



Estimation of longshore sediment transport direction from varying coastal morphodynamics due to shore structures

V. Noujas^{1,2} · K. V. Thomas¹

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Abstract

The present study has considered the shoreline morphological changes following the construction of coastal structures, viz., groins and breakwaters along the southwest coast of India. Shoreline modifications adjoining breakwaters and groins can be utilized as an indicator of the nature of sediment transport, as direct measurements involve tedious and sophisticated methods. The 590 km coastline of Kerala is characterized by complex coastal hydrodynamic and morphological features along with coastal protection measures. Shoreline modifications were estimated using multidated maps, images, and GPS shoreline mapping. The net sediment transport is northerly along southern and some part of the northern sectors, while no net sediment transport is observed for many other parts of the northern sector. The central sector shows net southerly sediment transport. In general, the sediment transport along the Kerala is a complex, multi-directional, and dynamic process. Moreover as the sediment transport is site-specific, appropriate analysis of sediment dynamics at a small scale is thus crucial for any coastal engineering work along this coast.

Keywords Sediment transport · Shoreline · Beach · Harbour · Breakwater

Introduction

An understanding of sediment transport in the littoral zone is of particular importance in the implementation of any engineering work and management of coastal system (CEM 2006). The 590 km long coastline of Kerala coast, southwest coast of India, is a challenging coast due to the complex features along this coast. As the sharp transitions in the shoreline orientation varies the exposure to waves from South Indian Ocean and significant differences in the nearshore gradient, a complex scenario prevails in the nature of the longshore sediment transport along the Kerala coast presenting contradictory findings; a major challenge is the management of this coast. Moreover, 350 km out of 590 km coast is already protected with seawalls/groins due to the significant erosion problem. Such interventions, although part of coastal protection plans, triggers important changes in the

coastal dynamics (Thomas et al. 2013; Noujas et al. 2017). The morphological impacts leading to shoreline changes due to such hard engineering constructions are dependent on the sediment transport characteristics. However, the complexities of the coastal processes resulting from inaccurate sediment transport studies, consequently place wrongly designed coastal structures along this coast. In some cases, designs were altered either during the construction phase or after the construction (Sheik Pareeth 2004; Noujas et al. 2014a). An understanding of the sediment transport process at a small scale is essential for appropriate coastal erosion management plans (Noujas et al. 2014a, b).

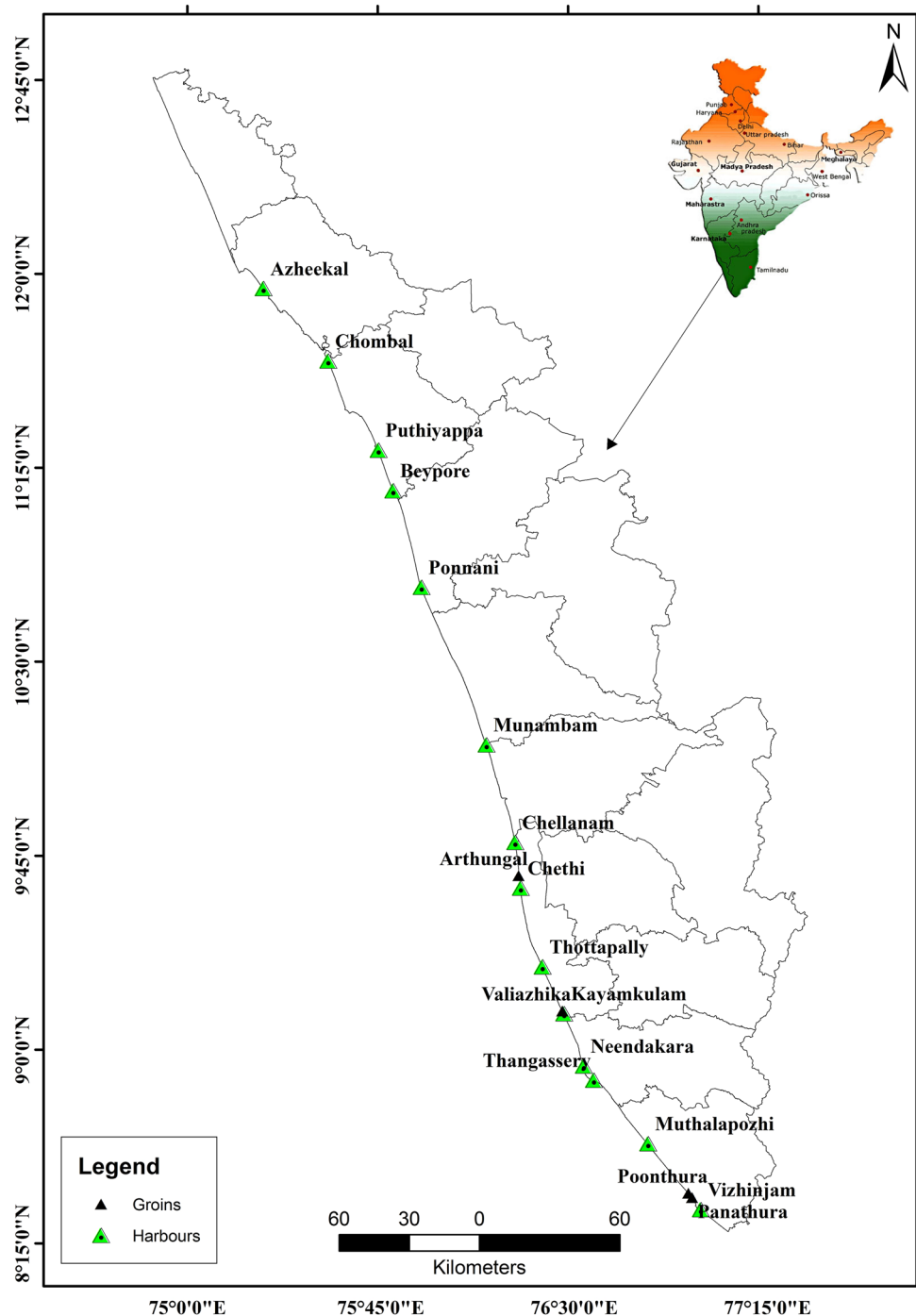
The physical processes associated with sediment transport around the breaker zone are highly complex. The wave-induced spatially varying currents and highly irregular flows make this environment extremely dynamic. Waves breaking near the coast mobilize the sediments around the breaker point and the currents generated by the waves transport the sediments along and across the coast. However, performing high-quality direct field measurements of sediment transport mechanisms in the surf zone is tedious due to the complexity of the processes. Therefore, different approximations are often used to estimate sediment transport along the world's coast. The measured beach profiles at regular intervals

✉ V. Noujas
noujasphy@gmail.com

¹ National Centre for Earth Science Studies, Akkulam, Thiruvananthapuram, India

² National Centre for Coastal Research (NCCR), Ministry of Earth Sciences, Chennai, India

Fig. 1 Location map of harbour breakwaters and groins along the Kerala coast



(Pilkey and Richter 1964; Wright and Short 1983; Troels et al. 2004), empirical methods using measured wave data (Komar and Inman 1970; Wang et al. 1975; CERC (USACE 1984; Walton and Bruno 1989; Bayram et al. 2001, 2007; Kamphuis 2002; Shanas and Kumar 2014; Sheela et al. 2015; Rajab and Thiruvekatasamy 2017) are some of the methods adopted. Furthermore, as nearshore measured wave data is not available for most of the locations, the hind-cast wave parameters from the regional spectral model have been

used for sediment drift estimation (Sean et al. 2004; Kelly et al. 2005). Third-generation numerical models have been used for the sediment transport estimation along the Indian coast (Rao et al. 2009; Shamji et al. 2010; Prasad et al. 2016; Pradhan et al. 2017; Noujas et al. 2014a, b, 2016, 2018a).

