Comparison of coastal hydrodynamics in different energy regime coasts along southwest coast of India

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Study of the complex physical processes of beach-nearshore system helps to understand the coastal processes and facilitate coastal planning and management. Since the SW coast of India has very dynamic and contrasting hydrodynamic features, the Veli–Varkala stretch of southern Kerala (SK) and Munambam–Chettuwa sector of central Kerala (CK) were selected for a comparative study of their hydrodynamics. SK is a high wave energy coast compared to CK. The contrasting wave energy regimes result from the differences in the inner shelf slope and shoreline orientation. However, just as in the case of SK, waves and wave induced littoral processes are the dominant driving forces in the coastal processes of CK too. Due to the favorable hydrodynamic and sedimentological characteristics, mudbanks set in at different locations of CK affecting the coastal processes of the locations of its occurrence. Mudbanks do not occur along the SK due to the unfavorable sedimentological features. Artificial morphologies such as seawalls, groins, harbour breakwaters have a great role for coastal processes along both the sectors. The long term shoreline change along the SK and CK can be linked to the contrasting characteristics of longshore sediment transport along the coasts.

Keywords. Coastal hydrodynamics; waves; currents; sediment transport.

1. Introduction

The coast is probably the most diverse and dynamic environment found anywhere on earth. Many geological, physical, biological, and anthropogenic factors are responsible for shaping the coast and keeping it in constant flux. Major natural factors responsible for coastal hydrodynamics are winds, waves, currents and tides. Information on the wave-current regime is important in understanding the beach erosion processes and planning and implementation of shore protection structures, harbours and other coastal structures. It is

also important in navigation, defense operations, fishing, offshore oil exploration, etc. Waves are the major force determining the coastal processes of the southwest (SW) coast of India. Current, unlike wave, is a continuous, directed movement of seawater. The commonly occurring currents in the coastal zone are nearshore wave induced currents, coastal currents and tidal currents. There are some localized, but important processes such as mudbanks which still require further research for planning better coastal management strategies.

The hydrodynamics of southwest coast of India had not been adequately studied till 1980, except

for isolated observations off Cochin (Srivastava *et al.* 1968) and Trivandrum (Swamy *et al.* 1979). In 1980, Centre for Earth Science Studies (CESS) took a major initiative by establishing coastal laboratories at Valiathura (Trivandrum), Alleppey, Calicut and Tellicherry covering the SW coast of India, for wave recording and littoral environmental observations (Baba and Kurian 1988). A unique set of year-round data for the Lakshadweep Sea was acquired using a directional wave rider buoy deployed off Kavaratti under a project sponsored by the Department of Ocean Development (Baba *et al.* 1992). The nearshore wave characteristics along the SW coast were studied by Hameed (1988), Harish (1988), Kurian (1988), Thomas (1988) and Kurian *et al.* (2002). The whole work carried out by NCESS during 1978–2003 related to hydrodynamics of coastal waters was synthesized by Kurian *et al.* (2004).

Based on hydrodynamic measurements in the surf zone and the inner shelf combined with mechanism focused numerical modeling, Black *et al.* (2008) proposed the step-ladder concept for circulation and sediment transport in the beach-inner shelf system of Chavara coast. Nearshore waves

and sediment transport regime off the south central Kerala coast were studied by Kurian *et al.* (2009). Coastal hydrodynamics and sediment transport pattern of southern Kerala and central Kerala were studied by Noujas *et al.* (2014b, 2016). Mudbank, a unique coastal phenomenon that occurs along the southwest coast of India, was studied by Mallik and Ramachandran (1985), Mathew (1992), Mathew and Baba (1995), Mathew *et al.* (1995) and Noujas *et al.* (2016).

The coastal zone of Kerala of length around 590 km has varying energy regimes, sedimentary characteristics and morphological features. The studies hitherto showed that the southern Kerala coast is characterized by high energy level, coarse sediments and steep inner shelf, while the central and northern Kerala coasts, unique for the occurrence of mudbanks at several locations, have moderate energy regime with gentle inner shelf blanketed by fine sediments. In addition to natural processes, anthropogenic factors play a

Figure 1. Veli–Varkala coastal sector, Thiruvananthapuram (southern Kerala).

Figure 2. Munambam–Chettuwa coastal sector, north of Kochi (central Kerala).

Figure 3. Nearshore steepness south of Muthalapozhi inlet in SK (a) Perumathura, (b) Pudukuruchi, and (c) St. Andrews.

significant role in the coastal processes of the whole Kerala coast. Thus, a comparative study of the contrasting hydrodynamics of the southern and central Kerala coasts is felt to be a very important topic for investigation and was taken up for the present study. The present study is also part of the CESS/NCESS program of continuous monitoring of the southwest coast of India initiated in 1980.

