.86	50.64	53.56	48.35	46.15

TABLE III (CONTD.)

	Station No.	22	23	24	25	26	27	28	29
[illegible] Sept. '72	Sand	1.65	1.63	1.68	0.00	0.00	0.00	2.51	3.29
	Silt	38.21	41.31	34.85	30.52	28.93	34.61	42.83	47.34
	Clay	60.14	57.06	64.47	69.48	71.07	65.39	54.66	49.37
10 Dec. '72	Sand	1.82	3.49	2.51	5.10	0.92	2.12	1.90	3.41
	Silt	34.15	32.31	34.81	28.93	35.63	41.24	42.83	37.43
	Clay	64.03	64.17	62.68	65.97	63.45	56.64	55.27	59.16
28 Feb. '73	Sand	3.44	1.68	1.66	4.07	6.79	3.42	5.13	5.17
	Silt	42.81	46.07	46.10	39.96	35.62	42.76	35.62	32.30
	Clay	53.75	52.25	52.24	55.97	57.59	53.82	59.25	62.53

The amount of sand is always less than 11% at all stations. The maximum percentage of sand is found at Station No. 28 (8 km offshore) during June and at Station No. 29 (10 km offshore) during July, 1972. The clay content in the bottom sediments decreases from April to July and shows a sudden increase during September. During this month, the bottom sediments at stations 25, 26 and 27 contain no sand, less silt and more clay. From September onwards, the clay fraction increases towards December and shows a slight decrease during February. During all months, the station nearest to the shore (Station No. 22) shows slightly more sand content than the other stations.

Fig. 32 shows the monthly variation of sand, silt and clay content of the bottom sediment at Station No. 26. The increase in the percentages of fine fractions during September may be due to the increased settling of the suspended load during this month due to the increase in the salinity of the overlying waters which enhances flocculated settlement. By September, the wave activity also decreases so that the bed load transport and also the supply by littoral currents diminishes considerably (see Chapter III). December, February and April observations show the typical characteristics of the bottom mud of the mud bank region as reported by earlier investigators. Dora, et al (1968) have reported that the mud bank sediments are essentially clays or silty clays whereas outside the mud banks, the sediments are silty clays or clayey silts and less commonly sand-silt clays or sandy silts. The results of the present investigations are in conformity with this.

(b) Density

The density of bottom sediments is important inasmuch as the processes of settlement, transport and suspension are concerned. The measurement of mud density is difficult as it has to be made on aggregates of fine particles. Attempts were made to estimate the density of the bottom mud by putting known weights of dried sediment particles in a long, narrow measuring flask and noting the volume of displaced water when all the particles have settled down. The density was found to be 2.6 gm/ml. The result may not be very accurate because of the likelihood of incomplete penetration of water into the interstices of the particles. It may also be noted that the density of the dehydrated mud thus determined does not represent the material as it occurs naturally (Grim, 1968). The density of the mud bank sediments can be slightly on the higher side of this value.

(e) Water content

Water is held by the bottom sediments at low temperatures in their interstitial spaces. The water content is of importance as it largely determines the plastic, bonding, compaction, suspension and other properties of the sediments. The weight percentage water content of the mud bank sediments was determined by finding the wet weight and dry weight of the bottom sediments. The *in situ* water content was found to vary between 59.28% and 72.47% (weight percentages). The minimum values were obtained during April and the maximum values during July. The water content increases from the premonsoon season to the monsoon season (mud bank active) and then again decreases towards the post-monsoon season (Fig. 32).

CHAPTER VI

WAVES AND CURRENTS

CHAPTER VI

WAVES AND CURRENTS

1. Introduction

The role of waves and wave-induced currents in the formation and movement of the mud banks has already been indicated in the foregoing discussion. This chapter deals with the characteristics and seasonal variation of waves and currents in the mud bank region at Purakad.

As waves approach shallow water, they lose energy due to bottom friction, percolation and the non-rigidity of the bottom. A wave moving from deep into shallow water continuously decreases in length and speed, while its height first decreases and then increases (Kinsman, 1965). When these waves enter water of depth approximately equal to the wave height, the waves become unstable and break. The depth of water in which waves break and the nature of the breakers depend upon the wave steepness (ratio of wave height to wave length) and the slope of the beach (Weigel, 1964). A breaking wave releases a part of the wave energy in the surf zone and this energy is used up in stirring up the bottom and carrying the material into suspension.

Refraction is an important process which changes the characteristics of the deep water waves as they pass through the shoaling waters. In depths smaller compared to the wave length, the wave velocity is dependent only on the water depth. If different parts of the wave crest are in waters of different depths, their velocities will also be different. This results in the bending of the wave which is known as wave refraction. The changes in wave characteristics caused by refraction can be assessed by constructing wave refraction diagrams (King, 1959).

A wave upon breaking becomes a wave of translation and because of the mass transport of water, a certain amount of water piles up against the coast when the wave breaks. The hydraulic head thus established is more in the region of convergence of energy and so there will be an alongshore flow from this region to the region of divergence. Converging alongshore currents will give rise to a strong offshore flow which is known as the rip current (Shepard, et al.,1941; Shepard and Inmann, 1950 and 1951; Mc Kenzie, 1959; Bowen, 1969 a and b; etc.).

2. Waves

The mud banks act as natural breakwaters by damping the waves considerably. During the southwest monsoon season, when the mud banks are active, the bank regions are calm but for small wavelets or ripples. Separating the calm area from the rough sea, there is a zone of moderate swells. Along the approximately semi-circular perifery of the calm zone, the wave height gradually increases outward. This feature can clearly be observed along the shore. Table IV gives the height and the orientation of the breakers with respect to the shoreline at 12 observation points (I-XII) along the shore. The location of these observation points are shown in Fig. 33. The breaker heights were determined using a graduated pole and the breaker orientation using an inclinometer. The observations were taken during a span of 3-4 hours on two consecutive days but have been considered synoptic in preparing Table IV.

From Table IV it can be seen that as the breaker height decreases towards the mud bank region, the angle between the breaker and the shoreline shows slight increase. There is successive damping of waves as we approach the centre of the mud bank from both north and south. The calm zone with only small wavelets or ripples is more extensive during July than during June and September. The extent of the mud bank seems to be determined by the wave activity outside the bank region. The higher the

TABLE IV

VARIATION OF HEIGHT AND ORIENTATION OF BREAKERS ALONG THE SHORELINE

Observation stations	10-11 June			16-17 July			3-4 September		
	Breaker height (cm)	Breaker angle (°)	Orientation w.r.t. shoreline	Breaker height (cm)	Breaker angle (°)	Orientation w.r.t shoreline	Breaker height (cm)	Breaker angle (°)	Orientation w.r.t. shoreline
I	200	0		250	0		250	0	
II	125	0		175	5		200	0	
III	50	5		125	5		200	0	
IV	25	13		50	15		175	10	
V	15	16		15	15		125	10	
VI	5 (W)	—		R	—		75	15	
VII	R	—		R	—		25	15	
VIII	R	—		R	—		W	—	
IX	10	5		R	—		W	—	
X	40	18		R	—		25	15	
XI	120	15		50	10		100	15	
XII	250	5		150	5		200	10	

(W - Wavelet; R - Ripples)

wave activity the more extensive is the mud bank.

The orientation of the breaker with the shoreline indicates that the direction of flow of the alongshore currents is towards the bank area from the northern as well as the southern side of the bank. This is in conformity with the results of the wave refraction studies reported by Thirupad (1971) and Reddy and Varadachari (1972) and the observations presented by Varma and Kurup (1969).

3. Damping of waves

As mentioned earlier, the most remarkable feature of the mud banks is the calmness of the bank areas. In 1860, Taylor (Records of the Geological Society, Vol. XVII, p. 21) explained the calmness of the mud bank as due to the soft mud that comes into suspension during the season when the mud bank is active. In 1881, King (Bristow, 1938) attributed the damping of waves in the mud bank regions to the presence of oil in the mud. Keen and Russel (Du Cane, et al. 1938) maintained that oil as such was not present in the mud bank region and that even if a little oil was present, a thin film of oil could not produce such a pronounced damping of waves as actually observed in the banks. They attributed the claiming effect to the mud, which, when in suspension, increases the viscosity of water and causes viscous damping of waves. Various authors (Damodaran and Hridayanathan, 1966; Varma and Kurup, 1969; Damodaran, 1973) seem to have generally accepted this view of viscous damping of waves in the mud banks. This aspect will be examined in greater detail in the following paragraphs.

It is known that substances which are either mixed with water, such as mud, ice, seaweed, eel grass, etc., or cover the sea, like some oils and even fresh water, can prevent the regular development of waves and cause existing waves to decay (Defant, 1961).

Observations of the author during a period of five years at various mud banks along the Kerala coast have shown that the mud banks present an oily appearance at the surface only after intense fishing activity starts in the bank region. This oil may be due to the oil (such as Sardine oil etc.) used generally for preserving the wood of the country boats and the oil released by the dead and degenerating fish in the area. The fishing activity is always preceded by the formation of the calm zones.

Viscosity is the internal friction of fluids caused by the intermolecular cohesive forces. For pure water the coefficient of viscosity, η has a value of 0.01797 gm cm/sec (poise) at 0°C, 0.01002 poise at 20°C and 0.00653 poise at 40°C. With increasing temperature η decreases rapidly but increases only slightly with increasing salinity. By comparison, the influence of pressure is very small (Sverdrup, et al. 1942). The internal friction of fluids can dampen any oscillations taking place within the fluid.

The theoretical treatment of viscosity of colloidal suspensions is one of considerable difficulty. In this case, the usual definition of η in the form

$$f = \eta \frac{du}{dz}$$

does not hold good because the viscosity coefficient varies with some function of the velocity gradient. No results on the viscosity of coagulating mud suspensions are available and the question of their Newtonian behaviour or otherwise is quite unanswerable.

The only available treatment that finds application in the present context is that of Albert Einstein (Ann. der. Physik., (1906) 19: 289), who in 1906 showed that if the colloidal particles are taken to be approximately spherical and are non-ionised, then for low concentrations the viscosity η' of the suspension is related to the viscosity η of the liquid and the volume concentration C by the relation

$$\frac{\eta'}{\eta} = 1 + 2.5\,C$$

It may be remembered that in the case of mud suspensions, this relation can be applied to mud in fresh water only (non-ionised). Only the aggregate volume of the spheres, not their size, comes into question. The formula has been tested with suspensions containing globules of 0.6 μ - 8 μ in diameter and found to hold good as long as the concentrations are not too high. For higher concentrations, a term C^2 has to be added (Hatschek, 1928; Newman and Searle, 1959; Encyclopaedia Britannica, 1973). At the suspension concentrations encountered in the mud banks the Einstein formula ought to apply fairly well (Dr. R. B. Whittington, personal communication).

Table V gives the dynamic viscosity η', density ρ' and kinematic viscosity $\nu = \frac{\eta'}{\rho'}$ of mud suspensions for various concentrations from 100 mg/l to 2000 mg/l in fresh water at 20°C (η = 0.01 poise) assuming the density of water to be 1.0 gm/ml, and the density of mud to be

2.6 gm/ml. As can be seen from Table V the kinematic viscosity increases from 0.01 poise for pure water to 0.029 poise when the concentration of suspension is 2000 mg/l. The maximum concentrations encountered in the mud bank in the surface, mid-depth and one metre above the bottom are only slightly above 1500 mg/l (Chapter III).

Let us now consider the damping that waves will undergo in liquids having these viscosity values. According to Lamb (1932), the damping time for waves is given by

$$\tau = \frac{\lambda^2}{8\pi^2 \nu} ,$$

where τ is the damping time or the modulus of decay which represents the time required in seconds for the wave height to be reduced to the fraction e of its original value, λ is the wave length in cm and ν is the kinematic viscosity.

Using this relation, the values of τ for various values of ν for waves having length of 1 m have been calculated and tabulated in Table V. A one metre long wave takes about 3.5 hours to be damped to $\frac{1}{e}$ of its original amplitude in pure water and it takes as much as 1.2 hours even when the suspension concentration is 2000 mg/l.

T A B L E V

RELATION BETWEEN SUSPENSION CONCENTRATION, VISCOSITY, AND WAVE DECAY

Concentration mg/l	Volume concentration ml/l	η' (Poise)	ρ' gm/ml	ν	τ (hours)
0	0	0.01	1.0	0.01	3.515
50	0.019	0.01048	0.00002	0.010479	3.348
100	0.038	0.01096	1.00005	0.010959	3.208
200	0.076	0.1190	1.00011	0.011898	2.954
300	0.115	0.01288	1.00017	0.012877	2.729
400	0.153	0.01383	1.00024	0.013826	2.543
500	0.192	0.01480	1.00030	0.014795	2.376
600	0.230	0.01575	1.00036	0.015744	2.233
700	0.269	0.01673	1.00042	0.016722	2.102
800	0.307	0.01768	1.00048	0.017671	1.989
900	0.346	0.01865	1.00053	0.018639	1.886
1000	0.384	0.01960	1.00061	0.019588	1.795
1100	0.423	0.02058	1.00067	0.020566	1.709
1200	0.461	0.02153	1.00073	0.021514	1.634
1300	0.500	0.02250	1.00079	0.022482	1.564
1400	0.538	0.02345	1.00085	0.023430	1.500
1500	0.576	0.02440	1.00091	0.024377	1.442
2000	0.769	0.02923	1.00122	0.029194	1.204

This shows that the viscosity increase due to contamination by suspended mud at the surface, mid-depth and at levels 1 m above the bottom has no appreciable effect on the decay of wave heights.

In addition to viscous damping by the medium, wave energy is dissipated by way of bottom friction and percolation (Putnam and Johnson, 1949; Putnam, 1949). A non-rigid bottom also contributes considerably to the loss of wave energy and to the changes in wave characteristics (Wiegel, 1964). The wave decay due to the elasticity of the bottom by far exceeds the rates given by bottom friction and percolation (Gade, 1958 and 1959). Gade refers to a location on the Louisiana coast where the bottom mud acts as a viscous fluid and causes so pronounced damping of waves that in rough weather, the local fishing boats use it as an emergency harbour. Gade has developed a model which shows that an 8 sec wave, 2.0 ft high, travelling in 4 ft of water over a bottom with a layer of mud which is 1.5 ft thick and 1000 ft long, will be only 37% as high at the end of the stretch of mud as at the start. Gade's model seems to have closer analogy with the process of wave damping in the mud banks than the classical contention of viscous damping by the muddy waters. In the mud bank, settlement of the suspended load of sediments takes place continuously (Chapter IV) and the settled muds remain in a loose, unconsolidated, ooze-like state having an in situ water content of about 70% (Chapter V). It appears that the energy absorption at the visco-elastic bed of the mud bank during the season when the mud bank is active affects the wave decay more than the internal viscosity of the overlying mud laden waters.

Thus, the premonsoon swells churn up the bottom mud and very near the shore they are in turn damped by the loose bottom mud in the regions of converging along-shore currents.

4. Currents

Figure 34 shows the speed and direction of surface currents within and around the Purakad mud bank region during June, July and September. The observations have been made using surface drifters and following up their movements by fixing their successive positions at regular intervals of time with a sextant. The first observations were taken on the 10th and 11th of June, 1972, when the mud bank activity had set in as indicated by surface calmness, turbidity, etc. The July observations were made during 18 - 20th July when the mud bank activity was at its maximum. During 3 - 5 September, when the third set of observations were taken, the mud bank activity had decreased as indicated by increase in wave activity in the mud bank region and decrease in turbidity. The observations have been made without considering the phase of the tides but the tides do not exert appreciable effect on the current pattern in this part of the Kerala coast where the shoreline is almost straight and where there are no rivers or streams joining the sea.

During June, when the mud bank has partially formed, the alongshore components of the currents are slightly stronger on the southern side than on the northern side of the mud bank. The offshore flows are quite strong (35 cm/sec.). During July also, the alongshore components are slightly stronger on the southern side of the mud bank. By September the alongshore components of the flow have decreased in strength and the trend of flow is towards south with speeds generally less than in July.

These converging alongshore currents give rise to offshore flows which can carry finer sediments offshore and prevent onshore transport by waves. Thus localisation of finer sediments in suspension takes place at the rip head. The onshore transport of bed-load by higher period waves might be taking place all along the Kerala coast during the premonsoon and monsoon months and in the regions of rip flows localisation of high concentrations of suspended sediments takes place.

The author of this thesis had suggested (Kurup, 1972) that the movement of mud bank is the result of changes in the location of rip flows which is determined by changes in the refraction pattern caused by changes in the bathymetry and in the spectrum of waves approaching the shoreline. The relative importance of these two parameters is difficult to judge. The bathymetric changes due to deposition of mud in the mud bank region are, however, gradual and uniform and may be responsible for the slight year to year shift in the location of the mud bank.

The direction of wave approach in relation to the orientation of the coastline may also be responsible for the slow southward movement of the mud banks. The predominant direction of wave approach varies between WSW and WNW which can be expected to produce a gradual year to year southerly shift of the mud bank formations along this coast which is oriented in the NNW - SSE direction. The relative strength of the alongshore currents on either side of the mud bank may be responsible for the slight alongshore movements exhibited by the mud banks within the period of their activity during a year.

CHAPTER VII

SUMMARY AND CONCLUSIONS

CHAPTER VII

SUMMARY AND CONCLUSIONS

A detailed survey of the present knowledge on the physical aspects of the mud banks has been presented in Chapter I. The physical, geographical and geological aspects of the Kerala coast, the shore-line and the sea bed and the various views on the formation, movements and dissipation of the mud banks have been discussed. The scope of the present work and a description of the area of study have also been given in this Chapter.

Results of hydrographic investigations conducted in the region of the mud bank at Purakad during 1971-73 are presented in Cahpter II. The seasonal variations in the hydrographic parameters of the mud bank region show close relationship with the rainfall during monsoon and the seasonal heating during summer. Though the general patterns of distribution and seasonal variations of temperature and salinity of the inshore waters at Purakad are identical both in the mud bank region and the surroundings, during the season when the mud bank is active, the surface and sub-surface waters in the mud bank show slightly greater dilution compared to the waters in the surrounding area. This dilution, which decreases from surface to subsurface waters and disappears near the bottom, is caused probably by rip-flows which carry low salinity water from the nearshore region into the mud bank region.

The horizontal and vertical distributions and the seasonal variations of the concentration of suspended matter in the mud bank region are discussed in Chapter III. It is seen that the mud bank rises above the bottom in the form of a ridged, irregular, solid cone with a flat top. The concentration of suspended matter attains maximum values during July when the extent of the mud bank is also more. The shape as well as the location of the centre of the mud bank undergo slight changes within the period of its activity during a year.

The isolines of concentration at the surface and mid-depth levels indicate supply of suspended sediment from either side of the mud bank into the mud bank along the shallow nearshore region. These opposing alongshore flows give rise to rip flows which carry suspended sediments towards offshore and meet with the onshore bed-load transport of sediments by waves. This leads to localisation of high concentrations of suspended sediments in the vicinity of the 10 m line. The mud banks appear to be formations similar to the coastal 'plumes' which have been identified at certain locations in the world where there is convergence of coastal currents resulting in a current across the shelf.

