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Coastal vulnerability assessment of the future sea level rise in Udupi coastal zone of Karnataka state, west coast of India

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A B S T R A C T

Udupi coast in Karnataka state, along the west coast of India, selected as a study area, is well known for sandy beaches, aquaculture ponds, lush greenery, temples and major and minor industries. It lies between 13°00′00″–13°45′00″ north latitudes and 74°47′30″–74°30′00″ east longitudes, the length of the coastline is 95 km, and is oriented along the NNW–SSE direction. It is vulnerable to accelerated sea level rise (SLR) due to its low topography and its high ecological and touristy value. The present study has been carried out with a view to calculate the coastal vulnerability index (CVI) to know the high and low vulnerable areas and area of inundation due to future SLR, and land loss due to coastal erosion. Both conventional and remotely sensed data were used and analysed through the modelling technique and by using ERDAS Imagine and geographical information system software. The rate of erosion was 0.6018 km^2/yr during 2000–2006 and around 46 km of the total 95 km stretch is under critical erosion. Out of the 95 km stretch coastline, 59% is at very high risk, 7% high, 4% moderate and 30% in the low vulnerable category, due to SLR. Results of the inundation analysis indicate that 42.19 km^2 and 372.08 km^2 of the land area will be submerged by flooding at 1 m and 10 m inundation levels. The most severely affected sectors are expected to be the residential and recreational areas, agricultural land, and the natural ecosystem. As this coast is planned for future coastal developmental activities, measures such as building regulation, urban growth planning, development of an integrated coastal zone management, strict enforcement of the Coastal Regulation Zone (CRZ) Act 1991, monitoring of impacts and further research in this regard are recommended for the study area.

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1. Introduction

The most obvious outcome of sea level rise (SLR) due to storms, tsunami or even global sea level change is the permanent inundation of coastal areas and it will have a serious impact upon the natural environment and socio-economic conditions in the coastal zone. Over time, inundation changes the position of the coastline and drowns natural habitat and coastal structures. Inundation can also exacerbate coastal erosion by transporting submerged sediments offshore, and extending the effects of coastal flooding by allowing storm waves to act further. Wave heights also increase when concentrated on head lands or when travelling into bays having wide entrances that become progressively narrower. Geographic features of nearshore and coastal land of an area can alter the inundation pattern of tsunami waves. During the tsunami, the maximum vertical height to which water is observed with reference to sea level (spring tide or mean sea level) is referred to as run-up. The maximum horizontal distance that is reached by a tsunami is referred to as inundation [33,34]. SLR would directly result in a corresponding higher shift to the zone of wave action on the beach. This would be reflected in a shoreline recession which will be larger on milder slopes.

Coastal vulnerability assessment has been carried out using remote sensing (RS) and geographical information system (GIS) by El-Raey [11] and Al-Jeneid et al. [1]. It is strongly linked to the socio-economic value assigned to coastal components. Possible changes to these values will assist in the selection and interpretation of

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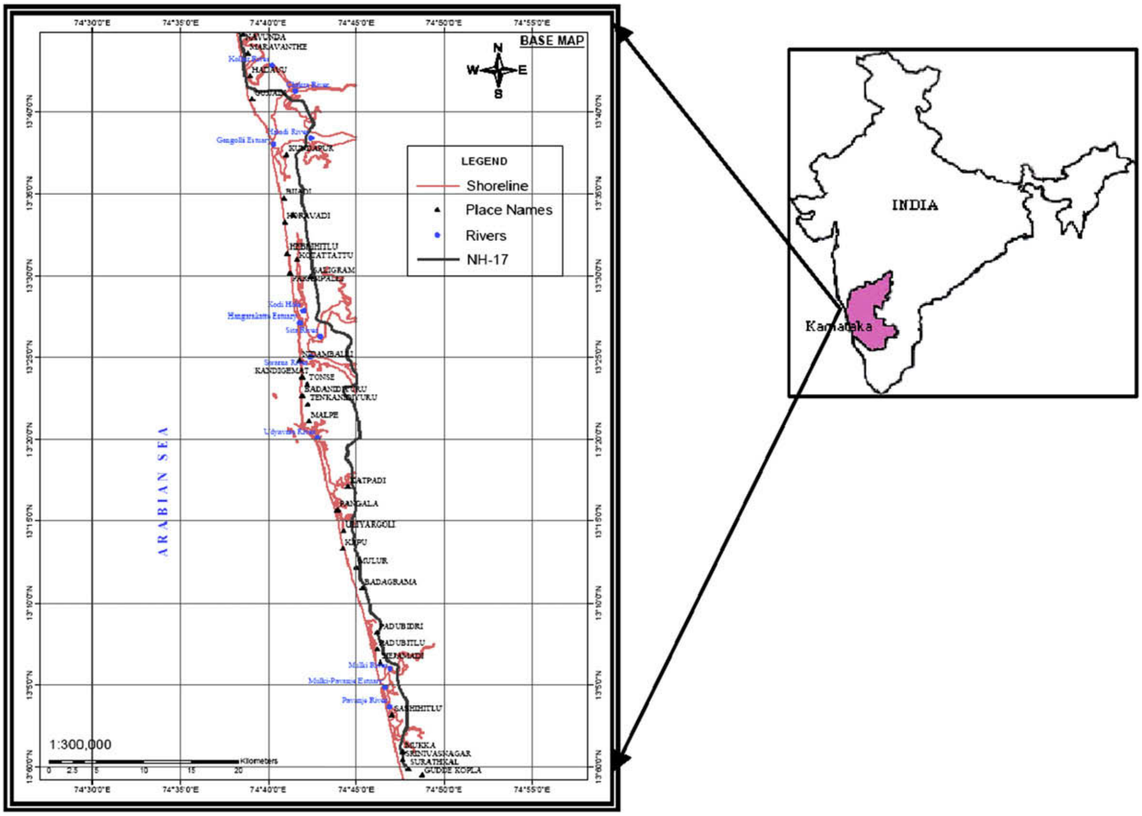

Fig. 1. Location of the study area.

possible responses to the changing boundary conditions such as SLR, human interference and other climatic changes [6]. The results of the vulnerability assessment will be very useful in integrated coastal zone management plan (ICZMP) [32]. A coastal vulnerability index (CVI) was used to map the relative vulnerability of the coast to future SLR within the study area. Thieler and Hammer [36] have completed extensive assessment of coastal vulnerability along various coasts based on the work of Gornitz [13]. They have incorporated six physical coastal variables: geomorphology, shoreline change rate, coastal slope, mean tide range, mean significant wave height and SLR. The main objectives of the present study were to develop a CVI for coastal erosion and then use it to assess the impact along the Udupi coast, with a view to identify and quantify the vulnerable low lying coastal areas of Udupi, due to SLR and land loss due to coastal erosion. RS and GIS tools can be used to prepare the land use and land cover map and shoreline change detection map [3,8b,12,18,20,22,25,26,28,30,31,37].

