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Fine Particle Deposition at Vainguinim Tourist Beach, Goa, India

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ABSTRACT

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Vainguinim Beach is a small and narrow pocket beach located on the rocky coast of Dona Paula Bay, at the estuarine front of the Zuari River in Goa, India. The beach has been widely used for recreation and swimming by a large number of tourists. The beach sediments consist primarily shell fragments and quartz, with heavy minerals composed of ilmenite, magnetite and manganese. The black stain of the fine-grained heavy minerals deposited on the beach face reduces the aesthetics of the beach. This paper summarises the various studies undertaken to identify the sediment processes and the possible measures to improve the usability of the beach.

ADDITIONAL INDEX WORDS: *Beach nourishment, heavy minerals, black sand, tourist beach, Indian coast, sediment transport.*

INTRODUCTION

The coastline along Goa can broadly be classified based on physiography as beaches, sea cliffs, promontories, estuaries, spits, dunes, weathering rocks and wave cut platforms (Figure 1). The prominent landform consists of laterite capped mesas extending 25 to 30 km inland (WAGLE, 1987). Laterite beds are found off the estuarine region of Mandovi and Zuari Rivers at about 30 m water depth. The Zuari River joins the Arabian Sea forming a large bay, and it encloses the Mormugao Port, which handles largely the loading of iron and manganese ores. The mechanical ore handling plant in the port has the capacity of 8000 tons per hour with an open stack yard of 80,000 m^2 for stocking one million tons of ore. In addition, three transhipper vessels operate for mid stream loading of iron ore owned by private exporters. The wind drift and spillage of ores during loading carry fine fractions to the water body, which are then partly transported to the neighbouring coast. The Dona Paula Headland and Odshel Point on the northern segment of the Mormugao Bay encompass Dona Paula Bay, wherein the Vainguinim Beach has been formed as a small pocket beach amidst the outcrops of laterite rocks (Figure 2). Vainguinim Beach is about 300 m long and 30 m wide, and is being widely used for recreation and swimming. The beach is subjected to low wave climate and weak currents. The location of the beach in the estuarine environment, slow degradation of adjacent laterite cliffs and the ore handling at the nearest port contribute sizable proportion of heavy minerals washed to the beach face. The beach sand primarily consists of shell fragments and quartz, with ilmenite, magnetite and manganese. The deposition of fine black sand on the beach face causes blackish tint and transforms the intertidal zone turbid. It reduces the aesthetic appearance and incites psychological concern for tourists that use the beach. The favourable conditions for the formation of black sand concentration on beaches has been discussed in detail (ZENKOVICH, 1967; WOOSLEY *et al.*, 1975). The size, shape, specific gravity, of the heavy mineral grains and the nearshore wave/current forces acting on the grains determine the onshore/offshore movement of the black sand. This paper presents studies made on the sediment processes and the associated factors influencing the deposition of the black sand with reference to the possible methods to improve the usability of the beach.

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MATERIALS AND METHODS

The oceanographic conditions in this region are distinguished by three seasons: a fair weather period (February to May), the southwest monsoon (June to September), and the northeast monsoon (October to January) (CHANDRAMOHAN *et al.*, 1989). Field observations were made in March, August and December of 1994 to represent the three seasons. The various measurements and their locations are shown in Figure 3. Continuous measurements of tidal currents were made for 24 hours duration at 3 m water depth using an Inter-Ocean S4 current meter. Current speed and direction were recorded at 10 minutes interval and each recording represented the average currents of 1 minute duration. Longshore currents along the beach were measured using fluorescent tracers in the surf zone in March, August and December. Wave refraction study covering the open coast and the sheltered region of the Vainguinim Beach was carried out using the numerical procedure explained in SKOVGAARD *et al.*

