

## **Sedimentological responses to coastal dynamics along the Thane District, North Maharashtra, West Coast of India**

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### **Abstract**

We present the results of sedimentological responses to coastal dynamics of the Arnala beach, located between Vaitarna and Ulhas rivers, Thane district, Maharashtra, India. The coast is remarkably flat and wide and in the backshore there is a semi-consolidated raised beach. Granulometric and mineralogical investigations and CaCO<sub>3</sub> measurements of the sediments were carried out to understand their variations. The CaCO<sub>3</sub> contents in the sediments from raised beach, sub-surface and sand pits vary between <1 and 20%. The medium-very fine sands are moderately well sorted-very well sorted, symmetrical, very platy- to mesokurtic and mostly uni- or bi-modal. Heavy minerals (av 39 wt%) are magnetite (av 17 wt%), ilmenite (av 15 wt%) and non-magnetic (av 7 wt%) fractions.

The sediments are derived from weathered Deccan Trap basalts that occur in nearby hillocks, as shore platform and along the Vaitarna River. These sediments are mainly transported and redistributed by littoral currents. In nearshore waters annual average wave height is ~0.8 m and gross littoral drift is 0.132 x 10<sup>6</sup> m<sup>3</sup>. Similarity in sediment parameters and mineralogy along the more than 20 km long and 400 m wide coast indicates prevalence of uniform oceanographic processes in a littoral cell along the coast. Significant variability in volumes of sediment accretion/erosion is noticeable.

**Keywords:** Sediment, coastal dynamics, seasonal changes, Maharashtra beaches

## 1.0 Introduction

A number of oceanographic processes influence sediment characteristics, accretion and erosion of sediments and distribution of placer minerals (Siddiquie et al., 1984; Gujar et al., 1988; 2004; 2010a,b, 2011; Iyer et al., 2010). Furthermore, sediment budget along a beach is influenced by provenance of sediments, beach morphology and hydrodynamic conditions and hydraulic sorting of sands (Komar, 2007; Garzanti et al., 2009; Rajganapathi et al., 2013; Armstrong-Altrin et al., 2015). Considering the diversity of activities in the coastal zone, an understanding of coastal processes is critical for coastal zone management (Jayappa and Narayana, 2009; Temitope et al., 2018) and to understand the shoreline changes (Pandian and Sukhtankar, 1989).

The study area (Lat. 19°20'-19°30'N; Long. 73°48.5'-73°45'E) lies in Thane district, Maharashtra, India and is bounded in the north by the Vaitarna (Agashi Creek) and in south by the Ulhas (Bassein Creek) (Fig. 1). In the offshore there are rock outcrops and islands which are remnants of the mainland. The only habited island is Arnalapada that lies opposite the Vaitarna River (Fig. 1) and this island was also included in our studies.

Between Agashi and Bassein creeks there exists extensive mud flats, and rock exposures (Fig. 2). Based on granulometric analysis of sediments of the intertidal zone and raised beach, it was opined that the latter represents an evidence of Holocene sea-level (Pandian and Sukhtankar, 1989). The raised beach sediments contain heavy minerals which have Fe<sub>2</sub>O<sub>3</sub> (30 wt%), FeO (23 wt%) and TiO<sub>2</sub> (~41 wt%) (Anon, 2000).

During low tide at Arnalapada Island, mercury globules that were derived from a deep source were deposited at mouth of the Vaitarna River and also in the offshore (Venkatesh et al., 1989). Mercury content was between 20 and 385 ppb in sediments, 20 and 100 ppb in seawater and 500 to 1,500 ppb in nearby hot springs. Offshore surveys also revealed mercury to be present in sediments of the Ulhas estuary, zooplankton and benthic samples (Zingde and Desai, 1981). The reported values of total mercury contents in water, sediments, zooplankton and fish vary from 0.12 to 1.4 µg l<sup>-1</sup> (Sanzgiry et al., 1988). Besides the above limited studies, the only other recent information is of magnetic susceptibility of the Arnala sediments (Badesab et al., 2017).

Considering the developments that have occurred in the last few decades in and around this coast, there was a need to understand its geology, sedimentology and mineralogy, and to assess the sediment dynamics and identify sites that are vulnerable to erosion/accretion.

## 2.0 Study Area

The studied coast (20 km long, 400 m wide) has the Sahyadri mountain ranges to the east, a plateau between the coastal ranges and steep scarps, and hills located 5 to 20 km away. The ranges are covered by Deccan Trap flows (20-113 m thick) of porphyritic to non-porphyritic basalts. Shear zones, faults and fractures are common especially upstream of the Vaitarna River. The basaltic flows are overlain by 6 to 84 m thick lateritic soil. The hinterland hosts 33 hot springs (30-70 °C) that originate from a depth of 820 m and are surrounded by several basic dykes (Anon, 1982).

The study area lies between two major rivers Vaitarna in the north and Ulhas in the south (Fig. 1). The former river is 154 km long and has a drainage area of 3,637 sq km, three tributaries and an average annual run-off of 2,937 million cubic metres. The sediment load between years 2015 and 2016 was 335 thousand tonnes ([www.cwc.gov.in](http://www.cwc.gov.in)). The 135 km long Ulhas River drains 4,637 sq km with an annual run-off of 2,816 million cubic metres (Anon, 2006).

In the study area, sand, tidal clays (locally called ‘mendha’) and flood loams are of Late Quaternary to Recent age and are 5 to 10 m thick, extend up to 6 km inland and were unaffected by catastrophic movements (Ghate, 1988). There is a prominent raised beach (colloquially called ‘karal’) of 2 to 3 m height, with semi-consolidated sand layers (4 to 6 mm thick). These layers have coarse-grained sands and large calcareous shells or fine-grained sands with submicroscopic to microscopic shells. The sand deposits are of intertidal complex, beach-dune complex and aeolinites in nature (Ghate et al., 1990).

Radiocarbon dates of karal samples range between  $5,070 \pm 105$  yrs BP (Before Present) and  $1,110 \pm 105$  yrs BP (Guzder, 1980). The  $^{14}\text{C}$  dates of drift wood and shells retrieved from karal samples revealed the shells to range between  $5,220 \pm 100$  yrs BP and  $2,755 \pm 100$  yrs BP while the wood samples were between  $6,850 \pm 130$  yrs BP and  $4,370 \pm 110$  yrs BP (Ghate, 1985). Sedimentation and cementation of karal rocks occurred between  $2,155 \pm 90$  and  $6,850 \pm 130$  yrs BP (Guzder, 1980). Foraminiferal assemblage and  $^{14}\text{C}$  dates suggest that the sea-level at ~8,000 yrs BP was 2 m lower and reached the present stage by about 5,500 yrs BP and since then the sea-level fluctuated narrowly (1-1.5 m). The present day beach is a result of depositional and erosion processes and the sea-level rise that occurred since the last 7,000 yrs (Ghate, 1988).

## 3.0 Field And Laboratory Techniques

A Garmin GPS (accuracy  $\pm 5$  m) was used to acquire geographical co-ordinates of 16 beach profiles (BP) (Fig. 2). Using a dumpy level and graduated staff the elevations were measured with reference to the benchmarks that were located at 5 m interval along the BP. The BP were spaced ~800

to 1000 m and selected considering a clear line of sight from backshore to water line and also the physiographic variations (if any). Beach profiling was carried out in 2013 during February (fair season), May (pre-monsoon), August (during monsoon), December (post-monsoon) and in 2014 March (fair season). A tidal software programme of the hydrographic office (Tidecalc Version 1.1, Tidecalc software, Author and Publisher UK Hydrographic Office) was used to reduce the height of survey points to chart datum prior to plotting the BP.

Using an acrylic tube (6 cm dia, 40 cm long) sediments were collected from foreshore (low-, mid- and high-tides) and backshore (berm, raised beach). Sixteen sand pits (1 × 1 × 1 m) were dug to observe, photograph and sample the sediments. A total of 122 samples were collected: 54 from sub-surface, 61 from 16 sand pits and 7 from raised beach. Sampling was carried out in February 2013 and May 2013.

The sediments were washed, dried, coned, quartered and treated with 10% HCl to determine CaCO<sub>3</sub>. Textural parameters (¼ phi intervals) (Table 1) were calculated for graphic and moment measures using the GRADISTAT software (cf. Blott and Pye, 2001). Heavy minerals were separated by using bromoform (sp gr 2.89) and were washed with methanol. Using a hand magnet, the magnetic components were separated from the total heavy minerals and the remaining fraction was passed through SG Frantz isodynamic separator (Hutchinson, 1974). The magnetic and non-magnetic fractions were weighted and their percentages were calculated (Table 2).