Chapter IV presents the results of laboratory experiments on flocculation and settlement of suspended mud under various salt concentrations in three different mud samples from the mud bank region. The flocculated settlement varies considerably with the grain size composition and the mud of the mud bank shows close response to salinity fluctuations. The results when applied to the mud bank region show that in the mud bank, even during the monsoon season, flocculated settlement prevails over deflocculated suspension and indicate that there is a continuous supply of suspended mud to the water column so that the mud bank continues to exist throughout the monsoon season.

In Chapter V, the results of textural analysis of 48 sediment samples, collected from 8 stations in the

Purakad mud bank region during different months, are presented and discussed. The sand content of the sediments is never above 11% and the clay fraction varies between 43.65% and 71.07% during the period June to September (weight percentage). The clay content decreases from April to July and shows a sudden increase during September. This may be probably due to the increased settlement of suspended material from the overlying waters during September. The density of the bottom mud is found to be 2.6 gm/ml and the _in situ_ water content varies from 59.28% to 72.47% (weight percentage) between April and July.

Chapter VI deals with waves and currents in the region of the mud bank. The orientation of the breakers on either side of the mud bank suggests the possibility of formation of opposing alongshore currents and convergence of energy caused by wave refraction. The extent of the mud bank is closely related to the wave activity in the surrounding region. The higher the wave activity, the more extensive is the mud bank.

The distribution of currents during the formative, mature and dissipating stages of the mud bank show that the converging alongshore currents give rise to offshore flows. These offshore flows can carry finer sediments offshore and prevent the onshore transport by waves. Thus localisation of finer sediments in suspension takes place at the rip head. The onshore transport of bed-load by higher period waves might be taking place all along the coast just before the monsoon and during the monsoon months and in the regions where this meets with the offshore transport of suspended matter by the rip flows, formation of mud banks takes place. With the decrease in wave activity during September, the supply of sediments in suspension from both the onshore and offshore directions decreases. Also, the increase in salinity during the post-monsoon months enhances settlement of suspended mud and the mud bank gradually disappears.

The predominant direction of wave approach in relation to the orientation of the coastline may be responsible for the slow, southward, year-to-year movement of the mud banks. The relative strength of the alongshore currents on either side of the mud banks caused by changes in the wave refraction pattern and the spectral composition of waves may be responsible for the slight alongshore movements exhibited by the banks during the period of their activity in a year.

The damping of waves in the mud banks is generally attributed to the increase in viscosity of water due to suspension of mud. Using the relation proposed by Albert Einstein for colloidal suspensions, it has been shown that viscosity increase due to contamination by suspended mud at the surface, mid-depth and at levels 1 m above the bottom in the mud bank region has no appreciable effect on the wave amplitude. In the mud bank, settlement of suspended mud takes place continuously and the settled mud remains in a loose, unconsolidated, ooze-like state. The energy absorption at this visco-elastic bed affects the wave decay more than the internal viscosity of the overlying mud-laden waters.

Results of the investigations on the seasonal and spatial variations of the hydrographic parameters and suspended mud and its flocculation and settlement, physical properties of the bottom sediments and waves and currents in the region of the mud banks along the Kerala coast with special reference to the Purakad mud bank, have been presented in this thesis. The investigations show that the formation and movement of the mud bank is closely associated with the activity of higher period waves and their refraction pattern and also the fineness of the bottom sediments in the nearshore regions of the Kerala coast adjacent to the backwater system. The location of the mud bank is decided by the location of the zone of converging littoral currents and the associated offshore flow which carries a large quantity of suspended sediments and low salinity water from the nearshore regions. Mud in suspension is supplied continuously to the mud bank from both the nearshore and offshore directions, the former by rip flows and the latter by the churning action of waves. This supply compensates the loss due to settlement of mud and due to currents which may take away some material out of the area. The decrease in wave activity and the enhanced settlement lead to the disappearance of the mud banks during the postmonsoon months. The studies show that the movement of the mud bank is related to the direction of wave approach and the relative strength of the littoral currents on either side of the mud bank.

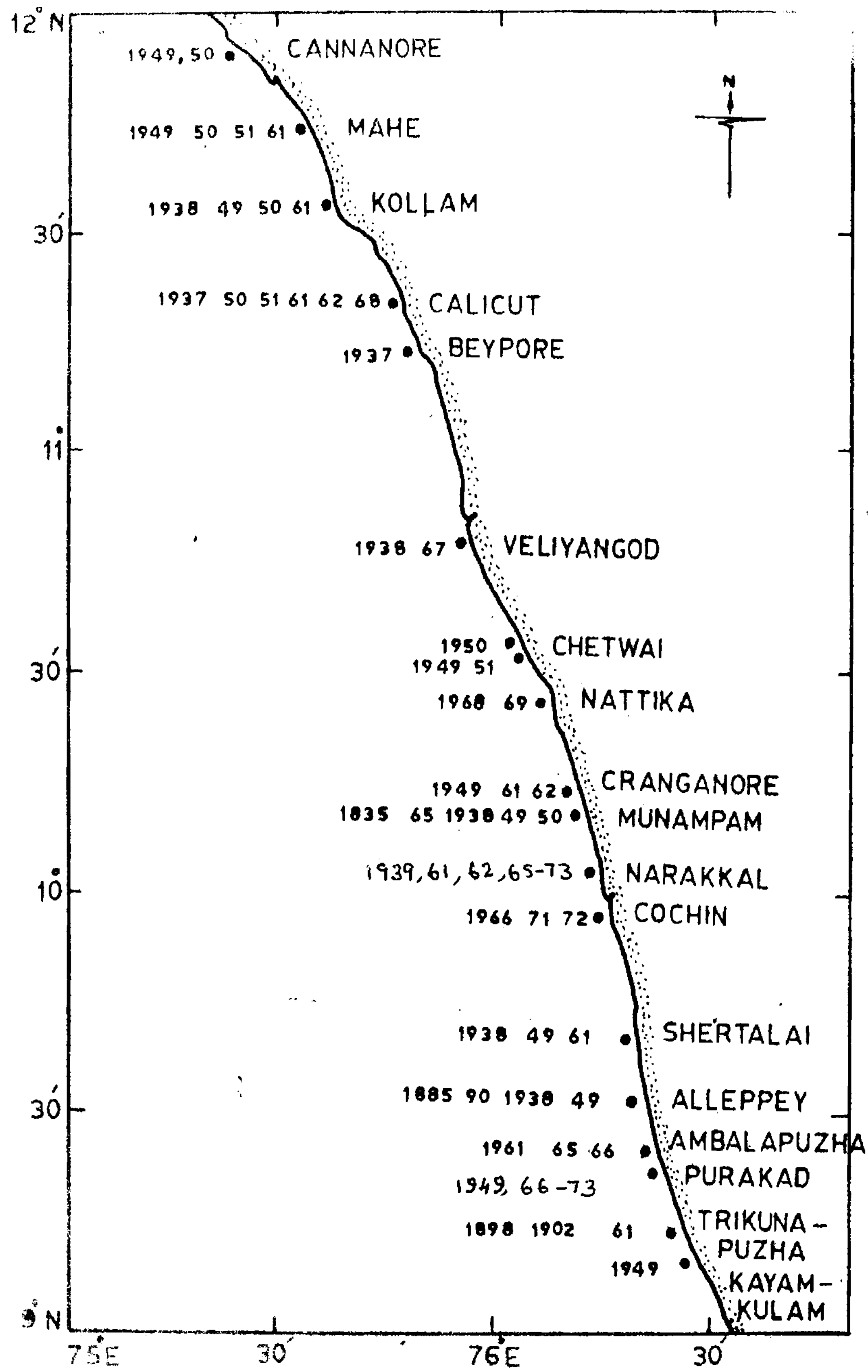


Fig.1 Location of mud banks during 1835 - 1973

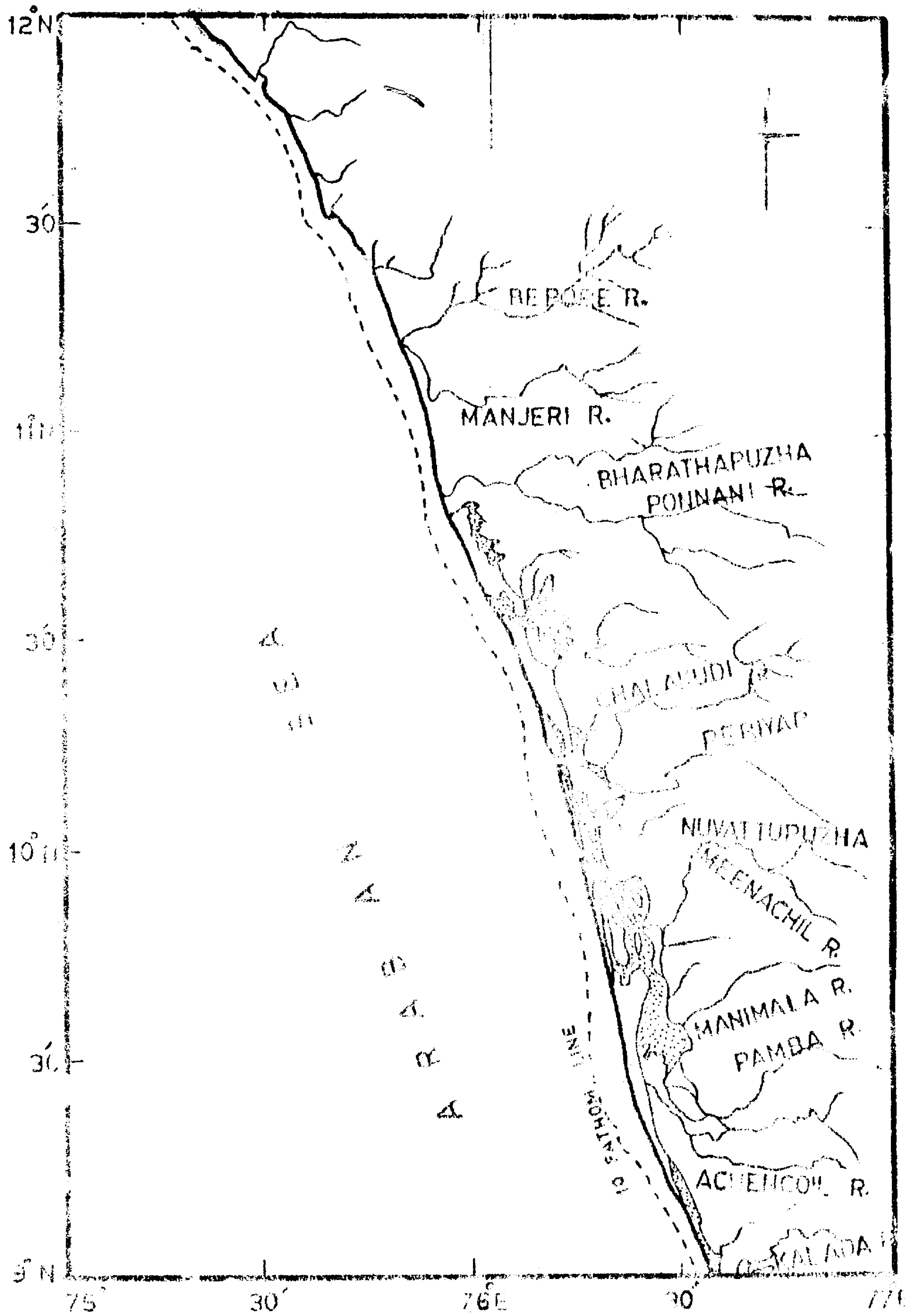


Fig.2 Geographical map of the Kerala coast

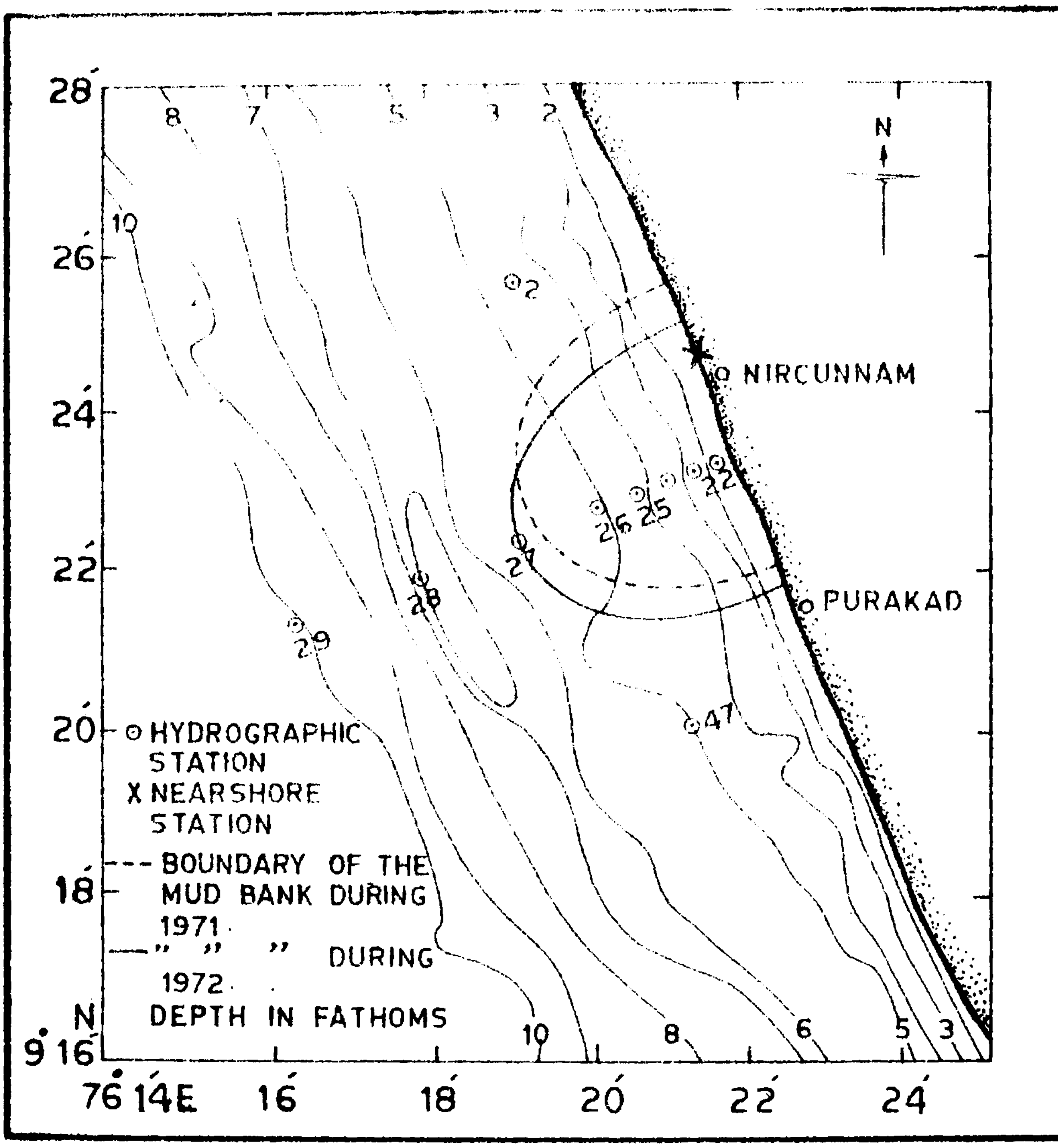


Fig.3 Location of hydrographic stations

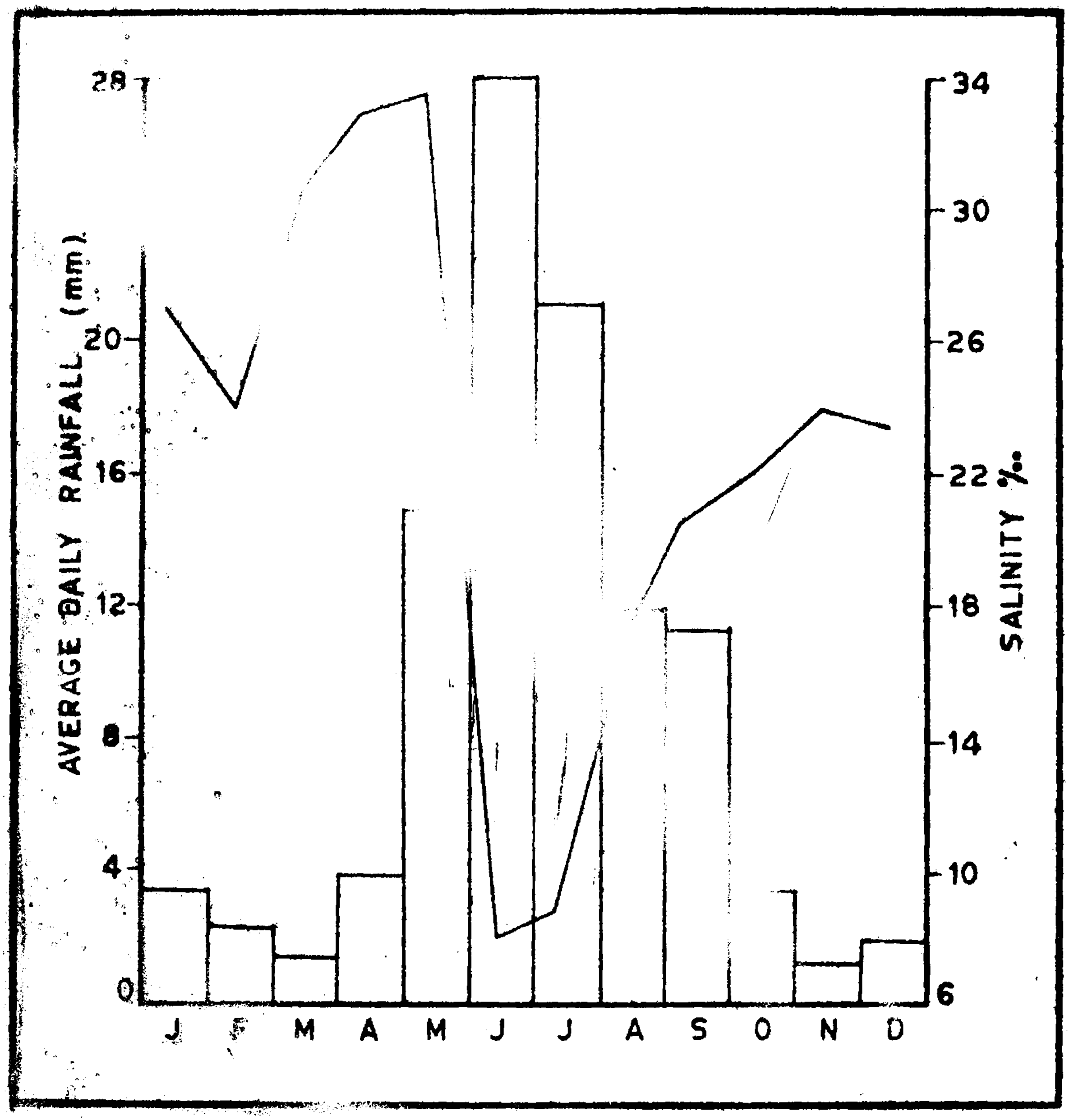


Fig.1 Monthly variation of salinity at nearshore station 'N'

