Study of intertidal molluscan diversity of the Dakshina Kannada coast, India using remote sensing and GIS techniques

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The intertidal fauna of the Dakshina Kannada coast, Karnataka, India, are facing a threat due to several factors. In the present study, we delineate various changes in the selected intertidal habitats along the coastline of the Dakshina Kannada district, to correlate these changes with the diversity of molluscs in the intertidal zones. The study also aims at understanding the threat faced by molluscs due to various factors. This study was carried out from November 2016 to September 2017. Mapping of the coastline of Dakshina Kannada was done using topographical maps and Indian Remote Sensing Satellite imageries (IRS-Resourcesat 1-LISS-III). Satellite data were processed using ERDAS IMAGINE 9.1 software and various land-use/land-cover classes were analysed using ArcGIS 10.1. The resulting coastal maps were used to estimate the geomorphological changes and shifting of the shoreline position due to erosion and accretion. Shoreline changes were correlated to diversity changes within intertidal mollusc communities. The study revealed the abundance of molluscs at the intertidal zone of Sasihithlu and species richness at Someshwar and Panambur during post-monsoon. Significant correlation was observed between water temperature and diversity of molluscs, indicating that water temperature is the important physico-chemical parameter responsible for the change in molluscan diversity of the Dakshina Kannada coast. The variation in land-use/land-cover during the study period was analysed. The coastline has been threatened by different land-use patterns such as urbanization, industrialization, developmental activities, erosion and accretion. The changes occurring along the coastline during this study due to industrialization and anthropogenic factors have been discussed, which help in the implementation of conservation measures and protect the sensitive habitats of the shelled organisms.

Keywords: Anthropogenic activities, coastline, geomorphology, molluscs, satellite data.

THE coastal marine ecosystems are hotspots of biodiversity which include a variety of habitats that support a wide array of species. The intertidal zone, commonly known as the littoral zone, is the area between land and sea that is covered by water at high tide but not during low tide[1]. It is part of the coast which is highly variable, and one of the diverse and most productive areas providing shelter to several intertidal fauna such as crustaceans, polychetes, amphipods and molluscs. Phylum Mollusca is the second largest invertebrate group after arthropods, with more than 200,000 species[2]. The littoral fauna, particularly molluscs, are a source of food for other organisms and contribute to huge amounts of biomass on the different trophic levels in ecosystems from primary consumers to top predators.

Remote sensing and GIS have been employed in mapping marine habitats, change detection, estimation of spatial relationships among benthic macrofauna and their habitats in the coastal zones[3,4]. Based on weights of evidence method, Choi *et al.*[5] generated macrofauna habitat potential maps for the Hwangdo tidal flat in South Korea. Molina[6] correlated shoreline changes in Puerto Rico with the diversity of molluscs using remote sensing and GIS. Several studies have been carried out on the diversity of intertidal molluscs in India[1,7–11]. Paul *et al.*[12] carried out molluscan mapping based on the biomass differences during different seasons and their physical attributes. Thematic mapping employing data from various remote sensors coupled with decision support through GIS spatial analysis provides more rigour and insight into aquaculture planning of molluscs[12]. Thomas *et al.*[13] observed that molluscan habitats could be mapped by coupling a dynamic energy budget approach with environmental data such as chlorophyll concentration and temperature extracted from satellite images. Studies on molluscan diversity from the Dakshina Kannada coast of Karnataka, India, are limited[14,15]. Furthermore, there are no studies from Karnataka on the application of remote sensing and GIS to examine seasonal variation in molluscan diversity.

Industrial development and the ever-increasing human population have an adverse effect on marine ecosystems[16]. The Dakshina Kannada coast has been experiencing negative impacts due to anthropogenic activities[14]. Industrialization and ongoing developmental activities on land and

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sea have led to the destruction of intertidal habitats. Hence the study of the effect of urbanization on intertidal molluscan assemblages becomes important.

Studies on changes in the coastal ecosystems with respect to the land-use patterns to assess the extent of anthropogenic impacts on the population structure of faunal assemblages have been suggested[17,18]. In this regard, remote sensing and GIS are excellent tools for coastal change detection, quantification of biodiversity and to assess the impacts of geomorphological processes on intertidal biodiversity in general and molluscs in particular. Remote sensing is useful to obtain a synoptic view of the habitat conditions on a real-time basis[19]. Thus the present study gains importance to generate a database using GIS and remote sensing, and to correlate the shoreline changes with population structure of intertidal molluscs.

Materials and methods

Study area

The Dakshina Kannada coast is a part of the Karnataka coast that lies between 12°45′–13°4′N lat. and 74°45′–74°53′E long. extending from Talapady in the south to Mulki in the north and covering a distance of 40 km (Figure 1). The study area is bordered by the Mulki-Pavanje river in the north and Talapadi river in the south. The two major rivers that drain the study area are Netravati and Gurpur, originating from the Western Ghats. The intertidal areas of Someshwar (12°47′24.78″–12°47′41.98″N, 74°50′86″–74°51′1.4″E), Panambur (12°55′55.89″–12°56′14.10″N, 74°48′16.47″–74°48′14.91″E) and Sasihithlu (13°4′15.64″–13°2′0.5″N, 74°46′37.64″–74°47′38.4″E) were selected for the study, which are at least 10 km apart (Figure 2). The tides of the Dakshina Kannada coast are semidiurnal in nature, with the lowest low tide of 0.01 m and highest high tide of 1.58 m.

Data procurement

Topographic maps are snapshots of the physical features of a country at a particular time. Maps of the same area can show how it was before development and also provide a detailed view of the changes over time. Topographic maps of the Dakshina Kannada coast for year 1967 were obtained from Survey of India (SoI), Bengaluru. They were used to generate the base map of the study area as well as to georeference the satellite images of the subsequent years.

Multispectral satellite images of IRS-Resourcesat 1-LISS-III (cloud-free) covering the area between 74.750–750E long. and 12.750–13.250N lat. were used for the study. Spatial resolution is a measure of the smallest object that can be resolved by a sensor, or the ground area imaged for the instantaneous field of view (IFOV) of the sensor, or the linear dimension on the ground represented by each pixel. LISS III has a spatial resolution of 23.5 (path 097 and row 065), as it can detect a small object which is at a distance of 23.5. Satellite images of the time series October 2009, November 2011 and January 2013 were downloaded from the Indian Space Research Organization (ISRO) portal BHUVAN. Landsat 8 images of 2016 were taken from Google Earth due to their high-spatial resolution, georeferenced and used to derive the shoreline of 2016. IRS-Resourcesat 1-LISS-III data of October 2017 were procured from National Remote Sensing Centre (NRSC), Hyderabad.

Table 1 provides the specifications of beaches such as width, slope and area of the intertidal sites. The selected beaches were visited monthly from November 2016 to September 2017 during low tide. Three locations at a distance of 300 m were selected for the study in each intertidal area. The sites of molluscan collection in the selected beaches were designated as S1, S2, S3 and earmarked with hand-held GPS. The total area of the molluscan collection sites of Someshwar beach, Panambur beach and Sasihithlu beach was 5416, 5000 and 7500 m^2 respectively. Molluscan shells were collected from high-, mid- and low-tide zones of the intertidal region using quadrates (0.25 m^2) at each study site[20,21]. There was no significant difference in width between the three tidal zones at each site. As the intertidal zones of Karnataka in general and Dakshina Kannada in particular are narrow compared to other coasts of India, the width of each zone was negligible. Molluscs that were present outside the quadrates up to 600 m distance were collected by handpicking to list the

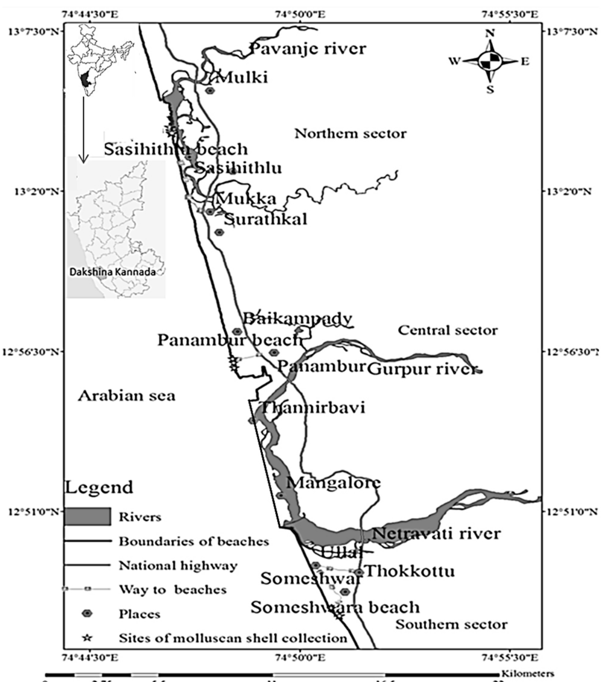

Figure 1. Location map of the study area.

