Journal of Indian Geomorphology
Volume 4, 2016 ♦ ISSN 2320-0731
Indian Institute of Geomorphologists (IGI)

Fifth Prof. S. R. Basu Memorial Lecture delivered at the 28th National Conference of the Indian Institute of Geomorphologists (IGI) held at the North Eastern Hill University, Shillong, during 29–31 October 2015

Morphodynamics of Beaches of the Southeastern Coast of Tamil Nadu

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It is a great honour and privilege to deliver the Professor S.R. Basu Memorial Lecture at IGI conference, Shillong, Meghalaya. I am extremely grateful to Prof. S.R. Basu's family members and IGI for having provided an opportunity to share my experiences on coastal sciences with young geomorphologists. My association with Prof. S.R. Basu was very short, but his constant motivations and support extended to me is unforgettable particularly the experience at coastal field trips in Kanyakumari during IAG Regional Workshop. I have great admiration for his commitment to this society and the discipline of geomorphology more so his humanity with youngsters. Therefore, I have accepted to deliver and share the data on beach morphodynamics of Tamil Nadu coast for the benefit of young geomorphologists.

Introduction

Natural beach processes and morphology are influenced by waves, tides, and sediment characteristics. Cross-shore morphology of sandy beaches is an important issue for coastal erosion. An ideal beach may be conceived as a smooth expanse of sand stretching indefinitely alongshore. About 50% of the sandy beaches along the southeastern coast are influenced by placer mining and development pressure which severelyaffect the natural morphodynamic processes and landforms. Many beaches topographically exhibit a complex variety of long shore and offshore structures at various scales. Shoreline feature that show a regular longshore periodically drawn the beach as beach cusps, sand waves, rhythmic topography or giant cusps. Cross-shore sediment fluxes are a few orders of magnitude smaller than long shore transport; the cross-shore beach profile has strong influences on long shore velocity profiles. The beach profile is the result of the trade-off between onshore and offshore fluxes. The direction of the cross-shore fluxes is a key point for predictive tools and is clearly related to the non-linear characteristics of the incoming waves. Beach profiles are generally more complex and the concept of equilibrium beach profile is very useful. Equilibrium of beach profile in the surf zone is controlled by uniform wave energy dissipation per unit of volume. In an ever changing wave climate, equilibrium profiles could be retrieved as spatial longshore scales or mean international profiles. The objective is to characterise the rates and nature of beach change and to evaluate whether these changes have significant effects on the resulting morphology of the shoreline of Tamil Nadu coast. Further, this shoreline has mixed grain size beach setting due to its configuration and variable wave energy. Depending on the deep water wave characteristics and shelf and inshore morphology, breaker wave energy may be high, moderate or low. The beaches of Tamil Nadu coast are highly mobile with wide range of beach forms. The zones of sediment storage reflect the beach mobility and beach forms in the area.

Geographical location of the study area

The coast between Tuticorin and Kanyakumari of southern coastal Tamil Nadu of India has different morphological features and diverse ecosystem (Fig. 1). The Tamil Nadu coast line extends over a distance of 906 km endowed with a variety of coastal habitats like coral reefs, mangroves, seaweeds, salt marshes, sand dunes, sea grass bed etc. Based on the existing characteristic features, the Tamil Nadu coast has been classified as a depositional plain. The lecture is restricted to the area lying between Kanyakumari (from ManakudyPalayarestuary) and Tuticorin urban coast which extends over a distance of 160 km and covering the latitudes from 8°N to 8.88°N and longitudes from 77.5°E to 78.30°E. The major coastal settlements are Tuticorin, Kanyakumari, Tiruchendur, Ovari, Manappad and Kayalpattinam. The area includes headlands along Manappad and Tiruchendur coast. There is a major port in

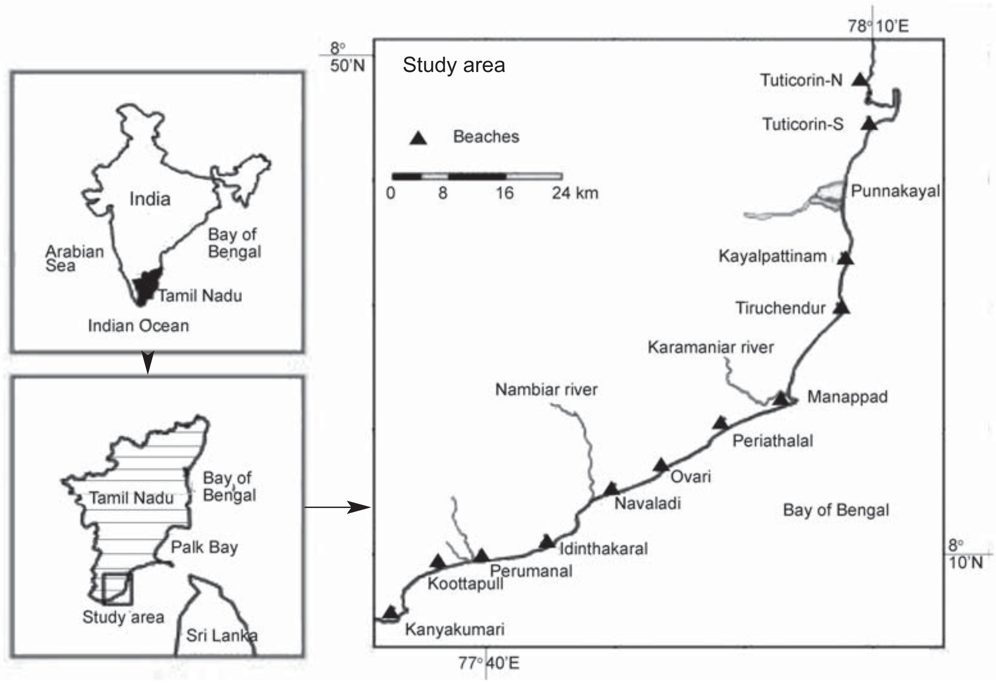


Figure 1. Geographical extend of the southeast coast of Tamil Nadu

Tuticorin and a fishing harbour near the Kanyakumari coast. The area is highly dynamic with many cyclic and random processes owing to a variety of resources and habitats. The coastal ecosystem is highly disturbed and threatened by industrial pollution, siltation, erosion, flooding, saline water intrusion, storm surges and ever-expanding human settlements.

Wave refraction

Wave refraction diagram has been constructed along the beaches between Ovari and Kanyakumari to investigate the changes that occur in the wave characteristics near the coast as deep water waves of different periods approach the coast from various directions (Fig.2a–2e). The wave climate is characterised by the southwest monsoon (June–September), northeast monsoon (October–January), and non-monsoon periods (February–May). The predominant wave directions prevailing in the region are referred in the wave atlas as SE during southwest monsoon and NW during the northeast monsoon. As the study area shows a trend of east-west to north-south orientation, the waves in the coast is predominantly from 45°SE during southwest monsoon and 20°NW during northeast monsoon. Since the orientation of the shoreline along the study area is in general, the north-south to east-west direction, the waves approaching the coast between 110°N and 135°N are of greatest significance in conjunction with littoral processes. Therefore, wave refraction diagrams have been prepared for the wave periods of 8 and 10 sec approaching from 110°N and 135°N by using the Tarangam Program developed by the National Institute of Oceanography (NIO), India, on the basis of finite amplitude wave theory for computing the wave transformation factors. The naval hydrographic chart (1973) was used for drawing bathymetric contours. The wave refraction pattern from southeast for the periods of 6, 8 and 10 sec are shown in Fig. 2A–2E. The wave energy condition prevailing

Table 1. Wave Energy conditions prevailing along the southeast coast (I: inept condition, D: divergence, C: convergence. OVR: Ovari, NAV: Navaladi, KUT: Kuttankuli, IDI: Identhakarai, PERU: Perumanal, KUP: Kuttapuli, VAT: Vattakottai, ARO: Arokiapuram, CHI: Chinnamuttom, KAN: Kanyakumari)

