Geospatial-Based Coastal Risk Assessment of Gujarat Coastline

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Abstract Nowadays due to the change in climatic conditions and proliferation in sea level, the coastlines are under high threat. The Gujarat coastline is studied in the current work. It is the longest coastline in India and is highly vulnerable to cyclones, earthquakes, floods, landslides, etc. These facts show the relevance of the present research. The parameters based on which the coastal vulnerability index is laid include seven physical parameters and one social parameter. The seven physical parameters are rate of shoreline change, coastal slope, coastal elevation, geomorphology, significant wave height, tidal range, sea level rise, and the social parameter is population density. The additional parameters used in this study, to increase the accuracy of the vulnerability index are coastal elevation, rise in sea level, and population density. The study is done using geospatial data and various other models and is analyzed with the help of geospatial tools. The high-resolution Cartosat DEM data is used to analyze the coastal elevation and makes this study stand out from the previous studies. Using the risk rating of each parameter, the coastal vulnerability index is prepared and it divides the coast into four zones, that is, very highly vulnerable, highly vulnerable, moderately vulnerable, and low vulnerable. According to the analysis, about 43.5% of the coastline is under highly vulnerable zone and about

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1% is under very highly vulnerable zone. The study shows that the area under high erosion is basically tidal flats and mangroves.

Keywords Shoreline change · Sea level rise · Geospatial data · Cartosat DEM · Population density

1 Introduction

Soon the world is going to be inundated due to global warming, and the present research work has been done to be a helping hand in the mitigation programs along the coastline. The wide variations in the climate have paved a way for many natural hazards and disasters in the environment. In the present scenario, coastlines are highly vulnerable to the change in climatic conditions, due to the presence of many natural resources like coral reefs, mangroves, and dense population along the shorelines. The present study analyzes and provides coastal vulnerability index for the whole Gujarat coastline based on eight parameters. The parameters include sea level rise, shoreline change rate (till 2016), elevation, geomorphology, slope, population density, tidal range, and significant wave height. The coastal vulnerability map is needed to protect the coastline from natural hazards.

As the decades are passing, more developments are taking place near coastline, and a study of United Nations in 1992 estimates that a greater number of people live within 60 km of a shoreline. The coastlines are being a major station for the rise of many megacities [1]. In 1990, the population occupying the space in the coastal floodplain was about 200 million and it is estimated that the number of people will reach about 600 million by 2100 [2].

The recorded data of sea level rise shows that there is an enormous rise in sea level during the twentieth century; the rise is about 1–2 mm/yr [3]. From the past decades' records, it is evident that the sea level rise has reached nearly 3 mm/yr [4]. The major noticed impact of climatic change combined with global warming is the rise in sea level [5]. In the long run, the shoreline will encounter the unfavorable impact in light of erosion, inundation, weakening of water quality in estuaries and aquifers, uneven tempest surge, and serious typhoon [6].

Many works have been done to calculate the coastal vulnerability index (CVI) of the coastlines, using the parameters landforms, geology, rate of change of sea level, coastline erosion or changes, wave and tide ranges [7–13]. The CVI can be estimated by geospatial techniques. The present work is done to get a more accurate CVI for the Gujarat coast. The previous work did not consider the elevation, sea level, and any of the social factors to determine the CVI. Hence, the present study is compensating all the limitations of the previous work.

2 Study Area

The area studied in this work is the coastline of Gujarat (Fig. 1). Gujarat is in the northwestern part of India. Some portion of the Gulf of Kutch region is not included in the study to avoid human inaccuracies. The Gujarat state lies between a geographical extend of 20°10′ N–24°50′ N latitudes and 68°40′ E–74°40′ E longitudes. The longest coastline in India is Gujarat (around 1600 km). The state has two Gulfs, i.e., Gulf