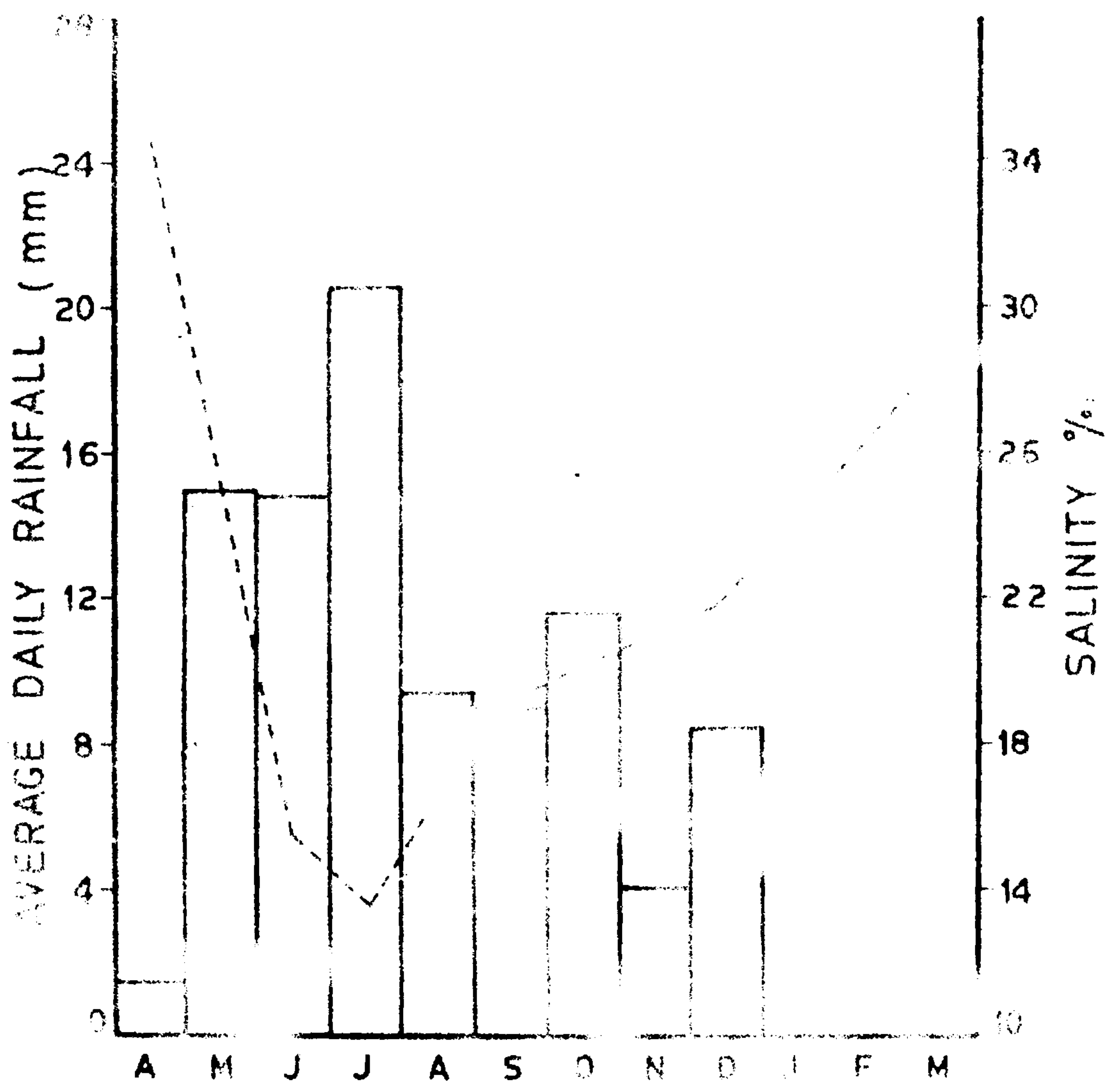
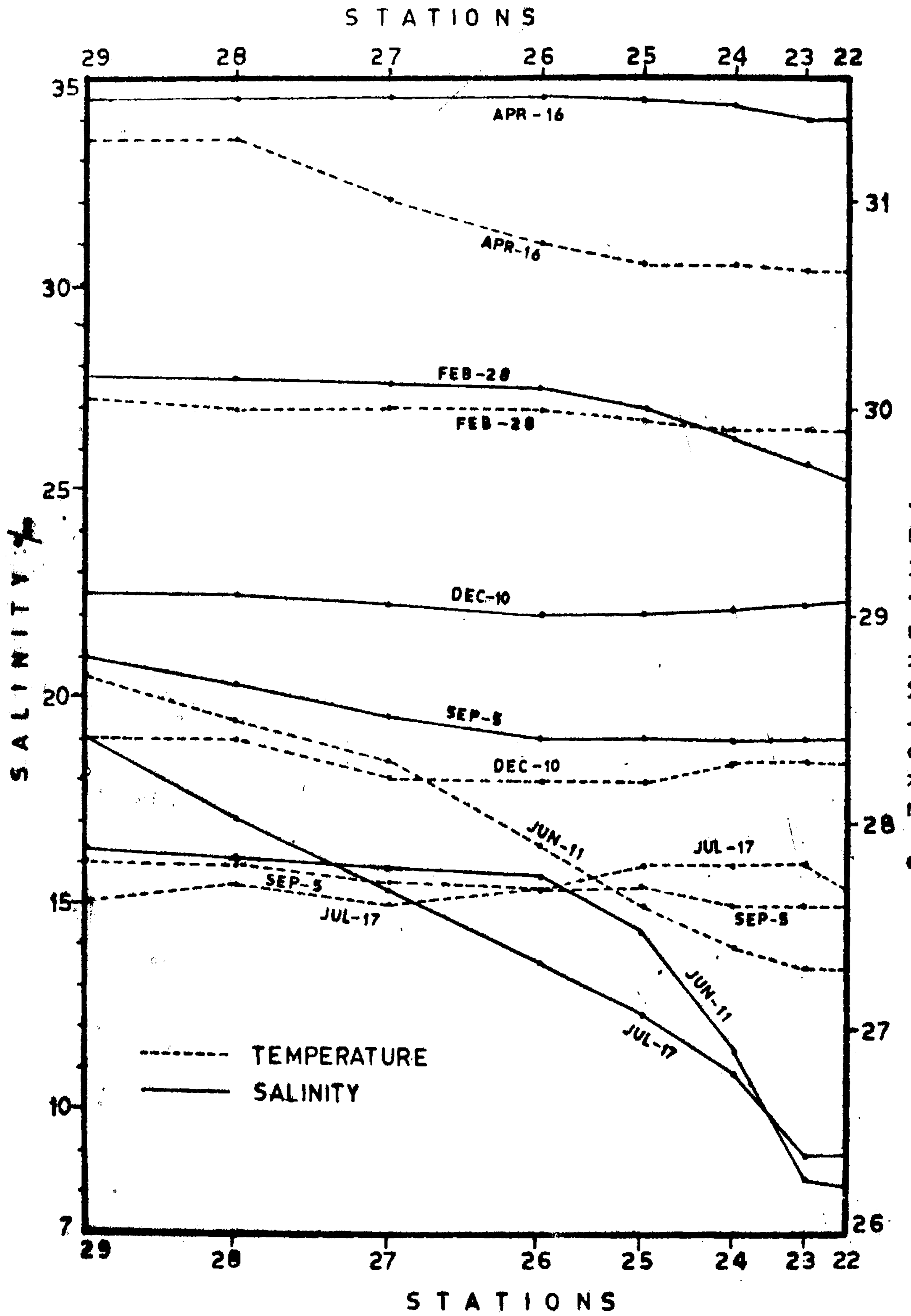


Fig.5 Seasonal variation of surface salinity at

Station No. 26



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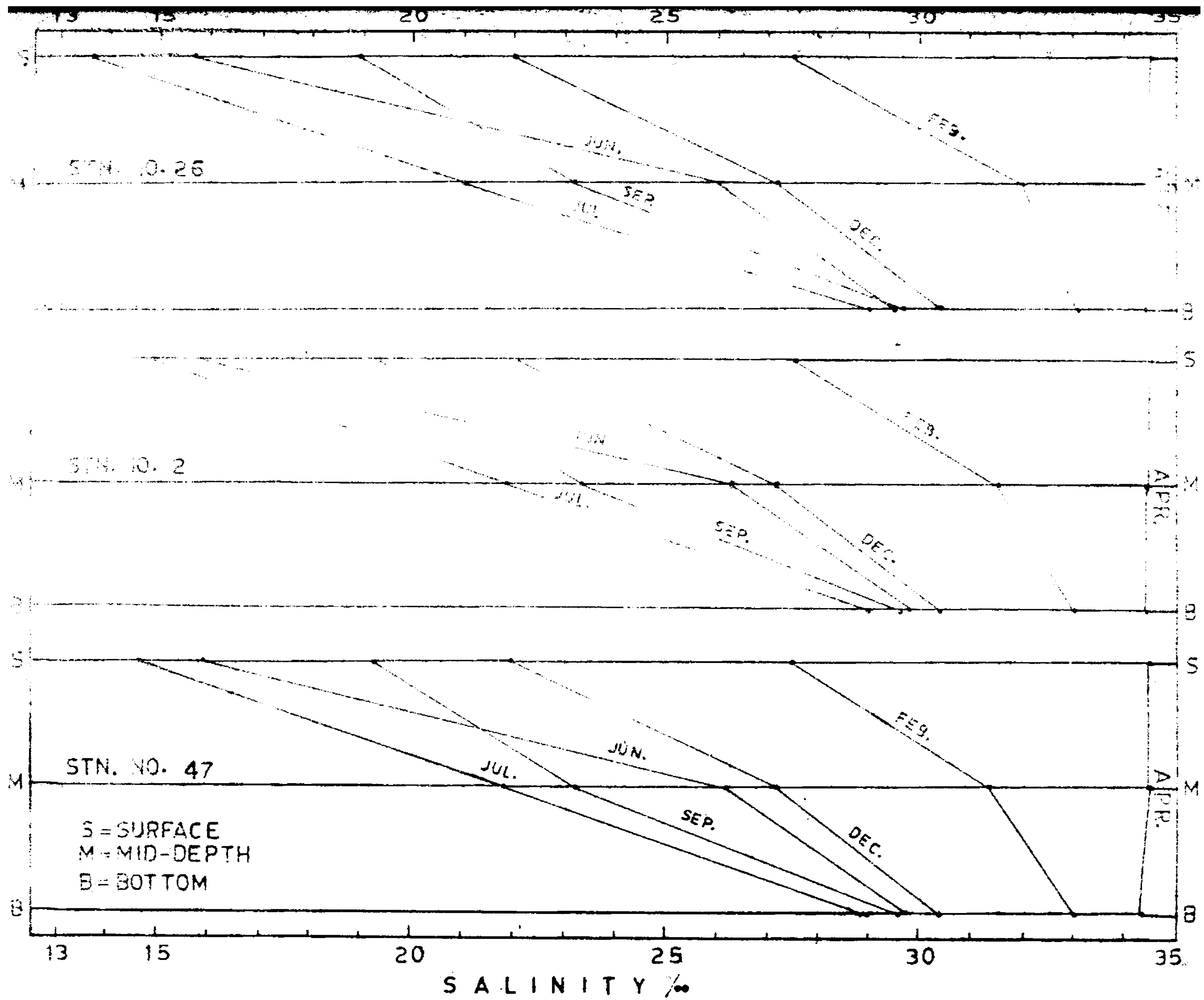
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S = SURFACE
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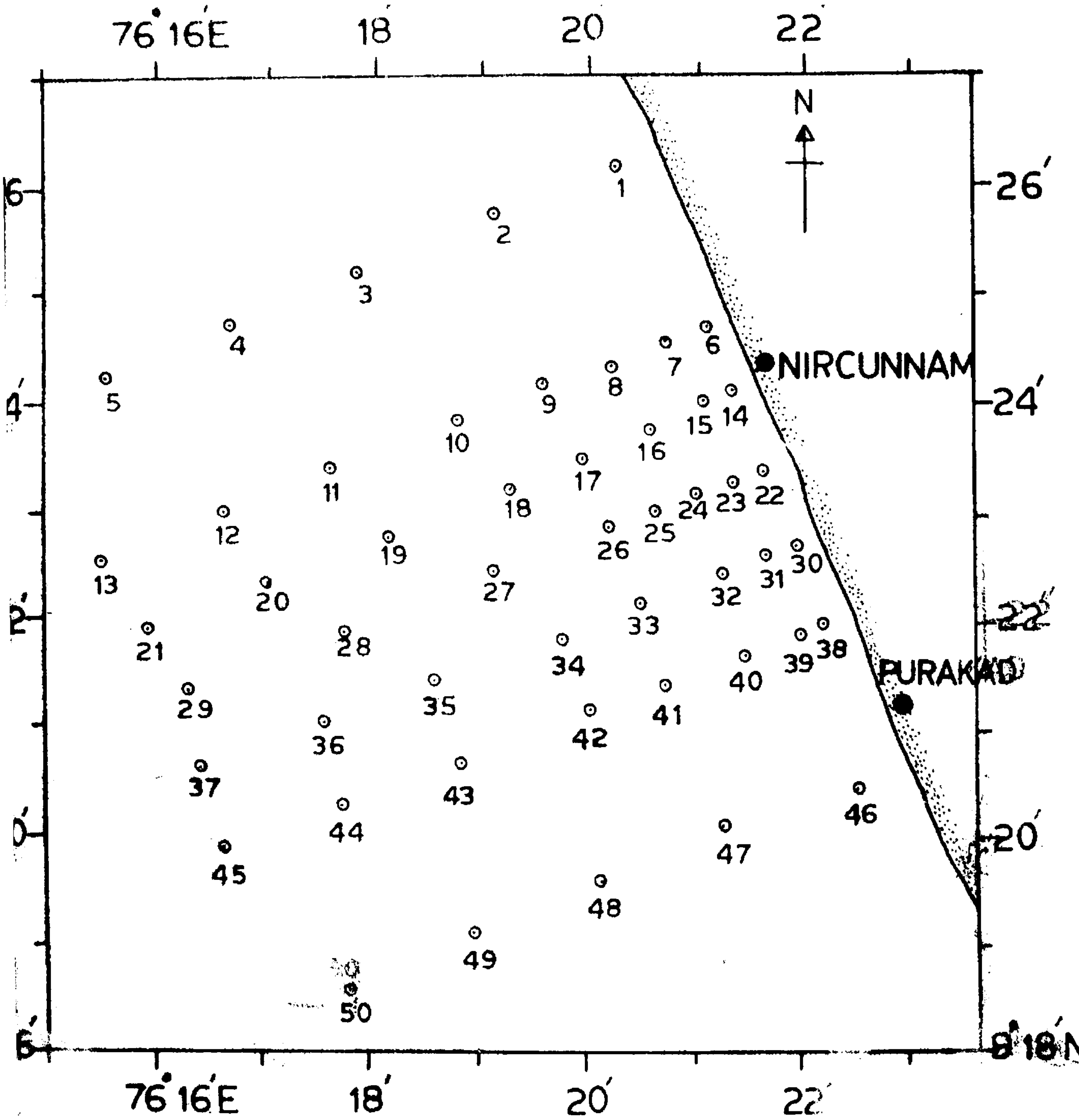