Station	SE			NW		SSW
	6s	8s	10s	8s	10s	8s
OVR	I	C	C	I	I	I
NAV	I	I	I	I	I	I
KUT	I	C	C	I	I	I
IDI	I	D	D	D	D	D
PERU	I	I	I	I	I	I
KUP	I	I	C	I	I	I
VAT	I	I	I	I	I	I
ARO	D	C	C	I	I	D
CHI	I	C	C	C	D	D
KAN	I	I	I	I	I	I

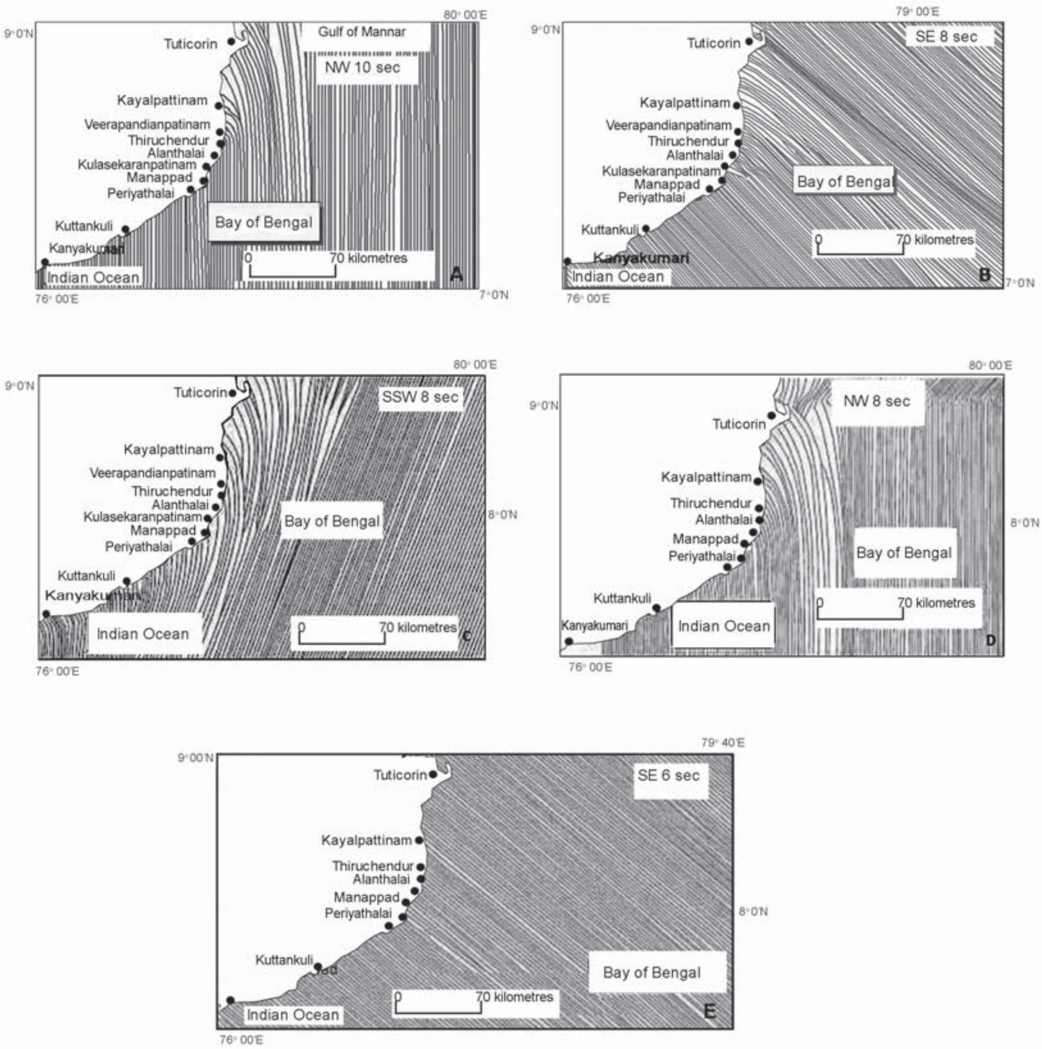


Figure 2. Wave refraction during SW monsoon (A and B), NE monsoon (C and D) and non-monsoon (E) period

along the area in different wave directions for different periods is given in Table 1.

In the pattern of 10 sec, wave convergence is observed at Thiruchendur, Manappad, Periyathalai, and Vattakottai. An overview of refraction pattern of three wave periods reveals that wave energy is more pronounced and concentrated in the wave period of 10 sec than in other two periods (Table 2). The wave period of 10 sec plays a predominant role in the shaping of various landforms of depositional and erosional nature and in the redistribution of sediments. The overall pattern of wave refraction in the area fromsoutheast direction displays strong convergence in the number of beaches, and the same may be ascribed to the prevalence of high energy conditions unlike the other two directions. This leads to the inference on sediment transportation and their degree of sorting and are likely to be more intensive in the southwest monsoon period. The change in wave energy from convergence to divergence in a particular beach with different period

Table 2. Monthly data of breaking wave height along the southeastern coast (OVR: Ovari, NAV: Navaladi, KUT: Kuttankuli, IDI: Identhakarai, PERU: Perumanal, KUP: Kuttapuli, VAT: Vattakottai, ARO: Arokiapuram, CHI: Chinnamuttom, KAN: Kanyakumari)

Stations	A	M	J	J	A	S	O	N	D	J	F	M
OVR	0.5	0.2	0.2	0.5	0.3	0.45	0.7	0.45	0.6	0.45	0.5	0.5
NAV	0.4	0.45	0.3	0.15	0.4	0.3	0.55	0.4	0.35	0.45	0.45	0.6
KUT	0.5	0.5	0.25	0.2	0.2	0.15	0.5	0.2	0.25	0.4	0.55	0.55
IDI	0.4	0.45	0.4	0.25	0.3	0.7	0.3	0.6	0.8	0.3	0.45	0.3
PERU	0.5	0.35	0.15	0.2	0.3	0.2	0.45	0.2	0.55	0.45	0.35	0.45
KUP	0.3	0.4	0.2	0.15	0.25	0.1	0.6	0.3	0.45	0.25	0.4	0.4
VAT	0.25	0.15	0.05	0.25	0.1	0.25	0.2	0.2	0.2	0.05	0.15	0.2
ARO	0.3	0.4	0.25	0.25	0.35	0.6	0.2	0.45	0.6	0.25	0.35	0.2
CHI	0.4	0.2	0.25	0.2	0.25	0.35	0.85	0.5	0.55	0.35	0.55	0.5
KAN	0.2	0.2	0.25	0.2	0.15	0.3	0.35	0.35	0.15	0.25	0.2	0.2

Table 3. Monthly data of longshore currents along the southeastern coast (northerly direction [–] and southerly direction [+] OVR: Ovari, NAV: Navaladi, KUT: Kuttankuli, IDI: Identhakarai, PERU: Perumanal, KUP: Kuttapuli, VAT: Vattakottai, ARO: Arokiapuram, CHI: Chinnamuttom, KAN: Kanyakumari)

Sta-tions	A	M	J	J	A	S	O	N	D	J	F	M
OVR	0.48	0.01	–0.16	–0.01	–0.18	–0.06	–0.36	–0.39	–0.43	–0.09	0.14	0.29
NAV	0.44	0.13	–0.20	–0.32	–0.22	–0.22	–0.30	–0.22	–0.32	–0.16	0.11	0.2
KUT	0.4	0.14	–0.21	–0.33	–0.24	–0.24	–0.30	–0.33	–0.33	–0.10	0.12	0.18
IDI	0.31	–0.10	–0.09	–0.07	–0.21	–0.08	–0.07	–0.01	0.03	–0.11	0.04	0.04
PERU	0.42	0.04	–0.20	–0.13	–0.26	–0.10	–0.29	–0.14	–0.34	–0.06	0.12	0.18
KUP	0.38	0.02	–0.23	–0.20	–0.23	–0.31	–0.26	–0.16	–0.32	–0.04	0.16	0.16
VAT	0.5	0.03	–0.05	–0.10	–0.01	–0.21	–0.31	–0.16	–0.30	–0.08	0.1	0.16
ARO	0.3	0.12	–0.10	–0.06	–0.28	–0.09	–0.07	–0.04	0.06	–0.13	0.06	0.08
CHI	0.39	0.02	–0.07	–0.04	–0.1	–0.07	–0.3	–0.4	0.05	–0.07	0.01	0.16
KAN	0.34	0.14	–0.04	–0.20	–0.07	–0.20	–0.30	–0.15	–0.30	–0.17	0.1	0.16

