

## **Quantitative estimation of sediment erosion and accretion processes in a micro-tidal coast**

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### **Abstract**

Spatio-temporal cross-shore profiles and textural characteristics are the key parameters for understanding dynamics of inter-tidal sedimentary environment. The study describes short-term dynamics of inter-tidal sedimentary environment along beaches at micro-tidal coast. Further a correlation is estimated in cross-shore morphodynamics and textural characteristics of surface sediments. The sedimentary environment is examined for a complete annual cycle using monthly collected cross-shore profiles and sediment samples. The Devbag beach (northern side) and Ravindranath Tagore beach (southern side) at Kali river mouth, Karwar, west coast of India are characterized from extremely gentle to average slope, and broadly composed of unimodal sands. The sedimentary environment is significantly composed of textures having fine to medium sand, well to moderately sorted, fine to coarse skewed, and platykurtic to leptokurtic nature. During the annual cycle a reversal pattern is observed between the two adjacent beaches, where a slower rate of sediment accretion is estimated at Devbag beach while Ravindranath Tagore beach exhibited erosion. The beach dynamics along with the propagation of SW and SWW waves towards the coast significantly exhibits a dominance of northward sediment transport with the existence of northerly alongshore current. In addition, the study reveals that eroded beach may not be identified significantly as a composed of coarse grains. The poor correlation in morpho-sedimentary characteristics reveals the prediction of grain characteristics based on beach profile and vice-versa is unrealistic.

**Key words:** Cross shore profile, beach volume, grain size distribution, textural characteristics, wave, Kali estuary.

## 1. Introduction

In view of the immense colonization of inhabitants around coastal regions, shore protection is a significant conscious for developing national economy as well as to build a sustainable environment for human society. Shoreline changes can be described as cyclic instability of beach morphodynamics where the degree of beach stability is directly related to the net result of sediment erosion and accretion. Thus an appropriate knowledge on beach morphodynamics is indispensable for shore protection. Beach morphological changes occur not only by the influence of natural phenomena, but also by human activities (Wilcoxon, 1986; Guillen et al., 1999; Daniel and Abkowitz, 2005; Van Rijn, 2011). Spatio-temporal beach profiles are useful for explaining short-term and long-term erosion/accretion processes (Larson and Kraus, 1994; Cooper et al., 2000). Textural characteristics can be used for describing sedimentary environment, sediment provenance, transport history, depositional conditions and also for differentiating wave energy environments (Folk and Ward, 1957; Friedman, 1961; Nordstrom, 1977; Friedman, 1979; Bui et al., 1989; Samsuddin, 1989; Pedreros et al., 1996; Blott and Pye, 2001; Srinivas and Sajan, 2010). Beach profiles and grain sizes are both essential tools in predicting beach morphodynamics and equilibrium beach profiles (Dean, 1977; Gallagher et al., 2011). Therefore, understanding beach morphodynamics and sedimentary environment becomes a requisite task for designing effective coastal-zone management strategy. Hence, the intertidal textural characteristics along with cross-shore profiles was analyzed simultaneously for a complete annual cycle to understand the intra- and inter-seasonal beach dynamics of two adjacent beaches [Devbag and Ravindranath Tagore (RT)] at Kali river mouth, Karwar, west coast of India (Figure 1).

Figure 1

The earlier studies show a slower rate in the hydro-morpho-sedimentary processes during annual cycles. Veerayya and Pankajakshan (1988) observed both southerly and northerly current patterns, where Chandramohan et al. (1992) was found that a northward alongshore current pattern predominately exists with maximum current speed of 0.24 m/s. Average nearshore current speed off Karwar was 0.2 m/s with a maximum value of 0.6 m/s (Kumar et al., 2012a). Also, Veerayya and Pankajakshan (1988) observed the northern part of Karwar shoreline is significantly influenced by high waves that propagate from south-west (SW) direction. Kumar et al. (2012b) reported the significant wave height off Karwar varied from 0.3 to 3.6 m, where the average wave direction was 238°. A significant seasonal variation in the textural characteristics was found by Nayak and Chavadi (1988), where the sediments were drifting both sides of the Kali river mouth (Nayak, 1996). Also,

Kunte (1994) observed a bi-directional sediment transport for a long stretch of area along the coast, where the net sediment transport was southward. Using satellite data of 13 years (1989 to 2003), Hanamgond and Mitra (2007) found net erosion of sediment along the shoreline, whereas Vinayaraj et al. identified accretion of sediments from 1981 to 1998, and erosion of sediments from 1998 to 2008. During last decades, the satellite data exhibited a net erosion of sediments along the Karwar shoreline, whereas in-situ observation showed a slower rate of sediment accretion at northern part of Kali river mouth and a strong winnowing and accretion of sediment at southern part (Mislankar and Antao, 1992). Following these, Dora et al. (2012) observed an accretion of sediments at Devbag beach for consecutive two years from February 2008 to February 2010. Simultaneous observation of beach profiles, sediment characteristics and waves were not carried out in the past studies along this region. Hence, a field observation was planned for understanding of relative dynamics between these two adjacent beaches of Kali river mouth. Further a correlation was examined in morpho-sedimentary parameters.

## **2. Study area**

Kali estuary is one of the productive estuarine zones along west coast of India, and also a popular tourist place. Kali River drains into Arabian Sea at  $14^{\circ} 50' 35.634''\text{N}$  &  $74^{\circ} 07' 10.625''\text{E}$  to  $14^{\circ} 50' 16.905''\text{N}$  &  $74^{\circ} 07' 31.196''\text{E}$ , and has a width of around 800 m near the coast. Devbag beach covers ~2 km along north part, whereas Ravindranath Tagore (RT) beach runs for ~4 km along south part of Kali river mouth, Karwar. Offshore region of Karwar shoreline contains few small islands named as Kurmagadgudda, Shimisgudda (Sungniri), Devgadgudda, Mandalgudda, Karkaigudda and East Island (NHO, 2008). The domain is in a micro-tidal coast (tidal range < 2 m) and there is no significant backshore zone. During the study period, the lowest low tide and highest high tide level was at -0.16 m and 2.36 m (Indian Tide Table, 2010 and 2011). Study domain is under the influence of three seasons such as pre-monsoon (February to May), monsoon (June to September) and post-monsoon (October to January) where the inter-monsoonal variation can be identified significantly in the wind pattern, precipitation and cloud amount (IMD, 1999).

## **3. Experimental setup and methodology**

Inter-tidal morphodynamics (beach width, slope and volume) were examined by monitoring cross-shore profiles, whereas sedimentary environment was analyzed through textural characteristics such as central tendency (mode, mean, and median), sorting, skewness and kurtosis. Cross-shore profiles and sediment samples were collected in a monthly interval for a complete annual cycle from February 2010 to February 2011. Cross-shore profiles were monitored using a dumpy level and

measuring staff. A total of six benchmarks such as BM1, BM2, BM3, BM4, BM5 and BM6 were selected from north to south along Karwar shoreline with BM3 and BM4 located close to Kali River mouth. Geographic positions (Figure 1) of six selected locations were collected using a DGPS instrument Ceeducer Pro (Brutton International Pty. Ltd., Australia). Base points of the selected benchmarks were located at a distance of 25 m at BM1, 35 m at BM2, 90 m at BM3, 75 m at BM4, 70 m at BM5 and 5 m at BM6 from high tide line (HTL) of the beaches. Cross-shore profiles were monitored from selected benchmarks to low water line at five meter intervals. Overall 78 cross-shore profiles were monitored along six locations with 13 transects at each location (Figure 2). Beach slope ( $\theta$ ) was calculated using a right angle triangle trigonometric formula ( $\sin\theta = \text{Opposite}/\text{Hypotenuse}$ ). Change in beach volume (accretion [+]/erosion [-]) for unit beach length ( $\text{m}^3/\text{m}$ ) was calculated using Beach Morphology Analysis Package (BMAP, 1995) for maximum common beach elevation of two selected beach profiles. Monthly change in beach volume was calculated using monitored cross-shore profiles of two consecutive months whereas annual change in beach volume was calculated using yearly monitored beach profiles. The seasonal change in beach volume was calculated using the profiles monitored in four month intervals. In addition, the surface waves at 7 m water depth off Karwar ( $14^\circ 49' 56'' \text{ N}$  and  $74^\circ 06' 04'' \text{ E}$ ) were measured at 30 minutes interval during 2010 using Datawell directional waverider buoy (Barstow and Kollstad, 1991) for studying the seasonal variation in wave characteristics.