In the last four decades, efforts have been made to understand sediment transport pattern using the geomorphic and sedimentologic indicators (Self 1977; Engstrom 1978; Finkelstein and Schwatz 1981; Finkelstein 1982; Morelock et al.

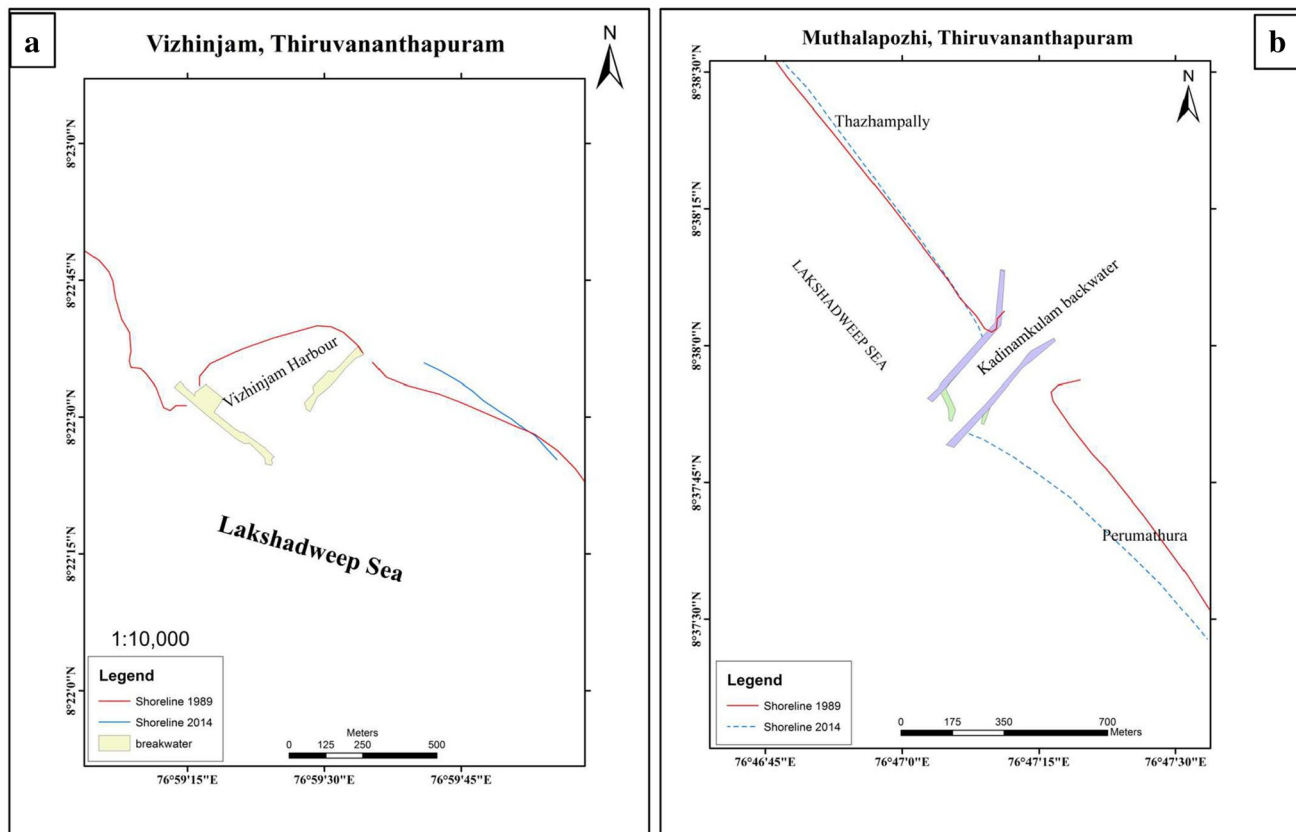


Fig. 2 Long-term shoreline change at **a** Vizhinjam; **b** Muthalapozi

1985; Schwartz et al. 1985; Schwartz and Anderson 1986; Wallace 1988; Kunte and Wagle 1993; Kunte et al. 2002, 2013). Landform indicators using remote sensing is one of the best methods for estimating net shore drift/sediment transport (Kunte et al. 2013). Different morphological indicators such as natural/artificial factors are used for identifying net sediment transport pattern. Coastal structures like groins and harbour breakwaters interrupt sediment transport and cause erosion and accretion along sandy coasts. Both cause accretion on the upstream side and erosion on the downstream side. Harbour breakwaters are constructed to provide tranquility in harbour basins while groins protect the coast. They differ mainly in length, i.e., harbour breakwaters are much longer when compared to groins. Shoreline changes adjacent to such shore structures are indicative of net sediment transport along a coastal sector (Thomas et al. 2013).

In the last few years, due to various factors mentioned above, the sediment transport of Kerala has received increased attention. However, most of the studies have restricted to a single location or some specific locations using different approaches (Sajiv et al. 1997; Sheela et al. 2015; Prasad et al. 2016; Noujas et al. 2014a, b, 2016, 2017;

Noujas and Thomas 2018). Sheela et al. (2015) studied the spatiotemporal variability of longshore transport adopting the empirical formulae of Kamphuis (2002). Their study further emphasizes the need to have a micro-level approach to understand the shoreline dynamics when site-specific coastal management measures are adopted. Such studies are particularly important for locations having a distinct variation in shoreline orientation and also for coastal areas affected by anthropogenic activities like extensive beach sand mining, construction of hard structures, etc., as these activities can have a direct impact on the short-term as well as long-term shoreline changes. Hence, in the present study, the sediment transport mechanisms are described, using a small-scale analysis using the long-term data (approximately 25 years). Such spatio-temporal analysis, considering the inter-relationship between flow processes and the different coastal structures built along the coast has not yet been performed for the challenging coastal system of Kerala. The analysis of this relationship will help the local government planners define the coastal structures and implement a monitoring system capable of improving the understanding of beach response to any engineering work along the Kerala coast.