Table 4. Monthly data of surf zone width along the southeastern coast (OVR: Ovari, NAV: Navaladi, KUT: Kuttankuli, IDI: Identhakarai, PERU: Perumanal, KUP: Kuttapuli, VAT: Vattakottai, ARO: Arokiapuram, CHI: Chinnamuttom, KAN: Kanyakumari)

Stations	A	M	J	J	A	S	O	N	D	J	F	M
OVR	18	20	20	22	15	19	18	17	20	18	20	20
NAV	19	20	16	18	17	20	16	16	20	20	20	20
KUT	18	16	15	15	20	18	17	15	17	15	20	20
IDI	13	12	12	11	12	14	13	12	14	12	12	14
PERU	17	20	15	15	20	18	17	15	17	15	20	20
KUP	20	18	15	16	17	20	18	17	16	18	19	20
VAT	16	14	18	14	14	17	15	14	17	18	16	16
ARO	20	22	20	17	19	20	17	16	18	19	22	22
CHI	17	17	16	18	17	19	20	17	20	18	20	20
KAN	16	14	13	16	15	12	14	15	14	17	18	16

wasattributed to the change in the quantum of sediment movement from one period to other. The nature of cliffed coastline from Kuttankuli to Vattakottai is with high order of erosion indicating a zone of high energy environment in the strong convergent zones.

Littoral sediment transport

The movement of material in this zone mainly depends on three factors: the nature of material available for transport (size and density), orientation and other features of the coast, and an angle of wave approach. Littoral transport plays a major role in the development of certain shoreline features like spits and bars and causes considerable coastal erosion and accretion. The monthly longshore sediment transport rates estimated on the basis of monthly observations on longshore currents and surf zone width are presented in the Table 3 and 4. The monthly volume of longshore sediment transport rates and directions are estimated for the coasts namely Kuttankuli, Vattakottai, Thiruchendur, Alanthalai, Manappad, Periyathalai, Ovari, and Kanyakumari. In general, the sediment transport is northerly during March to October and southerly during November to February. The longshore sediment transport is higher in the northerly direction as compared to southerly direction at all locations except Kanyakumari. This occurs because of the rocky outcrops sheltering the Kanyakumari beach, and manmade features such as a harbour across the surf zone would act as a barrier and sand deposited on the up-drift side of this barrier

Beach morphodynamic classification

The wave refraction analysis has delineated different wave energy conditions prevailing in the area. There are areas of erosion and accretion observed along the coastal stretch, which depends primarily on the direction of wave approach, wave period, and wave refraction pattern. In the near shore

Table 5. Beach morphodynamic classification along the southeastern coast

I. Breaker type (Battjes, 1974)	Spilling $\xi b<0.4$	Plunging $0.4<\xi b<2.0$	Surging $\xi b>2$
II. Beach type (Wright and Short, 1984)	Reflective $\Omega<1$	Intermediate $1<\Omega<6$	Dissipative $\Omega>6$
Locations	Kuttapuli, Vijayapathi, Arokiapuram and Vattakottai	Kuttankuli, Chinnamuttom and Kanyakumari	Ovari and Perumanal

zone of the area, the movement of sand alongshore is due to the action of waves and currents. A complete study of wave dynamics is imperative at this instant, which includes the measurement across the swash and surf zones of local sediment transport, wave height, wave energy conditions, longshore current, etc., to comprehend and describe the swash processes precisely. Also the time scale of each study should be commensurate with that of the duration of the directional wave event that drives the transport. Further, emphasis has to be placed on formulating computer models to conjecture the performance of sediment movement for the development and management of the coastal zone. The direction of littoral drift is from south to north during the period of March to October when the waves are between south and southeast and from north to south during the period of November to February when the wave directions are between east and east-northeast. The seasonal changes in the direction of littoral drift with southwest and northeast monsoons cause cyclic variations of the beach morphology along the coast under investigation. The rocky outcrops scattered across the littoral zone causes the reversal of beach cycles at different stations along the coast. For example, at Kanyakumari (October) during southwest monsoon, the southerly movement of sediment is observed. The net littoral drift at all stations is generally from south tonorth with the exception of the Kanyakumari station, where the net drift is southwards. The net erosive nature of the study area (except Kanyakumari) from March to October is due to the prevalence of high waves from south and southeast directions. The morphodynamic states of reflective, dissipative, and intermediate beaches of the area (Table 5) are assessed on the basis of energy regimes, gradient of beaches, beach width, backshore width, wave type, coast exposure, and morphological features in the near shore zone. The morphodynamic status of the beaches along the southeast coast of Tamil Nadu is shown in Figure 3.

Dissipative beaches

The high wave energy condition with low gradient beach slope has asurf scaling parameter. They have higher rate of dune and backshore recession. Dissipative beaches in the study area are composed of fine to medium sand, and, hence, the mobility of the beaches is more enhanced than the higher energy conditions of the reflective beaches. Due to repeated oscillations of high wave energy condition in the dissipative beaches, scarping of the beach profiles occur. Beaches falling under this category are Ovari and Perumanal.

Reflective beaches

Low modal wave heights and steep

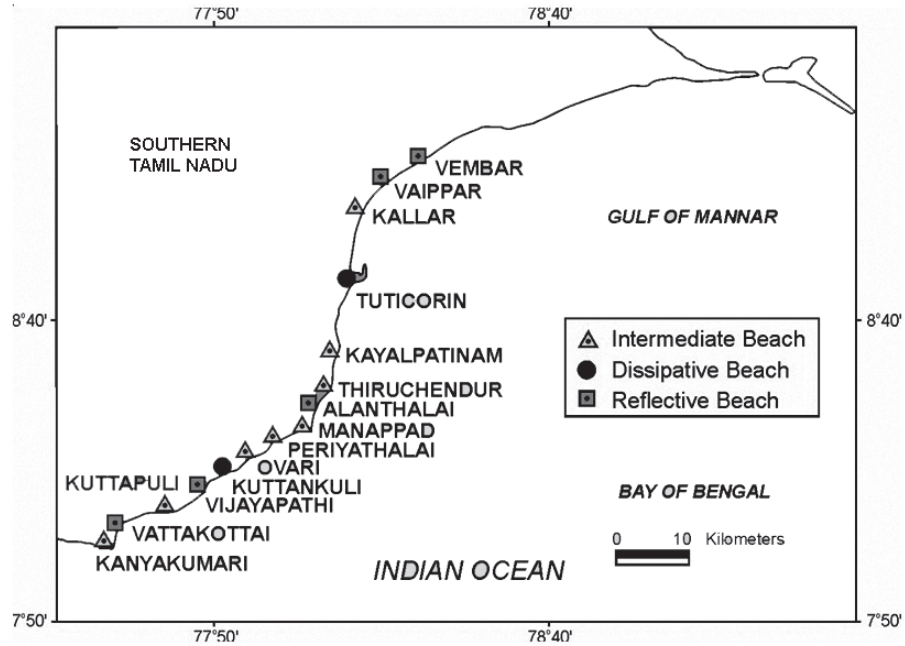


Figure 3. Morphodynamic state of the beaches along the southeastern coast of Tamil Nadu

gradients of the beach have resultedin a low surf scaling parameter. However, if the wave height increases seasonally, the beaches in these environments would be severely affected by erosional processes. The same is attested in the region during the northeast monsoon, and the erosion-sensitive concave beach profiles dominate over convex profiles. The mobility of the beaches is hindered by the coarseness of the sediment,low energy condition, and steep beach gradient. Beaches like Kuttapuli, Vijayapathi, Arokiapuram, and Vattakottai fall under this category.