Wave patterns were determined by using wave data that were collected over a period of one year at 10 m water depth using the Datawell directional wave rider buoy off Mumbai. The details about the measurement and wave characteristics are available in Kumar et al. (2019). The nearshore wave parameters were derived by using numerical wave model of Delft Hydraulics (2011). The wave transformation is based on a third-generation wave model SWAN (Booij et al., 1999). The measured significant wave height (H<sub>s</sub>), mean wave direction and period were used as inputs. The littoral drift was estimated using the bulk transport formula (CERC, 1984).

$$Q_{LST} = 0.023 \sqrt{\frac{g}{K_i}} H_b^{2.5} \sin(2\theta)$$

where, Q<sub>LST</sub> is littoral drift in volume per unit time, K<sub>i</sub> breaker index (H<sub>br</sub>/h<sub>br</sub>; H<sub>br</sub> breaking wave height, h<sub>br</sub> water depth at breaking), g acceleration due to gravity (9.81 m/s<sup>2</sup>), H<sub>b</sub> breaking wave height (m), θ angle between breaking wave crest and local shoreline.

## 4.0 Results

**4.1 Beach Morphology:** The coast under study is remarkably flat with a gentle slope (Fig. 3A-C) and is similar to Mantanani Besar Island, Sabah (Malaysia) (Koiting et al., 2017). There are berms (Fig. 3D), shelly sands (Fig. 4A), ripple marks (Fig. 4B), vegetation (Fig. 4B, C), runnel (Fig. 4D), raised beaches, tidal flats, sand spits and bars and extensive rock platforms (Fig. 5), creeks (Fig. 6), and retention walls (Fig. 7).

We divided the coast into four sectors based on presence of rivers, creeks and change in BP (Fig. 2). Sector A: Arnala beach (near Vaitarna River mouth) to Nirmal/Kalampada (Kalamb) creek. Sector B: Bhuigaon creek to Rangaon beach. Sector C: Rangaon beach to Bassein creek (Vasai beach, near Ulhas River mouth). Sector D: Arnalpada Island (opposite Vaitarna River mouth).

**Sector A:** This flat, gentle and slightly undulated sector (~6.5 km long, 65-410 m wide) has shelly and black sands and ripple marks with heavy minerals (Fig. 5D). A ~300 m long raised beach has thin laminations of heavy minerals (Fig. 5A). The basaltic rock platform is altered. The foreshore is smooth and gently slopes (1:0.01 to 1:0.03) while backshore is relatively steep (1:0.1 to 1:0.30).

**Sector B:** This ~4.5 km long sector is 70-380 m wide with a broad foreshore, a flat backshore and in the raised beaches there are high concentrations of heavy minerals. At Bhuigaon the rock platform made of altered fine grained basalt has a gradual seaward slope and is exposed during low tide (Fig. 6A). Such Type B platforms are best developed along microtidal coasts where tidal range is small and induration or hardening of shore rocks is aided by precipitation of cementing materials, mainly  $\text{CaCO}_3$  or iron oxides. The rock platform represents remnants of landmass between mainland and nearby islands and indicates coastal stability for a substantial period, perhaps up to 6,000 years (Bird, 2008). This observation corroborates the earlier report that the sea-level at this coast reached its present position at 5,500 yrs BP (Ghate, 1988). The foreshore has gradients between 1:0.009 and 1:0.03 and 1:0.14 while the backshore has 1:0.07 and 1:0.25.

**Sector C:** The Vasai beach (Fig. 2) is ~2 km long, 55-130 m wide and has a raised beach with heavy minerals. A berm that separates backshore and foreshore is cut by a runnel through which tidal water that enters the marshy land reverses its direction during low tide. A retention wall protects the casurina trees and fields in backshore. Scouring of backshore and uprooting of trees occur before and during monsoon times (Fig. 7A,B). The BP has gentle to moderate gradients in foreshore (1:0.01 and 1:0.08) and gentle to steep in backshore (1:0.04 to 1:0.25).

Sector D: The rocky Arnalapada Island (Fig. 2) has a sandy beach to its east and a well-developed 50 cm high berm (Fig. 6B). The beach is 175-195 m wide and has a gentle to moderate gradient in foreshore but is moderate to steep in backshore.

**4.2 Calcium carbonate contents and Granulometry:** The CaCO<sub>3</sub> content, granulometry and heavy minerals of 122 samples are tabulated (Tables 1, 2) and discussed below.

**4.2.1 Raised Beach:** The sediments have CaCO<sub>3</sub> between 0.92 and 5.4% (av 3.66%) and grain size is 2.5-3.5  $\Phi$  (3  $\Phi$ ), sorting 0.4-3 (1.1), positive skewness and kurtosis 0.3-4.7 (2.5). The fine-very fine sands are moderately to well sorted, symmetrical to coarse skewed and lepto- to meso-kurtic. Uni- to bi-modal distribution indicates single/dual sources for the sediments. The heavy minerals are 19-74% (55%), with magnetite 8-27% (21), ilmenite 64-37% (25%) and non-magnetic 1-16% (7%).

**4.2.2 Sub-surface:** The sediments have CaCO<sub>3</sub> from 2.5 to 20% (10%) while grain size is 1-4  $\Phi$  (2.5  $\Phi$ ), sorting 0.3-2.4 (0.63), negative skewness and kurtosis 1-10 (4). The sediments are mostly very fine sands, moderately to well sorted, symmetrical to coarse skewed and lepto- to meso-kurtic. The sediments are mostly uni- to bi-modal in distribution but some sediments also show tri- to poly-modal characteristics. The heavy minerals are 4-75 wt.% (39%), with magnetite 1-28% (13%), ilmenite 2-22% (~13%) and non-magnetic 1-27% (~12%).

**4.2.3 Sand pits:** The sediments in Sector A from 8 pits have CaCO<sub>3</sub> <1-10% (4%), with grain size 0.8-3.5 (2.5  $\Phi$ ), sorting 0.4-1.2 (0.6), mostly negatively skewed and kurtosis 2-12 (3.6). The medium-fine sands are moderately well sorted and uni- to poly-modal. The heavy minerals are 1-88% (37%), with magnetite 0.3-43% (20%), ilmenite 0.4-33% (12%) and non-magnetic <1-34% (5%).

In Sector B sediments from 5 pits have CaCO<sub>3</sub> 0.9-15% (5%), grain size is 2-3.4  $\Phi$  (2.9  $\Phi$ ), sorting 0.2-1 (0.6), mostly negatively skewed and kurtosis 2-14 (5.2). The fine-very fine sands are medium to moderately well sorted and bi- to poly-modal. The heavy mineral are 12-74% (35%), with magnetite 0.2-42% (14%), ilmenite 1-30% (14%) and non-magnetic 0.4-15% (6%).

In Sector C sediments from 2 pits have CaCO<sub>3</sub> 2.4-10% (5%), and grain size 2-3  $\Phi$  (2.9  $\Phi$ ), sorting 0.5-1 (0.6), mostly negatively skewed and kurtosis 1.9-5.8 (4). The fine-very fine sands are moderately well sorted and bi- to tri-modal. The heavy mineral are 18-65% (43%), with magnetite 9-35% (17%), ilmenite 7-30% (17%) and non-magnetic 1-20% (9%).

In Sector D sediments from a pit has CaCO<sub>3</sub> ~5%, grain size 2.49  $\Phi$ , sorting 0.4, negatively skewed and kurtosis 4.5. The fine sands are well sorted and bimodal. The sediments have 25% heavy minerals, with magnetite 16%, ilmenite 13% and non-magnetic forming 5%.

In summary, the 122 sediment samples, collected from raised beach, sub-surface and sand pits, show moderate contents of CaCO<sub>3</sub> (<1 to 15%, av 7%), grain size 0.8-4.8  $\Phi$  (2.7  $\Phi$ ), sorting 0.18-3 (0.65), dominantly negatively skewed and kurtosis 0.3-14 (4). The sediments are mostly medium to very fine sands that are moderately well sorted to very well-sorted and are symmetrical. Further, the sediments are very platykurtic to dominantly mesokurtic; and mostly uni- to bi-modal except some which are tri- to poly-modal (Table 1). The heavy minerals range from 1 to 88% (39 wt%) with magnetite 0.2-43 wt% (~17 wt%), ilmenite 0.4-38 wt% (15 wt%) and non-magnetic <1-34 wt % (7 wt%) (Table 2).

### 4.3 Interpretations

**4.3.1 Calcium carbonate content:** The CaCO<sub>3</sub> contents in raised beach sediments, subsurface sediments and in sand pits vary between <1% and 20% with higher contents in beach sediments (avg. ~10%), intermediate in pits (~5%) and lowest in raised beach (3%). These values indicate contribution of shells to the beach from the sediments eroded from the raised beach. During monsoon, the shells that lie below the subsurface sediment are exposed, eroded, transported and deposited in intertidal region together with those brought from offshore (Figs. 3A, 4A).

