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RESEARCH ARTICLE

Shoreline Dynamics and Vulnerability Assessment Along the Karnataka Coast, India: A Geo-Statistical Approach

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Abstract
Coastal areas are dynamic transition zones between land and sea. Their vulnerability is increasing due to human interventions with the natural processes. In the present study, we focused on coastal vulnerability assessment along Karnataka, south-west coast of India to identify the erosion-prone areas by integrating thematic datasets such as shoreline dynamics, land-use/land-cover, geomorphology, geology, elevation and bathymetry using remote sensing and GIS techniques. The 304 km coastline of Karnataka is divided into fourteen littoral cells, and each into a number of transects at uniform intervals. In this coastal stretch, $\sim$ 265 km (87%) is vulnerable to erosion of which $\sim$ 179.5 km (59%) is undergoing erosion at various magnitudes. Littoral cells in the south are subjected to high erosion and vulnerability, and the areas having human interventions are the most erosion-prone. This approach provides valuable information on the degree of potential vulnerability risk which serves as a guide to develop adaptation measures by the coastal zone management authority.

Keywords Littoral cells · Shoreline dynamics · DSAS · Geomorphology · Coastal vulnerability index

Introduction

Urbanisation and rapid growth of coastal cities have been the trend over the last few decades, leading to numerous mega cities around the world facing diverse coastal hazards. One of the major hazards due to these anthropogenic influences is coastal erosion, which leads to permanent loss of valuable land, property and natural resources along the coastal region. The shorelines are dynamic as they change spatially and temporally in response to variations in coastal processes (Forbes et al. 2004) induced either naturally or anthropogenic. Shoreline change rate is one of the most common measurements used by coastal scientists, engineers and land planners to indicate the dynamics and the hazards of the coast (Savage and Foster 1989). Multi-dated satellite images are widely used for shoreline change rate estimation around the world (Armenakis et al. 2003). Coastal erosion is considered as a major threat worldwide. Indian shoreline on the either side of its peninsula is subjected to erosion in varied strengths (Rajawat et al. 2015). Assessment of vulnerability of a coast due to erosion is the prerequisite for the coastal zone management authorities in proposing new coastal protective measures. Vulnerability can be defined as the degree to which a system is likely to experience harm due to external stress. Vulnerability assessment is the process to assess the risk of formulating strategies to reduce the risk arising from coastal erosion by proper planning and sustainable management. It is an estimate of the degree of damage that could result from a hazardous event. When natural processes affect human activities or infrastructure, the former becomes a natural hazard. Around the world, vulnerability maps are prepared for several coasts using remote sensing and geographical information systems (GIS) techniques, multivariate analysis and numerical models (Cooper and McLaughlin 1998; Dominguez et al. 2005; Srinivasa Kumar et al. 2010). Vulnerability assessments along the Indian coasts have been so far focused on the impact of sea-level rise

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(Nageswara et al. 2008; Dwarakish et al. 2009; Anitha and Usha 2015).

Coastal vulnerability index (CVI) was carried out to understand relative vulnerability of various segments (Hegde and Raju 2007; Mahendra et al. 2011). The rapidly growing coastal residents and their demand for reliable information on vulnerability necessitate classifying and evaluating the hazard. To prevent impact of natural hazard and associated losses, environmental managers need to know the intrinsic vulnerability. This is determined using information on the physical and geological coastal features. Desai et al. (2000) reported the significant advantages of geospatial technology in the integration of various thematic layers for coastal zone management practices. Varied coastal processes dominate the erosional hazards and monitoring the coastal zone is necessary to understand and to decipher these coastal processes for hazard zonation, regional sediment budgeting, modelling coastal morphodynamics and coastal zone management planning (Nayak 2002; Jana et al. 2013; Mahapatra et al. 2014). Satellite data proved its efficiency in understanding various coastal processes (Anbarasu et al. 1999; Kaliraj et al. 2013) by providing pertinent information for mapping and classification of land-use/land-cover and geomorphology of the coastal area. The lack of a management policy and rapid increase in human activities resulted in urban sprawl and considerable coastal stress. To prevent the losses in future along the Indian coast, Ministry of Environment and Forests (MoEF), Government of India issued Coastal Regulation Zone (CRZ) notification in 1986 and amended in 1991, under Environmental Protection Act (1986) to ensure the livelihood of the coastal communities and conserve/protect coastal areas.

CVI is a numerical approach to classify the coastline in terms of their potential harm. In the present study, multivariable approach is considered, implying the evaluation of impacts induced by shoreline dynamics, land-use/land-cover, geomorphology, geology, elevation and bathymetry to develop CVI using high-resolution satellite images and GIS techniques to assess the erosion hazard level along this coast. The results obtained enabled identification and prioritisation of vulnerable areas of the region to further assist the government and the residing coastal communities in better conservation and management.

