

# Response of Barrier Beaches along the Southwest Coast of India to Monsoonal Forcing

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## ABSTRACT

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The response of a small stretch of barrier beach along the southern part of the west coast of India to the southwest wind and wave climates showed wide variations when examined through empirical Eigen function analysis. The observed intra- and inter-variability has been found to be the result of differential wave activity which is, in part, due to the flat inshore bottom topography with localised static mud suspensions present close to the central part of the area investigated. In addition, the inadequate supply of sediments from both the mainland and offshore sources makes the prevailing littoral flows undersaturated, thereby giving rise to erosion of existing material from the beach zone.

**ADDITIONAL INDEX WORDS:** Barrier beach, monsoon, erosion, mudbank, empirical Eigen function, sediments, longshore flows, littoral cell



## INTRODUCTION

Of the many forms of beaches bordering the coast, barrier beaches form unique depository systems along the world's coastline. Considering their fragile nature and intense occupancy by man, these coastal features have long been a subject of study by coastal oceanographers, geomorphologists and engineers. These studies emphasise examination of basic processes operating within such valuable environments for conservation and protection from continuous erosion.

In the nearshore zone, changes occurring in the beach geometry have been related to the prevailing dynamic forces due to waves, tides and the associated currents. These forces together with the available sedimentary material control the nature and extent of variability in the beach morphology. The present study is an attempt to understand the nature of such changes of the barrier beaches of Kerala in response to various forcing functions over time scales of the order of one month.

## ENVIRONMENTAL SETTING

Along the southern half of the west coast of India,

barrier beaches backed by extensive lagoonal systems exist. Adjacent to this coast, the continental shelf shows a widening from south to north. In the nearshore areas the sediments have been found to be mostly silty-clays or clayey-silts with marginal differences in their depths of occurrence. Semi-diurnal tides with their range less than 2.0 m prevail along this coast. The entire coast is exposed to seasonally changing winds—the monsoons. The reversal of these winds take place predominantly from southwest (May-September) to northeast (December-March) direction. They exhibit spatial differences in their times of onset and magnitude (ANONYMOUS, 1952). The wave climate associated with these winds also show similar changes as their intensities and the spectral ranges depend mostly on the available fetches and their proximity to the coast.

The area under study is about 57 km of shore (approximately 10% of Kerala's coastline) from Azhikode to Anthakaranazhi (Figure 1). The strip from Azhikode to Vypeen (26.5 km) and Fort Cochin to Anthakaranazhi (30 km) forms two barrier islands known as Vypeen and Chellanam Islands, respectively, with widths varying from 1.6-2.4 km. The bordering beaches composed of fine sands possess a low profile in general. The River Periyar opening at Azhikode, the entrance

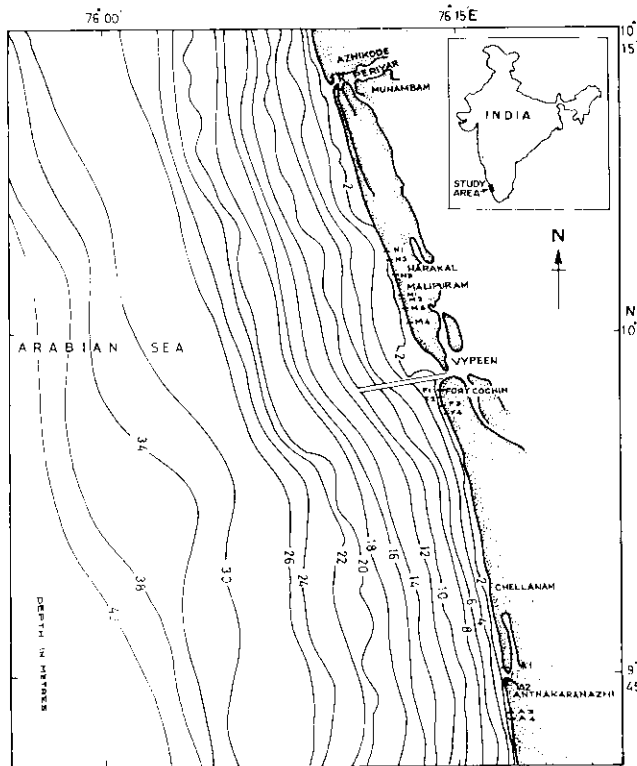


Figure 1. Area of study showing the bathymetry and location for field observation.

channel of harbour at Cochin and a seasonal opening at Anthakaranazhi provide sediments at varying levels to the adjoining shores. During the southwest monsoon season, static mud suspensions (locally called mud banks) prevail off southern stretches of Vypeen Island. Shore protection structures in the form of seawalls and groins exist along the stretch from Fort Cochin to Anthakaranazhi which are in a dilapidated condition in places.

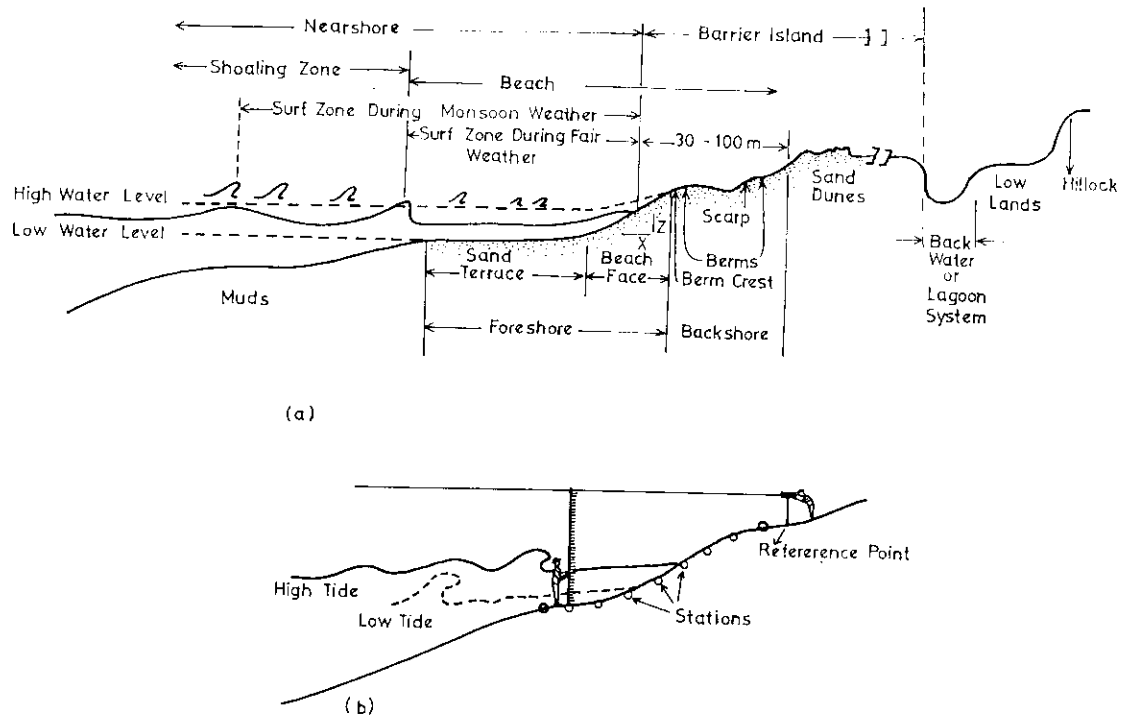
#### DATA COLLECTION AND ANALYSIS

Considering the environmental setting, the region under study has been divided into four zones (Table 1). In all, fifteen locations have been selected for field observations (Figure 1). The beach profiles (Figure 2) have been monitored at each of these locations following the technique similar to that of EMERY (1961) for a period of 16 months from October, 1980 at regular intervals. From the data collected during these surveys, the beach profiles were drawn using an HP 1000 computer (Figure 2).