2. Description of the study area

Udupi coast starting from Surathkal in the south and Navunda in the north along Karnataka coast, west coast of India is the study area. It lies between 13°00′00″–13°45′00″ north latitudes and 74°47′30″–74°30′00″ east longitudes (Fig. 1). The length of the coastline is 95 km and is oriented along the NNW–SSE direction. The study area has a tropical climate. March–May constitute the hot season. With respect to the mean daily temperature, May (36 °C) and December (23 °C) are the hottest and coolest months respectively. The area receives a very heavy downpour between June and September due to the southwest monsoon. The average annual

Table 1
Database of the present study.

Sl. no.	Type of data	Source	Purpose
Conventional data			
1	Toposheet	Survey of India (SOI), Bangalore	To prepare base map, shoreline change map, geomorphology map, CRZ map, and to delineate the HTL and LTL
2	Naval hydrographic charts	New Mangalore Port Trust, Panambur	To develop bathymetry map
3	Wave data, mean tidal range	New Mangalore Port Trust, Panambur	To incorporate in the CVI calculation
4	GPS survey data	Field visit	To finalize shoreline change detection map and LU/LC map
5	Intergovernmental Panel on Climate Change technical guidelines, 2001	IPCC [15]	To get the SLR details and to use in CVI calculation
Remote sensing data			
1	IRS-1C/P6 LISS III + PAN merged data (February 2000, February 2006)	National Remote Sensing Centre, Hyderabad	To prepare LU/LC map, shoreline change detection map, geomorphology
2	SRTM data	http://srtm.csi.cgiar.org	To prepare the DEM and then the inundation map

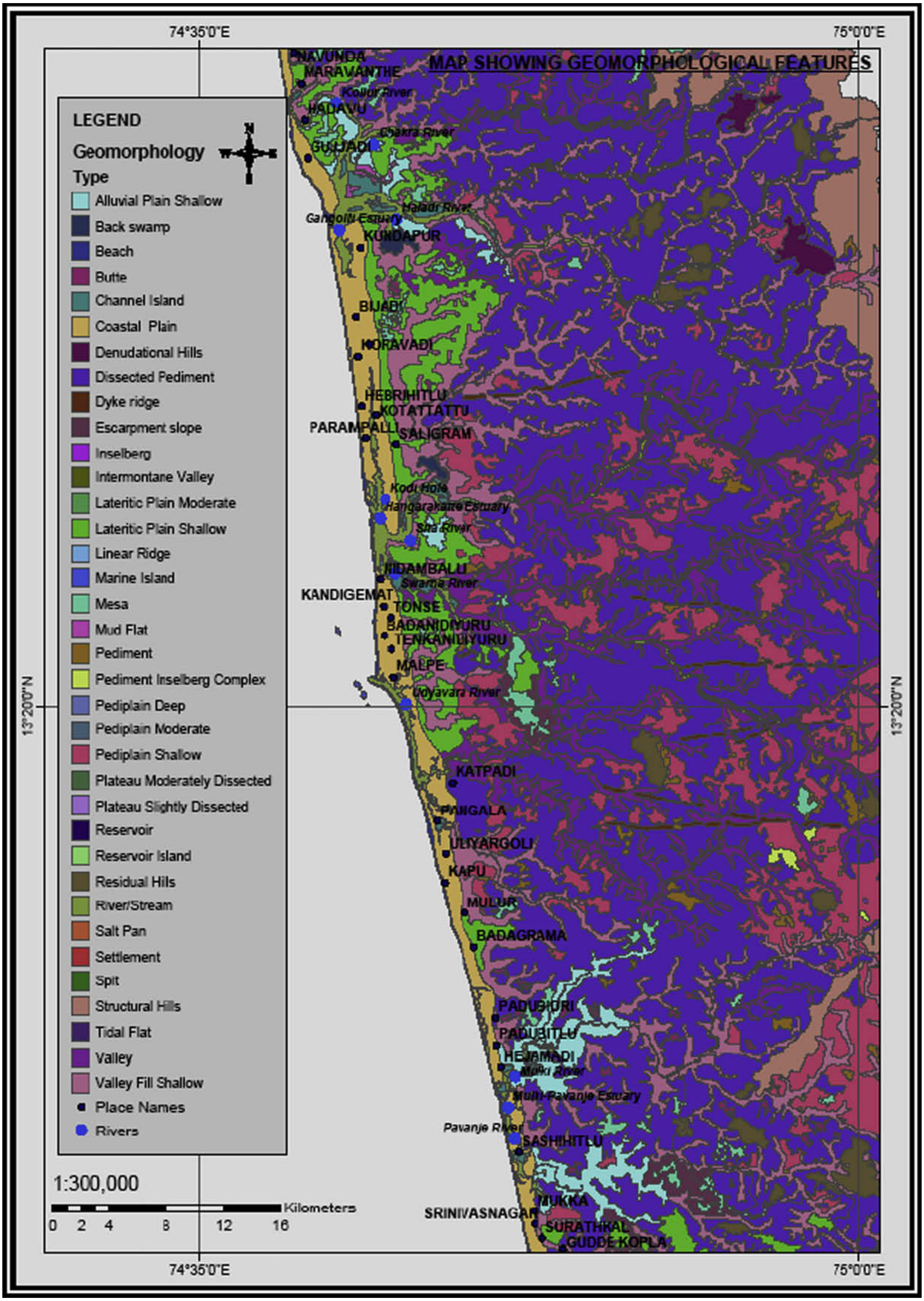

Fig. 2. Geomorphology map of the study area.

