J. Earth Syst. Sci. (2023)132 31
https://doi.org/10.1007/s12040-023-02047-8

Quantitative assessment of shoreline changes along the tropical West Coast, Maharashtra, India: A remote sensing and GIS approach

Milind A Herlekar[1,*], Prafull B Kamble[1], Praveen B Gawali[2], Pramod T Hanamgond[3] and Sainath P Aher[4]

[1]*Department of Geology, Savitribai Phule Pune University, Pune 411 007, India.*
[2]*Indian Institute of Geomagnetism, Navi Mumbai 410 218, India.*
[3]*Department of Geology, GSS College, Tilakawadi, Belagavi 590 006, India.*
[4]*Department of Geography, S.N. Arts, D.J.M. Commerce and B.N.S. Science College, Sangamner 422 605, India.*
**Corresponding author. e-mail: milindaherlekar@gmail.com*

MS received 4 December 2021; revised 19 October 2022; accepted 20 October 2022

Shoreline changes have been monitored for the tropical West Coast of Maharashtra using the Survey of India (SOI) toposheet, Remote Sensing (RS) data, and its incorporation in the Geographical Information System (GIS) for the time period from 1980 to 2013. Indian Remote Sensing (IRS) Resource Sat (P6-R2) satellite data of 2013 year were geocoded using an image-to-image rectification process with the help of permanent points on the ground. The registered satellite imageries were added in Arc GIS 10.3 software with a false colour composite (FCC) band combination (3:2:1) to get clear contrast of the land–water boundary. The toposheet and satellite imagery waterlines were digitised using the line feature in Arc GIS 10.3 software. The shorelines digitised for different years were overlaid, and polygons were created for every changed location to compute shoreline changes from 1980 to 2013 to quantify the rate of erosion or accretion along the shoreline under investigation. Computed results were validated through detailed ground observations. The obtained results indicate that ∼265 km (45.28%) of the coast is under erosion, ∼234.17 km (40.02%) under deposition and ∼85.97 km (14.70%) of the coast is stable. Maximum shoreline erosion is observed in the northern part extent from the Alibag to Shrivardhan and the deposition in the southern part of the coastal tract. The Maharashtra coast lost ∼1.65 km^2 net area during 1980–2013. In some places, sand spits are growing or receding in response to coastal currents and storm events. The present pattern of shoreline changes is related to physical setting of the shoreline, varying wind and wave climate and anthropogenic activity.

Keywords. Shoreline changes; RS-GIS; erosion–accretion; Maharashtra coast.

1. Introduction

It is well known that the Indian coastline stretches over 7500 km and is quite densely populated (Sanil *et al.* 2006). The west coast of India experiences southwest (summer) monsoon (June–September) and fair-weather (October–May), which includes northeast (winter) monsoon, pre- and post-monsoon seasons. The coast is quite diverse, where wind, waves and tidal processes modify or shape, making it one of the most dynamic environments. Indian beaches attract millions of visitors from

Published online: 13 February 2023

within and outside the country for their aesthetic value and recreational purpose, lending a helping hand to the tourism industry (Gawali *et al.* 2010). The conspicuous geomorphological features along this coast include sea cliffs, sea caves, wave-cut platforms, embayed coves, beaches, estuaries, river mouths, tidal inlets, sandbars and spits (Herlekar and Sukhtankar 2011). Shoreline morphology and nearshore hydrodynamics are manifested by offshore and nearshore waves through tidal variations, breaking or multiple breaking waves, waves, rip currents and longshore currents aided by anthropogenic influences. This coastline and allied coastal zone are economically productive, providing livelihood to millions of people in its vicinity. Thus, shoreline change can alter the economic returns of the coastal community.

The last few decades have shown many developmental and construction activities like jetties, harbours, landing centres and sea walls. These natural resources and anthropogenic facilities were prone to natural hazards, viz., coastal flooding and cyclone (2009) and tsunami (2004). The coast of Maharashtra experiences waves in WNW–NW direction, though most waves shift westward (Chowdhury *et al.* 2019). Yang *et al.* (2020) studied the coastlines of southeast Asia (Myanmar, Vietnam, and Malaysia) from 2000 to 2015. Their study indicated a reduction in the length from 15440 (83.33%) to 14909 km (79%).

The quantitative changes in shoreline geometry are essential to understand the areas that are susceptible to erosion and accretion. Such a study will help for all the coastal zone management programmes such as-recreational structures, harbour development, fishery culture, etc., that will uplift the economic status of the coastal community as well as resources to the government. The SOI toposheets, remote sensing data, GIS software, etc., have been used extensively by several researchers to estimate erosion/accretional patterns to understand beach and nearshore processes on small to regional scales.

Several studies have been attempted (Agrawal and Guzder 1972; Kale and Rajaguru 1985; Wagle 1989; Nayak 2000; Hanamgond and Mitra 2008, 2012; Gawali *et al.* 2010; Hanamgond 2012; Misra and Balaji 2015) to delineate coastline changes at varying spatial scales. The dynamical nature of the nearshore zone needs to be monitored closely and periodically to catch up with the shoreline changes that can impact the geometry and geomorphology of the coastal zone. In the present study, an attempt was made to study the Maharashtra coast (between Alibag and Tarkarli) to understand the morphodynamic changes it has undergone over the three decades from 1980 to 2013.

2. Study area

The coast of Maharashtra, well known as the Konkan coast, is a narrow coastal strip of land lying between the Sahyadri Ghats and the Arabian Sea (figure 1). The coastal stretch of Maharashtra is topographically very rugged with great mountain peaks and deep winding valleys, besides gorges, transverse ridges, faults, lineaments, dykes, bays and coves (Gawali *et al.* 2017; Aher *et al.* 2019). Mudflats and mangroves stretches occur in estuarine zones, which get exposed during low tide significantly.

The geology of coastal Maharashtra has been dealt with by several researchers earlier; the noted ones are Bruce Foote (1876); Iyer (1939); Powar (1993); Sukhtankar (1995); Widdowson and Cox (1996); Mitchell and Widdowson (1991). According to Deshpande (1998), the oldest rocks in the area are biotite gneiss (3500 ma). The area also contains Proterozoic formations represented by the Kaladgi formations, such as conglomerate, sandstone, and shale. These occur as inliers and are termed as Konkan Kaladgis. The southern part of Maharashtra (Sindhudurg district) reveals the occurrence of peninsular gneissic complex, Deccan Traps, banded magnetite quartzite, amphibolites, meta-gabbros, etc. (Sarkar and Soman 2010), whereas the Deccan volcanic basalts cover most of the northern parts. Deccan basalts representing Poladpur and Ambenali formations belonging to Upper Cretaceous to Lower Eocene are found in the Konkan coastal terrain (Subbarao and Hooper 1988). Laterite deposits occur as blankets and cover most of the coastal plains forming the plateaus. The Miocene–Pliocene formations can be found in Tertiary sediments comprising lignite and shale, which are observed at places along Ratnagiri and Sindhudurg coastal tracts. The Uran beach rock is suggested to have formed during the last interglacial period at high sea level or formed due to neotectonic activity (Kale *et al.* 1984).