#### Figure 2

Sediment samples were collected at water line (WL), high water line (HWL) and high tide line (HTL) in monthly interval at the selected benchmarks to understand the cross-shore, alongshore and also the inter-seasonal variation of inter-tidal sedimentary environment. A snapshot of sampling points at BM3 is presented in Figure 3. Total of 234 sediment samples were collected along with monitored beach profiles. During the complete annual cycle, there was no change in HTL sampling positions at all six locations, but WL and HWL sampling points varied with respect to time, depending on tidal variation and beach dynamics (erosion/accretion). Grain size distribution of beach sediments was carried out using electromagnetic sieve shaker, which contains six sieves having mesh sizes such as 2000, 1000, 500, 250, 125, 63  $\mu\text{m}$  along with pan, and presented in frequency distribution curve (Figure 3). Statistical parameters such as central tendency (mean, mode and median), sorting, skewness and kurtosis were analyzed by following geometric (modified) Folk and Ward (1957) graphical measures using GRADISTAT - a grain analysis package (Blott and Pye, 2001).

Figure 3

## 4. Results and discussion

### 4.1 Wave characteristics

Waves were more energetic and dynamic during monsoon as compared to the pre-monsoon and post-monsoon (Figure 4). Equal time duration (continuously 45 days) was considered during each season to distinguish the inter-seasonal variation of wave characteristics. Together during pre-monsoon (1<sup>st</sup> February to 17<sup>th</sup> March) and post-monsoon (1<sup>st</sup> October to 14<sup>th</sup> November), the peak wave direction ( $D_p$ ) was found from  $185^\circ$  to  $303^\circ$ , where the average  $D_p$  was  $230^\circ$ . About 87% data was approaching from  $210^\circ$  to  $240^\circ$  indicates a dominance of south-west (SW) waves. The spectral wave energy ( $E_{max}$ ) was up to  $3.81 \text{ m}^2/\text{Hz}$  with an average of  $0.50 \text{ m}^2/\text{Hz}$ , where the  $E_{max}$  was found less than  $1 \text{ m}^2/\text{Hz}$  in 90% of total data. Significant wave height ( $H_{m0}$ ) was found up to 1.05 m, where the average  $H_{m0}$  was 0.53 m. But during monsoon (1<sup>st</sup> June to 15<sup>th</sup> July), the  $D_p$  varied from  $206^\circ$  to  $276^\circ$ , where the average  $D_p$  was  $248^\circ$ . In this period, the south-west-west (SWW) waves ( $240^\circ < D_p < 270^\circ$ ) were dominating to the coast which was found in 79% of total data, where the SW waves were only 20%. The peak  $E_{max}$  was measured at the level of  $17.77 \text{ m}^2/\text{Hz}$ , where the average  $E_{max}$  was  $2.69 \text{ m}^2/\text{Hz}$ . Also more fluctuation was observed in the monsoon waves in which about 31% data was found more than  $3 \text{ m}^2/\text{Hz}$ . The  $H_{m0}$  varied from 0.44 to 3.21 m with an average of 1.32 m, which is similar to the earlier observed data (Kumar et al., 2012b).

The high energetic SWW waves during monsoon influences significantly that approach orthogonally to the west-ward inclined Karwar shoreline whereas during non-monsoon period, SW waves were observed. The dominance of SW waves results northerly alongshore current at the coast which is similar to the observation of Chandramohan et al. (1992). The average significant wave height during monsoon was more than two times that observed during remaining periods whereas in case of spectral energy density that was found five to six times which reflects the roughness of sea surface during monsoon.

Figure 4

### 4.2 Beach Morphodynamics

#### 4.2.1 Beach width and slope

Along Karwar shoreline the beach width showed non-uniform variation during monthly intervals (Table 1). Along Devbag beach, the annual average beach width at BM1, BM2, and BM3 were

respectively 68, 249 and 69 m with mean beach slope of 3.1, 0.9 and 3.8°. Along RT beach, the average beach width at BM4, BM5 and BM6 were respectively 110, 115 and 77 m, where mean beach slope was 2.3, 1.9 and 2.0°. The Devbag beach at BM1 and BM3 varied from moderate (1:33) to average slope (1:20) along with seasonal variation, but at BM2, the beach was identified only as extremely gentle slope (slope < 1:50) due to a sheltered zone of Kurmagadgudda and Shimisgudda islands (Figure 1). During the annual cycle, the RT beach was observed from gentle (1:50) to average slope at BM4, and from gentle to moderate slope at BM5. However, there was no significant change in beach slope at BM6 where the beach was characterized only as moderate slope due to the sheltered zone of Karwar head (Figure 1). Seasonally, there was no significant change in beach width at BM6 as it is protected from wave action by Karwar head, but more variation was found at the remaining five locations. Even though the beach at BM2 is an island sheltered zone, the change in beach width was due to the impact of current on the sediments at lower intertidal zone. A wide beach was found from BM1 to BM5 during pre-monsoon and post-monsoon whereas a narrow beach was identified during the monsoon due to heavy precipitation and river discharge. During the period of 30 years (1951-1980), the average precipitation during monsoon was 2821 mm, whereas it was 185 mm during pre-monsoon, and 204 mm during post-monsoon (IMD, 1999). Also, during the period of four years (2001 to 2004), Raghavan and Chauhan (2012) observed the annual average precipitation of 2534 mm, where high precipitation was measured during June (946 mm), July (631 mm) and August (447 mm). Nigam and Khare (1995) measured the annual average discharge of Kali River as 207 m<sup>3</sup>/s. Coe and Nick (1999) observed the Kali river discharge was high during monsoon compared to pre and post-monsoon and the monthly average discharge was high during July (523 m<sup>3</sup>/s) and August (469 m<sup>3</sup>/s). During the annual cycle, there was no change in beach width at BM1 and an increase of 5 m at BM6 indicated the stability of the beach which are away from river mouth. However beach width decreased by 40 m at BM2, and 10 m at BM3, and also a decrease in beach width was found at BM4 (60 m) and BM5 (25 m). The lower inter-tidal zone of the beaches closer to the river mouth was under erosion due to the river influence. There was no significant change in annual variation of beach slope at all the three locations along Devbag beach where the beach slope slightly increased at BM2 and BM3, but a decreased beach slope was observed at BM1. Along RT beach, the variation of beach slope was gradually decreasing from BM4 to BM6. The annual change in slope at both the beaches also reflects the instability of beaches near river mouth. During the annual cycle, variation of beach slope exhibited dissipative to slightly reflective nature along the Karwar shoreline.

Table 1

#### 4.2.2 Beach volume

Monthly change in beach volume showed non-uniform sediment erosion and accretion processes at all the six locations (Table 2). The beaches at river mouth (BM3 and BM4) and also at extremely gentle slope (BM2) showed significant variation in beach volume due to the combined influence of wave and tidal current. Lorang et al. (1993) had earlier observed more erosion at dissipative beach than reflective beach. Seasonal variation in beach volume change revealed that all the five locations from BM1 to BM5 were eroded during monsoon by SW and SWW high waves (significant wave height > 2 m), but very small quantity of sediments was accreted at BM6 as it is protected by Karwar headland (Figure 1). However during pre and post-monsoon seasons, both the beaches exhibited a non-uniform variation along the selected locations. As the wave intensity was comparatively low during these two seasons, the non-uniform sediment erosion and accretion pattern reflects the variation of current patterns along the shoreline. Annual change in beach volume showed sediment accretion at BM1 and BM2, but beach sediments were winnowed at remaining locations (BM3, BM4, BM5 and BM6). Also, the quantity of winnowed sediment decreased from BM4 to BM6 which exhibits the stability of beaches away from the river mouth. The study revealed that the dissimilar activity at the two adjacent beaches was due to the different nearshore topographic features (Karwar head and Islands). At Devbag beach (average of BM1, BM2 and BM3) more sediment accretion ( $28.23 \text{ m}^3/\text{m}$ ) was observed during November to December and more sediment erosion ( $18.35 \text{ m}^3/\text{m}$ ) during September to October. Simultaneously, the RT beach (average of BM4, BM5 and BM6) showed more sediment accretion ( $22.45 \text{ m}^3/\text{m}$ ) during June to July whereas the beach was eroded extremely ( $71.43 \text{ m}^3/\text{m}$ ) during July to August. Devbag beach sediments were winnowed only during monsoon, whereas the beach accreted during the remaining two seasons. But at RT beach, the sediments were winnowed during all the three seasons. Annual change in beach volume at Devbag beach showed an accretion of sediments ( $11.32 \text{ m}^3/\text{m}$ ) for an average elevation of 3.91 m which is similar to the observation of Mislankar and Antao (1992), and Dora et al. (2012). However at RT beach, erosion of beach sediments ( $31.73 \text{ m}^3/\text{m}$ ) was found for an average elevation of 3.57 m which is similar to the observations of Hanamgond and Mitra (2007) and Vinayaraj et al. (2011). Sediment erosion at southern beach was due to the frequent occurrence of cross-shore currents generated by the orthogonal incident waves. The eroded sediments accrete at nearshore zone, which are then transported northward with predominately existing northern alongshore currents (Chandramohan et al., 1992). Sediment accretion at northern beach was due to the presence of islands at nearshore zone which obstruct the incident waves and hence the source of accreted sediment at northern beach is due to the transport of eroded sediment and also from Kali River. The

erosion at southern beach and accretion at northern beach exhibits a dominance of northward sediment transport along Karwar shoreline. Earlier Nayak (1993) observed that the beach morphodynamical changes are cyclic following the three seasons, whereas the present study revealed that these beaches are not stable significantly. The monthly observation showed that there was both erosion and accretion during all the three seasons which reveals that the analysis of beach profile once in a season may not reflect the changes in inter-tidal sedimentary environment.