**4.3.2 Sediment Provenance And Depositional Environment:** In the study area the sediments have quartz, calcite, feldspar, bioclasts, magnetite, ilmenite and basaltic rock pieces. Quartz grains with conchoidal fractures, V-shape notches, pits and grooves suggest reworking of grains for a prolonged period and their residence in the sediment depot.

The fine-grained sands (2.5-3  $\Phi$ ) are well- to moderately-sorted (0.4-1) and deposited under low to medium energy conditions. The pit sediments are bi- to poly-modal while those from sub-surface and raised beach are uni- to bi-modal. The beach sediments are mostly derived from the Vaitarna River, nearby creeks, raised beach, and rock platform. Areas with coarse grain size have negatively skewed sands (pits 2 to 8, 11, 12, 16 and also most sub-surface sediments) because fine sands would be transported offshore due to winnowing by waves and aerial transport. Sediments with a mixed skewness (pits 9, 10, 14, 15) suggest them to be in a state of flux while positive skewness (pits 1, 13) point to accretion (cf. Duane, 1964). The extremely leptokurtic sediments (kurtosis 2.5-4.5) reaffirm their fluvial derivation.

The insignificant variations in sediment parameters and heavy minerals suggest uniform oceanographic processes to operate along the Arnala coast. Similar observations have been made for the central west beaches of India (Chauhan, 1995). This fact is also attested from magnetic

susceptibility study of the Arnala sediments which did not reveal large variations in magnetic minerals that are fresh and have minimal surface indentations (Badesab et al., 2017).

**4.4 Nearshore waves:** The energy and direction of nearshore waves that effectively transport and redeposit coastal sediments are influenced by bottom topography, water depth, coastal configuration, nature of wind and tide amongst other factors (Gujar et al., 2008, 2011). Wave refraction depends on water depth and wave amplitude and these cause the waves to move parallel to and break at an angle to the coast. As a result, the currents move sediments along the coasts as littoral drift (Masselink and Hughes, 2003).

At the studied coast the waves progressively increase in height from January and reach ~3.6 m during monsoon. The wave characteristics are presented for pre-monsoon (FMAM), monsoon (JJAS), post-monsoon (ONDJ) (Fig. 8). The waves are mainly from SW-W but due to their bimodal characteristics, high frequency waves are from NW when wind-sea is predominant. The swell generally comes from SW and wind-sea varies from NW due to Shamal wind and from SW-W during monsoon. The waves from S to W (180-270°) are predominantly swell waves. The coastal inclination along the study area is 16° to the west. The waves with direction more than 254° produce a littoral drift towards south and waves with direction <254° induce a northward drift. Wave transformation leads to an annual wave height of 0.4 m at 2 m water depth. The gross transport of littoral drift in June is less (~0.333 x 10<sup>5</sup> m<sup>3</sup>), maximum in July (~0.347 x 10<sup>5</sup> m<sup>3</sup>) and least in November (~0.015 x 10<sup>5</sup> m<sup>3</sup>) (Fig. 9). The near-surface coastal current off Mumbai flows southward during May–September with weak intensity and northward during November–February (Amol et al., 2014).

## 5.0 Discussion

**5.1 Grain size:** The parameters that could control sediment characteristics and grain size are: provenance, sediment composition, conditions of depositional energy (Garzanti et al., 2009; Rajganapathi et al., 2013; Armstrong-Altrin et al., 2015) coastal geomorphology, type and mode of riverine input; morphology and density of grains, transport by short-lived and recurrent fluvial systems, and offshore wave and wind climate. These factors result in transport of fine, low density grains to far distances from source while coarse low density and fine high-density grains are moved to shorter distances and/or settle together at or close to source (Ergin et al., 2018).

The above factors coupled with longshore currents, offshore hydraulic sorting and selective entrainment of grains during transport and deposition, causes the finer sediments to move towards south along this coastal stretch. The sources for the sediments are DT basalts that are weathered, eroded and transported by the Vaitarna River. Along the Arnala coast, except for the wide shore platform and



low beach slope, there are no obstructive features viz headlands, cliffs and outcrops. Hence, during most times of the year there are uniform wave and current actions along the Arnala coast.

**5.2 Coastal processes and influence on sediments:** To west of the study area there are two barriers that affect sediment transport: (1) coast-parallel basaltic shore platform (Fig. 6A,B) and (2) Arnalapada Island. These features constrain sediment exchange, and also the movement and deposition of riverine and nearshore sediments that are carried by the Vaitarna River and also by Bhuigaon and Rangaon creeks. A cross-shore transport of riverine sands leads to minimized accumulation of offshore sands that are compelled to move along- and cross-shore in a littoral cell that is formed between the coast and rock platform. During monsoon, wave direction is parallel to coast and littoral drift is minimal and hence nearshore sands are transported into rivers and creeks. When tide reverses, lighter sands trapped in dense mangrove vegetations return to nearshore. During ebb tides heavy minerals from backshore are not efficiently eroded but re-deposited nearshore and later transported offshore. These processes result in zones of heavy minerals along the area as commonly noticed along southwest coast of India (cf. Prakash et al., 2007).

The littoral cell along the Arnala coast (Fig. 10) receives copious sediments from the Vaitarna River and to a lesser extent from Bhuigaon and Rangaon creeks. This cell also consists of an open-coast, a flat, gentle beach and a nearshore region that are potential sites for sediment deposition. Furthermore, minor tidal variations, natural barriers and moderate oceanographic conditions all confine the sands within the cell. Under this set-up the sands undergo minimal longshore transport but are efficiently winnowed, broken down, well sorted and become rounded. This mechanism could help explain the striking uniform characteristics of the studied sediments.

**5.3 Sediment budget and accretion/erosion:** It is well recognized that beach morphology and sediment distribution help to assess rate of sediment accretion/erosion. Shoreline changes are natural phenomenon that affects 70% of the world's sandy beaches (Anon, 2000, Bird, 2008; del Rio et al., 2013) and result due to sediment accretion/erosion. Such changes are of 3 types: long-term, short-term and episodic (Gibeaut et al., 2001). Long-term beach changes occur between 10 and 1000s of years because of sea-level fluctuations (Prasetya, 2007). Short-term changes happen within 5-10 years due to waves, tides, winds and currents while episodic changes are due to short-lived events such as storms (Kumar et al., 2010; Gujar et al., 2011; Dora et al., 2012).

The data of accretion/erosion observed in 80 profiles from 16 BP (i.e., 5 seasons) are shown (Fig. 11) and tabulated (Table 3). The quantum of sediment deposited/eroded, and volume and percentage rate of volume change of sediment were determined (Table 4). In Sector C because of

continuous erosion trees were uprooted (Fig. 7B) and the raised beach had partially collapsed. Measurements reveal that an area of ~240 sq m of backshore was eroded in about 5 months (Aug-Dec 2013). An analysis of Tables 3 and 4 reveals that during May-Dec 2013 in Sector A sediment erosion and accretion are equal, erosion occurs in Aug 2013 and accretion in March 2014. In Sector B during May 2013 there is erosion, accretion in Aug 2013 and March 2014 and severe erosion during Dec 2013. In Sector C, at BP 14 erosion is continuous and slight accretion in March 2014 while at BP 15 it is the converse. In Sector D there is accretion during May 2013 and March 2014 and erosion in Aug-Dec 2013.

Based on sediment accretion/erosion (Table 4), we classified the study area into 3 zones: (1) zones of accretion due to input of sediments from creeks (Fig. 2); (2) zones of constant erosion because of seawater incursion into a large creek; and (3) zones that are perennially eroded but have some accretion of sediments.

**5.4 Role of nearshore waves:** Wave refraction influences seasonal changes in sediment transport and deposition (Pattiaratchi and Harris, 2003), shaping of coastline features (Ashton et al., 2001; Slott et al., 2006) and distribution of placer minerals (Gujar et al., 2008; Sarvanan and Chandrasekar, 2015). Nearshore data for the Arnala coast indicate that high waves approach parallel to coast and hence, onshore-offshore transport of sediment is enhanced during monsoon vis-à-vis littoral drift. In contrast, during non-monsoon period the annual gross and net littoral drifts are  $0.131 \times 10^6 \text{ m}^3$  and  $0.123 \times 10^6 \text{ m}^3$ , respectively towards the south. This fact indicates that along this coast a sedimentary equilibrium perhaps exists during non-monsoon period because of continuous supply of littoral drift, absence of sands from offshore due to its less variable bathymetry (Fig. 1). This explains the uniform granulometric parameters and accretion/erosion processes in the area. A similar scenario exists along the coast of Kerala, India (Black et al., 2008).