Table 1. Intertidal habitats of the Dakshina Kannada coast, Karnataka, India chosen for the study

Beach	Beach type	Average beach width (m)	Beach slope (%)	Area of the intertidal zone (km^2)	Area of molluscan collection sites (m^2)	Wave exposure
Someshwar	Rocky	36.33	5.04	1	5416	High
Panambur	Sandy	39.33	2.88	0.52	5000	Moderate
Sasihithlu	Sandy	44	5.21	0.30	7500	Moderate

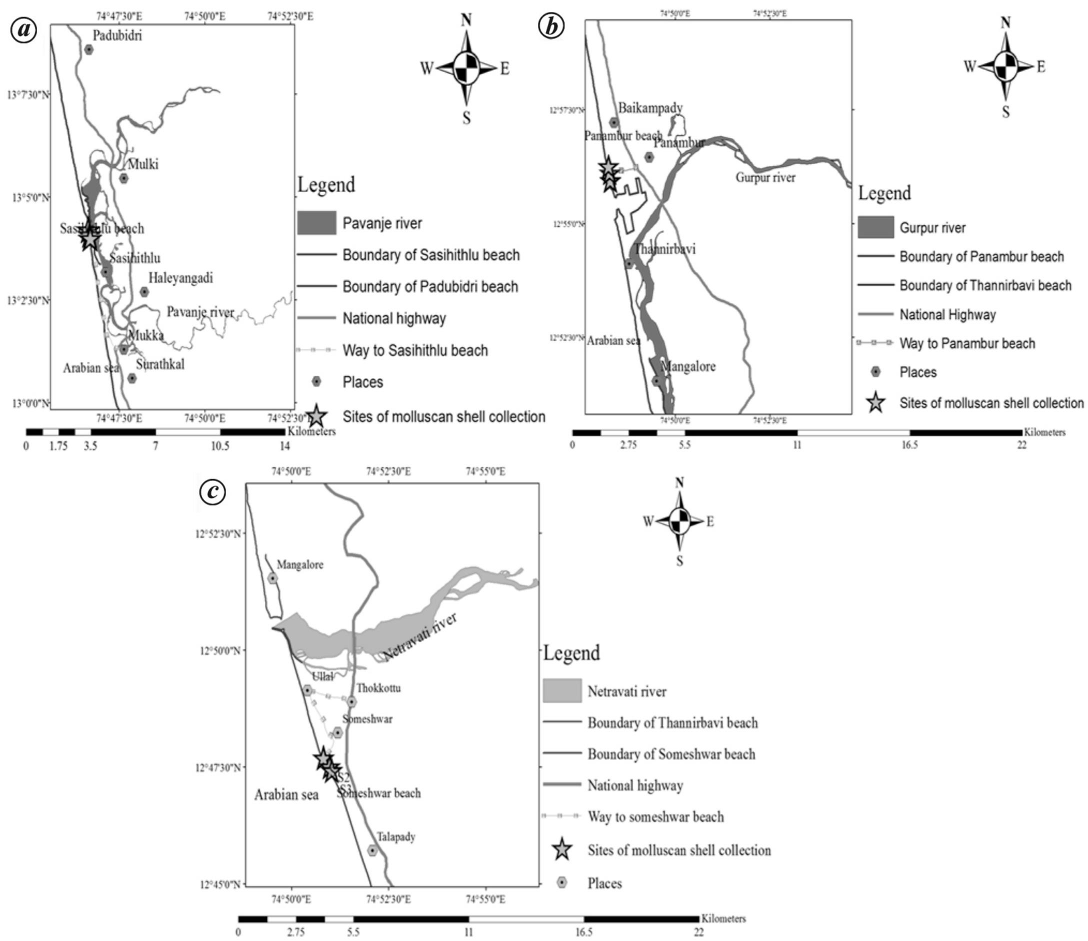

Figure 2. Base maps of (***a***) northern, (***b***) central, (***c***) southern sectors of the Dakshina Kannada coast, Karnataka, India.

overall molluscan diversity in each intertidal area. They were preserved in 70% ethanol and identified using the standard literature[22–24].

Data processing

Topographic maps 48L/13 (Someshwar) and 48K/16 (Sasihithlu and Panambur) were scanned and opened in ArcGIS 10.1. They were geo-referenced by providing 49 corner points and projected as WGS 1984 datum. Clipping and mosaiking was done to remove the unwanted portions. The topographic maps were merged to digitize the permanent features. A buffer zone at a distance of 10 km^2 from the shoreline was established and the features lying within it were studied. Shorelines and national highways were digitized using line feature, whereas rivers were digitized as a polygon and sites of molluscan collection were digitized as point features. Base maps were generated based on the SoI topographical maps surveyed in 1967 for the Dakshina Kannada district (Figure 2), geo-registered by providing corner points after geographic projection with Modified Everest as the datum.

Land-water boundary was considered as a high-tide line. It is well known that tides leave their distinct signatures in the form geomorphic formations on the coast which can be captured as high-resolution satellite images. High-resolution satellite images, especially Google Earth images were used to demarcate the land and water bodies

(Figure 3). The high-tide line may be determined, in the absence of actual data, by a line of oil or scum along the shore objects, a more or less continuous deposit of fine shells or debris on the foreshore or berm, other physical markings or characteristics, vegetation lines, tidal gauges, or other suitable means that delineate the general height reached by a rising tide[25].

Cloud-free satellite data during low-tide conditions were obtained to easily demarcate HTL/LTL. The selection was done using tide tables available on-line. These tide tables enlist predicted time and height at low and high water periods and are published for the entire Indian coast every year. The tide tables, in conjunction with the satellite calendar, can help in selecting the imagery of low-tide conditions; if required, tidal conditions for the secondary ports can be calculated. Satellite orbits are fixed. Based on the satellite orbit calendar, the time of satellite pass in Dakshina Kannada was predicted and field visits were planned to have a synchronization with the satellite pass and tidal conditions along the coast.

IRS-P6 (LISS-III) imageries of the time series 2009, 2011, 2013, 2017 were geo-registered with the location map using more than 25 corresponding ground control points (GCPs). GCPs were collected using permanent features like road intersections, railway lines, National Highway junctions, etc. Topographic maps and satellite images of different time series were overlaid to crop the images to a proper dimension.

Band extraction and image interpretation in ERDAS IMAGINE 9.1 were performed. Accuracy of the geo-correction was tested by swiping one image above the other. The geo-corrected data were imported into ArcGIS 10.1 for digitization of the shoreline. Land and water bodies were easily demarcated on false colour composite (Figure 4). High tide line shown in the satellite imageries (2009, 2011, 2013, 2017) and topographic sheets for all the three study sites were digitized as line features. Shorelines representing different years of the same study area were presented by overlaying together. Quantification of erosion/accretion rate was done by digitization as polygon features using ArcGIS 10.1.

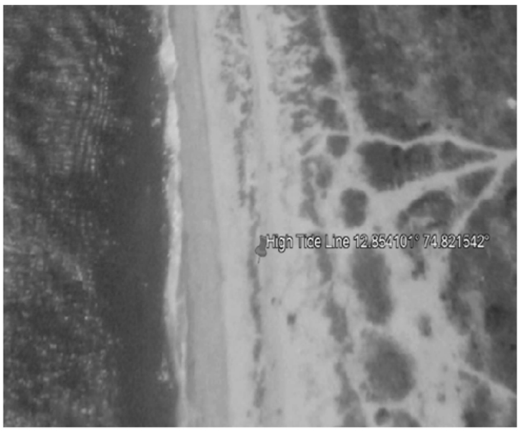

Figure 3. High-resolution satellite imagery (Google Earth image) showing the high tide line near Bengre, south of Sasihithlu.