Intermediate beaches

Intermediate domains exhibit the characters of both reflective anddissipative beaches. Moderate gradient and abundant supply of sediments are seen more with dominant alongshore movement than with onshore–offshore movement. Broad backshore width is observed in the intermediate state of beaches in Perumanal and Vijayapathi coast. Flat and moderate beach gradients with strong rip current and well developed cusps that disappear as the reflective shoreline conditions dominate over the intermediate state are perceptible in the zeta form bay between Kuttapuli and Arokiapuram. The gradients of the beaches that are gentle with low energy conditions are seen in Ovari coast. Along with other modes of beach cuttings, rip currents developed in this coast caused the continual erosion. Along the area, such beaches as Kuttankuli, Chinnamuttom, and Kanyakumari are to this category.

Beach topographical analysis

The profiles of beaches, cliffs and other coastal landforms are often studied and analysed in the coastal areas. These cross sections through coastlines can give a good idea on the changes that can occur over time at one point on the coast, either in the shape of a beach or cliff, or in its size and volume. Beach topography is a result of complex interactions between natural coastal processes and anthropogenic activities. The most common method for measuring beach topographic change is the beach profile. Coastal morphology is the result of combined action of hydrodynamic, geologic and climatologic processes. The beach morphology of coast undergoes perpetual and rapid changes. Generally, the influencing natural forces can be subdivided into long term processes, which shape the coastal morphology on large spatial scales in the order of kilometres or more and short-term processes. More recently, anthropogenic effects may also influence substantially the shape of the coastline. Consequently, the beach morphology can be regarded as a sensitive indicator for the on-going coastal dynamic processes of a particular coastline. By monitoring the spatial and morphological changes of a beach over time, a good estimate of the rate and direction of coastal changes can be obtained. The beach profiles obtained from the level surveys are processed by using sophisticated software tools like 'The Beach' and 'BMAP'. The temporal and spatial representations of beach profiles have been delivered. The morphological parameters such as beach width and slope have been analysed. The volumetric change of beach sediment and their annual and seasonal variations have been evaluated. The morphodynamics of beaches can be investigated by performing the EOF analysis of profiles. The shoreline change, erosion and accretion made along the beaches have been predicted.

Spatial and temporal representation of profiles

Beach topographic analysis with short-term and long-term change in different spatial and temporal scales in the coastal dynamic environment is crucial for sustainable coastal management. A study of number of profiles from different points can produce information about the transportation of sediment along a coast, or how one area differs from another. The numerical profile data can be analysed statistically or it can be plotted as a graph to give a physical representation of the shape of a coastline. The beach profiles have been observed to change overa range of spatial and temporal scales; however techniques for quantifying this variability have not been fully established. Beach erosion may be a short-term (order of hours to seasons) process that reflects adjustment to wave energy changes, or a longer-term (order of years) one that reflects an increasingly deficient beach sediment budget and shoreline changes. Also, the seasonal changes in beach profiles constitute an important aspect of the variability of the coastal environment. The topographical and morphological changes of beach profiles are mainly oriented with coastal geology, shore configuration and seasonal oscillation prevailing along the study area. The topographical representation of different beaches reveals that the profiles are higher during March 2006 and the profile rises further during from March to May. During April or May, the profile of almost all beaches attains maximum level. The low energy littoral currents and waves prevailing along the area during the summer deposit sediment on the beach berms and dune, thereby raising the beach profile. From the month of June, the profiles start to lower due to the increase in wave energy due to the south-west monsoon. The lowering of profiles still continues up to the month of September (northeast monsoon period, winter). The seasonal migration of the sand exists, with sediment transport towards the beach in the summer, resulting steep beach face and high berms at the end of the summer. On sandy beaches, short-term changes involving erosion are commonly part of a so-called morphodynamic cycle of adjustment of the beach profile to seasonal or non-seasonal changes in wave energy. The short-term seasonal changes commonly correspond to the classic winter profile flattened by storms and the summer profile that accretes under fair weather conditions. The profile of beaches during the different periods such as pre-monsoon, monsoon (southwest and northeast) and the post-monsoon are shown in Figure 4. The profiles during March, April and May (pre-monsoon and summer) implies that the beaches have experienced accretion. The shift in profile level is more along the backshore due to more deposition of sediments. During this period, well developed berms have been observed in the hightide region of beaches. Accretion is noticed along the foreshore of Navaladi, Ovari and Periathalai beaches, which indicates the landward movement of sediment.

Beach morphodynamics

The beach width is defined as the horizontal dimension of beach measured at right angles to the shoreline from the line of extreme low water inland to the landward limit of a beach. It is also defined as the distance between dune crest and shoreline position at high tide. It is an important parameter measuring the 'health' of a beach. Understanding how beach width changes over varying timescales is vital for future shoreline management planning, for example, planning of beach nourishment or seawall construction, defining hazard setbacks, identifying 'hot spots' (locations of enhanced erosion) and the threat to human structures and/or recreational activities. The width of different beaches along the study area undergoes dynamic changes in both spatial and temporal scales (Tables 6–8) which have been controlled by both natural and human induced activities particularly beach sand mining. The Profiles are characterized by a large seasonal and annual variation in the incident wave height and beaches exhibit a distinct change in beach morphology. However the morphological changes are better explained by seasonal reversals in the littoral drift direction and by the variations in the incident wave energy conditions.

The seasonal change in beach morphology is traditionally ascribed to a variation in the incident wave energy level with calm conditions in summer resulting wide beaches with pronounced sub-aerial berms and energetic conditions in winter causing narrow beaches with near-shore bar morphology. The seasonal and annual variations of beach width have been represented in Figure 5A. It is observed that the beaches of Kanyakumari, Koottapuli, Idinthakarai, Navaladi and Ovari have experienced a reduction of beach width during the study period while the other beaches have experienced an increase in beach width. This indicates the spatial variation of erosion and accretion along the different beaches of the study area. During the period of March to May, the widths of beaches are in increasing trend, and it reaches a maximum value in April to May. The berms area is also more during these months. After this period, the increase in wave climate due to south-west monsoon lowers the profile and reduces the beach width considerably. In most of the beaches the beach width attains minimum values during August or September. From September onwards, the beach width slightly increases from its minimum level. It is due to comparatively low wave energy and