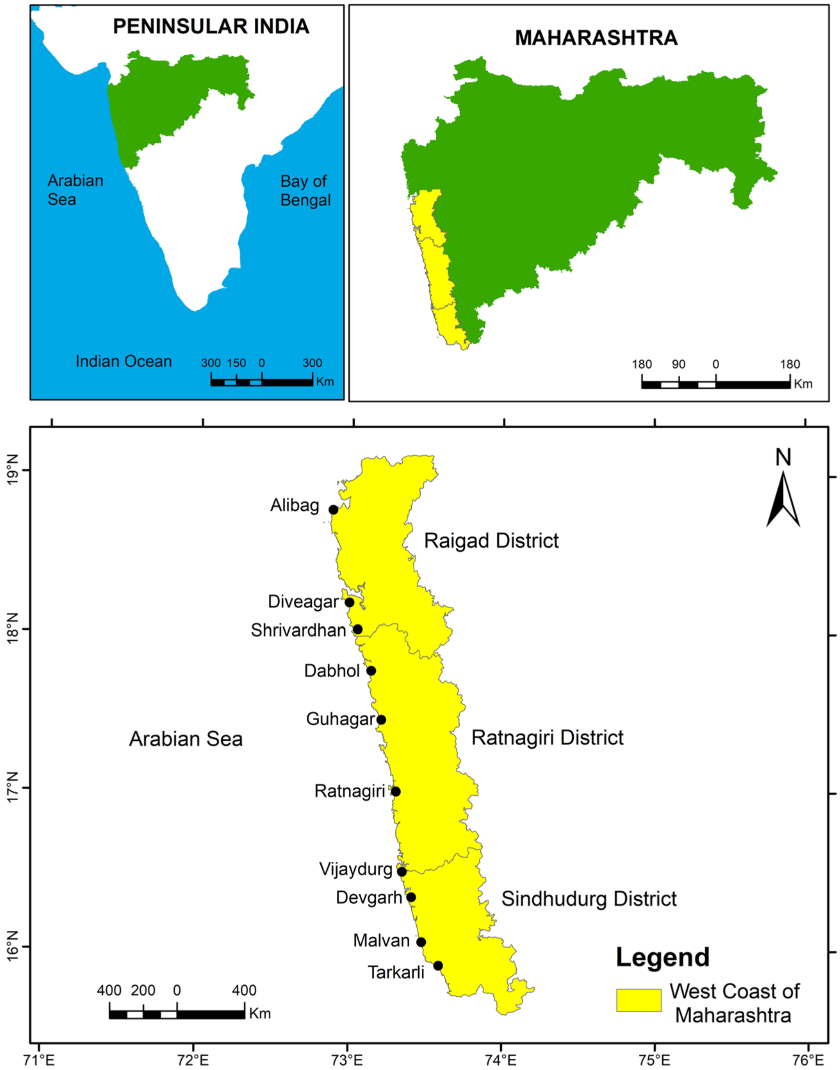

Figure 1. Location map of the study area.

3. Materials and methods

The base maps were prepared by using SOI toposheets 47B/14, 47B/15, 47B/16, 47G/1, 47G/2, 47G/3, 47G/4, 47G/5, 47G/6, 47G/7, 47H/4, 47H/5, 47H/6, 47H/7, 47H/8 and 48E/5 of a scale 1:50,000 (1980) and LISS-IV satellite imageries IRS Resource Sat-2 satellite imageries for the year 2013 (table 1). Both the datasets were incorporated in the GIS environment, and the shoreline changes over three decades from 1980 to 2013 were studied.

The shorelines digitised for different years were overlaid, and polygons created, which were used to quantify the rate of erosion or accretion or the equilibrium state (erosion and accretion). Spatial shoreline changes have been inferred from the high tide line traced from 1980 and the variation through time till 2013. To check out the veracity of the results obtained, ground truth investigations were carried out along the study area.

Table 1. *Used Indian Remote Sensing satellite data.*

Sl. no.	Satellite	Sensor	Path/row	Resolution (m)
1	IRS-P6-R2	LISS IV	095/062	5.8
2	IRS-P6-R2	LISS IV	095/061	5.8
3	IRS-P6-R2	LISS IV	096/061	5.8
4	IRS-P6-R2	LISS IV	095/061	5.8
5	IRS-P6-R2	LISS IV	094/060	5.8
6	IRS-P6-R2	LISS IV	094/059	5.8
7	IRS-P6-R2	LISS IV	095/060	5.8

4. Results

The Maharashtra coast extends from the Palghar district, just north of Mumbai, to the South of Redi near Terekhol River. The coastline around Mumbai is continuously and anomalously affected by anthropogenic activities and hence, not considered in this study. The present study area, from north to south, has been divided into (1) Alibag to Rajapuri, (2) Rajapuri to Shrivardhan, (3) Velas to Anjarle, (4) Anjarle to Murud, (5) Murud to Kolthare, (6) Kolthare to Palshet, (7) Palshet to Tavsal, (8) Saitavada to Bokarwadi, (9) Bokarwadi to Devgarh, (10) Devgarh to Kolamb, and (11) Malvan to Tarkarli.

4.1 *Alibag to Rajapuri*

This stretch can be divided into three units based on their morphological characteristics. The first unit comprises the shoreline between Alibag and Revdanda; and is characterised by a linear beach, stretching NW–SE. The stretch has been observed to be significantly eroded. The second stretch from Revdanda to Mazgaon, is almost north–south. The third stretch extends from Mazgaon to Dande near Rajapuri creek towards south, which also shows significant erosion, is oriented NW–SE and is quite steeper than the Alibag–Revdanda stretch. It can be observed from figure 2(A) that in the areas in proximity to all the water bodies/rivers, the incision is prominent, giving rise to bays near Revdanda, Mazgaon, and Dande. Alibag to Rajapuri shoreline of about 63.28 km (23.88%) has undergone erosion, whereas the depositional shoreline is 3.59 km (1.53%), with a stable region of 6.75 km (7.86%).

4.2 *Rajapuri creek to Shrivardhan*

The shoreline between Rajapuri creek and Shrivardhan can be divided into three stretches. The first stretch from Kudgaon to Adgaon can be defined as a promontory, which has been eroded near the mouth of the Mandad River. The shoreline is almost NS, with processes of erosion more active in the northern portion and deposition in the southern. The second stretch from Adgaon to Shekadi is an incised bay having crescent-shaped pocket beaches (figure 2B). The entire stretch is inferred to be eroded, with maximum erosion occurring between Adgaon and Diveagar (figure 3a, b, and c). The third stretch from Shekadi to Shrivardhan is oriented in NW–SE direction. The estimated shoreline of erosion from Rajapuri creek to Shrivardhan is 40.47 km (15.27%), whereas deposition occurs along 6.60 km (2.82%), with the stable shoreline around 9.09 km (10.57%) (table 2).