## **6.0 Vulnerable Areas And Possible Remedies**

Coastal areas are prone to sediment erosion/accretion and need to be protected (Prasetya 2007; Aagard et al., 2012). Several areas along the Arnala coast are vulnerable to vagaries of nature. Sites south of Sector A are less affected by erosion/accretion because of fields and retention walls in backshore (Fig. 7D). In Sector B the unconsolidated raised beach formation is severely eroded during monsoon. Rock platform and outcrops that are present from intertidal zone to ~3 km offshore and at a water depth of <5 m reduce the intensity and height of incoming waves. The beaches being protected from large-scale erosion, host shelly sands and heavy minerals in backshore.

In Sector C during monsoon runnel and berm form in backshore while the raised beach is eroded and trees get uprooted. Near Ulhas river mouth, there is a berm and the beach slope changes from gentle to steep due to sand accretion. A fishing jetty here affects sedimentation patterns and oceanographic parameters. The rocky Sector D is well-shielded from intense erosion.

In general, the Arnala coast could be safeguarded from erosion by afforestation measures, restricting manual sand removal activities and by building retention walls. As beach slope, wave period and bedforms play vital roles in controlling littoral drift, these variables need to be assessed while planning shore protection measures.

## **7.0 Conclusions**

This first detailed study based on several field works, seasonal topographic profiling and sediment characteristics, revealed the following salient features of the coastal zone between the mouths of Vaitarna and Ulhas rivers.

1. The Arnala coast is broad and remarkably flat with rock platform extending from the intertidal zone to the nearshore. In backshore a semi-consolidated and discontinuous raised beach runs for a few km in an N-S direction.
2. The fine grained (2.5-3  $\Phi$ ) sediments with sorting (0.40-1.08), negative skewness and kurtosis (2.5-4.5) indicate uniform oceanographic processes to be operative along the coast. This may be because the Arnala coast has a low slope coupled with an absence of topographic expressions that could impede wave energy. Therefore, there is a placid swash and back-swash movement of sediments in a littoral cell during most months of the year.
3. Significant concentrations of magnetite, ilmenite and titanomagnetite occur in backshore and raised beach.
4. The coast is largely naturally protected, yet human interventions are needed to reduce erosion occurring during monsoon. Post-monsoon months witness resumption of beach building activity.

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Table 1. Range and average (within brackets) of CaCO<sub>3</sub>, sediment parameters and sediment types from raised beach, sub-surface and sand pits along the Arnala coast.

Sites (number of samples)	CaCO <sub>3</sub> (%)	Mean (Φ)	Sorting (σ)	Skewness (Sk) (+/-)	Kurtosis (K)	Sediment type
Raised Beach (7)	0.92-5.4 (3.7)	2.55-3.54 (3.0)	0.43-3.07 (1.08)	Positive	0.3-4.7 (2.5)	moderately well sorted fine sand, uni- to bi-modal
Sub-surface (54)	2.5-20 (10.6)	1.55-4.84 (2.5)	0.33-2.42 (0.63)	Negative	1.05-10.74 (4.0)	Moderately well sorted-well sorted, medium-very fine sand (mostly), uni- to bi-modal, few tri- to poly-modal
8 pits, Sector A (32)	<1-10.8 (4.4)	0.8-3.5 (2.5)	0.39-1.17 (0.60)	Mostly Negative	2-12 (3.6)	moderately well sorted medium-fine sand uni- to poly-modal
5 pits, Sector B (20)	0.9-15.5 (5.8)	2.1-3.4 (2.9)	0.18-1.05 (0.59)	Mostly Negative	2.58-14 (5.2)	Medium-moderately well sorted fine-very fine sand bi- to poly-modal
2 pits, Sector C (8)	2.5-10 (4.9)	1.8-3.3 (2.9)	0.5-1.2 (0.60)	Negative	1.92-5.83 (4.0)	moderately well sorted fine-very fine sand bi- to tri-modal
1 pit, Sector D (1)	4.7	2.4	0.40	Negative	4.5	well sorted very fine sand bi-modal

Table 2. Range and average (within brackets) concentrations of heavy, light, magnetite, ilmenite and non-magnetic minerals. Values are in wt%.

Sites (Number of samples)	Heavy	Light	Magnetite	Ilmenite	Non-magnetic
Raised beach (7)	19.92-74.5 (54.80)	80.08-25.5 (45.2)	8.75-27.36 (21.4)	6.56-37.97 (25.6)	1.36-16.04 (7.8)
Sub-surface (33)	4.5-75 (39.3)	95.5-75 (60.5)	1.4-28 (13.3)	2-22 (12.9)	1-27 (11.7)
8 pits, Sector A (32)	1-88 (37)	99-12 (63)	0.3-43 (20.1)	0.4-33.7 (12.4)	<1-34 (5.4)
5 pits, Sector B (20)	12.2-74.2 (34.9)	87.8-25.8 (65.5)	0.2-42 (14.2)	1.5-30 (14)	0.4-15 (5.8)
2 pits, Sector C (8)	18-65.7 (43.6)	82-34.3 (56.4)	9-35 (16.9)	7-30 (17.3)	1.7-20 (9.6)
1 pit, Sector D (1)	25.3	74.7	15.4	8.4	1.5
Avg of 61 from 16 pits	35.2	64.9	16.6	13.0	5.6
Avg of 101 samples	39	61	17	15	7

Table 3. Accretion/erosion of sediments along Arnla. BP = Beach Profiles (see Fig. 2).

May 2013		Aug 2013		Dec 2013		March 2014	
Sectors	Remarks	Sectors	Remarks	Sectors	Remarks	Sectors	Remarks
A	Significant deposit. Fore- & back-shore less eroded and intertidal least.	A	Erosion (BP 2, 3, 5). Accretion back-shore (BP 1, 4), intertidal & near-shore (BP 6).	A	Accretion backshore & intertidal (BP 1, 4). Back-shore & intertidal eroded (BP 2, 5, 6). Continuous erosion back- & nearshore (BP 3). Accretion (BP 8).	A	Erosion (BP 2, 3, 5, 6, 7). Deposition (BP 1, 6, 7, 8).
B	Deposition fore- and back-shore. Nearshore eroded.	B	Major erosion (BP 11, 12). Severe erosion (BP 13). Deposition (BP 9, 10).	B	Accretion & erosion nearly equal.	B	Mostly deposition. Backshore (BP 9). Intertidal (BP 11) eroded. Severe erosion (BP 13) by creek.
C	Intertidal & fore-shore eroded.	C	Accretion back-shore. Eroded intertidal & near-shore	C	Continuous erosion.	C	Erosion & accretion equal.
D	Accretion	D	Accretion back- & nearshore. Intertidal eroded.	D	Continuous erosion.	D	Notable accretion.

Table 4. Quantum of sediment deposited (+) or eroded (-) along the Arnala coast. The volume of sediments (in cubic metres) for February 2013 was used as baseline datum to calculate percentage of rate of change of volume of sediments for other seasons.

BP	Feb 2013	May 2013	Aug 2013	Dec 2013	March 2014
1	139.12	-4.5	-7.2	+3.70	+7.4
2	115.82	-8.5	-11.6	-2.08	+8.6
3	172.85	+4.9	-22.1	-19.60	+4.8
Sector A 4	191.88	-2.8	-20	-11.70	-14.4
9	171.53	-0.8	+3.4	+7.20	+6.9
10	116.74	+50.5	+28	+33.40	+44.2
11	119.98	-14.2	+3.7	+2.80	-5.5
12	198.27	-0.6	-13.6	-1.10	+12.4
5	181.08	+5.5	-18.6	+8.90	-0.4
6	195.60	-4.10	-4.7	-2.70	+0.8
Sector B13	249.37	-1.6	-38.9	-71.90	-53.7
14	152.52	-0.1	-35.1	-36.20	+3.4
15	207.30	+3.4	-10.2	-10.90	-6
Sector C 7	121.13	+12.5	-14.9	+1.10	+9.8
16	163.56	+3.6	-43.3	-43.30	+15.2
Sector D 8	147.95	+10.9	+16.8	+8.90	+13.4