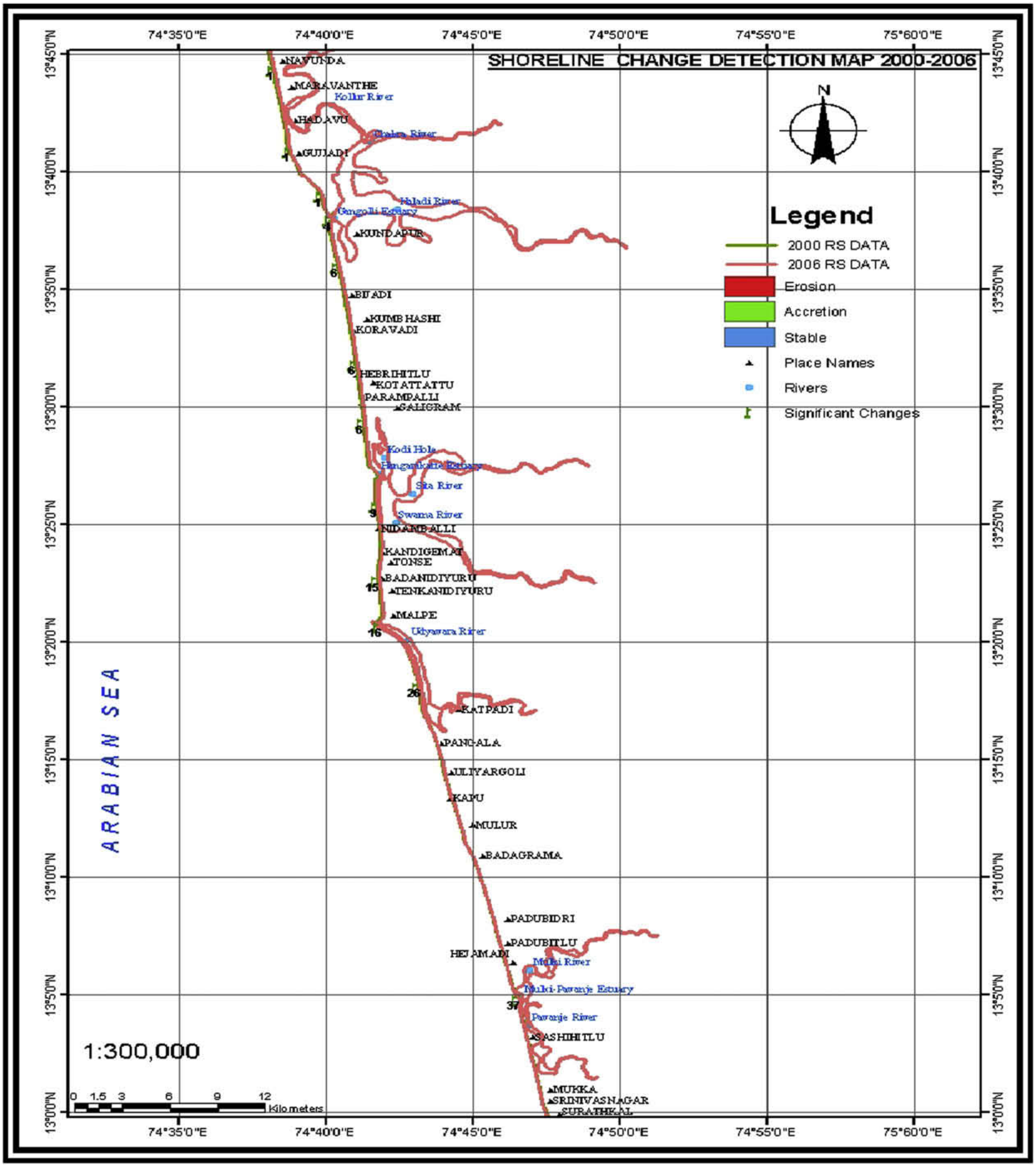

Fig. 3. Shoreline change map, 2000–2006.

rainfall is 3954 mm of which 87% is received during the monsoon season [19]. The main economic activities of the area are fisheries, agriculture, tourism and industrialisation and hence there is an increase in urbanisation along the coast. In addition to these, this coast is well known for the coastal ecosystem such as mangroves, coastal forest, aquaculture ponds and long sandy beaches. All these activities will be increasing the vulnerability of the Udupi coast to future SLR.

3. Data products

Any study related to coastal processes involves the analysis of both conventional and remotely sensed data. Conventional data are more accurate and site specific, but data collection is time consuming, expensive, requires more manpower and it may not be possible to extrapolate to a larger area. Remotely sensed data on the other hand have got advantages due to repetitive and synoptic coverage of the large, inaccessible areas quickly and economically. In the present study, to take the dual advantages, both conventional and remotely sensed data were used. The Survey of India (SOI) toposheets were prepared during 1971 on a 1:50 000 scale used to prepare the base map, and other thematic maps were registered with respect to this base map. The National Institute of Ocean Technology (NIOT), Chennai, India, deployed wave rider buoys off Bay of Bengal and Arabian Sea; one of them is located nearer to the New Mangalore Port Trust (NMPT), and all the required wave

Table 2
Details of shoreline change for the period 2000–2006.

Stn. nos.	Longitude and latitude for the stretch of the beach	Location	Beach width (m)	Beach length (m)	Area (km^2)	Status of the beach: erosion (−) accretion (+)
1	74°35′08″ 13°55′17″ 74°40′01″ 13°38′16″	Navunda, Maravanthe, Hadavu, Gujjadi, Gangolli estuary	96	33 206	2.3014	Erosion
5	74°40′15″ 13°36′50″ 74°40′16″ 13°36′41″	Kundapur	10	294	0.0015	Accretion
10	74°41′48″ 13°24′54″ 74°41′49″ 13°24′50″	Nidamballi	8	100	0.0005	Accretion
15	74°41′47″ 13°21′25″ 74°41′52″ 13°21′06″	Malpe, Udyavara river mouth (northern part)	44	4305	0.1354	Erosion
20	74°42′33″ 13°20′00″ 74°42′41″ 13°19′47″	Udyavara river mouth (southern part)	10	483	0.0026	Erosion
25	74°43′06″ 13°18′22″ 74°43′06″ 13°18′19″	Udyavara river mouth (southern part)	8	102	0.0004	Accretion
30	74°43′52″ 13°15′12″ 74°43′53″ 13°15′09″	Pangala, north of Uliyargoli	3	99	0.0002	Erosion
35	74°44′21″ 13°13′03″ 74°45′59″ 13°06′48″	Mulur, Badagrama, Padubidri, Padubitlu	42	11 980	0.3201	Accretion

parameters were collected from NMPT. Trimble hand held GPS of accuracy ±10 m was used to map the shoreline and to collect the coordinates of important LU/LC features in the study area during the pre and post classification field visits while preparing the LU/LC map. IRS-1C/P6 LISS III + PAN merged remotely sensed data for the year 2000 and 2006 were purchased from the National Remote Sensing Centre, Hyderabad, India. The resolution of the merged data was 5.8 m, and was used to prepare the LU/LC map, shoreline change detection map and geomorphology map. Finally Shuttle Radar Topography Mission (SRTM) data of approximately 90 m resolution were downloaded from the website and used to prepare the digital elevation map (DEM) and then the inundation map of