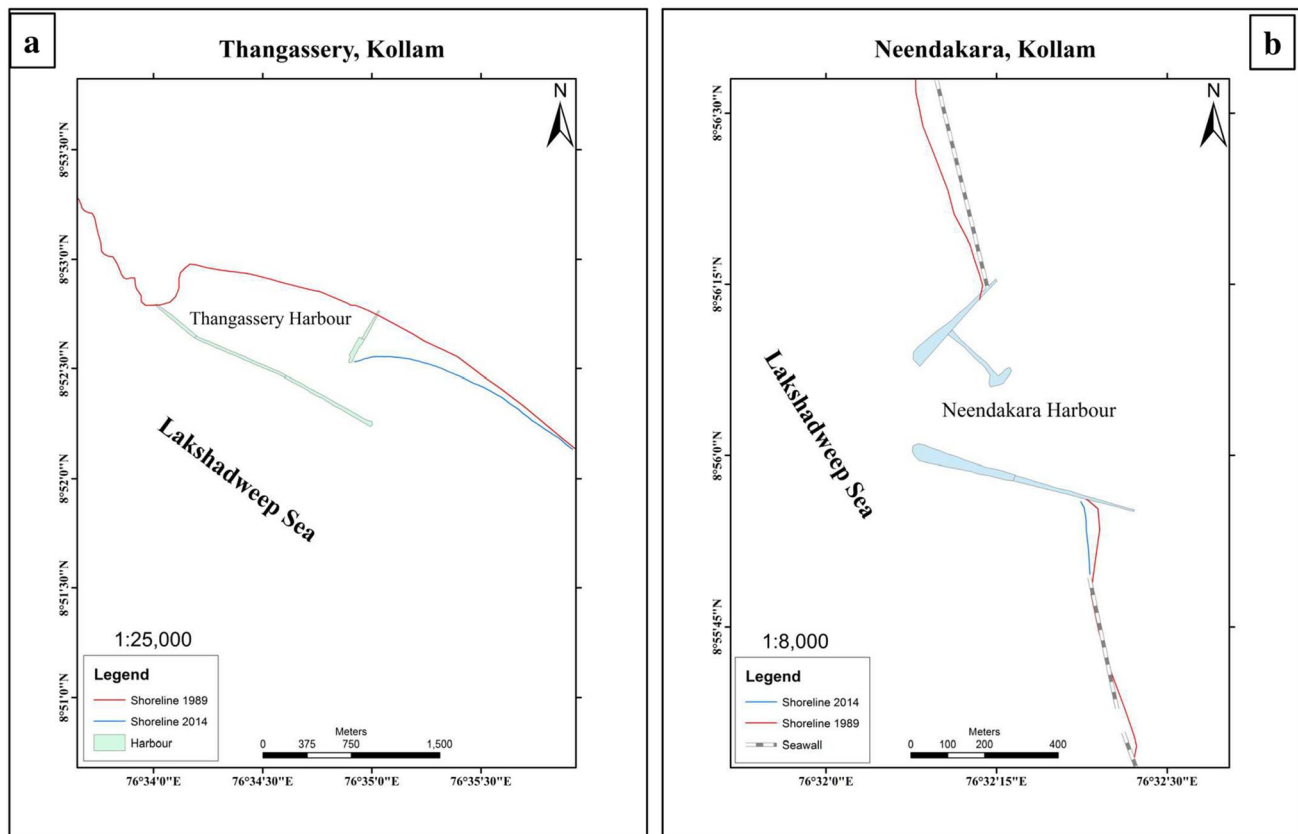


Fig. 3 Long-term shoreline variation at **a** Thangassery; **b** Neendakara

Regional settings

The Kerala coast is characterized by narrow stretches of sandy beaches interspersed by lateritic cliffs, rocky promontories, spits and bars, backwaters/kayals, estuaries and lagoons (Government of Kerala 2015). Sand dunes, barrier islands and 35 tidal inlets, both seasonal and perennial, add to its complexity. Sandy beaches and tidal inlets make this coast morphologically highly dynamic. Furthermore, the shoreline exhibits sudden changes in its orientation close to many of the cliffs and promontories. Recent observations indicate that the shoreline as a whole is dynamic and neotectonically active leading to considerable erosion and loss of surface area. Regional administration authorities have spent a large amount of money in the execution shore protection projects as a measure to counter erosion and reduce its negative impact on the coastal process and associated economic activities. About 20% of the economy of the state of Kerala depends upon the coastal areas (tourism, fishing, etc.). About 18 harbours and associated breakwaters have already been constructed. Furthermore, the construction of additional five harbours are in progress and few more have been proposed. There are also groins constructed at different locations along the Kerala coast (Fig. 1). In addition,

60% of coast is protected by seawalls and groins. All such modifications of the coast are part of the development and management plans; it may also trigger important changes in the coastal dynamics.

The Kerala coast experiences high wave activity during the southwest monsoon with relatively calm sea conditions prevailing during rest of the year. The waves approach from west and WSW during southwest monsoon, west and WNW during northeast monsoon and southwest during fair weather period (Kumar et al. 2006). The tidal range is in micro-tidal range and less than 1 m in central Kerala coast (Noujas et al. 2016) and hence plays a comparatively less role on the coastal processes. The net sediment transport along Kerala coast is not of uniform direction and it varies from place to place (Kumar et al. 2006; Thomas et al. 2013; Noujas et al. 2017; Neelima et al. 2018).

The southwest monsoon (June–September), post-monsoon (October–January), and pre-monsoon (February to May) are the major seasonal classifications 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 process have been classified under fair and rough seasons consisting of November–April and June–September, respectively (Baba and Kurian 1988).

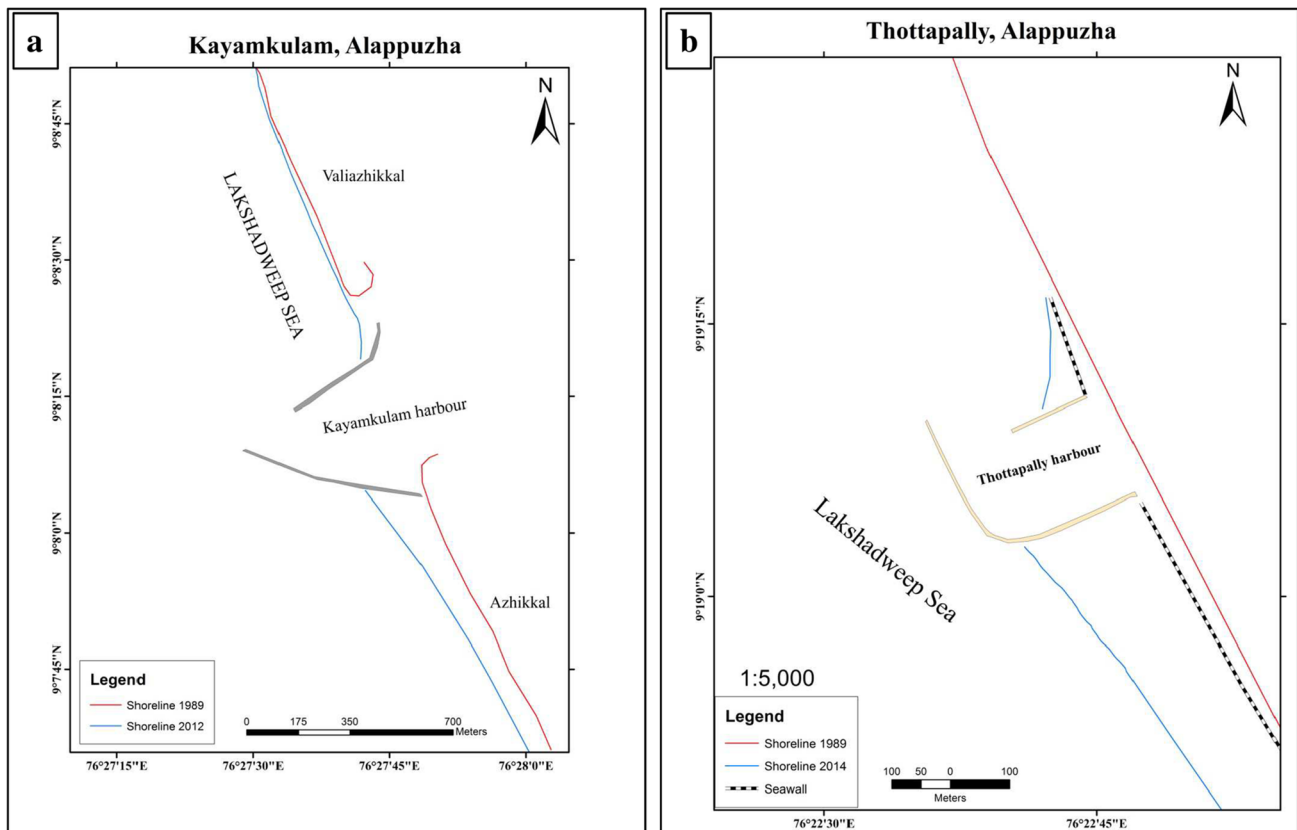


Fig. 4 Long-term shoreline change at **a** Kayamkulam; **b** Thottapally

May and October are transitional months. The rough season represents mostly monsoon period, while the fair season represents both pre-monsoon and post-monsoon months.