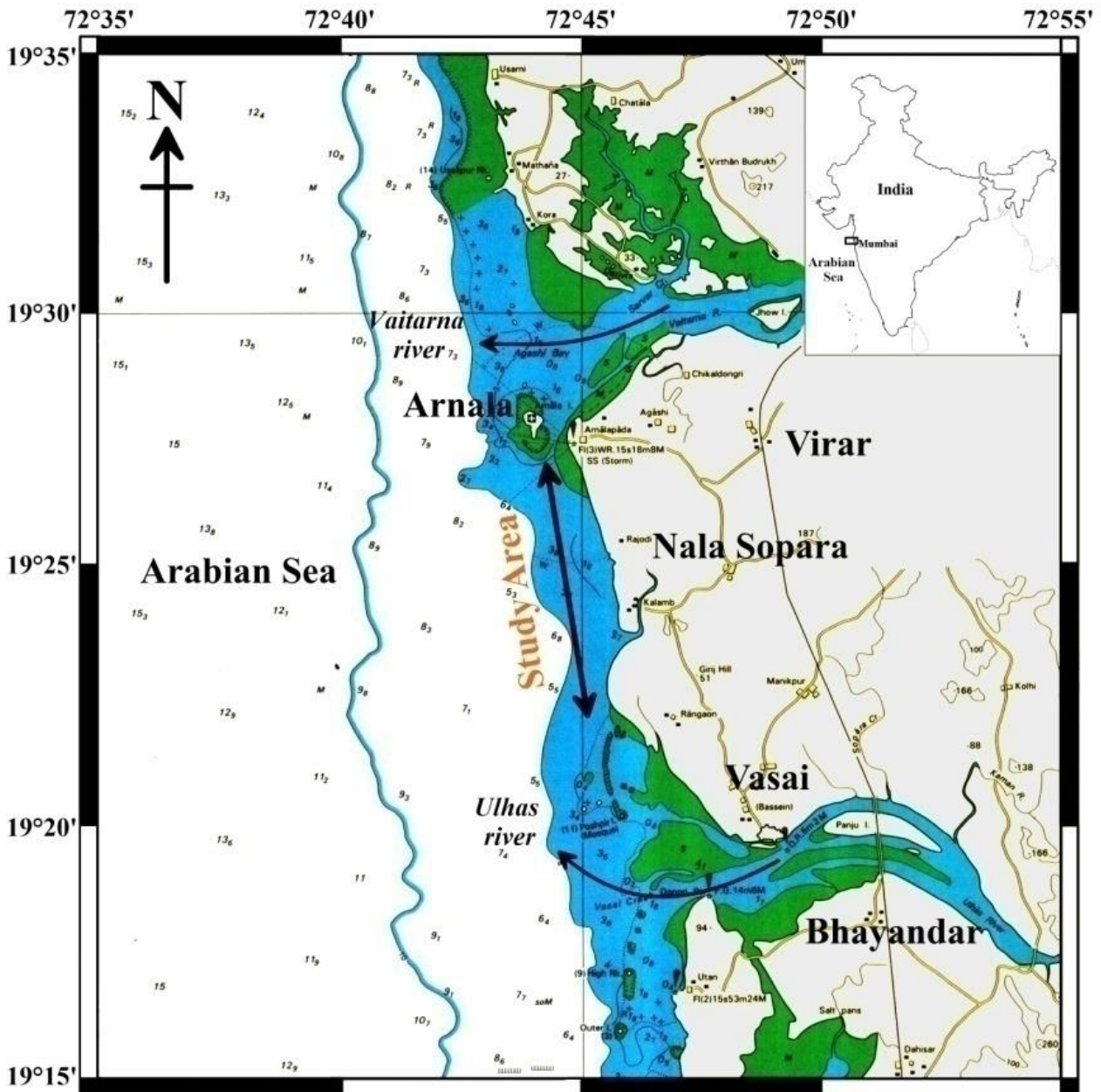


Fig. 1. Location of the study area. The map was prepared from NHO Chart No. 211.

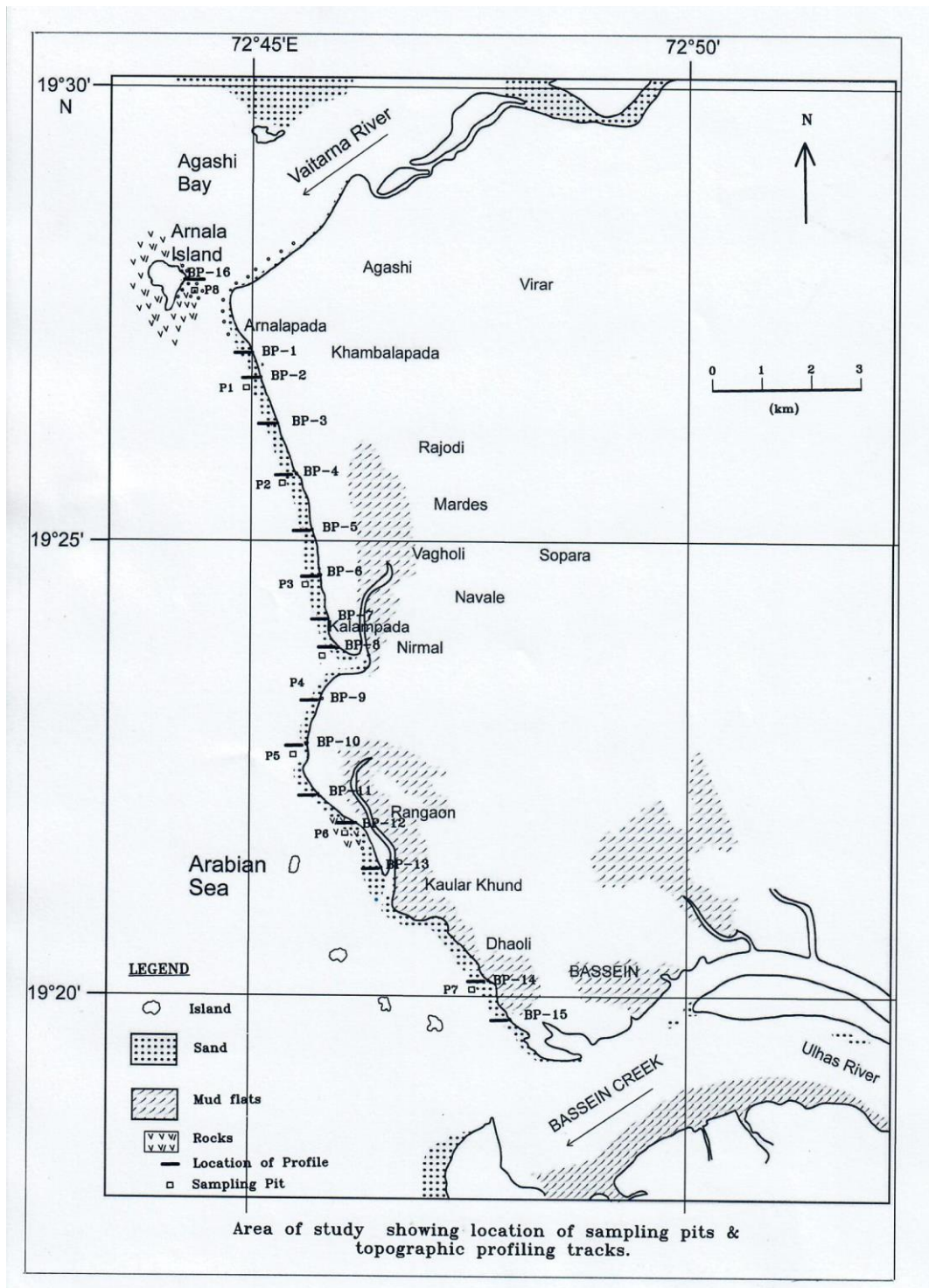


Fig. 2. Geological map modified after Pandian and Sukhtankar (1989).



Fig. 3

Fig. 3. A: Flat, wide fore- and back-shore with shelly sand between Rajodi and Kalampada. B: Broad, flat backshore area with ripple marks. Inset depicts a sand pit. C: Hummocky, intertidal zone and gently sloping foreshore, north of Rajodi. D: Berm at Arnalapada Island.



Fig. 4

Fig. 4. A: Shelly beach. B: Wide backshore with vegetation that minimizes sand erosion, Bhuigaon. Note heavy minerals in ripple marks. C: Grassland and horticultural fields in backshore. D: Runnel between Vasai beach (right) and the Arabian Sea (left).



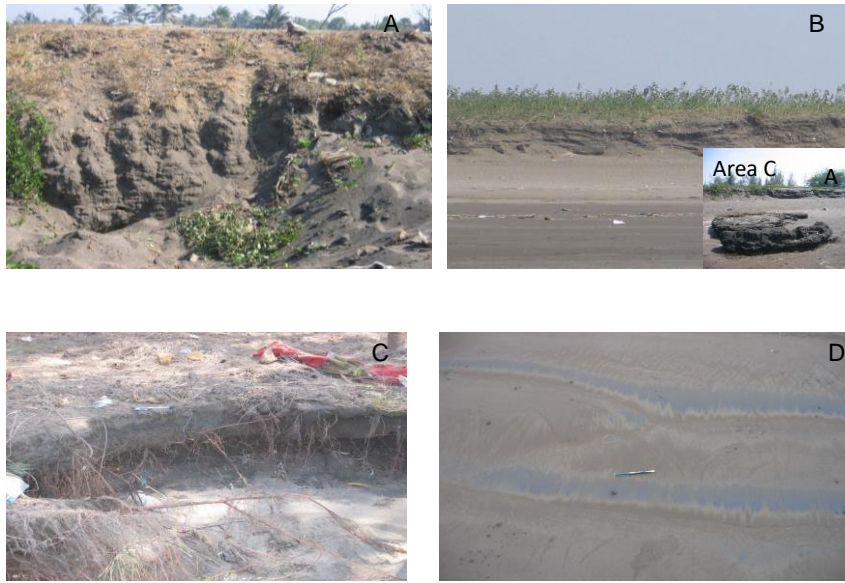


Fig. 5

Fig. 5. A: Semi-consolidated raised beach with heavy minerals as laminations and in small gullies. B: Part of raised beach formation. Inset shows a sample of raised beach with heavy minerals. C: Small band of raised beach with heavy minerals. D: Heavy mineral in ripples present in intertidal zone.