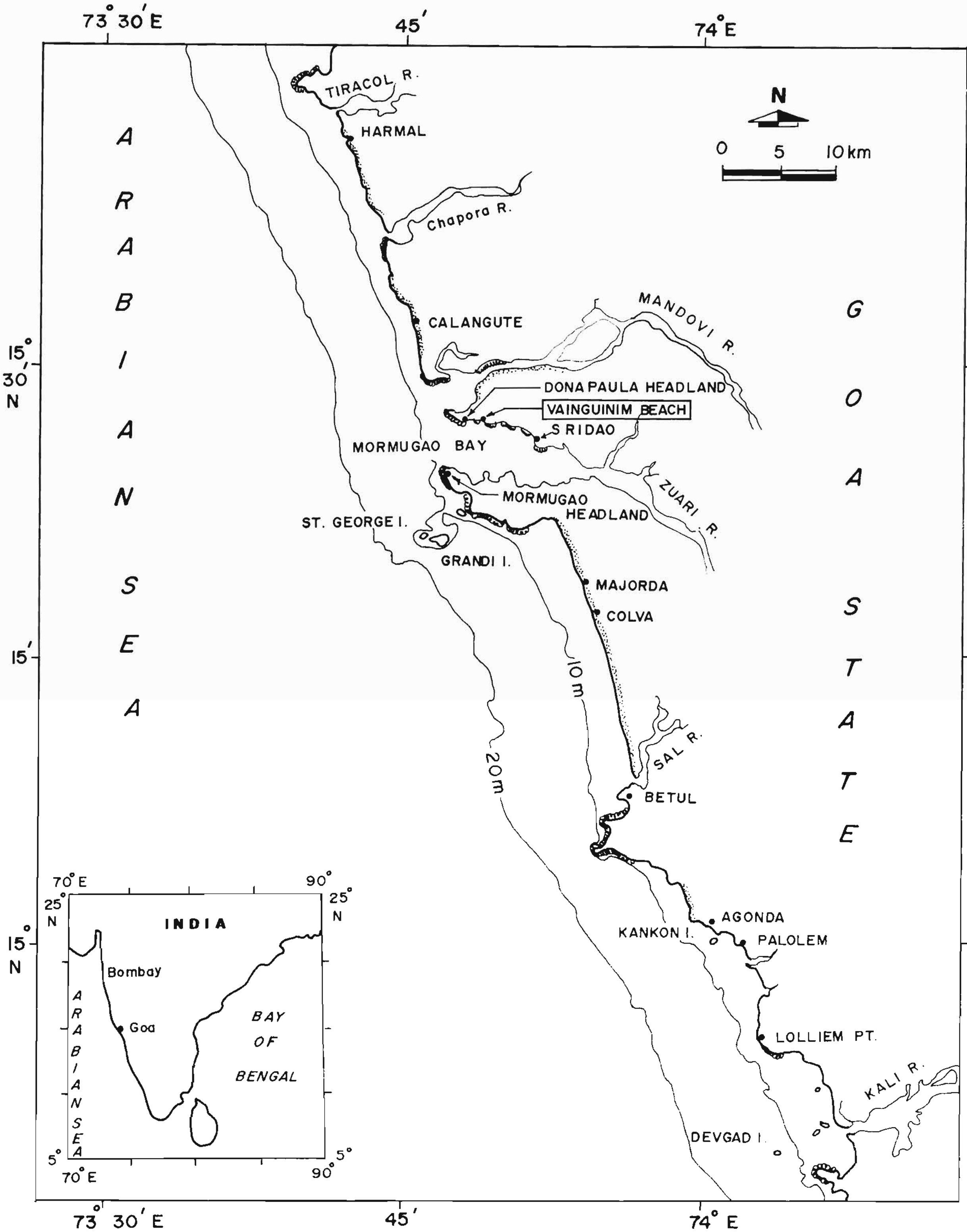

Figure 1. Map showing the morphology of Goa Coast, India.