Study Area

The study area stretches in three districts—Uttara Kannada, Udupi and Dakshina Kannada—of Karnataka State in the southern Indian peninsula. The coastal stretch is ~ 304 km from Devbagh in the north to Talapady in the south (12°45′–15°00′N lat. and 74°00′–75°00′ E long.; Fig. 1) oriented in the NNW–SSE direction. The northern part is characterised by low-energy coast with headlands, pocket beaches, and the southern part is high energy coast with spits and straight sandy beaches. The later one is densely populated and experiences erosion of beaches and siltation of navigation channels of ports/harbours. Nine major river systems (Kali, Gangavali, Aghnashini, Sharavathi, Panchagangavali, Sita, Swarna, Netravati and Gurupur) originate in western slopes of the Western Ghats, flow westward and debouch in single or pair of two/three into the Arabian Sea. These rivers are the major source of sediment for beaches, but due to large-scale sand mining from the estuaries/rivers and construction of about 250 vented dams across the rivers/streams resulted in the deficit of sediment input which in turn is responsible for erosion of beaches (Kumar et al. 2010). Majority of this coastline is protected with artificial structures such as seawalls, groins and breakwaters which intervene natural coastal processes. There are a few islands off the coast, the major being St. Mary's near Malpe and Netrani near Murudeshwara. The coastal belt experiences hot humid condition, south-west and northeast monsoons with average annual rainfall of ~ 3900 mm and temperature ranging from 17 to 34 °C. Local community mainly depends on agriculture (paddy, coconut and arecanut), fishing (fresh and saline water), salt production from estuarine water, small to large-scale industries and tourism. This coastline is receiving increased attention due to industrial base like oil refinery, thermal power plant and ports. Due to extensive urbanisation and overexploitation of coastal environment, agriculture and fishery resources are drastically decreasing.

Materials and Methods

To understand the relative vulnerability of various segments and classify the vulnerable zones along the coast, the littoral cell concept was considered. The study area was divided into fourteen primary littoral cells (LC-01 to LC-14) on the basis of shoreline configuration and natural/artificial features like estuaries, rock outcrops and breakwaters (Fig. 1), and six physical–geological variables were considered (Table 1). To understand the shoreline dynamics between 2014 and 2017, multi-dated high-resolution (5.8 m) LISS-IV images (96-63-B: 06/02/14, 08/01/15, 27/01/16, 14/02/17; 97-63-C: 11/02/14, 13/01/15, 01/02/16, 19/02/17; 97-64-A: 11/02/14, 13/01/15, 01/02/16, 19/02/17; 97-64-B: 07/03/14, 06/02/15, 08/01/16, 02/01/17; and 97-64-D: 07/03/14, 06/02/15, 08/01/16, 15/03/17) of Resourcesat-2 satellite were procured from National Remote Sensing Centre (NRSC), India (www.nrsc.gov.in). Using autosync georeferencing wizard in Erdas Imagine 2013 software, satellite imagery of 2014 was considered as