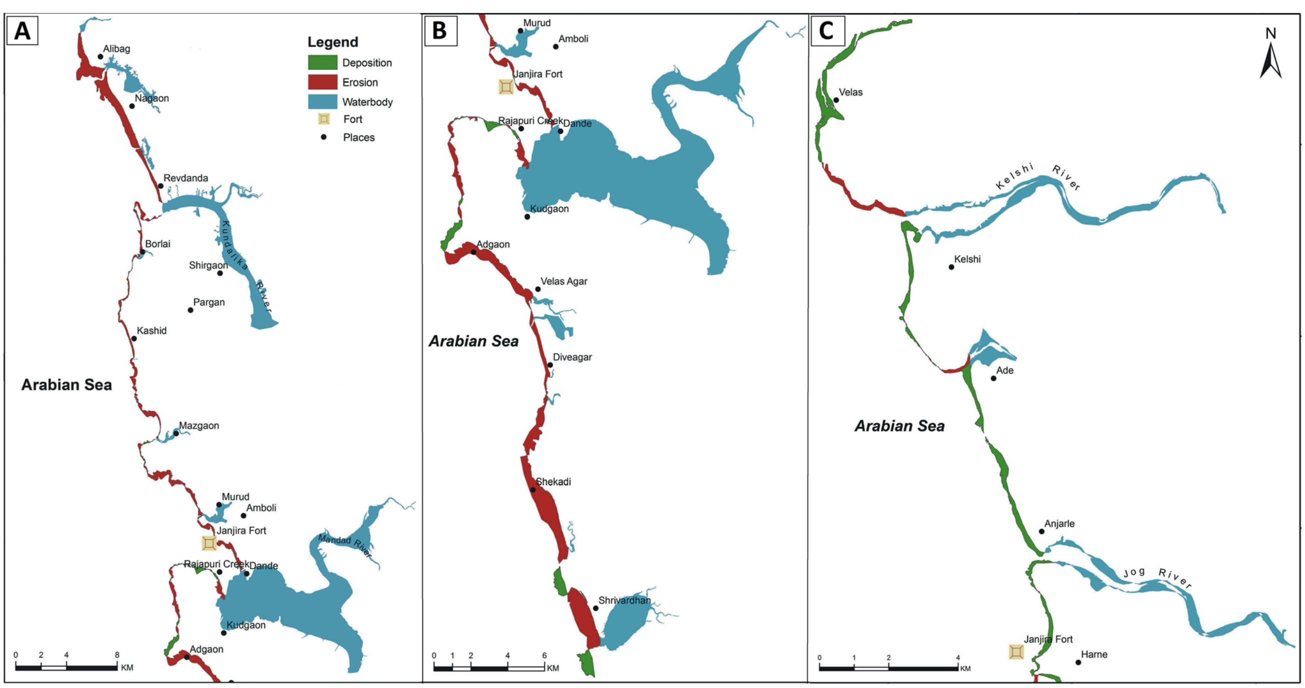

Figure 2. Shoreline changes from **(A)** Alibag to Rajapuri, **(B)** Rajapuri creek to Shrivardhan, and **(C)** Velas to Anjarle.

Figure 3. **(a)** Coastal erosion at Diveagar beach, locality: Diveagar, **(b)** Erosion at Maliwadi beach, locality: Maliwadi, Diveagar, **(c)** Erosion at Maliwadi beach, locality: Maliwadi, Diveagar, **(d)** At the mouth of Jog River recurved sandspit are formed, locality: Anjarle, **(e)** Wave-cut notch are formed at the base of Harnai headland, locality: Harnai and **(f)** At the base sea cliff eroded and rock felled down, locality: Harnai.

4.3 *Velas to Anjarle*

This coastal stretch exhibited both erosion and deposition (figure 2C). At Velas, the beaches are arcuate and narrow. The cliff is very steep and is seen to be retreating due to strong wave activity at its base. There is also substantial subaerial erosion of the cliff face. The erosion has occurred south of Velas near the mouth of the Kelshi River. The Ade to Anjarle shoreline is linear, trending NW–SE is characterised by deposition. At the mouth of the Jog River, near Anjarle, a sand spit is formed stretching towards the south (figure 3d). The spit length increases when the prevalent waves and currents are generated by shore drift. The Velas to Anjarle shoreline is experiencing an erosion of 15.98 km (6.03%), and deposition occurred along 16.62 km (7.12%), with a stable area of 1.28 km in length (1.49%).

4.4 *Anjarle to Murud*

The shoreline changes at this stretch are totally in the realm of deposition. Murud beach is almost straight, with a very low gradient exhibiting sandbar and spit (figure 4A). Near Harnai, the headland is present, which has been eroding (figure 3e and f). The estimated shoreline with

Table 2. *Alibag to Tarkarli shoreline changes under erosion, deposition and stable length.*

Sl. no.	Shoreline location	Erosion length (km)	Deposition length (km)	Stable length (km)
1	Alibag to Rajapuri	63.28 (23.88%)	3.59 (1.53%)	6.75 (7.86%)
2	Rajapuri to Shrivardhan	40.47 (15.27%)	6.60 (2.82%)	9.09 (10.57%)
3	Velas to Anjarle	15.98 (6.03%)	16.62 (7.12%)	1.28 (1.49%)
4	Anjarle to Murud	1.00 (0.37%)	23.15 (9.88%)	1.12 (1.30%)
5	Murud to Kolthare	13.85 (5.22%)	9.34 (3.99%)	0.80 (0.93%)
6	Kolthare to Palshet	18.26 (6.89%)	21.39 (9.13%)	7.01 (8.15%)
7	Palshet to Tavsal	19.34 (7.34%)	16.26 (6.94%)	13.77 (16.01%)
8	Saitavada to Bokarwadi	30.97 (11.69%)	66.86 (28.55%)	15.87 (18.46%)
9	Bokarwadi to Devgarh	29.87 (11.27%)	28.45 (12.15%)	25.36 (29.50%)
10	Devgarh to Kolamb	17.17 (6.48%)	26.41 (11.27%)	1.44 (1.68%)
11	Malvan to Tarkarli	14.73 (5.56%)	15.50 (6.62%)	3.48 (4.05%)
	Total	**264.92**	**234.17**	**85.97**