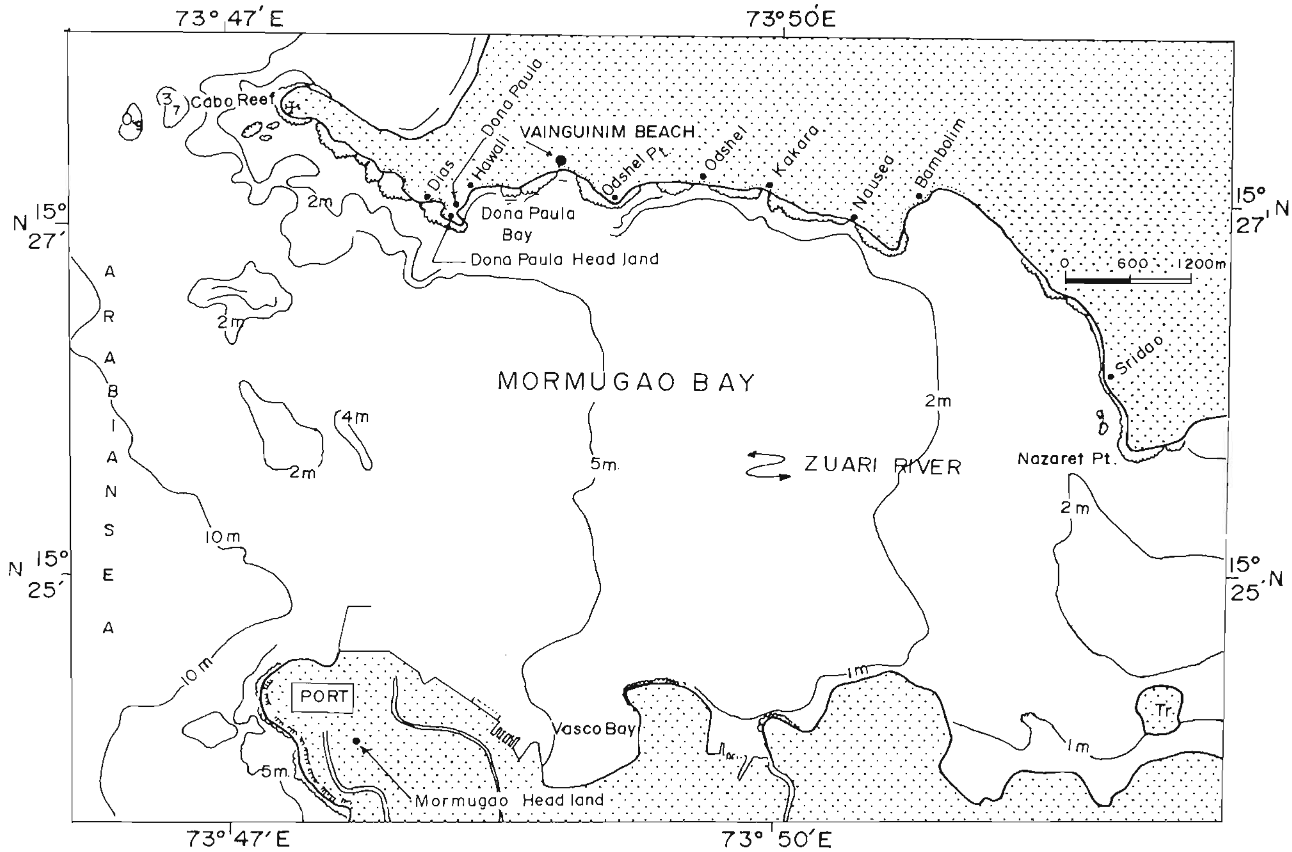

Figure 2. Vainguinim Beach located in between the headlands on the northern side of Mormugao Bay.

(1975). The measured wave data corresponding to the open sea condition near Goa Coast has been extracted from NAGARAJ (1990). Sediment samples on the beach were collected using 0.4 m long core at three locations along the intertidal zone of the beach. Seabed sediments were collected at nine locations using a van Veen grab. The heavy minerals were separated by a magnetic separator. Sediment traps were installed in the surf zone at 1.6 m water depth, one close to the surface and another near the bottom, to assess the pattern of sediment movement in the surf zone. Sediment laden water samples were collected at the surface and bottom using a van Dorn water sampler to estimate the suspended sediment load. Beach profiles were measured using a wave sled out to a depth of 4 m.

RESULTS

Coastal Morphology

Goa Coast can broadly be classified into a coastal tract consisting of beaches, sea cliffs, promontories, pocket beaches, estuaries, dunes, hard rock wave cut platforms *etc.* (Figure 1). Along the 125 km long Goa coastline, there are more than 17 beautiful beaches having significant importance to tourism. The sea bed consists of silty clay out to the 50 m water depth and sandy silt between 50–100 m water depth (NAIR and HASHMI, 1989). The beaches situated along the open coast consist mainly of quartz along with feldspars and other heavy minerals. They are represented by medium to fine sand, well to moderately sorted (WAGLE, 1987). Many investigations have been carried out along the Goa Coast on the beach processes and the littoral sediment transport (MURTHY *et al.*, 1975; ANTONY, 1976; VEERAYYA *et al.*, 1981; MURTHY and VEERAYYA, 1985). The Vainguinim Beach is a small and narrow pocket beach situated in the estuarine bay protected by headlands (Figure 2). The coast surrounding Vainguinim Beach consists of a plateau marked by the presence of duricrust laterite at the top. The geotechnical investigations carried out in the vicinity indicate that the duricrust layer is up to 7.5 m thickness, below which laterite silty and clayey soils are encountered. Weathered phyllites are present 15 m below the seabed (TILAK, 1995). The laterites along the sea front undergo disintegration due to weathering and the constant wave action. The weathered fragments are then carried by coastal currents, and are supplied as black sand to the littoral system.