Fig.8 Location of seston stations

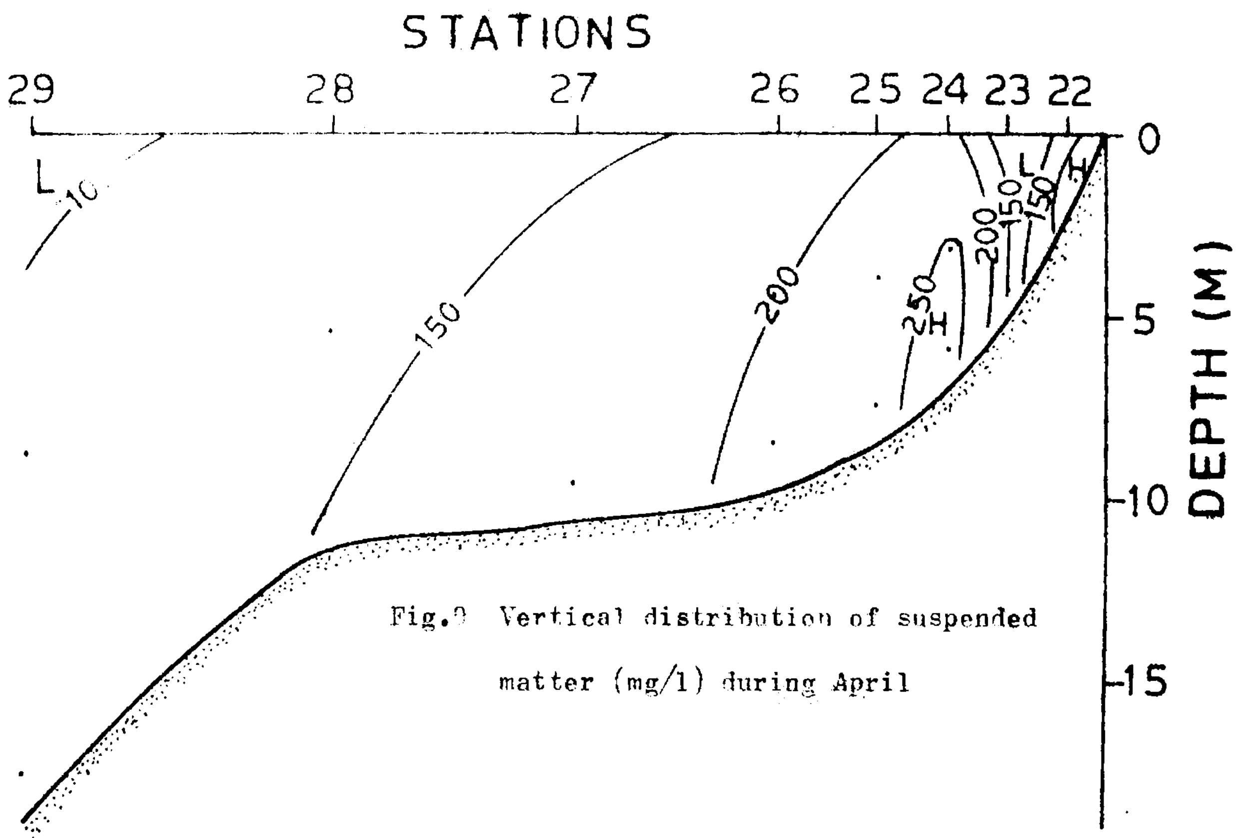


Fig.9 Vertical distribution of suspended matter (mg/l) during April

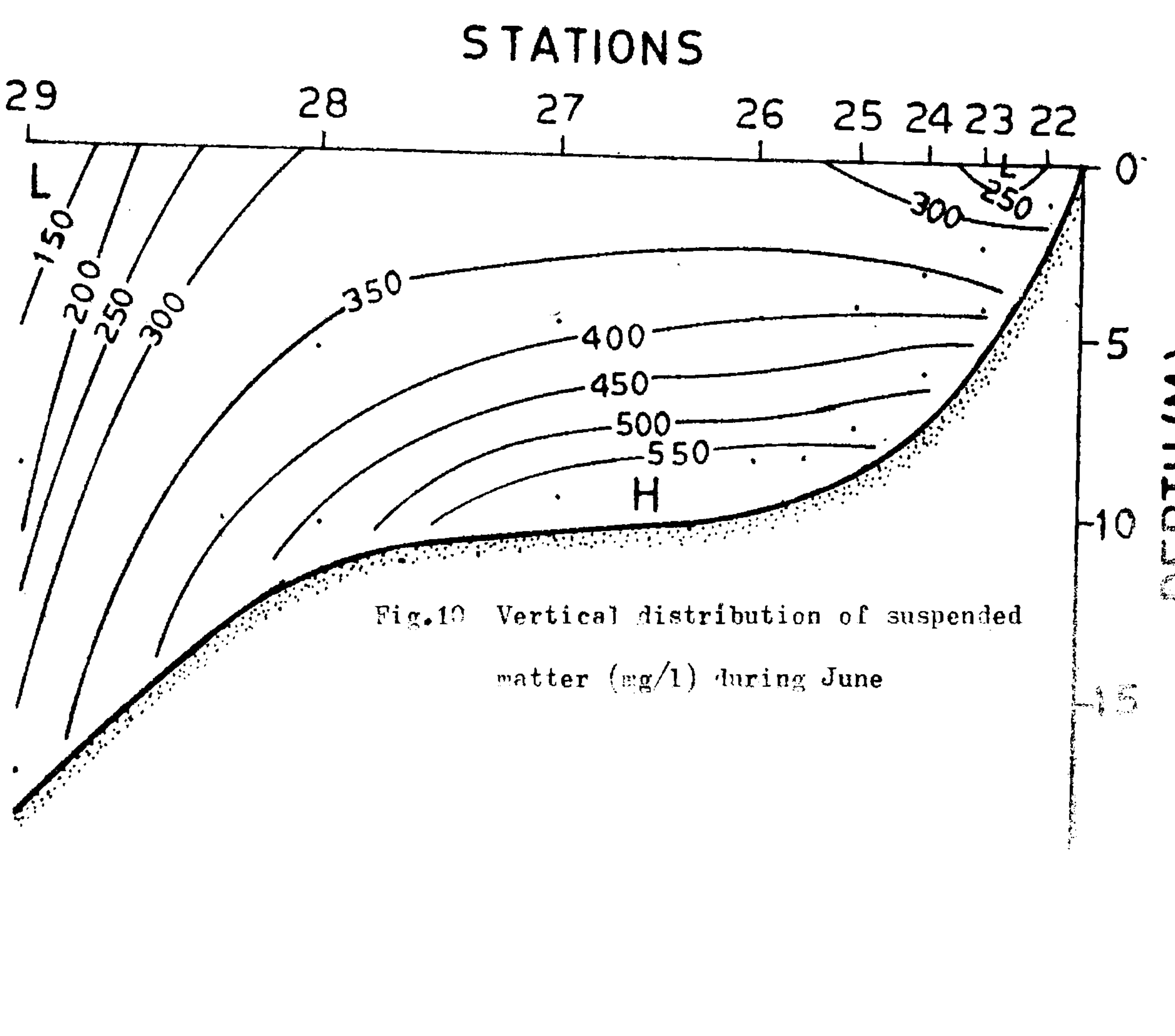


Fig.10 Vertical distribution of suspended matter (mg/l) during June

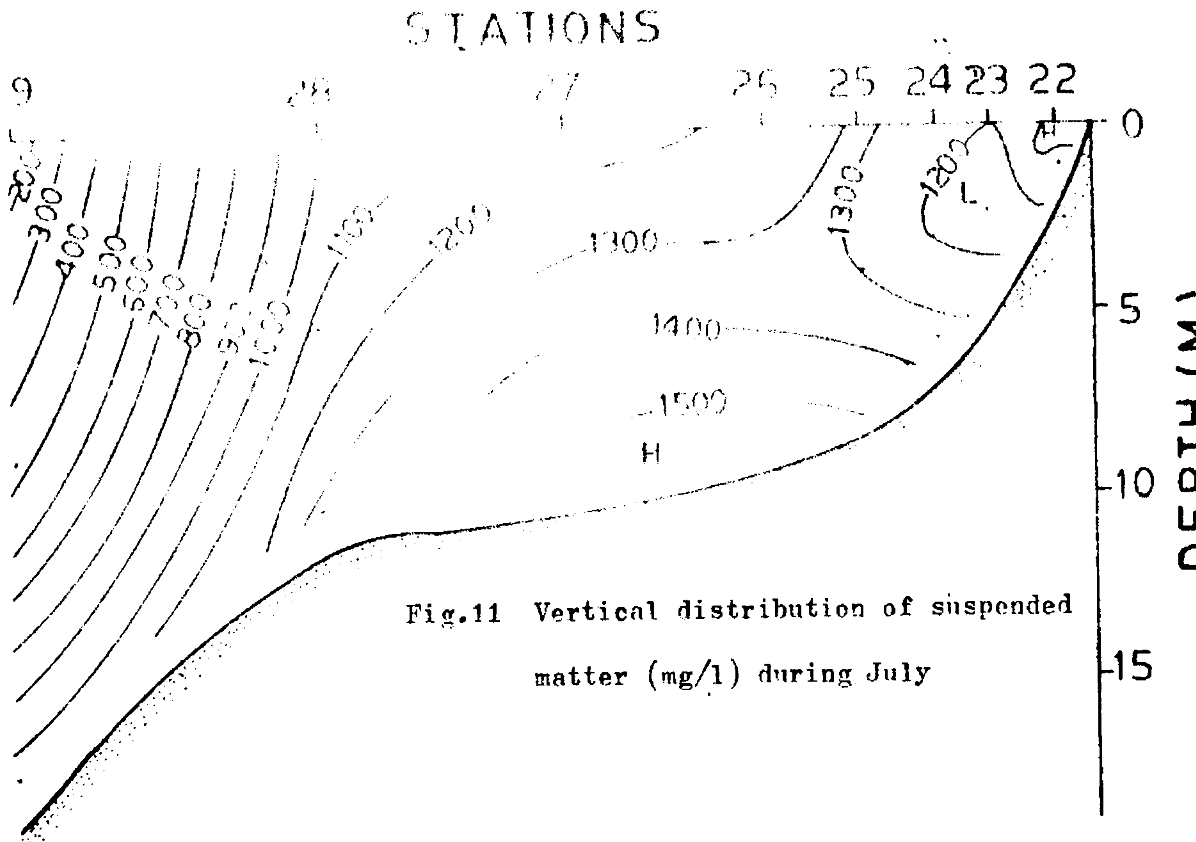


Fig.11 Vertical distribution of suspended matter (mg/l) during July

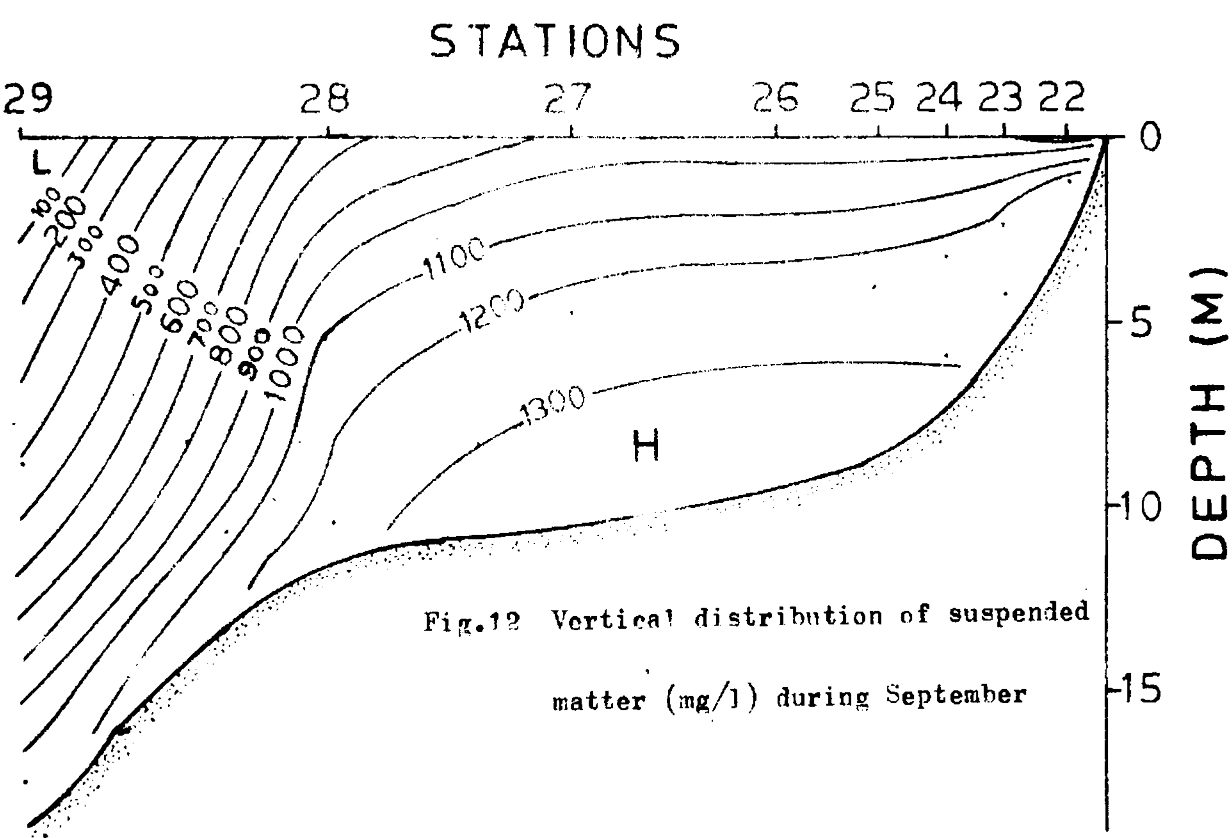


Fig.12 Vertical distribution of suspended matter (mg/l) during September

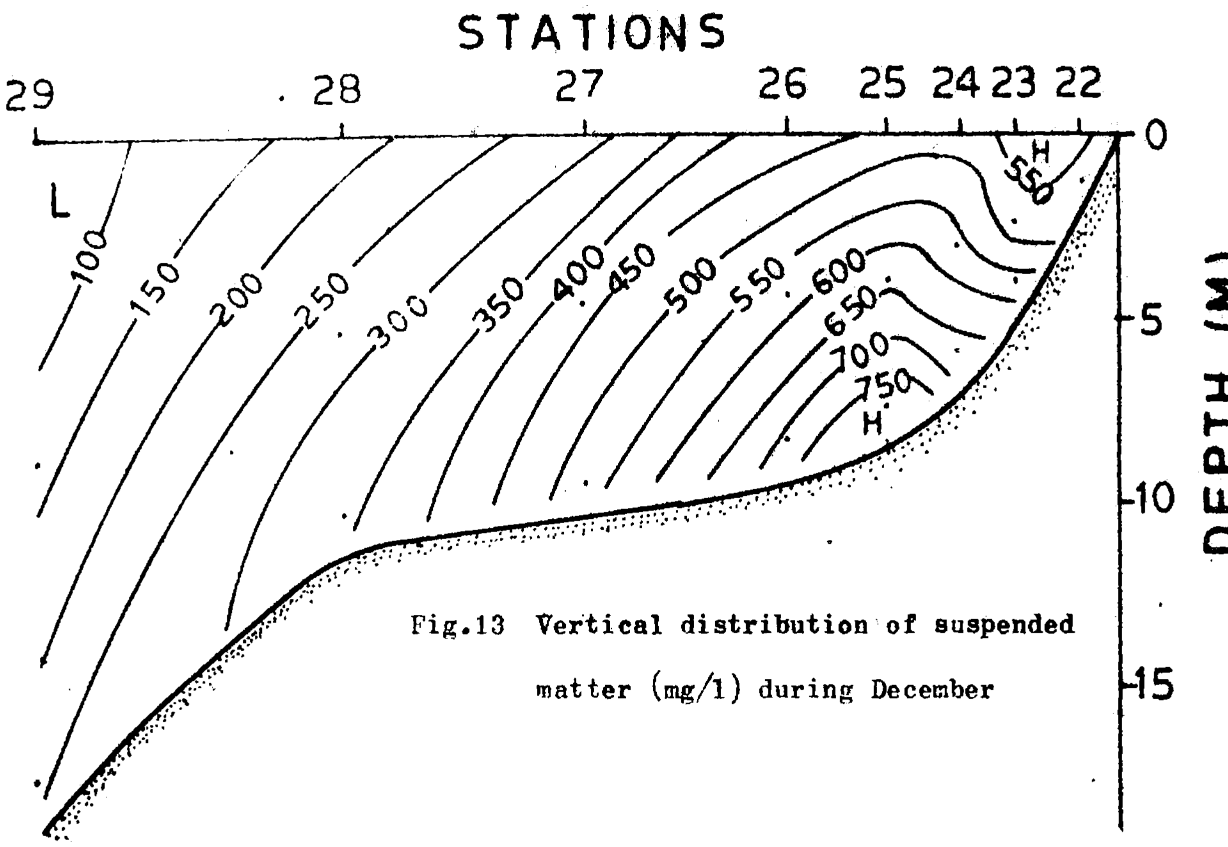


Fig.13 Vertical distribution of suspended matter (mg/l) during December

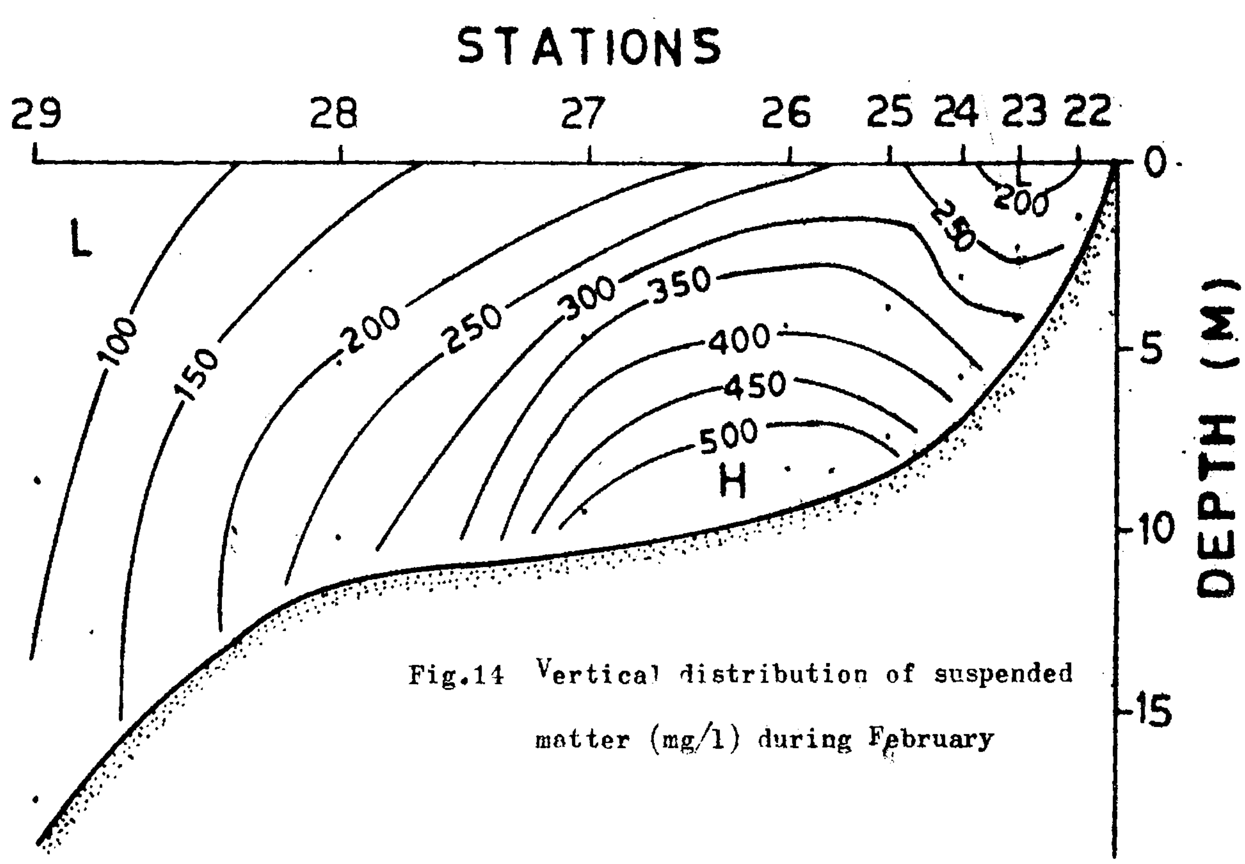


Fig.14 Vertical distribution of suspended matter (mg/l) during February

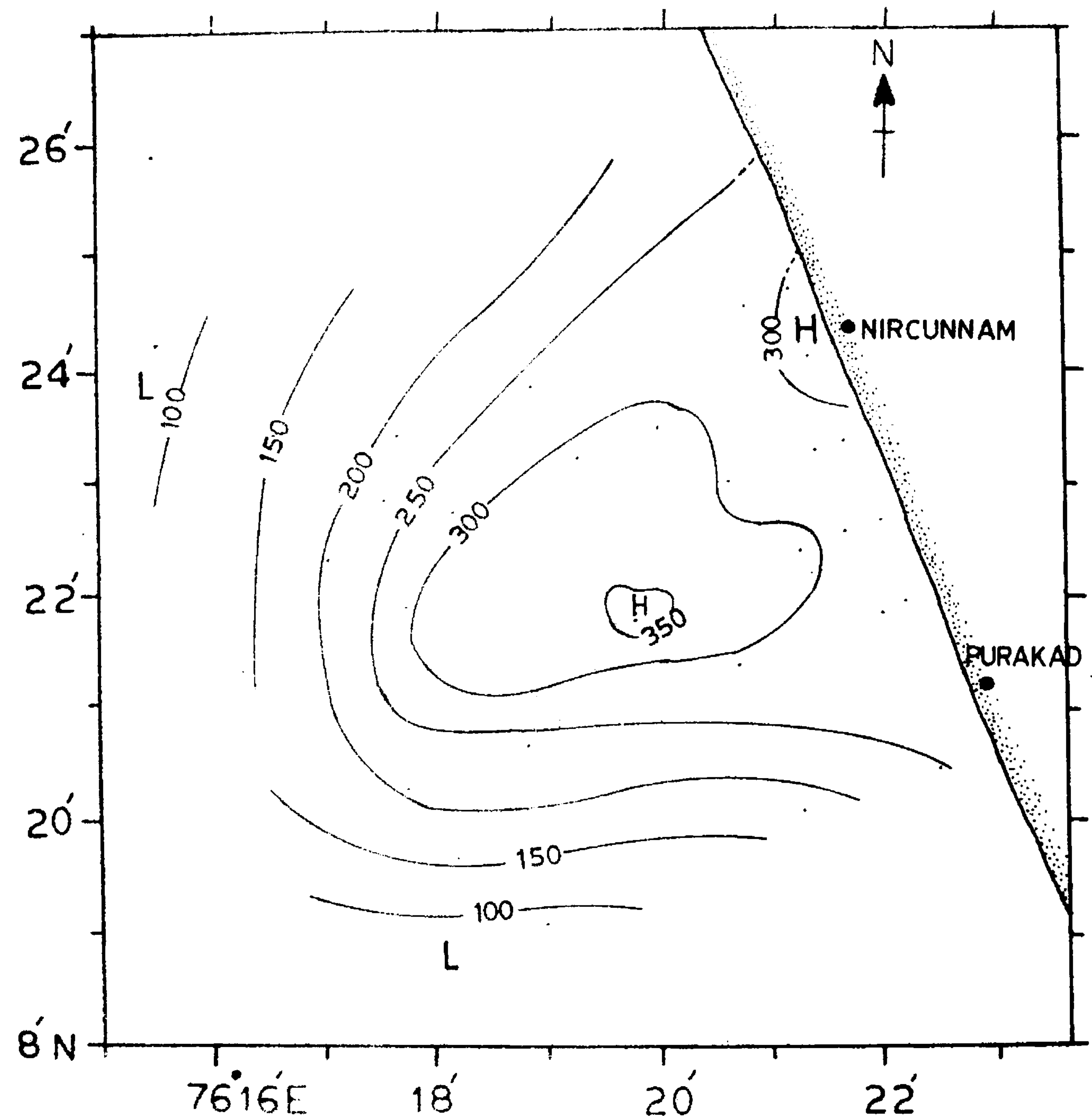


Fig.15 Horizontal distribution of suspended matter (mg/l) during June (surface)