2. Regional setting

The Veli–Varkala stretch of southern Kerala coast, north of Thiruvananthapuram (figure 1) and Munambam–Chettuwa sector of central Kerala coast, north of Kochi (figure 2) were chosen as representative sites for southern Kerala coast (SK) and central Kerala coast (CK), respectively for the present study.

Figure 4. Nearshore steepness north of Muthalapozhi inlet in SK (d) Thazhampally, (e) Anchuthengu, and (f) Nedunganda.

The Veli–Varkala stretch of SK (figure 1) is part of a high energy sandy coast. Muthalapozhi is a tidal inlet in this sector. This coast was considered to be dynamically stable except for the morphological changes associated with inlet oscillations till the development of a fishing harbour at Muthalapozhi inlet. The tidal inlet at Muthalapozhi has been developed into a fishing harbour for which

two breakwaters were constructed on either side during 2002–2008. The harbour is expected to provide access to the sea for fishing crafts throughout the year. Even after the breakwater construction the harbour remained unusable due to spit formation at the mouth during fair season and breaking waves at the mouth during rough season. Design modifications are being implemented for rectifying

Figure 5. Nearshore steepness off different locations of central Kerala (CK) (a) Azhikode, (b) Kara, (c) Kaipamangalam, and (d) Vatanapally.

the problems by extending the length of both the arms with slight changes in alignment (CWPRS 2011). Construction of breakwaters has resulted in serious erosion immediately north of the inlet and beach build up on the southern side of the inlet.

The CK has the rivers Periyar and Chettuwa debouching into the Lakshadweep Sea through the inlets at Munambam and Chettuwa, respectively. The two inlets which are important morphological features, were significantly modified with the construction of harbour breakwaters in the region. Munambam–Chettuwa coast is characterized by mudbank formation at locations like Chettuwa, Vatanapally, Thalikkulam, Nattika, Kuzhimuttom, Kaipamangalam, during the last many years (Mallik and Ramachandran 1985; Mathew 1992). The breakwater of Munambam fishing harbour has a length of 625 m for northern arm and 360 m for the southern arm, while Chettuwa breakwater has a length of 300 m for south arm and about 500 m for the north arm. Seawalls are prevalent along the coast with a total length of 18 km distributed at Kara–Kaipamangalam, Thalikkulam and Vatanapally–Chettuwa sectors. There are around 10 fishing gaps in CK along the seawall locations.

3. Materials and methods

Offshore observations consisted of waves, tides and currents at locations close to south and north boundaries and in between, at each of the study area at 7–15 m depth. Wave and Tide Recorder (non-directional), Directional Wave Recorder and

Recording Current Meter (RCM) were used for data collection. Directional and non-directional MIDAS wave recorders were set up for measuring waves and tides with a sampling rate of 2 Hz with wave burst duration of 2048 samples and tide burst duration of 60 sec. The interval for measuring waves and tides was set up as 1 hr and 30 min, respectively. The RCM was set up to obtain current data every 15 min with an average current of 5 min.

Instruments to measure waves, tides and currents were deployed at different stations along the study area during different seasons. The southwest monsoon (June–September), post-monsoon (October–January) and pre-monsoon (February–May) are the three seasons of the year along the Indian coastline (Kumar and Deo 2004). For the description of the coastal and nearshore processes along the southwest coast of India, wave climate and coastal processes have been classified as fair season (November–April) and rough season (June–September) by Baba and Kurian (1988). May and October are considered as transitional months. Rough season represents mostly monsoon months while fair reason represents both pre-monsoon and post-monsoon months.

Instruments for measurement of hydrodynamic parameters off SK coast were deployed in the offshore at 6 and 15 m depth at St. Andrews, 6 and 12 m depth at Nedunganda and 15 m depth at Perumathura. The periods of deployments were 22nd February–24th March 2008, 22nd July–8th August 2008 and 5th – 27th November 2008 representing the pre-monsoon, monsoon and post-monsoon season, respectively.

Table 1. Mean size (in mm) of the sediments during pre-monsoon and post-monsoon at SK.

Beach sampling site	St. Andrews		Perumathura		Thazhampally		Nedunganda	
	Pre*	Post*	Pre	Post	Pre	Post	Pre	Post
Backshore	0.39	0.29	0.31	0.19	0.69	0.54	–	0.46
Berm	0.37	0.37	0.33	0.32	0.43	0.27	0.36	0.28
Foreshore	0.37	0.41	0.31	0.32	–	0.29	0.43	0.28

Pre*: pre-monsoon, Post*: post-monsoon.

Table 2. Beach sediments size in mudbank and non-mudbank locations of CK.

