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Observation on foreshore morphodynamics of microtidal sandy beaches

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Foreshore morphology and morphodynamics were examined to identify stability of two microtidal sandy beaches, Kundapura and Padukare, along the Karnataka shoreline on the west coast of India during three annual cycles from March 2008 to March 2011. The net observation at both sites exhibits slow rate of sediment accretion followed by non-uniform sediment erosion and accretion processes. Study revealed that the beaches are unfavourable for recreational activity because of their narrow width and steeper slope. During summer monsoon, the absence of backshore zone at Padukare makes it more vulnerable to erosion than Kundapura beach.

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Keywords: Beach profile, erosion/accretion, Kundapura, Padukare, west coast of India.

INFORMATION on beach morphodynamics is one of the primary requirements for integrated sustainable coastal zone management studies. Beach profiles provide significant insights for understanding short and long-term spatio-temporal beach morphodynamics[1,2]. Also, beach profile is an essential tool in predicting beach morphodynamics and for estimating equilibrium beach profiles[3]. Hence, understanding beach morphology and morphodynamics is crucial for planning coastal development strategies. Undoubtedly, the sandy beaches are more dynamic and the beach morphodynamics are usually associated with artificial constructions as well as natural phenomena, and exhibit dramatic variation with respect to space and time[4–7]. Kumar *et al.*[8] observed that ~75% of the Karnataka coast is covered with sandy beaches. In this study, morphodynamic observation was carried out at two sandy beaches, Kundapura and Padukare, spaced at a distance of ~40 km along Karnataka coast (Figure 1). The Kundapura beach, south of Gangoli river mouth covers a stretch of ~3 km, whereas the Padukare beach, south of Udiyavara river mouth runs for ~6.2 km along the shoreline. Both sites are well-known fishing zones along west coast of India and also popular tourist places. However, there was no field data available on the beach morphodynamics covering different annual cycles at these two locations. In this context, our study aims to observe the foreshore sediment accretion and erosion processes in

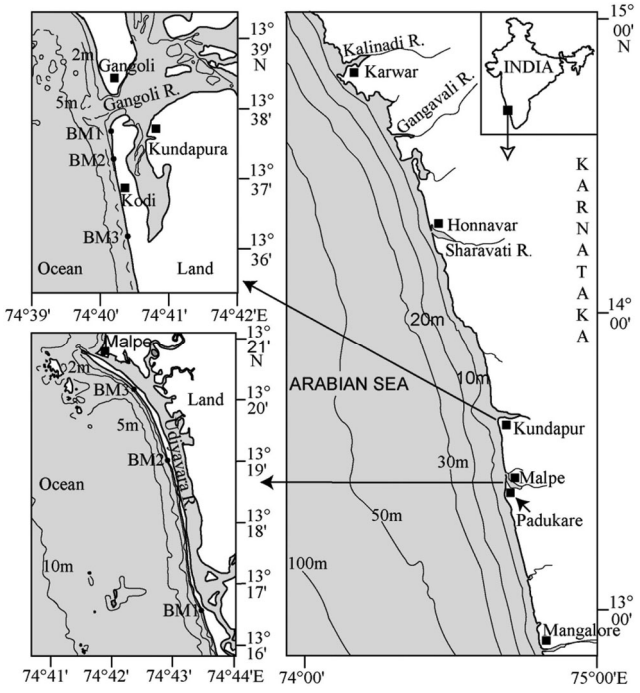

Figure 1. Study area covering two microtidal sandy beaches (Kundapura and Padukare) along Karnataka shoreline, west coast of India.

order to identify the beach dynamics and stability. The tidal range at Karwar (located ~200 km north of the Kundapura), is 1.58 m during spring tide and is 0.72 m during neap tide[9], whereas at Mangalore (located ~60 km south from Padukare), the average spring tidal range is 1.22 m and average neap tidal range is 0.56 m. The tidal range at Karwar and Malpe indicates that the study sites are located in a microtidal (tidal range < 2 m) coast, and hence the beaches are referred to as microtidal beaches.