Methodology

Shoreline modifications and erosion accretion due to breakwaters and groins are obtained from a comparison of shoreline information derived from multdated maps (toposheets), imageries and GPS shoreline mapping. The shoreline prior to the construction of breakwaters and groins is obtained from Survey of India toposheets. The toposheets used pertain to the period 1989–1990 in 1:25,000 scale. Toposheets were initially registered with corner coordinates given by Survey of India and furthermore the collected ground control points (GCPs) were used in the process of georeferencing by applying affine transformation (first-order polynomial). The GCPs were well-distributed in the respective maps for improving the accuracy of shoreline analysis. Maps positional error is 0.25 mm on scale (6.25 m) and including all other errors, the resultant error for 1:25,000 scale toposheet is 12 m.

Thus, the shoreline variation above 12 m is only considered as shoreline change. Negative shoreline variation (> -12 m) indicates erosion and positive shoreline variation (> 12 m) indicates accretion. If shoreline variation is within 12 m range, it is considered as ‘no change’.

Toposheets were geo-referenced, vectorised and used as base map. The high water line (HWL) was extracted from the geo-referenced toposheets. Shoreline mapping using GPS survey was relied upon to get the present shoreline. It is ensured that the shoreline measured using GPS was tied to the control points identified in the toposheets. Extraction of shoreline was done after dividing the entire coastal stretch into morphological sub-cells with a sufficient number of GCPs in each sub-cell. Through this process, whatever error that occurs due to accuracy and resolution limitations of GPS and imageries or distortions in base maps will be confined within each sector. This could reduce the spatial errors getting accumulated and compounded. This approach was successfully used for the Panchayat Resource Mapping undertaken for the state of Kerala (Chattopadhyay et al. 2004).

Extensive field work was carried out during the year 2011–2014 using handheld GPS for collecting present

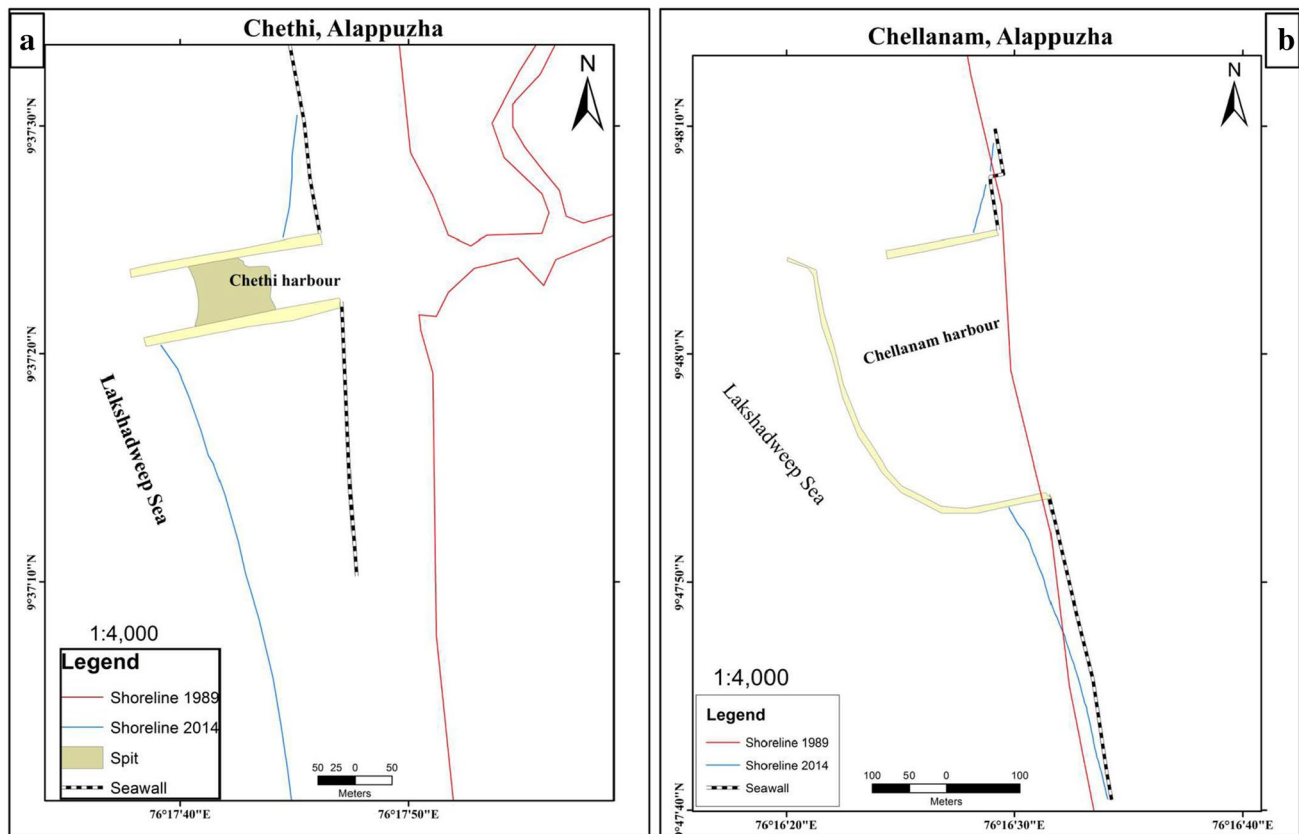


Fig. 5 Long-term shoreline change at **a** Chethi; **b** Chellanam

shoreline position, mapping coastal protection measures and harbour breakwaters. Local information was also collected further to confirm the shoreline change and sediment transport direction. Trimble GeoXT and Trimble Juno SB were the two types of GPS used in the present study. The GeoXT is 12 channel GPS with sub-metre accuracy. Without real-time differential correction capability, it has an accuracy of 2.5–3 m. When used as single units, the positions are always tied to known points at regular intervals to contain and minimise loss of spatial accuracy. Trimble Juno SB is a high sensitivity GPS receiver with a field computer powered by the Windows Mobile version of 6.1 operating system. The integrated GPS receiver provides accurate positioning information within 2–5 m when using real-time or post-processed differential correction and 1–3 m accuracy after post processing. Both GPS operated in geographic coordinates system and datum is WGS 84.

Results and discussions

The Kerala coast is mainly classified into three sectors based on its energy (Kurian 1987). The southern sector is a high-energy coast when compared with central

and northern sectors. The southern Sector includes three coastal districts Thiruvananthapuram, Kollam and Alappuzha. The central sector includes three coastal districts Ernakulam, Thrissur and Malappuram. The northern sector includes the coastal districts of Kozhikode, Kannur and Kasaragod.

Southern sector

The major/minor harbours and groins in the southern sector are considered for the present study for obtaining real scenario of the net sediment transport direction. Fishing harbours are constructed at Vizhinjam, Muthalapozi, Neendakara, Thangassery, Kayamkulam, Thottapally, Chethi and Chellanam along this sector. The breakwaters associated with these harbours continue to disturb the natural sediment transport in the vicinity of the structure. In the present investigation, groins constructed at Panathura, Poonthura, Valiazheekal and Arthungal were also considered.