Table 2

### 4.3 Beach Sedimentology

#### 4.3.1 Textural characteristics

Textural characteristics such as central tendency, sorting, skewness and kurtosis together describe the activity of sedimentary environments with respect to space and time. Devbag beach was characterized by unimodal (U), bimodal (B) and trimodal (T) sands. Unimodal sand was dominated at all the three locations along WL, HWL and HTL. Less quantity of bimodal sand was found at BM1 and BM3 whereas trimodal sand was identified only at BM3 along WL (Table 3). Primary mode of unimodal sediments was identified with grain diameter of 168.5, 187.5, 318.5, 375.0 and 750.0  $\mu\text{m}$ . Secondary mode (primary mode) in bimodal sediments was identified with 318.5 (750.0), 750.0 (168.5), 750.0 (318.5), 2100 (168.5) and 2075.0  $\mu\text{m}$  (187.5  $\mu\text{m}$ ). In trimodal sediments the tertiary mode was found with 750.0  $\mu\text{m}$  where the secondary and primary mode was 318.5 and 2100.0  $\mu\text{m}$  respectively. Mean grain size varied between 165 and 599  $\mu\text{m}$  with an average value of 251  $\mu\text{m}$  where median ( $D_{50}$ ) was between 161 and 658  $\mu\text{m}$  with an average value of 249  $\mu\text{m}$ . The gentle beach at island sheltered zone (BM2) showed fine sand (Fs) significantly as the location frequently interacts with only low wave activities. But the beach at BM1 and BM3 showed both fine and medium sands (Ms) along with few quantity of coarse sand (Cs) by interacting SW and SWW waves. Further, the medium sand along with few quantity of coarse sand was found along WL due to the impact of breaking waves whereas fine sand (Fs) exceeded the medium sand along HWL. Along HTL, more quantity of fine sands were found at BM1 and BM2, but a significant quantity of medium sand was identified at BM3 due to steeper slope. Earlier Bryant (1982) observed the coarser particle at steeper slope is due to the influence of gravity effect. Klein et al. (2005) observed fine sand at dissipative beach whereas the reflective beach showed coarser grains. Imhansoloeva et al. (2011) observed the high current and strong wave energy are responsible for beach grain size distribution. Sorting of beach sediments varied from 1.26 to 2.48  $\mu\text{m}$  with an average value of 1.57  $\mu\text{m}$ , and characterized by very well sorted (VWS) to poorly sorted (PS). Along the three locations, maximum



sediment samples showed moderately well sorted (MWS) to moderately sorted (MS) nature whereas poorly sorted (PS) sediment was identified at BM3 along WL during monsoon. While Hegde et al. (2007) had observed better sorted sediments with the result of high waves during monsoon. Beach sediments at BM1 and BM3 were characterized by well sorted (WS) to PS, whereas the sediments at BM2 were varying from VWS to MS. During monsoon, high waves were not reaching the BM2 location due to the presence of islands within 1 to 2 km from the shoreline and due to diffraction predominantly longshore current were generated. Hence comparatively more quantity of better sorted sediments was observed at BM2 during monsoon. On moving gradually from WL to HTL, the WS sediment was exceeding PS which exhibits role of alongshore current on sorting of beach sediments. Blackley and Heathershaw (1982) also observed that waves and tidal current significantly affect the sorting of sediments at wide surf zone beaches. Beach sediments were characterized by very fine skewed (VFSk) to very coarse skewed (VCSk) which were varying from -0.25 to 0.40 with an average value of 0.03 indicating very slower rate in the accretion of finer particles. Kurtosis value of beach sediments varied from 0.68 to 1.78 with an average value of 0.98 and found to be platykurtic (P) to very leptokurtic (VL) nature. The present study and the earlier two years observation (Dora et al., 2012) showed that at Devbag beach, the quantity of fine sand was gradually increasing. It revealed that the Devbag beach was under slower rate of sediment accretion which is similar to the results that obtained from cross-shore profiles. But there was no significant variation in other characteristics of beach sediments due to the slower rate of sediment dynamics.

Table 3

At RT beach, the sediments were characterized by unimodal and bimodal sands whereas the beach was dominated by unimodal sand at all three locations (BM4, BM5 and BM6). Primary mode of beach sediments was identified with grain diameter of 168.5, 187.5, 318.5 and 375.0  $\mu\text{m}$ . In bimodal sediments the secondary mode (primary mode) was identified with 750.0 (168.5) and 750.0  $\mu\text{m}$  (318.5  $\mu\text{m}$ ). Mean grain size varied from 140 to 344  $\mu\text{m}$  with an average value of 229  $\mu\text{m}$ , where median ( $D_{50}$ ) was found in a range of 151 to 344  $\mu\text{m}$  with an average value of 228  $\mu\text{m}$ . At the three locations, the quantity of fine sand exceeded the medium sand significantly. But quantity of medium sand along WL was higher than that found along HWL as that observed at Devbag beach. Quantity of fine and medium sand along HTL vary spatially and temporally depending on beach slope and also due to beach recreation by local society which was observed during sampling period. An increased quantity of fine sand was found from BM4 to BM6 along WL, HWL and also HTL, where quantity of medium sand decreased (Table 4). This indicates the influence of wave action along Karwar shoreline is gradually decreasing away from Kali river mouth. Beach sediments were

characterized by very well sorted to poorly sorted, and varied from 1.26 to 2.42  $\mu\text{m}$  with an average value of 1.56  $\mu\text{m}$ . At BM5, more quantity of poorly and moderately sorted sediments along with less quantity of well sorted sediments was found due to the direct influence of waves on the coast. The well sorted sediments at BM4 were observed due to tidal current and that at BM6 was due to calm wave condition. Comparatively more quantity of well sorted sediments was found along HWL and HTL, whereas the sediments along WL showed poorly and moderately sorted in nature. Prospathopoulos et al. (2004) also observed very good sorting in backshore sediments where poorly sorted sediments were identified in the surfzone. Skewness of beach sediments was characterized by very fine skewed to very coarse skewed and varied from -0.35 to 0.31 with an average value of 0.01. During monsoon, quantity of coarse skewed sediment was more at RT beach (49%) compared to Devbag beach (23%) due to direct approach of waves which reveal removal of finer particles by high wave condition. Earlier Friedman (1961) had also observed strongly fine skewed and fine skewed sediment implying introduction of fine material or removal of coarser fraction. In addition sediments were characterized by platykurtic to very leptokurtic nature where kurtosis value varied from 0.74 to 2.32 with an average value of 1.03. The quantity of platykurtic sediment exceeded leptokurtic sediment from WL to HTL. Along WL at BM5, a significant quantity of very leptokurtic sediment was observed along with platykurtic where the leptokurtic sediment was absent. It showed an instant accretion and erosion of finer particles as a result of direct approach of waves. But at BM4 and BM6, a sequential change in the quantity of kurtosis from platykurtic to very leptokurtic revealed a gradual change in wave activity.

Table 4

#### 4.3.2 Sedimentary environment

Monthly collected sediment samples showed a complex trend in a marginal range in their textural characteristics at all the locations. A random change in textural characteristics along WL and HWL showed the variation of nearshore hydrodynamics along Karwar shoreline. Variation in textural characteristics along HTL was due to the human activity (movement of fishing boats at BM1, construction of revetments at BM1 and BM3 and recreation at BM5 and BM6), and also heavy precipitation (IMD, 1999) during the monsoon. Net result showed both beaches were dominated by unimodal sediments (90% at Devbag beach and 94% at RT beach). A considerable quantity of fine and medium sand was found at both the beaches. Fine and medium sand at Devbag beach were 58 and 40% whereas those at RT beach were 73 and 27%. Nayak and Chavadi (1988) and Nayak (1993) also revealed fine to medium sand significantly at both the beaches. During the annual cycle, sorting

characteristics were almost similar at both the beaches whereas Nayak (1996) observed better sorted sediments at the northern beach of Kali river mouth compared to the southern beach.