Locations	Beach sediment size (mm)		
	Pre-monsoon (mm)	Monsoon (mm)	Post-monsoon (mm)
Kara	0.32	0.43	0.3
Kaipamangalam#	0.15	0.22	0.17
Vatanapally	0.27	0.26	0.35

#: mudbank location.

For the CK coast, instruments for hydrodynamic measurements were deployed off Kara at 8.5 and 4 m depths, off Kaipamangalam at 6 and 4 m depths and off Vatanapally at 6.5 and 4 m depths. Data collection was spread over 24th July–9th August 2009, 19th April–10th May 2010 and 15th September–10th October 2010 for representing pre-monsoon, monsoon and post-monsoon season, respectively.

Close grid bathymetric surveys were carried out in the inner shelf of SK and CK for generating fine grid bathymetric data. The survey was carried out along transects normal to the shore extending upto 20 m depth using Bathy-500 echo-sounder. The echo-sounder was integrated with GPS for accurate positions using HYPACK hydrographic software. Prior to the start of bathymetric survey, sounding lines were generated normal to the shore at required spacing using the HYPACK software selecting the reference ellipsoid WGS-84 for the survey. HYPACK software was used to navigate the boat along the survey lines. The Ceeducer, fixed onto a country boat, was used to carry out soundings in the nearshore region as the survey boat was unable to sail due to shallow waters and rough seas.

Bathymetric survey in the inner shelf region of SK was conducted during March–April 2008 and February–March 2009. Transects were located at a spacing of 100 m at nearshore (2–6 m) and 200 m further offshore (6–20 m). Along the CK coast, bathymetric survey was carried out in March 2009 in the nearshore (2–6 m) and was extended further offshore upto 12 m depth in October 2009. Transects were at a spacing of 500 m in the nearshore and 1 km further offshore.

Long term shoreline changes at the inlet regions of Muthapozhi (SK) and Munambam (CK) were analysed with the information derived from multi-dated imageries, toposheets and shoreline mapping using GPS. Image processing and GIS techniques have been used for the analysis of data and presentation of results.

4. Results

The coastal processes are dependent on parameters such as coastline orientation, nearshore bathymetry, sediment characteristics and hydrodynamic parameters. These parameters show significant

Figure 6. Wave parameters during pre-monsoon at SK.

differences between SK and CK coasts and are described in the following sections.

4.1 Shoreline orientation

The obliqueness of the wave with the shoreline is the deciding factor in longshore sediment transport. In general, shoreline orientation is SE–NW in SK and SSE–NNE in breakwaters. One intervention that caused considerable anomalies in the shoreline orientation at SK is the construction of Muthalpozhi harbour during 2002–2008. Construction of harbour caused drastic changes in the shoreline orientation on either side of the inlet. Consequently, shoreline has different orientations on either side of the inlet. Shore normal is about 217°N immediately south of the breakwater and further south it changes to about 230°N . Shoreline orientation is about 240°N immediately north of the breakwater and there is a shift to 230°N further north. At CK, the shore normal is about 240°N at

Chettuwa and it changes to 245°N further south. Close to Munambam breakwater, shore normal is about 254°N . As in the case of SK, the variations in the orientation of the shoreline within this sector are due to the artificial constructions.

4.2 Nearshore bathymetry

Nearshore steepness between the two sectors and within each sector shows significant variations. The steepness of the nearshore of SK varies from 1:22 to 1:42 (figures 3 and 4).

Within the SK, the southernmost part is more steeper with maximum slope at St. Andrews (1:22). The steepness close to Muthalpozhi breakwater in the southern side is comparatively lesser (1:27) due to the intense accretion processes (Noujas *et al.* 2014b). The steepness was least at Nedunganda (1:42) in the northern side of the Muthalpozhi breakwater.

Figure 7. Wave parameters during monsoon at SK.

The nearshore profile of CK is gentle when compared to SK with steepness varying from 1:100 to 1:153 (figure 5). The lowest steepness of 1:153 was observed at Kaipamangalam, which is a highly accreting zone in the middle of the CK and maximum steepness (1:100) was observed at Kara in the south, which has an erosion tendency (Noujas *et al.* 2016).

4.3 Beach sediment characteristics

As expected for a high energy coast, the beach sediment is coarser at SK. Mean grain size at SK is in the range of 0.27–0.69 mm (table 1), whereas it is in the range of 0.15–0.43 mm at CK (table 2). The beach sediment size in the mudbank locations was in the range of 0.15–0.22 mm. SK comprises of moderately sorted to moderately well sorted, medium to coarse sand. The mean grain size distribution along the beach face reveals that coarser sand dominates the southern part and

medium sand in the north. CK comprises of moderately to moderately well sorted medium to fine sand. The beach sediment at CK coast comprises of fine to very fine sand at the mudbank site while it is medium to fine sand in the non-mudbank areas such as Vatanapally and Kara (table 2).