The profile data were further subjected to Empirical Eigen Function analysis to examine the space and time variability (Figures 3a-d) of the beach responses. This method has been applied for morphological studies of the beaches at Torrey Pines (WINANT *et al.*, 1975; AUBREY *et al.*, 1976 and AUBREY, 1979); at Gorleston and Great Yarmouth (ARANUVACHAPUN and JOHNSON, 1979) and at Coledale (CLARKE *et al.*, 1984), and for prediction of beach changes at Torrey Pines (AUBREY, 1978).

#### METHODOLOGY

The profile data were set into a data matrix  $H$  with each of the matrix containing a time series of the elevation/depression at particular stations along the profile and each column containing the beach profile at a particular time. The variability of the data matrix  $H$  is explained in terms of a few simple Eigen functions of the matrix  $H$ . This is achieved by normalising and decomposing  $H$  into a product of three matrices using Singular Value De-



(a)

(b)

Figure 2. (a) Schematic diagram showing beach terminology along a barrier beach system. (b) Diagram showing methodology of beach profiling (not to scale).

Table 1. Details of beach profile locations.

Zone	Number of profiles	Survey interval	Beach width (m)	Distance between profiles (km)	Remarks
Narakal	3: N1, N2, N3	Monthly	30-35	N1-N2 0.5	Low beach composed of fine sand. Seawall-groin assembly present prior to this investigation. In recent years, the groins collapsed. Receives partial protection from the mud bank active during the SW monsoon season.
				N2-N3 0.3	
Malipuram	4: M1, M2, M3, M4	Fortnightly	55-75	M1-M2 0.4	Low beach composed of fine sand. Seawall exists well behind the backshore and unaffected by waves. Mud deposits exist in the nearshore bed.
				M2-M3 0.9	
				M3-M4 0.8	
Fort Cochin	4: F1, F2, F3, F4	Fortnightly	40-90	F1-F2 0.5	Relatively high beach composed of medium sand. Locations F1, F2 and F4 are backed by seawall. Partially protected by mud bank.
				F2-F3 0.7	
				F3-F4 0.5	
Anthakaranazhi	4: A1, A2, A3, A4	Monthly	30-50	A1-A2 0.5	Low beach composed of fine sand. Seawall-groin assembly exists but in a damaged condition. At present buried seawall exists at all locations except A3, where seawall is present and a collapsed groin exists.
				A2-A3 0.3	
				A3-A4 0.4	

composition (SVD) technique:

$$X_{m \times n} = H/(m \times n)^{1/2} = U_{m \times r} \Gamma_{r \times r} V_{r \times n}^T \quad (1)$$

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

$U$ ,  $\Gamma$  and  $V$  satisfying Equation (1) are obtained by solving the Eigen value problem

$$(B - \lambda I)V = 0 \quad (2)$$

$$(A - \lambda I)U = 0 \quad (3)$$

where  $B = X^T X$  and  $A = X X^T$ . Values of  $\lambda$  are obtained by solving the characteristic of Equation (2), *i.e.*,  $|B - \lambda I| = 0$  and its substitution in Equation (2) leads to a system of equations which are solved following the standard Gaussian elimination method (MCCORMICK and SALVADORI, 1968) to obtain values of  $V$ . Knowing  $V$  and  $\lambda$ ,  $U$  is determined from Equation (3).

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

$$\text{Measure of closeness} = \frac{\sum_{i=1}^k \lambda_i}{\sum_{i=1}^y \lambda_i}$$

is the number of factors.

## RESULTS

In the Narakal zone the observed beach profiles at the three locations show the presence of fully grown berm at N1 and N2, at distances varying from 5-15 m from the reference point (Figure 3a). The berm undergoes a maximum change (0.5 m) in the vertical at N2. The profiles at all the three locations exhibit maximum elevation changes near MLW (2 m at N1, 1 m at N2 and N3) with a decreasing trend from north to south.

In the Malipuram zone, berm and wide backshore (at M1, Figure 3b) experiences elevation changes to a maximum of 1.5 m. The foreshore at all the locations is comparatively steep. At M1 and M2 these changes are maximum (2.0 and 1.5 m) as against M2 and M3.

In the Fort Cochin zone the effective changes in the beach width increases from north to south while

their magnitudes decrease, barring F2 (Figure 3c). The maximum change (2.5 m) occurred at F1 and the minimum (1.25 m) at F2.

The beaches within Anthakaranazhi zone characterised by the presence of a berm situated at distances of 5-20 m from R.P (Figure 3d) present maximum changes at A2 and A3.

The overall features inferred from EEF analysis are detailed here. The Eigen functions are ranked according to the percentage of mean square value of the data (Table 2). At location N1 the first Eigen function accounts for 96.90% of the mean square value of the data, while the second and third functions account for 2.94% and 0.07% respectively of the individual indicating the insignificant contribution from the higher order functions. The first spatial function U1 (Figure 4) is analogous to the arithmetic mean of the data (mean beach profile) and is termed the mean beach function (WINANT *et al.*, 1975). This shows the presence of a berm at 5 m from R.P and a moderately sloping foreshore. The associated temporal function (V1) indicates the general trend and overall stability of the beach over the period over the period of investigation—a constant value reflecting the near-stable nature of the beach. The second spatial Eigen function (U2) represents the berm function and identifies clearly the spatial location where the beach profile experiences maximum changes. This feature could be seen at lower foreshore, near the mean low water (30-40 m from R.P) and to a lesser magnitude at the berm extending to 15 m (Figure 4). The associated temporal function (V2) is characterized by a strong temporal (seasonal) dependence. Its distribution shows the overall depositional feature of the beach

Table 2. Mean square values (%) of the data as explained by the first three Eigen values

Location	Eigen values		
	First	Second	Third
N1	96.90	2.94	0.07
N2	96.27	3.18	0.37
N3	98.83	0.76	0.33
M1	96.54	2.12	0.87
M2	97.81	1.02	0.72
M3	98.55	1.02	0.23
M4	89.96	9.16	0.50
F1	91.29	6.96	1.64
F2	98.20	1.27	0.23
F3	98.66	1.02	0.19
F4	98.13	1.28	0.38
A1	88.02	11.19	0.36
A2	77.53	20.69	1.30
A3	93.90	5.29	0.52
A4	91.91	7.59	0.82