The harbour breakwater at Vizhinjam has been constructed at a headland-pocket beach system. No significant

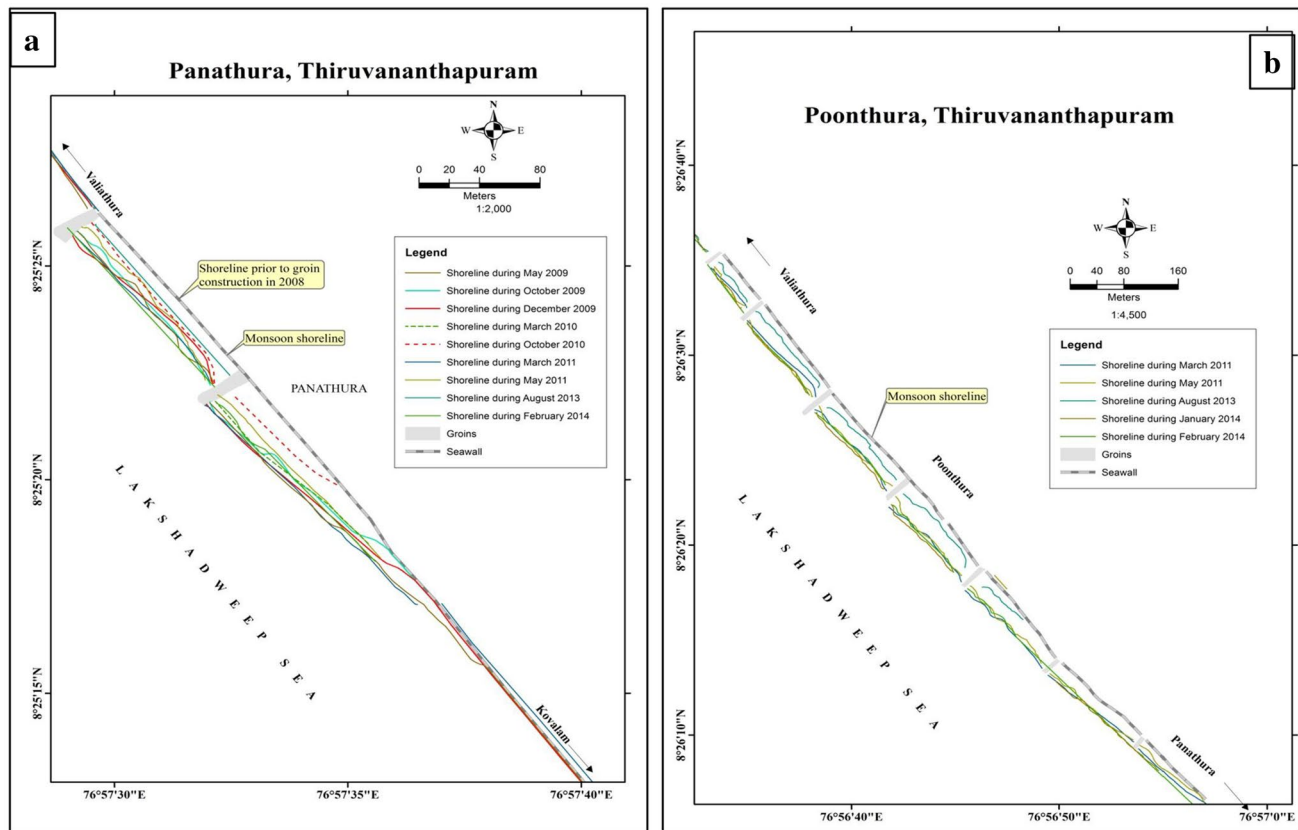


Fig. 6 Shoreline change at **a** Panathura; **b** Poonthura, Thiruvananthapuram

changes in the shoreline were noticed along the rocky headlands or pocket beaches on the northern side consequent to the Vizhinjam breakwater construction. However, the sandy coast towards south was affected by erosion during the construction of north breakwater (Fig. 2a). The construction of Muthalappozhi harbour breakwaters on either side of a seasonal tidal inlet resulted in the accumulation of sediment to the south of the breakwater. More than 100 m of shoreline advancement is observed towards south of the breakwater and erosion along the northern side (Fig. 2b). In general, the pattern of sediment deposit and shoreline change indicates that the net sediment transport along Muthalappozhi coast is northerly and in accordance with earlier reports for the region (Sajeev et al. 1997; Kumar et al. 2006; Shamji et al. 2010; Thomas et al. 2013; Noujas et al. 2014a; Sheela et al. 2015). However, it was observed that the cliff erosion immediately south of Vizhinjam harbour breakwater is a deviation from the above observed pattern (Neelima et al. 2018).

The waves along the Thiruvananthapuram coast are coming from southsouthwest (SSW) during the non-monsoon period (fair season) and from westsouthwest (WSW) with the onset of monsoon followed by west direction (Noujas et al. 2014a) resulting in the northerly transport

of sediment during most of the year, except during the rough monsoon period. The significant wave height (H_s) is less than 1 m during fair season and is upto 3.3 m during monsoon season (Noujas et al. 2017). Therefore, the breakwater at Muthalappozhi adversely affects the northern side of the harbour and hence identified as a critically eroding sector of Kerala coast (Noujas and Thomas 2015).

Thangassery breakwater is located further north of Muthalappozhi harbour, in Kollam coastal district. A similar pattern of beach building as in Muthalappozhi is observed at Thangassery with beach developing on the south side of the southern arm of the breakwater (Fig. 3a). This indicates that the net sediment transport along this sector is northerly and corroborates with study of Sheela et al. (2015) based on empirical methods. North of the north breakwater being a headland, its impact on the shoreline is minimum. Neendakara harbour is one of the oldest harbours in Kerala and sediment gets accumulated immediate south of this harbour and severe erosion is observed to the north side of the harbour (Fig. 3b), further confirming that the net sediment transport is northerly along this sector. Compared to other locations, sediment deposition is lesser along this sector which could be attributed to the lack of sediment availability towards

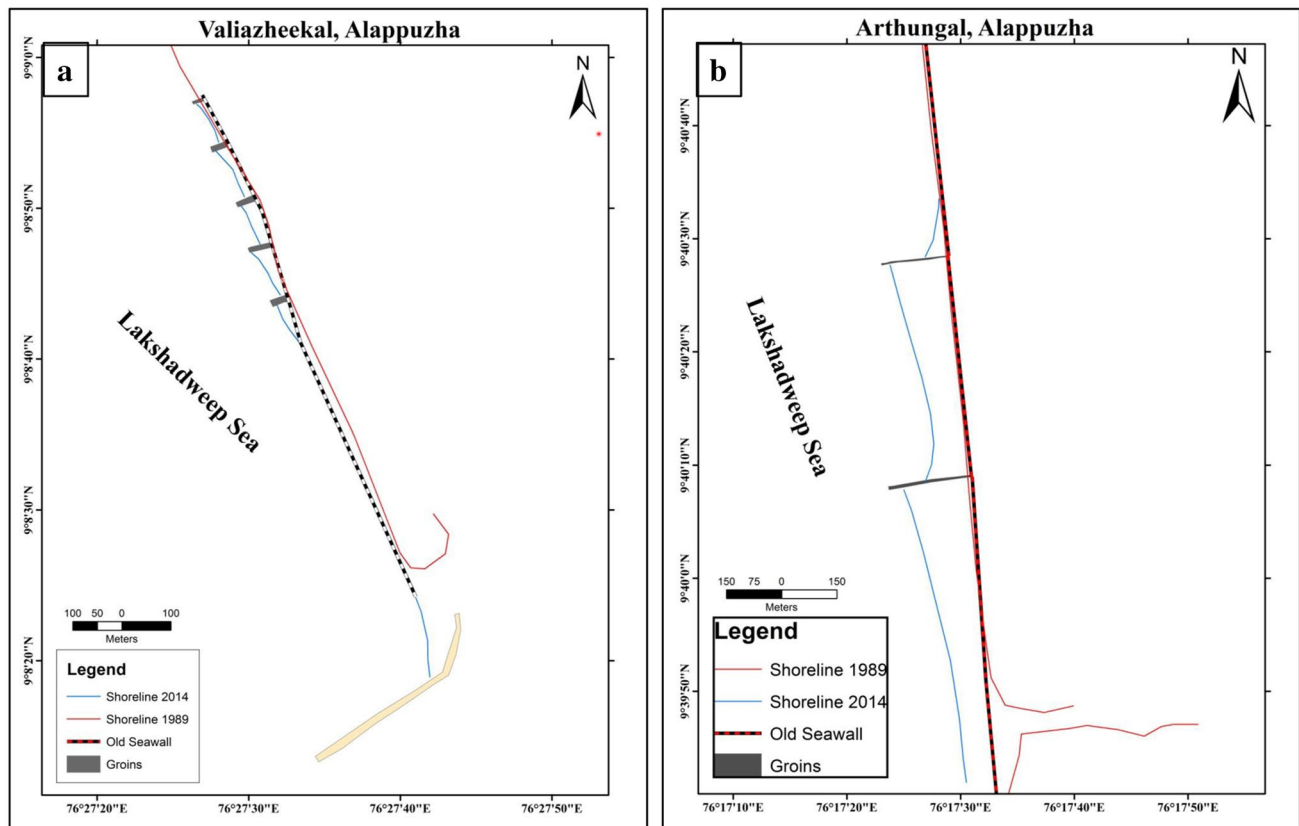


Fig. 7 Long-term shoreline change at **a** Valiazheekal; **b** Arthungal

south side of the Neendakara harbour due to the presence of Thangassery headlands.