Studies on beach morphology were based on three characteristics, viz. width, slope and volume, estimated from cross-shore profiles monitored using dumpy level and measuring staff. Beach morphodynamics were analysed by estimating 'change in beach width' (CBW), 'change in beach slope' (CBS) and 'change in beach volume' (CBV) during monthly intervals in the three annual cycles from March 2008 to March 2011. The period from March 2008 to March 2009 was considered as first annual cycle, March 2009 to March 2010 as second annual cycle and March 2010 to March 2011 as third annual cycle. The cross-shore profile monitored during March 2008 was considered as reference profile to identify annual change in beach morphology. Total three locations (BM1, BM2 and BM3) at each beach were selected for the observation of beach morphology and morphodynamics. The BM1 location at Kundapura beach was close to Gangoli river mouth, whereas the BM3 location at Padukare beach was close to Udiyavara river mouth (Figure 1). The benchmarks at Kundapura beach were marked at a distance of 30 m at BM1, 40 m at BM2 and 15 m at BM3 from the high tide line for achieving stable positions. The distance of stable benchmarks at Padukare beach was 15 m at BM1, 45 m at BM2 and 25 m at BM3. During the 3 years, a total of 222 cross-shore profiles were monitored up to low water level at 5 m intervals (Figure 2). Beach slope (θ) was calculated using a right angle triangle trigonometric formula ($\tan\theta$ = opposite/base), where beach volume for unit beach length (m^3/m), and beach width was estimated using Beach Morphology Analysis Package[10].

During the 3 years, beach volume at BM1 varied from 121 to 289 m^3/m, while beach width was 50 to 123 m and beach slope was 1.60° to 3.88° (Table 1). The beach at this location was characterized as moderate slope ($1:33 \leq$ slope $< 1:20$) in 70% of the total cross-shore profiles, where 22% was average slope ($1:20 \leq$ slope $< 1:10$) and the remaining 8% was gentle slope ($1:50 \leq$ slope $< 1:33$). Moderate and average slopes were observed during monsoon (June–September) seasons. The beach volume at BM2 varied from 39 to 114 m^3/m and the beach was significantly narrow (24 to 51 m in width) with steeper slope (3.68° and 7.47°) during the entire period (Table 1). The beach at this location was characterized as average slope in 78% of the total cross-shore profiles, whereas the remaining 22% exhibited steep slope ($1:10 \leq$ slope $< 1:5$). The average and steep slopes were observed during all the seasons in first and second annual cycles, whereas only average slope was observed during the third annual cycle. The beach volume at BM3 varied from 75 to 161 m^3/m, while the beach width was between 40 and 86 m, and beach slope was between 1.66° and 4.02° (Table 1). At this location, cross-shore profiles exhibited mostly moderate (54%) and average (35%) slopes, whereas the remaining few profiles (11%) were gentle slopes. The moderate to average slopes existed throughout the period, but gentle slope beach was observed during non-monsoon period.

At Kundapura, beach slope varied from 1.60° to 7.47° during the first annual cycle, 1.74° to 6.26° during the second annual cycle and 1.71° to 4.88° during the third annual cycle. The mean beach slopes were 3.52°, 3.28° and 3.08° during first, second and third annual cycles respectively (Table 1). From first to third annual cycle, the gradual decrease in maximum and mean beach slopes exhibited sediment accretion, whereas the variation in minimum beach slopes were minor. The beach width was 24 to 123 m during the first annual cycle, 29 to 110 m during the second annual cycle and 37 to 103 m during the third annual cycle. The annual average beach width was similar (62, 60 and 62 m) during different years (Table 1). However, slight increase in minimum beach width during successive years revealed sediment accretion along upper intertidal zone, whereas gradual decrease in