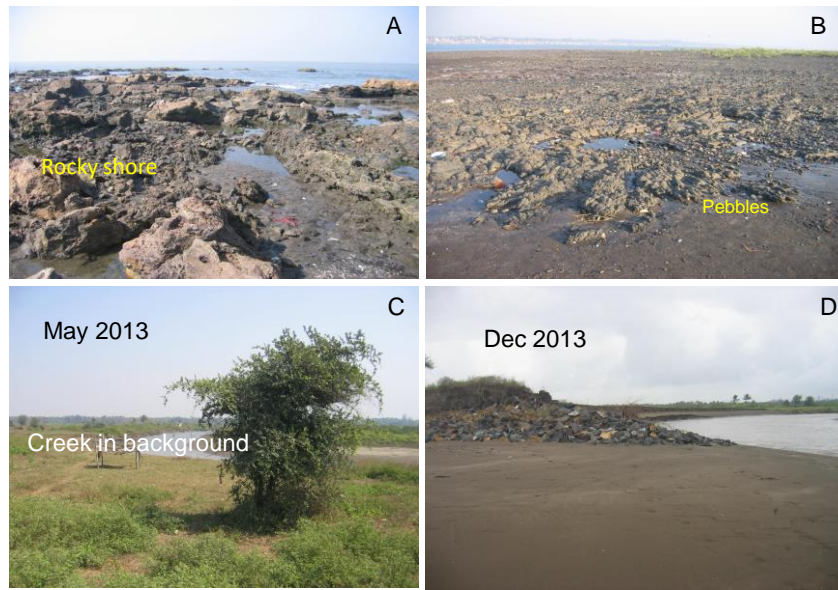


Fig. 6

Fig. 6: A: Rock platform along Arnala. B: Rock platform and pebbles on Arnalapada Island. C: Site BP 13 (May 2013) with a large creek in the background. D: The same site (Dec 2013) was severely eroded.

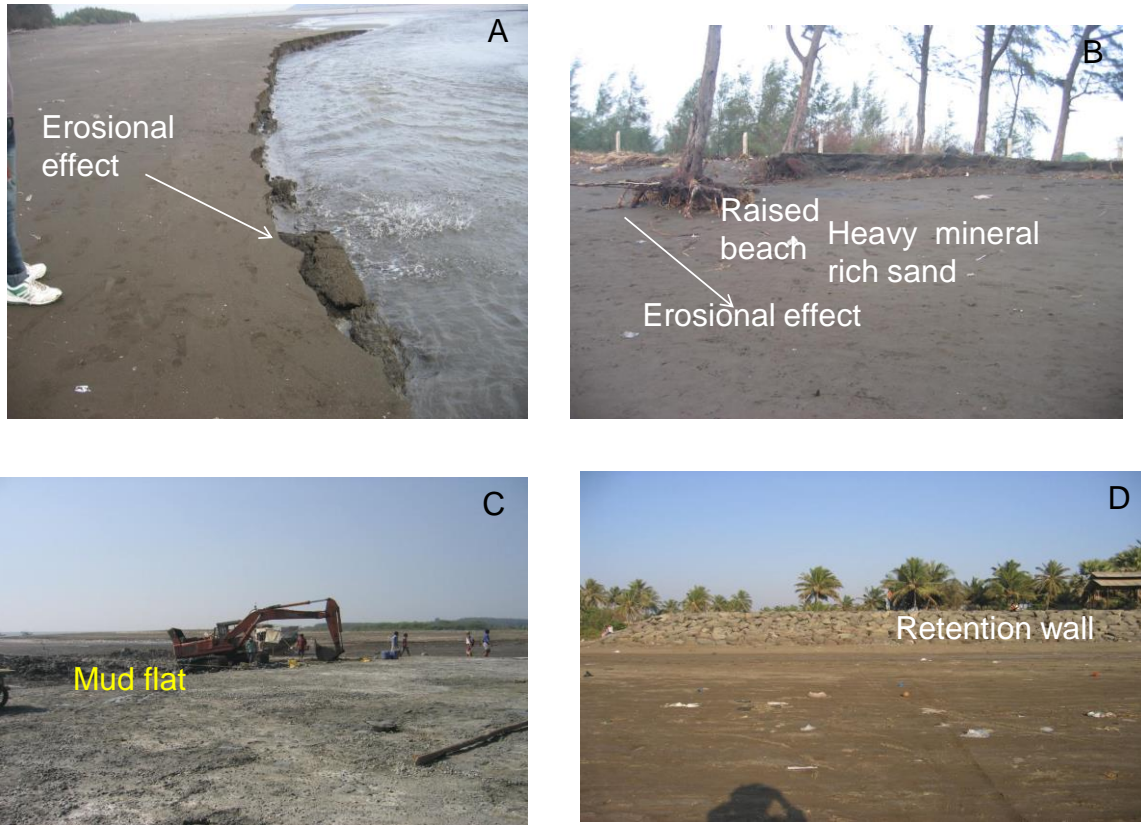


Fig. 7

Fig. 7. A: Erosion of banks of creek with unconsolidated sediment lumps in water. B: Heavy minerals loosened and transported to nearshore from eroded raised beach. C: Construction of a fishing jetty. D: A portion of retention wall along the beach.

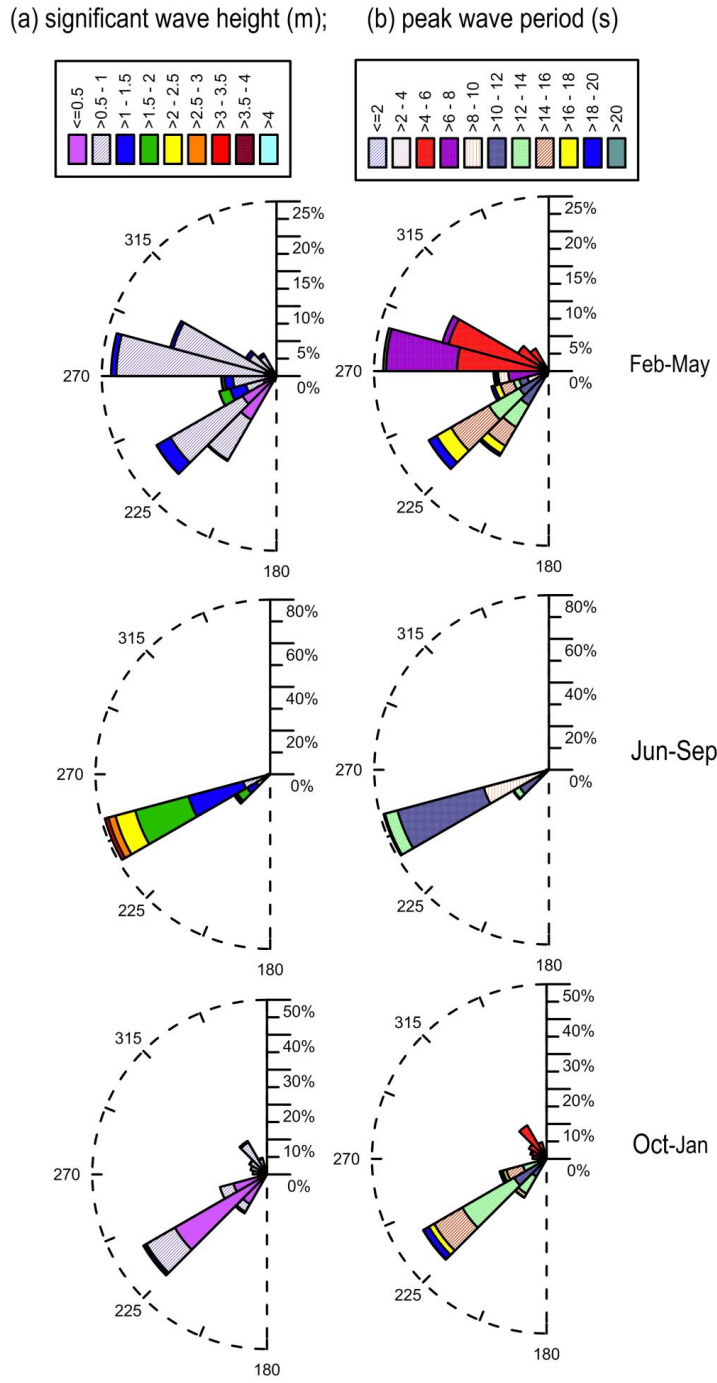


Fig. 8. Wave roses during different periods along the Arnala coast. Top: Feb-May, Middle: June-Sep, Bottom: Oct-Jan. Left panel shows significant wave height and mean wave direction. Right panel depicts peak wave period and mean wave direction. The radius of figure indicates percentage occurrence of waves from a particular direction.