Kayamkulam harbour is further north of Neendakara harbour and the shoreline has advanced south of the breakwater (Fig. 4a) after its construction in turn exhibiting northerly net sediment transport along Kayamkulam sector. H_s is in the range of 0.29–3.2 m along Neendakara to Kayamkulam sector (Prasad et al. 2016). Of these, about 55% of the H_s are in the range of 0–1.0 m and it is mostly during the non-monsoon period. The percentage occurrences of H_s in the range of 1–2 m is 36% and 9% H_s is more than 2 m. High wave activity is normal during the monsoon season, and hence, the percentage occurrence in a year is relatively low. About 73.3% of the waves are southerly to south-southwesterly direction, and this happens during the non-monsoon period. For the rest of the year, southwesterly to northwesterly directions dominate. Hence, the sediment transport is towards north except during the monsoons in the south of Kayamkulam inlet (Prasad et al. 2016). There is no change in shoreline on the north of the breakwater where seawalls are in position and regularly maintained. Wide beach has been observed south side of the Thottapally harbour due to

net northerly transport (Fig. 4b). Some beaches have formed immediate to the north side of the breakwater, whereas erosion is observed further northwards.

A wide beach is observed on the south side of the Chethi harbour (Fig. 5a) which reveals that the sediment transport is northerly along this sector. A small beach is also found immediately north of the harbour. Chellanam is a small harbour constructed further north of Chethi. Some beaches are observed on the immediate south and north side of the Chellanam harbour (Fig. 5b). In comparison with the other locations, beach advancement is less along this sector and dominant sediment transport along this sector is also northerly. The monthly averaged H_s along Allappuzha coast is in the range of 0.68–2.52 m and wave directions are 221°–250° (Sheela et al. 2015). The coastline orientation is around 255° with respect to true north and hence net sediment transport is towards north for all months (Sheela et al. 2015).

There are groin fields constructed along various locations of the southern sector and it can be also used as a sediment transport indicator. As a pilot project, two groins were constructed at Panathura along the southern side of Southern sector for protecting severely eroding coast (Noujas et al.

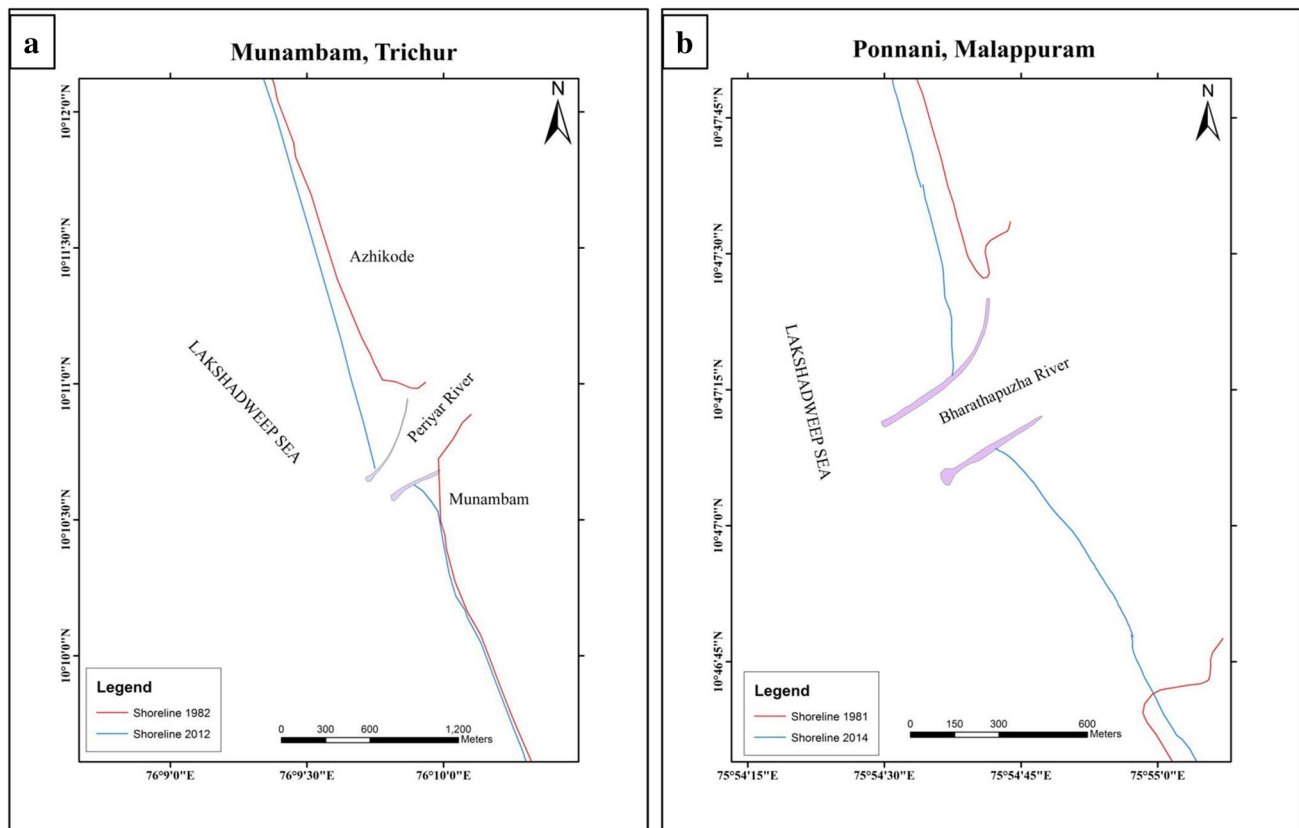


Fig. 8 Long-term shoreline change at **a** Munambam; **b** Ponnani

2017). Beach is formed in between groin field and south side of the groins. There is no beach on the north side of the northernmost groin (Fig. 6a). The same pattern was observed at Poonthura, a nearby coast, which also has a groin field (Fig. 6b). The result indicates that net sediment transport along this sector is northerly and it is supported with the results obtained using breakwater indicator. During the fair season, the wave direction is 199° – 214° and during the rough season the wave direction is in the range of 220° – 254° along this sector (Noujas et al. 2017). The shoreline normal is approximately 230° with respect to true north. Hence, the sediment transport during the second half of June to third week of August is southwards and for the remaining period it is towards the north at Panathura sector (Noujas et al. 2017). Recently, groins were constructed north side of Kayamkulam breakwater (Valiazheekal) and two groins were constructed at Arthungal of Alappuzha district. Beach development at this sector is further supporting the northerly net transport along Alappuzha coast (Fig. 7a, b). The results obtained from morphological indicators are very well-collaborating with the study of Sheela et al. (2015).