Land-use/land-cover study

To determine the recent changes in land use, it is necessary to know the land-use patterns prevalent during previous years. IRS-P6 (LISS III) images of 2009, 2011, 2013, 2017 for the Dakshina Kannada coast on a 1 : 50,000 scale (1 cm on paper is 500 m on the ground) were imported into ArcGIS 10.1. Then the base map was prepared from the toposheets by clipping and mosaicking. Geo-registration of satellite images was done using the prepared base map. The images were made into subsets of the required size and shape as that of the study area. These images were reprojected using Universal Transverse Mercator (UTM) projection in zone 43N; the study area lies in this region.

The satellite images were digitized using line and polygon features. The recognizable features of the images were visually interpreted and grouped into different classes and classified up to level II of Anderson's classification system (1976). The ground truth information was collected by field visits to the selected sites. The land-use/land-cover maps of 2009, 2011 and 2013 were prepared and compared with the satellite images of 2017. The area of the land-use categories of these time series was calculated and changes in land use were derived. The shoreline and land-use/land-cover changes were correlated with richness and abundance of molluscs in the study area (Figure 5).

Results

Shoreline changes

The topographic maps of 1967 were considered as the base to compare the shoreline changes that occurred during 2009, 2011, 2013 and 2017. Multidated satellite data provide precise information on the pattern of variation in the shoreline over a period of time. They determine whether any man-made changes, such as construction of breakwaters and geomorphological changes, such as formation of spits have occurred, resulting in alteration of accretion–erosion patterns and leading to littoral drift, resultant movement and deposition of molluscs at particular sites of the coast.

Figure 6 shows the shoreline changes in the Dakshina Kannada coast from 1967 to 2017. Erosion was common from 1967 to 2013 in Sasihithlu. About 0.565 km^2 area was lost in the molluscan collection sites from 2016 to 2017, which has exposed the burrowing bivalves (Figure 7). Someshwar and Panambur beaches showed continuous erosion from 1967 to 2013 and accretion was prominent in these sites from 2016 to 2017 (Table 2).

Table 2. Erosion/accretion from 1967 to 2017 at molluscan collection sites of the Dakshina Kannada coast

	1967–2009		2009–2013		2013–2016		2016–2017		Total changes from 1967 to 2017	
	E	A	E	A	E	A	E	A	E	A
Sasihithlu	0.003	0.000	0.013	0.000	0.000	0.402	0.565	0.000	0.582	0.402
Panambur	0.124	0.023	0.022	0.000	0.000	0.449	0.0005	0.037	0.147	0.509
Someshwar	0.123	0.000	0.023	0.000	0.000	0.088	0.033	0.052	0.179	0.140

*E, Erosion (km^2), A, Accretion (km^2).

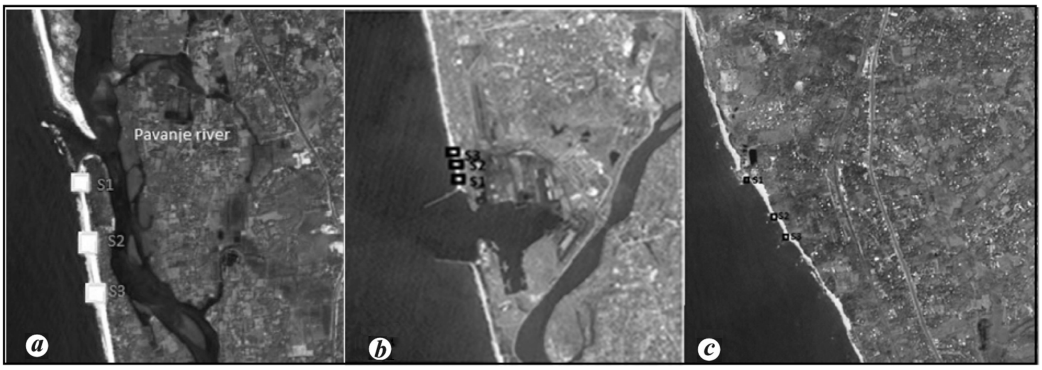

Figure 4. IRS Resourcesat LISS-III false colour composite images showing (***a***) northern, (***b***) central and (***c***) southern sectors.

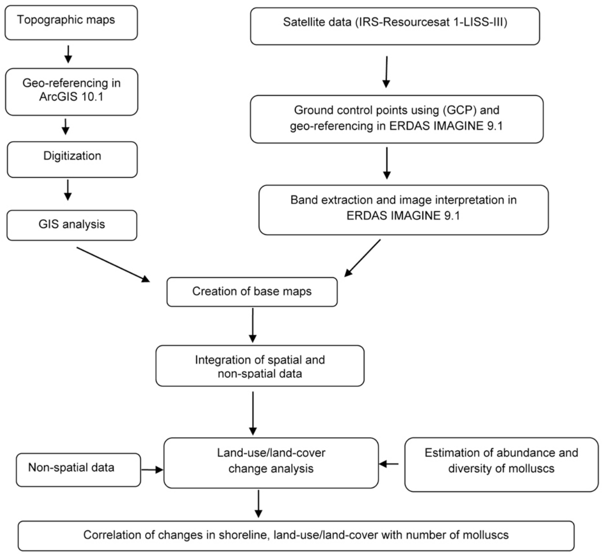

Figure 5. Schematic representation of steps involved in the study of molluscan diversity using remote sensing and GIS techniques.

Minor erosion was seen along with accretion at Panambur and Someshwar during 2016–17 (Figures 8 and 9 respectively). There was accumulation of sediments up to 0.037 and 0.052 km^2 in the molluscan collection sites of Panambur and Someshwar respectively, during this period (Table 2). Construction of seawalls along the intertidal zones of Someshwar and Sasihithlu had resulted in the shifting of the erosion sites to adjacent areas, whereas breakwaters at Bengre and Panambur had prevented littoral drift.

Land-use/land-cover changes

Various land-use/land-cover classes found in the study area were grouped based on the classification system of Anderson *et al.*[26] and are discussed below.

(i) Built-up area

Residential: Regions where houses are on plots of more than 1 acre, on the periphery of urban expansion. This land-use type has increased by 1.20% from 2009 to 2017 (Table 2). It may be because of the expansion of urban areas adjacent to the settlements.

Commercial and services: Urban central business centres, shopping malls, usually in suburban and outlying areas; commercial developments, etc. are included in this category. There was rapid expansion of commercial land uses in the northern and central sectors of the Dakshina Kannada district during the study period.

Mixed urban: This category is characterized by developments along transportation routes and in cities, towns and built-up areas, where separate land uses cannot be mapped individually. It includes highly populated areas with human settlements, buildings, industrial and occasionally other land uses. The geographical extent of such land-use type was 70% of the study area.

Other urban: This category typically consists of uses such as golf-driving ranges, zoos, urban parks, etc. Only a minor fraction of such land-use type was found in the study area.