Both beaches were dominated by moderately well sorted sediments along with an appearance of moderately sorted and well sorted. About 63% of moderately well sorted sediment was found at Devbag beach whereas RT beach was characterized by 67% of total sediment samples. During the early decades, Chaudhri et al. (1981) characterized the beach sediments along west coast of India as moderately sorted to moderately well sorted. Both beaches were found with approximately equal activities of skewness and kurtosis characteristics. At Devbag beach, the sediments were characterized by fine skewed (29%), symmetrical (31%) and coarse skewed (36%) sediments, and at RT beach those were 29, 34 and 36%. Remaining sediment samples were identified as very fine skewed and very coarse skewed in nature. Even though the RT beach sediments were eroded, and Devbag beach was found as accretion of sediments, both the beaches showed same quantity of fine skewed and coarse skewed sediments. This indicated a slower rate of sediment erosion and accretion process during annual cycle at both the beaches. Duane (1964) observed less positive skewed samples along with more negative skewed indicate a beach was undergoing erosion or non-deposition. Devbag beach sediments showed 44% of platykurtic, 33% of mesokurtic and 22% of leptokurtic sediment whereas at RT beach those were about 44, 35 and 16% respectively along with few quantities of very leptokurtic sediment. During the annual cycle, the statistical parameters of beach sediments except mean grain size showed approximately same quantity at both the beaches (Figure 5). In addition, the study results reveal that the cross-shore and alongshore variation of textural characteristics along the Karwar shoreline are highly dependent on topographic features.

Figure 5

#### 4.4 Morpho-sedimentary correlation

Linear correlation between monthly change in cross-shore morphodynamics such as beach width, slope and volume was obtained at six selected locations along Karwar shoreline. Change in beach width (CBW) and change in beach slope (CBS) showed a negative and strong ( $R^2 > 0.7$ ) correlation from BM1 to BM5, whereas it was negative and moderate ( $0.5 < R^2 < 0.7$ ) at BM6, which indicates a significant sediment accretion and/or erosion at lower intertidal zone along the shoreline except at the extremely southern part (BM6) of RT beach. Also, in case of change in beach slope (CBS) versus change in beach volume (CBV), the correlation was estimated from poor ( $R^2 < 0.3$ ) to moderate, but it was positive at BM1 and negative at the remaining locations (BM2 to BM6). Further, at BM1, a negative and poor correlation was identified between CBV and CBW, whereas it was positive and

varied from poor to moderate at the remaining locations. No strong negative correlation in CBS versus CBV, and no strong positive correlation in CBV versus CBW reveal sediment erosion and/or accretion at middle and upper intertidal zone along with lower inter-tidal zone. Among the six locations, the island sheltered dissipative zone (BM2) showed comparatively good correlation in all the three cases which indicate uniform change in cross-shore profiles, whereas a non-uniform variation was observed at the remaining locations. Furthermore, correlation was obtained between consecutive locations with respect to monthly change in beach width, slope and volume individually. A negative, but poor correlation was observed between BM3 and BM4 with respect to both CBW and CBS, whereas correlation was positive and varied from poor to moderate at the remaining consecutive locations. With respect to CBV, a negative and mild ( $0.3 < R^2 < 0.5$ ) correlation was found only in BM1 versus BM2, whereas remaining consecutive locations showed positive correlation and varied from poor to mild. With respect to all the three parameters, there was neither negative nor positive strong correlation between the consecutive locations which revealed the existence of both cross-shore and alongshore sediment transport. Turker and Kabdasli (2007) observed that cross-shore sediment transport affects beach profile significantly.

#### Table 5

A poor correlation was found between the textural characteristics of beach sediments which are similar to the earlier study (Dora et al., 2011). Earlier researchers (Anwar et al., 1979; Finkelstein, 1982; McLaren and Bowles, 1985; Edwards, 2001) observed that fine sands were well sorted and negative skewed whereas present analysis also showed similar results, but not significantly. This study exhibited the finer sands to be leptokurtic nature whereas coarser sands were platykurtic (Figure 6). A poor correlation was obtained between beach slope and textural characteristics. The beaches having equal slope exhibited different mean grain size where a particular grain size was found at different beach slope which results a “many to one” relation i.e., along with the beach slope there are many external agents responsible simultaneously in variation of grain size. Klein et al. (2005) found a positive relation between beachface slope and grain size, whereas Reis and Gama (2010) observed beachface slope varies proportional to mean grain size raised to the power 4/3. Present analysis shows that a unique relation between beach slope and grain size cannot be derived for all types of beaches. Further textural characteristics along with beach erosion/accretion exhibited poor correlation although Medina et al. (1994) had identified a strong correlation between textures and beach profile. This study revealed both finer and coarser particles significantly during erosion as well as accretion conditions. However, Cin (1976) had found that the eroded beach was significantly composed of coarse sand, and Anwar et al. (1979) had identified coarser particles on the accreted

sands. Lakshmi et al. (2010) found positive skewed sediments at deposited beach whereas present analyses showed positive to negative skewed sediments along with depositional condition. These analyses exhibited that the textural characteristics of beach sediments are a combined result of both beach morphology and nearshore hydrodynamics which are non-linearly correlated with each other.

Figure 6

## 5. Conclusion

Beach morpho-sedimentary dynamics along with nearshore wave activity showed closer resemblance to earlier observations made during the last few decades. Present study reveals that the dynamics of inter-tidal cross-shore profiles and textural characteristics along two adjacent beaches at Kali river mouth are neither intra-seasonal nor inter-seasonal due to dissimilar feature of the nearshore topography, even though the nearshore wave follows the inter-seasonal variation. The study showed that the inter-tidal sedimentary environment is significantly composed of fine to medium sand, well to moderately sorted, fine to coarse skewed, and platykurtic to leptokurtic nature, where both the beaches are predominantly unimodal sands. During the annual cycle, study estimated a slower rate of sediment accretion at Devbag beach, which is having extremely gentle to average slope whereas sediments eroded at Ravindranath Tagore beach, which is having the slope between gentle to average. Dominance of SW and SSW waves in the study domain indicates a significant existence of northerly alongshore current. The eroded southern beach and accreted northern beach indicates a northward sediment transport along the Karwar shoreline. Although the sediments were eroded at Ravindranath Tagore beach, more quantity of fine sand was identified whereas accreted sediment at Devbag beach was characterized by fine and medium sands significantly. In addition, a non-linear correlation is estimated between cross-shore profile and textural characteristics. Hence, it suggests that the analysis of beach surface sediment along with cross-shore profile is essential whereas the prediction of grain characteristics based on monitored beach profiles and vice-versa is unrealistic.

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Table 1: Monthly measure beach widths and slopes

Month and year	Devbag beach						K A L I R I V E R M O U T H	Ravindranath Tagore beach					
	BM1		BM2		BM3			BM4		BM5		BM6	
	Beach width (m)	Beach slope (degree)	Beach width (m)	Beach slope (degree)	Beach width (m)	Beach slope (degree)		Beach width (m)	Beach slope (degree)	Beach width (m)	Beach slope (degree)	Beach width (m)	Beach slope (degree)
Feb-2010	70	3.5	265	0.8	75	3.3	R	135	1.8	125	1.8	70	2.2
Mar-2010	55	4.0	225	0.9	70	3.7	I	100	2.1	115	1.9	70	2.3
Apr-2010	60	3.7	270	0.8	65	3.8	V	90	2.5	115	1.9	65	2.2
May-2010	70	3.0	285	0.8	55	4.7	E	145	1.6	115	1.8	70	2.3
Jun-2010	75	2.9	275	0.8	75	3.4	R	145	1.7	120	1.8	75	2.2
Jul-2010	70	2.8	275	0.8	60	4.1	M	145	1.7	130	1.6	95	1.6
Aug-2010	40	4.7	195	1.1	50	4.9	O	60	3.5	95	2.1	80	1.8
Sep-2010	75	2.1	245	0.9	75	3.5	U	70	3.4	95	2.4	75	1.8
Oct-2010	80	2.4	220	1.0	45	5.6	T	130	2.0	145	1.6	90	1.7
Nov-2010	80	2.4	260	0.8	90	3.0	H	105	2.4	105	2.0	80	1.9
Dec-2010	70	2.7	260	0.8	95	2.6		135	1.9	140	1.6	85	1.9
Jan-2011	65	3.1	235	0.9	75	3.5		100	2.4	95	2.4	75	2.2
Feb-2011	70	3.2	225	0.9	65	3.7		75	3.2	100	2.2	75	2.2