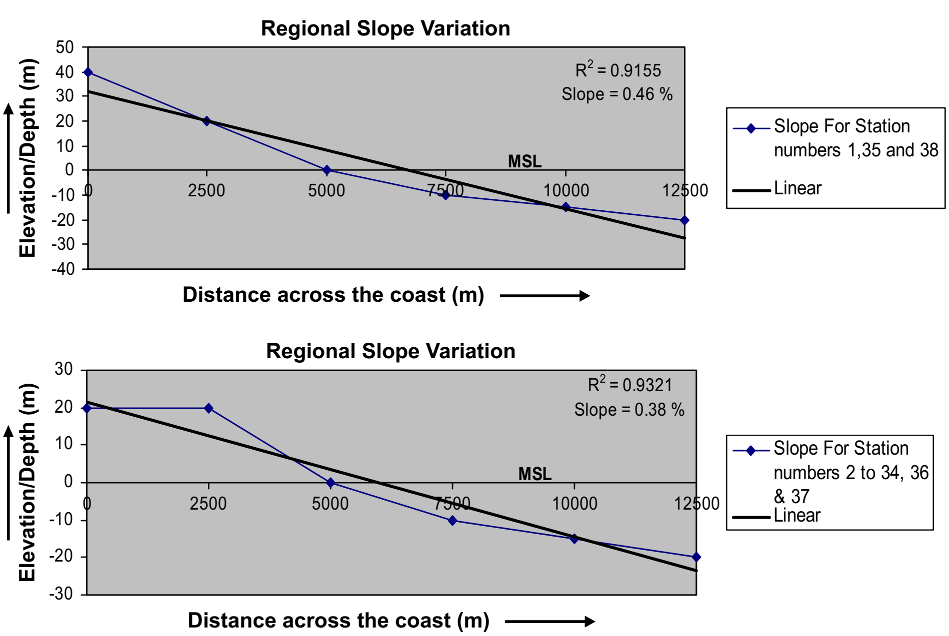

Fig. 4. Graphs showing the regional coastal slope.

Table 3
Ranges of vulnerability ranking for the study area.

Sl. no.	Variable	Ranking of coastal vulnerability				
		Very low	Low	Moderate	High	Very high
		1	2	3	4	5
1	Geomorphology	Rocky cliffed coasts	Medium cliffs, indented coasts	Low cliffs, lateritic plain	River deposits, alluvial plain	Coastal plain, beach, mud flats
2	Shoreline erosion/accretion (m/yr)	>+15	+5 to +15	−5 to +5	−15 to −5	<−15
3	Coastal slope (%)	>0.6	0.5–0.6	0.4–0.5	0.3–0.4	<0.3
4	Mean tide range (m)	>4.0	3.0–4.0	2.0–3.0	1.0–2.0	<1.0
5	Mean significant wave height (m)	<0.7	0.7–1.4	1.4–2.1	2.1–2.8	>2.8
6	Mean sea level rise (mm/yr)	<1.8	1.8–2.5	2.5–3.0	3.0–3.4	>3.4

the study area. All these data sets were utilised to study the impact of SLR on land loss, LU/LC, and coastal erosion. Further details about the data products are provided in Table 1.

4. Methodology

The CVI allows the six variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea level rise. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea level rise may be the greatest and it is the same as that used by Gornitz et al. [14] and Thieler and Hammer [36]. Land/beach loss due to coastal erosion and coastal inundation are the two types of physical impacts considered in the present study.

The six variables are classified into two groups:

1. Geologic variables,
2. Physical variables.

The geologic variables include (a) historic shoreline change, (b) geomorphology and (c) coastal slope. The physical variables include (a) mean tidal range, (b) mean significant wave height and global SLR.

Once each section of the coastline is assigned a vulnerability value for each specific data variable, the CVI was calculated as the square root of the product of the ranked variables divided by the total number of variables.

$$\mathrm{CVI} = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \quad (1)$$

where, a = geomorphology, b = shoreline change rate (m/yr), c = coastal slope (%), d = mean tidal range (m), e = mean significant wave height (m), f = global SLR (mm/yr).

The geologic variables consist of geomorphology, historic shoreline change rate, and coastal slope; they account for a shoreline's relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The physical process variables include significant tidal range, wave height, and global SLR, all of which contribute to inundation hazards of a particular section of the coastline over time scales from hours to centuries. These six variables include both qualitative and quantitative information. Actual variable values are assigned a vulnerability ranking based on value ranges, whereas the non-numerical geomorphology variable is ranked qualitatively according to the relative resistance of a given landform to erosion. In the present study, ranking was assigned for these variables along 38 stations in the study area and thus CVI was calculated for these stations. The stations were selected based on the magnitude of the changes in shoreline from 2000 to 2006. The CVI can be used by scientists and engineers to evaluate the likelihood that physical change may occur along a shoreline as the sea level rises and to take necessary actions. The CVI may also be used to judge suitable sites of industrialisation, development of ports and harbours, urbanisation or tourism. The values and ranking assigned for each variable are described in the following paragraphs.

4.1. Geomorphology

The geomorphology variable expresses the relative erodibility of different landform types. The ranking is on a linear scale from 1 to 5 in order of increasing vulnerability due to SLR [13]. The value of 1 represents the lowest risk (rocky cliffed coast) and 5 represents the highest risk (coastal plain, beach, mud flats) as far as coastal erosion is considered. In the present study, a detailed geomorphology map has been prepared by using toposheets of 1: 50 000 scale as shown in Fig. 2. Only important geomorphology features required for the calculation of CVI are given in Table 3.

4.2. Shoreline change rate

Approximately 70% of the world's sandy beaches have been identified as eroding [2]. Though beaches along the Karnataka coast are maintaining dynamic equilibrium, there will be temporary sea erosion during the southwest monsoon, due to high wave activity [8b,19]. To calculate the shoreline erosion/accretion rate along the Udupi coast, IRS-1C/P6 RS merged digital data of 2000 and 2006 were analysed using the ERDAS Imagine software. The analysis of high resolution merged data will have fewer errors than manual methods that use a photographic comparator or stereo zoom transfer scope [24]. The vector layers of 2000 and 2006 were overlaid using ArcMap GIS software [5] and the final map was obtained as shown in Fig. 3. During this period of RS data analysis, some of the sites showed significant erosion and all the river mouths showed a tendency of shifting towards the south. Out of 38 stations selected for the analysis, 18 erosion sites, 20 accretion sites were identified, with no stable locations. The total area of erosion was 3.611 km^2 and that of accretion was 2.011 km^2. The minimum width of beach was 3 m under accretion and erosion, whereas the maximum beach width was 100 m under accretion and 96 m for erosion. The details of shoreline change during 2000–2006 only for eight important stations are given in Table 2 and these station numbers and station name(s) correspond to the station details shown in the shoreline change map (Fig. 3).