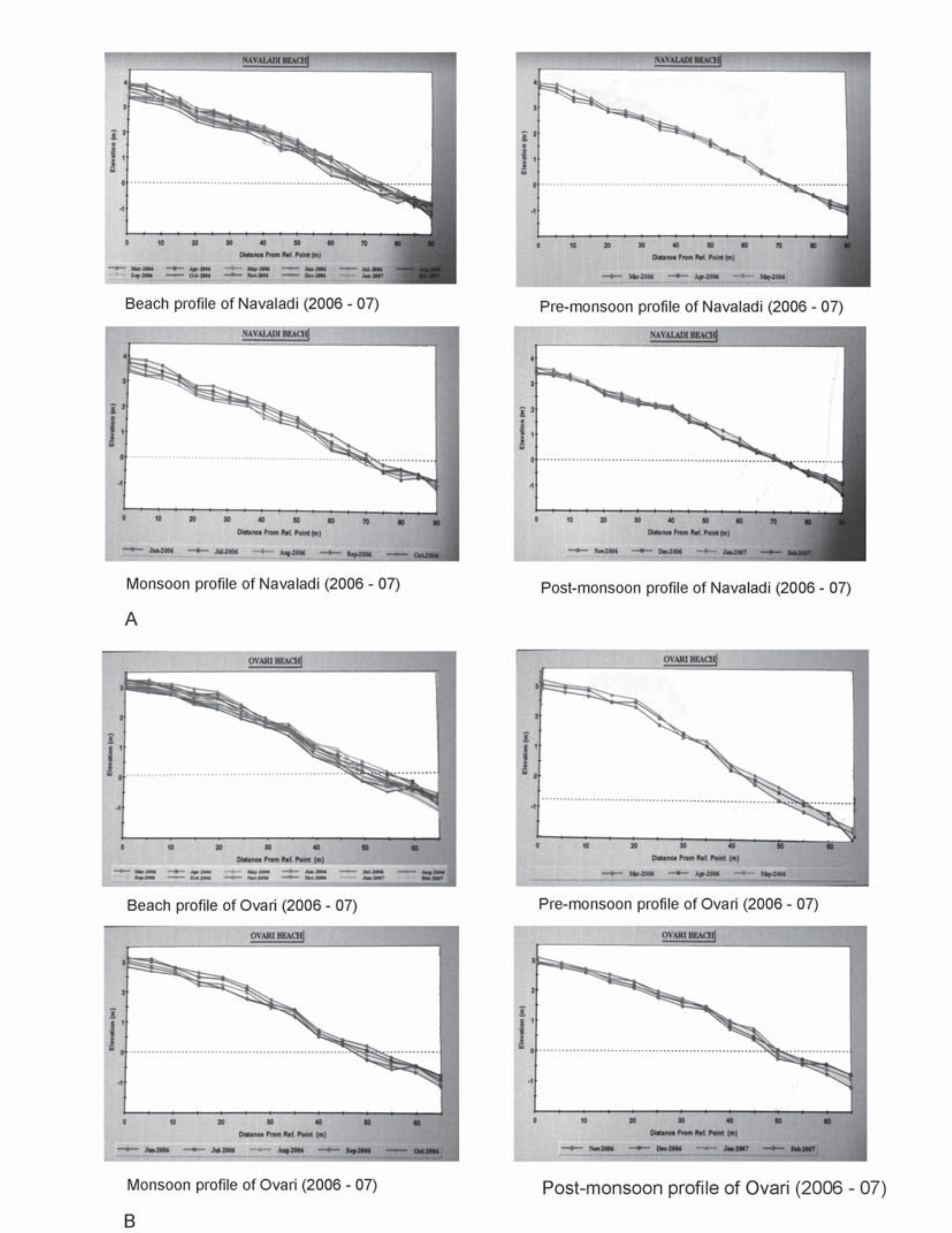
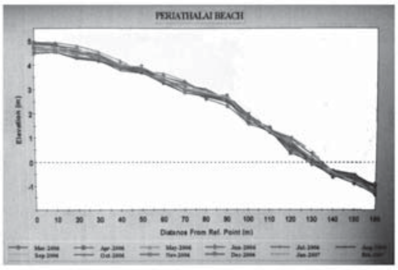
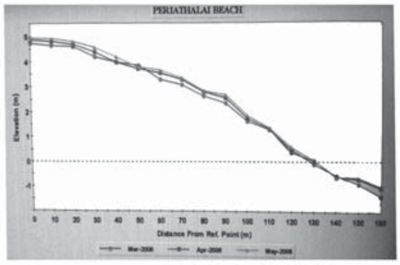


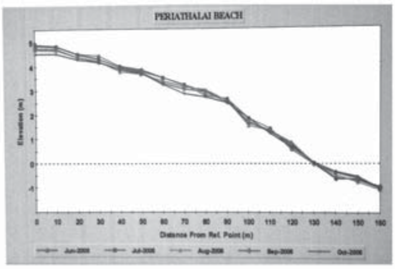
Figure 4A and B. Spatial and temporal variations of the beach profile along the southeast coast



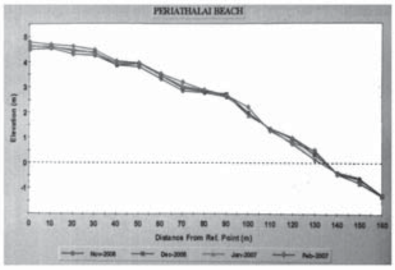
Beach profile of Periathalai (2006 - 07)



Pre-monsoon profile of Periathalai (2006 - 07)

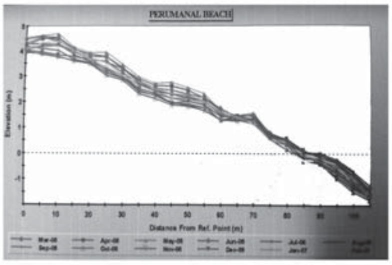


Monsoon profile of Periathalai (2006 - 07)

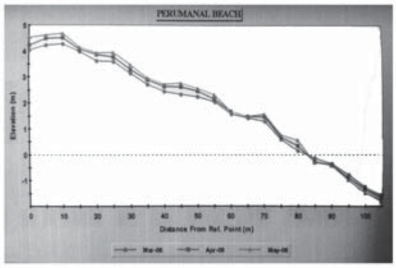


Post-monsoon profile of Periathalai (2006 - 07)

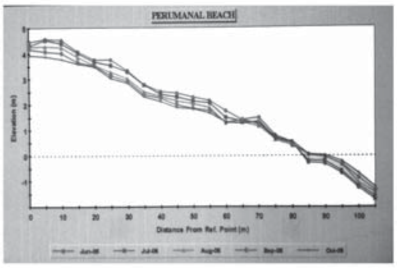
C



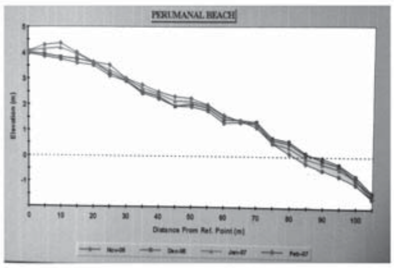
Beach profile of Perumanal (2006 - 07)



Pre-monsoon profile of Perumanal (2006 - 07)



Monsoon profile of Perumanal (2006 - 07)



Post-monsoon profile of Perumanal(2006 - 07)

D

Figure 4C and D. Spatial and temporal variations of the beach profile along the southeast coast reversal trend in the direction of sediment transport prevailing during northeast monsoon. The littoral currents were moderate to strong during the southwest monsoon, variable during the northeastmonsoon and weak during non-monsoon period. The direction of these currents also varies during the southwest and northeast monsoons.

The beach is eroded during southwest monsoon, but despite the prevalent moderately high wave regime, and moderately strong littoral currents, the beach profiles of the northeast monsoon had accretion over the profiles of the southwest monsoon. During northeast monsoon, the influence of littoral currents and waves is comparatively lower than that of southwest monsoon and the widths of most beaches are in increasing trend. But severe storms may also attack the shoreline during this period and the storm-generated waves that cut away the berm cause an offshore sediment motion and bar formation. From December to March, the beach profiles are gradually raised and attain maximum level during April or May. The annual changes in beach widths (Table 7) indicate that the beaches of Kanyakumari, Koottapuli, Idinthakarai, Navaladi and Ovari are eroding considerably and the beaches of Periathalai, Manappad, Kayalpattinam, Tiruchendur and Tuticorin south have an accreting trend. It has been noted that the width of beaches along the intensive mining sites have been considerably decreased which leads to more erosion along the coast. Here, the beach slope has been measured from the beach profile data. The size of the beach slope or degree of beach slopes by more or less, fixing the width of the beaches covered by tidal water. During non-monsoon, the slopes are more almost in all beaches due to the accumulation of sediment along the berm and high-tide zones (Fig. 5B). The reduction of beach slope during monsoon indicates the removal of sediment from the berm and dune to the off-shore. After the monsoon the beach slope again increases. There is no significant annual changes in beach slopes have been noticed.