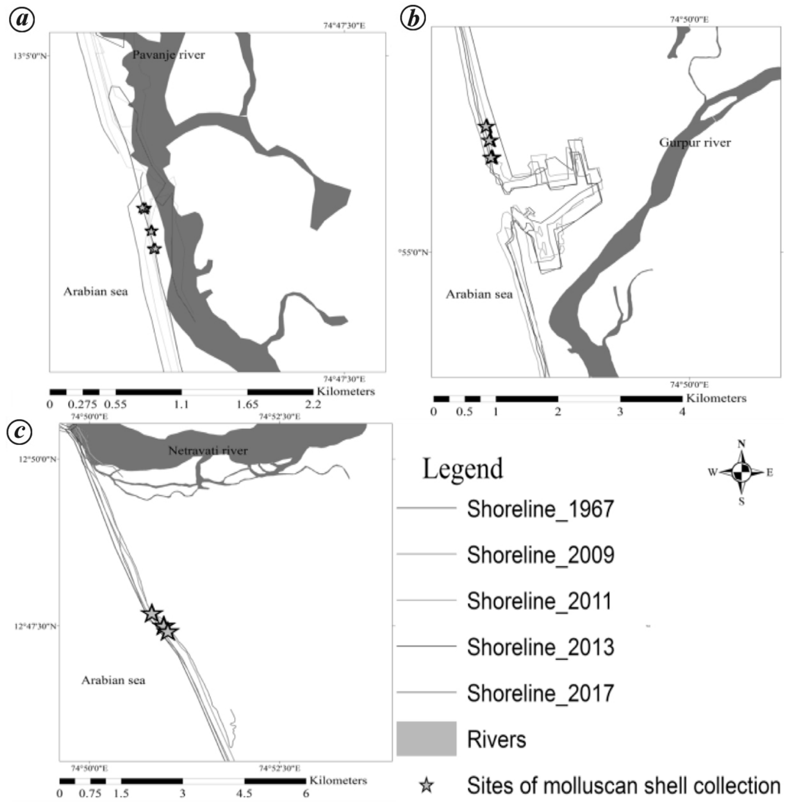

Figure 6. Shoreline change maps of (***a***) northern; (***b***) central and (***c***) southern sectors of the Dakshina Kannada coast from 1967 to 2013.

(ii) Agricultural

Cropland and pasture: These are the areas with standing crop as on the date of satellite overpass. They included paddy fields and coconut and arecanut plantations in the study area. Two types of crops were grown in the study area, namely *kharif* and *rabi*. The former is grown during the onset of monsoon and ends with the end of the season, whereas the latter is grown from winter till the beginning of summer. In addition, this category includes land that is left for grazing by cattle. This covered 20% of the study area.

Fallow land: An agricultural system with an alternation between a cropping period of several years and a fallow period. The areas where crops are grown during one season and allowed to rest in the other seasons. Fallow land may turn into cropland, and vice versa, in the satellite images of different seasons in a year.

(iii) Water bodies

These include both natural and man-made water features such as estuaries, rivers, ponds, lakes, tanks and reservoirs (Figure 10). They are represented by light blue to dark blue in tone and smooth to mottled texture on satellite imagery. Surface water bodies such as tanks/ponds were identified in the central sector of the study area and were distributed in an area of 0.18 km^2. The two important estuaries in the study area are Netravati and Pavanje that join the Arabian Sea at Ullal and Sasihithlu respectively (Figure 10). Lakes were found in the central sector of the study area and constituted about 0.08 km^2 of the land use.

Rivers, streams and canals: These constitute 5% of the total geographic area and include the west-flowing Netravati, Gurpur and Pavanje rivers joining the Arabian Sea.

Wetlands: The forested wetlands or mangroves are situated near rivers. Non-forested wetlands are dominated by wetland herbaceous vegetation, or are non-vegetated. These wetlands include tidal and non-tidal fresh, brackish, and salt marshes, and non-vegetated flats and also freshwater meadows, wet prairies and open bogs. They occurred as lagoons in the study area, constituting 0.23% of the southern sector.

(iv) Barren land

Sandy areas: Coastal sandy areas are more significant in the northern and southern sectors, whereas the central sector has ports and industries which contribute to urbanization, thus reducing the sandy areas along the coast.

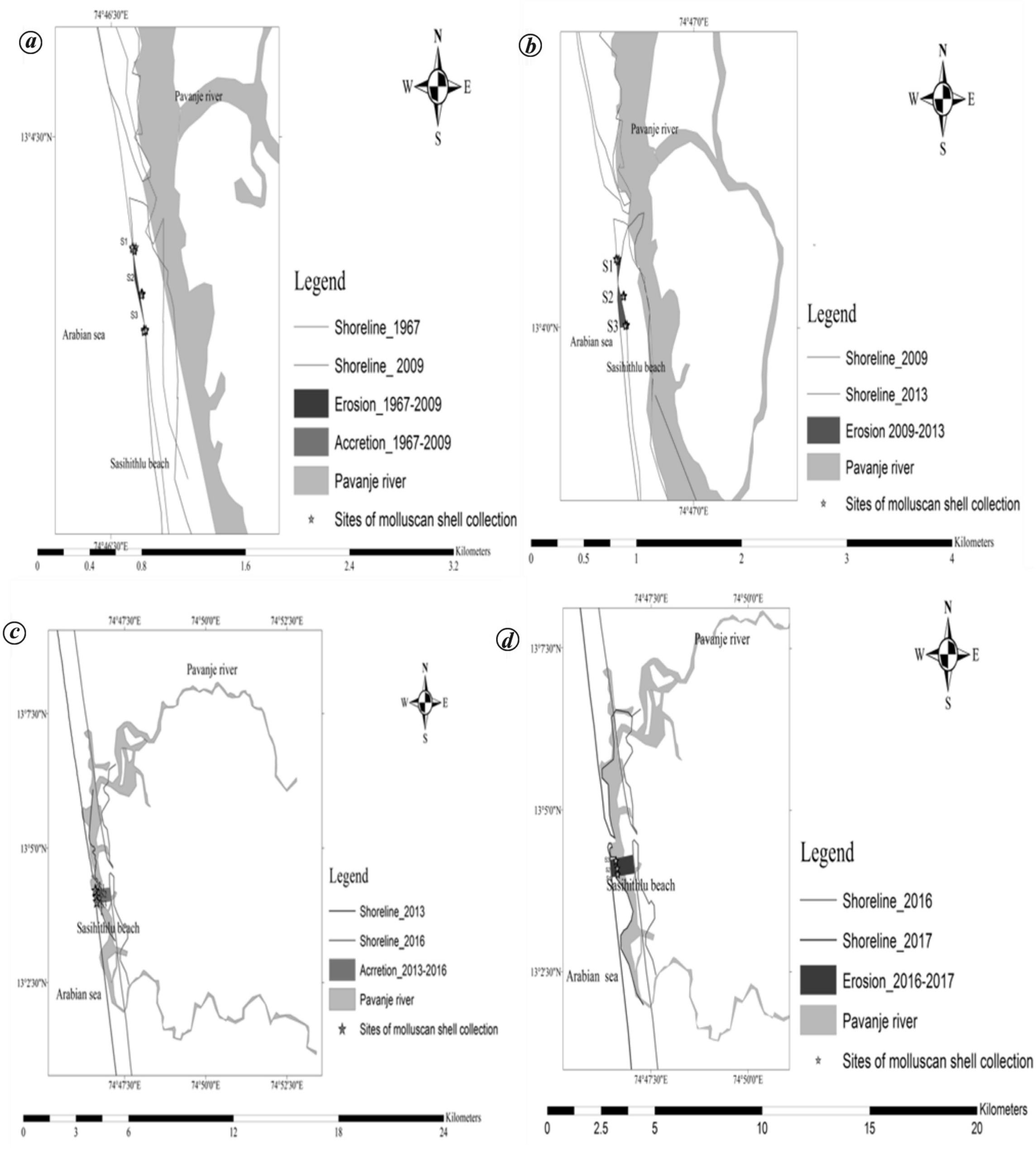

Figure 7. Erosion–accretion patterns for the intertidal area of Sasihithlu at the molluscan collection sites from (***a***) 1976 to 2009, (***b***) 2009 to 2013, (***c***) 2013 to 2016 and (***d***) 2016 to 2017.

Riverine sandy areas were prominent near the banks of Netravati river in the southern sector.

Bare exposed rock: These are areas of bedrock exposure without soil or vegetative cover. Such rocks were found in the intertidal zone of Surathkal and Someshwar with scattered distribution.

There has been continuous increase in urban and built-up land from 331 to 383 km^2 in the Dakshina Kannada coast along with the appearance of commercial land uses. Industrial lands have increased by 4.38%, and sea ports and airports have increased by 0.07% from 2009 to 2017. The cropland has decreased from 110.532 to 41.78 km^2 during 2009–17 (Table 3). The non-forested wetlands have transformed to fallow land during post-monsoon. Fallow land has decreased from 65.58 to 46.85 km^2 during 2009–17. Fallow land has been replaced by human dwellings and urban settlements, as well as on-going developmental activities. The anthropogenic activities have led to deforestation of mangroves and the area is being utilized for residential land uses.