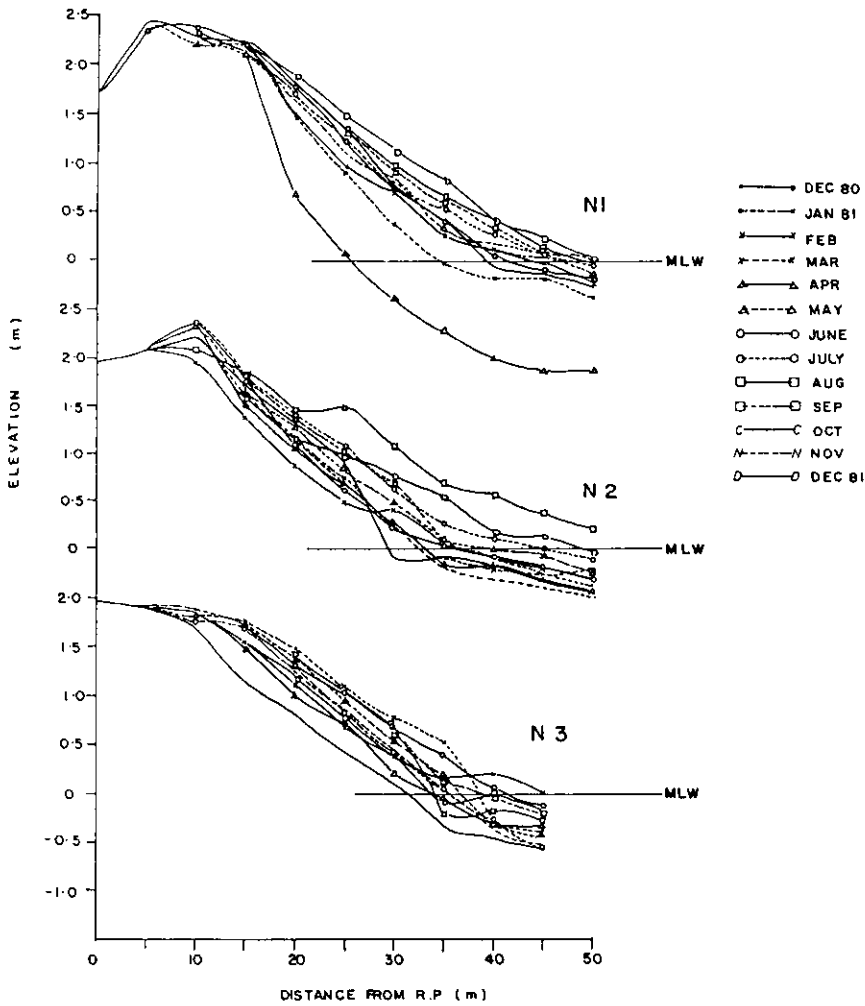


Figure 3a. Beach profiles at Narakal zone.

achieved through two conspicuous cycles of erosion and accretion. The third spatial Eigen function ( $U_3$ ), which is the terrace function (WINANT *et al.*, 1975), has a broad maximum near the mean low water. The temporal dependence of this function ( $V_3$ ) shows a complicated nature probable due to changes associated with the differential wave activity. It also reflects the changing position of the low water itself on the beach face during the course of an year because of the seasonal changes in sea level and erosion or accretion taking place at the beach under the influence of seasonally reversing wind and wave climates.

In this study only two Eigen functions and their

distribution in space and time are considered in view of the fact that the higher order functions are negligibly small. In addition, the beach profile surveys did not extend well beyond the level of low tide. The spatial and temporal changes of the beaches within the four zones examined through EEF analysis are presented below.

### Narakal Zone

The distribution of the first spatial Eigen function  $U_1$  (Figure 5a) shows the presence of fully grown berm at locations N1 and N2, while at N3 no clearcut berm is seen. Moreover, it shows that the

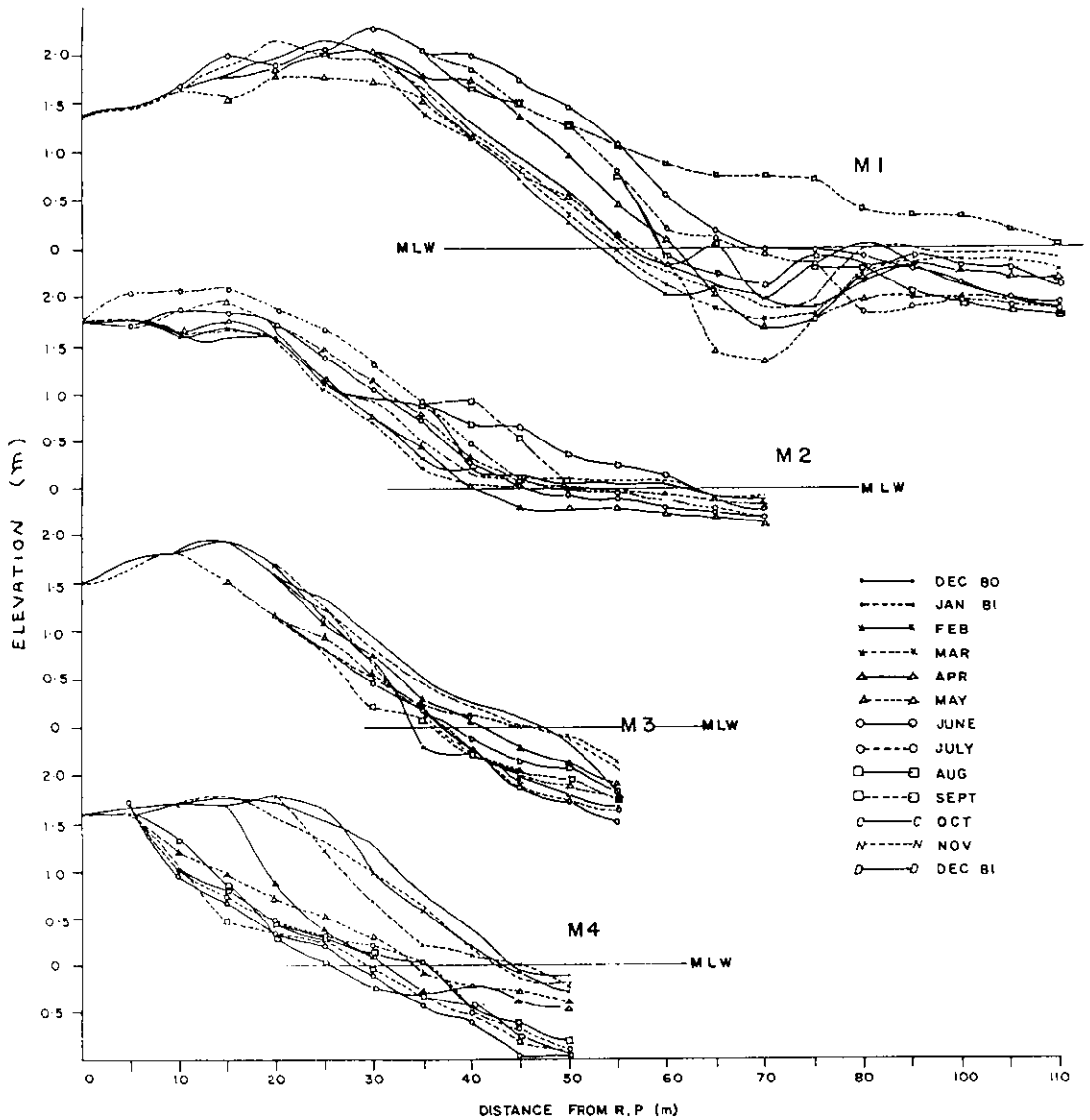


Figure 3b. Beach profiles at Malipuram zone.

beaches at these locations have relatively steep foreshore above the mean low water (MLW) whereas the slopes become flat below MLW. The temporal function associated with the mean beach function (MBF) indicates an overall accretional trend for all the beaches within this zone over the period of study though the beaches at N1 and N2 present greater temporal fluctuations compared to the one at N3.