The ranking of the shoreline change rate is based on the range of change in beach width values. By superimposing the RS data on the base map, the area of accretion and erosion was calculated and then the maximum erosion and maximum accretion rate were estimated as −16.00 m/yr and +16.67 m/yr respectively. Shorelines with erosion/accretion rates between −5 m/yr and +5 m/yr are ranked moderate. With ±5 increments, increasingly higher erosion or

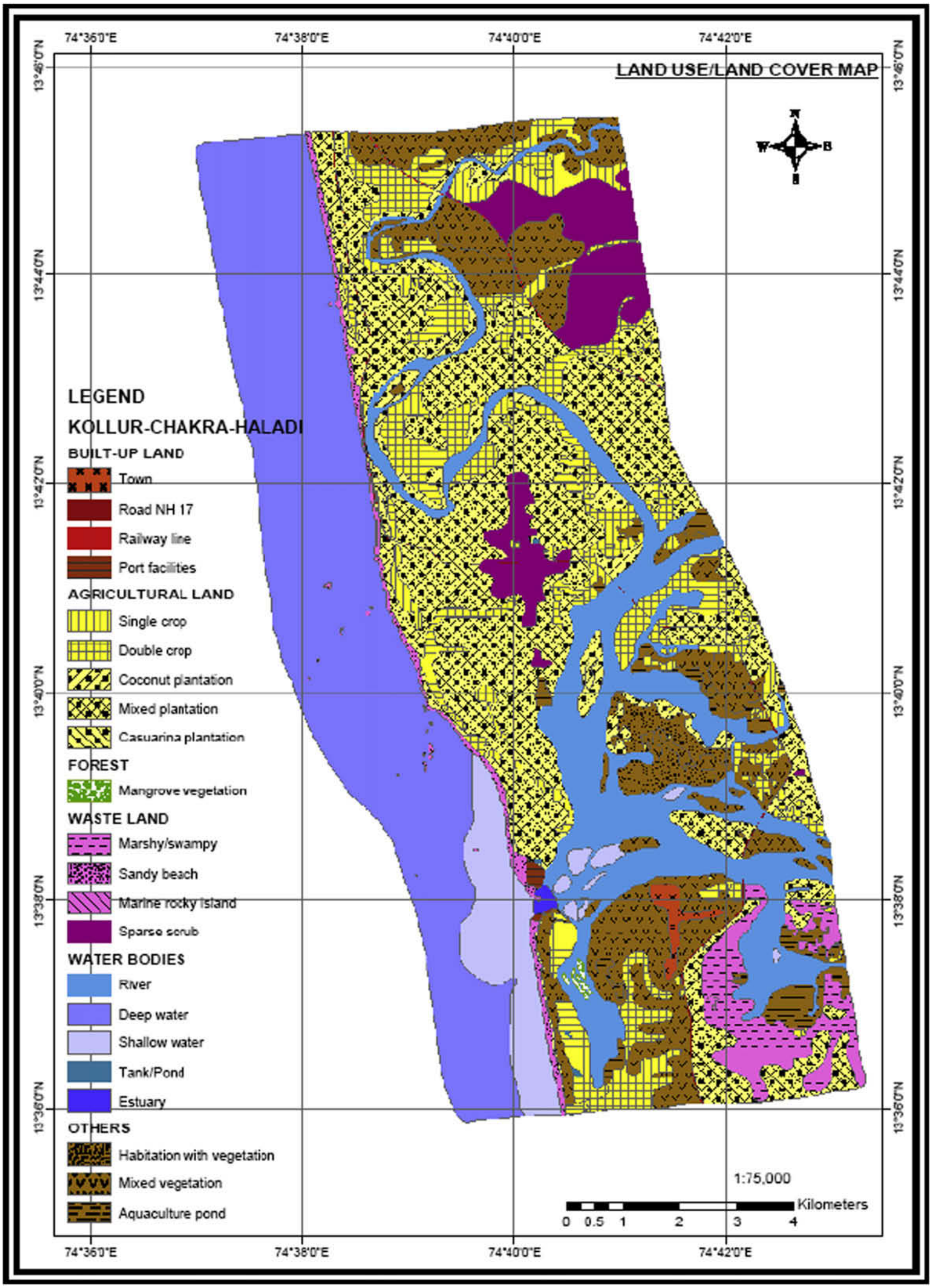

Fig. 5. Land use/land cover map for Kollur–Chakra–Haladi, 2006.

accretion rates are ranked as correspondingly higher or lower vulnerability. Along the Udupi coast waves approach the coast with their crest parallel to the coast and hence there will be an offshore–onshore movement of the sediments. During the southwest monsoon season, due to severe wave activity, a large quantity of sediment will be moved to the offshore region; once the wave activity is reduced during the non-monsoon period, almost the same quantity of sediment will be brought back to the coast, by the

Table 4
Land use/land cover details of Kollur–Chakra–Haladi, 2006.

Land use/land cover classification for Kollur–Chakra–Haladi – 2006		Area (m^2)
Built-up land	Town	543 574
	Road NH 17	222 183.96
	Railway line	100 179.62
	Port facilities	143 493.5
	Total	1 009 431.08
Agricultural land	Single crop	2 426 077.11
	Double crop	12 429 659.61
	Coconut plantation	2 962 876.18
	Mixed plantation	29 681 433.66
	Casuarina plantation	262 914.80
	Total	47 762 961.37
Forest	Mangrove vegetation	94 109.19
Waste lands	Marshy/swampy	3 796 454.30
	Sandy beach	1 452 555.19
	Marine rocky island	59 357.54
	Land with scrub	6 051 219.79
	Total	11 359 586.84
Water bodies	River	16 770 330.4
	Deep water	30 117 400
	Tank/pond	37 469.72
	Shallow water	5 199 084.79
	Estuary	144 357
	Total	52 268 641.92
Others	Habitation with vegetation	1 695 530
	Mixed vegetation	13 599 476.8
	Aquaculture pond	2 309 115.30
	Total	17 604 122.1

waves, and hence, the beach is in dynamic equilibrium. However some stretches of the beach are subjected to severe wave attack and hence erosion at these places will be more and they are identified as critical erosion areas (CEAs) [8a–10,16,17,19]. Because of this reason the net erosion is more than the net deposition, which forms the basis for the present analysis.