Tides, Waves and Wave Refraction

The tides in this region are semi-diurnal with the average spring tidal range of 2 m and neap tidal range of 0.25 m. The

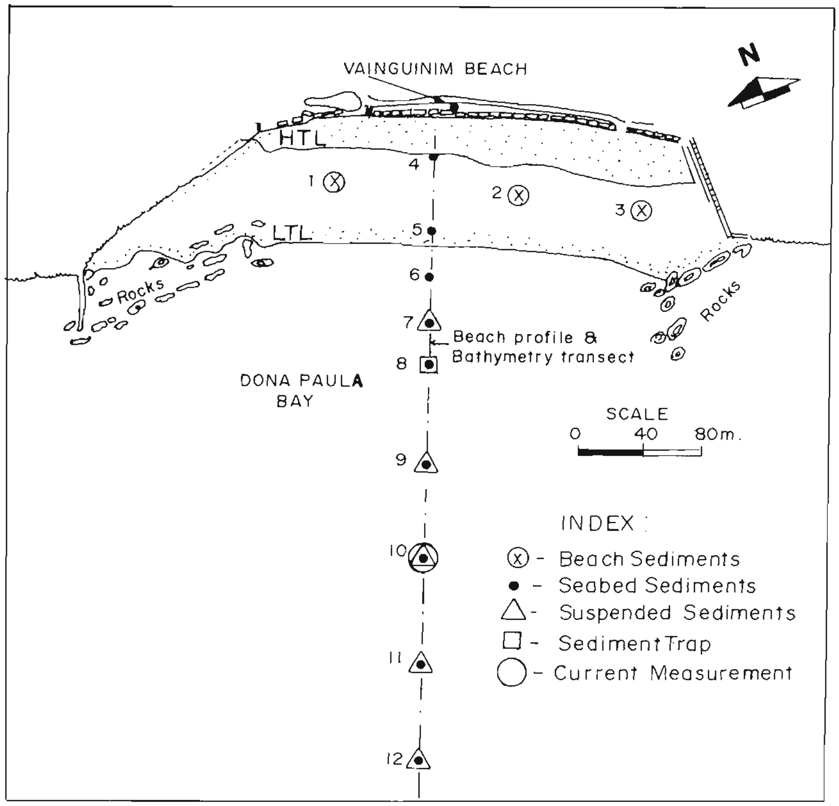

Figure 3. Location showing various field measurements.

measured wave data using a Datawell Directional wave rider buoy at 15 m water depth in the open sea near Goa were presented in NAGARAJ (1990). Based on these measurements, the monthly average significant wave height, zero crossing wave period and the predominant wave direction are presented in Table 1. The significant wave heights were higher than 1.5 m during June to August, and low showing less than 0.7 m during October to April. These waves undergo significant refraction in the Mormugao Bay and attain large attenuation before reaching the Vainguinim Beach. The typical wave refraction diagram for the waves approaching from 250° with respect to North is shown in Figure 4. The wave refraction study shows that waves having directions between 215° and 237° directly approach the Vainguinim Beach. The waves

Table 1. *Average monthly wave characteristics off Goa.*

Month	Significant Wave Height (m)	Zero Crossing Wave Period (sec)	Wave Direction with Respect to North (deg)
January	0.49	5.0	280–290
February	0.65	5.1	290–300
March	0.69	4.8	210–220
April	0.63	5.1	210–230
May	1.02	5.3	210–240
June	1.84	6.6	215–220
July	2.09	7.0	240–250
August	1.69	6.7	240–250
September	0.84	5.6	210–240
October	0.60	5.6	200–210
November	0.45	5.7	207–210
December	0.37	4.9	200–220

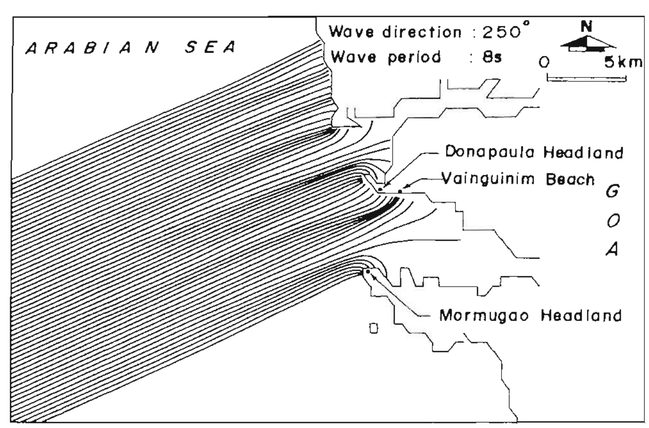

Figure 4. Wave refraction diagram for the waves of 8 s period coming from 250 w.r.t. North.