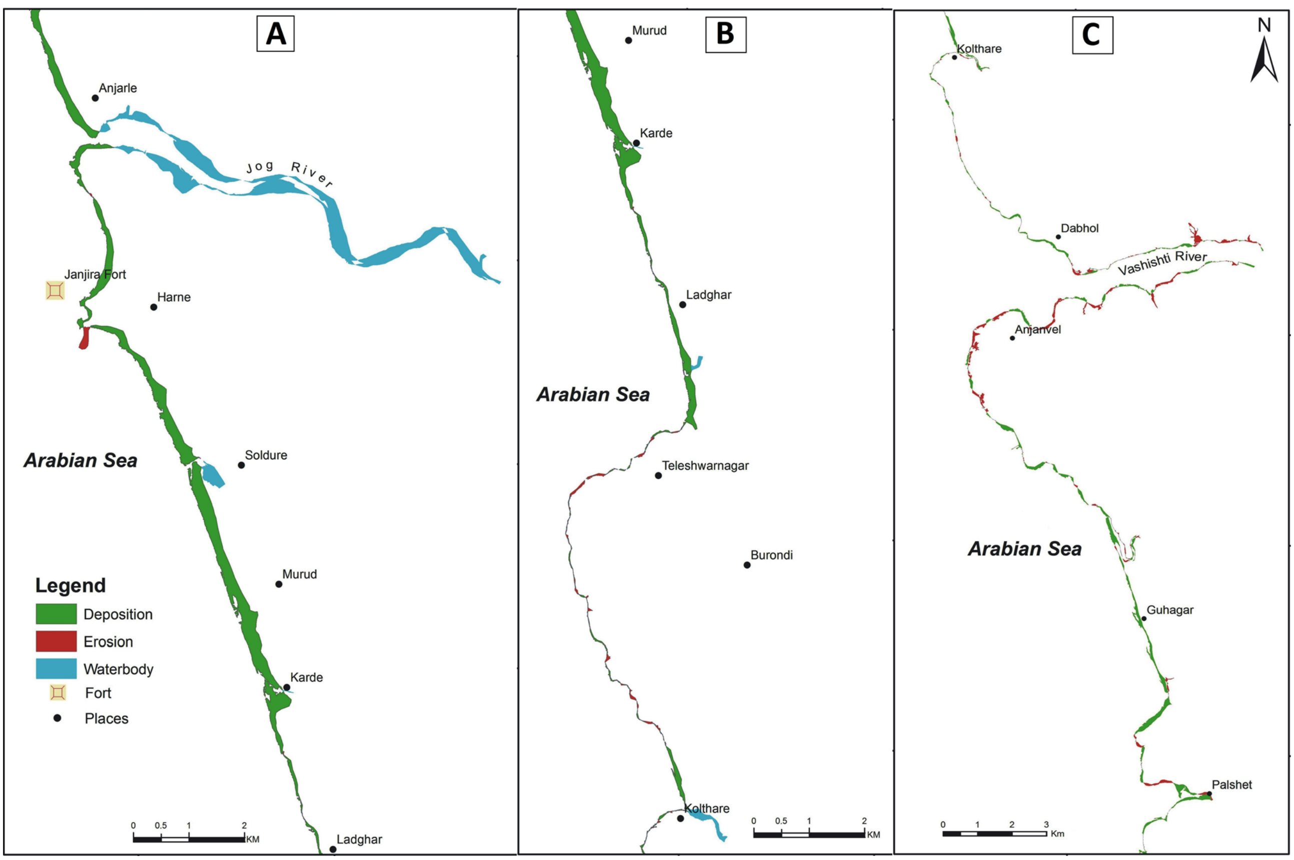

Figure 4. Shoreline changes from **(A)** Anjarle to Murud, **(B)** from Murud to Kolthare, and **(C)** from Kolthare to Palshet.

erosion is about 1.00 km (0.37%), deposition occurring along 23.15 km (9.88%), with stable shoreline around 1.12 km (1.30%) in length.

4.5 *Murud to Kolthare*

Murud to Teleshwarnagar shoreline is linear and oriented in NW–SE direction, exhibiting almost gentle beaches with a very low gradient. The beaches are quite expansive because of significant deposition. A jagged shoreline marks the stretch from Teleshwarnagar to Kolthare because of the presence of headlands and promontories at Burondi (figure 4B). The constant wave attack on this headland has given rise to a distinct physical setup, resulting in pocket beaches of variable extent. The estimated shoreline with erosion is 13.85 km (5.22%), and deposition along 9.34 km (3.99%) with a stable shoreline of 0.80 km (0.93%) (table 2).

4.6 *Kolthare to Palshet*

The stretch from Kolthare to Dabhol is seen to have undergone accretionary process with some strands of erosion that have been observed in its middle part. The estuarine belt associated with the Vashishti River displays alternating erosion and deposition along its banks on both sides. The erosion has been observed at Anjanvel headland, whereas deposition is a dominant process till Palshet. The Guhagar beach is almost linear, stretching in NW–SE direction (figure 4C). Along the Kolthare to Palshet shoreline, erosion is found to be 18.26 km (6.89%), whereas deposition occurred along 21.39 km (9.13%), with a stable shoreline of 7.01 km (8.15%) (table 2).

4.7 *Palshet to Tavsal*

The Palshet to Tavsal shoreline is variable, with pocket beaches and bays formed due to intense erosion. At Palshet, accretionary processes were active, whereas erosion was active near Boria Bandar headland. The wave energy concentration is due to wave refraction at Boria Bandar headland, and a reduction of wave energy is seen along the Velneshwar bay (figure 6A). The pocket beaches are observed at Hedvi, Narvan, and Rohile. The estimated shoreline of erosion is deciphered to be 19.34 km (7.34%), and deposition along 16.26 km (6.94%), with a stable shoreline of 13.77 km (16.01%) (table 2).

4.8 *Saitavada to Bokarwadi*

From Saitavada to Bokarwadi, the shoreline is gently trending NW–SE exhibiting pocket beaches and embayments (figure 6B). The beaches straddling at Malgund and Bhandarpule are quite linear and marked by large swaths of the deposited material. Mirya and Ratnagiri headlands experience wave convergence, because of which the headland gets eroded and facilitates the removal and dispersal of detrital material. The southern stretch from Ratnagiri to Bokarwadi depicts alternate extents of erosion and deposition. The erosion is quite significant at the base of the headlands, especially at Ranpur (figure 5a). The Saitavada to Bokarwadi shoreline experiences erosion of 30.97 km (11.69%) in length, and deposition is observed along 66.86 km (28.55%), with a stable shoreline of 15.87 km (18.46%).

4.9 *Bokarwadi to Devgarh*

This stretch can be divided into three units; the first stretch, Bokarwadi to Ambolgarh, exhibits conspicuous erosion, especially from Wada Vetye to Ambolgarh (figures 5b, c, d, and e). The headland marks the middle portion from Ambolgarh to Vijaydurg, where Tulsunde cove can be seen with significant erosion (figure 6C). The erosion is quite significant on the northern side of Vijaydurg. The beaches are partially sheltered due to the tombolo effect formed along the lee side of Vijaydurg island. Gujar *et al.* (2008) have studied wave refraction and the effects of sediment redistribution along Wada Vetye, Ambolgarh, and Vijaydurg coast. From Vijaydurg to Devgarh, the coastline is linear, trending NW–SE, punctuated at places by bays and coves. At Kolwadi and Kothar, erosion is more than deposition (figures 5f, 7a, b). The estimated eroded shoreline is 29.87 km (11.27%), deposition occurred along 28.45 km (12.15%), with a stable shoreline of 25.36 km (29.50%).

4.10 *Devgarh to Kolamb*

The Devgarh to Kolamb shoreline is linear and trends NW–SE, exhibiting significant deposition. The erosion is active at the south of Devgarh, Kunkeshawar promontory and Shegulwadi, whereas the middle and southern stretches are observed to have significant deposition (figure 8A). The formation of spits at Morvewadi, Munge, Apwadi, and Tondavali is due to the shifting of the river mouths towards the south (figure 7c, d, e, and f). The estimated eroded shoreline is 17.17 km (6.48%), and deposition along 26.41 km (11.27%), with a stable shoreline of 1.44 km (1.68%).