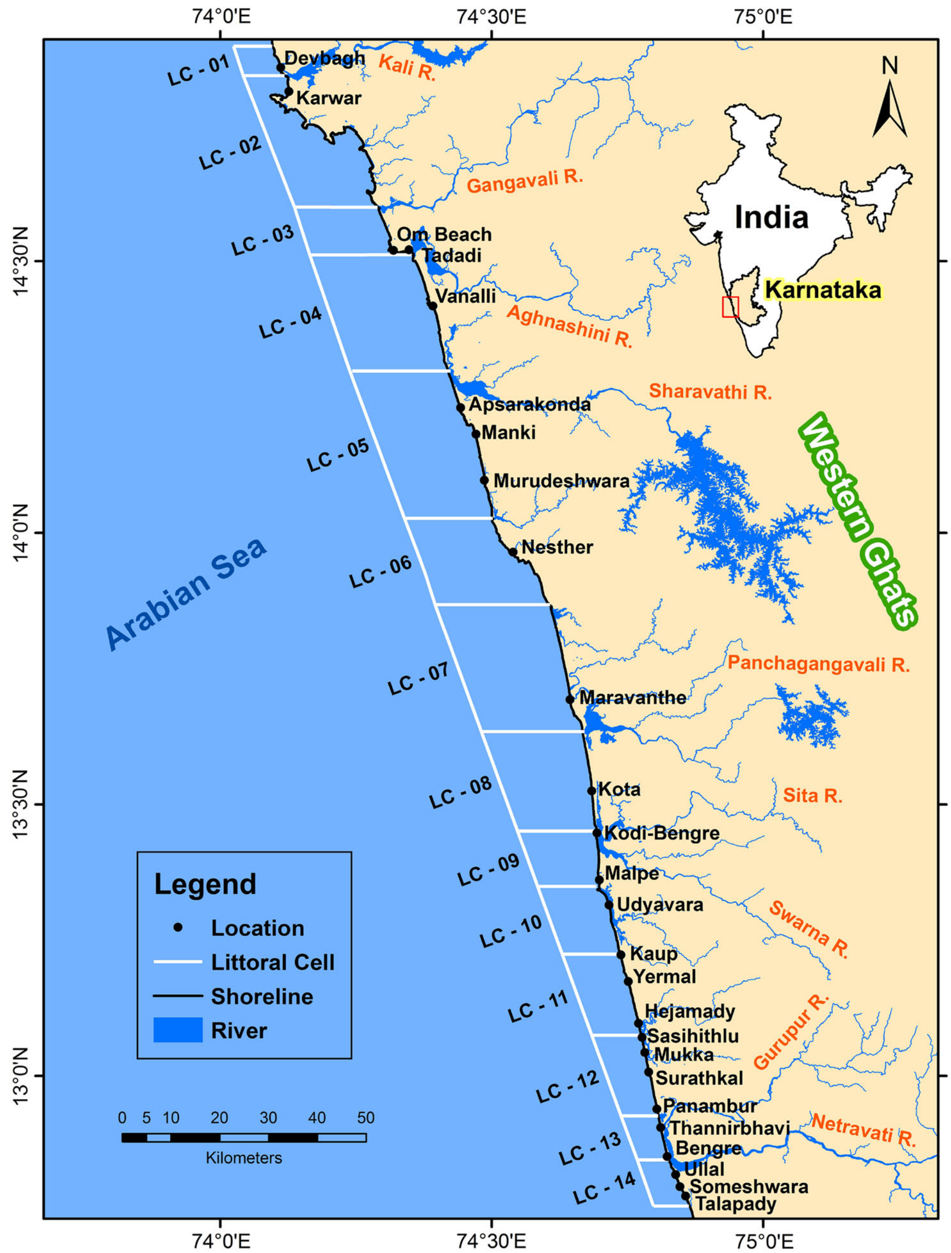

Fig. 1 Location of littoral cells (LC-01 to LC-14) along the Karnataka coast

Table 1 Variables used for the assessment of coastal vulnerability

CVI variable	Source	Period
(a) Shoreline dynamics	IRS Resourcesat-2 (LISS-IV)	2014–2017
(b) Land-use/land-cover	IRS Resourcesat-2 (LISS-IV)	2017
(c) Geomorphology	IRS Resourcesat-2 (LISS-IV)	2017
(d) Geology	Geological Survey of India	2005
(e) Elevation	Cartosat-1 (DEM), NRSC	2015
(f) Bathymetry	National Hydrographic Office of India	2004, 2005

baseline and the data sets of 2015, 2016 and 2017 have been coregistered (UTM projection with zone 43 N and WGS-84 datum) with second-order polynomial transformation strategy and root-mean-square error (RMSE) was maintained at less than a pixel. Thereafter shorelines were manually digitised for all the periods using ArcGIS 10.1 software. The transects were generated at each 0.5 km using digital shoreline analysis system (DSAS) tool

(Thieler et al. 2009). Tidal influence, rectification and digitisation errors were considered as the uncertainty value (4–5 m) to determine the erosion and accretion zones and net shoreline movement (NSM) statistics.

$$\text{Rate of shoreline change} = \frac{\text{Distance } (A - B) \text{ in } m}{\text{Time between recent and oldest shoreline}} \quad (1)$$

Using the LISS-IV satellite imagery of 2017, coastal land-use/land-cover and geomorphology map were prepared. Geology of the hinterland, regional elevation and nearshore bathymetry were extracted from the district resource map, Cartosat-1 digital elevation model (DEM) and Naval hydrographic chart, respectively. Coastal vulnerability index (CVI) has been calculated as the sum of vulnerability risk for each variable divided by the total number of variables (Gornitz and White 1991; Thieler and Hammar-Klose 1999; Boruff et al. 2005).

$$\text{Coastal Vulnarability Index (CVI)} = \frac{(a + b + c + d + e + f)}{n} \quad (2)$$

where a = shoreline dynamics; b = land-use/land-cover; c = geomorphology; d = geology; e = elevation; f = bathymetry; and n = number of variables.

Coasts subjected to accretion are considered less vulnerable as coast move towards the sea. Whereas, erosion is considered highly vulnerable due to the loss of natural habitats, private/public properties and beaches. Vegetation cover protects the coast and is less vulnerable compared to built-up areas. Plateaus are high elevated areas which are less vulnerable compared to the low-lying coastal plains which are highly vulnerable. Metabasalt withstand the strong wave impact, whereas beach alluvium gets washed off which increase the vulnerability of the area. Coastal regions having high elevation are considered less vulnerable as they provide more resistance for inundation; regions having low elevation are highly vulnerable areas. Nearshore areas having high depth are considered highly vulnerable with that of moderate depth. Most vulnerable features represent high risk, whereas least vulnerable feature represents low risk. In the present study, risk of these variables was assigned for every 0.5 km to get comprehensive information about the vulnerable zones. The variables are locally defined and modified according to the coastal specifications (Pendleton et al. 2005). The vulnerability risk of six variables (Table 2) was assigned to each transect and CVI is calculated. According to the obtained CVI values, vulnerability levels are classified.

Results

The shoreline dynamics between 2014 and 2017 periods reflect the rate of erosion and accretion in the corresponding area as the net shoreline movement (NSM). Six littoral cells (43%) are classified as low erosion, three (21%) as moderate erosion, one (7%) as high erosion, three (21%) as very high erosion and one (7%) as low accretion (Table 3). The shoreline along the Uttara Kannada district is classified as low erosion, Udupi as moderate erosion and Dakshina Kannada as high erosion (Table 4). In the study area, 3.5 km is classified as very high erosion, 4 km as high erosion, 14 km as moderate erosion, 158 km as low erosion, 20 km as stable, 100.5 km as low accretion, 3.5 km as moderate accretion and 0.5 km as high accretion zones (Table 5).