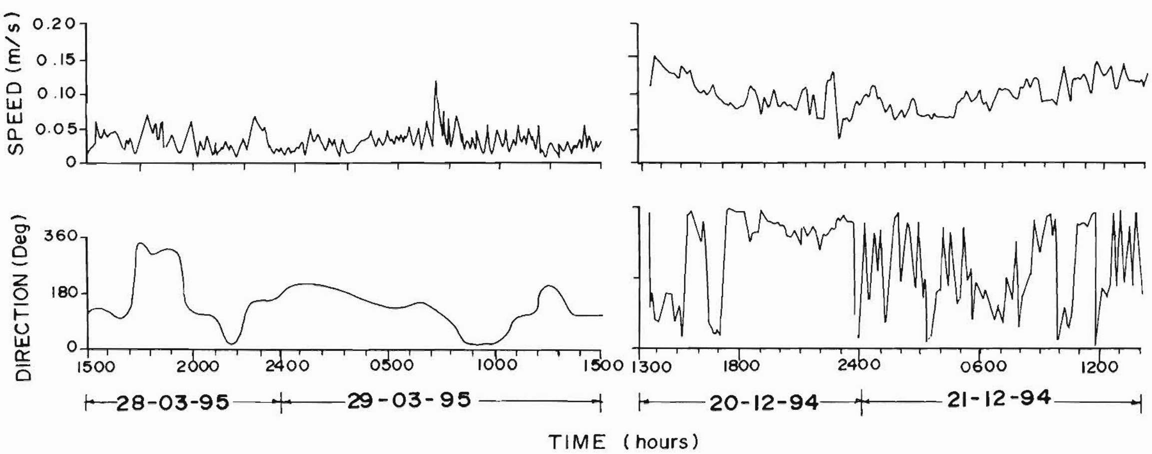

Figure 5. Variation of current speed and direction using S4 current meter at 3 m water depth.

less than 215° are totally obstructed by the Mormugao Headland, while waves greater than 237° undergo considerable refraction before reaching the Vainguinim Beach. The refraction analysis further indicates that the relatively high waves approach the Vainguinim Beach only during April to August, and the wave activity is very low during the rest of the year. The wave heights visually observed at Vainguinim Beach, showed 0.25 m in March, 0.5–0.8 m in August, and 0.1–0.3 m in December. The wave period varied between 8 and 10 s, and the waves were breaking almost parallel to the shoreline throughout the year. Thus it is observed that the wave energy acting on the Vainguinim Beach is low compared to the wave energy acting on the beaches exposed to open sea along the Goa Coast.

Currents and Littoral Sediment Transport

The mean tidal current at 3 m water depth during March was 0.05 ms^{-1}, and its direction was about 90° during flood and 270° during ebb tides. In December, the current speed was about 0.09 ms^{-1}, with a marginal shift in current direction with tide (Figure 5). The results show that the tidal currents close to Vainguinim Beach are very weak. The distribution of longshore currents along the Vainguinim Beach is shown in Figure 6. The currents were weak in March and December with less than 0.08 ms^{-1} during flood and ebb tidal conditions. It was 0.08–0.2 ms^{-1} in August. The longshore current direction was predominantly westward during flood tide, typically a reverse of the expected current pattern, indicating the behaviour of an eddy circulation. During ebb tide, the current was westward over the eastern part of the beach, and eastward on the western part of the beach indicating eddy region over the western part of the beach.

Using the data on breaker heights, longshore currents and surf zone width collected daily for a period of one year at open beach near Calangute (Figure 1), ANAND *et al.* (1991), have reported that the longshore sediment transport rate along the open coast is relatively low. The sediment transport was northerly during September to December, and southerly during the rest of the year. The transport rate was about 0.39 × 10^5 m^3 per month in July and August, and was less than 0.04 × 10^5 m^3 per month in January, March, June, October, November and December. The annual net transport was 0.89 × 10^5 m^3 per year towards south and gross transport was 1.2 × 10^5 m^3 per year. The littoral transport is mostly confined to local regions as the littoral zone is obstructed by various headlands protruding into the sea.