Table 2: Monthly change in beach volume (m<sup>3</sup>/m)

Time Duration	Devbag beach						Ravindranath Tagore beach					
	BM1		BM2		BM3		BM4		BM5		BM6	
	Beach Elevation	Change in volume	Beach Elevation	Change in volume	Beach Elevation	Change in volume	Beach Elevation	Change in volume	Beach Elevation	Change in volume	Beach Elevation	Change in volume
Monthly												
Feb-Mar	3.86	-1.42	3.57	-6.38	4.33	-7.71	3.69	+15.02	3.74	+1.22	2.64	-16.81
Mar-Apr	3.83	+21.49	3.57	+37.35	4.32	-30.20	3.69	-12.03	3.74	+3.18	2.55	+2.62
Apr-May	3.72	+8.66	3.75	-9.54	4.32	-35.22	3.89	-25.55	3.68	+5.82	2.55	-5.02
May-Jun	3.72	+7.73	3.77	+6.10	4.49	+40.15	4.17	+11.54	3.68	+20.04	2.82	+0.76
Jun-Jul	3.43	-42.90	3.70	+28.78	4.29	-13.81	4.26	+81.49	3.76	-25.06	2.61	+10.91
Jul-Aug	3.30	+28.06	3.67	-51.65	4.29	-11.03	3.28	-123.66	3.48	-67.29	2.53	-23.35
Aug-Sep	2.81	-19.63	3.67	+52.51	4.30	+13.64	3.28	+20.39	3.48	+22.01	2.35	+6.27
Sep-Oct	2.81	+19.98	3.74	-65.36	4.40	-9.68	4.17	+21.11	3.90	+16.24	2.35	+6.56
Oct-Nov	3.33	-13.00	3.77	+41.55	4.40	+16.64	4.32	-21.98	3.72	+1.35	2.66	-6.65
Nov-Dec	3.33	-7.70	3.67	+55.63	4.39	+36.76	4.32	+40.34	3.72	+9.27	2.66	+16.26
Dec-Jan	3.35	-6.34	3.67	-16.66	4.39	-13.98	4.26	-23.94	3.92	-11.52	2.86	-23.03
Jan-Feb	3.50	+6.78	3.68	-40.56	4.14	+3.50	4.25	-3.86	3.89	+7.782	2.85	+7.07
Seasonally												
Pre-monsoon	3.85	+38.51	3.73	+28.25	4.33	-34.62	4.18	-10.83	3.81	+29.61	2.64	-19.48
monsoon	3.35	-2.07	3.77	-36.52	4.40	-20.24	4.26	-26.63	3.81	-57.81	2.69	+2.20
Post-monsoon	3.35	-21.54	3.68	+39.24	4.14	+43.39	4.25	-11.50	3.89	+2.45	2.69	-6.33
Annually												
Yearly	3.90	+13.32	3.68	+31.98	4.14	-11.34	4.18	-47.32	3.89	-24.86	2.64	-23.02

Note: Accretion (+), Erosion (-)

Table 3: Textural classification (%) of surface sediments collected at Devbag beach

Characteristics and behaviours		Range	BM1			BM2			BM3		
			WL	HWL	HTL	WL	HWL	HTL	WL	HWL	HTL
Mode	Unimodal (U)	-	77	100	100	100	100	100	62	85	62
	Bimodal (B)	-	23	0	0	0	0	0	30	15	38
	Trimodal (T)	-	0	0	0	0	0	0	8	0	0
Mean ( $\mu\text{m}$ )	Fine sand (Fs)	125 to 250	38	69	62	85	92	77	38	69	8
	Medium sand (Ms)	250 to 500	62	31	38	15	8	23	46	31	92
	Coarse sand (Ts)	500 to 1000	0	0	0	0	0	0	16	0	0
Sorting ( $\mu\text{m}$ )	Very Well Sorted (VWS)	< 1.27	0	0	0	0	0	8	0	0	0
	Well Sorted (WS)	1.27 to 1.41	0	23	15	0	0	30	8	15	15
	Moderately Well Sorted (MWS)	1.41 to 1.62	38	54	85	77	92	54	46	70	54
	Moderately Sorted (MS)	1.62 to 2.00	54	15	0	23	8	8	15	15	31
	Poorly Sorted (PS)	2.00 to 4.00	8	8	0	0	0	0	31	0	0
Skewness	Very Fine Skewed (VFSk)	-1.0 to -0.3	0	0	0	0	0	0	8	0	0
	Fine Skewed (FSk)	-0.3 to -0.1	8	38	46	24	31	31	23	15	39
	Symmetrical (S)	-0.1 to +0.1	62	31	16	38	38	15	31	31	15
	Coarse Skewed (CSk)	+0.1 to +0.3	22	31	38	38	31	46	23	46	38
	Very Coarse Skewed (VCSk)	+0.3 to +1.0	8	0	0	0	0	8	15	8	8
Kurtosis	Platykurtic (P)	0.67 to 0.90	31	46	69	31	46	23	54	54	54
	Mesokurtic (M)	0.90 to 1.11	46	38	23	31	16	62	15	23	31
	Leptokurtic (L)	1.11 to 1.50	15	8	8	38	38	15	31	23	15
	Very Leptokurtic (VL)	1.50 to 3.00	8	8	0	0	0	0	0	0	0

Table 4: Textural classification (%) of surface sediments collected at RT beach.

Characteristics and behaviours		Range	BM4			BM5			BM6		
			WL	HWL	HTL	WL	HWL	HTL	WL	HWL	HTL
Mode	Unimodal (U)	-	85	92	85	100	92	100	77	100	100
	Bimodal (B)	-	15	8	15	0	8	0	23	0	0
	Trimodal (T)	-	0	0	0	0	0	0	0	0	0
Mean ( $\mu\text{m}$ )	Fine sand (Fs)	125 to 250	62	77	38	69	85	54	85	92	77
	Medium sand (Ms)	250 to 500	38	23	62	31	15	46	15	8	23
	Coarse sand (Cs)	500 to 1000	0	0	0	0	0	0	0	0	0
Sorting ( $\mu\text{m}$ )	Very Well Sorted (VWS)	< 1.27	0	0	0	0	0	0	0	0	8
	Well Sorted (WS)	1.27 to 1.41	15	8	23	0	8	15	0	31	23
	Moderately Well Sorted (MWS)	1.41 to 1.62	62	69	77	69	54	85	69	46	69
	Moderately Sorted (MS)	1.62 to 2.00	23	23	0	8	38	0	23	23	0
	Poorly Sorted (PS)	2.00 to 4.00	0	0	0	23	0	0	8	0	0
Skewness	Very Fine Skewed (VFSk)	-1.0 to -0.3	0	0	0	0	8	0	0	0	0
	Fine Skewed (FSk)	-0.3 to -0.1	31	15	38	46	15	31	23	23	31
	Symmetrical (S)	-0.1 to +0.1	46	31	31	31	31	31	46	46	31
	Coarse Skewed (CSk)	+0.1 to +0.3	23	54	31	23	38	38	31	31	38
	Very Coarse Skewed (VCSk)	+0.3 to +1.0	0	0	0	0	8	0	0	0	0
Kurtosis	Platykurtic (P)	0.67 to 0.90	38	46	23	47	38	46	46	31	62
	Mesokurtic (M)	0.90 to 1.11	31	38	54	15	31	46	23	38	38
	Leptokurtic (L)	1.11 to 1.50	23	16	23	0	23	8	31	31	0
	Very Leptokurtic (VL)	1.50 to 3.00	8	0	0	38	8	0	0	0	0