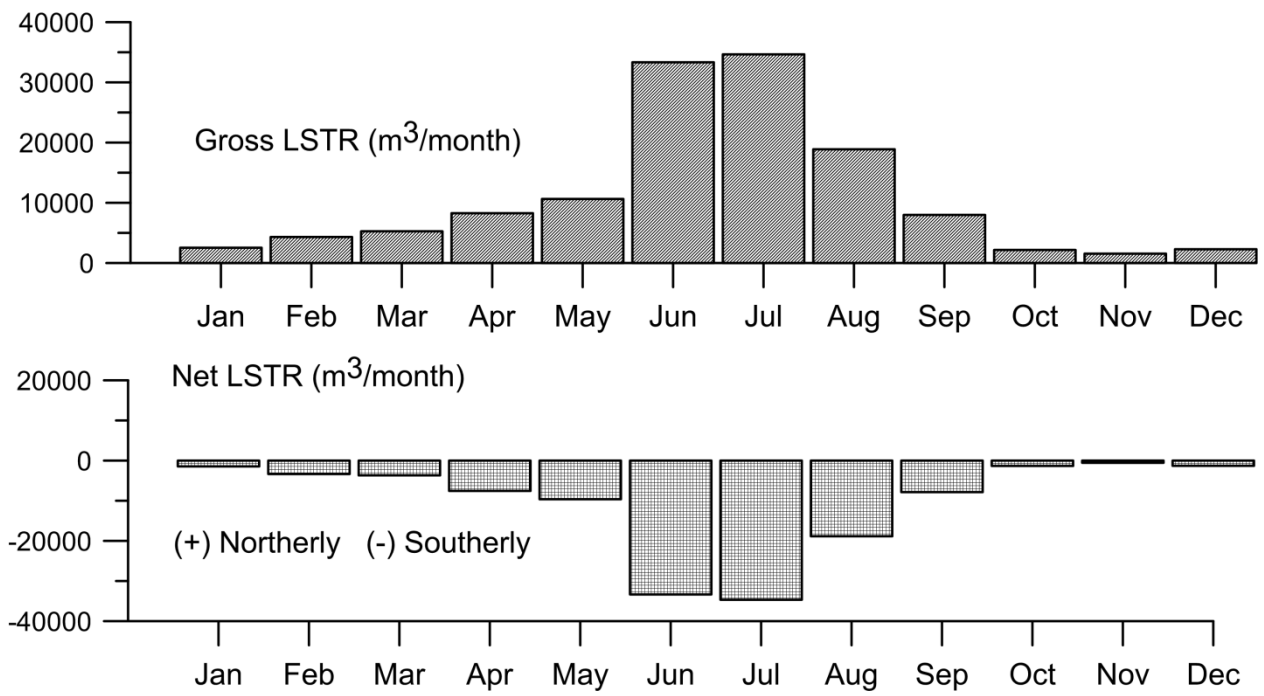


Fig. 9. Net and gross littoral drifts in different months along the Arnala coast.

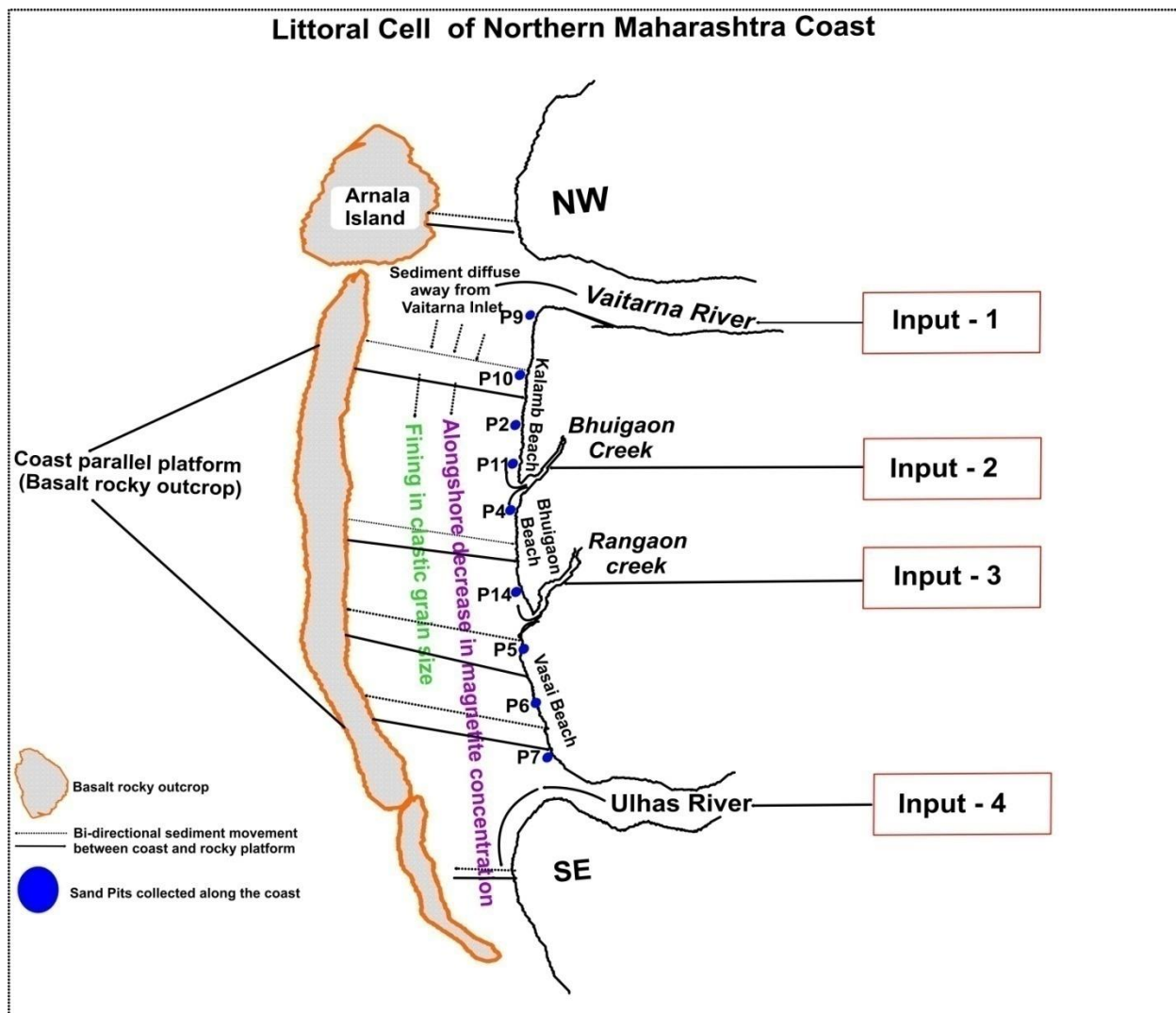


Fig. 10. A model that portrays causative factors involved in sorting and transport of sediments and enrichment of heavy minerals along the Arnala coast. P9, P10 etc. are location of sand pits. Inputs of sediments are from the rivers and creeks. Figure modified after Badesab et al. (2017).