Beach volumetric analysis

The morphodynamics of beach refers to the interaction and adjustment of seafloor topography and fluid hydrodynamic processes. The hydrodynamic processes include those of waves, tides and wind-induced currents respond instantaneously and lead to the morphological change and redistribution of sediment. The seafloor morphologies and sequences of change dynamics involves in cross-shore and longshore sediment transport. As sediment takes a finite time to move, there is a lag in the morphological response to hydrodynamic forcing. Sediment can therefore be considered to be a time dependent coupling mechanism. Since the boundary conditions of hydrodynamic forcing change regularly, this may mean that the beach never attainsequilibrium. The beach profiles vary with time, both seasonally as the wave climate changes and over the long-term, in response to the pressures of erosion or accretion. Beach profiles measured at the same location over time can provide details about the behaviour of the beach. The behaviour of the entire beach can be examined in terms of shoreline recession and volumetric sand loss by the continuous profile measurements along the beach; moreover, an overall sand budget (sources and sinks of sand) can also be determined. Interpretation of beach response to coastal processes can be done with geometric and volumetric comparison of beach profiles sets. The convenient use of beach profiles is the determination of volumetric change of a beach, ΔVs. The volumetric calculation of profiles provide a time history of the volume of beach, and by determining the volume differences between surveys the erosion or accretion of the beach can be assessed as a function of time. There are no common standards for quantifying rates of beach change and for determining high-tide shoreline position. Beach erosion is generally quantified through some statistical treatment of retreat rates and volumetric losses. The variations on beach sediment volume have been widely used to quantify the changes and to understand the beach response to coastal processes. For any geometric and volumetric calculations an arbitrary vertical datum is needed. Here, the mean sea level has been considered as the reference datum for performing geometric and volumetric analysis of beach profiles. For each profile at a given time, the area of sand above the arbitrary datum, from the baseline to the offshore limit of the profile, is determined. For all profiles of the survey, the volume of sand in the beach above the arbitrary datum is obtained by the areas of the profiles along the beach which provides the beach sediment volume per unit length of beach.

Seasonal changes

The computed seasonal beach sediment volume changes from March 2006 to February 2008 of all beaches have been given in Table 8. It implies the sediment volume along the different beaches undergoes typical seasonal changes due to the hydrological conditions. During the period March–May, the volume of sediment in beaches is more almost in all beaches. The low wave energy prevailing along the study area during this summer period enhances the trapping of sediments across the beaches.

From June onwards the sediment volume decreases due to the changes in the wave climate due to the southwest monsoon. The sediment from the berms and high-tide zone of the beaches are eroded and transported due to the littoral currents. The change in beach profile shows the movement of sediment from berms to the off-shore and it also indicates the development of small bars along the low tide region and off-shore of the coasts. In addition

Table 6. Annual changes of beach slope along the southeastern coast

Beach name	Beach slope			Annual changes in beach slope (m^3m^{-1})		
	Mar-06	Mar-07	Feb-08	2006-07	2007-08	Net
Kanyakumari	3.69	3.66	3.7	–0.03	0.04	0.01
Koottapuli	4.75	4.57	4.91	–0.18	0.34	0.16
Perumanal	3.13	3.49	3.24	0.36	–0.25	0.11
Idinthakarai	4.34	4.56	4.58	0.22	0.02	0.24
Navaladi	3.04	3.26	3.26	0.22	0	0.22
Ovari	3.42	3.45	3.42	0.03	–0.03	0
Periathalai	2.12	2.26	2.38	0.14	0.12	0.26
Manappad	3.47	3.62	3.45	0.15	–0.17	–0.02
Tiruchendur	3.38	3.77	4.08	0.39	0.31	0.7
Kalayalpatinam	2.63	2.63	2.65	0	0.02	0.02
Tuticorin – S	2.56	2.23	2.29	–0.33	0.06	–0.27
Tuticorin – N	3.06	3.18	3.59	0.12	0.41	0.53

Table 7. Seasonal and annual changes of beach width along the southeastern coast

Beach name	Beach slope			Annual changes in beach slope (m^3m^{-1})		
	During March 2006 to February 2007			During March 2007 to February 2008		
	Pre-monsoon	Monsoon	Post-monsoon	Pre-monsoon	Monsoon	Post-monsoon
Kanyakumari	122	105	110	119	89	97
Koottapuli	143	128	134	148	127	132
Perumanal	232	194	203	235	196	214
Idinthakarai	132	121	125	135	113	121
Navaladi	164	132	145	157	127	138
Ovari	103	82	92	102	87	87
Periathalai	411	390	404	459	399	424
Manappad	224	194	214	216	181	197
Tiruchendur	116	92	103	121	100	109
Kalayalpatinam	265	237	257	265	252	259
Tuticorin – S	306	275	304	320	286	320
Tuticorin – N	101	88	96	100	89	98

Table 8. Seasonal and annual changes of sediment volume along the southeastern coast

Beach name	Beach sediment volume			Annual changes sediment volume (m^3m^{-1})		
	Mar-06	Mar-07	Feb-08	2006-07	2007-08	Net
Kanyakumari	116	110	98	–6	–12	–18
Koottapuli	132	130	131	–2	1	–1
Perumanal	208	214	216	6	2	8
Idinthakarai	128	128	123	0	–5	–5
Navaladi	151	146	130	–5	–16	–21
Ovari	96	92	88	–4	–4	–8
Periathalai	383	412	424	29	12	41
Manappad	203	200	202	–3	2	–1
Tiruchendur	102	110	113	8	3	11
Kalayalpatinam	243	262	263	19	1	20
Tuticorin – S	284	311	335	27	24	51
Tuticorin – N	100	103	105	3	2	5

to the changes in the beach morphology, the sediment volume undergoes rapidly decreases in beaches. The reduction of sediment volume continues up to October. From November onwards the beaches start to regain the sediments. The comparatively low wave climate of north-east monsoon than the southwest monsoon enhanced the slight increase in sediment volume during the period of October and November. After the end of December it has been noticed that the beaches regain more amount of sediment due to the landward movement of off-shore sediment. Well developed berms have been noticed in some beaches due to movement off-shore sand bar towards the berms. There is a spatial and temporal variation of beach sediment volume with respect to the seasonal wave parameters along the beaches. It also indicates the cyclic changes on the beach morphology and morphodynamics. The seasonal changes in beach profiles constitute an important aspect of the variability of the coastal environment. It has been understood since late 1940's that with few exceptions the sand level on the exposed portion of a beach is higher towards the end of the summer than at any other time of the year. The winter storm waves overtop the summer berms and erode the backshore, their action thus reducing the width of the exposed beach. The winter beach is typified by a gently sloping beach face that in places extends shoreward to the toe of the sea cliff. The changes in beaches are significantly different with respect to physiography, incident wave energy and direction, available sediment supply, tendency to erode or accrete, and level of development. The cycles of change in beach profile configuration and sediment volume may be associated with changes in the relative energy levels of winter and summer wave climates. The changes during the southwest monsoon are more than the northeast monsoon due to the difference in the wave climate during these monsoons. The beaches are highly responding to the southwest monsoon than thenortheast monsoon due to the high wave conditions. Southwest and the northest monsoons and non- monsoon periods, the average wave energy flux (P) is 1.35, 0.66 and 0.4 kW m^{-1} along the east coast of India. During northeast monsoon the sediments accumulate and depositional environment prevails on the beaches along central east coast of India. The relatively high wave and current regime during the northeast monsoondoes not produce any erosions effect on the beach, and the area has accretionary tendency. High input of the fluvial sediments and their deposition on the beach due to fluctuations in the wave energy flux, from the turbid water plumes during this monsoon, appears to be the contributing process.