Central sector

Central sector mainly consists of the area extending from Munambam (Thrissur) to Ponnani (Malappuram). Pattern of shoreline advancement is unique at Munambam which is located in the central sector of the southwest coast. Sediments accumulated mostly on northern side of the breakwater (Fig. 8a) revealing dominance of southerly transport of sediment along this sector. The net sediment transport is $-119,271 \text{ m}^3/\text{year}$ at Munambam prior to breakwater construction (Noujas 2015) and negative sign indicates sediment transport direction is towards south. When the construction of the breakwater began, sediment was deposited on the north side of the breakwater due to the groin action and southerly transport. With the continuation of sediment accumulation during the succeeding years the shoreline attained equilibrium by 2004 and the coastline became concaved. Sediment drift computation with new shoreline showed a nominal value of $21,771 \text{ m}^3/\text{year}$ for the net sediment transport which indicates more or less equilibrium conditions (Noujas 2015).

The sediment deposited on the either side of Ponnani breakwater and the sediment deposition is observed more on the north of the breakwater (Fig. 8b). Beach build-up

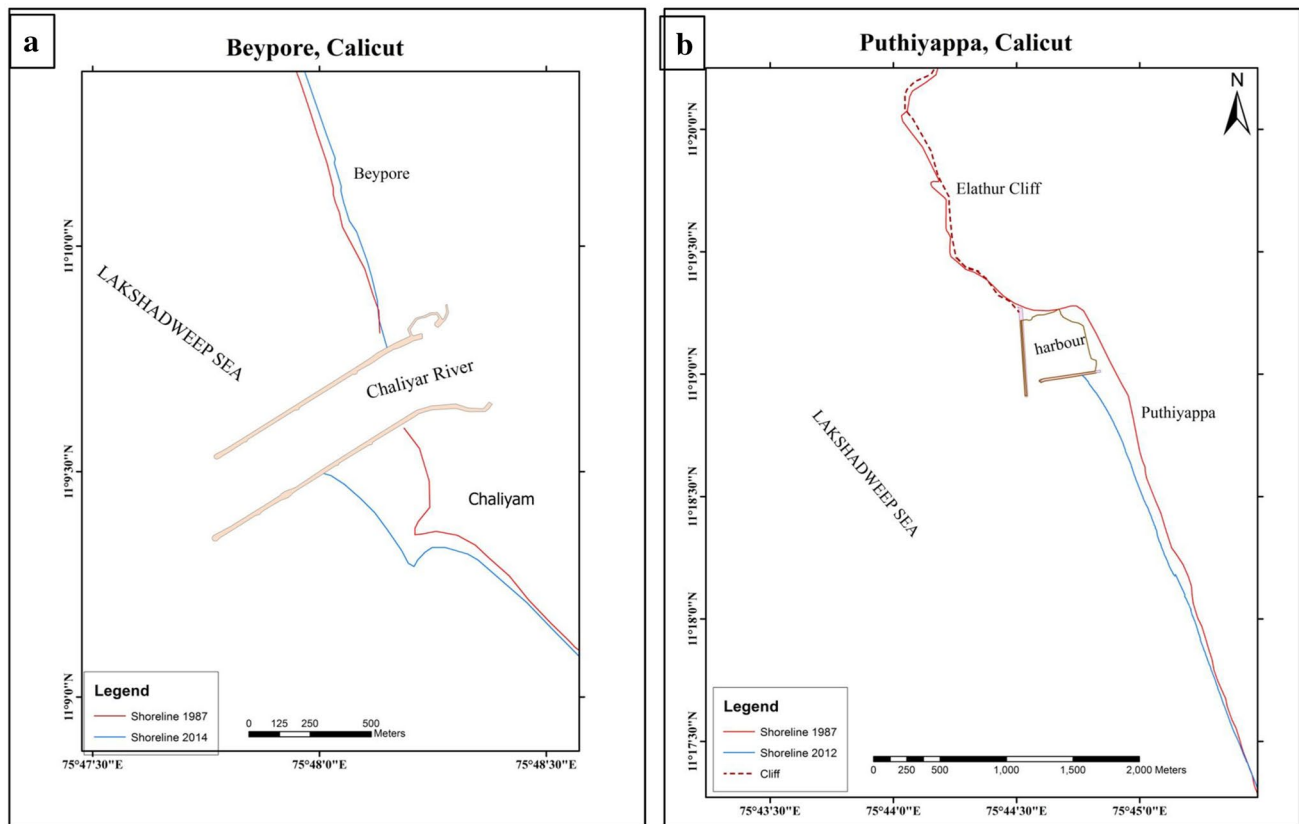


Fig. 9 Long-term shoreline change at **a** Beypore; **b** Puthiyappa

was limited immediately south of the breakwater and wide beach is observed on the north side of the breakwater and it continues towards north. The present study confirmed the net southerly sediment transport along this sector.

Northern sector

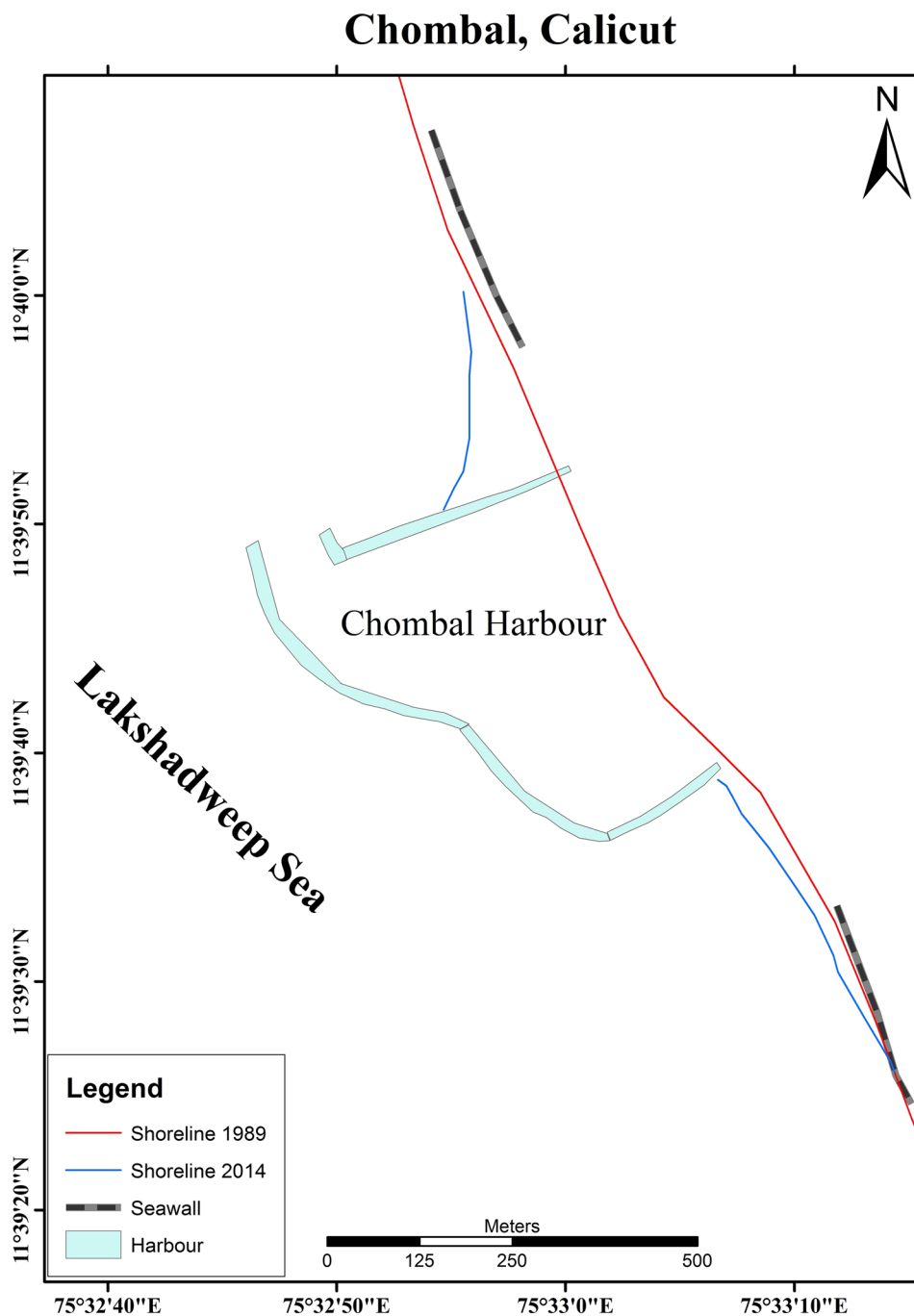
Northern sector includes the coastal districts of Kozhikode, Kannur and Kasaragod. The shoreline progradation shifts again to south at Beypore, Kozhikode and net northerly transport was seen further north too. Substantial beach build-up is noticed here, while the shoreline exhibited an erosion tendency north of the inlet except for a sand accumulation that was observed immediately north and close to the north breakwater (Fig. 9a). The net sediment transport along this sector is northerly and hence shoreline advanced south side of the breakwater. Similar pattern is evident at the south side of Puthiyappa harbour breakwater and more than 200 m beach has been formed (Fig. 9b). The result shows substantial net northerly sediment transport along this sector. The monthly average waves show majority of waves are coming from westsouthwest (WSW) except during monsoon months and hence northerly transport was dominant throughout the year except second week of July to first week of August at