Table 5: Linear correlation (R2) in the dynamics of width, slope and volume

Linear correlation between the monthly change in morphodynamics along different locations					
Location	Width vs Slope		Slope vs Volume		Volume vs Width
Devbag beach					
BM1	0.90 <sup>(-)</sup>		0.19 <sup>(+)</sup>		0.06 <sup>(-)</sup>
BM2	0.94 <sup>(-)</sup>		0.65 <sup>(-)</sup>		0.55 <sup>(+)</sup>
BM3	0.96 <sup>(-)</sup>		0.40 <sup>(-)</sup>		0.39 <sup>(+)</sup>
Ravindranath Tagore beach					
BM4	0.94 <sup>(-)</sup>		0.37 <sup>(-)</sup>		0.33 <sup>(+)</sup>
BM5	0.92 <sup>(-)</sup>		0.18 <sup>(-)</sup>		0.25 <sup>(+)</sup>
BM6	0.65 <sup>(-)</sup>		0.46 <sup>(-)</sup>		0.44 <sup>(+)</sup>
Linear correlation between the locations with respect to change in morphodynamic parameters					
Parameter	Devbag beach		Kali River mouth	Ravindranath Tagore beach	
	BM1 vs BM2	BM2 vs BM3	BM3 vs BM4	BM4 vs BM5	BM5 vs BM6
Width	0.60 <sup>(+)</sup>	0.30 <sup>(+)</sup>	0.01 <sup>(-)</sup>	0.58 <sup>(+)</sup>	0.62 <sup>(+)</sup>
Slope	0.68 <sup>(+)</sup>	0.47 <sup>(+)</sup>	0.04 <sup>(-)</sup>	0.45 <sup>(+)</sup>	0.30 <sup>(+)</sup>
Volume	0.36 <sup>(-)</sup>	0.13 <sup>(+)</sup>	0.07 <sup>(+)</sup>	0.34 <sup>(+)</sup>	0.30 <sup>(+)</sup>

Note: Directly proportional (+), Inversely proportional (-)

## Figure Captions

Figure 1: Study area shows waverider buoy position and six sampling locations (BM1, BM2, BM3, BM4, BM5 and BM6) at two adjacent beaches (Devbag and RT beach) of Kali river mouth, Karwar, west coast of India.

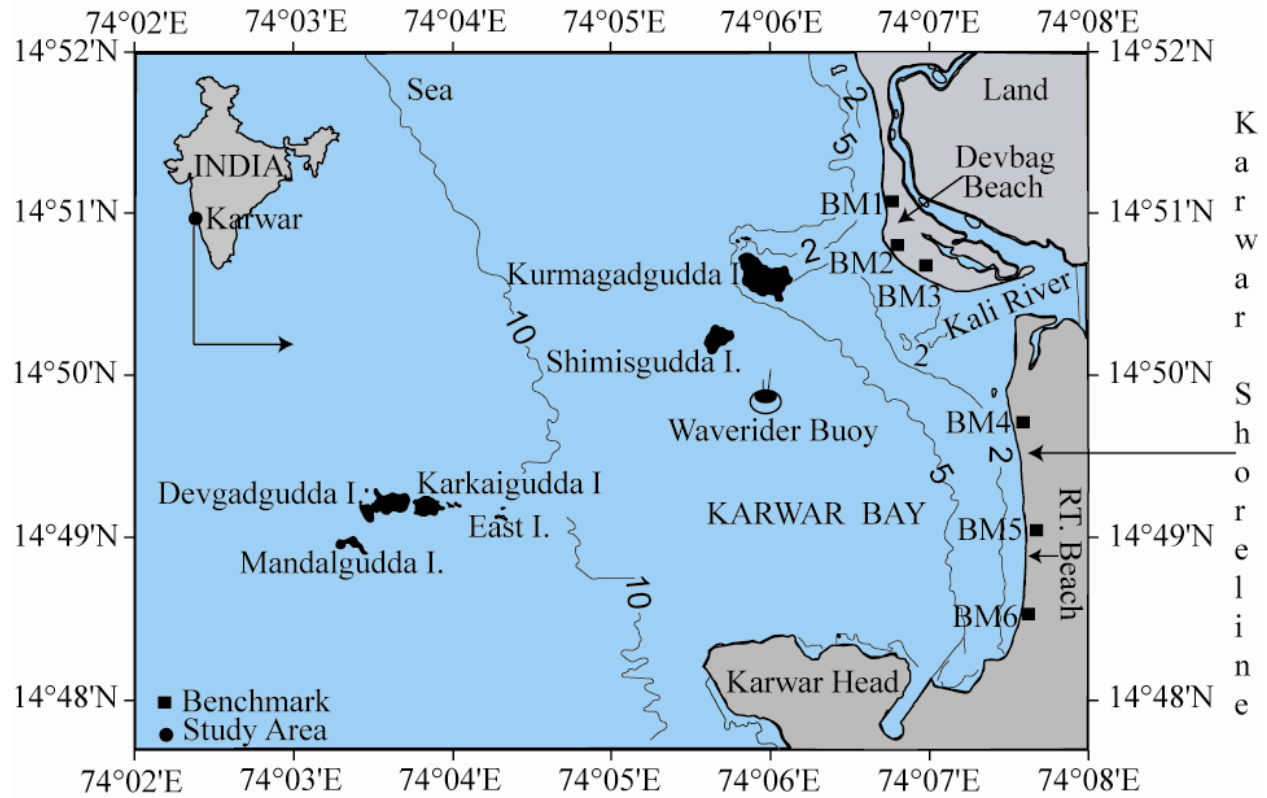
Figure 2: Monthly monitored cross-shore profiles at six locations of the two beaches along Karwar shoreline.

Figure 3: Frequency distribution of monthly collected sediment samples at six locations of the two beaches along Karwar shoreline.

Figure 4: Seasonal variation of spectral peak wave direction ( $D_p$ ), wave energy ( $E_{max}$ ) and significant wave height ( $H_{m0}$ ) at ~7 m water depth off Karwar shoreline.

Figure 5: Net activities in textural characteristics of inter-tidal surface sediments during February 2010 to February 2011.

Figure 6: Bivariate plots among textural characteristics, and morpho-sedimentary parameters.



Geographic Positions

BM1	BM2	BM3
14° 51' 15.12"N	14° 50' 52.98"N	14° 50' 39.94"N
74° 06' 42.27"E	74° 06' 44.64"E	74° 06' 56.24"E
BM4	BM5	BM6
14° 49' 44.97"N	14° 49' 03.25"N	14° 48' 32.70"N
74° 07' 30.80"E	74° 07' 37.78"E	74° 07' 30.64"E

Figure 1: Study area shows waverider buoy position and six sampling locations (BM1, BM2, BM3, BM4, BM5 and BM6) at two adjacent beaches (Devbag and RT beach) of Kali river mouth, Karwar, west coast of India.