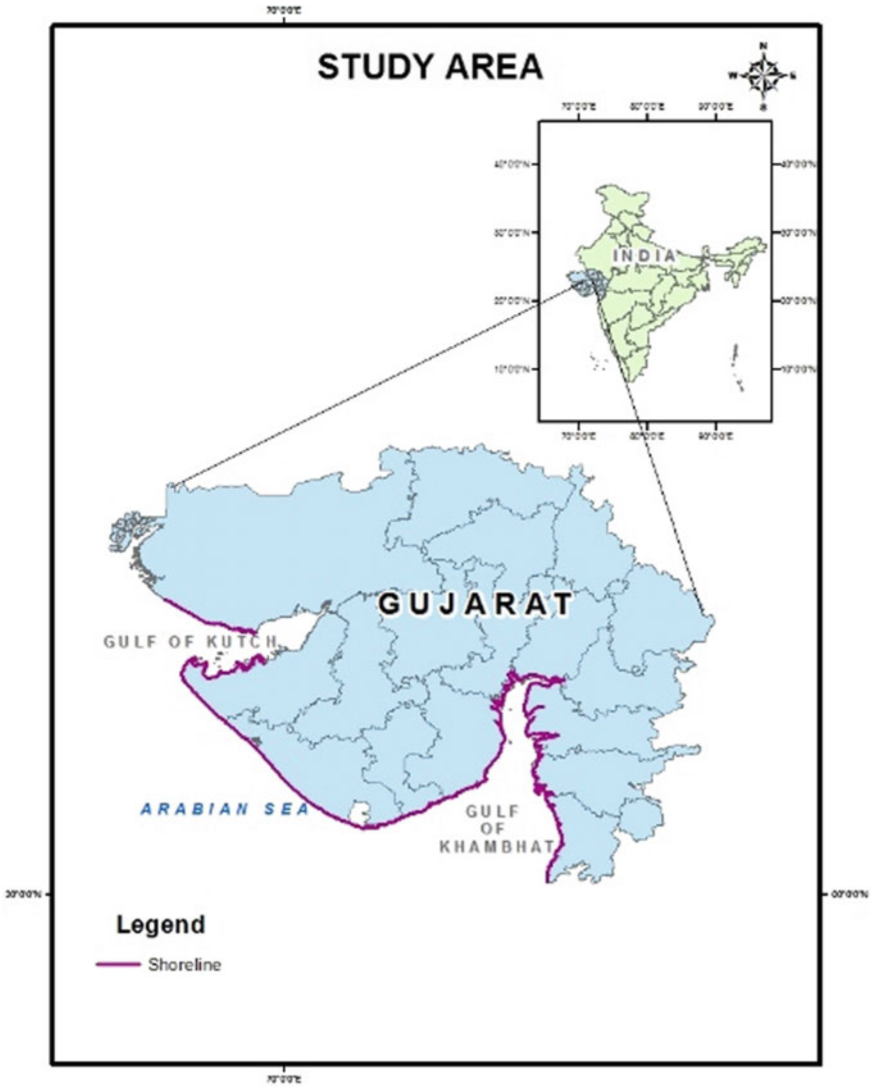

Fig. 1 Study area

of Kutch and Gulf of Khambhat. About 1300 km of the coastline is considered for this study. Some portions of Gulf of Kutch are avoided to reduce the human error. Gujarat has 16 coastal districts out of total 33 districts. Gujarat coastline has a very high variation in geomorphology and climate. Gulf of Kutch is a home to a wide variety of coral reefs and it has the first Marine National Park of India. Gujarat coastline is facing an assault of rapid urbanization and industrial development.

Two of the major ports of India are located in Gulf of Kutch, which allows the import of about 70% of India's crude oil. Gulf of Kutch also has two of the world's biggest refineries, quite a lot of blooming towns and industries, in addition to India's biggest salt industry. Gulf of Khambhat has extensive areas of tidal flats, salt marshes, and mangroves, mostly in the deltas of Mahi and Sabarmati rivers and it is one of the areas in Gujarat coastline with the largest intertidal mudflats (about 300 km). The population in the coastline is increasing by the decades.