Puthiyappa sector since shoreline normal is approximately 250°N (Noujas and Thomas 2018). Maximum northerly transport was obtained during May and northerly transport is more prominent during September–December. The impact on shoreline on the north side of the breakwater is minimum due to the presence of Elathur cliff.

Further north at Chombal, Kozhikode which is an open coast fishing harbour without a tidal inlet, beach build-up is visible on the either side of the harbour (Fig. 10). Northern side has a sand accumulation for a small area immediately north of the north breakwater. The same trend follows for Azhikkal, Kannur which is further north of Chombal, but the deposition is maximum on the south side of the breakwater (Fig. 11) indicating net northerly transport.

Sediment transport pattern is towards north in Southern sector and towards south in Central sector. The net sediment transport is bidirectional in a few places in northern sector. This difference in sediment transport pattern is due to changes in the quantum and direction of longshore sediment transport which is dependent on the obliqueness of waves with the shoreline. In general shoreline orientation is SE–NW in Southern sector and SSE–NNE in Central and Northern sector. The waves along Southern sector are mainly from southsouthwest (SSW) during the non-monsoon period

Fig. 10 Long-term shore-line variation at Chombal, Kozhikode



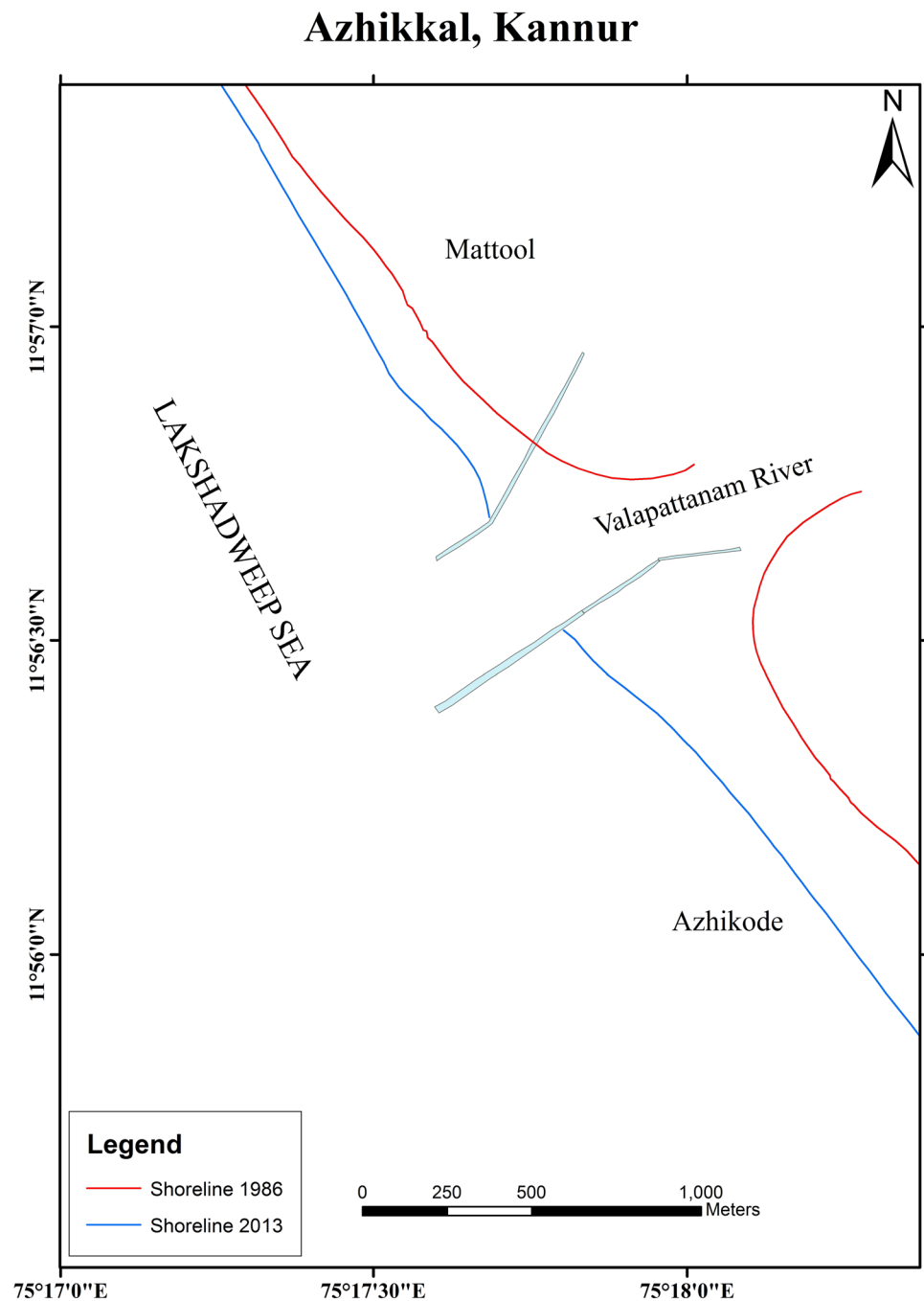
(fair season) and from westsouthwest (WSW) with the onset of monsoon followed by west direction. This resulting the northerly transport of sediment during most of the year, except during the rough monsoon period in Southern sector due to SE–NW shoreline orientation. The majority of waves are coming from west and westsouthwest (WSW) in Central sector and hence southerly transport is dominating in this sector. Majority of waves are from westsouthwest (WSW) except during monsoon months in Northern sector and hence northerly transport was dominant throughout the year where

majority of waves makes an inclination to the coast favoring northerly transport.

Conclusion

Sediment deposition pattern adjoining breakwaters and groins are indicative of net sediment transport direction. The southwest coast of India reveals northerly trend for sediment

Fig. 11 Long-term shoreline change at Azhikkal, Kannur



transport along its southern and some part of the northern sectors. Cliff erosion immediately south of Vizhinjam harbour breakwater is a deviation from the above observed pattern. The central sector witnesses net southerly sediment transport. The northern sector shows net northerly transport, however, the transport is found to be balancing in both directions at few locations. The present study is in good agreement with the available studies and also confirms that the sediment transport along the Kerala coast is highly complex and site specific.

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