4.4 Wave characteristics

Wave characteristics of SK and CK shows major variation and is discussed in the following sections.

4.4.1 SK

Pre-monsoon wave climate has low to medium wave intensity. Significant wave height (H_s) observed during February–March is between 0.39 and 1.03 m. Zero crossing wave period (T_z) has a range from 6.1 to 10.8 s. Wave direction is mostly from S and SSW, which could be due to the swell waves from the south Indian Ocean. In general, during

Figure 8. Wave parameters during post-monsoon at SK.

the fair season/pre-monsoon long period, low waves from S to SSW dominates the region (figure 6). Daily average wave height, period and direction at different stations during pre-monsoon are presented in figure 6.

H_s does not show much spatial variation during pre-monsoon. Nearshore H_s at St. Andrews was higher compared to offshore station which may be due to the shoaling of the waves in the shallow water. Only 9 days data was obtained from Nedunganda and shows almost similar pattern as observed in the other stations. T_z at offshore shows a trend similar to that of nearshore data. Wave direction was measured from two stations, both at St. Andrews in the southern sector of SK. Wave direction ranges from 175 to 220°N. The change in the direction of the waves from southerly at the inner shelf to SSW at the nearshore is indicative of the significant influence of refraction.

Waves are generally high during monsoon and the H_s varies between 1.24 and 2.73 m (figure 7). The highest wave recorded during the period of observation is on 23rd July 2008. Unlike fair season, the periods are low with T_z ranging between 7.6 and 9.2 s. The wave direction is mostly confined to SW–WSW, which is typical of monsoon waves. In general, monsoon waves are dominated by short period waves from SW to WSW directions. The high fluctuation seen at St. Andrews could be due to instrumental error. Spatially, southern sector (St. Andrews) shows higher wave intensity than northern sector during the monsoon. T_z is slightly higher in southern sector compared to northern sector. Since the St. Andrews directional data has some problem, no spatial comparison could be made. However, the comparison between nearshore and inner shelf wave directions at Nedunganda shows the pronounced effect of refraction.

Figure 9. Wave parameters during pre-monsoon at CK.

Figure 10. Wave parameters during monsoon at CK.

Similar to pre-monsoon, the wave heights during post-monsoon are low with H_s ranging from 0.40 to 1.2 m (figure 8). Wave period is higher with T_z ranging from 6.2 to 11.3 s (figure 8). The directional data shows even larger variability than pre-monsoon with values ranging from 190 to 238°N (figure 8). Spatially, H_s at St. Andrews is comparatively higher than at Perumathura and Nedunganda. In southern and northern stations, nearshore H_s is higher than the inner shelf locations. Although directional wave gauges were deployed at four stations, two each off St. Andrews and Nedunganda, the instrument deployed in the offshore location of St. Andrews did not function and hence directional data are presented only for three stations. Mean wave direction at nearshore does not show much of variability between Nedunganda and St. Andrews. However,

comparison between inner shelf and nearshore data shows a pronounced effect of refraction for longer period waves during the first fortnight.

4.4.2 CK

During the pre-monsoon period, the wave heights are low and H_s fall in the range of 0.23–1 m (figure 9). The wave periods are generally high, but have a wide range of 6.5–13.6 s. The wave directions are predominantly SW to W and ranged from 216 to 256°N. As regards to spatial variation, the nearshore H_s at Kaipamangalam stands out distinctly from the rest during the first fortnight of the measurement. There are some minor variations among other stations, which are expected due to the complex wave transformation processes. However, there is not much spatial variation as

Figure 11. Wave parameters during post-monsoon at CK.

far as T_z is concerned. As expected, considerable spatial variation is observed in the wave direction, which could be due to the refraction effect. The waves off Kaipamangalam were more refracted and aligned to the west when compared to the other locations.

Wave heights during monsoon season are higher than pre-monsoon season and H_s is in the range of 0.15–1.25 m. H_s is observed to be very low in Kara nearshore, which may be due to the presence of mudbank during that period (figure 10). As seen for SK, wave period is less during monsoon and T_z is in the range of 6.3–9.6 s. Wave period is almost the same in all locations including the mudbank site. Mean wave direction is in the range of 242–268°N. However, at the mudbank location of Kara, there is a significant shift in the wave direction to SW–SSW in the first week of August coinciding with the intensified mudbank dampening.

Wave intensity is of medium to high during post-monsoon and the daily averaged wave parameters are presented in figure 11. The H_s is in the range of 0.0–1.16 m with a mean value of 0.87 m (figure 11). Wave height is generally less in all the three nearshore locations, but it is completely

dampened by mudbanks at Kaipamangalam towards the end of September and beginning of October. The T_z is in the range of 5.1–9.9 s, and wave direction in the range of 207–260°N. Wave direction at Kara at 7 m depth is north of the shore-normal and the refraction effect aligns the wave more closer to the shore-normal at nearshore location, but with abrupt variations, possibly due to the mudbank.