3 Methodology

The risk assessment for the Gujarat coastline is done by developing a CVI index. The geospatial data are used majorly for the assessment of the CVI index and geospatial techniques are used to process the data. The parameters analyzed in the present study are the rate of change of shoreline, elevation, slope, population density, geomorphology, rate of change of sea level, tidal range, and significant wave height. The geospatial data is digitized by 1:25,000 scales. It gives more accurate results. Figure 2 shows the flowchart representing the methodology of the estimation of CVI index.

3.1 Shoreline Change Rate

Shoreline is easily affected by the climatic changes and sea level ascent. The data is obtained from LANDSAT satellite (Table 1) and is processed using geospatial techniques and the shoreline change rate estimation is done using DSAS software, using the end point rate method (EPR). Till the latest year (2016), data is also used to get the accurate estimation for erosion rate along the Gujarat coastline. The shoreline shift for up to 4.3 decades is determined using the data. The near-infrared range of wavelength is used to analyze the data, as it is easy to distinguish land and water in that band. The permanent shoreline features were digitized along the coast associated with large tidal flats. The coastline is divided into five classes based on the EPR values, i.e., accreting area, no change area; low erosion area, moderate erosion area, and high erosion area and risk ratings are given for the coastline.

Fig. 2 Flowchart showing the methodology

Table 1 Data source of shoreline change estimation

Year	Data source	Band used
1973	LANDSAT MSS	Near IR
1991	LANDSAT TM	Near IR
2001	LANDSAT ETM	Near IR
2010	LANDSAT ETM	Near IR
2016	LANDSAT OLI	Near IR

3.2 Elevation

Regional elevation of the coastline is the average height of the coast above the mean sea level. Elevation is the major factor influencing the inundation of the land area across the coastline. Data is collected from Bhuvan site. The data used is of CARTOSAT DEM images. The CARTOSAT DEM is a digital image of elevation and shows the land area of India. It is high-resolution data compared to SRTM, which is used mostly to analyze the elevation. The spatial resolution of CARTOSAT DEM is 2.5 m and its swath covers about 30 km. The data is processed using geospatial techniques. The data is mosaicked and clipped along the shoreline using the geospatial tool. The raster image is converted to points, and the elevation value is connected with the shoreline shapefile. The coastline is given the risk rating according to the fact that the area of the coastline with high elevation is less vulnerable to sea level ascent than low elevated area.

3.3 Slope

The steepness of the coastline is described using slope, and the slope is estimated in degrees in the present work. The gentle the slope, the more is the amount of inundation and shoreline erosion [17]. "General Bathymetric Chart of the Oceans (GEBCO)" data is used in the present work to estimate the regional slope of the coast. From the obtained data, the slope values are estimated using the geospatial tools. The image is clipped using the buffer and is converted to points. The values of slope from the points are given to the shoreline shapefile. Slope risk index is developed. The slope risk map is created using risk index. The slope index is given using natural break method. The coastline is divided into five classes based on the slope value.

3.4 Geomorphology

Geomorphology shows the landforms which are more prone to erosion and which can help in resisting erosion. The Gujarat coastline has a wide variety of landform. Build-up areas are also included in the analysis. The narrow beach area and marshy intertidal areas are under erosional risk at high waves. The LANDSAT data is used to analyze the geomorphology of Gujarat. The data is to be processed to categorize the geomorphological features. The geospatial tools are used to categorize the Gujarat coastline into different geomorphological classes. The risk is assigned based on the geomorphological classes. The risk index is classified based on natural break method. The map of coastal geomorphology is developed.

3.5 Population Density

Population density is the most important parameter of this study as it is the only socio-economic factor considered in the present study. Population is also included in the economic parameter as people invest a lot of money to protect their buildings from the hazards [14–16]. The population density data is obtained from the 2011 census. The values are attached to the shoreline shapefile. And the population density risk index is given using the natural break method. The Gujarat coastline is classified into five classes based on the population risk value.