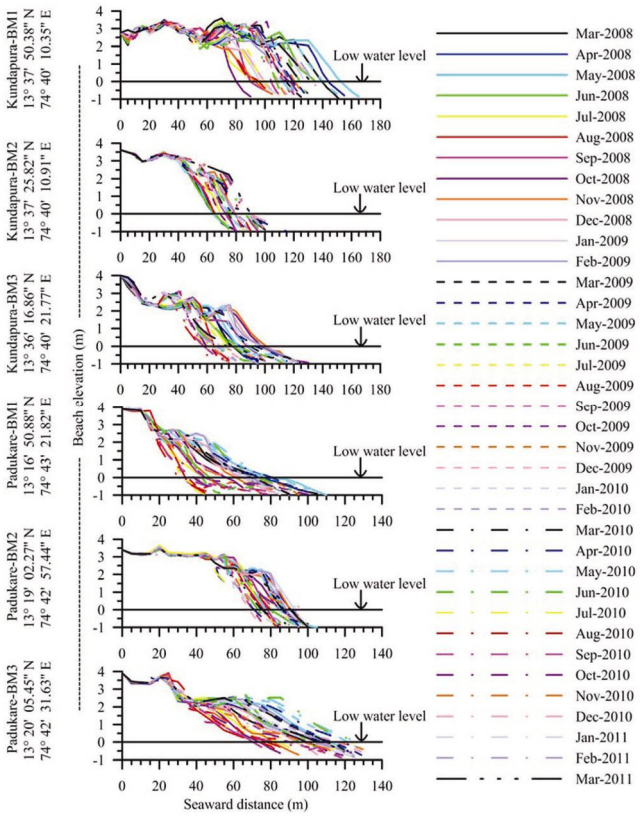

Figure 2. Monthly monitored cross-shore profiles at six locations in Kundapura and Padukare beaches during March 2008 to March 2011.

Table 1. Minimum (min), maximum (max) and mean (avg) beach width, slope and volume during first (1st), second (2nd) and third (3rd) annual cycles at Kundapura and Padukare beach

		Beach width (m)			Beach slope (°)			Beach volume (m^3/m)		
Annual cycle	Range	BM1	BM2	BM3	BM1	BM2	BM3	BM1	BM2	BM3
Kundapura beach										
1st	Min	50	24	50	1.60	4.60	1.66	121	39	109
	Max	123	39	86	3.88	7.47	2.98	289	80	161
	Avg	82	31	72	2.57	5.95	2.05	187	56	134
2nd	Min	69	29	43	1.74	4.09	1.79	163	58	91
	Max	110	45	79	2.81	6.26	3.31	248	87	141
	Avg	87	37	57	2.24	5.03	2.58	209	74	110
3rd	Min	58	37	40	1.71	3.68	2.49	140	80	75
	Max	103	51	63	3.33	4.88	4.02	247	114	107
	Avg	87	47	53	2.23	3.96	3.04	208	102	96
Padukare beach										
1st	Min	19	30	45	2.88	3.76	2.19	35	62	64
	Max	67	48	88	11.34	6.15	4.85	98	101	156
	Avg	46	40	69	4.57	4.50	3.09	72	84	114
2nd	Min	18	24	52	2.68	4.11	1.97	25	49	72
	Max	63	42	96	10.39	7.60	3.62	103	89	179
	Avg	42	32	79	4.91	5.77	2.51	62	64	125
3rd	Min	15	26	49	2.55	3.50	1.88	20	42	68
	Max	65	52	105	10.47	6.82	4.12	98	89	186
	Avg	44	39	79	4.80	4.79	2.60	65	68	124