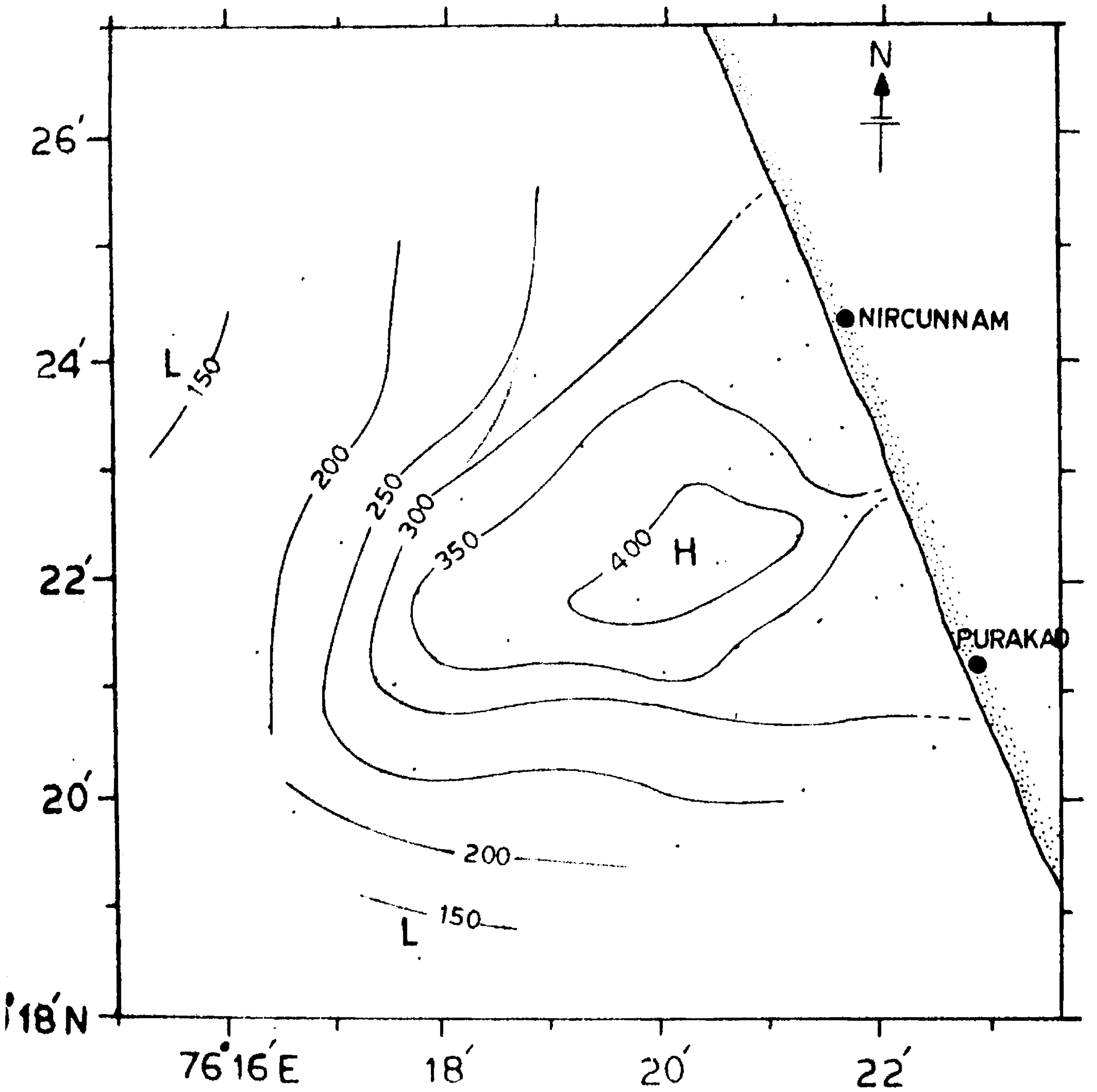


Fig.16 Horizontal distribution of suspended matter (mg/l) during June (mid-depth)

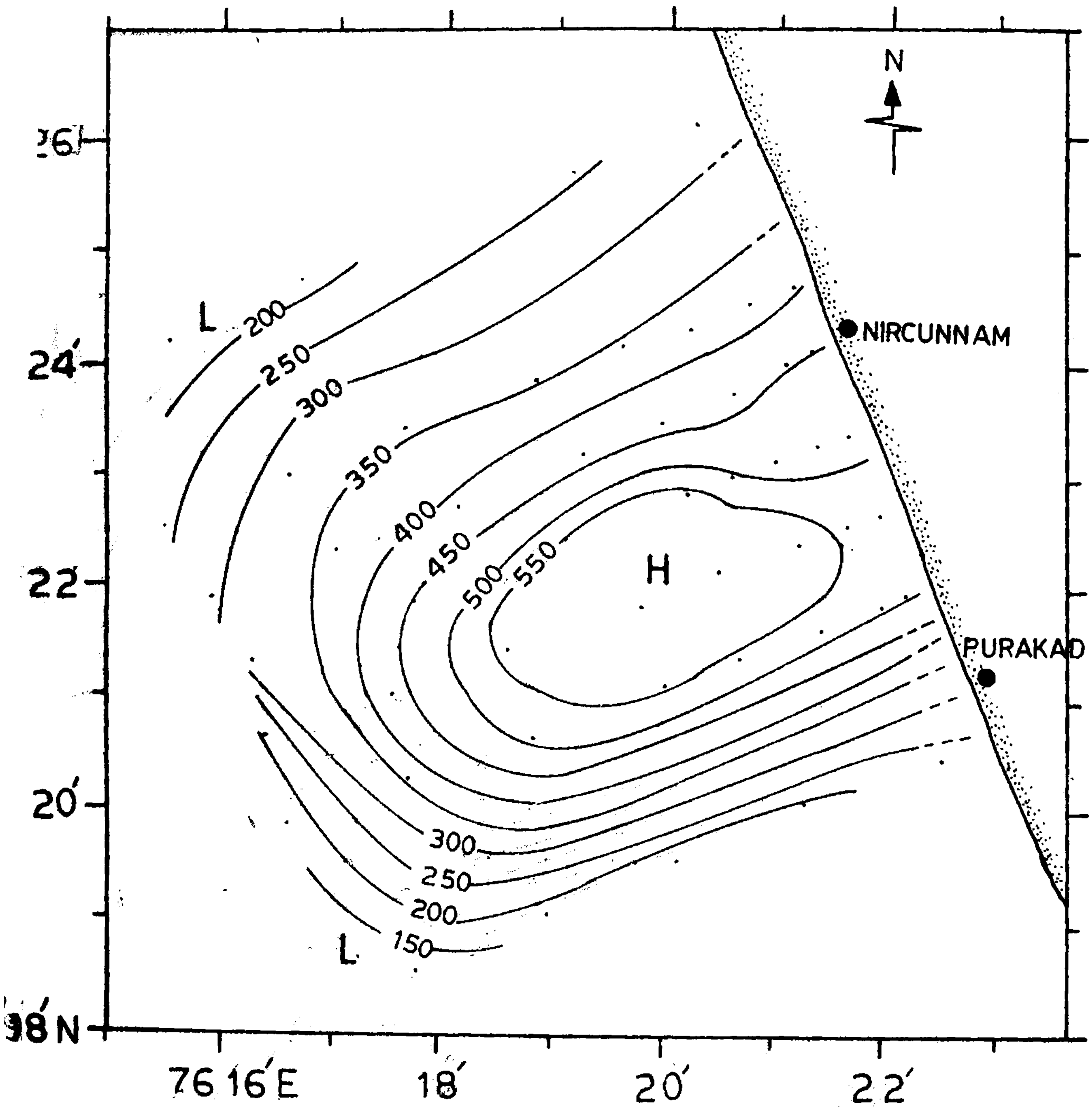


Fig.17 Horizontal distribution of suspended matter (mg/l) during June (bottom)

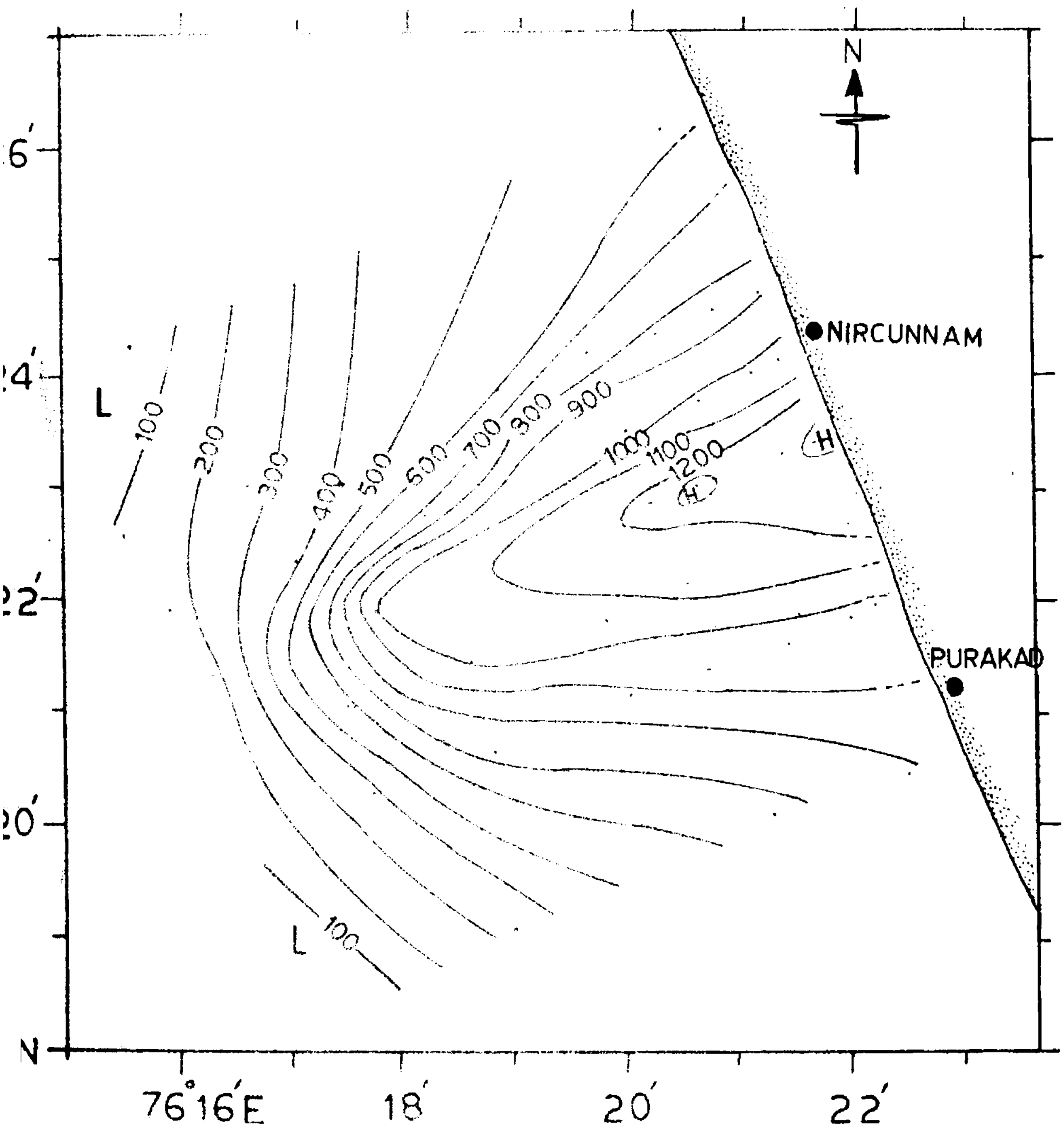


Fig.18 Horizontal distribution of suspended matter (mg/l) during July (surface)

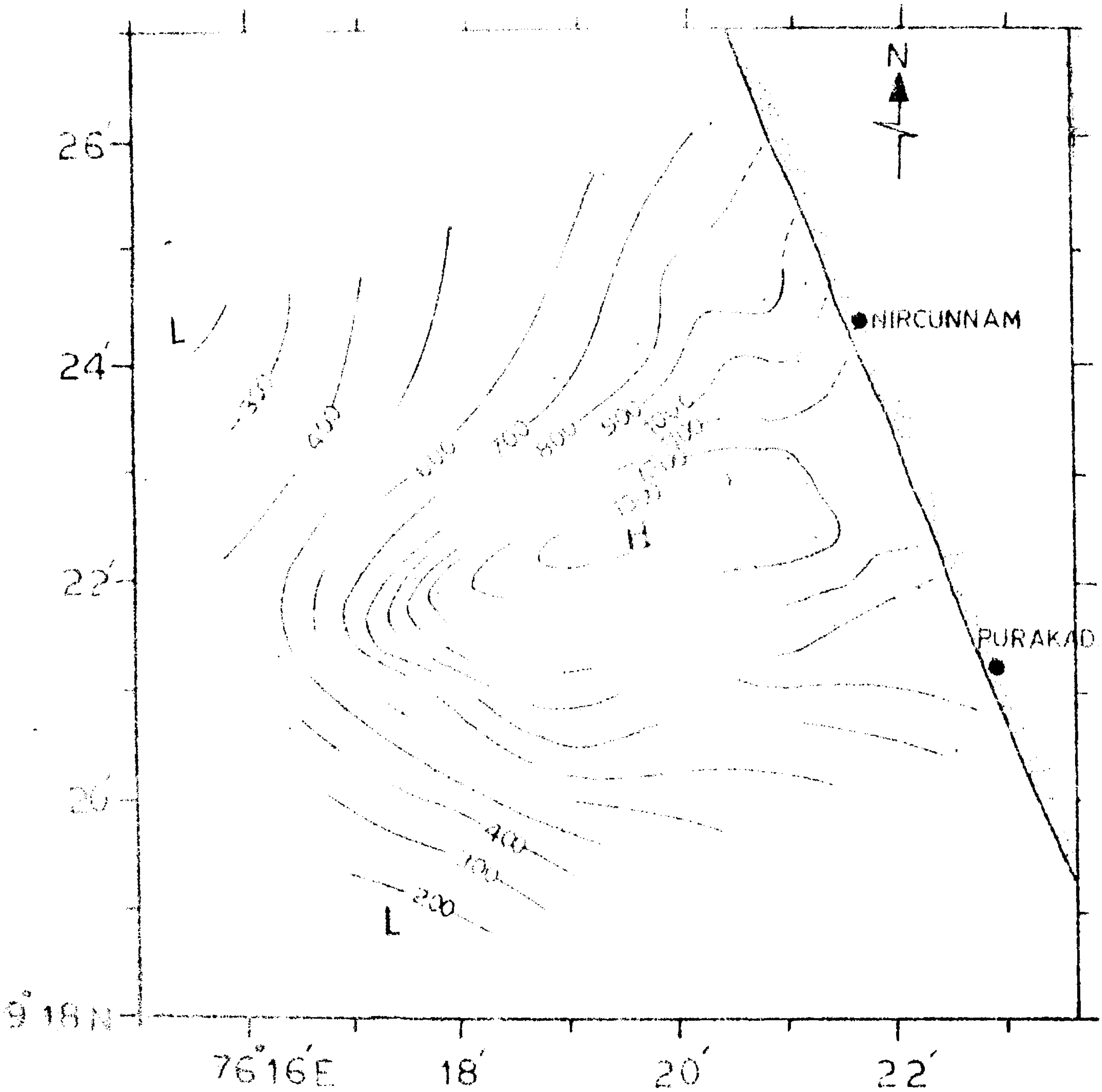


Fig.19 Horizontal distribution of suspended matter (mg/l) during July (mid-depth)

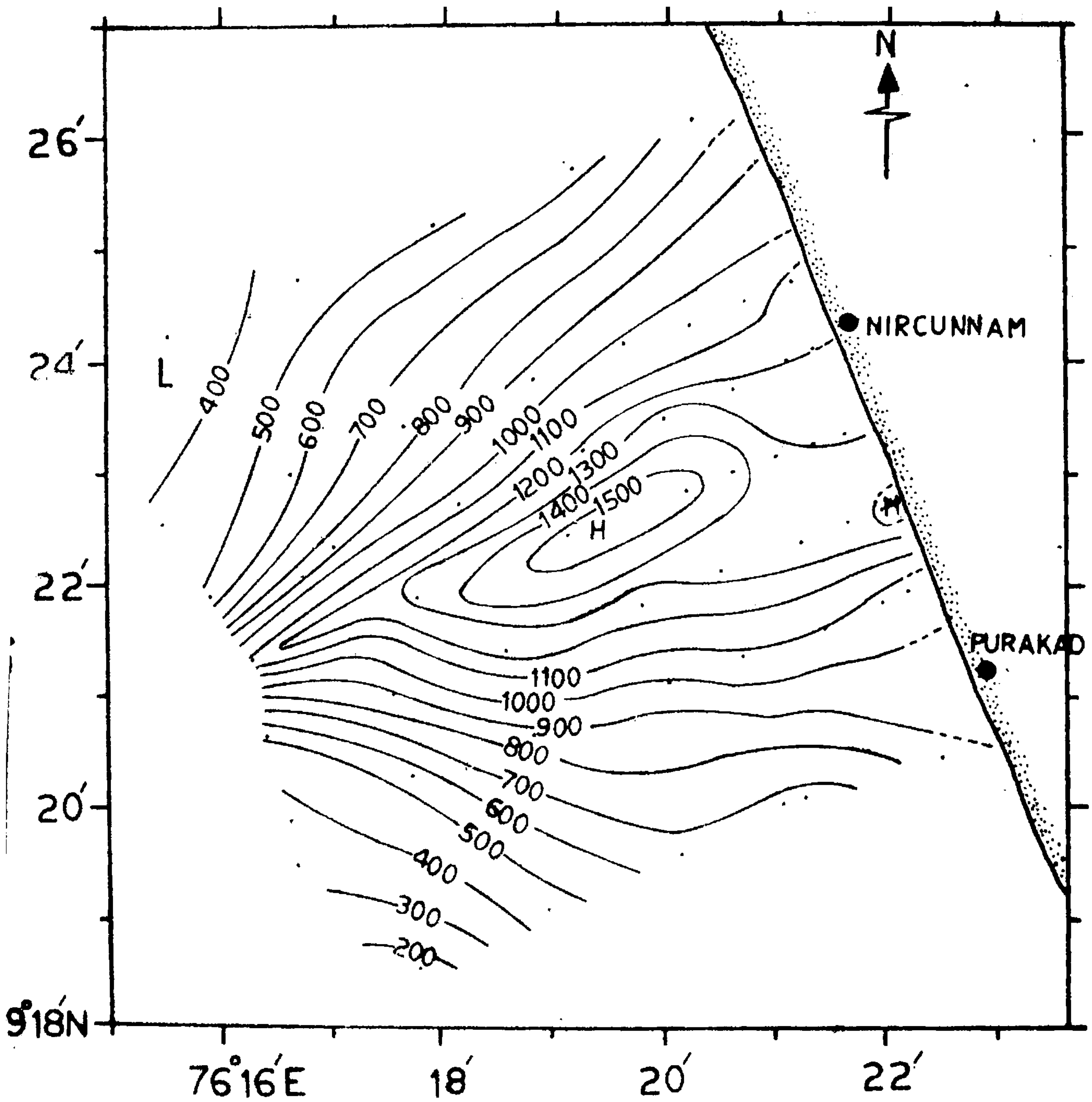


Fig.20 Horizontal distribution of suspended matter (mg/l)