3.6 Significant Wave Height

The significant wave height helps to assess the area more vulnerable toward erosion, as the wave energy responsible for the sediment transportation increases with the square of significant wave height [17]. The data for the significant wave height analysis is obtained from INCOIS, Hyderabad. The entire image obtained is converted to points and then further processed to attach the values with the shoreline shapefile. The higher the value of significant wave height more will be the wave energy in that region.

3.7 Sea Level Changes

The main reasons for the sea level rise are the thermal expansion of the water in the sea and glacial melting. Sea level rise makes the coast more vulnerable toward storm surges and tsunamis. It affects shoreline change rate, geomorphology, and aquatic life. The data for the sea level change is obtained from NOAA Web site. The annual sea level change data is considered in the present study. The stations used are Kandla, Okha, Mumbai, and Karachi. Using the data obtained, the graph was drawn with year in x-axis and sea level (mm) in y-axis, and the annual sea level change rate is determined from the slope of the drawn graph (Table 2).

Table 2 Data source of shoreline change estimation

Station	Latitude (radians)	Longitude (radians)	Sea level rise (mm/yr)
Kandla	23.017	70.217	2.129
Okha	22.467	69.083	1.974
Mumbai	18.917	72.833	0.795
Karachi	24.812	66.975	1.889

3.8 Tidal Range

The tidal range mainly relates to inundation and storm surges. Tidal range is defined as the vertical difference of high and low tide. The higher the tidal range, the more vulnerable is the coast. The data of 29 stations are considered for the analysis of tidal range. The data is obtained from the Web site of INCOIS. The data for the entire Gujarat coastline is obtained by interpolating the data using the method of kriging. The interpolated values are used to divide the coast into risk classes.

3.9 Coastal Vulnerability Index Calculation

The CVI can be estimated by either taking the square root of the geometric mean of the variables considered or as the sum of separately weighted parameters, based on the importance of each parameter. The coastal vulnerability index is calculated using the indices of all the parameters considered in the present study. The estimation is done using geospatial analysis tools. Equation (1) for finding the CVI for the whole coast is

$$\mathrm{CVI} = \sqrt{\frac{(\mathrm{SCR} \times \mathrm{Elevation} \times \mathrm{Slope} \times \mathrm{Geomorphology} \times \mathrm{Population} \times \mathrm{SWH} \times \mathrm{Sealevel} \times \mathrm{Tidalrange})}{8}} \tag{1}$$

4 Results and Discussions

4.1 Shoreline Change Rate

The present study shows that about 79 km of the 2333 km of coastline studied is under high risk of erosion. The 2333 km of the coastline is including the small creeks and estuaries. More area is under the category of accretion, i.e., about 627 and 605 km of the coast are safe with low erosion rate. The medium risk area is about 145 km. The area without any change from 4.3 decades is 877 km. The total of 3% of the coastline is highly eroding and according to geomorphological and sea level change maps of the present study, those are areas of tidal flats and mangroves with moderate sea level rise. The highly eroding portion is having erosion rate more than 10 m/yr.

4.2 Elevation

From the present study, it is revealed that 146 km is under very high risk and 1131 km of the Gujarat coastline is under high risk and only 5 km of the whole coastline is having very low risk class. The low risk areas are easily inundable portion of the Gujarat coastline. About 130 km is under low risk class and 921 km is under medium risk class. The districts coming under very high risk class are Valsad and Jamnagar and the very high risk region has elevation less than 9 m.

4.3 Slope

The present study found that 858 km of the coastline is under very high risk based on the slope parameter. Only 31 km is under very low risk class in the Gujarat coastline. Low risk portion includes about 180 km and high risk portion includes about 825 km. The medium risk area is about 438 km. Low slope area is having high vulnerability toward inundation. By analyzing the map prepared in the present study, it can be said that very low risk class is in the Bhavnagar district and except Jamnagar and Junagadh, all other districts have very high risk region (Figs. 3, 4, and 5).