4.5 Currents

The commonly occurring currents in the coastal zone are nearshore currents (wave induced), coastal currents (wind induced) and tidal currents. Coastal currents were collected for all the three seasons along the study region. The current speed is observed to be in the range of 0.29–84 cm/s. Current direction is oscillatory, primarily due to the tidal currents. At SK, during pre-monsoon, current speed is in the range 0.29–40 cm/s with an average of 9.5 cm/s, while during monsoon the speed is in between 0.29 and 54 cm/s and average current speed is 12 cm/s. During the post-monsoon current speed is in the range 0–68 cm/s

Figure 12. The progressive vector plots of currents during pre-monsoon season at SK.

with an average of 13.5 cm/s. At CK, during pre-monsoon, current speed is in the range 0.29–41 cm/s with an average of 14 cm/s, while during monsoon it ranges between 0 and 84 cm/s with an average current speed of 15.4 cm/s. During the post-monsoon current speed is in the range 0–47 cm/s with an average of 10.5 cm/s.

“Progressive Vector Diagram” (PVD), can be constructed by integrating the measured velocities over a specified time interval to obtain a position vector (Tomczak 2000; Emery and Thomson 2001).

The PVD at SK for 30 days during the pre-monsoon (figure 12) shows both northwesterly and southeasterly directions with considerable spatial variation. Even between the offshore and nearshore stations there is considerable difference as can be seen at St. Andrews. While the offshore

PVD at St. Andrews has a net magnitude of about 20 km in the northerly direction and 25 km towards offshore, there is no net movement in the nearshore of St. Andrews in spite of a southeasterly movement which got reversed subsequently. No net movement is seen at Nedunganda nearshore too. The reversal of the vector is seen at Perumathura offshore too though with a net northerly movement of 25 km.

During monsoon, PVD at SK for 17 days of observation shows vectors that are prominently in the southeasterly direction, though reversal of flow is noticed here too (figure 13). At the offshore stations of depth 14 m at St. Andrews and Nedunganda, the net vector is about 40 km in the SE direction in spite of the reversals in direction. At 10 m depth off Nedunganda, the vector again is

Figure 13. The progressive vector plots of currents during monsoon season at SK.

SE in direction with magnitude of 46 km towards south and about 34 km towards shore.

During post-monsoon, PVD at SK for 22 days of observation shows vectors are reversed and prominently in the northwesterly direction (figure 14). The PVD is much higher compared to monsoon period at SK. At the offshore stations of both St. Andrews and Nedungunda, the net vector is in the NW direction, about 150 km towards north and 100 km offshore. At the nearshore stations the PVD follows the offshore in terms of direction, though the magnitudes are much lesser and are about 50–70 km north and 50 km offshore.

At CK, the pre-monsoon measurements pertain to the inshore locations. All the three locations show a strikingly similar current pattern with net

southerly movements of about 70–110 km in spite of reversal in directions (figure 15). This is strikingly different from the pattern for the SK where northwesterly movement was seen in the offshore stations with no net transport for the nearshore.

The PVD for nearshore and inner shelf locations at CK during monsoon does not show the uniform pattern spatially during pre-monsoon. However, there is a net movement towards south at all stations except for the northern location of Vatanapally, which shows a net northwesterly movement (figure 16). Off Kaipamangalam, at both the nearshore and offshore stations, the southerly vector is prominent with a magnitude of around 120 km. The magnitude of the southerly vector is 22 km for offshore and 45 km for nearshore of

Figure 14. The progressive vector plots of currents during post-monsoon season at SK.

Kara. Off Vatanapally, the PVD has a magnitude of about 35 km offshore and 65 km in the northerly direction. The magnitudes of the vector are generally higher for CK when compared to SK during monsoon.

The PVD from 25 days observation at 3 stations off CK shows much spatial variation during post monsoon season (figure 17). The PVD vectors at offshore and nearshore stations off Vatanapally shows northwesterly directions, but the magnitude is considerably higher at offshore (120 km) when compared to the nearshore (70 km). Off Kara, PVD shows an opposite direction with lesser magnitudes of about 25 km towards south and 15 km onshore. The observed northwesterly direction off Vatanapally is similar to the observation at all stations off SK during post-monsoon.

4.6 Tides

The maximum and minimum water levels with reference to mean sea level at different stations during each deployment period are presented in tables 3 and 4 for SK and CK, respectively. The water level variation is mainly controlled by tides. There is not much of difference in the water level range between CK and SK. The tide is micro-tidal and the maximum range is about 1 m. The seasonal variation in water level is negligible. In general, the tidal range at CK is slightly higher than SK.