A few mega industries are located in the Dakshina Kannada district. A coal-based thermal power plant at

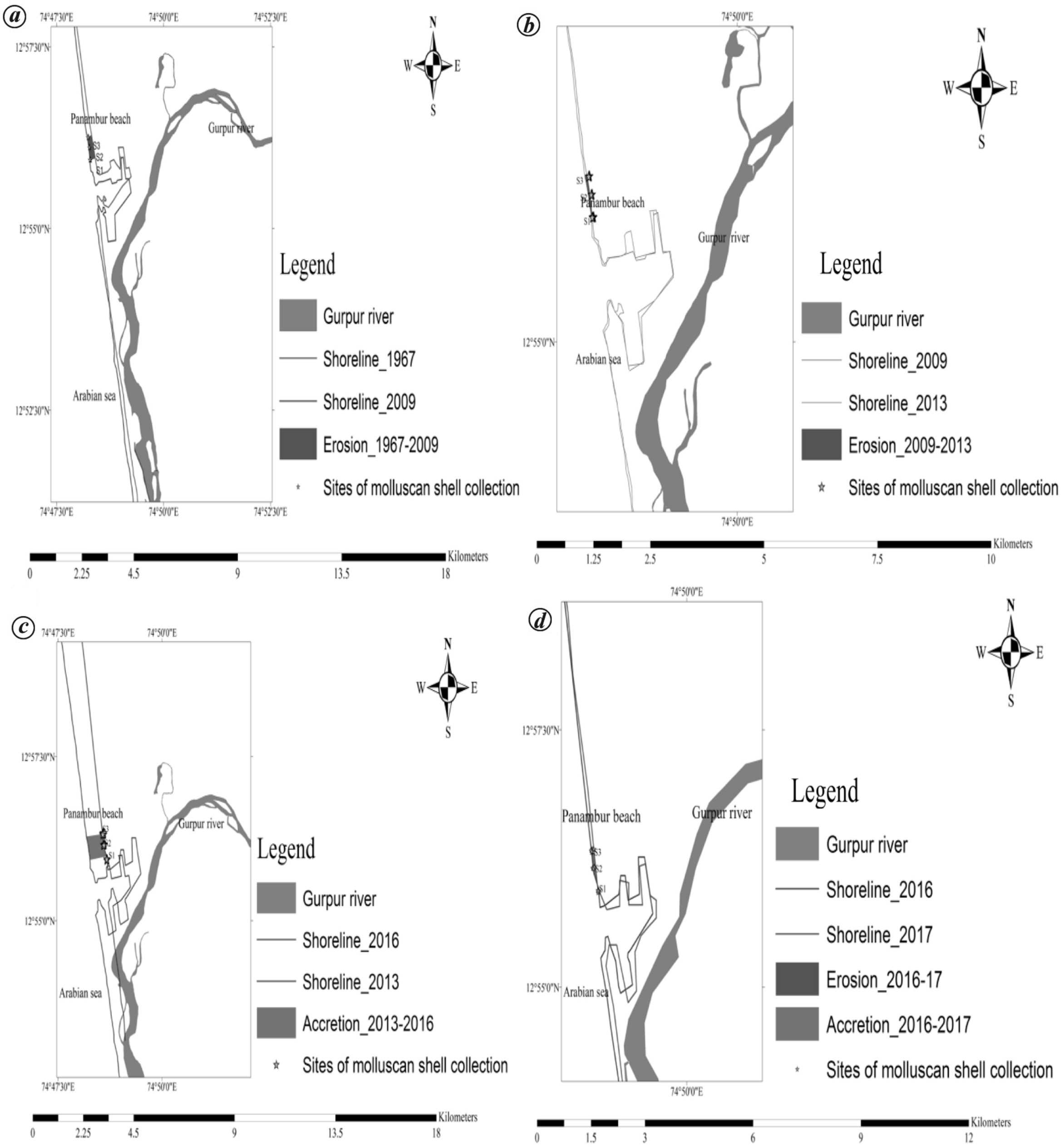

Figure 8. Erosion–accretion patterns for the intertidal area of Panambur at the molluscan collection sites from (***a***) 1976 to 2009, (***b***) 2009 to 2013, (***c***) 2013 to 2016 and (***d***) 2016 to 2017.

Nandikur lies in the northern sector of the study area. The industrial area has shown gradual increase of 5.5% during 2009–17. Hence, coastal sandy areas have reduced due to rapid industrialization adjacent to the coastline. Tourism and construction of beach resorts for tourists have utilized the coastal sandy areas.

From the present study it is evident that the residential areas have increased towards the coast. Resorts have been constructed at Someshwar along the Mangalore coast. Sasihithlu beach has been developed as a tourist destination. Dumping of iron ore is prevalent near Panambur. As a result black soil gets accumulated towards the ocean. Thus use of multidated satellite data has helped us understand the changes in land use along the seashore.

Correlation of shoreline changes with molluscan population structure

During the present study, 20 species of molluscs belonging to 11 families and 16 genera were found in the Dakshina Kannada coast. Of these, ten were gastropods and ten were bivalves (Table 4).