Figure 11 (Sector A, BP 1 and 2)

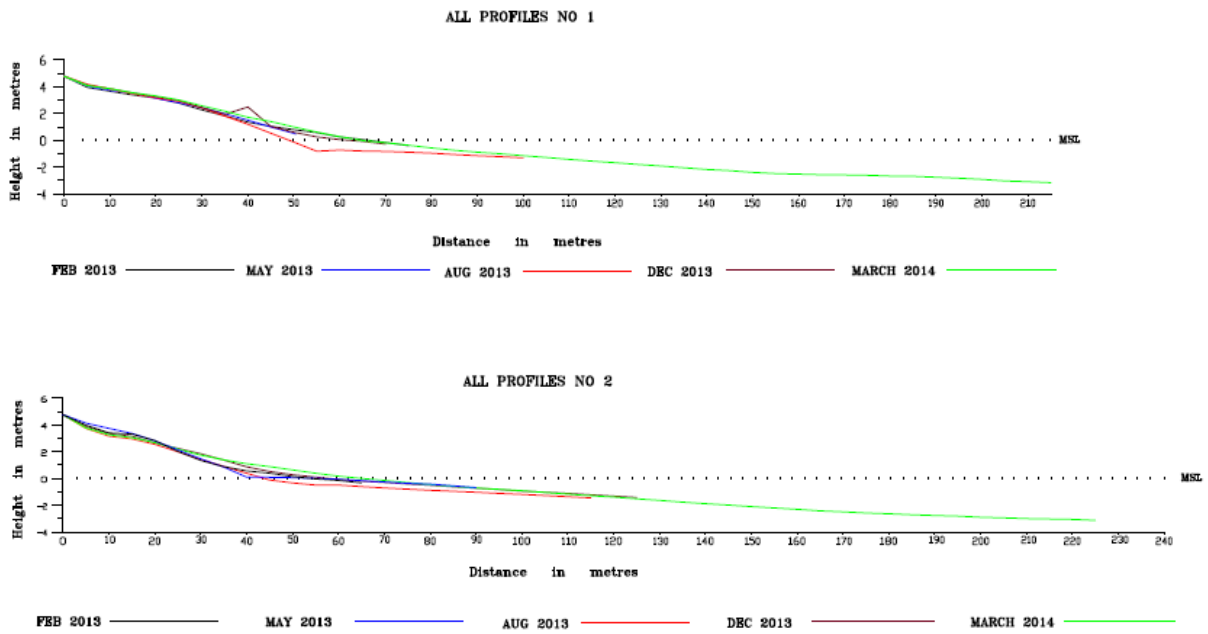


Figure 11 (Sector A, BP 11 and 12)

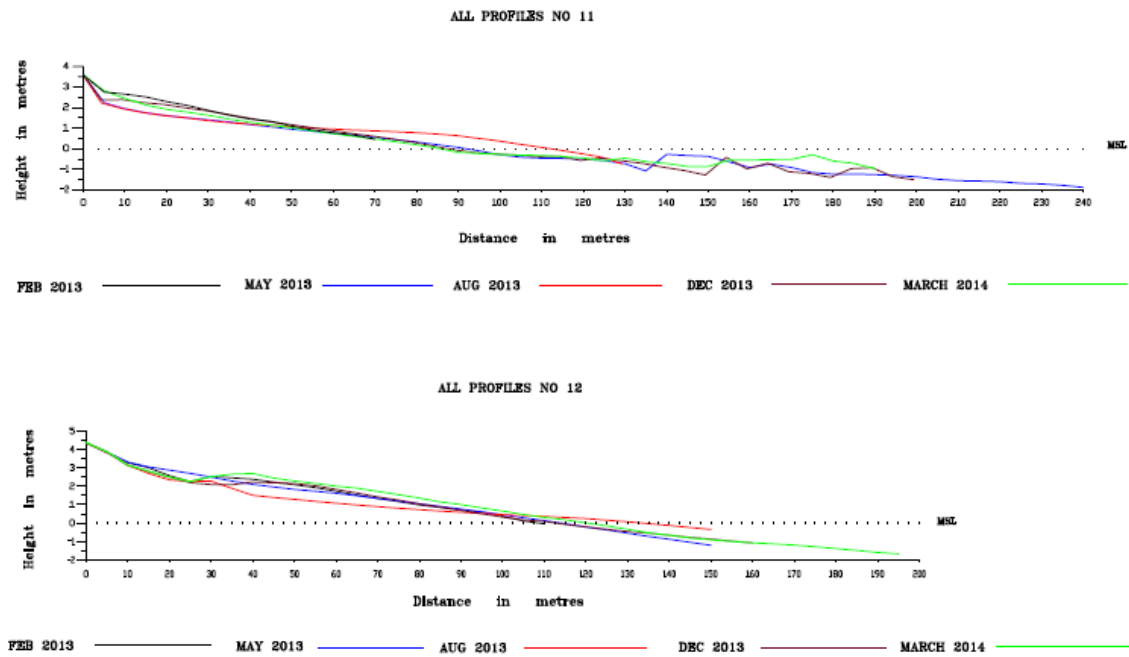


Figure 11 (Sector B, BP 13 and 14)

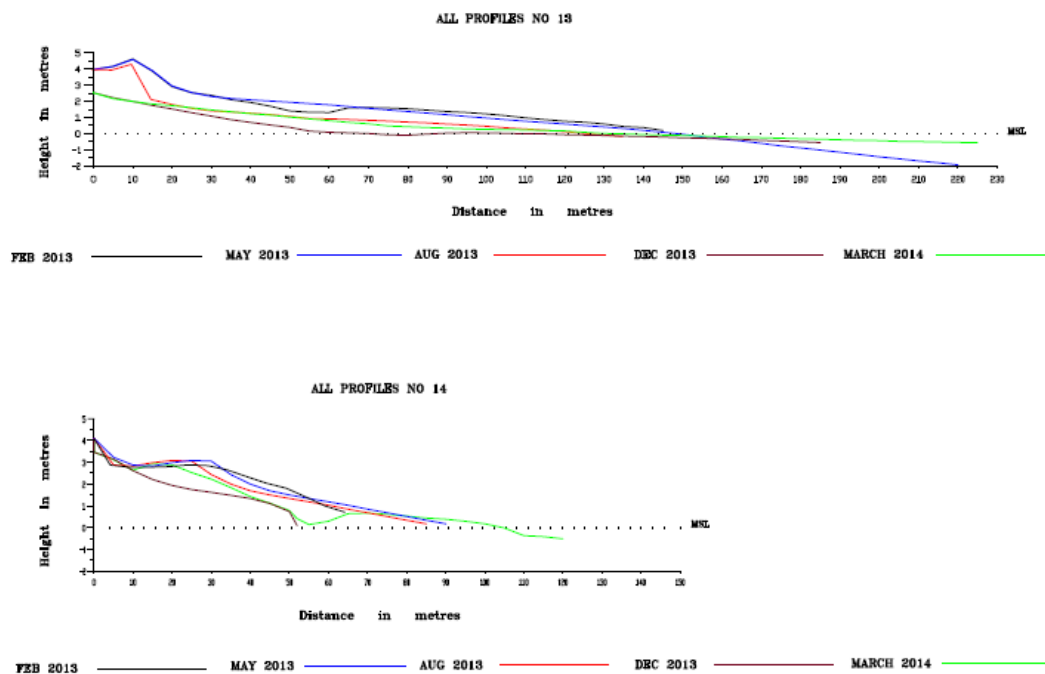


Figure 11 (Sector C, BP 7; Sector D, BP 8)

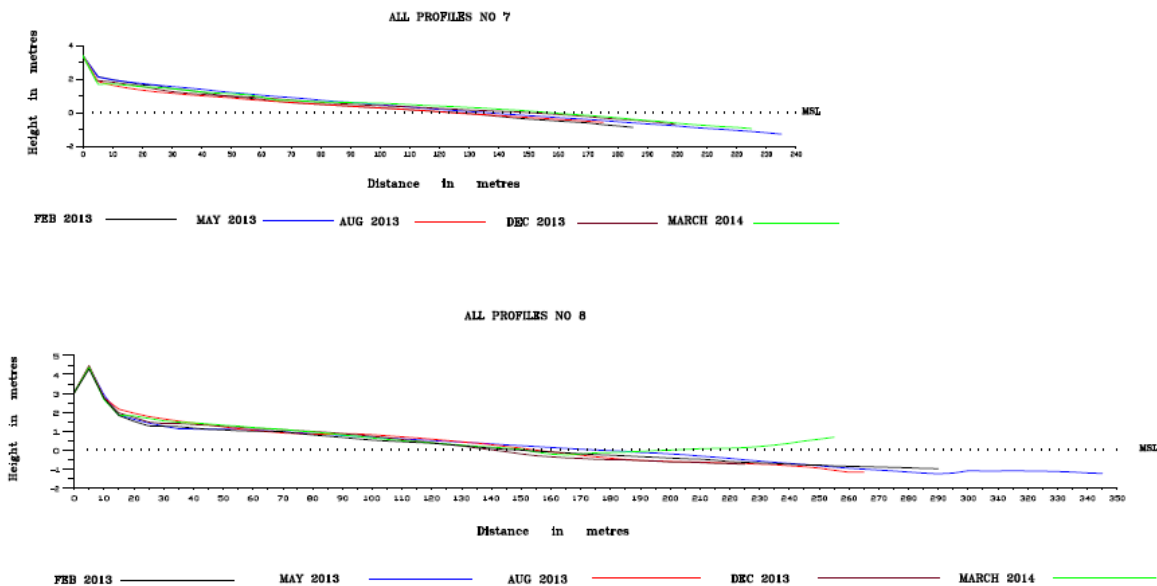


Fig. 11. Representative seasonal beach profiles of the study area.