4.7 Mudbanks

Mudbanks are morpho-dynamic formation triggered by monsoon high waves on a clayey

Figure 15. The progressive vector plots of currents during pre-monsoon season at CK.

bottom. The nearshore sediments at SK are fine to medium sand (Noujas 2015) and hence mudbanks have never occurred in SK. mudbanks occur in CK, which has silt and clay bottom (Noujas *et al.* 2016).

Observations during the present study along CK showed the occurrence of mudbanks in the Kara–Bhajanamodom–Kaipamangalam sector during the southwest monsoons of 2009–2013 (figure 18). After its formation the mudbank start spreading on either side of the initial location of occurrence. Once fully formed, it is about 12 to 14 km in the alongshore direction and about 1 to 2 km towards offshore from the beach. Malik and Ramachandran (1985) have identified mudbank formation in the past at Chettuwa, Vatanapally and Nattika along the CK. Present observations, however, do not show the occurrence of mudbanks in the above locations. As per the literatures and traditional knowledge from local communities, the location of occurrence of mudbanks have moved southward from Chettuwa to Thalikkulam to Nattika to Edamuttom to Kaipamangalam to Bhajanamodom successively in the last 40 years (figure 18). Once formed, it stayed in the same sector for 5–10 years. mudbanks generate accretion in its shores and erosion in the downstream areas. The line of old seawall (indicative of eroding site downstream of mudbank in the past) has been pushed landward subsequently due to beach build up as a result of shifting mudbanks. Erosion tendencies are evident south of Kara, where mudbanks currently occur (Noujas and Thomas 2015).

4.8 Long term shoreline change

The long term shoreline change estimated from satellite images vary drastically between SK and CK. Figure 19 presents the shoreline change at the Muthalapozhi harbour area (SK) during 1989–2014. The notable feature of the shoreline change is the tremendous accretion leading to advancement of the shoreline by about 150 m at the south breakwater, which tapers off to the south for a distance of about 1.5 km. This is indicative of a strong northerly sediment transport. As expected, the accretion south of the inlet is accompanied by erosion, which starts immediately north of the breakwater reaching a maximum at Thazhampally, and extends for about 2.5 km north of the inlet (Figure 19).

The long term erosion/accretion pattern at Munambaminlet (CK) is quite different (figure 20).

Figure 16. The progressive vector plots of currents during monsoon season at CK.

Figure 17. The progressive vector plots of currents during post-monsoon season at CK.

Accretion here is on the northern side of the inlet, indicating the prevalence of a net southerly transport. Surprisingly, southern side of the inlet does not show any erosion indicating that the longshore transport south of the inlet is more or less neutral with a slight edge for northerly transport.

5. Discussion

The hydrodynamic characteristics and resultant sedimentary processes are distinct at SK and CK. The waves at SK were higher compared to CK during all the season can be attributed to the higher nearshore steepness of SK. Kurian (1989) concluded that the wave energy levels of coastal zone are well correlated with the bottom slope. Least reduction in height and energy during wave propagation in shallow waters is found in cases of extreme shelf slope and vice versa. Based on this dependence of the coastal energy regime on the shelf slope, the SW coast of India is categorized into different energy regimes (Kurian 1987). According to this categorization, SK falls in the highest energy regime and CK in the third level of lower energy. Another factor which contributes to the higher wave energy level at SK is the orientation of the shoreline in the SE–NW direction, which exposes the coast directly to the long period swells from the southern Indian Ocean. Thus, the observed differences in energy levels can be well correlated with the bottom slope and shoreline orientation. Another important aspect is the relation between wave energy level and sediment size. The higher the wave energy, the coarser the sediment (Baba and Kurian 1988), which is validated in the present case too (see tables 1 and 2).

Hameed (1988) and Thomas (1988) presents the wave climate of Valiathura and Alleppey based on year round measured wave data for the period 1980–1984. While Valiathura is only about 25 km south of Muthalapozhi, Alleppey is about 100 km south of the central part of CK. Hence the hydrodynamic characteristics of Valiathura may be comparable with SK, while the characteristics of Alleppey may not be comparable with CK (Tables 5, 6).

Thomas (1988) observed that >90% of H_s was above 1 m and 60–80% was above 2.5 m during June–September at Valiathura. In the present study, at SK >75% H_s was above 0.7 m and 45% of H_s was above 2 m during the wave recorded

monsoon period. With the onset of monsoon, waves from 250 to 270°N become prominent at Valiathura (Thomas 1988), but in the present study wave direction is in the range 232–249°N (Table 5). Comparison of wave data from the present study for the other seasons too show that the data are not completely in correspondence with earlier study (Thomas 1988). This may be due to the fact the data of the present study pertains to a limited period during each season while Thomas (1988) uses year round data for 5 years.