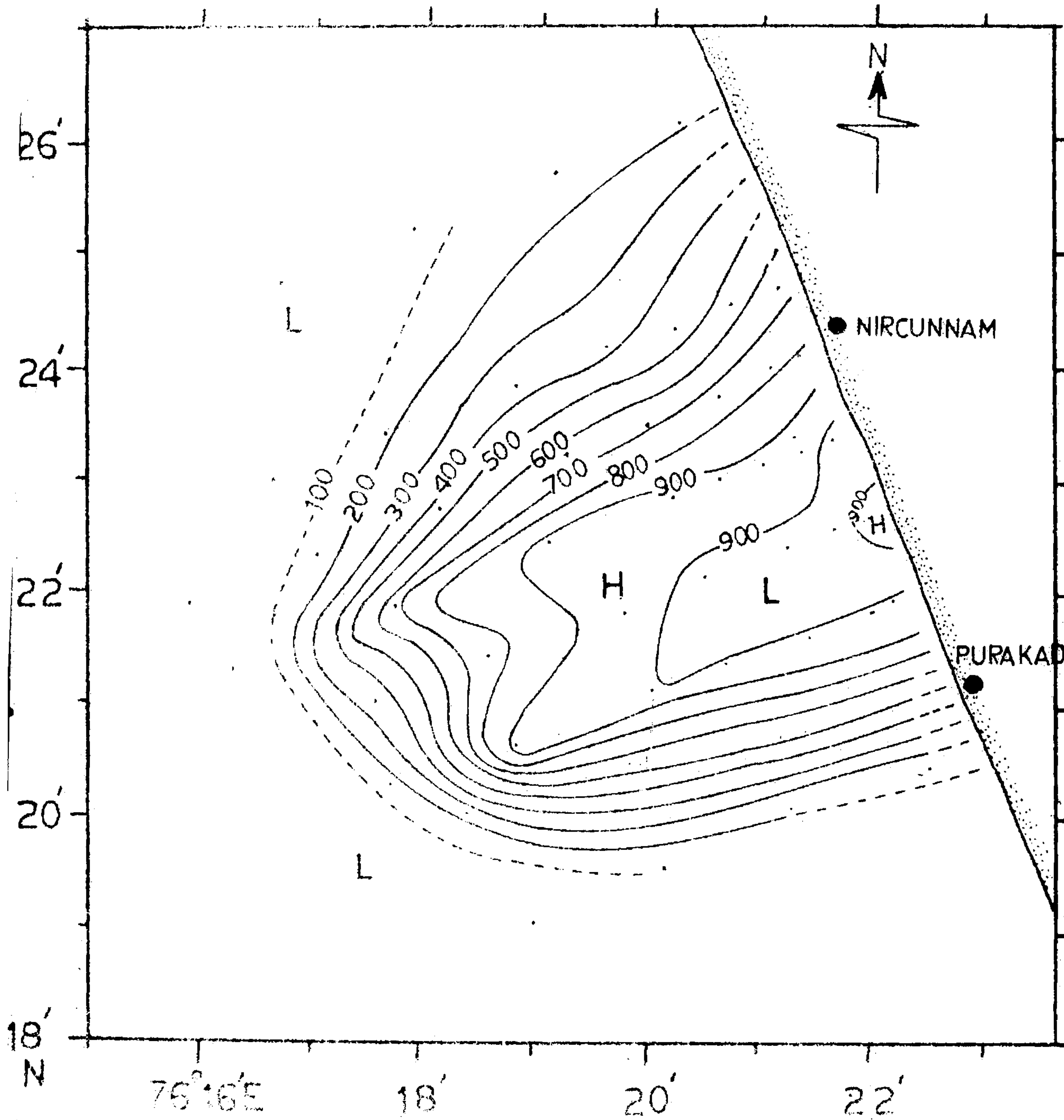


Fig.21 Horizontal distribution of suspended matter (mg/l) during September (surface)

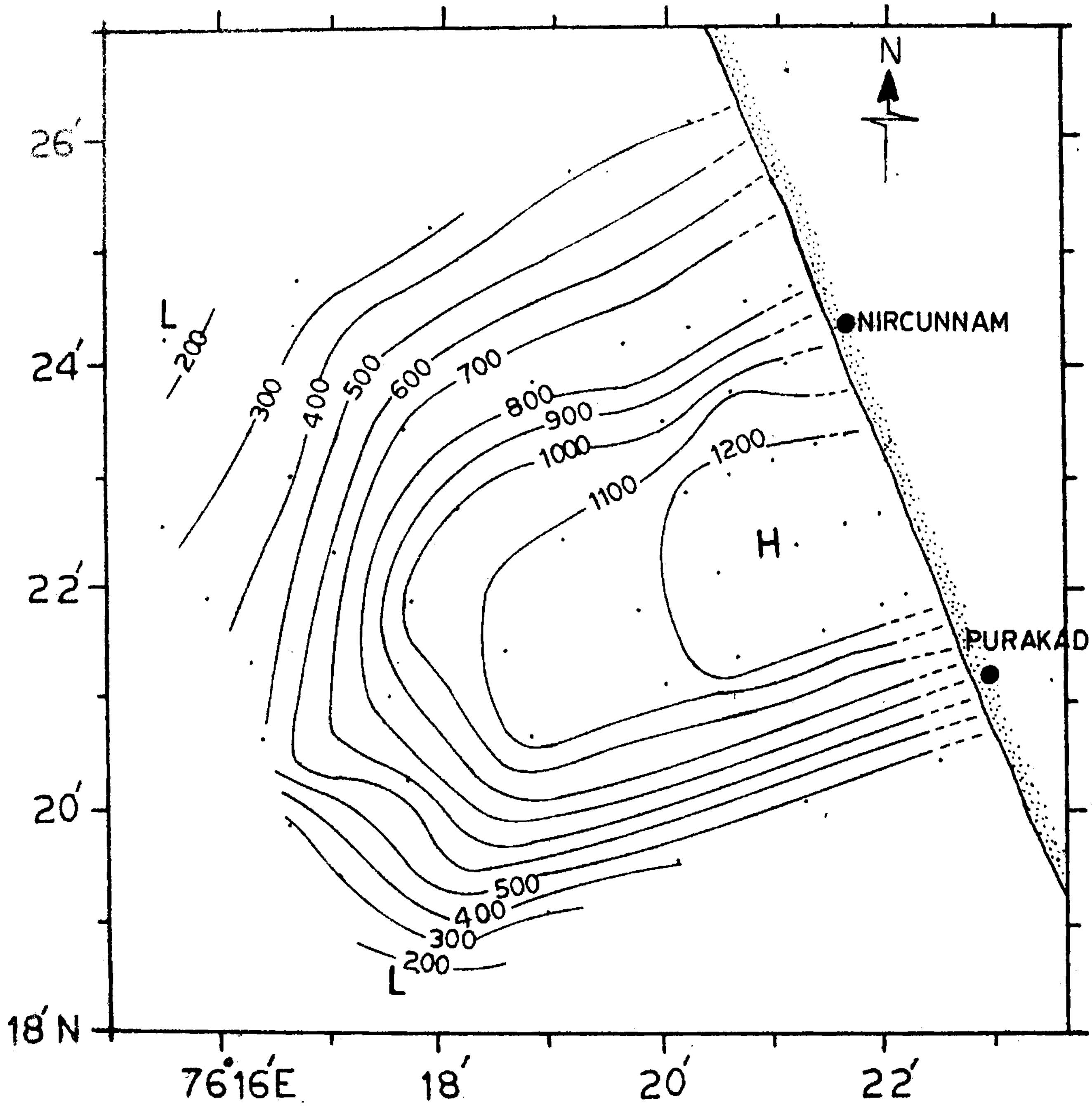


Fig.22 Horizontal distribution of suspended matter (mg/l) during September (mid-depth)

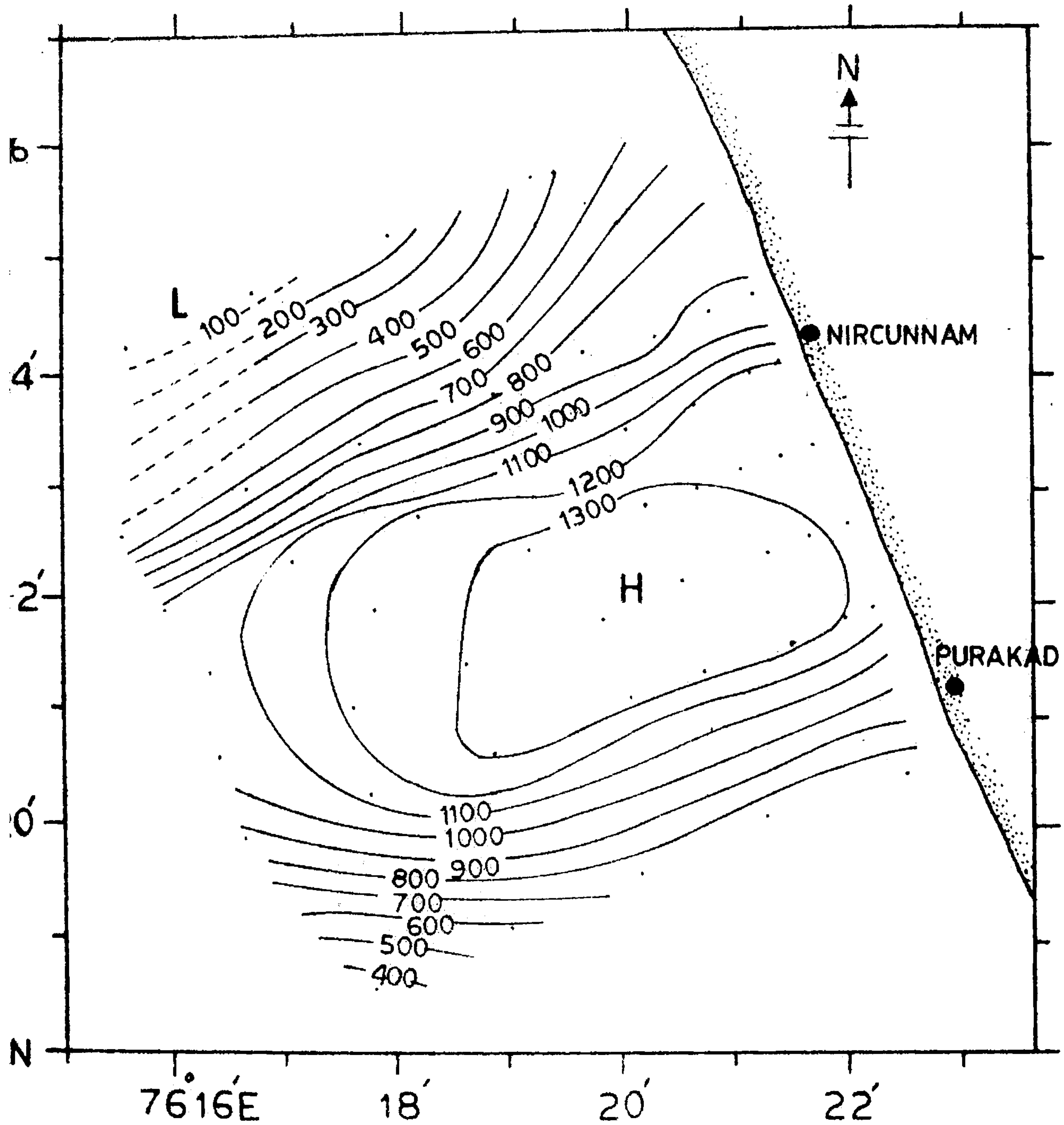


Fig.23 Horizontal distribution of suspended matter (mg/l) during September (bottom)

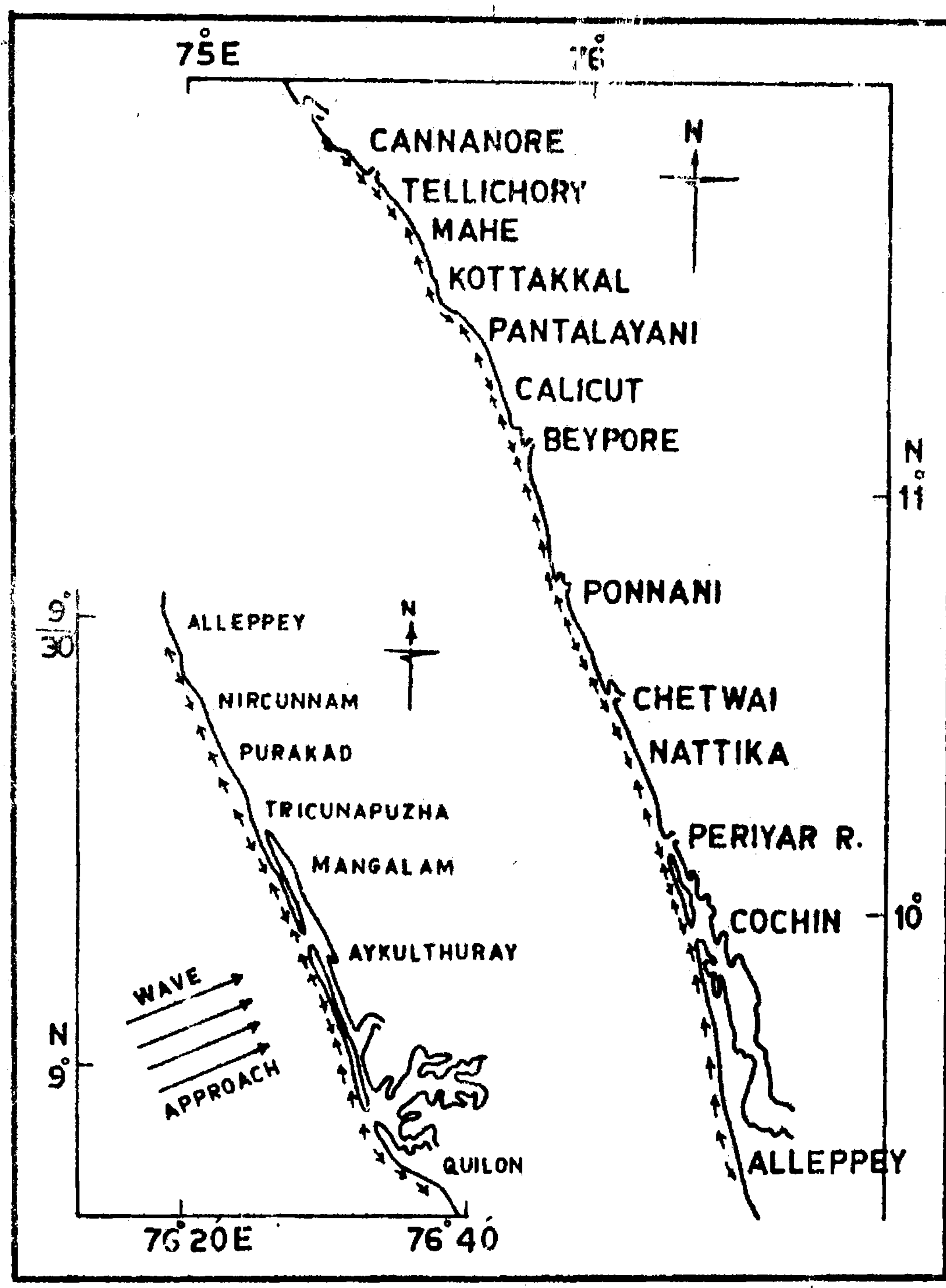


Fig.24 Littoral currents along the Kerala coast during SW monsoon season (after Reddy and Varadachari, 1972)

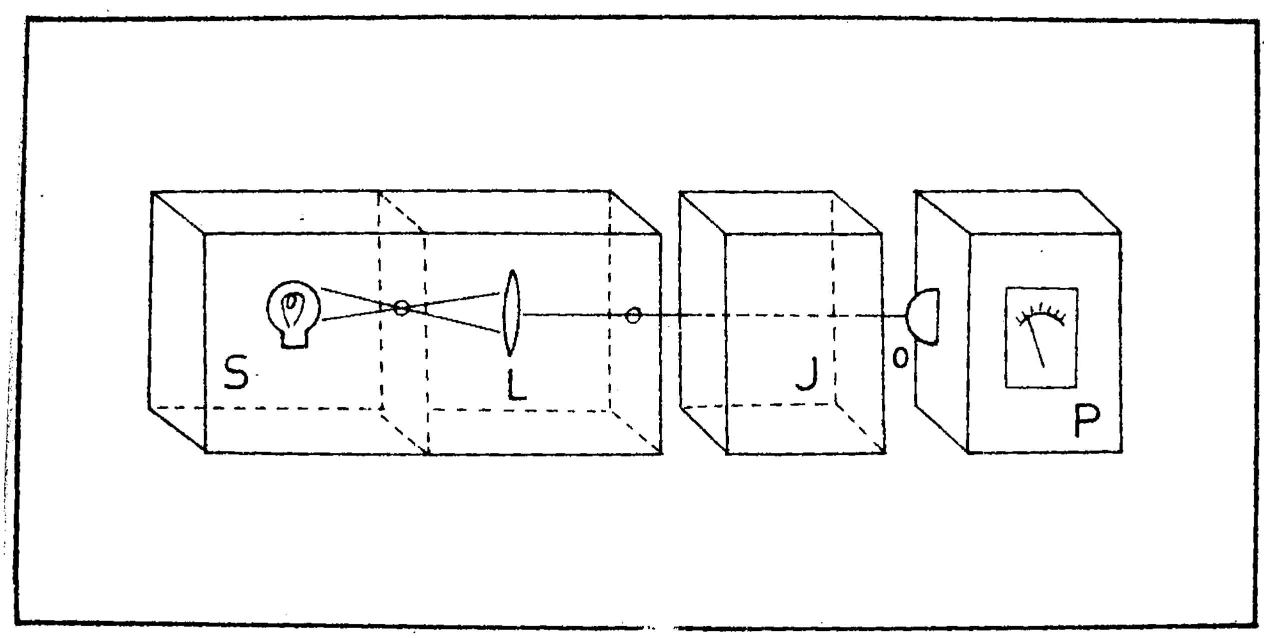


Fig.25 Flocculation studies--experimental set-up

(schematic- S:lamp; L:lense; J:jar; O:opal glass; P:photometer)