4.3. Coastal slope

Determination of the regional coastal slope identifies the relative vulnerability of inundation and the potential rapidity of shoreline retreat because low-sloping coastal regions are thought to retreat faster than steeper regions [38,39]. The regional coastal slope was calculated for a distance of 12.5 km perpendicular to the shoreline (7.5 km on the sea side and 5 km towards the land side). The bathymetry details were obtained from naval hydrographic charts and contours using toposheets. The graphs shown in Fig. 4 represent the coastal slope of the study area at different stations. The regional coastal slope ranges from 0.38% to 0.46%. A slope greater than 0.6% is assigned low vulnerability and less than 0.3% is assigned high vulnerability. These values are also fixed based on the physiography, contour details from SRTM data and generated DEM.

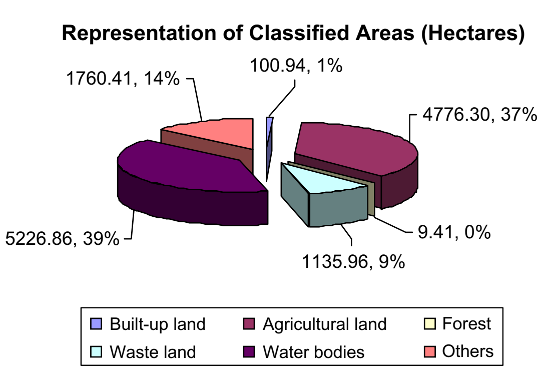

Fig. 6. Pie chart showing the LU/LC percentage area.

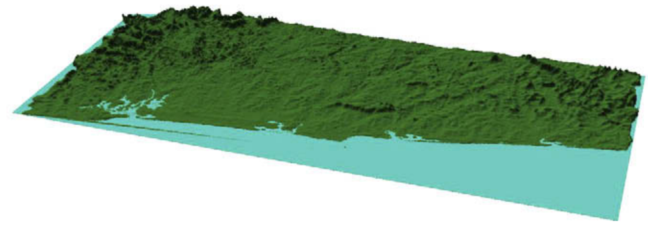

Fig. 7. Inundation map for 1 m rise in sea level.

4.4. Mean tidal range

Tides along the Udupi coast and other areas of the Dakshina Kannada coast are of the mixed type with semi diurnal components dominating. Semi diurnal tides would mean two high waters and two low waters in a day. The tidal data as obtained from the New Mangalore Port have a tidal range of approximately 1.6 m. Tidal range is ranked such that micro tidal (tide range $<$2.0 m) coasts are at high risk and macro tidal (tide range $>$4 m) coasts are at low risk. The reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. For example, on a tidal coastline, there is only 50% chance of a storm occurring at high tide. Thus, for a region with a 4 m tide range, a storm having a 3 m surge height is still up to 1 m below the elevation of high tide for half a tidal cycle. A micro tidal coastline, on the other hand, is essentially always “near” high tide and therefore always at the greatest risk of inundation from storms. Therefore a high vulnerability has been assigned for the present study area with a tidal range of 1.6 m.

4.5. Mean significant wave height

The mean significant wave height used for the calculation of CVI is a proxy for wave energy which drives the coastal sediment budget; wave energy is directly related to the square of wave height:

$$E = (1/8)\rho g h^2 \tag{2}$$

where, E = energy density (N/m^2), h = wave height (m), ρ = water density (N/m^3), g = acceleration due to gravity (m/s^2).

Thus, the ability to mobilize and transport coastal sediments is a function of the wave height squared. For, statistical analysis wave records containing at least 100 waves are required. For every 100 waves, the significant wave heights can be calculated. As per the KREC study team [19], the significant wave heights range from 1.6 m to 2.8 m, out of which the maximum number of waves occurring are of 2 m height. Therefore as per the data available for the study area, these waves are considered moderately vulnerable.

4.6. Mean sea level rise

A sea level rise would directly result in a corresponding higher shift to the zone of wave action on the beach. This would be

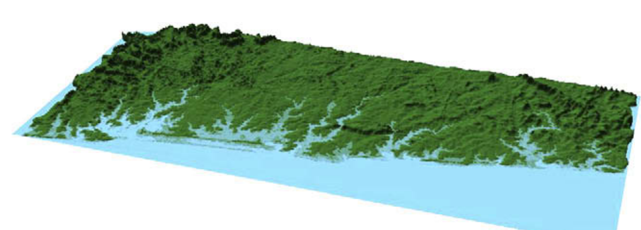

Fig. 8. Inundation map for 10 m rise in sea level.

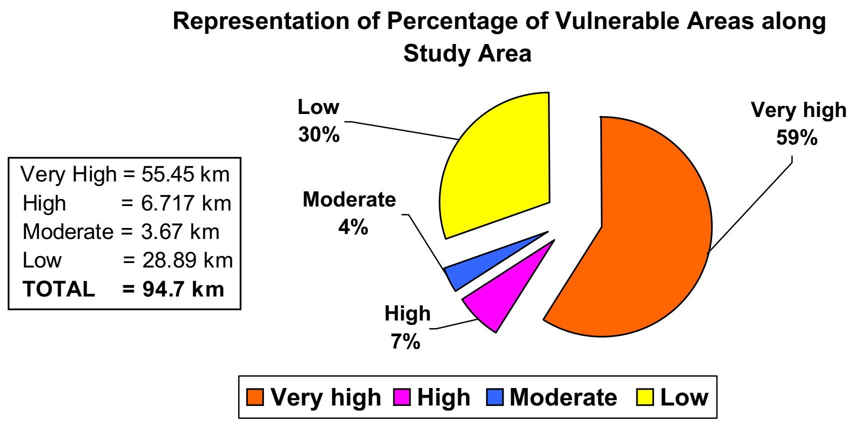

Fig. 9. Percentage of vulnerable areas along the Udupi coast.

reflected in a shoreline recession which will be larger on milder slopes. Bruun [4] has presented a theory which estimates the shoreline recession for a given rise in sea level. According to this estimate, every millimetre rise of sea level on the Karnataka coast must result in a shoreline retreat of about 1 m. There are also reports from earlier studies that there is a relative sea level fall than a sea level rise along the Mangalore coast, since the land is rising along the Mulky–Pulicat lake (MPL) axis close to 13°N latitude [34]. Udupi coast (13°00′00″–13°45′00″) towards the north and on the down slope of MPL, is susceptible to SLR. By considering a global sea level rise of 1.8–2.0 mm/yr [15] and also reports from earlier studies, a sea level rise is considered as low vulnerability for the study area [35]. Finally the ranges of vulnerability rankings assigned for all the six variables are furnished in Table 3.