Coastal currents were collected for all the three seasons along the study region. The current speed is observed to be in the range of 0.3–84 cm/s. Current direction is oscillatory, primarily due to the tidal currents. The PVDs show consistency between SK and CK with southerly transport only during the monsoon. During pre-monsoon both northwesterly and southeasterly directions are prevalent at SK, but the direction is consistently southerly at CK. During post-monsoon, the northwesterlies are dominating at SK while both northwest and southeast directions are noticed at CK. No measured current data is available for

comparison for locations proximate to the present study area.

The tide along both SK and CK is micro tidal and ranged between −0.4 and 0.8 m, with not much seasonal variation (tables 3 and 4). Hence, the tide has no significant role in coastal processes along SK and CK but spring high tide synchronized with highly grouped remotely forced waves cause flooding all along the southwest coast of India (Kurian *et al.* 2008; Remya *et al.* 2016).

The CK is notable for the regular occurrence of mudbanks, which is a unique phenomenon along the Kerala coast (Ramachandran and Mallik 1985; Mathew 1992). mudbanks are known to dissipate wave energy better than coastal protection structures (Anthony and Gratiot 2012). The mudbank area at Kaipamangalam has low wave heights during different seasons as observed in 2009–2010 at CK (Noujas *et al.* 2016). This indicates that the mudbank system at Kaipamangalam existed throughout the year, occasionally extending to Kara during part of the monsoon season (figure 10). On all occasions when the mudbanks formed, it begun at Bhajanamodom

Table 3. *Water level variation along southern Kerala coast.*

Location and depth	Period	Water level (m) wrt MSL	
		Min	Max
St Andrews at 15 m	22/02/08–24/03/08	−0.42	0.47
St Andrews at 8 m	22/02/08–24/03/08	−0.5	0.5
St Andrews at 14 m	22/07/08–08/08/08	−0.52	0.48
Nedunganda at 14 m	22/07/08–08/08/08	−0.55	0.47
Nedunganda at 10 m	22/07/08–08/08/08	−0.53	0.45
St Andrews at 6 m	05/11/08–27/11/08	−0.56	0.55
Nedunganda at 12 m	05/11/08–27/11/08	−0.48	0.57
Nedunganda at 6 m	07/11/08–27/11/08	−0.52	0.56

Table 4. *Water level variation along central Kerala coast.*

Location and depth	Period	Water level (m) wrt MSL	
		Min	Max
Vatanapally at 6.5 m	24/07/09–09/08/09	−0.56	0.56
Kara at 8.5 m	24/07/09–09/08/09	−0.56	0.56
Kara at 5 m	24/07/09–09/08/09	−0.53	0.58
Kaipamangalam at 6 m	19/04/10–10/05/10	−0.65	0.76
Kaipamangalam at 4 m	19/04/10–10/05/10	−0.63	0.78
Kara at 4 m	19/04/10–10/05/10	−0.66	0.77
Vatanapally at 5 m	19/04/10–10/05/10	−0.64	0.79
Vatanapally at 4 m	15/09/10–10/10/10	−0.66	0.79
Kara at 7 m	15/09/10–10/10/10	−0.56	0.9
Kara at 4 m	15/09/10–10/10/10	−0.5	0.87

Figure 18. Mudbank locations along CK during 2009–2013.

(between Kaipamangalam and Kara) and later extended alongshore. Beach sediment was fine to very fine sand at the mudbank site while, medium to fine sand was observed at non-mudbank location like Vatanapally. The offshore sediments at mudbank locations were clay and very fine or fine silt, while those at non-mudbanks locations are medium to coarse silt or fine sand (Noujas *et al.* 2016).

Both SK and CK have artificial structures like harbour breakwaters, seawalls and groins, which

have a significant impact on shoreline processes. SK has harbour breakwaters at Muthalapozhi inlet and seawalls mostly north of the breakwater along the eroding Thazhampally-Poothura sector extending for about 3 km. The CK has breakwaters at Munambam inlet and Chettuwa inlet. All the three inlets were stabilized with embankment prior to the construction of breakwaters. The seawalls were constructed along the coast, adjoining the inlets as a continuation of embankments.

All the three harbour breakwaters have beach sediment accumulation on one side and erosion on other side barring Munambam. Such patterns have

been observed in most coastal regions of the world (Black *et al.* 2017). Examples in Indian scenario are the Kayamkulam inlet in Kerala and Ullal inlet in Karnataka (Kurian *et al.* 2007; NITK 2007). Accretion at Muthalapozhi is on the southern side of the inlet, while at the other two locations of CK, the accretion is on the northern side. This difference in erosion/accretion pattern at the inlets protected by the breakwaters is due to changes in the quantum and direction of longshore sediment transport, which is decided by the obliqueness of waves with the shoreline.