The distribution of the second spatial Eigen function (U2) shows that the maximum variability prevails close to MLW. This could be clearly seen in the vicinity of the lower foreshore for N1 and N2 where as below MLW for N3 (Figure 5a). The second temporal function (V2) indicates a short term cyclicality of about two to two and a half months period. In general, the beaches of the Narakal zone exhibit buildup during the period of

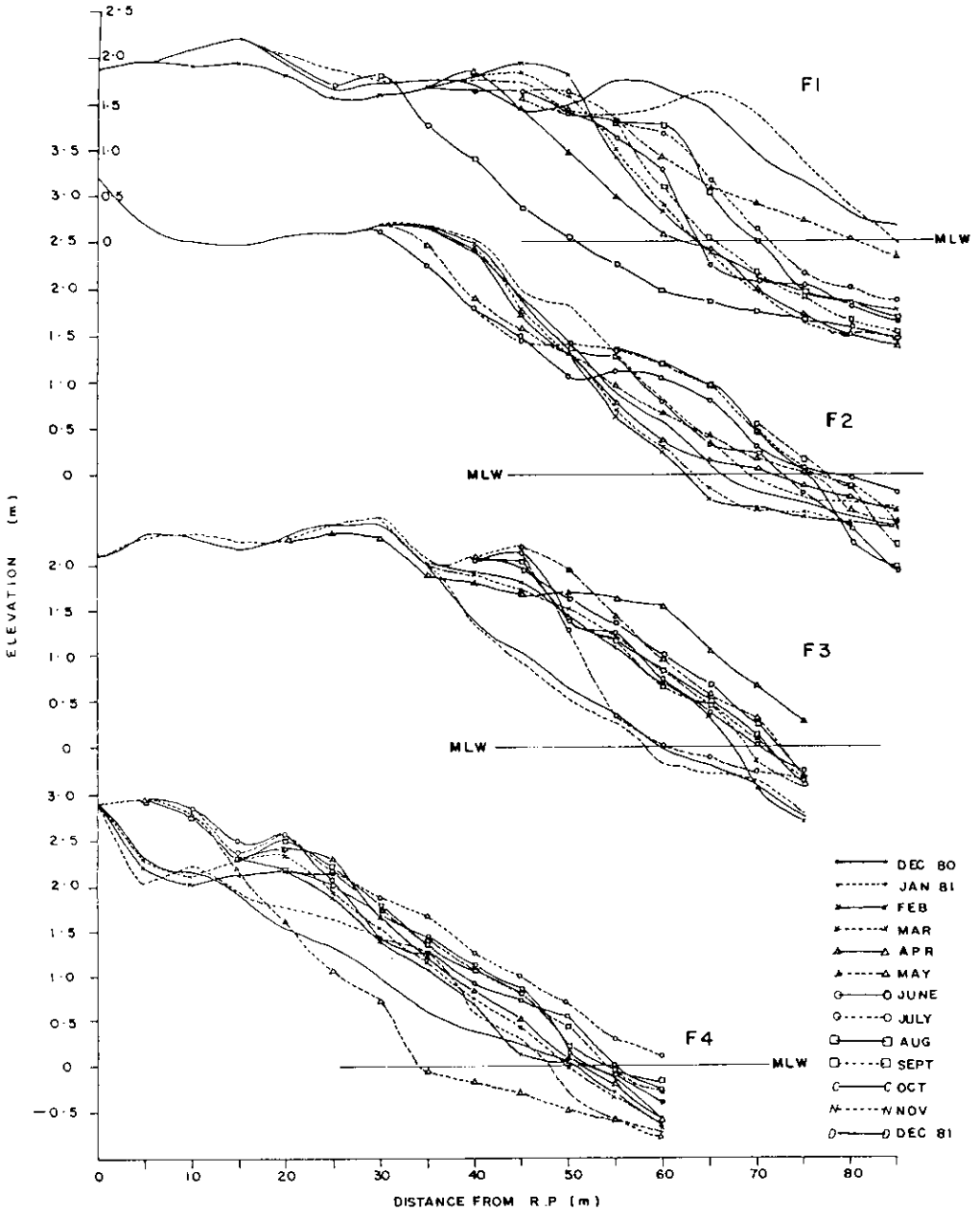


Figure 3c. Beach profiles at Fort Cochin zone.

study through alternate cycles of accretion and erosion (Figure 5a). During the period May-December, the response of the beaches at all three locations is similar except for minor departures as far as the

times of accretion are concerned. However, during December (1980) to May (1981), the sedimentation trend indicates greater variability at all three locations.

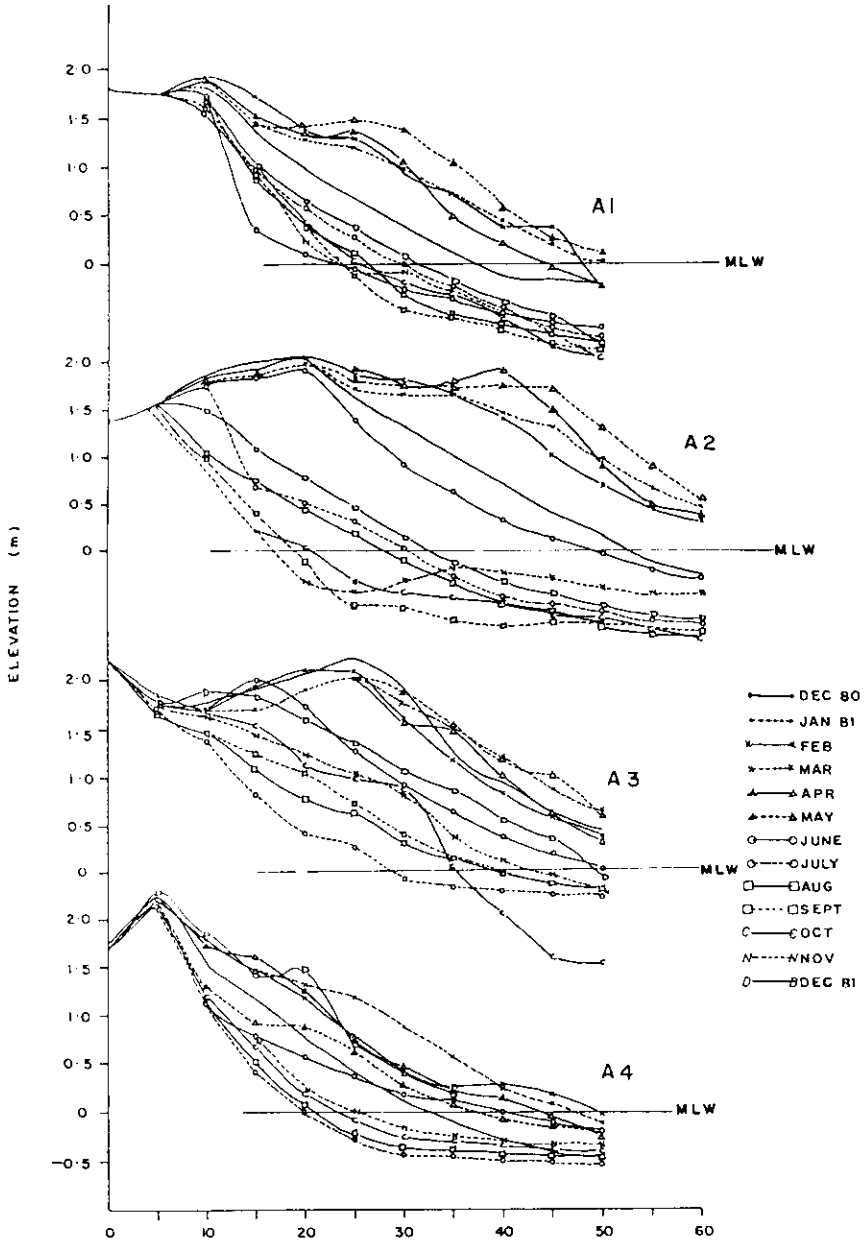


Figure 3d. Beach profiles at Anthakaranazhi zone.