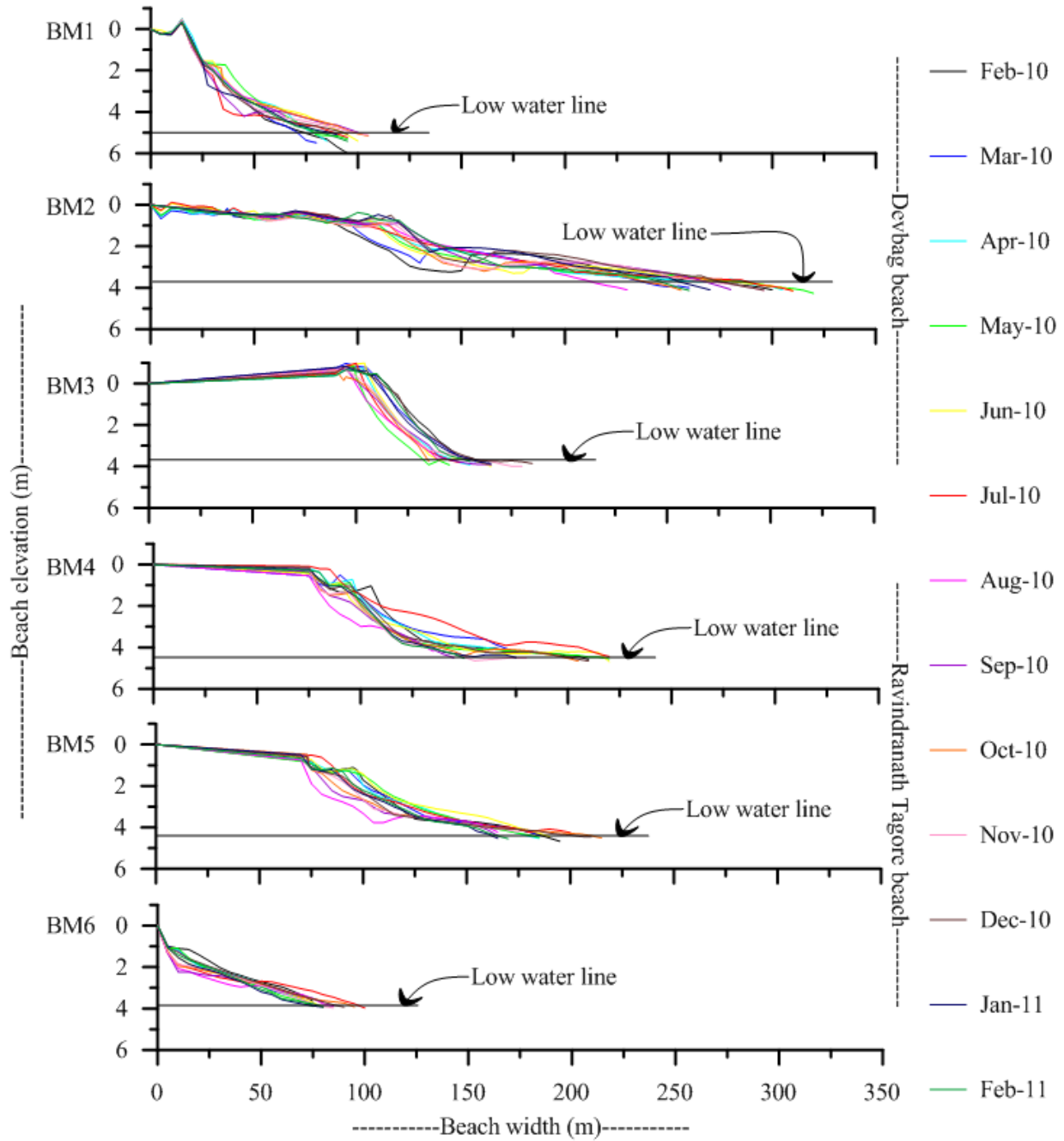


Figure 2: Monthly monitored cross-shore profiles at six locations of the two beaches along Karwar shoreline.

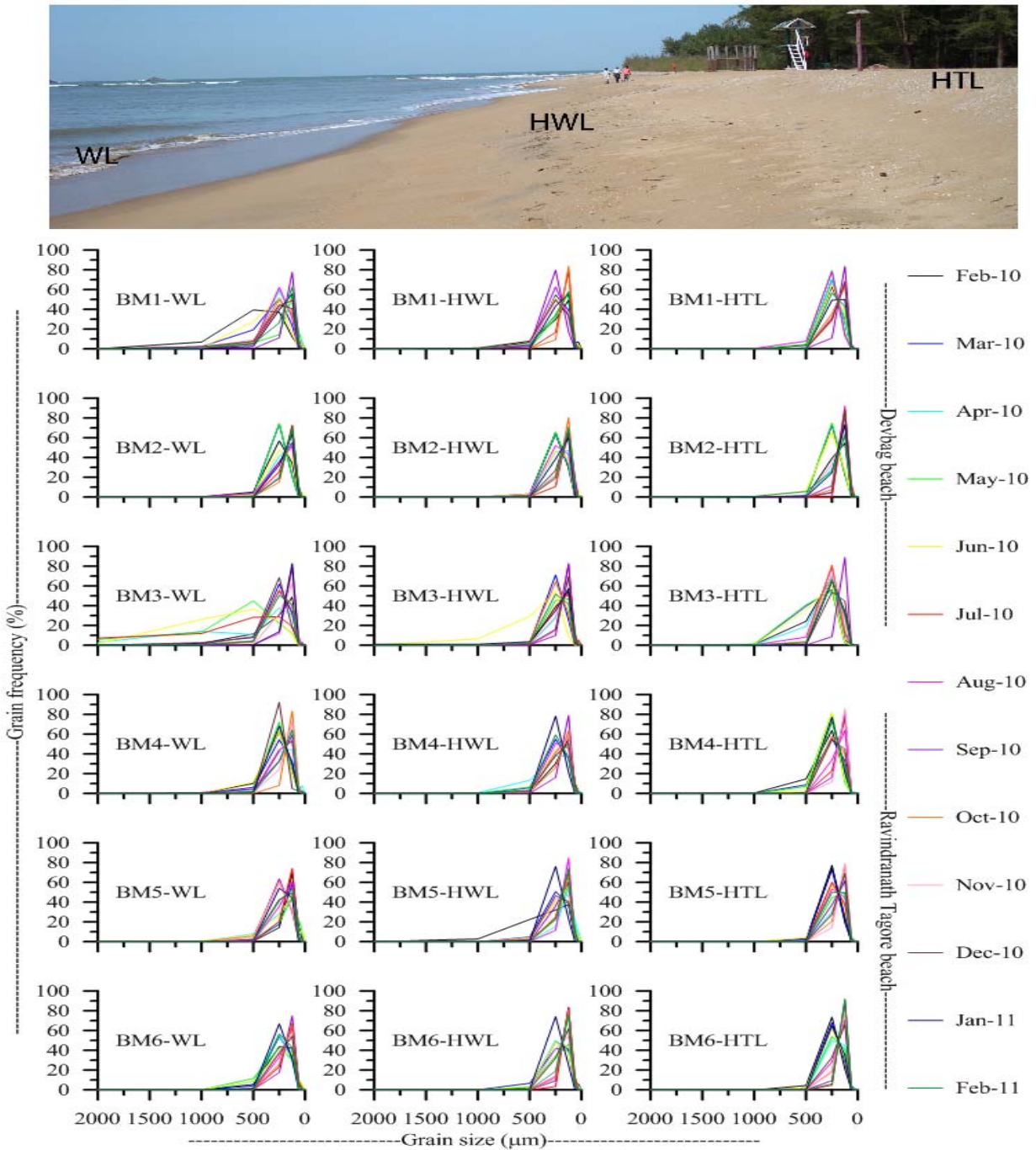


Figure 3: Frequency distribution of monthly collected sediment samples at six locations of the two beaches along Karwar shoreline.

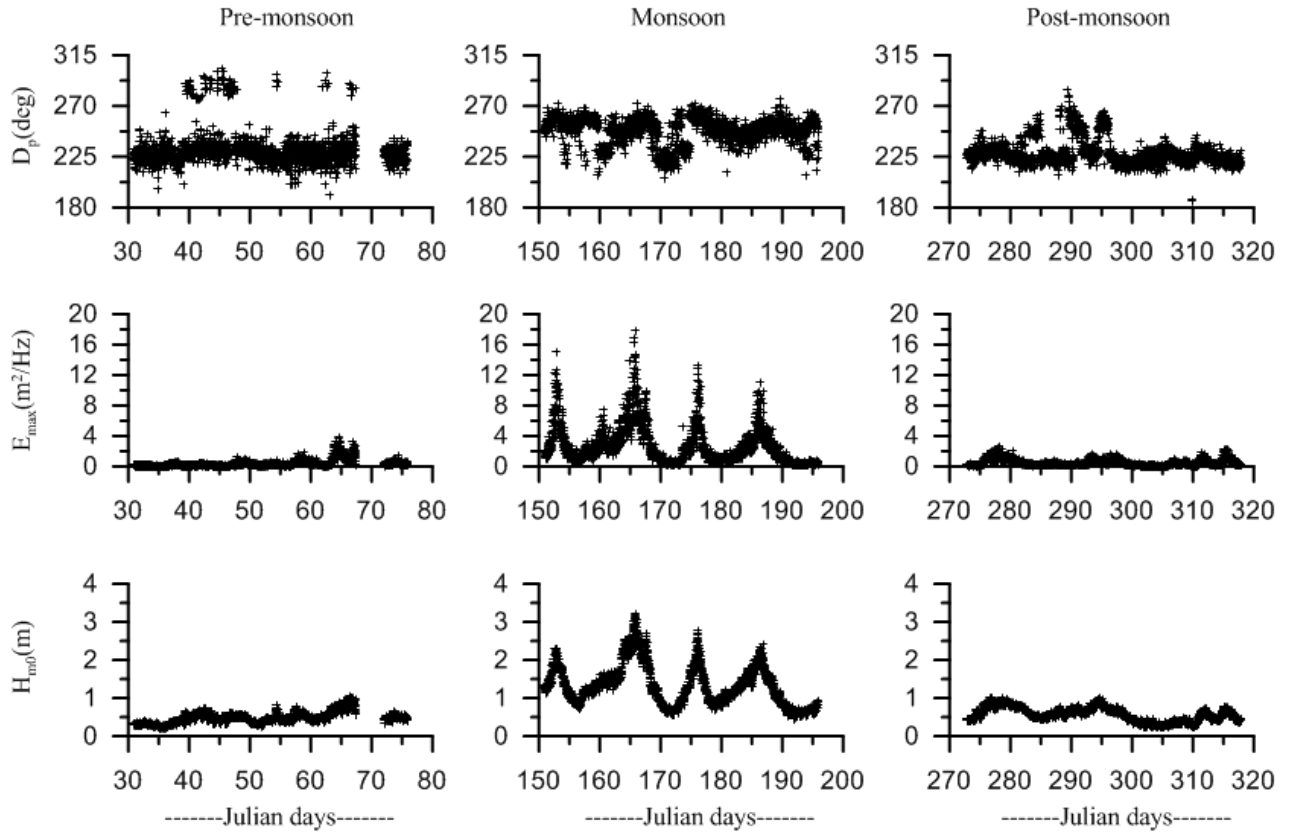


Figure 4: Seasonal variation of spectral peak wave direction ( $D_p$ ), wave energy ( $E_{max}$ ) and significant wave height ( $H_{m0}$ ) at  $\sim 7$  m water depth off Karwar shoreline.