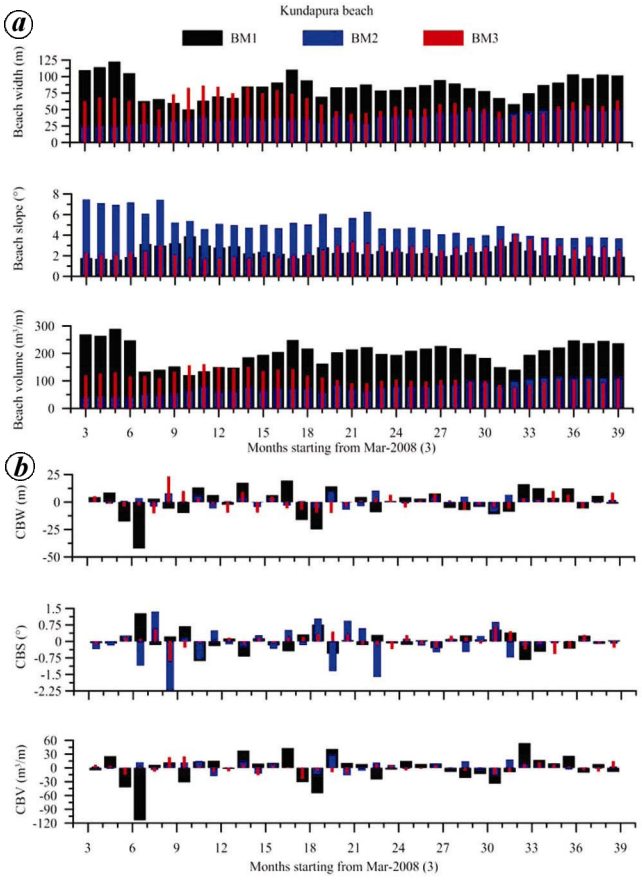

Figure 3. ***a***, Beach width, slope and volume; ***b***, change in beach width (CBW), change in beach slope (CBS) and change in beach volume (CBV) during monthly intervals at three locations in Kundapura beach.

maximum beach width revealed sediment erosion along lower intertidal zone. The monthly estimated beach volume (average of the three locations) varied from 99 to 153 m^3/m with an average of 126 m^3/m during the first annual cycle, 111 to 154 m^3/m with an average of 131 m^3/m during second annual cycle and 105 to 154 m^3/m with an average of 135 m^3/m during third annual cycle. The minor change in annual average beach volume revealed the interannual beach morphodynamics were quantitatively similar. Further, the CBV showed erosion (11 m^3/m) of beach sediments during first annual cycle, whereas 8 and 13 m^3/m of sediments accreted during the second and third annual cycles. The net CBV showed sediment accretion (10 m^3/m) with an annual rate of ~3 m^3/m. The study revealed slow rate of sediment accretion during annual cycle at Kundapura beach, which is similar to the result observed in textural characteristics during the same period[11,12].

The spatio-temporal cross-shore profiles at Kundapura beach exhibited moderately non-uniform beach width, slope and volume (Figure 3 *a*). The monthly CBW, CBS and CBV showed sediment erosion and accretion processes during all the seasons (Figure 3 *b*). During the study period, the maximum CBW, CBS and CBV were 42 m, 2.21° and 114 m^3/m during sediment erosion phase, and 23 m, 1.36° and 54 m^3/m during accretion phase. During 3 years, the monthly estimated (average of the three locations) beach volume varied from 99 to 154 m^3/m where the tendency of beach width was from 24 to 123 m and beach slope was from 1.60° to 7.47°. Further, gradual decrease in beach slope from first to third annual cycle together with

increase in beach volume and width indicated continuous accretion of sediment at BM2. Narrow beach width, steeper slope and less beach volume was identified at BM2 during summer monsoon and wider beach width during non-monsoon period at other locations. However, a good seasonal variation in beach characteristics was observed at BM1 and BM2. In addition, the three locations showed that the monthly CBW and CBV were comparatively more at BM1 which was closer to the Gangoli river mouth, where the beach is influenced by tidal currents also. Shanas and Kumar[13] reported the maximum significant wave height (H_s) of 3.5 m in the nearshore off Kundapura; and Kumar *et al.*[14] observed the tidal current up to 25 cm/s with an average value of 8 cm/s in the nearshore zone off Karnataka coast. Also, the beach morphodynamics near river mouth showed similar result as that observed at the Kali estuary, west coast of India[15]. However, the monthly CBS was higher at BM2 where the initial beach slope was steeper. A marginal tendency in the monthly CBW, CBS and CBV was observed at BM3, where the beach varied from gentle to average slope and also the location was far away from the river mouth. Following these analyses, the beach was characterized as significantly intermediate to reflective in nature.