The coastal belt of Karnataka is dominated by crop land (992 km^2, ~ 31%) with paddy, groundnut, sugarcane and pulses and agriculture plantation (584 km^2, ~ 18%) mostly with coconut, arecanut and cashew on the coastal plain, pediplain and alluvial plain. Mixed forest (564 km^2, ~ 17.7%) comprises mainly of acacia, casuarina and bamboo on the pediplain and dense forest (475 km^2, ~ 15%) with teak, rosewood, sandalwood, many non-timber and other medicinal plant species grow naturally on denudational and structural hills. Barren land (401 km^2, ~ 12.6%) is associated with plateau; built-up (59 km^2, ~ 2%) areas are concentrated along the coast and water bodies (115 km^2, ~ 3.6%) like lakes and rivers are seen all around the coastal belt (Table 6).

The erosional and depositional geomorphic units like alluvial plain, coastal plain, denudational hills, flood plain, pediplain, plateau and structural hills are mapped and their areal extent is conferred (Table 6). Denudational hills formed due to differential erosion and weathering are mainly seen in the northern part with areal extent of 644 km^2 (~ 20%) and gently sloping pediplain (1660 km^2, ~ 52%) in the southern part of the coastal belt. Flat and gently undulating alluvial plain (218 km^2, ~ 7%) is seen near the river banks, whereas flood plains (59 km^2, ~ 2%) are subjected to periodic flooding in the estuaries. The coastal plain (261 km^2, ~ 8%) with low relief is bound parallel to the coast. Plateau (171 km^2, ~ 5%) with flat top and steep slopes, structural hills (13 km^2, < 1%) with acruate valley and high relief are mapped in few regions.

Granitic gneiss also called as peninsular gneiss of the Archaean age is the basement/dominating rock type (1055 km^2 i.e. ~ 33%) along this coast (Table 6). Gneissic rocks occur mainly in the form of banded biotite gneiss and streaky biotite gneiss. Mica (2 km^2 i.e. < 1%) and chlorite schists (~ 17 km^2 i.e. < 1%) of Dharwar

Table 2 CVI variables and vulnerability risk given for different classes along the Karnataka coast

CVI variables	Vulnerability risk (low to very high)				
	1	2	3	4	5
(a) Shoreline dynamics	> 0 m	− 1 to − 5 m	− 6 to − 10 m	− 11 to − 15 m	> − 15 m
(b) Land-use/land-cover	Mixed forest	Agriculture plantation	Crop land	Barren	Built-up
(c) Geomorphology	Plateau	Denudational hills	Pediplain	Alluvial plain	Coastal plain
(d) Geology	Metabasalt	Granite	Granitic gneiss	Laterite	Beach sand/alluvium
(e) Elevation	+ 4 to + 5 m	+ 3 to + 4 m	+ 2 to + 3 m	+ 1 to + 2 m	+ 0 to + 1 m
(f) Bathymetry	+ 0 to − 1 m	− 1 to − 2 m	− 2 to − 3 m	− 3 to − 4 m	− 4 to − 5 m

Table 3 Net shoreline movement (NSM) data and classification of littoral cells (LC-01 to LC-14)

LC	Transect	Length (km)	NSM between 2014 and 2017 (m)		Net rate of change (m)	Shoreline dynamics (%)	Classification
			Accretion	Erosion			
01	01–15	07.5	+ 07.50	− 31.16	− 23.66	− 0.32	Low erosion
02	16–146	65.5	+ 28.07	− 141.23	− 113.16	− 0.17	Low erosion
03	147–180	17.0	+ 08.90	− 153.06	− 144.16	− 0.85	High erosion
04	181–239	29.5	+ 37.01	− 81.75	− 44.74	− 0.15	Low erosion
05	240–306	33.5	+ 66.66	− 152.13	− 85.47	− 0.26	Low erosion
06	307–353	23.5	+ 14.48	− 72.84	− 58.36	− 0.25	Low erosion
07	354–407	27.0	+ 62.31	− 214.22	− 151.91	− 0.56	Mod. erosion
08	408–450	21.5	+ 75.51	− 142.81	− 67.30	− 0.31	Low erosion
09	451–473	11.5	+ 12.13	− 187.16	− 175.03	− 1.52	V.H. erosion
10	474–503	15.0	+ 21.22	− 84.41	− 63.19	− 0.42	Mod. erosion
11	504–538	17.5	+ 48.18	− 175.28	− 127.1	− 0.73	Mod. erosion
12	539–570	16.0	+ 51.11	− 267.37	− 216.26	− 1.35	V.H. erosion
13	571–587	08.5	+ 43.62	− 12.98	+ 30.64	+ 0.36	Low Accr.
14	588–608	10.5	+ 07.49	− 145.67	− 138.18	− 1.32	V.H. erosion
Overall		304.0	+ 484.19	− 1862.07	− 1377.88	− 0.45	Mod. erosion

Mod. = Moderate; V.H. = Very High; Accr. = Accretion

Table 4 Net shoreline movement (NSM) data and classification of districts (Uttara Kannada, Udupi and Dakshina Kannada)