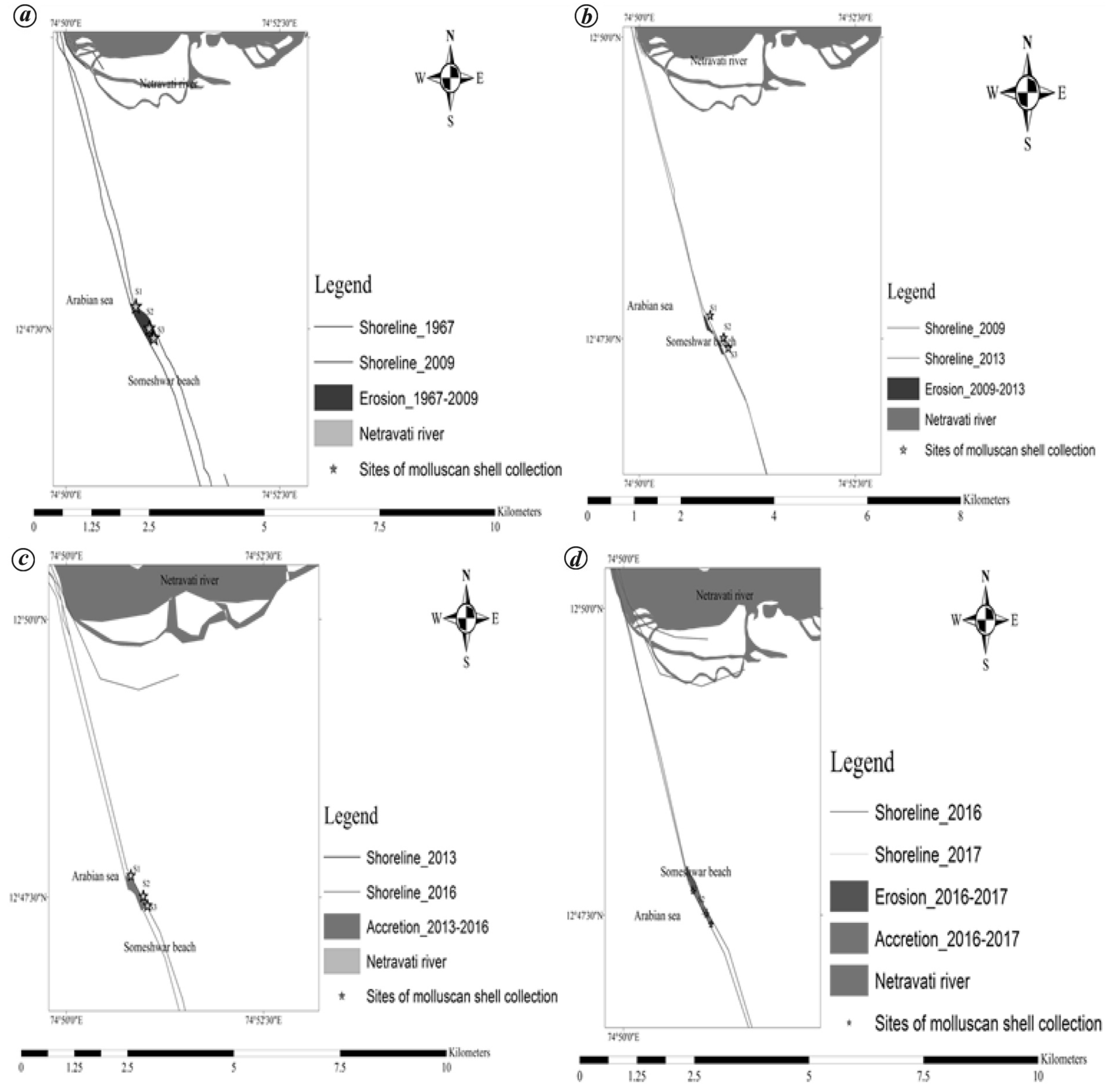

Figure 9. Erosion–accretion patterns for the intertidal area of Someshwar at the molluscan collection sites from (***a***) 1976 to 2009, (***b***) 2009 to 2013, (***c***) 2013 to 2016 and (***d***) 2016 to 2017.

Rocky shore species such as *Cellana radiata*, *Echinolittorina leucostica*, *Littorina scabra* and *Brachydontes striatulus* were confined to Someshwar beach, whereas molluscs belonging to family Veneridae, Donacidae and Olividae were observed in the sandy shores of Panambur and Sasihithlu. *Donax* spp. were abundant in the sandy shores of the Dakshina Kannada coast. The abundance and richness of molluscs declined from the lower littoral zone to the upper littoral zone. *Bullia melanoides* was found in the sandy beaches of the Dakshina Kannada coast throughout the study period. Rocky shore species like *C. radiate* and *Perna viridis* were present during all the seasons. Richness of gastropods peaked in the pre-monsoon and that of bivalves in the post-monsoon. *Sunetta scripta*, *Donax scrotum* and *Donax pulchellus* were seen only in the post-monsoon. *Mactra luzonica*, *Sunetta concinna* and *Sunetta solanderii* were the rare species seen occasionally.

Figure 11 shows species richness and abundance of molluscs. Abundance of molluscs was more in the post-monsoon at Sasihithlu. This could be due to recruitment of juveniles after monsoon. Panambur and Someshwar were rich in molluscan species in the post-monsoon, which could be due to the presence of rocks in the intertidal area of Someshwar and boulders in Panambur that provide microhabitats. The intertidal area of Sasihithlu that showed erosion during the study period consisted of both gastropods and bivalves. Diversity and abundance of molluscs was more in sampling site 1 of Sasihithlu beach

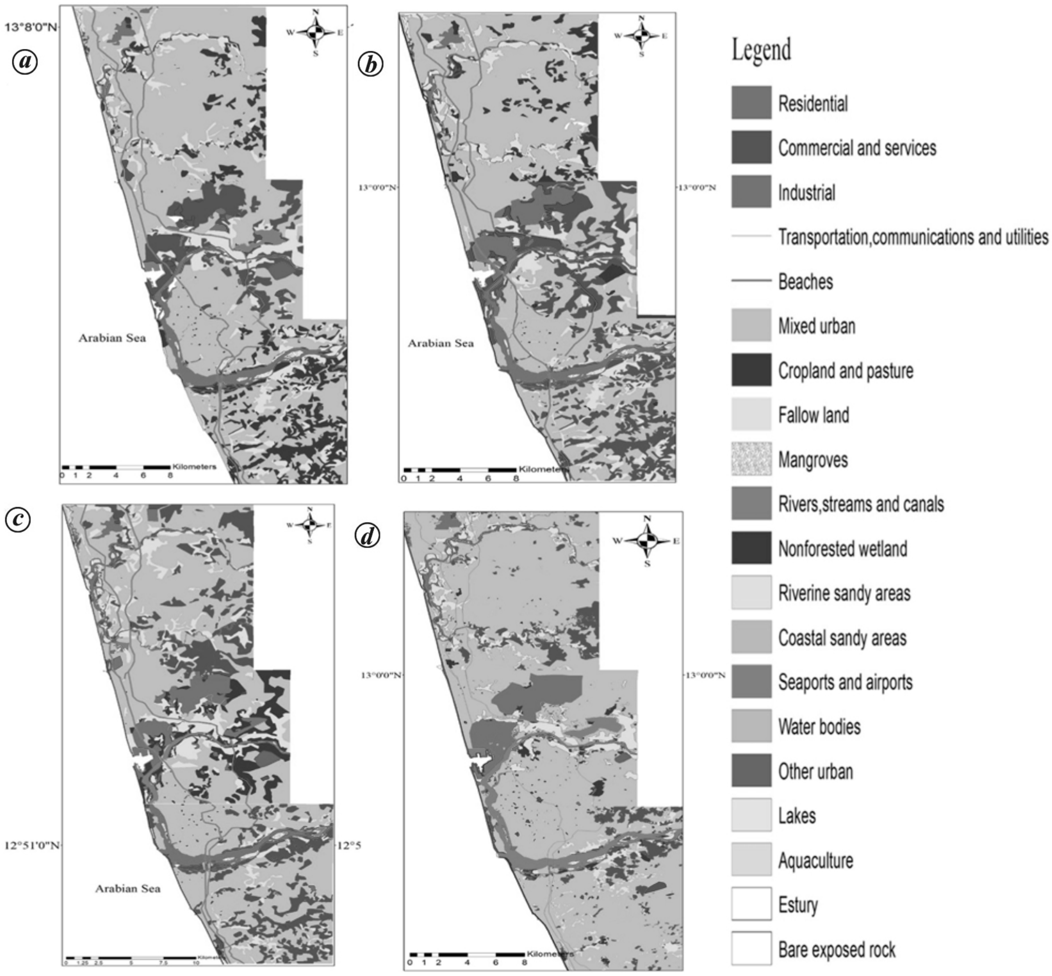

Figure 10. Land-use/land-cover changes in Dakshina Kannada coast in (***a***) 2009, (***b***) 2011, (***c***) 2013 and (***d***) 2017 (according to Anderson's classification system[26]).

Table 3. Area under different land-use/land-cover classes during 2009–17 in the Dakshina Kannada district

Land-use/land-cover type	Area 2009 (km^2)	Area 2011 (km^2)	Rate of change 2009–2011 (%)	Area 2013 (km^2)	Rate of change from 2011 to 2013 (%)	Area 2017 (km^2)	Rate of change from 2013 to 2017 (%)	Rate of change from 2009 to 2017 (%)
Residential	2.997	5.060	0.547	5.606	0.91	6.530	0.840	1.209
Commercial and services	2.182	3.561	0.398	4.880	2.19	5.313	0.708	0.787
Industrial	21.194	22.045	3.86	25.040	4.98	30.863	4.387	5.449
Mixed urban	311.355	331.391	56.81	355.21	39.57	383.767	64.637	69.848
Cropland and pasture	110.532	93.231	20.17	69.612	39.24	41.783	12.520	–7.442
Fallow land	65.588	59.606	11.9	53.979	9.35	46.854	9.668	–8.368
Rivers, streams and canals	25.866	25.008	4.72	24.484	0.86	24.718	4.285	–4.328
Lakes	0.083	0.086	0.015	0.083	0.00	0.183	–0.167	0.149
Water bodies	0.107	0.105	0.019	0.084	0.32	0.098	–0.167	–0.165
Mangroves	1.619	1.353	0.295	1.314	0.07	0.244	0.057	+0.138
Sea ports and airports	2.852	2.868	0.520	3.979	1.84	4.907	0.544	+0.071
Other urban	1.929	2.127	0.352	2.323	0.33	2.441	0.241	+0.026
Riverine sandy area	0.789	0.661	0.143	0.692	0.05	0.355	–0.056	–0.118
Coastal sandy area	0.430	0.458	0.078	0.366	0.15	0.575	–0.116	+0.078
Non-forested wetland	0.417	0.373	0.076	0.290	0.13	0.244	0.130	–0.138
Aquaculture	0.059	0.067	0.01	0.06	0.00	0.048	–0.941	–0.952
Total	548	548	100	548	100	548	100	100

–, Decrease, +, Increase.