**Malipuram Zone**

In this zone the distribution of MBF (U1) indicates the presence of a berm and a wider backshore. The width of the backshore, however, de-

creases progressively from M1 to M4 (Figure 5b). The beaches in general exhibit a moderately sloping foreshore. A decrease in this slope could be seen conspicuously for locations M1 and M2. The temporal function associated with MBF (V1) shows



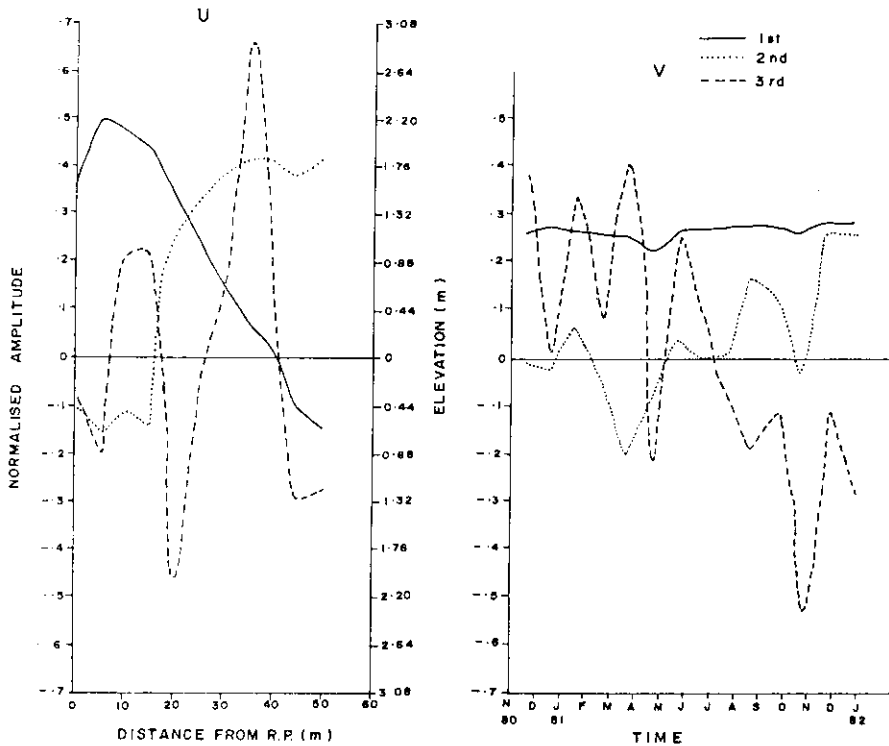


Figure 4. Spatial and temporal distribution of the empirical Eigen function at location N1.

that the beaches at M1 and M2 exhibit accretional tendency in contrast to M3 and M4 where the beaches present erosional trends.

The second spatial function (U2) shows that at M1 and M3 maximum variability of the profile occurs beyond MLW while at M2 it occurs at the lower foreshore. At M4 the entire foreshore is subjected to maximum changes. This could also be seen from the observed profiles (Figure 5b). For all the four locations a secondary maximum in the variability is clearly noticed at the berm crest (Figure 5b). The second temporal function (V2) shows that the response of the beaches in this zone varies considerably in time, especially during January to June. But during June to December the accretional and depositional patterns are nearly symmetric. The beaches at M1 and M2 even though experience alternate cycles of accretion and erosion, as could be seen from the distribution of V2 function, the net change points to a build up of beach. Lack of such well projected features in the case of beaches at M3 and M4 make the assessment of beach behaviour

difficult.

### Fort Cochin Zone

The distribution of MBF (U1) shows that the beaches, in general, have a well defined berm and moderately sloping foreshore except at F4, where the berm is absent and foreshore is comparatively steep (Figure 5c). It also shows a step-like feature at F1, F2 (at 30-40 m from R.P) and at F4 (at 15-20 m from R.P). In this zone the beaches exhibit moderately sloping foreshore that flattens out in the off-shore direction below MLW. The temporal function (V1) associated with MBF shows that the beaches at F1 and F4 experience greater changes compared to those at F2 and F3. The overall trend of V1 indicates erosional tendency at F1 and F2 and depositional tendency at F3 and F4.

The second Eigen function (U2) indicates that maximum variability of beaches occurring at various reaches of the foreshore above MLW (e.g., near the step for F1 and F2, upper foreshore for F3). The

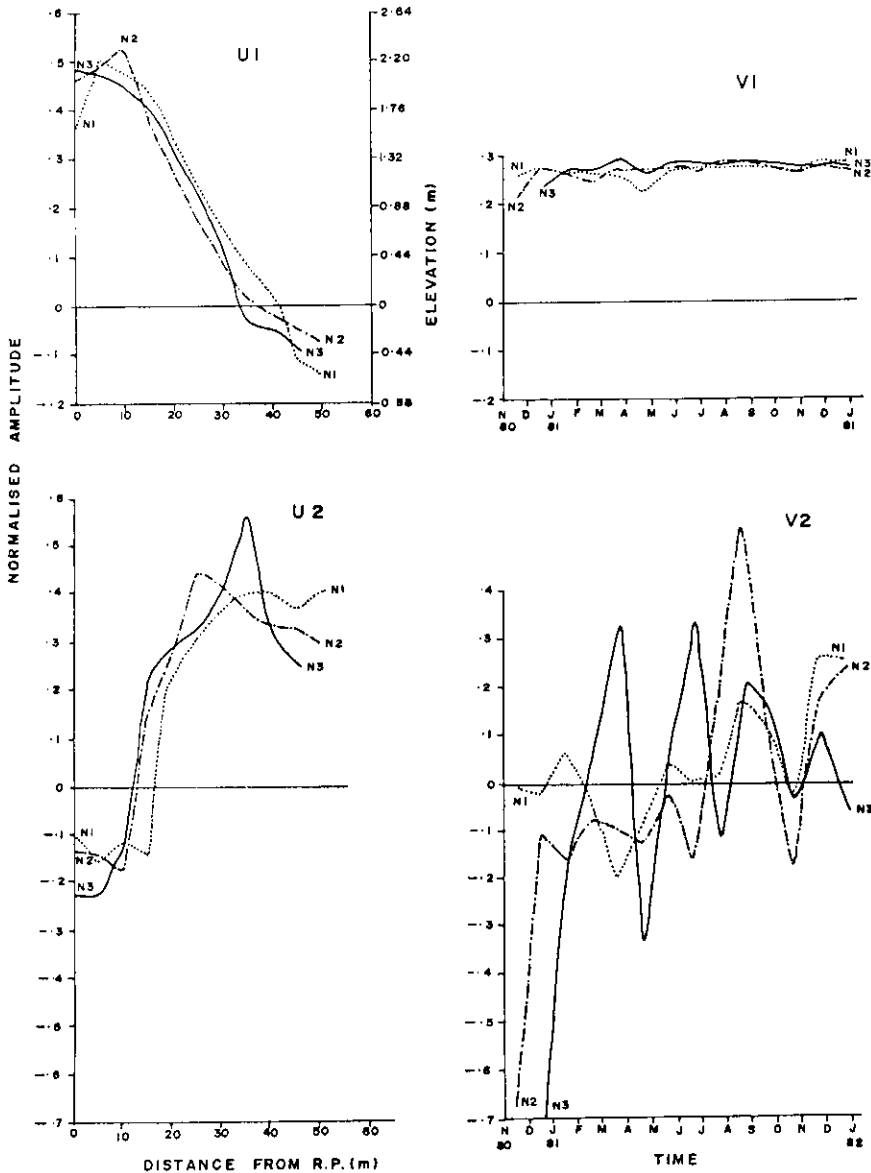


Figure 5a. Spatial and temporal distribution of the empirical Eigen function at Narakal zone.

distribution of the second temporal function (V2) shows that the beaches are subjected to accretion and erosion with varying lags and leads (Figure 5c).

**Anthakaranazhi Zone**

In this zone the distribution of MBF (U1) indi-

cates the presence of berm (Figure 5d). The beaches at A2 and A3 have moderately sloping foreshores while at A1 and A4 the steepness increases. The temporal function associated with MBF (V1) shows that the beaches at A1 and A3 are subjected to greater temporal variations.