The beach volume at BM1 varied from 20 to 103 m^3/m, while the beach width was between 15 and 67 m and beach slope ranged from 2.55° to 11.34° (Table 1). The beach at BM1 was characterized as moderate, average and steep slopes during 11%, 57% and 30% of the total monitored profiles; whereas only 2% was characterized as very steep slope ($1:5 \leq$ slope). Moderate to average slopes were frequently observed during non-monsoon season, whereas steep and very steep slopes were observed during monsoon season. The beach volume at BM2 varied from 42 to 101 m^3/m and beach slope was 3.50° to 7.60° along with narrow beach width of 24 to 52 m (Table 1). Cross-shore profiles at this location were characterized with 68% of average slope and 32% of steep slope. The beach at BM3 exhibited comparatively wider width (up to 105 m) and less steep slope (up to 4.85°) and the beach volume varied from 64 to 186 m^3/m (Table 1). The beach slopes at BM3 was characterized as 73% moderate and 27% average. However, a large number of cross-shore profiles exhibited moderate slope during nonmonsoon period, whereas average slope frequently occurred during monsoon season.

Beach width and beach slope at three locations of Padukare beach during the first annual cycle varied from 19 to 88 m and 2.19° to 11.34° respectively. During the second annual cycle, beach width and slope varied from 18 to 96 m and 1.97° to 10.39° respectively; whereas, during the third annual cycle their variation was 15 to 105 m and 1.88° to 10.47° respectively. The mean beach widths were 52, 51 and 54 m during the first, second and third annual cycles, and the mean beach slopes were 4.05°, 4.40° and 4.06° (Table 1). An increase in mean beach slope during first to second annual cycle revealed erosion of beach sediments, whereas the decreased beach slope from second to third annual cycle showed sediment accretion. However, the average beach width during the three annual cycles showed minimum change. From first to third annual cycle, slight decrease in minimum beach width exhibited sediment erosion along upper intertidal zone, while the increased maximum beach width exhibited sediment accretion along lower intertidal zone. Even though the maximum beach width gradually increased during consecutive annual cycles, decreased minimum beach width showed that the shoreline is unsafe at Padukare. During the three annual cycles, minimum beach volume was 54 m^3/m for each year, whereas maximum beach volume was 115, 123 and 113 m^3/m during first, second and third annual cycles. The annual average beach volumes were 90, 84 and 86 m^3/m respectively (Table 1). During the 3 years, there was not much variation in the annual average as well as in the minimum and maximum beach volumes which revealed similar inter-annual beach morphodynamics. The CBV showed sediment accretion of 14 and 8 m^3/m during first and third annual cycles, where the beach sediments eroded (18 m^3/m) during second annual cycle. During the 3 years, net CBV showed sediment accretion (4 m^3/m), with an annual rate

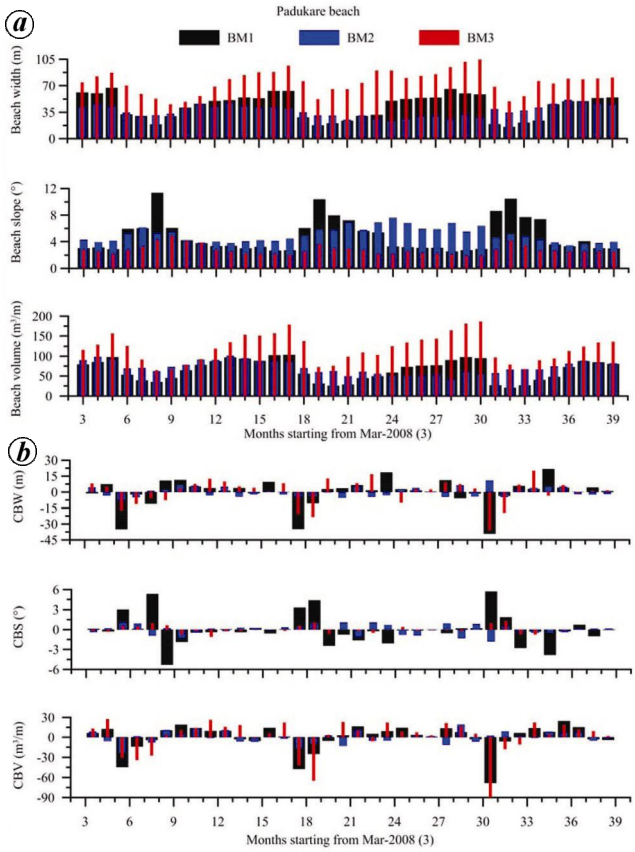

Figure 4. ***a***, Beach width, slope and volume; ***b***, CBW, CBS and CBV during monthly intervals at three locations in Padukare beach.