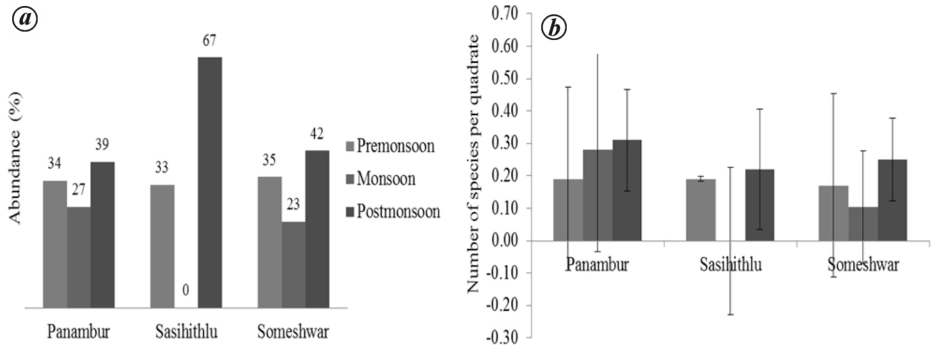

Figure 11. Molluscs in the beaches of the Dakshina Kannada coast: (***a***) abundance and (***b***) species richness.

Table 4. List of molluscs found in the Dakshina Kannada coast during the study period

Family	Species	Post-monsoon	Pre-monsoon	Monsoon
Gastropods				
Bullidae	*Bullia melanoides* (Deshayes, 1832)	+	+	+
	Echinolittorina leucostica (Philippi, 1847)	–	–	+
Littorinidae	*Littorina scabra* (Linnaeus, 1758)	–	–	+
	Indothias lacera (Born, 1778)	+	–	–
Muricidae	*Purpura bufo* (Lamarck, 1822)	+	–	–
	Semirincinula tissoti (Petit de la Saussaye, 1852)	+	+	–
Nacellidae	*Cellana radiata* (Born, 1778)	+	+	+
	Oliva oliva (Linnaeus, 1758)	–	+	–
Olividae	*Agaronia gibbosa* (Born, 1778)	–	+	–
Cymatidae	*Gyrenium natator* (Roding, 1798)	–	+	–
Bivalves				
Donacidae	*Donax pulchellus* (Hanley, 1843)	+	–	–
	Donax incarnates (Gmelin, 1791)	+	+	+
	Donax scrotum (Linnaeus, 1758)	+	–	–
Mactridae	*Mactra luzonica* (Reeve, 1854)	–	+	–
	Brachydontes striatulus (Hanley, 1843)	+	+	–
Mytilidae	*Perna viridis* (Linnaeus, 1758)	+	+	+
Ostridae	*Saccostrea cucullata* (Born, 1778)	+	+	+
	Sunetta scripta (Linnaeus, 1758)	+	–	–
Veneridae	*Sunetta concinna* (Deshayes, 1853)	–	+	–
	Sunetta solanderii (Grey, 1825)	–	–	+

+, Present; –, absent.

in comparison with the other sites, as this beach experienced erosion during the study period (Figure 7).

The Shannon diversity index is commonly used to characterize species diversity in a community. In this study, its value ranged between 0 and 1, the lower value indicating less diversity and the higher value indicating more diversity. The Shannon index value of 1 indicates that all groups have the same frequency. The Simpson index value also ranged between 0 and 1 in this study; the greater the value, greater is the sample diversity. In this case, the index represents the probability that two individuals randomly selected from a sample will belong to different species. Pielou's evenness index (J') measures the evenness of a habitat and ranges from 0 to 1, a low value for J' indicates less evenness in spatial distribution pattern and the value of 1 indicates that the individuals are distributed equally. In Sasihithlu, the Shannon diversity index of bivalves was observed in post-monsoon, which indicates that the environmental conditions of post-monsoon favoured the diversity of bivalves and prevalence of stressed conditions in monsoon and pre-monsoon. Panambur showed more deposition and least erosion, and was rich in bivalves during monsoon and the corresponding diversity indices were higher during monsoon (Table 5). The abundance of molluscs was seen in Panambur in their place of collection (site 1), which was subjected to erosion during 2016–17, whereas diversity remained the same in the sites of deposition and erosion (Figure 8). The rocks of Someshwar showed abundance and richness of molluscs in site 3 followed by site 1 (Figure 9). Although the intertidal area of Someshwar showed deposition, snails and clams were not found in the sandy areas during the study period. This may be due to the steep slope of the beach face and swash speed in reflective beaches that provide less feeding time

Table 5. Diversity indices of gastropods in the study sites in the Dakshina Kannada coast

	Post-monsoon			Pre-monsoon			Monsoon		
Intertidal areas	*H′*	*D*	*J′*	*H′*	*D*	*J′*	*H′*	*D*	*J′*
Sasihithlu	0	0	1	0	0	1	0	0	0
Panambur	0	0	1	0.484	0.213	0.405	0	0	1
Someshwar	0	0	1	0	0	1	0.808	0.457	0.748

**H′*, Shannon; *D*, Simpson; *J′*, Evenness.

Table 6. Diversity indices of bivalves in the study sites of the Dakshina Kannada coast

	Post-monsoon			Pre-monsoon			Monsoon		
Intertidal areas	*H′*	*D*	*J′*	*H′*	*D*	*J′*	*H′*	*D*	*J′*
Sasihithlu	0.061	0.021	0.531	0	0	1	0	0	1
Panambur	0.184	0.086	0.601	0	0	1	0.803	0.454	0.744
Someshwar	0.628	0.437	0.937	0. 912	0. 535	0.829	0	0	1

for the molluscs. Shannon and Simpson indices increased with the increase in evenness of molluscs in the intertidal zones of the Dakshina Kannada coast. Gastropods were distributed unevenly during almost all the seasons (Table 5), whereas distribution of bivalves was more in the littoral zones of Sasihithlu and Panambur in the post-monsoon (Table 6).

Analysis of physico-chemical parameters of the environment

During the study, air temperature ranged from 27°C to 31.9°C and water temperature from 25.5°C to 33°C, while pH was in the range 6.92–8.83. Salinity varied from 7.9 to 39.73 ppt. Electrical conductivity was in the range 15.13–60.35 mS/m and wave frequency varied from 6 to 10. When the relationship between physico-chemical parameters of the environment and molluscan diversity was analysed, significant correlation was observed between water temperature and species richness ($\rho = 0.362$, $P = 0.039$), abundance and water temperature ($\rho = 0.426$, $P = 0.014$) and species richness and abundance (Table 7).

Discussion

Using multispectral satellite data along with field observations, shorelines during different time-series along the Dakshina Kannada coast have been extracted, and variations in shoreline and land-use/land-cover have been analysed. The shoreline of the Dakshina Kannada district is threatened by erosion[27]. The rate of erosion was slightly higher in comparison with accretion in the study area. The erosion and accretion patterns observed along the coast were influenced mainly by coastal processes and riverine inputs[28]. Sand mining, climate change, rainfall and sediment discharge also contributed to erosion at the study sites. Erosion favoured the presence of bivalves and decreased the diversity of gastropods in the intertidal zones of the Dakshina Kannada coast. The sites of accretion showed less number of gastropods. Similar observations have been made by Molina[6] on the Peurto Rico coast.

During the study, 20 species of molluscs were found on the Dakshina Kannada coast and their abundance varied between the sites. This could be due to the difference in geomorphology of the beaches at the selected sites, resulting in different distribution patterns of molluscs. Abundance of molluscs was observed on the rocky shores of Someshwar in comparison with the sandy shores of Panambur and Sasihithlu. The rock fragments form small tide pools and moist microhabitats, which may enhance the distribution of rocky shore species in the intertidal areas[29].