Annual changes

The annual beach sediment volume and changes for all beaches along the study area are shown in Table 8. During the period 2006-07, the beaches of Kanyakumari, Koottapuli, Navaladi, Ovari and Manappad have experienced a reduction of sediment volume while the remaining beaches have gained sediment. The Kanyakumari, Navaladi and Ovari beaches have experienced more loss of sediment (6, 5, 4 m^3m^{-1} respectively). The beaches of Manappad and Koottapuli have very low sediment losses. The Idinthakarai beach has no net loss or gain. The beaches of Periathalai, Tuticorin, Kayalpatinam, Tiruchendur, Perumanal and Tuticorin-S have gained sediments. The beaches of Periathalai, Tuticorin-S and Kayalpattinam have experienced more gain of sediment during this period. The Periathalai beach has gained sediment of volume

29 m^3 m^{-1} and the Tuticorin-S has gained 27 m^3 m^{-1} of sediment. The construction of breakwater (Groin) at the Periathalai has enhanced the trapping of sediment along the coast. During monsoon, large amount of sediments from the Thambraparani river are discharged along the Punnakayal coast are transported by littoral currents and waves. The bay nature of Tuticorin-S beach effectively enhances the trapping of more amount of sediments. During the period 2007-08, the same trend is observed almost in all the beaches. But, the beaches of Kanyakumari and Navaladi have experienced more loss of sediment than that of during 2006-07. The Kanyakumari beach has experienced a loss of 12 m^3 m^{-1} of sand and the Navaladi beach has lost 16 m^3 m^{-1} of sand. Idinthakarai has experienced a sand loss of 5 m^3 m^{-1} of sand while it gained sediment during 2006-07. The Koottapuli beach has gained sediment during 2006-07 while it lost sediment during 2006-07. The beaches of Perumanal, Periathalai, Tiruchendur, Kayalpatinam, Tuticorin-S and Tuticorin-N have experienced gain of sediments.

But the amounts of deposition of sediment on these beaches are decreased than that of

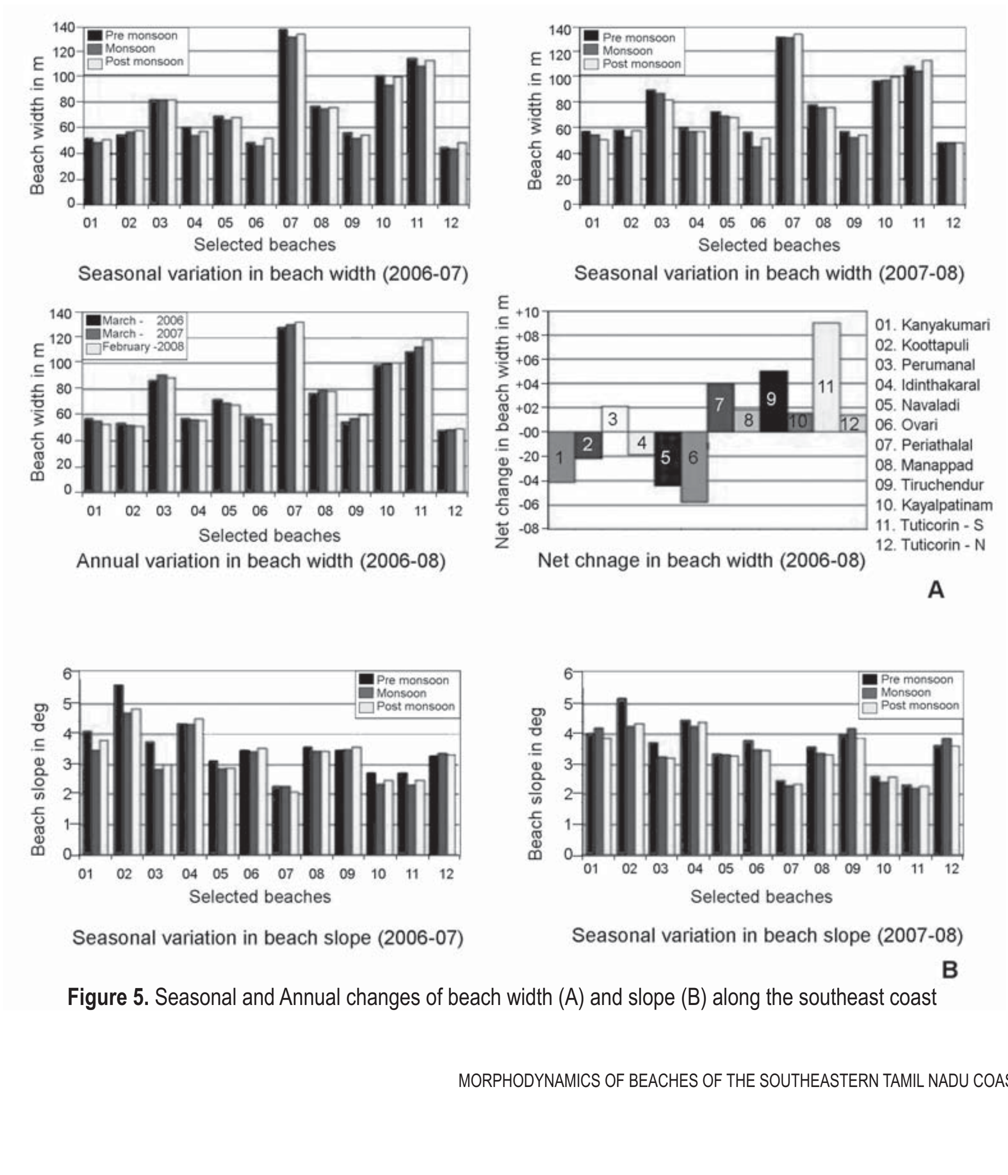


Figure 5. Seasonal and Annual changes of beach width (A) and slope (B) along the southeast coast

Table 9. Mean grain size variations of sediment along the southeastern coast

Beach name	Mean size of beach sediment during March 2006 to February 2007 (mm)											
	Mar	Apr	may	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Kanyakumari	0.37	0.48	0.53	0.67	0.58	0.49	0.47	0.43	0.38	0.37	0.24	0.29
Koottapuli	0.34	0.34	0.38	0.57	0.62	0.59	0.34	0.47	0.39	0.32	0.28	0.27
Perumanal	0.21	0.24	0.28	0.37	0.35	0.34	0.27	0.47	0.34	0.31	0.24	0.24
Idinthakarai	0.37	0.38	0.29	0.57	0.54	0.45	0.67	0.58	0.34	0.28	0.37	0.32
Navaladi	0.32	0.34	0.37	0.58	0.67	0.62	0.57	0.52	0.43	0.34	0.31	0.3
Ovari	0.24	0.34	0.37	0.42	0.72	0.68	0.64	0.57	0.34	0.31	0.29	0.24
Periathalai	0.32	0.31	0.27	0.34	0.45	0.58	0.51	0.45	0.42	0.37	0.42	0.48
Manappad	0.48	0.53	0.52	0.58	0.55	0.53	0.49	0.49	0.57	0.45	0.57	0.64
Tiruchendur	0.41	0.47	0.49	0.57	0.64	0.68	0.72	0.64	0.54	0.49	0.52	0.45
Kalayalpatinam	0.21	0.23	0.24	0.28	0.29	0.22	0.24	0.27	0.23	0.21	0.2	0.18
Tuticorin – S	0.19	0.24	0.21	0.24	0.21	0.22	0.24	0.32	0.28	0.27	0.24	0.21
Tuticorin – N	0.12	0.13	0.15	0.23	0.17	0.14	0.15	0.17	0.17	0.14	0.12	0.14

Table 10. Annual variations of sediment grain size along the southeastern coast

Beach name	Average values of statistical indices of grain size parameters			
	Mean (mm)	Standard deviation	Skewness	Kurtosis
Kanyakumari	0.44	0.49	0.35	1.1
Koottapuli	0.41	0.31	–0.15	1.4
Perumanal	0.31	0.483	0.24	0.86
Idinthakarai	0.43	0.63	–0.04	1.03
Navaladi	0.45	0.51	–0.10	1.13
Ovari	0.43	0.56	–0.07	1.19
Periathalai	0.41	0.67	0.1	0.8
Manappad	0.53	0.61	–0.14	1.28
Tiruchendur	0.55	0.77	0.48	2.12
Kalayalpatinam	0.23	0.43	0.03	0.9
Tuticorin – S	0.24	0.43	0.1	0.95
Tuticorin – N	0.15	0.53	–0.23	1.14

during the period 2006-07. During 2006-07, the Periathalai beach has gained a sand of volume 29 m^3m^{-1} but it is considerably decreased to 12 m^3m^{-1} during 2007-08. Similarly the Tuticorin-south beach has gained a sand of volume 27 m^3m^{-1} but it is considerably decreased to 24 m^3m^{-1} during 2007-08. The gains of sediment of other beaches are also reduced during this period due to the changes in hydrological and littoral sediment transport. The reduction of sediment volume has also indicates the lack of sediment supply along beaches.