Table 2. Categorization (%) of beach morphodynamics with respect to monthly CBW, CBS and CBV during first (1st), second (2nd) and third (3rd) annual cycles at Kundapura and Padukare beaches

	Kundapura beach									Padukare beach								
	BM1			BM2			BM3			BM1			BM2			BM3		
Type	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
Case 1	42	50	33	50	50	50	42	42	42	42	59	42	34	34	42	59	50	42
Case 2	33	26	59	25	34	25	42	42	33	34	17	25	42	50	42	25	17	17
Case 3	17	8	0	0	8	8	16	8	0	8	8	8	8	0	8	8	8	8
Case 4	8	8	0	0	8	0	0	8	0	8	8	17	8	8	8	8	8	8
Case 5	0	8	8	8	0	0	0	0	8	8	8	8	8	8	0	0	17	25
Case 6	0	0	0	17	0	17	0	0	17	–	–	–	–	–	–	–	–	–

of ~1 m^3/m. The beach morphodynamics at Padukare revealed slow rate of sediment accretion during annual cycles, which is similar to the Kundapura beach morphodynamics. Results obtained from beach morphodynamics are comparable to the textural characteristics earlier analysed at Padukare beach[11,12].

The spatio-temporal cross-shore profiles at Padukare beach during the 3 years exhibited moderate variation in beach width, slope and volume (Figure 4 *a*). No unique pattern in the sediment erosion and accretion processes was estimated in monthly CBW, CBS and CBV (Figure 4 *b*). The maximum CBW, CBS and CBV were 39 m, 5.29° and 89 m^3/m during sediment erosion phase; and 22 m, 5.70° and 27 m^3/m during sediment accretion phase. The beach volume at Padukare varied from 54 to 123 m^3/m, while beach width was 15 to 105 m, and beach slope was 1.88° to 11.34°. The beach width was narrow during monsoon season and wider during non-monsoon period. All three locations showed seasonal variation in beach width, slope and volume. Narrow beach width, steeper slope and less beach volume were observed at BM1. However, the beach at location BM3 which was closer to Udiyavara river mouth showed more volume and wider width along with moderate slope. The Udiyavara river mouth is protected by coastal structure and hence the beach closer to the river mouth is not affected directly by the tidal current. Thus, the beach morphodynamics at Padukare is mainly due to the wave action. The beach slope was steeper at BM2 during most of the time, whereas the maximum beach slope was found at BM3 during monsoon season. Among three locations, the CBW and CBV were comparatively more at BM3 with a marginal tendency in CBS. Along Karnataka coast, waves are predominantly southwest to northwest during premonsoon period (February–May), whereas southwest waves are significantly observed during monsoon season[13,16]. At BM1, during monsoon season, CBS was more due to southwest high energy waves; whereas during the remaining period, CBS was not prominent as the nearshore islands obstruct the northwest waves from reaching BM1. Hence, during non-monsoon season, the CBS was more at BM2, which is an open coast during all the seasons.

The spatio-temporal cross-shore profiles revealed the following six cases observed from the beach morphodynamics.

Case 1: Increase in beach volume and width, and decrease in beach slope is a sign of sediment accretion at lower intertidal zone along with/without accretion and/or comparatively less erosion of beach sediments at upper and/or mid intertidal zone(s).

Case 2: Decrease in beach volume and width, and increase in beach slope is a sign of sediment erosion at lower intertidal zone along with/without erosion and/or comparatively less accretion of sediments at upper and/or mid-intertidal zone(s).

Case 3: Increase in beach volume and slope, and decrease in beach width is a sign of sediment accretion at upper and/or mid-intertidal zone(s), whereas comparatively less erosion of beach sediments was observed at lower intertidal zone.

Case 4: Decrease in beach volume and slope, and increase in beach width is a sign of sediment erosion at upper and/or mid-intertidal zone(s), whereas comparatively less accretion of sediments was observed at lower inter-tidal zone.