District	Transect	Length (km)	NSM between 2014 and 2017 (m)		Net rate of change (m)	Shoreline dynamics (%)	Classification
			Accretion	Erosion			
UK	01–339	169.5	+ 154.09	− 609.74	− 455.65	− 0.27	Low erosion
Udupi	340–538	99.5	+ 227.88	− 826.31	− 598.43	− 0.60	Moderate erosion
DK	539–608	35.0	+ 102.22	− 426.02	− 323.80	− 0.93	High erosion
Overall		304.0	+ 484.19	− 1862.07	− 1377.88	− 0.45	Moderate erosion

supergroup (Archaean to lower Proterozoic age), associated with quartzites are noticed in some areas. Laterites of Cainozoic age are generally seen (914 km^2 i.e. ~ 29%) as capping on the basement rock. Beach sand/alluvium of Holocene/Recent age is restricted (136 km^2 i.e. ~ 4%) to the coastal and alluvial plains. A number of dolerite/gabbro dykes of the lower Proterozoic age are found as basic intrusives. Granite (542 km^2 i.e. ~ 17%) and metabasalt

Table 5 Net shoreline movement (NSM) data and classification of the Karnataka coast

Classification	NSM between 2014 and 2017 (m)	Length (km)	Shoreline dynamics (%)
Very high erosion	− 31 to − 133	03.5	1.15
High erosion	− 21 to − 30	04.0	1.32
Moderate erosion	− 11 to − 20	14.0	4.61
Low erosion	− 1 to − 10	158.0	51.97
Stable	0	20.0	6.58
Low accretion	1–10	100.5	33.06
Moderate accretion	11–20	03.5	1.15
High accretion	21–30	0.5	0.16

Table 6 Variables and areal extent of their classes along the Karnataka coast

Variables/classes	Area (km^2)	Area (%)
Land-use/land-cover		
Agriculture plantation	584	18.31
Barren land	401	12.57
Built-up	59	1.85
Crop land	992	31.10
Dense forest	475	14.89
Mixed forest	564	17.67
Water body	115	3.61
Geomorphology		
Alluvial plain	218	6.83
Coastal plain	261	8.19
Denudational hills	644	20.18
Flood plain	59	1.84
Pediplain	1660	52.05
Plateau	171	5.36
Structural hills	13	0.41
Water body	164	5.14
Geology		
Banded magnetite quartzite	04	0.13
Beach sand/alluvium	136	4.26
Columnar basalt	01	0.03
Dolerite/gabbro	04	0.13
Granite	542	16.99
Granitic gneiss	1055	33.07
Laterite	914	28.65
Meta greywacke argillite	48	1.50
Meta ultramafics	06	0.19
Metabasalt	303	9.50
Quartz-mica schist	02	0.07
Quartz-chlorite schist	17	0.53
Water body	158	4.95

(303 km^2 i.e. ∼ 10%) of the lower Proterozoic age occupy portion of the study area. Columnar basalt (1 km^2 i.e. < 1%) of Cretaceous to Eocene age is found as outcrops near St. Mary's island off Malpe beach which is declared as the National Geological monument (Abbas et al. 1991; Radhakrishna and Vaidyanadhan 1994).

Regional elevation is referred as the elevation above mean sea level. It is important to study the coastal regional elevation to identify the area threatened by vulnerability point of view. The regional coastal elevation extending 12 km landward comprises of a minimum elevation (0–10 m) mainly in the coast and southern part due to the presence of flat topography with coastal plains, flood plains, pediplains and water bodies. Whereas, a maximum elevation (1021 m) mainly seen in the north-eastern parts of the coastal belt with plateau, denudational and structural hills. Bathymetry is the essential baseline depicting the depth from the coast towards the open ocean; it is the underwater equivalent of contour lines on the land. The variation in nearshore bathymetry shows deepening of the nearshore. Slope is an important variable in deciding the vulnerability. The continental shelf along Karnataka coast is about 70 km wide and the shelf topography is smooth with gentle slope and the sediments are delivered by rivers originating in the Western Ghats (Avinash et al. 2010).

CVI is used to evaluate the probability of physical changes which may occur along the coastline. Based on the integration of the physical variables, viz., shoreline dynamics, land-use/land-cover, geomorphology, geology, elevation and bathymetry, vulnerability along Karnataka coast is demarcated as low, moderate, high and very high categories (Fig. 2). Out of 14 littoral cells, two (14%) are classified as low vulnerable, seven (50%) as moderately vulnerable, four (29%) as highly vulnerable and one (7%) as very highly vulnerable (Table 7). The shoreline along the Uttara Kannada district is classified as moderately vulnerable, Udupi and Dakshina Kannada as highly vulnerable to erosion. Along the Karnataka coast ∼ 9 km is classified as very high, ∼ 90.5 km as high, ∼ 165.5 km as moderate and ∼ 39 km as low vulnerable zones (Table 8).