4.11 *Malvan to Tarkarli*

The Malvan to Tarkarli shoreline is marked by an undulating shoreline exhibiting conspicuous deposition. The southern part of the Malvan coastline is crescent and experienced erosion. At Tarkarli, deposition is observed. At Tarkarli, a long curvilinear spit is formed at the Karli River mouth (figure 8B). The estimated shoreline of erosion is

Figure 5. **(a)** Sea cliff eroded near Ranpur headland, locality: Ranpur, **(b)** Coastal sea cliff erosion, locality: Ambolgarh, **(c)** Coastal erosion occurs near Ambolgarh headland, locality: Ambolgarh, **(d)** Recession of sea cliff at Ambolgarh, locality: Ambolgarh, **(e)** Large lateritic boulder toppled, locality: South of Ambolgarh Plate, **(f)** Recession of coastal headland, locality: Kolwadi, Vijaydurg.

14.73 km (5.56%), and deposition occurred along 15.50 km (6.62%), with a stable shoreline of 3.48 km (4.05%).

5. Discussion

Our present results suggest that the coast of Maharashtra is in a dynamic flux. The northern portion is undergoing significant erosion as compared to the central and southern portions (table 2). The present study also reveals that the erosion is more prominent along the coasts from Alibag to Shrivardhan; Murud to Kolthare; and Palshet to Tavsal (figure 9); whereas the deposition has been observed along Anjarle to Murud; Saitvada to Bokarwadi; Devgarh to Kolamb (figure 9); and from Malvan to southern end of Tarkarli. At other places, no observable changes were noticed in beach morphology (erosion or accretion).

5.1 *Natural and anthropomorphic causes of beach erosion and deposition*

Wind and waves, diurnal and seasonal forcings, and sources and nature of sediments strongly influence the hydrodynamical, sedimentological and littoral transport processes. Based on the direction of wave approach and the physical setup of the coast, sediment movement has been found to be both towards the north and south (Gawali *et al.* 2010). The onshore and offshore sediment transport is primarily dependent on the tidal fluctuation, type of breakers, steepness of waves, wave

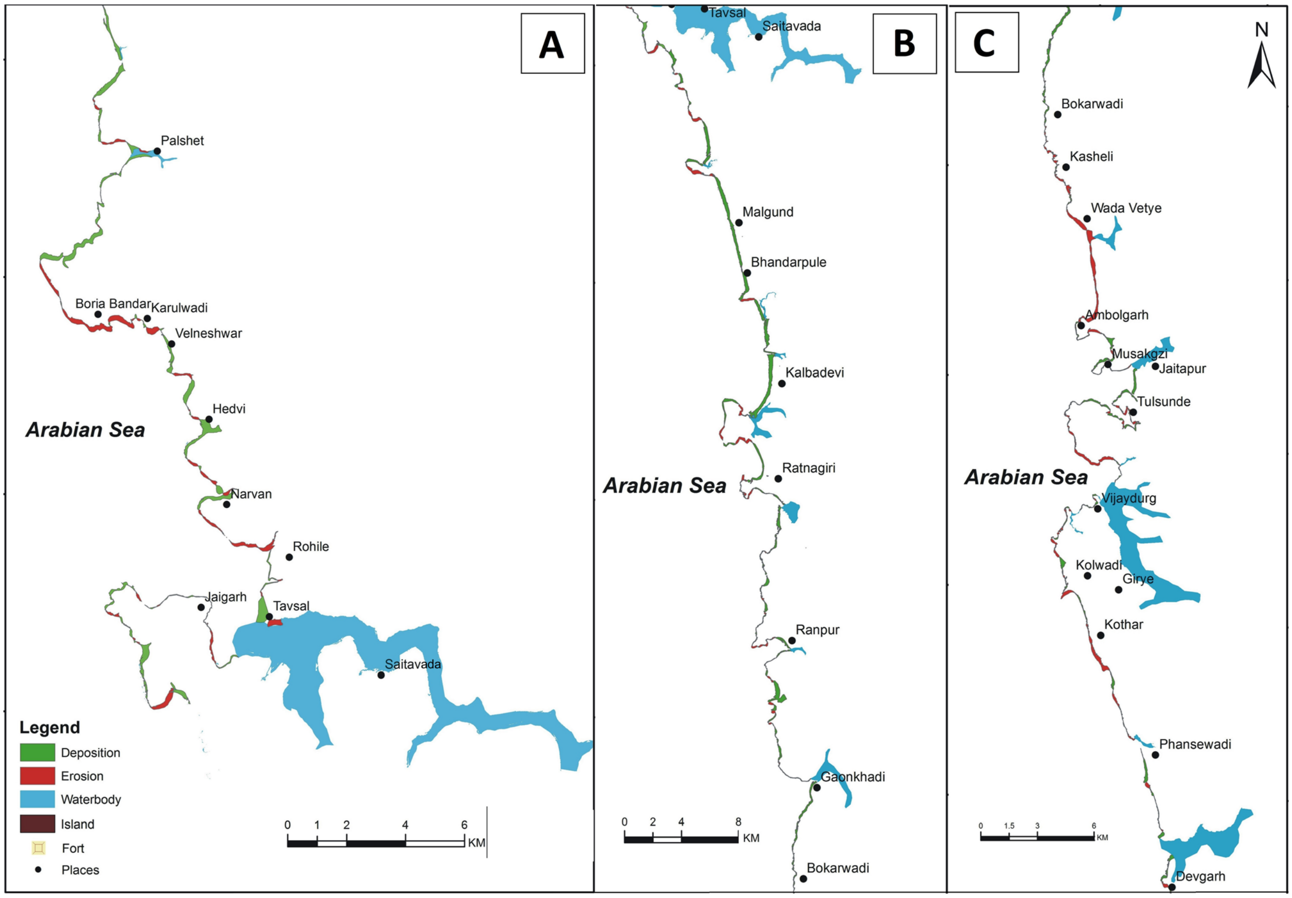

Figure 6. Shoreline changes from **(A)** Palshet to Tavsal, **(B)** Saitavada to Bokarwadi, and **(C)** Bokarwadi to Devgarh.

refraction, type of sediments and beach slope, etc. Sediment movement along the Maharashtra coast is found to vary with season, i.e., southerly during SW monsoon and northerly during the fair-weather season (Chandramohan and Nayak 1991; Hanamgond 2012; Hanamgond and Mitra 2012). The sediment accumulation or removal is ascribed to prevalent waves, tides, and longshore current reversal or convergence. The Jaigarh and Warori headlands are the regions of wave convergence which drive the light minerals in opposite directions along the coast (Rajamanickam *et al.* 1986). On the other hand, the divergence of wave energy along Rohile and Tavsal coasts leads to constructive wave activity.