Case 5: Increase in beach volume along with approximately no change in both beach width and slope is a sign of sediment accretion at upper and/or mid-intertidal zone(s), whereas there is no accretion and erosion of sediments at extreme lower intertidal zone.

Case 6: Decrease in beach volume along with approximately no change in both beach width and slope is a sign of sediment erosion at upper and/or mid-intertidal zone(s), whereas there is no accretion and erosion of sediments at extreme lower intertidal zone.

Monthly change in cross-shore profiles was reflected in all six cases at Kundapura beach, whereas Padukare beach showed only the first five categories. Case 1 was 45% at both the beaches, whereas Case 2 was 35% at Kundapura beach and 30% at Padukare beach. The Cases 1 and 2 together exhibited that both Kundapura and Padukare beaches were significantly dynamic along the lower intertidal zone. Case 3 was 7% at both the beaches, whereas Cases 4 and 5 were 4% and 9% each at Kundapura and

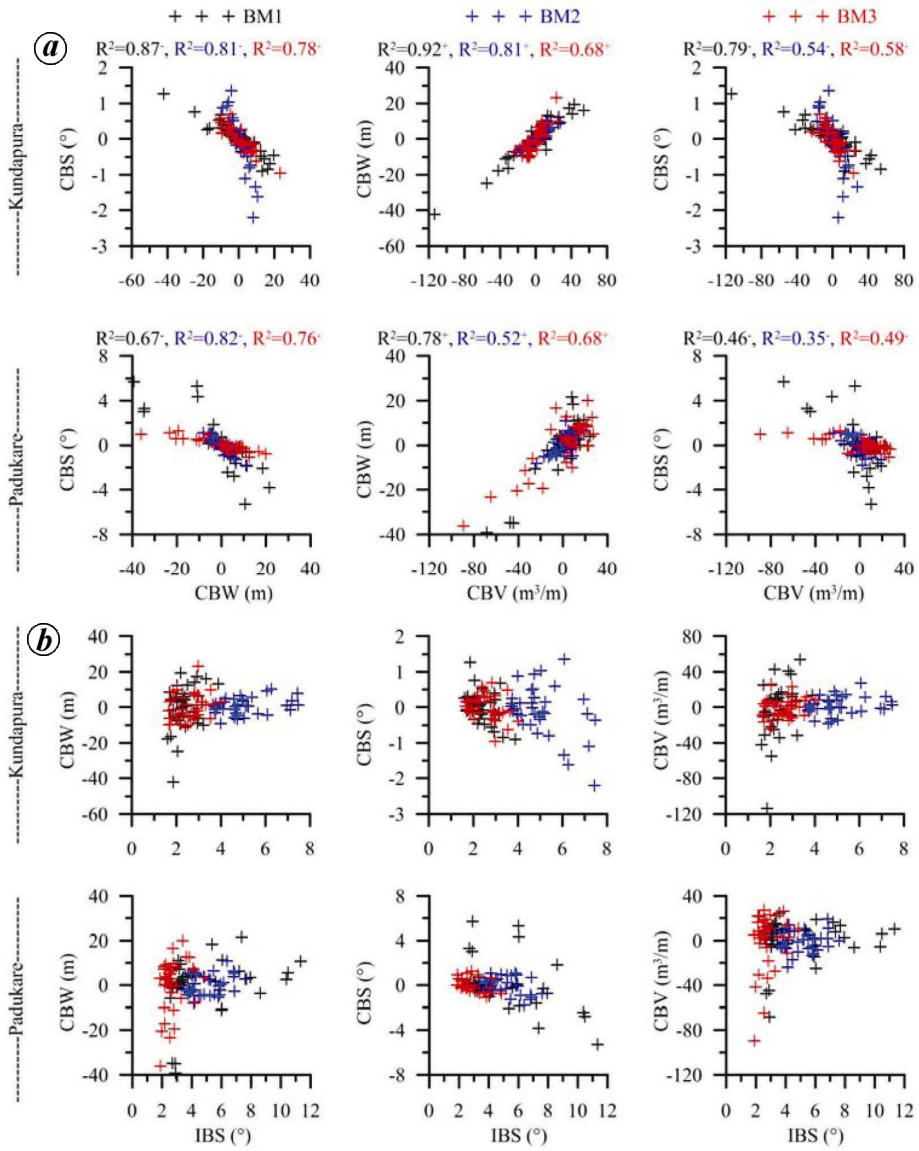

Figure 5. (***a***) Bivariate plots among monthly CBW, CBS and CBV; whereas (***b***) Bivariate plots of monthly CBW, CBS and CBV with respective initial beach slope (IBS) in Kundapura and Padukare beaches.