In addition to the estimation of the above parameters, the land use/land cover [LU/LC] map for the river mouth areas and DEM for the complete study area have been prepared, for the inundation analysis and to know the submergence of different LU/LC features due to future SLR.

4.7. LU/LC map

In the study area all the rivers originate in the western ghats, flow westward and take a 90° bend near the coast and then flow either northward or southward, two or three rivers join together, before joining the Arabian Sea (Fig. 1). The length of the sand spit at some places is more than 7 km, and they are highly vulnerable to sea erosion and these areas are also highly populated in addition to several fish processing industries. Because of this reason river mouths in the study area were selected for the LU/LC map preparation. IRS-P6 LISS III + PAN merged data of 2006 were analysed up to the level-II classification by adopting the maximum likelihood algorithm of the supervised classification technique [21] for the preparation of the LU/LC map. The classified output only for the Kollur–Chakra–Haladi river mouth, which is one of the biggest estuaries in the study area is provided in the present paper as shown in Fig. 5, and the corresponding details are provided in Table 4. The pie chart in Fig. 6 shows only the percentage of level-I LU/LC features, which is required for the inundation analysis.

4.8. Inundation map

Bruun [4] has presented a theory which estimates the shoreline recession for a given rise in sea level. According to this estimate, every millimetre rise of sea level on the Karnataka coast must result in a shoreline retreat of about 1 m. Factors such as nearshore topography, location and orientation of the coastal segment, tidal range, morphology of the coast etc are responsible for the resistance of the coast to the rise in water level. The intensity and magnitude of the water level rise are also an important factor governing the magnitude of inundation of the area. By keeping the SLR and tsunami in mind, an inundation map was prepared for the study area using the virtual GIS module of ERDAS Imagine software for six run-up values i.e., 1–5 m with 1 m interval and then 10 m with reference to the mean sea level, by taking the digital elevation model [DEM] as a base map. This DEM was prepared using Shuttle Radar Topography Mission (SRTM) data, which are available as 3 arcsec (approx. 90 m resolution) DEMs. The maximum value of 10 m was taken based on the recent Indian Ocean earthquake (26.12.2004) of magnitude 9.0 on the Richter scale, the largest earthquake after the 9.2 magnitude Good Friday earthquake of Alaska in 1964. The resulting tsunami devastated the shores of Indonesia, Sri Lanka, south India, Thailand and other countries with waves up to 15 m (50 feet) high [7]. The inundation module available in ERDAS Imagine was used to generate different scenarios of sea level rise. Out of the six run-up values used to prepare the inundation map only two maps, Fig. 7 for 1 m and Fig. 8 for 10 m SLR are given in this paper. This map is useful in determining the extent of vulnerability of the area to SLR as well as storm and tsunami waves.

Once, the calculations of each parameter were completed, they were assigned a relative risk value based on the potential magnitude of its contribution to physical changes on the coast as the sea level rises, and CVI was computed using Eq. (1). Detailed discussion about land loss, erosion of beach due to SLR is provided in Section 5.

5. Results and discussion

After assigning the risk value based on each specific data variable to each section of the coastline, the CVI has been calculated using Eq. (1). The calculated CVI value for the coastal stretch ranges from 7.5 to 17.89. The mean value is 14.33 and standard deviation is 1.95. The 25th, 50th and 75th percentiles are 10.29, 12.82 and 15.36 respectively. The CVI scores are divided into low, moderate, high and very high vulnerability categories based on the quartile ranges and visual inspection of the data. CVI values below 10.29 are assigned low vulnerability. Values from 10.29 to 12.2 are assigned moderate vulnerability; high vulnerability lies between 12.82 and 15.36. CVI values more than 15.36 are assigned very high vulnerability. Locations along the coastal stretch such as Maravanthe, Gujjadi, Bijadi, Parampalli are under the very high vulnerability category. Places such as Kapu and Malpe fall under the moderate