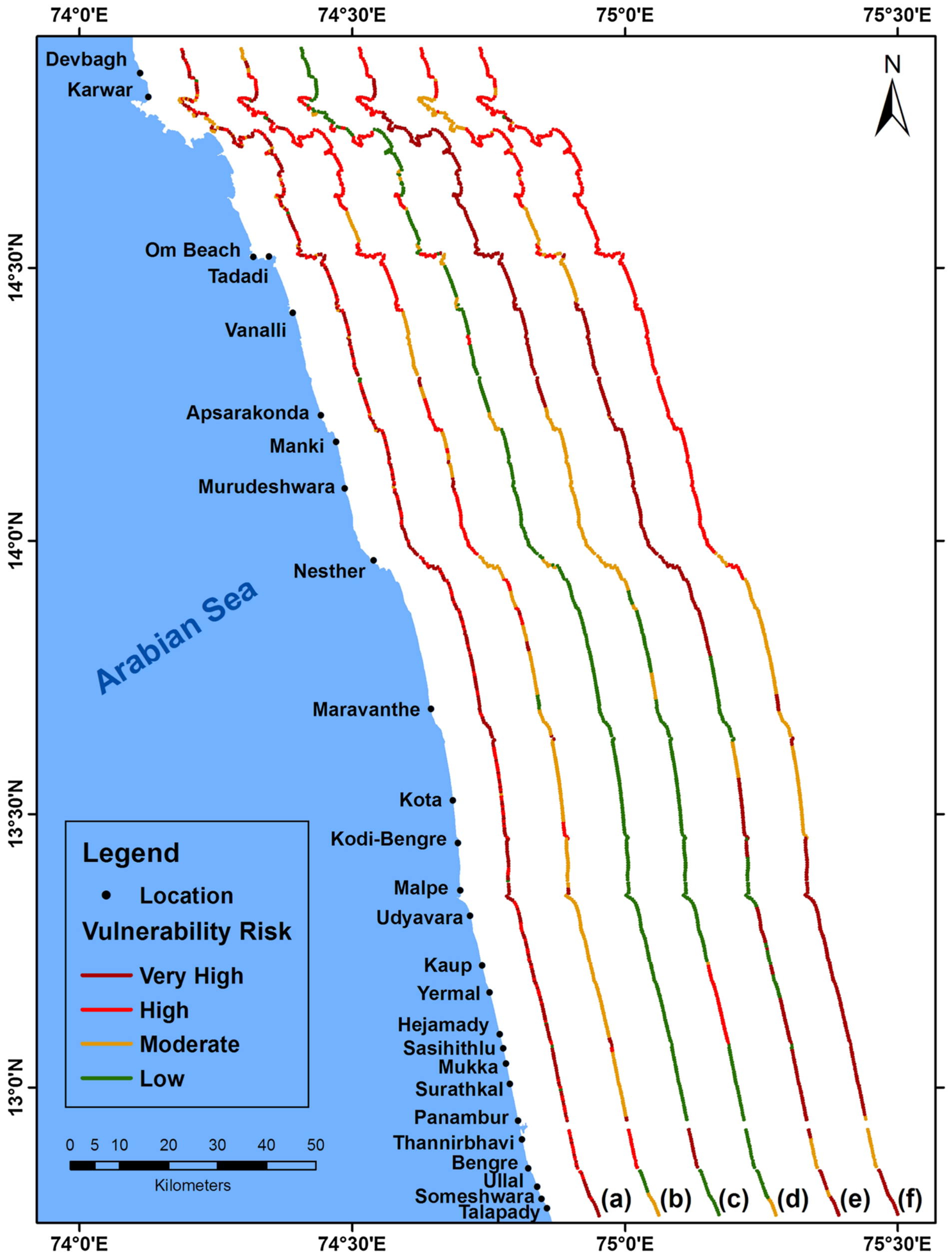

Fig. 2 Map showing vulnerability risk of the six physical variables mapped (**a**) net shoreline movement, (**b**) land-use/land-cover, (**c**) geomorphology, (**d**) geology, (**e**) regional elevation and (**f**) nearshore bathymetry along the Karnataka coast

Discussion

The landward displacement of the shoreline is a major crisis as it potentially impacts the coastal environment. It leads to loss of land into the sea due to primary natural processes such as waves, currents, tides and winds, or even due to the sand sources and sinks, changes in relative sea level, geomorphological characteristics of the shore etc. Anthropogenic interference triggers beach erosion by the construction of artificial structures, mining of beach sand, offshore dredging and building of vented dams across the rivers/streams. With growing population along the coast, artificial structures are constructed to protect the coastal community/property from the natural process which led to severe hardening of coastlines and changes in sediment dynamics (Airoldi et al. 2005). The coastal areas with man-made structures such as, groins and revetments intervene with the littoral drift direction (Greenwood and Orford 2007). Offshore bathymetry and slope are important factors influencing the deposition of sediments (Ridderinkhof et al. 2000). Along the Karnataka coast, very high erosion (− 31 to − 133 m) is noticed on the southern spits like Kali, Gangavali, Sharavathi, Sasihithlu and high erosion (− 21 to − 30 m) mainly in the beaches intervened by breakwater on the northern side. Moderate erosion (− 11 to − 20 m) of beaches with seawalls is observed, whereas

Table 7 Vulnerability of littoral cells (LC-01 to LC-14) along the Karnataka coast