Padukare beaches. However, Case 6 was 5% only at Kundapura beach (Table 2). During the three annual cycles, Cases 4 and 6 revealed that the Padukare shoreline was more unsafe than the Kundapura shoreline. In addition, the study showed that no special trend existed in the six cases, which indicated that beach morphodynamics was highly dependent on the magnitude of sediment erosion and accretion processes.

At both the beaches, sediment erosion and accretion patterns were observed during all three seasons. However, the morphodynamic study shows that the beaches are cyclic annually with a slow rate of sediment accretion. Long-term study from remote sensing data also showed slow rate of beach morphodynamics during annual cycles[17]. Previously, Bhat *et al.*[18] and Jayappa *et al.*[19] observed similar results at other beaches along the Karnataka shoreline. Further, our study revealed that the upper and/or mid-intertidal zone(s) at Padukare was more dynamic compared to Kundapura beach; whereas, the lower intertidal zone was more dynamic at both the beaches. Narrow beach width, steeper slope and less beach volume was observed in erosion phase usually during monsoon period due to the influence of high waves (Hs > 1 m). Along the Karnataka shoreline, Kumar *et al.*[16] observed that the Hs exceeds 4 m during monsoon, where average Hs was ~2 m. However, wider beach width, gentle slope and more beach volume were observed during non-monsoon period. Even though seawall is constructed along most parts of the shoreline at both the study sites, the Padukare shoreline was noticed to be unsafe at constructed as well as non-constructed places during monsoon season. The sediment erosion can be

minimized by either soft or hard engineering structures. Hegde[20] observed that the soft structures are better than hard structures. Also, the CBW and CBV were observed frequently at gentle slope, whereas the CBS was more at steeper slope.

The correlation was carried out between the characteristics of monthly change in cross-shore profiles at individual locations on both the beaches. A negative correlation was found in CBW versus CBS, and also in CBV versus CBS, whereas a positive correlation was observed between CBV and CBW at both beaches (Figure 5 *a*). At Kundapura beach, all the locations showed a strong ($0.7 \le R^2 \le 1.0$) correlation of CBW with CBS, whereas a moderate ($0.5 \le R^2 < 0.7$) to strong correlation was found in CBV versus CBW, and also in CBV versus CBS. The locations at Padukare beach showed moderate to strong correlation in CBW versus CBS, and also in CBV versus CBW, whereas a mild correlation ($0.3 \le R^2 < 0.5$) was found between CBV and CBS. The existence of mild correlation in CBV versus CBS, and moderate correlation in CBV versus CBW showed that the cross-shore profiles did not change uniformly. This non-uniform change revealed existence of both cross-shore and alongshore sediment transport. In addition, this study exhibited more CBW and CBV, while the initial beach slope (IBS) was gentle to moderate; and the CBS was more while IBS was steep. Further, the change in beach characteristics with IBS exhibited nonlinear correlation (Figure 5 *b*) due to the existence of beach morphodynamics of Case 3 to Case 6 categories. Also, both beaches showed that CBW, CBS and CBV with respective to IBS was more during erosion phase compared to those observed during accretion phase.

The study revealed non-uniform variation in beach morphodynamics during intra-annual period, whereas the annual average beach morphology was similar. The observation on morphodynamics explains that the beaches are annually cyclic, where slow rate of sediment accretion and/or erosion processes is observed during the consecutive annual cycles. In addition, the study revealed that the change in beach morphodynamics is nonlinearly related to respective initial beach morphology. Sediment erosion at upper intertidal zone indicates a probable change in shoreline at Padukare as compared to Kundapura. Further, the narrow beach width and steeper slope at both beaches makes them unfavourable for recreational activities.

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