The distribution of U2 shows that beaches in this zone have undergone maximum changes at the

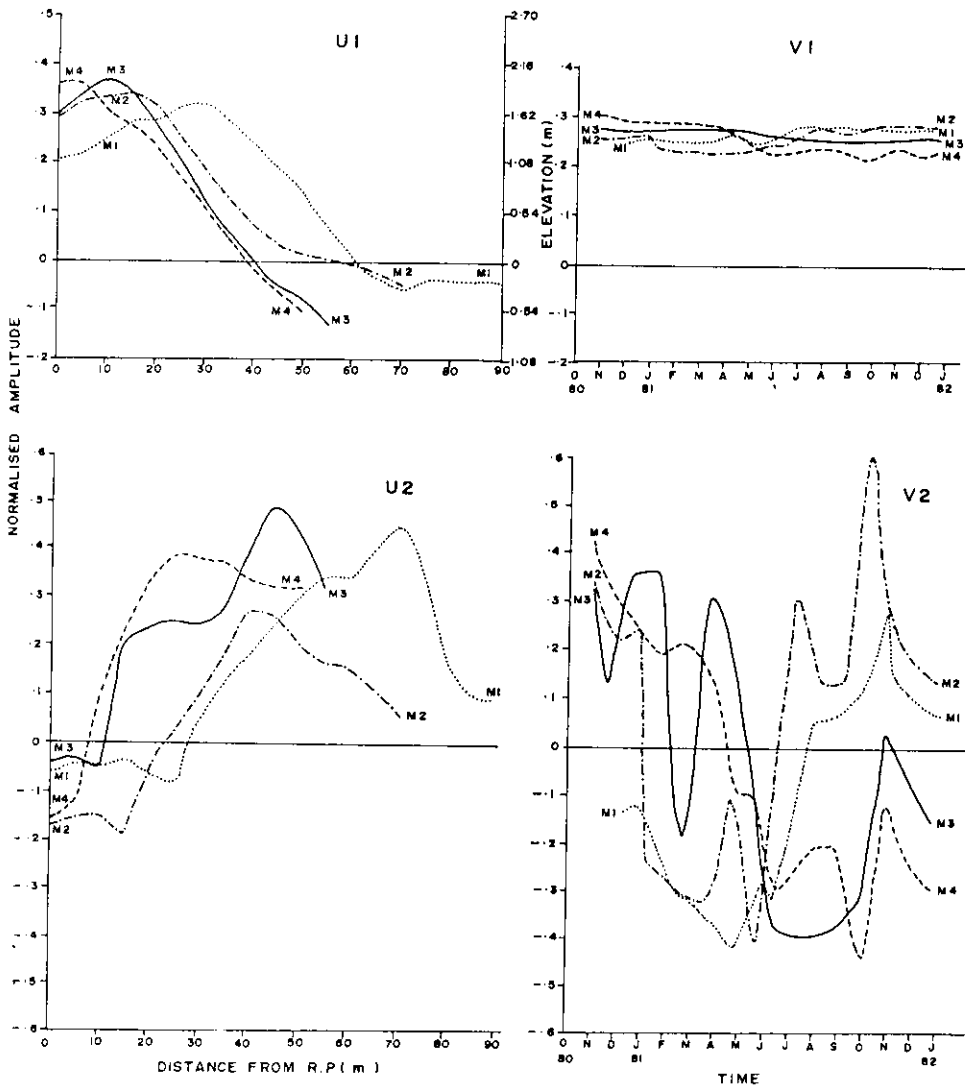


Figure 5b. Spatial and temporal distribution of the empirical Eigen function at Malipuram zone.

lower foreshore above MLW. At A2 and A4 the berm also shows some amount of variability. The second temporal function (V2) indicates that all the beaches in this zone responded in a similar manner showing depositional tendency during January to April and rapid erosion during May to July. The beach once again shows recovery trend during the subsequent months (Figure 5d).

## DISCUSSION

The beaches investigated from the four zones have

experienced erosion and accretion to varying extents. The observed intra- and inter-variability suggests to the fact that the changes in the response of the beaches are the result of differential wave activity and the associated flows close to the shore. In order to elucidate this aspect, the forcing parameters giving rise to such changes are examined.

Associated with the prevailing wind systems mentioned earlier, the seas present calm conditions for eight months in a year and rough to confused states of the seas during the rest of the year (MURTY, 1977).

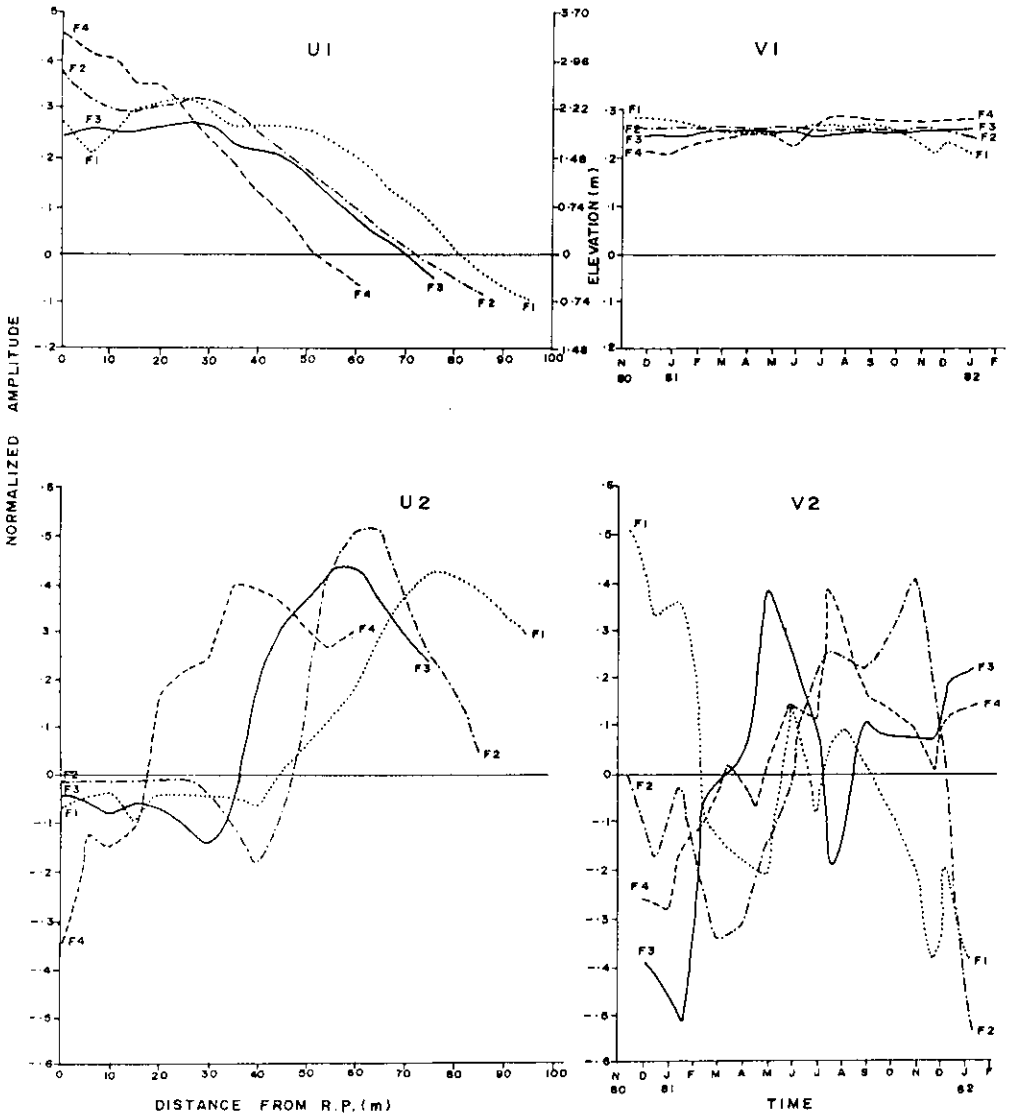
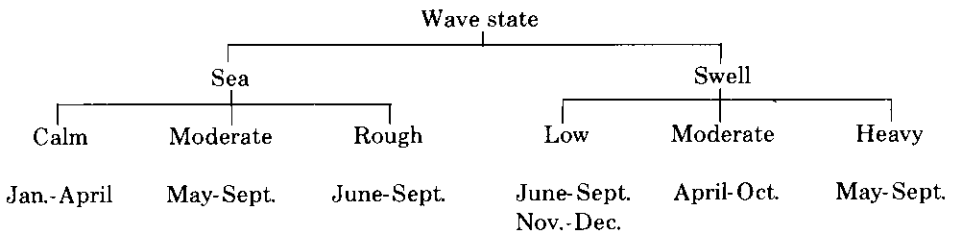


Figure 5c. Spatial and temporal distribution of the empirical Eigen function at Fort Cochin zone.