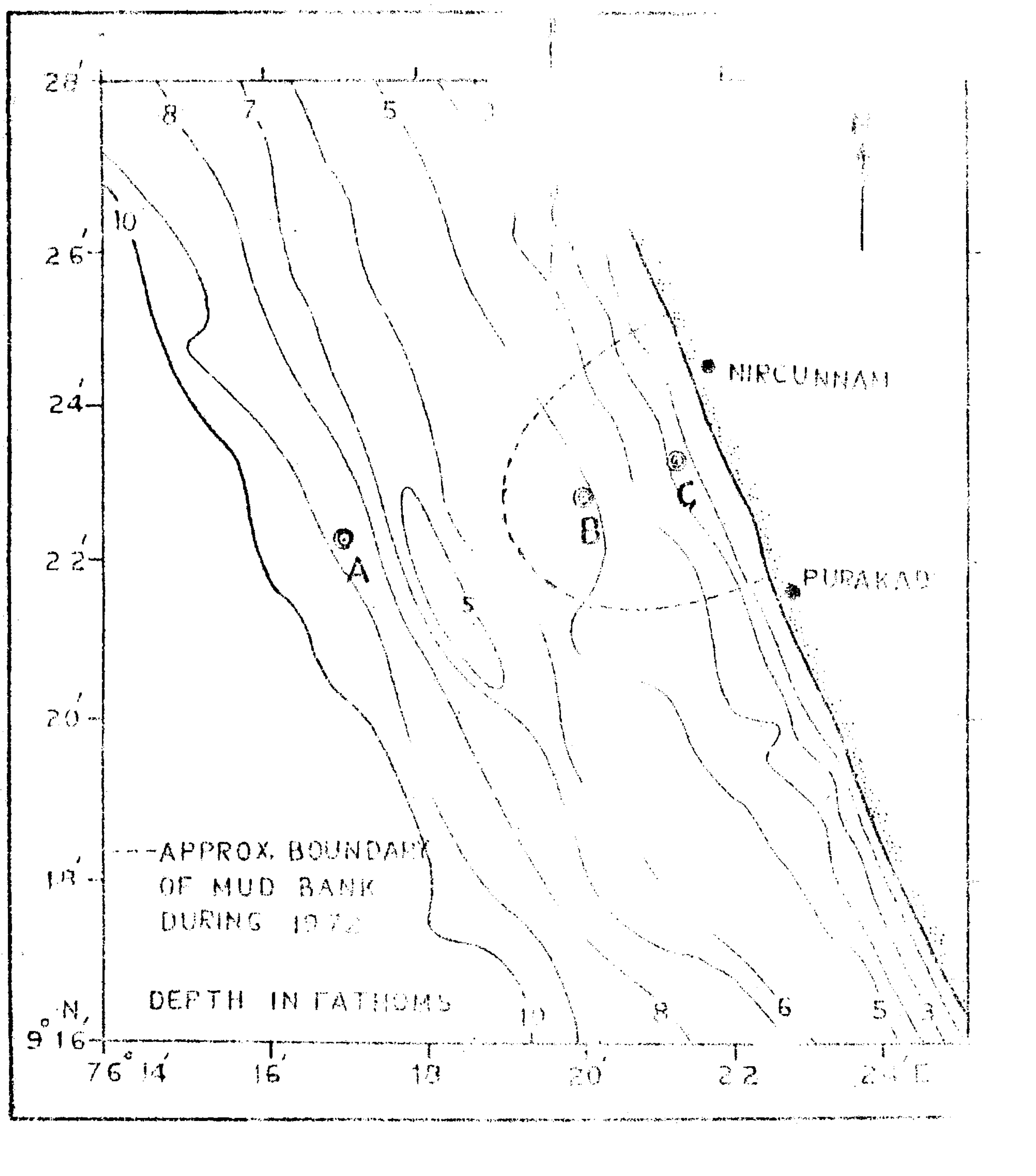


Fig.26 Flocculation studies--station positions

Fig.27 Variation of relative attenuance with time under different salt concentrations

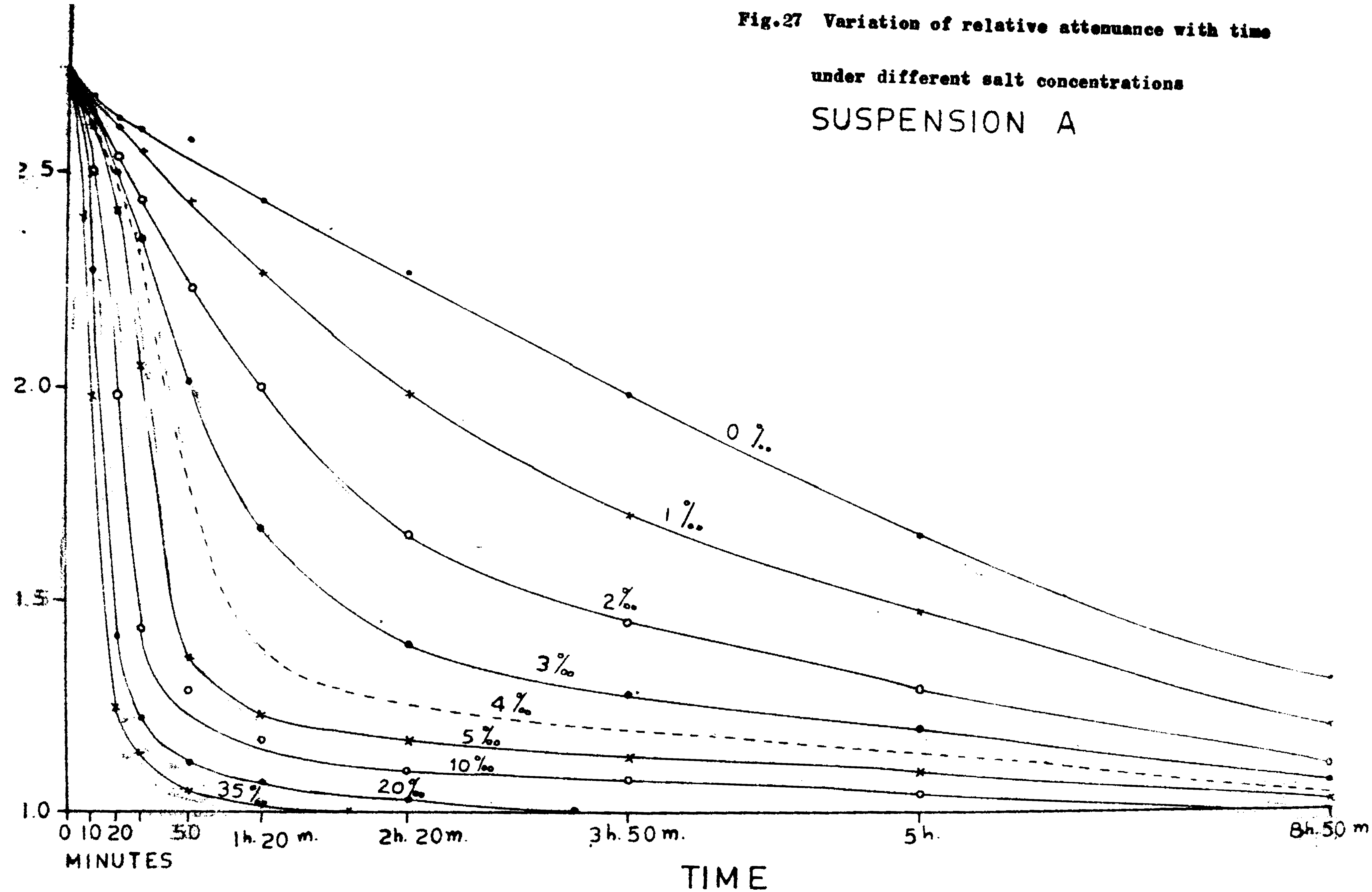


Fig.28 Variation of relative attenuance with time under different salt concentrations

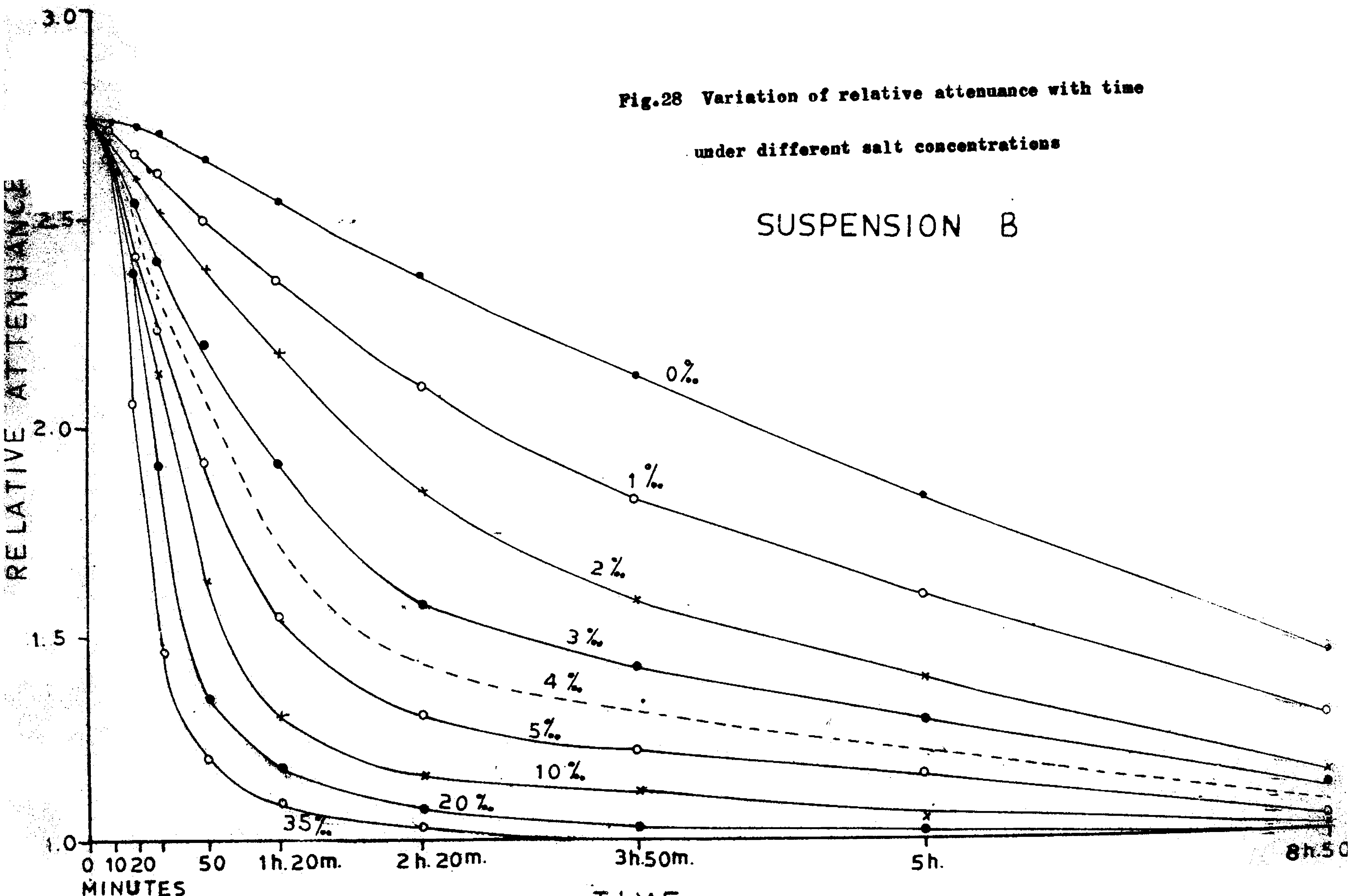
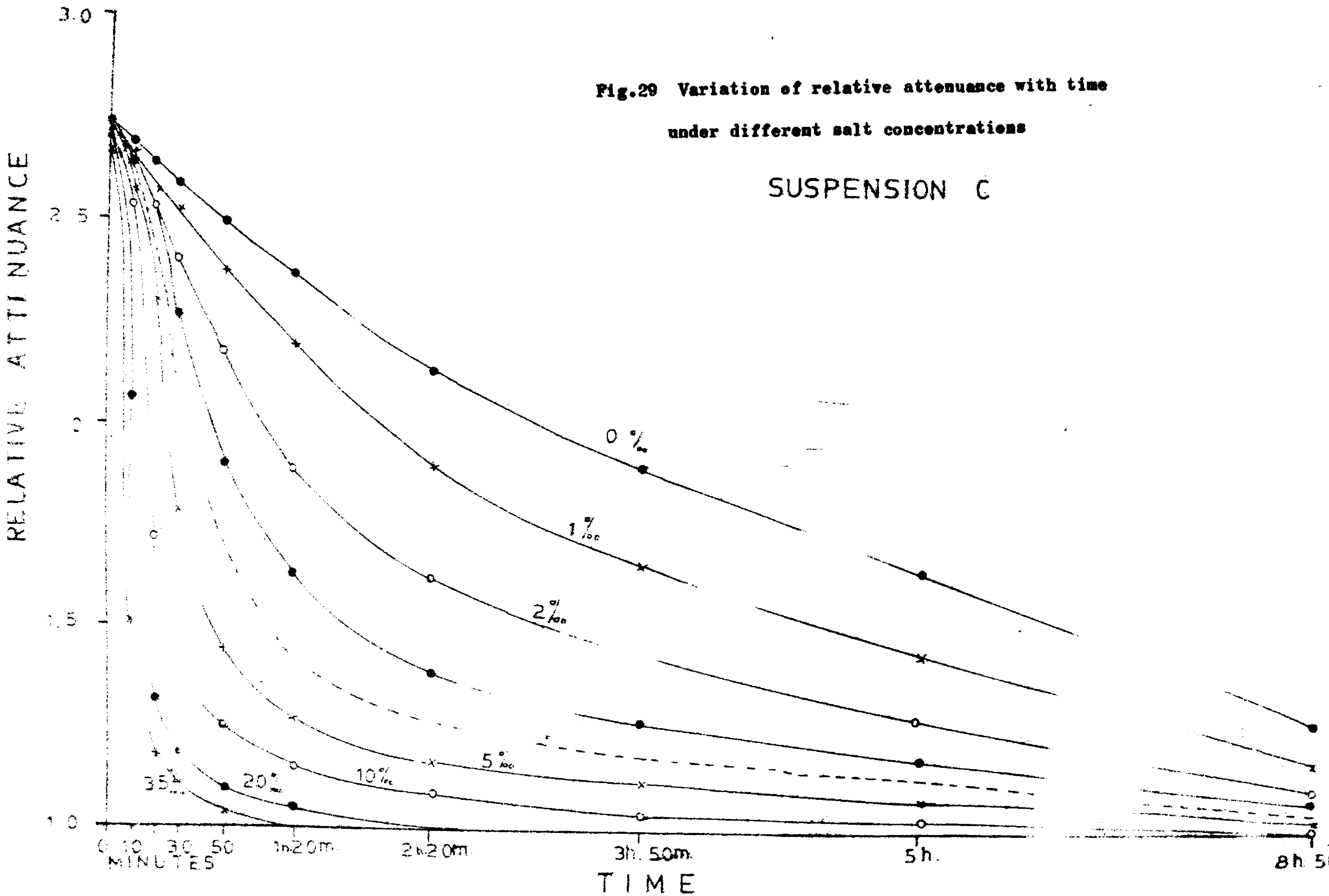


Fig.29 Variation of relative attenuance with time under different salt concentrations