The remote sensing and GIS studies on temporal variations can average out the dissimilarities and yield a more detailed and reliable spatial information on the coastline changes. Our present results are in agreement with Hanamgond and Mitra (2008) that the Malvan coast is affected by the increased settlement, mining of sand, felling of trees, desiltation of harbours, coastal protection walls and reclamation of coastal zones. Herlekar and Sukhtankar (2009) and Herlekar *et al.* (2017) found that the textural distributions of sediments are in agreement with the wave energy distribution along the Ratnagiri coast.

5.2 *Environmental factors affecting beaches*

The beaches are vulnerable to atmospheric pressure and wind modifications and respond quickly (Simm *et al.* 1996). The cyclones and storm surges that occurred during the last decade have led to significant changes in beach morphology and shoreline. According to Mahapatra (2015), out of 96 districts that include 72 coastal districts, 12 are very highly prone to cyclones, 41 are highly prone, 30 moderately prone, and the rest are less prone. The cyclones along the west coast of India are lesser than in the east. But since the last decade or so, the cyclones along the west coast have increased, especially Thane, Mumbai, and Raigarh districts regarded as highly prone, and Ratnagiri and Sindhudurg are moderately prone (Evan and

Figure 7. **(a)** Recession of sea-cliff, locality: Girye, Vijaydurg, **(b)** Coastal erosion and formed wave-cut platform and sea stack at Girye, Vijaydurg, **(c)** Headland eroded at Devgarh, locality: Devgarh, **(d)** Sea-cliff eroded at Kunkeshawar, locality: Kunkeshawar, **(e)** Large extensive sandbar are developed at Tondavali, **(f)** Sandspit are formed near Talashi, locality: Talashi.

Camargo 2011; Shaji *et al.* 2014). Cyclones Vayu, Hikka, Kyarr, Maha, Phyan, and Nisarg have ravaged the west coast of India and changed the morphology of the beaches significantly through anomalous erosion or accretion. During the Phyan cyclone of 9–12 November 2009, a significant wave height of ∼3 m was observed along Sindhudurg and Ratnagiri coasts. The storm surges generated by cyclones lead to low-lying coast inundation and flooding. Water pilling occurred along the coast due to excess river flow caused by heavy rains (Joseph *et al.* 2010).

It is quite conspicuous that during storm surges, waves erode the sand from beaches and foredunes, carrying it to the nearshore, forming the longshore sandbars. With the arrival of constructive waves during the fair-weather season, long waves with low amplitude move the sand landwards, creating berm(s) and wide backshore.

Rajawat *et al.* (2015) studied Indian coastal changes from 1989 to 1991 and 2004 to 2006. Their study shows that from the total Indian coastline, 3829 km (45.5%) coastline is eroding, 3004 km (35.7%) is undergoing accretion, and the remaining 1581 km (18.8%) is stable.

5.3 *Impact of sea-level changes*

Based on satellite-derived altimeter and tide-gauge data, the Indian coastal sea-level rise was 3.2 mm/yr from 1993 to 2012 (Unnikrishnan *et al.* 2015). The sea-level rise since 1960 can be attributed to changes in surface wind fields in this region. The sea-level rise occurred in the mid-latitude south

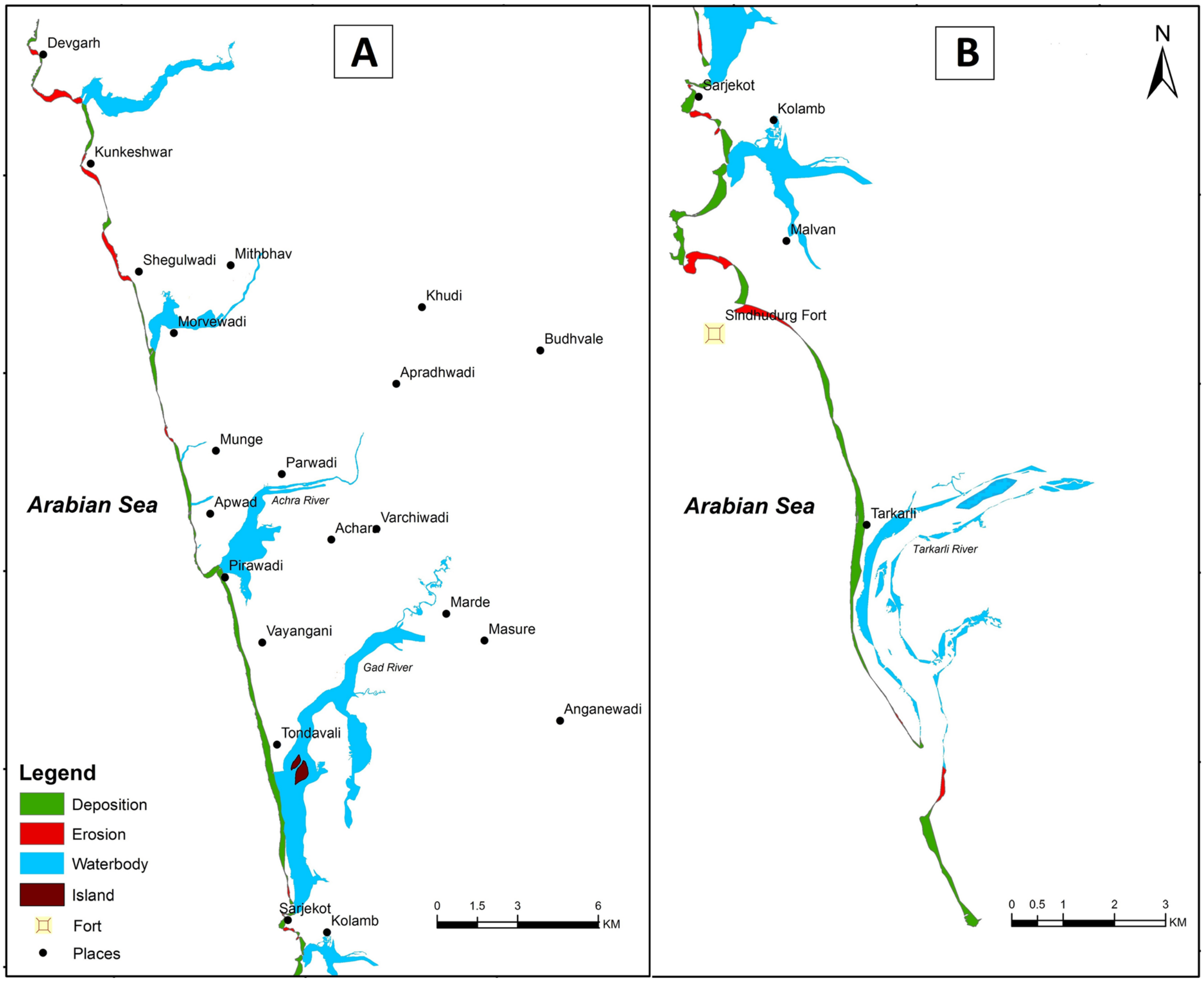

Figure 8. Shoreline changes from **(A)** Devgarh to Kolamb and **(B)** from Malvan–Tarkarli.