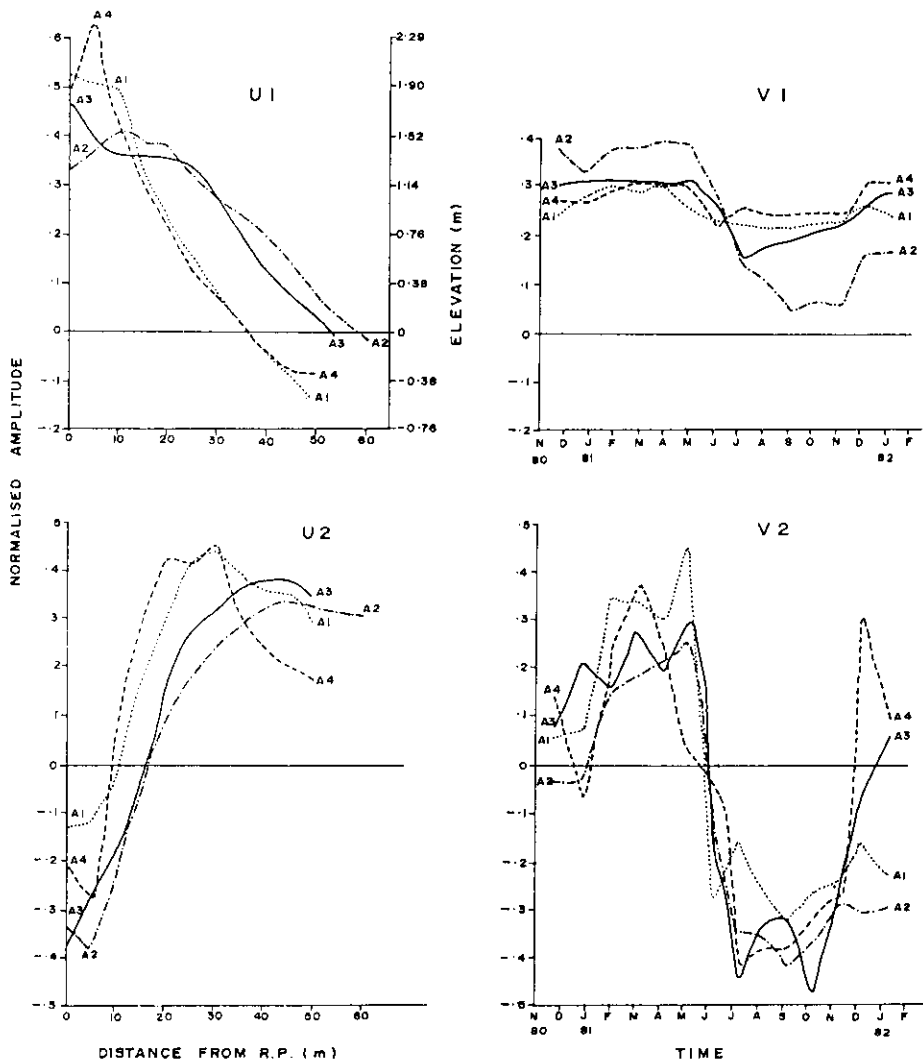


Figure 5d. Spatial and temporal distribution of the empirical Eigen function at Anthakaranazhi zone.

Increase in wave activity precedes the winds over this area during May in addition to their higher inconsistencies in the direction of approach (VARKEY *et al.*, 1982). The significant heights of these waves are conspicuously high during June through August (Figure 6b). As the strength of the monsoonal wind decreases by about September, low and long period swell waves (Figure 6a) approach the shoreline up to about November. Further onwards, low and short swell waves dominate.

The wave energies computed along this coast from wave refraction studies are of the order of  $10^4$

$\text{kg m}^{-1} \text{day}^{-1}$  at the onset of the southwest monsoon. This is one order of magnitude higher than the energies prevailing during the rest of the time (KUMAR *et al.*, 1983). Under the influence of this increased wave energy, the beaches experience erosion. But the presence of fine to very fine sediments of these beaches and their irregular responses to incoming wave energy—by way of accretion of beaches at the Narakal and Malipuram zones during the southwest monsoon periods—present an anomaly (Figure 5a, b). A plausible explanation for this could be sought from a feature which absorbs or

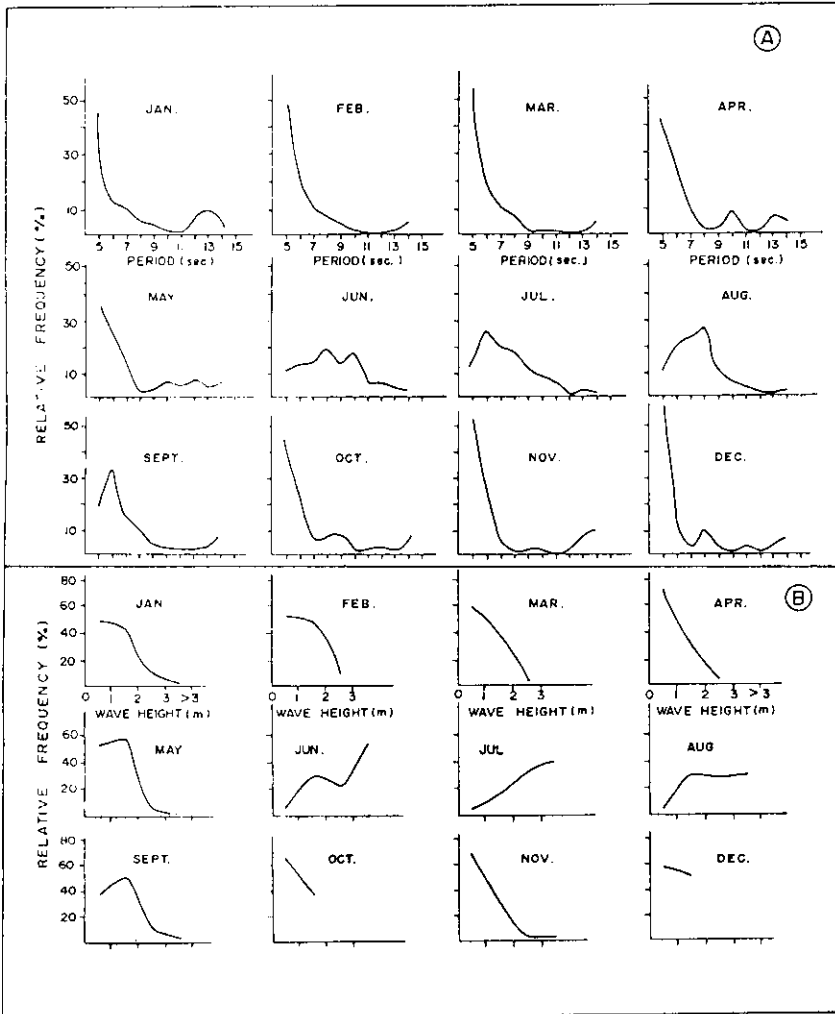


Figure 6. Relative frequency distribution of wave (A) period and (B) heights (after MURTY, 1977).

attenuates most of the increased wave energy in reaching the shore during the monsoon season. This feature appears to be only the loose and unconsolidated nearshore sediments in the silty-clay and clayey-silt size limits.