Computations show that the annual net longshore sediment transport in SK is 71,771 and 64,386 m³ on the southern and northern side of Muthalapozhi inlet, respectively (Noujas 2015). Unlike SK, the net sediment transport direction along the CK varies. It is southerly in the southern sector with a magnitude of 1,19,274 m³/yr as per sediment transport computations, which is confirmed from the sediment accumulation north of Munambam breakwater (figure 20). However, after attaining equilibrium conditions with a concave shape for the shoreline, the sediment transport is reduced to a nominal value of about 20,000 m³/yr. The net annual sediment transport is southerly with a magnitude of 63,420 m³/yr for the northern sector, while it is still a higher quantity of about 80,000 m³/yr towards north for the central sector (Noujas 2015). The pattern of long term shoreline change (figures 19 and 20) corresponds well with the sediment transport computations.

Figure 19. Long term shoreline change at Muthalapozhi, SK (after Neelima *et al.* 2018).

Table 5. Measured mean wave parameters along southern Kerala (SK).

Location and depth	Period	H _s (m)	Mean wave direction	
			(degree)	T _z (s)
St Andrews at 15 m	22/02/08–24/03/08	0.7	190	9
St Andrews at 8 m	22/02/08–24/03/08	0.76	208	9
Perumathura at 15 m	23/02/08–24/03/08	0.68	–	9
Nedunganda at 8 m	23/02/08–02/03/08	0.63	–	8.5
St Andrews at 14 m	22/07/08–08/08/08	1.9	–	8.6
Nedunganda at 14 m	22/07/08–08/08/08	1.8	232	8.4
Nedunganda at 10 m	22/07/08–08/08/08	1.74	249	8.4
St Andrews at 15 m	05/11/08–27/11/08	0.68	–	8.6
St Andrews at 6 m	05/11/08–27/11/08	0.73	212	8.6
Nedunganda at 12 m	05/11/08–27/11/08	0.6	208	8.4
Nedunganda at 6 m	07/11/08–27/11/08	0.7	212	8.3
Muthalpozhi north at 15 m	05/11/08–27/11/08	0.63	–	8.7

Table 6. Measured mean wave parameters along central Kerala (CK).

Location and depth	Period	Mean wave direction		
		H_s (m)	(degree)	T_z (s)
Kaipamangalam at 7 m	24/07/09–09/08/09	1.1	–	7.4
Vatanapally at 6.5 m	24/07/09–09/08/09	1.1	248	7.4
Kara at 8.5 m	24/07/09–09/08/09	1.1	257	7.3
Kara at 5 m	24/07/09–09/08/09	0.28	241	7.6
Kaipamangalam at 6 m	19/04/10–10/05/10	0.57	246	9.8
Kaipamangalam at 4 m	19/04/10–10/05/10	0.39	243	10.3
Kara at 7 m	19/04/10–10/05/10	0.59	233	9.3
Kara at 4 m	19/04/10–10/05/10	0.51	229	9.8
Vatanapally at 6 m	19/04/10–10/05/10	0.55	–	9.8
Vatanapally at 5 m	19/04/10–10/05/10	0.58	225	9.5
Vatanapally at 6 m	15/09/10–10/10/10	0.93	–	6.6
Vatanapally at 4 m	15/09/10–10/10/10	0.56	235	7.4
Kara at 7 m	15/09/10–10/10/10	0.87	251	6.4
Kara at 4 m	15/09/10–10/10/10	0.56	230	6.9
Kaipamangalam at 4 m	15/09/10–10/10/10	0.27	–	–

Figure 20. Long term shoreline change at Munambam, CK.

6. Conclusion

A detailed study of the costal hydrodynamics of SK and CK was carried out with seasonal hydrodynamic data measured at different locations of

the two coastal sectors during 2008–2010. The SK is a high wave energy coast compared to CK in all seasons and this is attributed to the relatively higher inner shelf steepness of SK coupled with the direct exposure of that coast to the long period swells from the southern Indian Ocean. In spite of the lesser wave energy level, the waves and wave induced littoral processes are the dominant driving forces in the coastal processes of CK as in the case of SK. Coastal currents and tides do not show much contrast between the two coasts. Occurrences of mudbank at different locations for which CK is well known were noticed during the period of the present observation too, but with a southward shift of the locations of occurrences. Accretionary processes set in at the mudbank locations followed by erosion downstream. Artificial morphologies such as seawalls, groins, harbour breakwaters have great role for coastal processes along both sectors. Long term shoreline changes along both the coasts can be well correlated with the longshore sediment transport regimes of the respective coasts. The characteristics of hydrodynamics and coastal processes brought out by this study can be used for development of shoreline management plans for these coasts.

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