LC	Transect	Length (km)	Vulnerability (km)				Beach/geo-tourism hotspots
			Very high	High	Moderate	Low	
01	01–15	07.5	–	–	05.5	02.0	Devbagh
02	16–146	65.5	–	03.5	34.0	28.0	Karwar
03	147–180	17.0	–	0.5	11.0	05.5	Om beach, Tadadi
04	181–239	29.5	–	–	28.0	01.5	Vanalli
05	240–306	33.5	–	02.5	29.0	02.0	Apsarakonda, Murudeshwara
06	307–353	23.5	–	01.5	22.0	–	Nester
07	354–407	27.0	3.0	20.5	03.5	–	Maravanthe
08	408–450	21.5	0.5	10.5	10.5	–	Kota
09	451–473	11.5	2.0	09.5	–	–	Kodi-Bengre, Malpe
10	474–503	15.0	–	15.0	–	–	Udyavara, Kaup
11	504–538	17.5	–	04.0	13.5	–	Yermal, Hejamady
12	539–570	16.0	0.5	15.5	–	–	Sasihithlu, Mukka
13	571–587	08.5	–	–	08.5	–	Thannirbhavi, Bengre
14	588–608	10.5	3.0	07.5	–	–	Ullal, Talapady
Overall		304.0	9.0	90.5	165.5	39.0	

Table 8 Vulnerability of districts (Uttara Kannada, Udupi and Dakshina Kannada)

District	Transect	Length (km)	Vulnerability (km)				Vulnerability (%)			
			Very high (4–5)	High (3–4)	Moderate (2–3)	Low (1–2)	Very high	High	Moderate	Low
UK	01–339	169.5	–	06.5	124.0	39.0	–	04	73	23
Udupi	340–538	99.5	05.5	61.0	33.0	–	06	61	33	–
DK	539–608	35.0	03.5	23.0	08.5	–	10	66	24	–
Overall		304.0	09.0	90.5	165.5	39.0	03	30	54	13

negligible erosion (− 1 to − 10 m) is found along the tourist beaches which are subjected to anthropogenic activities. Stable zones are along the rocky coast, low accretion (1–10 m) takes place in the pocket beaches. Whereas, moderate accretion (11–20 m) in the beaches with natural vegetation and high accretion (21–30 m) is seen on the up-drift side of the breakwaters (Fig. 3). Belekeri, Nesther, Maravanthe, Kota, Malpe, Yermal, Ullal, Talapady beaches and Kali, Gangavali, Sharavathi, Kodi-Bengre, Udyavara, Sasihithlu and Kotepura spits are the erosion hot spots which need to be protected by proper planning. Coastal processes in the study area are controlled by the natural processes—waves, littoral currents, offshore relief and river mouth/sea-level changes—and anthropogenic activities, such as construction of coastal structures, sand mining and dredging of navigation channels (Kumar and Jayappa 2009; Kumar et al. 2010).

The objective of the coastal vulnerability index is to classify the coastline into uniform entities bearing similar features. This classification helps in the development of coastal management policies in sensitive areas. CVI enables identification of vulnerable areas that could support policy decisions. The geological and physical observations combining with geospatial techniques can be useful for policy makers and coastal managers to protect the natural and coastal communities along the coast (Anitha and Usha 2015). High vulnerability is observed along the littoral cells subjected to high erosion, intervened by built-up structures (private/public property, seawalls, breakwaters etc.), low-lying coastal plains with beach alluvium and the nearshore areas with steep slope. Whereas, littoral cells subjected to accretion are protected by vegetation cover and high elevated plateaus with metabasalt withstand the strong wave impact and the near shore areas with moderate-to-low relief thus experiencing low vulnerability. The northern Karnataka coast (LC-01 to LC-06) is subjected to moderate vulnerability, whereas the southern coast (LC-07 to LC-14) is subjected to high vulnerability (Fig. 4). Maravanthe, Malpe, Mukka, Panambur, Ullal, Talapady beaches and Kodi-Bengre, Udyavara, Sasihithlu, Kotepura spits are the highly vulnerable sites. If proper management measures are not followed, the erosion rate along the Karnataka coast

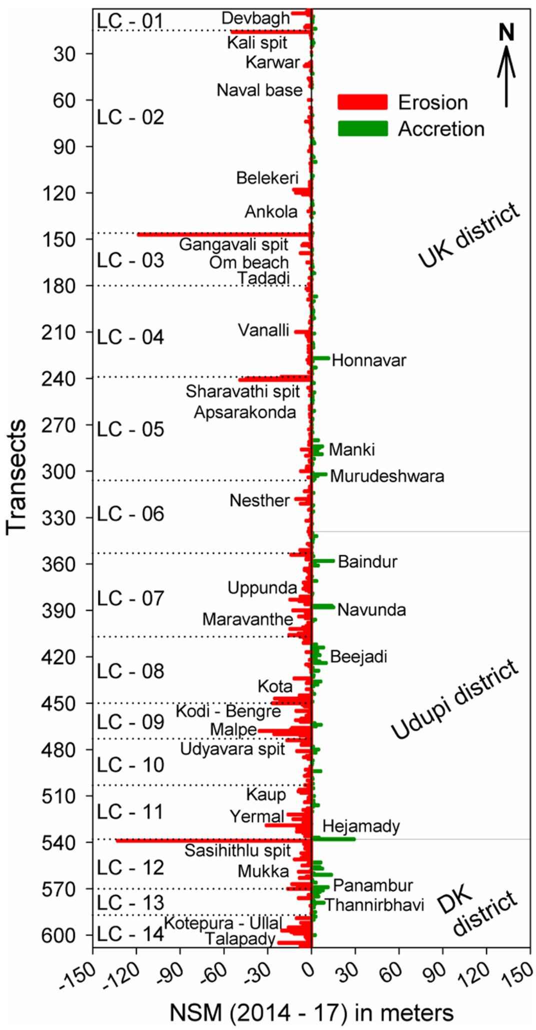

Fig. 3 Net shoreline movement (NSM) of littoral cells (LC-01 to LC-14) along the Karnataka coast