According to LONGUETT-HIGGINS (1953) the oscillatory wave motion generates strong vorticity within the boundary layer which gets transported into the fluid interior by viscous diffusion and gives rise to changes in the viscosity of the interior column. An increase in the viscosity (MACPHERSON and KURUP, 1981) of the waters in the nearshore areas off Narakal and Malipuram could be expected

because of the above process. During the monsoon months, these waters are muddy with local sea surface presenting a placid appearance with more suspended sediment. KEEN (1938) reported values of kinematic viscosity ( $\nu$ ) as high as  $450 \text{ cm}^2 \text{ sec}^{-1}$  from this area. This increase in kinematic viscosity gives rise to changes in the thickness of the boundary layer [ $\delta \approx 2.821 (\nu T)^{1/2}$ ] wherein an order of magnitude increase could be noticed for a given wave period (Table 3). For example, for  $\nu$  in the range  $1\text{-}10 \text{ cm}^2/\text{sec}$  (a value much less than that reported by KEEN), the boundary layer thickness increases from 9 cm to 28 cm for a wave of 10 sec

Table 3. Bottom boundary layer thickness ( $\delta$ -cm) for different wave periods ( $s$ ) and kinematic viscosities ( $\delta$ -cm/s<sup>-1</sup>).

Kinematic viscosity	Period				
	6	8	10	12	14
0.001	0.22	0.25	0.28	0.31	0.33
0.01	0.69	0.80	0.90	0.98	1.06
0.1	2.19	2.52	2.82	3.09	3.34
1.00	6.91	7.98	8.92	9.77	10.56
10.00	21.85	25.23	28.21	30.90	33.38
100.00	69.10	79.79	89.21	97.72	105.56
450.00	146.59	169.26	189.23	207.30	223.91

period (Table 3). This increase in the apparent viscosity of the water column and the thickness of the boundary layer brings about reduction in the wave energy. A wave of 1.5 m height and 10 sec period at the seaward periphery of the mud bank (~20 m water depth) loses 50% of its energy over a distance of about 1.5 km (~10 wavelengths) and nearly 100% over a distance of about 4 km (~24 wavelengths) for kinematic viscosity of 1 cm<sup>2</sup>/sec (SHENOI and MURTY, 1986). Thus, the presence of patches of muddy water over the wide and shallow nearshore area immediately north of Cochin Harbour entrance channel (Figure 1) offers maximum resistance and provide shelter to the beaches on the lee side. The beaches of the Narakal zone lying on the leeside of these patches accordingly receive protection from the high waves of the southwest monsoon season as evidenced from the accretion of these beaches during this season. During the field surveys the observed absence of wave activity within Narakal and Malipuram region lends support to the dissipation of waves in this region in contrast to the high wave activity in the adjoining zones.

The differential response of the beaches of Fort Cochin zone from those of the other zones may be due to the partial protection received from the mud banks of this region and the differential rate of sediment supplies from the zones north of Cochin Harbour entrance channel.

The beaches at Anthakaranazhi zone are the only beaches that responded to the monsoonal wave activity in a manner similar to the mainland sandy beaches with erosion during the period of increased wave energy associated with monsoonal wave climate and accretion during the rest of the season.

The observed diverse responses of these beaches also depend on the vergence field associated with the incoming waves. These waves, as they propagate over the shelf, experiencing refraction to variable degree, give rise to divergence of wave energy followed on either side by convergence.

These zones influencing the accretion/erosion of the beaches have been found to shift along the shore with changes in the wave period (KUMAR, 1985) and reflect on the alongshore sediment movement. This aspect has been examined following the littoral cell and sediment budget concept of INMAN and FRAUTSCHY (1966), where the cell is defined as a coastal segment that contains a complete sedimentation cycle including sources, transport paths and sinks. In the present area, two such cells could be identified—one each along the Vypeen and Chellanam Islands. The river Periyar is the principal sediment source during the freshet for Vypeen cell while the Chellanam cell is free from any natural sources, though the opening at Cochin harbour contributes some sediments to the adjoining beaches. Sediment transport studies indicated a net southerly drift along this region (KUMAR *et al.*, 1983) with the transport occurring mostly in a meandering pattern depending upon the direction of deep water wave approach. When these sediments reach the southern most point of the Vypeen cell the relatively intense flood and ebb tidal currents within the approach channel (which acts in a way similar to that of a dynamic barrier for these sediments) prevent any natural by-passing of these sediments from Vypeen littoral cell further south towards Chellanam cell. The most obvious effect of this channel is, therefore, to impound material and increase the width of the nearshore area on the northern side leading to progression of shoreline near the southern end of Vypeen.

For the Chellanam cell, the inadequate supply of sediments from north cause the southward flows undersaturated. In the absence of sufficient quantities of sediment available to the littoral flows from the upper reaches, these undersaturated flows erode the existing material from the beach zone along this sector as could be seen from the shore protection structures which are in a dilapidated state. Under these conditions, the longshore flows affect the stability of the beaches and make them more vulnerable for continuous erosion leading to recession of the shoreline in contrast to seasonal erosion observed on many of the mainland beaches.

This study clearly identifies the following features of morphological changes of sections of the barrier beaches along the southwest coast of India:

(1) The responses of the beaches to wind and wave climate are variable, particularly during the southwest monsoon.

(2) The observed inter-variability of the beaches of the four zones is due to the differential wave activity together with the static mud suspensions at places in the nearshore area.

(3) Within each zone the observed intra-variability of the beaches is due to the influence of quasi-stationary zones of convergence and divergence of wave energy induced by wave refraction.

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### □ ZUSAMMENFASSUNG □

Die Erwiderng eines kleinen Strandteil südwestliches Indiens auf die südwestlichen Wellen- und Windumstände zeigte grosse Abänderungen, als sie durch erfahrungsmässige Eigenanalyse untersucht wurde. Die bemerkte Innen- und Zwischenveränderlichkeit wurde durch differentiale Wellenrührigkeit verursacht, und sie wird teilweise durch die flache Seebodentopographie mit lokalisierten Schlammabhängungen in der Nähe des Forschungsgebiets verursacht. Zusätzlich ist der Sedimentfluss vom Festland und küstennahen Quellen sehr arm; diese Umstand macht die Littoralflüsse untersättigt, und dadurch wäschen die Sedimente von der Strandzone aus.--Stephen A. Murdock, CERF, Charlottesville, Virginia, USA

### □ RÉSUMÉ □

Une petite extension de la barrière littorale située sur la partie Sud de la côte Ouest de l'Indie répond aux vents du SW et au régime de houle par de larges variations. Elles sont examinées à travers une analyse des fonctions propres empiriques. L'inter et l'intra-variabilité résulte de l'action différentielle des vagues, qui et due en partie à la topographie plane de la plage, avec localement des vases statiques en suspension. L'approvisionnement en sédiments provenant de sources continentales ou du large rendent sous-saturés les principaux courants littoraux, ce qui provoque une érosion du matériel en place de la plage.--Catherine Bressolier, EPHE, Montrouge, France