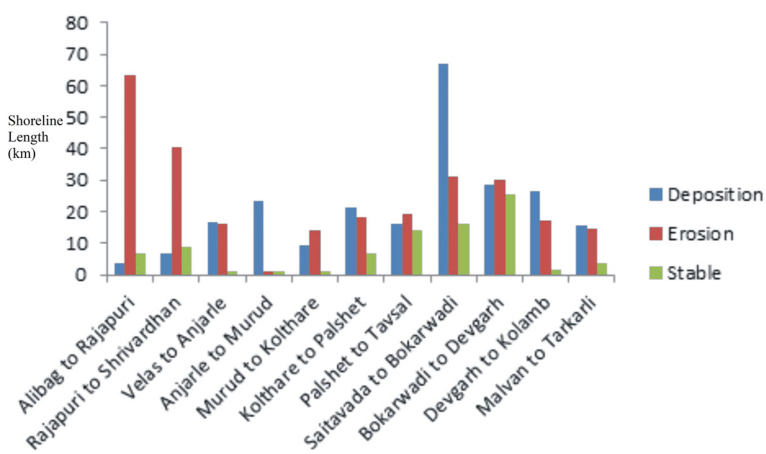

Figure 9. Histogram showing the coastal length of different parts of the area erosion, deposition and stable from Alibag to Tarkarli.

subtropical basin, the equatorial region of the Bay of Bengal, and the Arabian Sea (Han *et al.* 2010). The spatially variable sea-level change impact is dependent on coastal characteristics of geomorphology and the ever-changing direction of waves and tides that bring about different processes along

Table 3. *Coastal area under erosion and deposition in different parts of shoreline.*

Sl. no.	Shoreline location	Area under deposition (km^2)	Area under erosion (km^2)	Net gain/loss (km^2)
1	Alibag to Rajapuri	0.52	4.02	−3.5
2	Rajapuri to Shrivardhan	1.12	3.15	−2.03
3	Velas to Anjarle	2.03	1.04	0.99
4	Anjarle to Murud	1.72	0.15	1.57
5	Murud to Kolthare	0.61	0.12	0.49
6	Kolthare to Palshet	1.12	0.52	0.6
7	Palshet to Tavsal	1.04	2.64	−1.6
8	Saitavada to Bokarwadi	2.77	1.76	1.01
9	Bokarwadi to Devgarh	1.62	3.58	−1.96
10	Devgarh to Kolamb	2.11	0.49	1.62
11	Malvan to Tarkarli	1.51	0.35	1.16
	Total	**16.17**	**17.82**	**−1.65**

the coast. Hashimi *et al.* (1995) have unravelled western India's Holocene sea-level changes. The release of carbon dioxide and other greenhouse gases in the atmosphere with increasing intensity has increased the global temperature, leading to thermal expansion of oceanic water and melting of ice. Fourth Climate Assessment Report suggests a 60 cm rise in sea level by 2100 (IPCC 2007). However, the fifth IPCC report on GMSL rise inferred it to rise by a median of 74 cm by 2100, likely ranging from 52 to 98 cm (Church *et al.* 2013).

Thus, the Maharashtra coast from Alibag to Tarkarli can be inferred to be undergoing spatial changes that are variable from one sector to another. Incidentally, erosion is seen more in the northern sector from Alibag to Shrivardhan. Down south from Shrivardhan, deposition is more than the remaining coastline till Tarkarli. However, from Bokarwadi to Devgarh, the length of erosion, deposition, and the stable shoreline is almost similar. In terms of percentage of the total length, 45.27% is eroding, 40.02% is accreting, and 14.70% is stable. Increasing frequency of cyclones and sea-level rise will have deleterious effects on the coastline. The growing wave energy can tilt the balance towards erosion, especially in the stable zone. In the long term, the Maharashtra coastline is in danger of eroding more quickly/severely than deposition.

6. Conclusions

The study of Alibag to Tarkarli, Maharashtra shoreline changes using RS and GIS has revealed a varying degree of erosion and deposition. It is seen that out of the total 585.06 km of coastline, 264.92 km (45.28%) was under erosion, 234.17 km (40.02%) was under deposition, and 85.97 km (14.70%) long coastline was stable. The coast lost a net area of about 1.65 km^2 during 1980–2013 (table 3). Through this study, the vulnerable and ecologically sustainable zones can be earmarked for better coastal management. The coastal geomorphology of Maharashtra is influenced mainly by the wind and wave climate, physical setup, geology, etc. The tropical seasonal precipitation pattern is also one of the deciding factors of the shoreline change, apart from the sea-level changes and increased cyclonic activity.

Acknowledgements

The financial support received from ISRO-Cell, Savitribai Phule Pune University (Project No. GOI-A-337(B) 129), Government of India is thankfully acknowledged. Thanks are due to the reviewer for his critical review and valuable suggestions. The authors (MAH and PBK) are thankful to the Head, Department of Geology, Savitribai Phule Pune University, Pune for extending all the facilities.

Author statement

Milind A Herlekar: Investigation, conceptualisation, supervision, writing an original draft, visualisation, fieldwork. Prafull B Kamble: Formal analysis, data curation, methodology, validation, fieldwork. Praveen B Gawali: Data acquisition, manuscript writing, and editing. Pramod T

Hanamgond: Scientific input. Sainath Aher: Analysis of GIS data, software analysis.

References

Agrawal D P and Guzder S J 1972 Quaternary studies on the western coast of India, preliminary observations; *The Palaeobotanist* **21**(**2**) 216–222.

Aher S, Shinde S, Gawali P B, Deshmukh P and Lakshmi B V 2019 Spatio-temporal analysis and estimation of rainfall variability in and around upper Godavari River basin, India; *Arab. J. Geosci.* **12**(**22**) 682.

Chandramohan P and Nayak B U 1991 Longshore sediment transport along the Indian Coast; *Indian J. Mar. Sci.* **20** 110–114.

Chowdhury P, Behera M R and Dominic E R 2019 Wave climate projections along the Indian coast; *Int. J. Climatol.* **39** 4531–4532.

Church J A, Clark P U, Cazenave A, Gregory J M, Jevrejeva S, Levermann A, Merrifield M A, Milne G A, Nerem R S, Nunn P D, Payne A J, Pfeffer W T, Stammer D and Unnikrishnan A S 2013 Sea level change; In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (eds) Stocker T F, Qin D, Plattner G-K, Tignor M, Allen S K, Boschung J, Nauels A, Xia Y, Bex V and Midgley P M, Cambridge University Press, Cambridge, U K and New York, NY, USA, 1177p.

Deshpande G G 1998 *Geology of Maharashtra*; Geological Society of India, Bangalore, 223p.

Evan A T and Camargo S J 2011 A climatology of Arabian Sea cyclonic storms; *J. Clim.* **24**(**1**) 140–158.

Foote B R 1876 The geological features of the south Maharatta country and adjacent districts; *Geol. Surv. India Memoir* **12** 268.

Gawali P B, Basavaiah N and Hanamgond P T 2010 Mineral magnetic properties of sediments of beaches Redi-Vengurla coast, central west coast of India: A seasonalcharacterisation and provenance study; *J. Coast. Res.* **263** 569–579.