Abundance of *Donax* species was at its peak on the Dakshina Kannada coast. These observations are in agreement with previous reports from Panambur beach[30]. The abundance of larvae of these species is known to change with changing hydrodynamics of the beaches[31]. The juveniles get transported from offshore to the near shore through tidal movement. Distribution of molluscs along the coast of Dakshina Kannada is also due to the changing wind patterns and currents. During the tidal transport juveniles settle at the bottom of the shore to avoid getting displaced towards the sea[32].

Richness of molluscs was seen in the low tide zones of the beaches studied. Water availability, increased feeding time, and decreased water and air temperature determine the occurrence of molluscs in the low tide zones[1]. The high species diversity of bivalves at Someshwar in pre-monsoon and gastropods at Someshwar during monsoon reveals that the environmental conditions are favourable for molluscs, whereas low values of diversity indices of gastropods (*H′*, *D′*, *J′*) at Sasihithlu in pre-monsoon and those of bivalves during monsoon at Someshwar represent stressed conditions at these sites.

Table 7. Spearman correlation of molluscan diversity with physico-chemical parameters of water

	Species richness	pH	Electrical conductivity	Salinity (ppt)	Water temperature (°C)	Air temperature (°C)	Wave frequency
Abundance	0.678*	–0.242	–0.047	0.052	0.426**	0.041	–0.165
Species richness	1.000	0.143	0.114	0.313	0.362**	0.036	0.124

*Correlation is significant at the 0.01 level (two-tailed).
**Correlation is significant at the 0.05 level (two-tailed).

Coastal landforms have been continuously modified by the action of waves, tidal processes, sea-level changes and long shore drift. According to Chapman[33], shorelines that are modified by the construction of breakwaters, seawalls and other artificial structures may lead to loss or alteration of intertidal habitats. The boulders placed across the intertidal zone near the breakwaters of Panambur provide novel habitats for the molluscs to colonize, thus increasing their richness around the breakwaters. Physical variables such as beach slope and sand particle size are important drivers of community structure and species distribution[34]. In addition, tidal range and beach morphodynamics play an important role in determining population structure of the molluscs. Someshwar is a partly reflective beach with steep slopes and coarse sand, whereas Panambur and Sasihithlu are dissipative beaches. Species richness of molluscs was maximum in Panambur, followed by Someshwar and was least in Sasihithlu. Highest diversity of molluscs at Panambur could be due to the gentle slope of the beach. Reciprocal beach slope enhances species richness in dissipative beaches[35]. Molluscs were least in number in the sandy regions of Someshwar. This could be attributed to the waves that break directly in the intertidal zone which carries the intertidal fauna to the supralittoral zones, where burrowing becomes difficult[36].

Remote sensing and GIS have helped understand the changes in land-use patterns along the Dakshina Kannada coast by providing a quantitative estimation of the same. The variations in land-use/land-cover along the shoreline of Dakshina Kannada occur mainly due to population pressure and coastal processes. Similar observations have been reported from the Digha coast of West Bengal, India[37]. Industrialization and urbanization are considered to be the major causes of loss of habitat and species associated with it in the coastal zones[38]. Industries and population growth are the key factors leading to changes in land-use patterns along the Dakshina Kannada coast, as evident from this study. Bhagyanagar *et al.*[39] reported similar land-use/land-cover changes on the Dakshina Kannada coast. Industries located in the coastal districts release pollutants to the sea which have an adverse effect on the molluscan population.

Results indicate that between 2009 and 2017, the Dakshina Kannada coast had experienced substantial land-use changes, with a dramatic increase in industrial and residential areas along with significant loss of sandy coast (Table 2). Over the last few years, the shoreline has undergone erosion and accretion position changes. However, accretion is more prominent and common in many locations. The net shoreline change observed is an accretion with an area of 1.051 km^2 in the molluscan collection sites (Table 1). Results further reveal that area changes in agriculture, residential, abandoned and aquaculture lands have caused a negative impact on the shoreline, moving it landward. However, area changes of industrial land and the sandy coast have exerted a positive impact (shifting the shoreline towards the sea). This positive impact is mainly due to land reclamation projects and destruction of natural coasts. As such, this is not favourable for natural coastal environments. The present study clearly indicates that human-induced coastal land-use changes exist on the Dakshina Kannada coast. These may result in long-term shoreline position shifts and also have a significant impact on the coastal environment as well as the molluscs.

The land-use patterns indicate the anthropogenic changes along the coast which alter the coastal geomorphology by shifting the shorelines, thus affecting the diversity of molluscs inhabiting these sites. Intertidal habitats of Dakshina Kannada are facing a threat due to the shifting of residential land uses towards coastlines[40]. Global climate change, population growth and sea-level rise increase the anthropogenic pressures, which in turn causes unusual impacts on coastal ecosystems[41]. Recent studies from the Dakshina Kannada coast have shown that anthropogenic disturbances influence molluscan species richness and evenness[14]. Hence, immediate priority should be given to avoid developmental activities on the Dakshina Kannada coast, which is impacted by receding shorelines. Then, the intertidal zone of Dakshina Kannada can be recovered as a microhabitat for the molluscs.

LISS III has a good spatial resolution which helps understand the spatial distribution and population structure of the common intertidal mollusc species (Figure 5). The sensor of LISS III can store information related to shoreline changes and land-use/land-cover over a period of time, which can be correlated with the diversity of molluscs in the intertidal sites.

The satellite images have helped us understand the topography of the land below, changes in position of the spits and river mouth, and changes in the area of the ports. Further, sedimentation patterns and algal blooms (if present) can be identified and their changes over a period of time can be documented by future studies in this area. Accretional landforms such as spits are formed towards the northern side of Someshwar beach and Sasihithlu beach, which leads to erosion in these intertidal zones. Presence of breakwaters at Panambur has resulted in sediment movement to the northern side of Someshwar. Hence erosion can be seen at Someshwar beach.

Correlation between molluscan diversity and water temperature indicates that sea-water temperature plays an important role in the distribution of molluscan diversity along the coast. Similar observations have been made by Trivedi *et al*.[42] from the Gujarat coast, India. Rumahlatu and Leiwakabessy[43] studied the molluscs of Indonesia and reported that the increase in water temperature caused decomposition of organic matter in the sediments, which helped in the survival of the molluscs.

In the present study, remote sensing and GIS techniques have helped quantify the shoreline and land-use/land-cover changes and correlate these with changes in richness of the molluscan species. The present study has helped generate baseline data for the Dakshina Kannada coast, in order to understand the threat faced by molluscs due to industrialization and urbanization. It also demonstrates that the synoptic coverage provided by remote sensing techniques combined with field sampling allows efficient monitoring of coastal changes and their impact on the diversity of the intertidal molluscs along the Dakshina Kannada coast. In future, we can generate maps of coastal landforms and land-use/land-cover of the area using high-resolution satellite images like Resourcesat LISS-IV and Cartosat satellite data (resolution merged data). The high-resolution satellite data and resolution-merged data will help demarcate the high tide line and low tide line with high accuracy. With the high-resolution satellite data, molluscan shells of the intertidal zone can be studied with better accuracy. In future, studies can be done on other organisms of the Dakshina Kannada coast and more details on the molluscan collection sites can be acquired.

Conclusion

The Dakshina Kannada coast has been subjected to shoreline changes along with changing seasons and tidal cycles. The erosion and accretion along the Dakshina Kannada coast have led to variations in the richness and abundance of molluscs. The geomorphology of beaches, tidal range and beach slope are the factors that determine the richness of molluscs. In the present study, remote sensing and GIS techniques have proved to be useful in delineating shoreline changes and to correlate with the intertidal habitats of the molluscs. Assessment of shoreline changes is important for the stakeholders and coastal planners to take the necessary action plans for coastal management. In this context, remote sensing and GIS linked with ground-truth data have proved to be effective for the analysis of coastal charges, land-use/land-cover changes and their impact on intertidal organisms. Acquiring high-resolution satellite data has helped monitor the shoreline changes and to understand the distribution of molluscan species along the coast. The Dakshina Kannada coast is facing a threat due to changes in land-use patterns, industrialization and urbanization. The present study stresses the need for minimizing anthropogenic activities such as the modernization of beaches for recreation, construction of resorts, ports and harbours, as well as sand and clay mining in order to protect the habitats of molluscs.

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