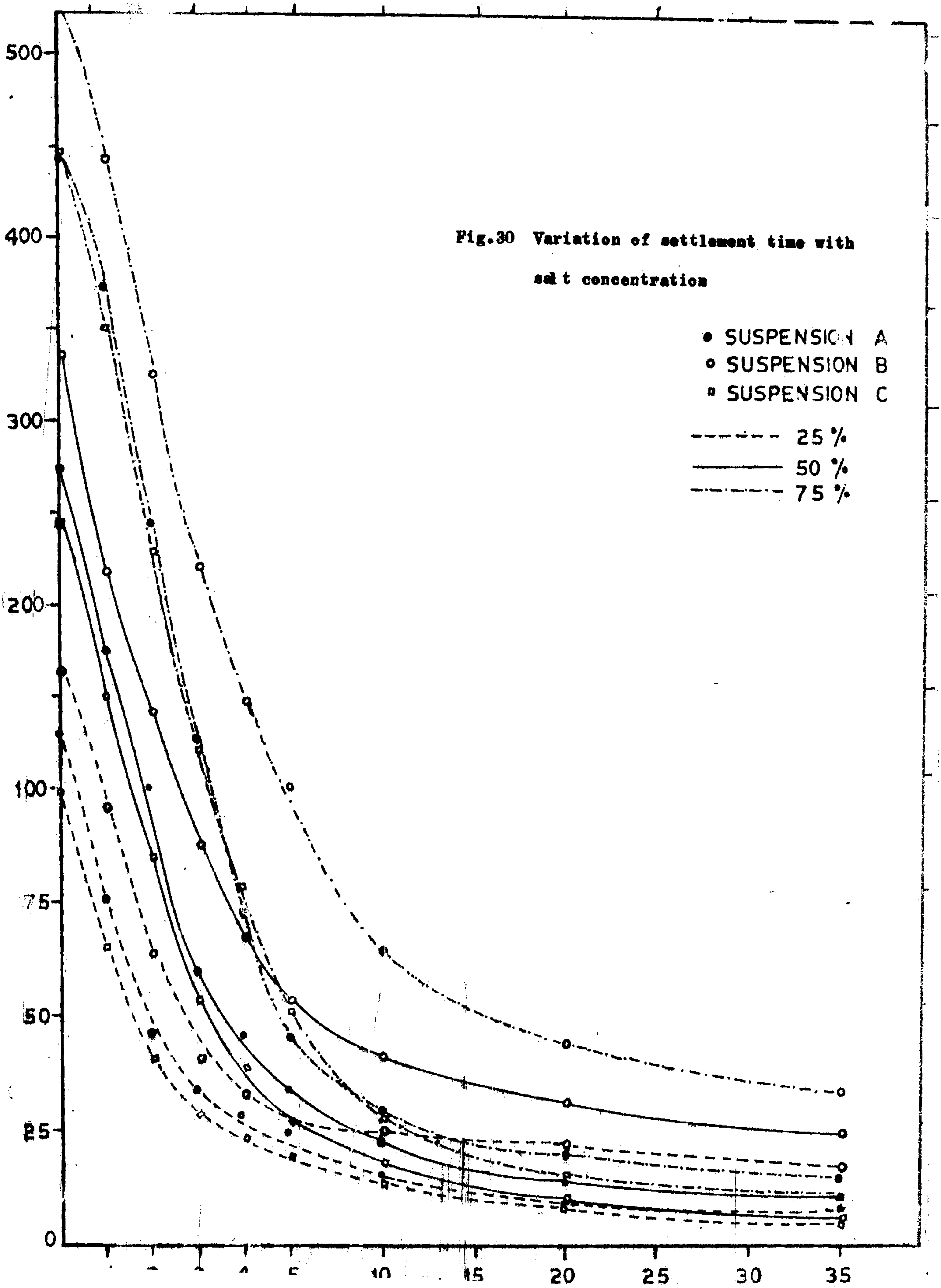


Fig.30 Variation of settlement time with salt concentration

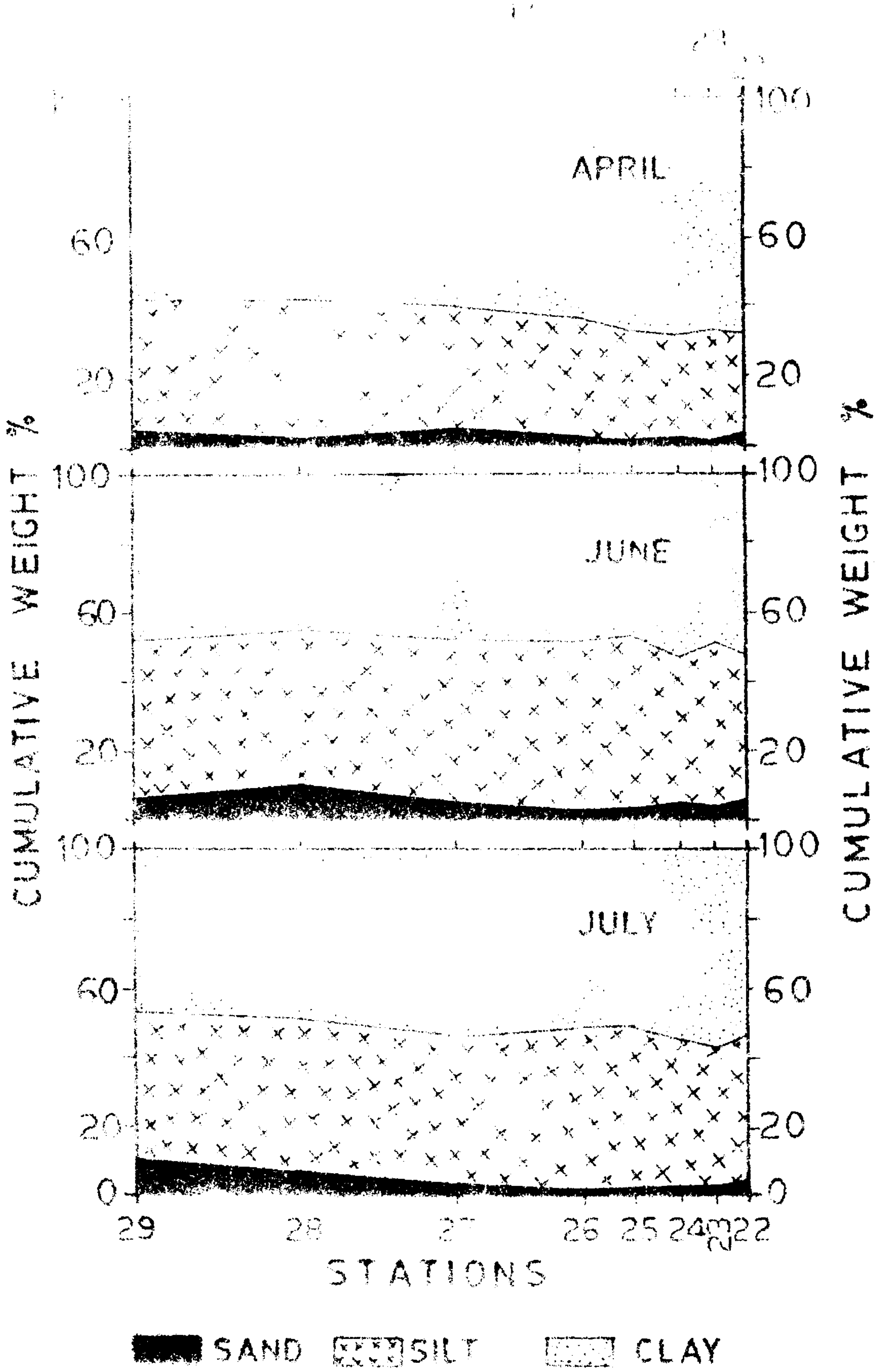


Fig.31(A) Seasonal variation of texture of bottom sediments

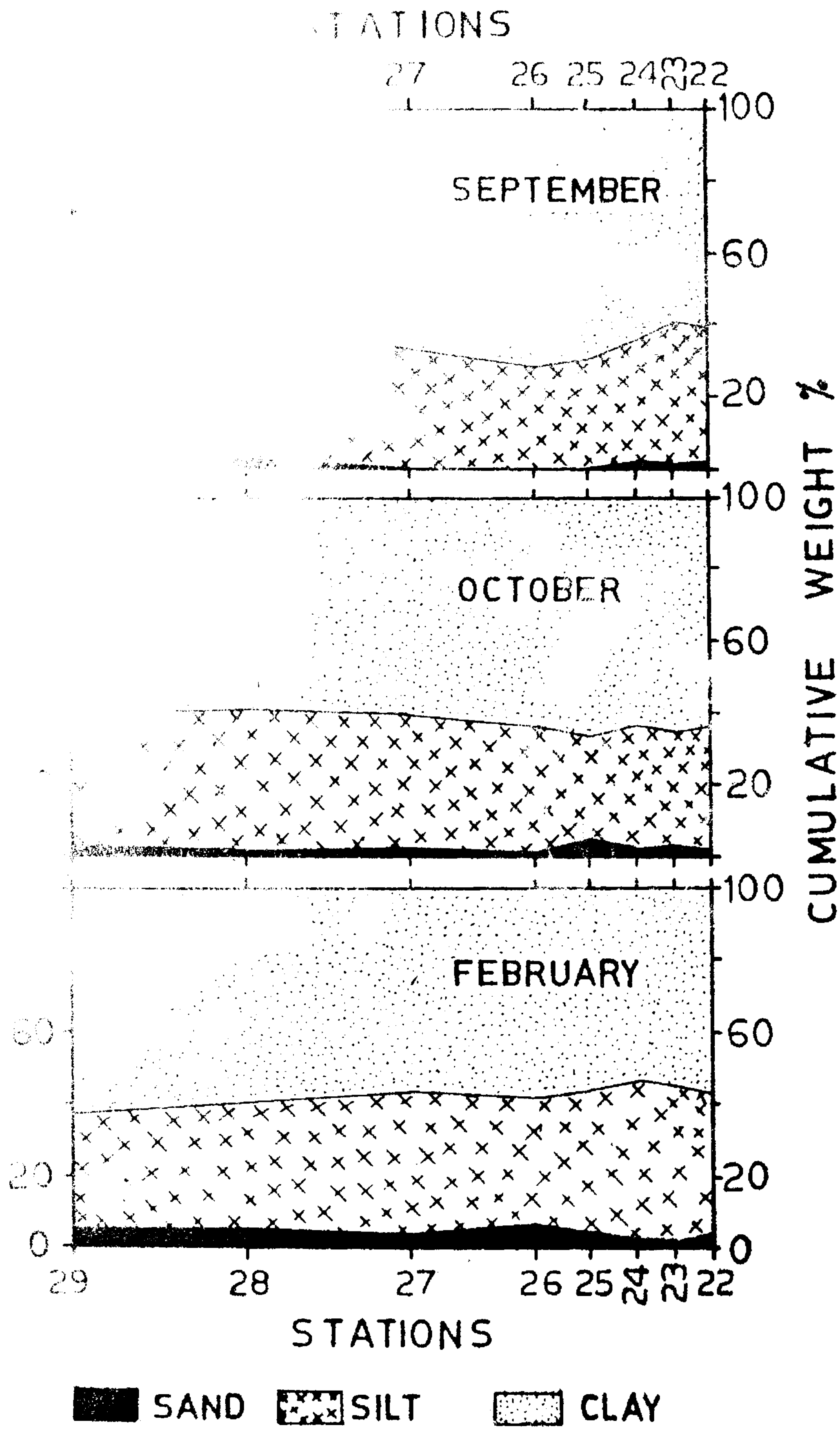


Fig.31(B) Seasonal variation of texture of bottom sediments

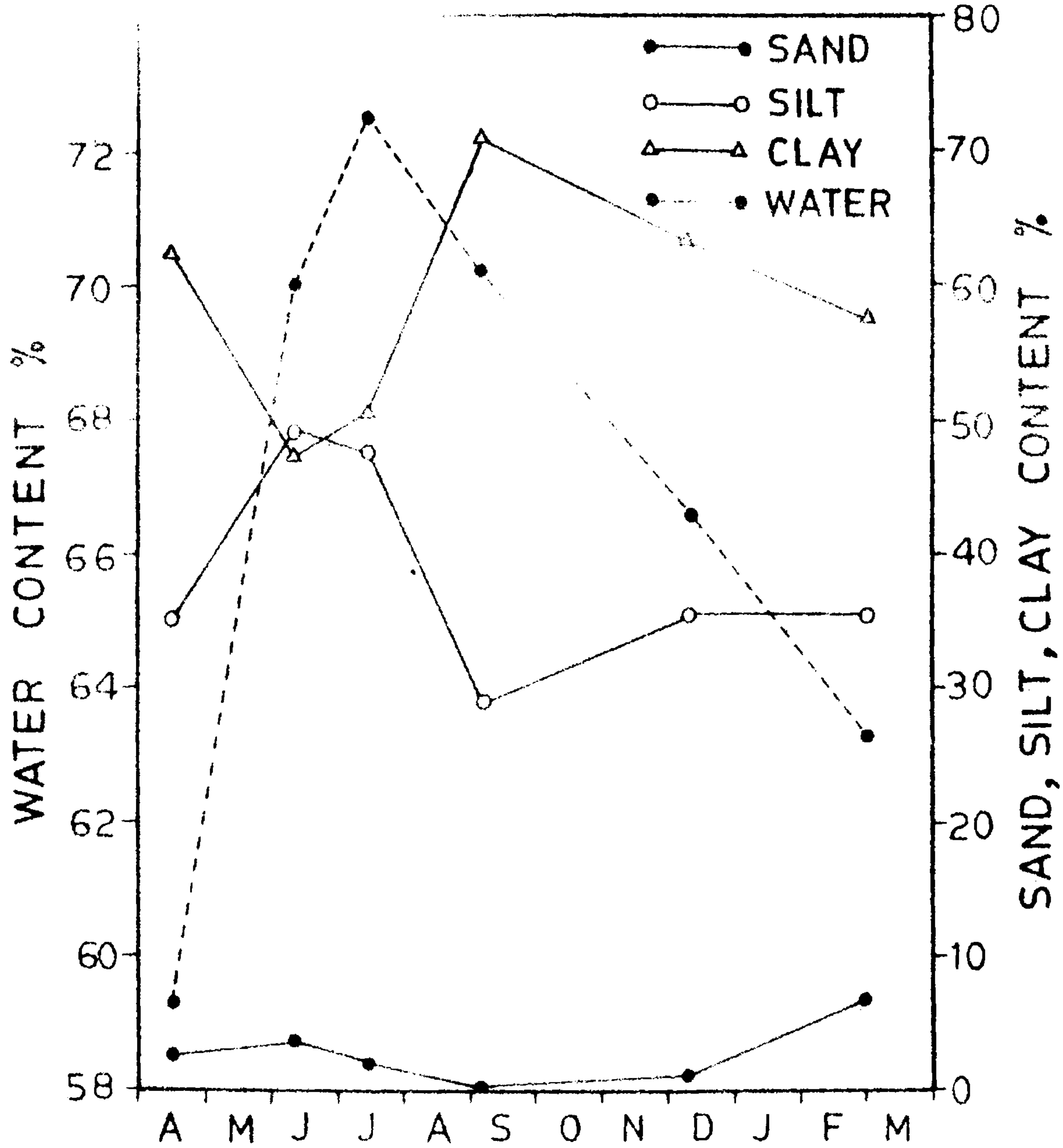


Fig.32 Monthly variation of water content and percentages of sand, silt and clay

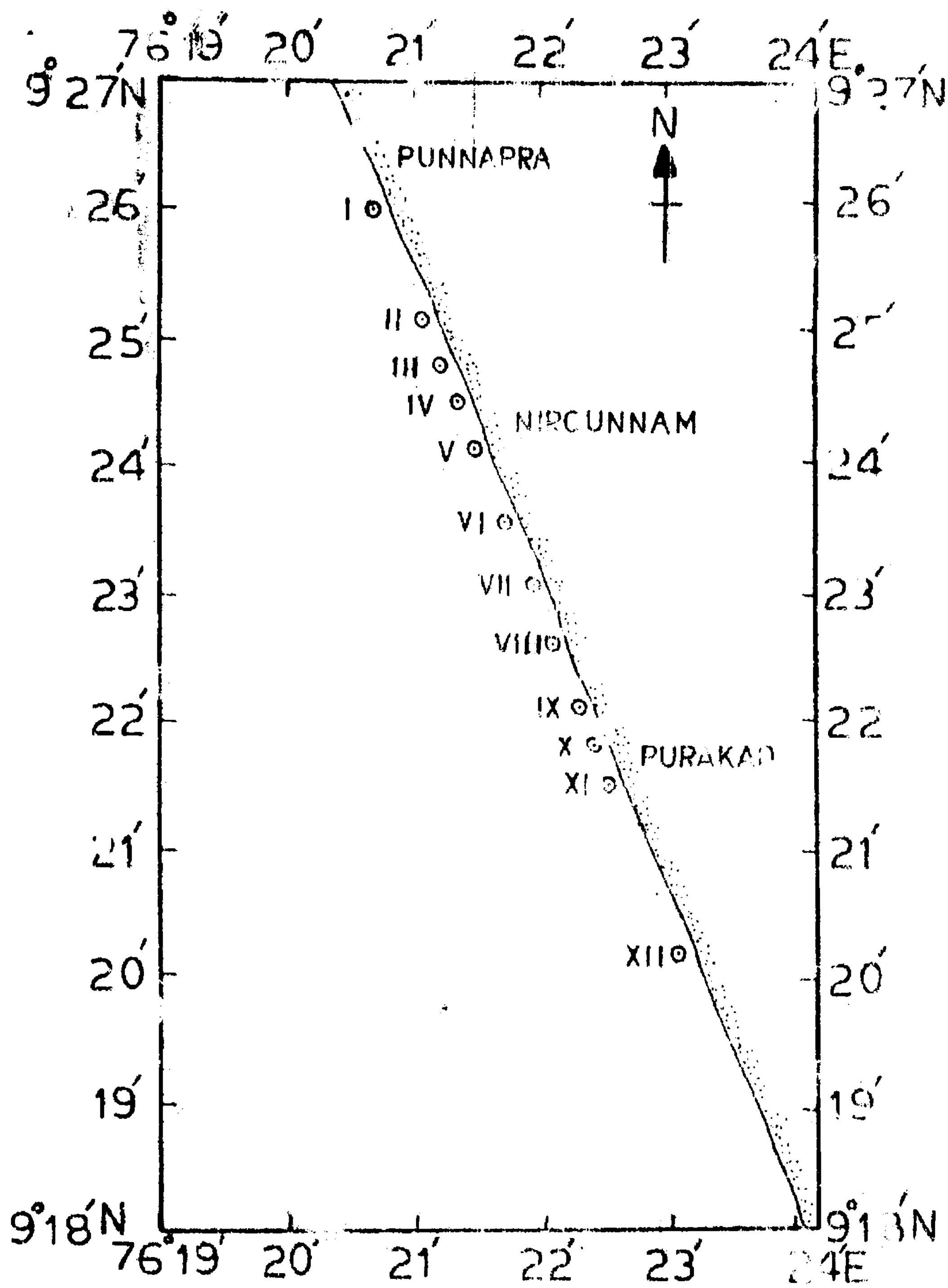


Fig.33 Location of Stations I to XII for breaker observations

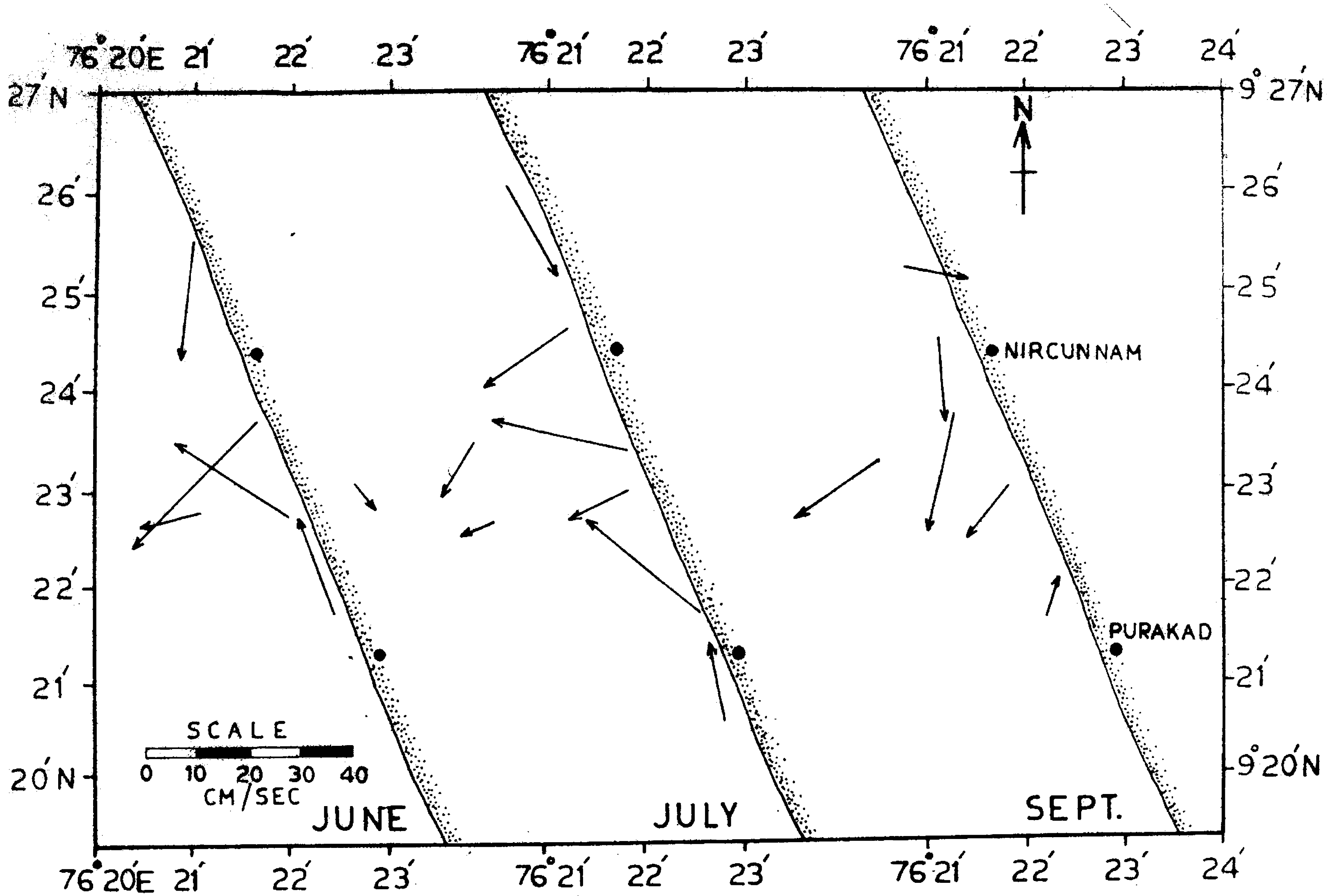


Fig.34 Vectors showing surface currents

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