Beach Sediments

The classification of sediments collected at three locations in the intertidal zone shows that the sand fraction was 89–91 per cent in March, 92–99 per cent in August and 87–94 per cent in December. The rest of the fraction consisted of silt. The mean diameter (D_{50}) was around 0.11 mm in March, 0.17 mm in August, and 0.09 mm in December. Most of the finer fractions consisting of black sand have been moved to offshore due to more wave energy acting on the beach during the southwest monsoon. Subsequent to the monsoon period, when the wave energy reduces, the heavy minerals are brought back to the shore.

The black sand particles were separated from the beach sediments, and the values are presented in Table 2. An average of 5 per cent of the beach consists of black sand. In general, the black sand proportion was relatively higher in March followed by December and August. Concentration was high on the surface layer and no significant variation in the concentration was noticed across the subsurface upto 0.4 m layer of the beach. Analysis of sediment samples collected at eight neighbouring beaches (Figure 2) shows the presence of significant proportions of black sediments in these regions. Nausea, Kakara and Dias Beaches show relatively higher proportions of black sand (>8 per cent) than Vainguinim Beach. Sridao, Bambolim and Hawaii Beaches contain about 4 per cent, and Odshel and Dona Paula Beaches about 2 per cent of black sand. The phenomenon of black sand deposition is common at all of these estuarine pocket beaches.

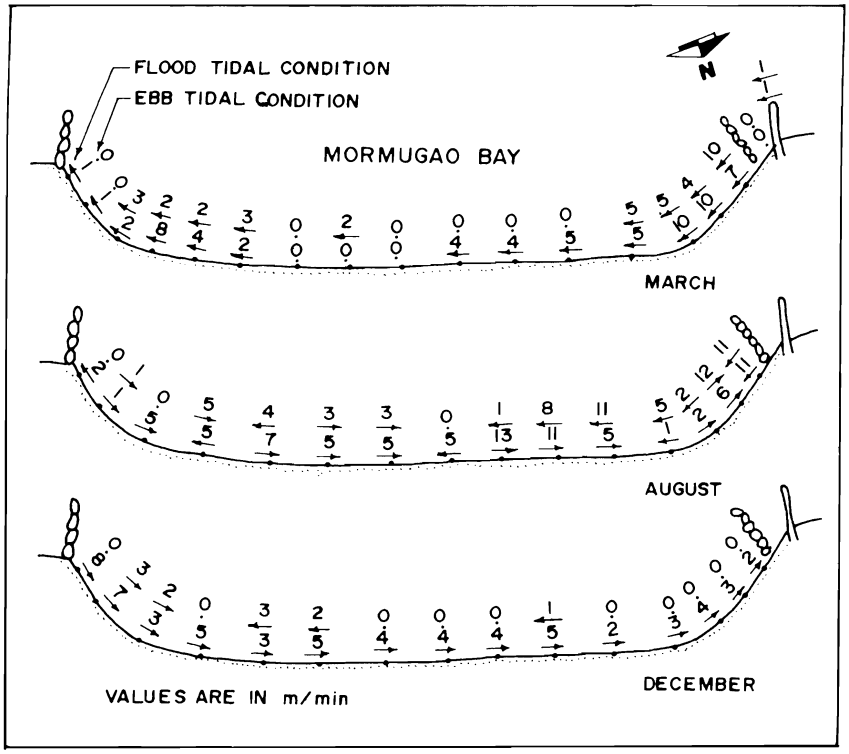

Figure 6. Distribution of longshore currents during 3 different seasons along the Vainguinim Beach.

Seabed Sediments

The size distribution was done for the sediment samples collected on the nearshore seabed at nine locations as indicated in Figure 3. In March, the sand fraction was 92 per cent on the beach berm (st. 4), 72 per cent in the intertidal zone (st. 5), 89 per cent at station 8, and 60–70 per cent at other locations. The rest of the fractions consisted of silt. The seabed near station 12 is exposed as laterite without any sediment cover. In December, the sand fraction was around 88 per cent at stations 4 to 7 and 70 per cent at stations 8 to 11. The distribution indicates significant proportions of silt in the nearshore upto 4 m water depth (st. 11). The silt fractions deposited on the seabed are higher (20–30 per cent) than on the beach. The percentage of silt was more in March than in December. The presence of rock close to surfzone at station 12 gives an indication that the movement of littoral sediment is restricted considerably in this region.