Beach dynamics and grain size analysis

The mean size, standard deviation, skewness and kurtosis of beach of sediments from beaches with different morphology have been calculated (Table 9 and 10). The changes in sediment characteristics are associated with corresponding variations in beach profiles, so the variations in grain size could be well explained by the changes in profiles. The dynamics of profiles and morphology of beaches have also been characterised by the seasonal and cyclic changes of beach sediment size. The variations of mean size, standard deviation, skewness and kurtosis are represented in Table 10. The mean sediment size varies from fine to coarser grade (0.12 mm to 0.72 mm). During the summer, the mean size of sediments undergoes small changes almost in all beaches. From the month of June onwards the sediments are changing from fine to coarser. The increase in the grain size indicates the erosional phase of the beaches. The volumetric analysis of the beach sediments emphasizes that there is a reduction of sand storage along the beaches during the southwest monsoon which is due to the high wave energy conditions. The beach grain size analysis reflects the same trend of beach dynamics and morphology. Thus it is evident that the maximum values of sediment size leads to the erosional activity along the beaches. It has been observed that, the standard deviation of samples collected from the estuarine beaches such as Kanyakumari, Manappad and Tuticorin-S have been moderately sorted during the month of June and July. The skewness values of samples collected from beaches attains negative values during the monsoon periods. The negative skewness values represent the erosional phase of beaches. Coarser sediments have been observed in most of beaches during both south-west and northwest monsoon periods. This reveals the erosional activities of sediments along the beaches. But, during the period of northeast monsoon (October and November), the beaches of Perumanal, Tiruchendur and Tuticorin-S have symmetrical skewness values even with the negative skewness. This indicates that these beaches have gain sediment during the post-monsoon periods. The volumetric analysis also emphasizes that the increase of beach sediment volume during October and November. The accumulation of fluvial sediments to the coastal turbid water along these coasts and the small fluctuations in low wave energy also enhances the deposition of sediments. Thus the grain size reveals that the morphological changes of beaches are cyclic and experiences erosion in monsoon and accretion in fair weather conditions.

EOF analysis of beach profiles

The empirical orthogonal function (EOF) method, a widely used statistical tool, can be applied to analyse the beach profiles to determine their variation through time or space. Even though the EOF method is only a descriptive tool and does not yield any information relating to the processes that govern the beach profile, it is a means of

Table 11. Spatial and temporal variations of EOF values along the southeastern coast

Beach name	Function	Net	I-EOF		II-EOF		III-EOF	
			λ	%	λ	%	λ	%
Kanyaku-mari	Spatial	4.52	4.43	98	0.057	1.26	0.006	0.13
	Temporal	7.81	7.63	97.6	0.079	1.01	0.005	0.06
Ovari	Spatial	3.53	3.43	97.2	0.01	0.28	0.004	0.11
	Temporal	3.37	3.25	96.4	0.112	3.32	0.003	0.09
Tiruchendur	Spatial	4.27	4.07	95.3	0.058	1.35	0.005	0.12
	Temporal	5.36	5.24	97.8	0.032	0.59	0.007	0.13
Tuticori-S	Spatial	7.45	7.31	98.1	0.025	0.34	0.008	0.11
	Temporal	4.25	4.02	94.6	0.053	1.24	0.013	0.31

examining the variations in the beach profiles and the importance of the variations in a compact statistical fashion. The data required for the EOF analysis consist of multiple beach profiles, either over time at a fixed location or over distance at a fixed time (Spatial and Temporal Empirical Orthogonal Functions). In this present research, the EOF analysis has been performed to cross-shore profiles. The pattern of cross-shore sediment exchange can more be closely investigated by the EOF analysis. The analysis shows that the largest Eigen value is much greater than the others. The obtained Eigen values and the related variance has been shown in Table 11. It is noted that the first eigen values of both spatial and temporal eigen functions are high and their corresponding percentage of variance are more than 90%. It was also known that for coastal profile data that only the first three largest Eigen values are significant. They represent the beach dynamics, accretion or erosion conditions along the beaches. The first spatial function of EOF'S are plotted against the distance from the reference point of the beach profile, which expresses the average of all profiles. The shape of an equilibrium coastal profile can be identified and calculated by using the first spatially-related Eigen function. The equilibrium slope-elevation curves of profiles may have spatial variations, particularly for the upper part of the profiles; this indicates that this part is more sensitive to equilibrium adjustment than the lower part. For all profile stations, the first temporally-related Eigen function is almost stationary, indicating that a stable slope-elevation relationship (i.e. equilibrium) exists. The first temporal Eigen function also fluctuates significantly during some period, but it recovers rapidly in a very short time. The second spatial Eigen functions associated with the second largest Eigen value are referred to the seasonal variations of the beach profiles. The Eigen values reach a maximum at the location of the summer berm and a minimum in the area of the winter sub-water bar formation. The Eigen values of first few spatial points are negative from the reference point of the survey, which indicates the erosion or transport of sediments from the berm or high tide region of beaches. It also represents the loss of sediment during the monsoon period. The Eigen values attain positive values when moves toward the off-shore of the beaches. This indicates that, during the monsoon the off-shore and low-tide zones of beaches gain sediment from the berm and high-tide zones. This variation in the amplitudes of different spatial points of the profile survey indicates the cross-shore sediment transport. It clearly indicates the berm erosion and the formation of sand bars during the monsoon. The trend of the second temporal Eigen function reflects the seasonal variations of beach profiles. During summer, the amplitudes attain positive values indicating the accretion and whereas in the monsoon the values are negative which indicates erosion. The time dependence of this function shows yearly periodicity. It is related to annual movement of sand towards onshore and offshore. The pattern of third spatial and temporal EOF functions indicates the rapid changes and random variations along the beaches. Therefore, the beach profile can respond efficiently to the morphological changes along the coast in the prevailing hydrodynamic conditions of beaches, by maintaining its equilibrium state.

The morphology of beaches along the study area undergoes dynamic changes in different spatial and temporal scales. Both cyclic (seasonal) and annual changes in the beach topography is more prominent. The morphodynamic and volumetric analysis of beach profiles indicates that the beaches of Navaladi, Kanyakumari and Ovari have experienced more annual loss of sediments and they poses severe beach erosion. The beaches of Tuticorin-south, Periathalai, Kayalpatinam and Tiruchendur have experienced more accretion. EOF analysis confirms the dynamic changes on the beach profiles of the region. The different morphological of appearance of the beaches show the morphodynamic behaviors have direct influence on the wave refraction, with the mechanical processes of a wave. Sediment transport processes in the littoral zone are of fundamental importance to beach morphology, shoreline stability and coastal landform dynamics. Beaches erode, accrete, or remain stable, depending on the rates at which sediment is supplied to and removed from the shore. Swash moves sand diagonally, while backwash moves it straight down. The net result of this zigzag movement is the downwind displacement of sandalong the beach, known as beach drift. Littoral sediment transport implies that the beaches of Kanyakumari, Navaladi, and Ovari have more transport rates. More changes in beach sediment volume are observed in the beaches of Tamil Nadu. It can also produce various coastal landforms modifications in the regions due to intensive sand mining.

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