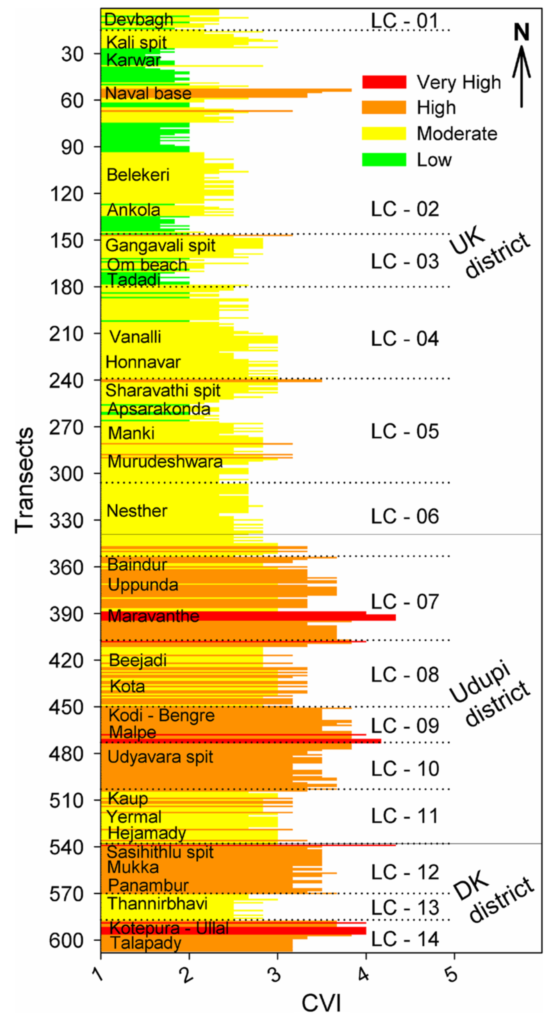

Fig. 4 Vulnerability of littoral cells (LC-01 to LC-14) along the Karnataka coast

will amplify from 59 to 87% in the next 25–30 years. CVI can be used as a stochastic approach to identify the relative risk due to coastal erosion. Evolving technologies in remote sensing and GIS are making accurate data available at better spatial and temporal scales (Nageswara et al. 2008; Srinivasa Kumar et al. 2010). Understanding the causes of erosion can help facilitate adaptation to reduce vulnerability (Ribot 2010). Highest priority should be to mitigate the high risk zones that are vulnerable to erosion due to anthropogenic activities along the coast. Erosion control, protecting natural barriers and banning illegal sand mining are the best adaptation options to protect the coastal areas. Engineering options such as seawall construction can minimise the effects of erosion along sensitive areas but results in shifting of erosion towards adjacent areas. The design of interventions must rely on analyses of vulnerability in adaptation measures (Heltberg et al. 2009). Man-made structures such as seawalls, groins, revetments and breakwaters are built to protect shorelines, and coastal landforms have modified the coastal processes causing erosion on the down-drift side and deposition of sediments on the up-drift side (Fig. 5).

Conclusions

Coastal vulnerability is an index-based approach to quantify vulnerability along the coastal regions. To assess the regional coastal vulnerability, the number of variables and their risk values differ. Vulnerability of the Karnataka coast mainly depends on the shoreline dynamics, land-use/land-cover, geomorphology, geology, elevation and bathymetry. On the basis of shoreline dynamics, the Karnataka coast is classified into very high erosion (1.15%), high erosion (1.32%), moderate erosion (4.61%), low erosion (51.97%), stable (6.58%), low accretion (33.06%), moderate accretion (1.15%) and high accretion (0.16%) zones. Coastal

Fig. 5 Field photographs showing highly vulnerable areas (**a**–**f**; Maravanthe, Kodi-Bengre, Malpe, Sasihithlu, Ullal, Talapady) and moderately vulnerable areas (**g**–**h**; Honnavar, Thannirbhavi) along the Karnataka coast

vulnerability along the Karnataka coast is classified into very highly vulnerable (3%), highly vulnerable (30%), moderately vulnerable (54%) and low vulnerable (13%) zones. Littoral cells on the north are subjected to moderate vulnerability, whereas on the south they are highly vulnerable. Although the CVI values compare significantly with the trend of erosion rates, they are more reliable in shoreline management as they involve other parameters that contribute to shoreline erosion. With the onset of south-west monsoon, people living along the coast raise lot of hue and cry about erosion and damage to their property. In order to monitor the volume of sediment eroded, a detailed analysis of beach profiles taken at closer intervals is necessary. Therefore, it is very much necessary to take up adaptation strategies in advance for the coastal vulnerability assessment which serves as an indicator of the threats to people living in coastal zones. The present study conclusively proves the application of remote sensing data and GIS technology by coastal scientists and administrators in the assessment of coastal vulnerability for better planning in order to mitigate the losses due to erosion.

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