Suspended Sediments

The suspended sediment concentration measured at five locations (Figure 3) showed 8–11 mgl $^{-1}$ in March and December. Two sediment traps, one near surface and another close to seabed were placed in four different configurations to trap (i) offshore movement of sediment, (ii) onshore movement of sediment, (iii) the sediments moving parallel to shore towards the west and (iv) sediments moving parallel to shore towards the east. The experiment showed that in March, the sediments collected in the traps were mostly of silt fraction, consisting more than 80 per cent. The sediment flux was higher close to the bed than at the surface. The sediment moving towards the east parallel to shore was highest, followed by movement towards the west parallel to shore, while the sediment movement in offshore-onshore direction was small. The movement of sediment in the offshore direction was found to be relatively higher than the movement in the onshore direction. The sediment trap results indicate that there is a supply of sediment to the Vainguinim Beach derived from the coast parallel currents, and a small amount of exchange of onshore-offshore sediments takes place even during the calm wave condition. Mostly silt fraction sediments are subjected to movement in March, whereas in December the sand fractions were observed to be in higher proportions. The sediments moving onshore were found to be high in December, indicating the depositional phase of the beach.

Beach Changes

The variation in the beach profiles is shown in Figure 7. The profile beyond the surf zone could not be measured in August due to unforeseen problem with wave sled. In general the beach is flat to 2 m water depth, falls relatively steeper to 4 m water depth and thereafter remains very flat. December profile shows scouring of 0.5–1 m in the surf zone due to monsoon waves.

Table 2. *Concentration of black sediments.*

St. No.	Depth (m)	March Mean Diameter (mm)	March Black Particles Concentration (%)	August Mean Diameter (mm)	August Black Particles Concentration (%)	December Mean Diameter (mm)	December Black Particles Concentration (%)
S1	0.0	0.108	6.2	0.210	4.13	0.094	3.46
	0.1	0.160	2.8	0.460	1.57	0.112	6.87
	0.2	0.240	4.6	1.000	1.26	0.092	7.37
	0.3	0.265	2.1	1.075	1.46	0.110	4.33
	0.4	0.280	2.0	1.025	1.32	0.144	5.25
S2	0.0	0.110	8.6	0.165	6.07	0.086	4.27
	0.1	0.172	4.1	0.340	4.90	0.160	2.92
	0.2	0.211	2.8	0.345	6.31	0.190	2.55
	0.3	0.230	3.1	0.360	4.54	0.185	4.08
	0.4	0.305	2.6	0.370	4.35	0.187	3.95
S3	0.0	0.110	8.4	0.120	7.58	0.230	4.03
	0.1	0.175	3.6	0.550	1.35	0.300	1.92
	0.2	0.245	2.4	0.400	1.69	0.152	5.41
	0.3	0.270	2.1	0.480	3.66	0.670	0.93
	0.4	0.310	1.8	0.850	0.80	0.670	1.39

DISCUSSION AND CONCLUSIONS

The Vainguinim Beach is subjected to very low wave energy compared to the other beaches exposed to open sea along the Goa Coast. Noticeable wave energy prevails on the Vainguinim Beach only during the southwest monsoon (June to September). Nearshore currents are weak, around 0.05 ms $^{-1}$, and are influenced by tides. The longshore current is also very weak, flowing towards the west during flood tide and towards the east during ebb tide, indicating the presence of an eddy region, particularly over the western part of the beach. The beach primarily consists of silty sand, and a considerable part of the silt fractions are carried offshore during southwest monsoon and are deposited back onshore during the ensuing fair weather period.

McIntyre (1959) established by experiments that depending upon the specific gravity and shape, mineral particles behave differently in the surf zone, and may be displaced up or down the profile, or along the coast, and heavy minerals overtake or lag behind light minerals. Stapor (1973) has evaluated the pattern of heavy mineral concentration at open beach facing Gulf of Mexico, sheltered beaches facing Rounds and bays and coastal dunes near Gulf of Mexico. His data strongly suggested that the black sands at both open and sheltered beaches, were not concentrated on the beach, but