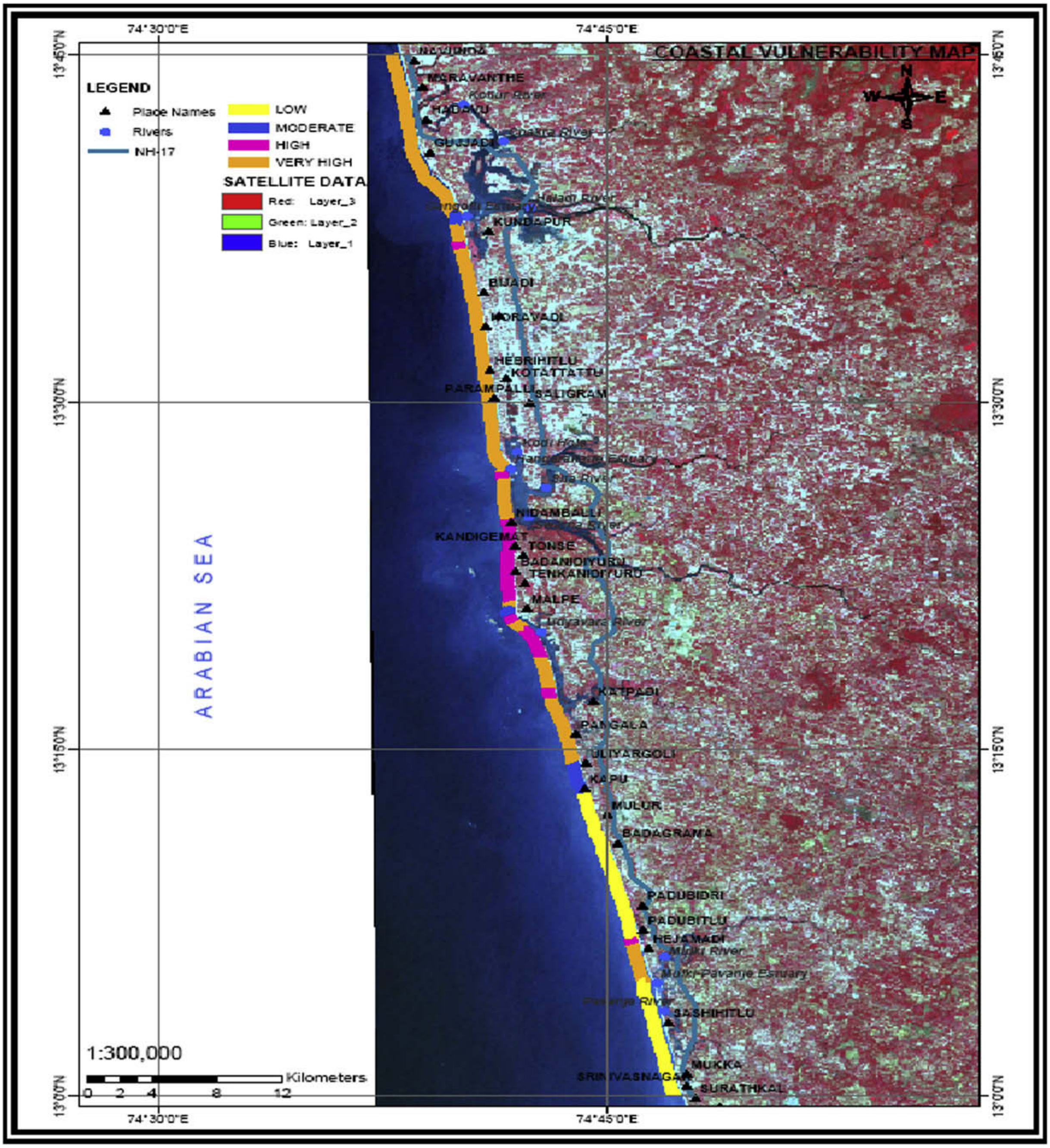

Fig. 10. Coastal vulnerability map.

category whereas Tonse, Padubidri, Sasihithlu and Surathkal have low vulnerability. The pie chart in Fig. 9 shows the percentage length of the coastal stretch that has very high, high, moderate and low vulnerability.

A total of 95 km of the shoreline is ranked in the study area, out of which 59% of the mapped shoreline is classified as being at very high risk due to future SLR. The percentage of high and moderate risk is only 11%, and the remaining 30% of the shoreline is under the low risk category. From this it is very clear that the Udupi coast is highly vulnerable for future SLR, and the different LU/LC features under the direct risk of flooding include coastal villages, agricultural land, wetland, salt pans, aquaculture ponds, link roads, beaches and coastal dunes. This implies that the population living presently in these areas would be displaced. Fig. 10 shows the vulnerable areas along the study area for the SLR determined using coastal vulnerability indices.

The area of submergence for different sea level rises in the form of a bar chart is shown in Fig. 11. The area of submergence for 1 m rise in water level is up to 42.19 km^2 and subsequently for 2 m, 3 m, 4 m, 5 m and 10 m rise in water level are 56.34 km^2, 75.04 km^2, 89.58 km^2, 150.67 km^2 and 372.08 km^2 respectively. The low lying areas of the study area are highly vulnerable for submergence in case of a tsunami or a rise in sea level. From the LU/LC map it is clear that the maximum area is covered by agriculture lands and other categories, which include aquaculture ponds in the low lying area, and they will get affected first by future SLR. The inundation maps can be overlaid on land use/land cover maps to find out the extent of submergence of different LU/LC areas. It is necessary to

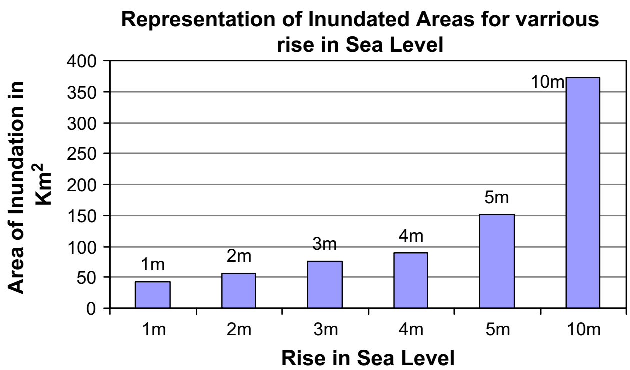

Fig. 11. Representation of the inundation area.

incorporate the elevation levels for new/expanded settlement areas under the town planning acts so that human life and property are saved from natural hazards/vulnerabilities. The run-up levels can be used as guidance to determine safe locations of settlements from the shoreline. Based on the vulnerability assessment study, it is clear that three issues are of great concern to the authorities and decision makers: coastal land loss, ecosystem disturbance and erosion and degradation of shoreline.

Coastal Regulation Zone (CRZ) notification was issued by the Ministry of Environment and Forests of the Government of India in February 1991, as part of the Environmental Protection Act of 1986 to protect the coast from eroding and to preserve its natural resources and was adopted in June 1992. Accordingly coastal stretches of seas, bays, estuaries, creeks, rivers and backwaters which are influenced by tidal action in the landward direction up to 500 m from the high tide line (HTL) were considered as coastal regulation zones [29] (MoEF [23]). The low lying nature of the Udupi coastal zone coupled with significant land reclamation investments and extensive industrial, commercial, and residential activity emphasizes that ecological and socio-economical systems are currently facing tremendous pressure due to rapid urbanisation, industrialisation, and economic development. SLR phenomena are going to accelerate degradation of the coastal and marine resources and could lead to serious displacement of people, commercial and industrial activities. Hence, strict enforcement of the CRZ Act is needed in order to protect the coastal ecosystem and to reduce degradation.

The options available for the protection of the Udupi coast from future SLR could be dune afforestation, mangrove restoration and management, periodic beach nourishment and building seawalls and groins. The construction of seawalls is costly and hence it would be used only for some settlements at high risk of inundation. The performance of properly constructed and maintained seawalls along the undivided Dakshina Kannada coast is satisfactory [9,19,27]. The integrated coastal zone management plan, though active in India, is still not fully functional. It must emphasize more on building regulation, urban growth planning, development of institutional capacity, involvement of local community, increasing public awareness and should be based on long-term sustainable developmental programmes.

6. Conclusions

The present study was carried out with a view to identify vulnerable areas due to future sea level rise (SLR) along the Udupi coast through the analysis of conventional and remotely sensed data, and the conclusions of the same are as follows.

The coastal vulnerability index (CVI) provides insight into the relative potential of coastal damage due to future SLR. The maps presented here can be viewed in at least two ways: (i) to identify areas where physical changes are most likely to occur as sea level rises; and (ii) as a planning tool for managing and protecting resources in the study area. The rate of erosion was 0.6018 km^2/yr during 2000–2006 and 46 km of the total 95 km is under critical erosion; and 59% is at very high risk, 7% high, 4% moderate and 30% in the low vulnerable category, due to future SLR. Based on the inundation study, it was found that 42.19 km^2 and 372.08 km^2 of the land area will be submerged by flooding at 1 m and 10 m inundation levels respectively. The most severely affected sectors are expected to be the residential and recreational areas, agricultural lands and the natural ecosystem. These are to be protected through strict enforcement of the Coastal Regulation Zone (CRZ) Act and any further coastal developmental activities and protection work along the Udupi coast should be based upon an integrated coastal zone management (ICZM) approach for long-term sustainable development.

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