Gawali P B, Aher S P, Lakshmi B V, Gaikwad R, Deendayalan K, Hanamgond P, Mahesh Babu J L V, Arote S and Bairage S 2017 Identification of landslide susceptible villages around Kalsubai region, Western Ghats of Maharashtra using geospatial techniques; *J. Geol. Soc. India* **90**(**3**) 259–384.

Gujar A P, Angusamy N and Rajamanickam V 2008 Wave refraction patterns and their role in sediment redistribution along South Konkan, Maharashtra, India; *Geoacta Int. J. Earth Sci.* **7** 69–79.

Han W, Meehl G A, Rajagopalan B, Fasullo J T, Hu Aixue, Lin J, Large W G, Wang J, Quan Xiao-Wei, Trenary L L, Wallcraft A, Shinoda T and Yeager S 2010 Patterns of Indian Ocean sea-level change in a warming climate; *Nat. Geosci.* **3** 546–550.

Hanamgond P 2012 Dynamics of Malvan Coast, Maharashtra, West Coast, India; MoES Govt of India Major Project, MoES/11-MRDF/1/17/07/-PCIII.

Hanamgond P T and Mitra D 2008 Evolution of Malvan coast Konkan West Coast of India: A case study using remote sensing data; *J. Coast. Res.* **24**(**3**) 672–678.

Hanamgond P and Mitra D 2012 Morphodyamics of Kwada and Belekeri Bay Beaches, West Coast of India: Implications from remote sensing studies; *Gondwana Geol. Mag.* **13** 119–123.

Hashimi N H, Nigam R, Nair R R and Rajagopalan G 1995 Holocene sea level fluctuations on western India continental margin: An update; *J. Geol. Soc. India* **46** 157–162.

Herlekar M A and Sukhtankar R K 2009 Significance of size parameters of the carbonate sands between Dabhol and Jaigarh Creek, Ratnagiri District, Maharashtra; *J. Indian Assoc. Sedimentol.* **28**(**1**) 39–48.

Herlekar M A and Sukhtankar R K 2011 Morphotectonic studies along the Part of Maharashtra Coast, India; *Int. J. Earth Sci. Eng.* **4**(**2**) 61–83.

Herlekar M A, Gaikwad S P, Awungshi R, Waware N and Kamble P B 2017 Grain size analysis and characterisation of depositional environment of Holocene sediments from Kelshi to Anjarle Creek, Ratnagiri District, Maharashtra; *J. Geosci. Res.* **2**(**2**) 103–114.

IPCC 2007 *Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the IPCC* (eds) Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt K B, Tignor M and Miller H L, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996p.

Iyer L A N 1939 Geology of south Ratnagiri districts; *Rec. Geol. Surv. India* **74** 504–529.

Joseph A, Prabhudesai R G, Mehra P, Vijay Kumar, Agarwadekar Y, Luis R, Rivankar P and Viegas B 2010 November 2009 tropical cyclone Phyan in the eastern Arabian Sea: Oceanic response along west India coast and Kavaratti lagoon; https://doi.org/10.1109/OCEANSSYD.2010.5603802.

Kale V S and Rajaguru S N 1985 Neogene and Quaternary transgressional and regressional history of the west coast of India – An overview; *Bull. Deccan College Res. Inst.* **44** 153–165.

Kale V S, Kshirsagar A A and Rajaguru S N 1984 Late Pleistocene Beach rock from Uran, Maharashtra, India; *Curr. Sci.* **53** 317–319.

Mahapatra M 2015 Cyclone hazard proneness of districts of India; *J. Earth Syst. Sci.* **124**(**3**) 515–526.

Misra A and Balaji R 2015 A study on the shoreline changes and land-use/land-cover along the South Gujarat coastline; 8th International Conference on Asian and Pacific Coasts (APAC); *Proc. Eng.* **116** 381–389.

Mitchell C and Widdowson M 1991 A geological map of the southern Deccan Traps, India and its structural Implications; *J. Geol. Soc. Lond.* **148** 495–505.

Nayak S 2000 Critical issues in coastal zone management and role of remote sensing; In: *Subtle issues in Coastal Management, Dehradun, India* (eds) Sudarshana R, Mitra D, Mistral A K, Roy P S and Rao D P, Indian Institute of Remote Sensing, pp. 75–98.

Powar K B 1993 Geomorphological evolution of Konkan coastal belt and adjoining Sahyadri uplands with reference to Quaternary uplift; *Curr. Sci.* **64** 793–796.

Rajamanickam G V, Vedamony P and Gujar A R 1986 Effects of waves in the redistribution of sediments along the Konkan coast; *Proc. Ind. Acad. Sci.* **95** 223–244.

Rajawat A S, Chauhan H B, Ratheesh R, Rode S, Bhanderi R J, Mahapatra M, Mohit Kumar R, Yadav S P, Abraham

S S, Singh K N and Keshri A 2015 Assessment of coastal erosion along the Indian coast on 1:25,000 scale using satellite data of 1989–1991 and 2004–2006 time frames; *Curr. Sci.* **109**(**2**) 347–354.

Sanil Kumar V, Pathak K C, Pednekar P, Raju N S N and Gowthaman R 2006 Coastal processes along the Indian coastline; *Curr. Sci.* **91**(**4**) 530–536.

Sarkar P K and Soman G R 2010 Environment of deposition of the Meatconglomerate-Quartzite Sequence (Equivalent of Basal Member of Bababudan Group) along the Malvan coast, Sindhudurg District, Maharashtra, India; *Origin and Evolution of the Deep Continental Crust*; Narosa Publishing House Pvt. Ltd., New Delhi, India, pp. 33–41.

Shaji C, Kar S K and Vishal T 2014 Storm surge studies in the North Indian Ocean: A review; *Indian J. Mar. Sci.* **43**(**2**) 125–147.

Simm J D, Brampton A H, Beech N W and Brooke J S 1996 Beach management manual: London, Construction Industry Research and Information Association (CIRIA) Report **153** 448.

Subbarao K V and Hooper P R 1988 Reconnaissance map of the Deccan Basalt Group in the Western Ghats, India; In: *Deccan Flood Basalts* (ed.) Subbarao K V, *Geol. Soc. India Memoir* **10** 393.

Sukhtankar R K 1995 An evolutionary model based on geomorphic & tectonic characteristics of the Maharashtra coast, India; *Quat. Int.* **26** 131–137.

Unnikrishnan A S, Nidheesh A G and Lengaigne M 2015 Sea-level-rise trends off the Indian coasts during the last two decades; *Curr. Sci.* **108**(**5**) 966–971.

Wagle B G 1989 Morphology and evolution of the central West coast of India; *Mahasagar* **22(1)** 13–21.

Widdowson M and Cox K G 1996 Uplift and erosional history of the Deccan Traps India: Evidence from laterites and drainage patterns of the Western Ghats and Konkan coast; *Earth Planet Sci. Lett.* **137** 57–69.

Yang S, Dong L and Xiyong H 2020 Characteristics of mainland coastline changes in southeast Asia during the 21st century; *J. Coast. Res.* **36(2)** 261–275.

Corresponding editor: Maripi Dileep