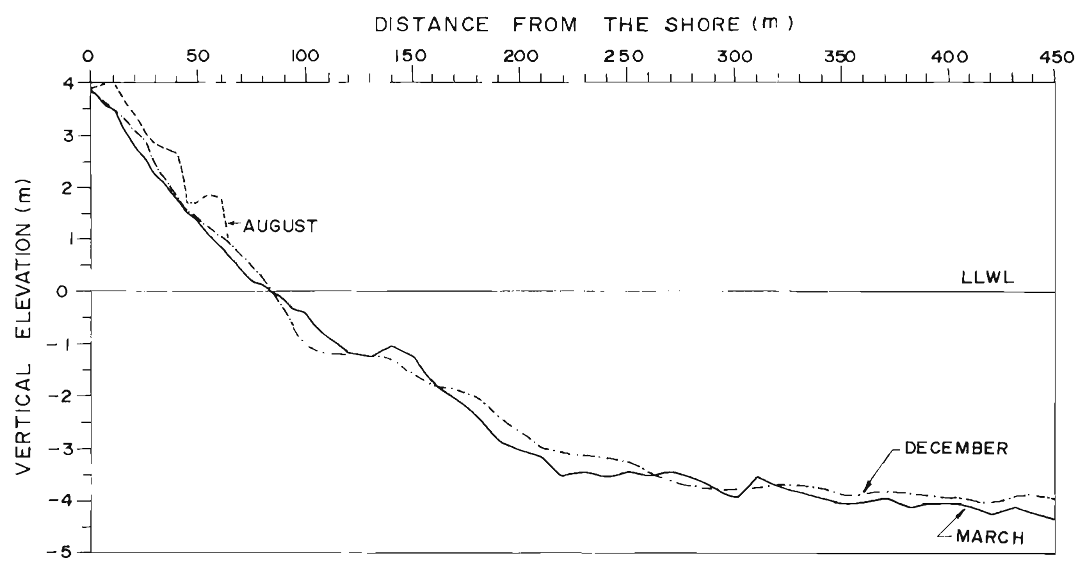

Figure 7. The change in beach levels at Vainguinim Beach.

were delivered to the beach face as a slug of heavy mineral rich sand from the concentration occurred offshore. He further stated that the heavy minerals of the sheltered beach possibly resulted from a dynamic process which tended to remove the finer particles from the parent quartz population. The extensive study in wave tanks by MAY (1973) showed that the formation of heavy mineral layers on the beach occur on moderate energy condition due to shoaling waves in the shallow water. Based on the dynamic forces acting on the sediment grains, he has classified three classes of particle motion *viz.*, (1) no motion—particle is too large to be moved (2) uni-directional motion—particle can be moved shoreward under the wave crest but not seaward under the trough and (3) bi-directional motion—the particle can be moved both shoreward and seaward over the passage of wave crest and trough. MAY (1973) has identified that the heavy minerals fall into class (2) category and the light minerals into class (3). Due to shoaling in very shallow waters, when the wave energy becomes moderate and the energy level is relatively higher below the crest than the trough, the heavy minerals are carried only shoreward, without much energy to move them back under the trough. On the contrary, under the same energy condition the light minerals could be carried back with the energy available under the trough. Wave shoaling increases the shoreward movement of black sand and preferential deposition on the beach face. The same phenomenon is experienced at Vainguinim Beach immediately after monsoon, as the high wave activity passes through a transitional stage before becoming calm. Hence at Vainguinim Beach, concentrations of the black sand particles were found to be higher in December than in August.

The main sources for the black sand are found to be the disintegration of the laterite rock outcrops and the fine particles derived from the ore handling site at nearby Port. The deposition of fine particles is found to be common at nearby estuarine beaches. The silt fractions are relatively higher beyond the breaker zone, than found on the beach. The supply of sediments to the Vainguinim Beach is from the coast parallel currents, and onshore movement was noticed immediately after the monsoon. Mostly the silt fractions are subjected to motion in March, and sand fractions are seen predominantly moving onshore in December.

Controlling or total prevention of the deposition of fine fractions is difficult, as the adjacent beaches and nearshore seabed have considerable black sand concentrations. Construction of any structures to improve the beach condition might seriously affect the stability of Vainguinim Beach and also the neighbouring beaches, as eddy currents were observed on the western side of the Vainguinim Beach and longshore drift supplies sand to the beach. Hence, in order to improve the beach without any adverse impact on the coastal environment, artificially replacing the sand is more appropriate. The mean diameter of the sediment on the top layer of the beach mostly remained 0.1–0.5 mm. A layer of 0.3 m on the entire beach may be removed to 0.5 m water depth with respect to lowest low tide level, and a sand fill of 0.6 m thickness with a mean diameter of 0.5 mm may be placed on the scarped beach. The sand used for artificial filling may consist of pure quartz without any black sand. In doing so, part of the sand filling may be lost by offshore transport during the southwest monsoon, and hence, partial replenishment may be needed every year after the monsoon. Close monitoring of the artificially filled beach is essential in order to evaluate its performance.

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