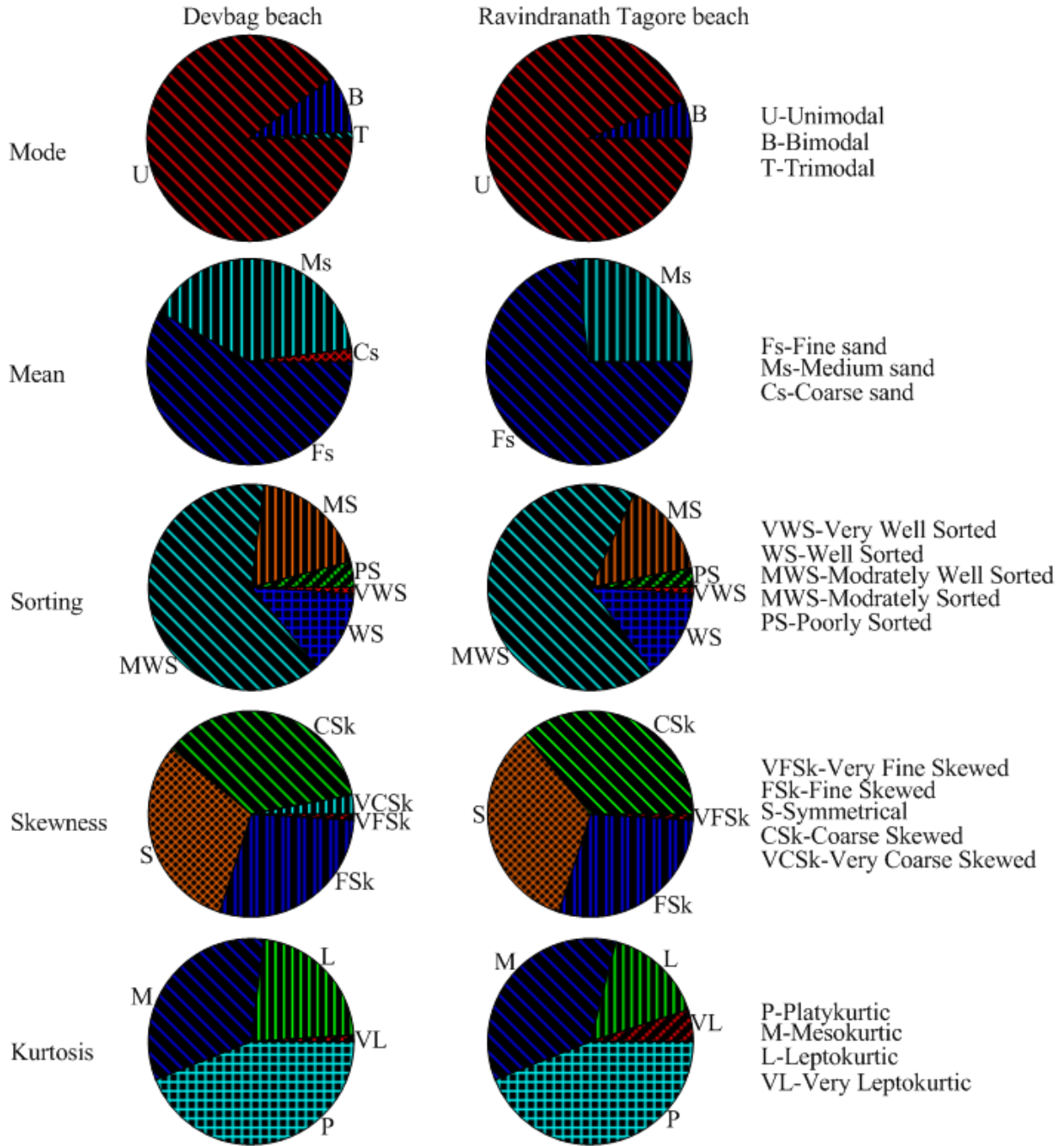


Figure 5: Net activities in textural characteristics of inter-tidal surface sediments during February 2010 to February 2011.

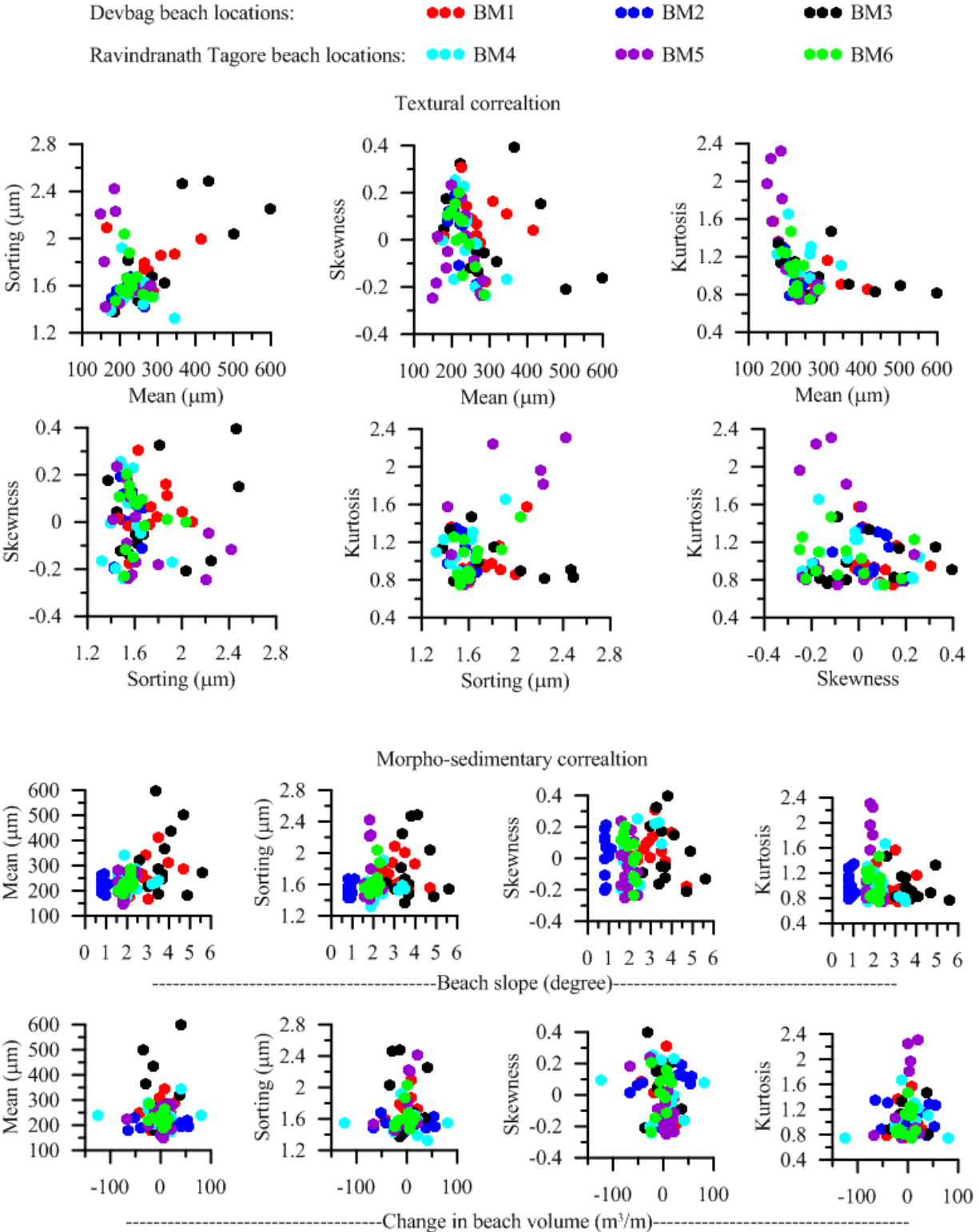


Figure 6: Bivariate plots among textural characteristics, and morpho-sedimentary parameters.