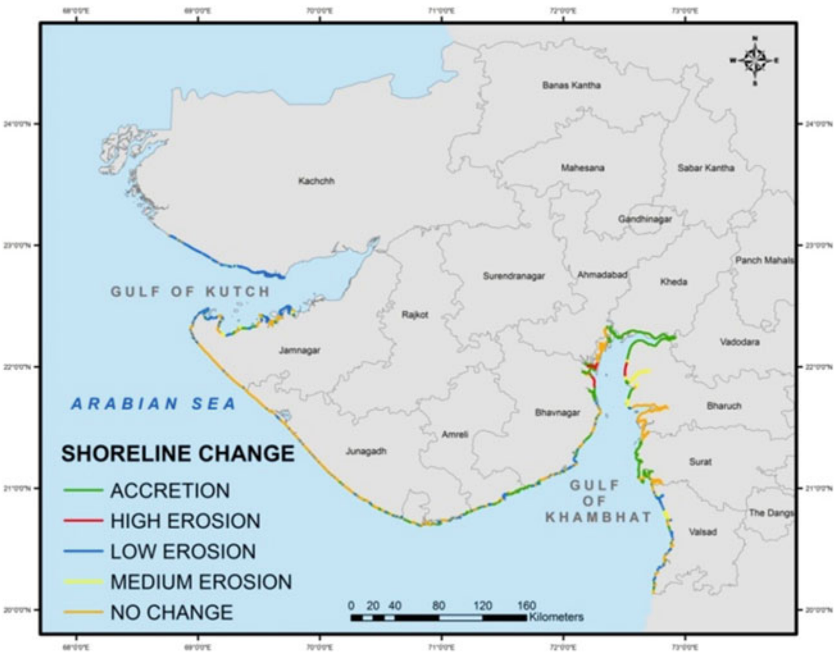

Fig. 3 SCR risk map

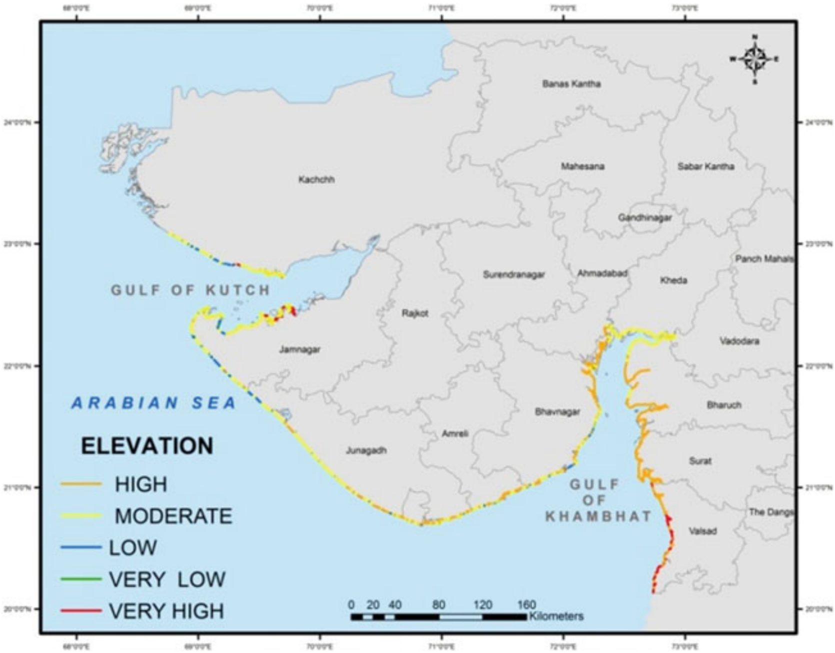

Fig. 4 Elevation risk map

4.4 Geomorphology

The length of coastline under very high risk is 736 km and under very low risk is 105 km. The major portion of the coastline is under low risk, i.e., 901 km of the total Gujarat coastline. The high risk area is 149 km and moderate risk area is 441 km of the coastline. According to the study, most of the area is under very high risk class and more than 80% of Junagadh is in very high risk (Fig. 6).

4.5 Population

About 240 km of the coastline is under very high risk class; i.e., Surat district is highly populated with 1376 per km^2 and is socioeconomically highly vulnerable toward hazards. Very low risk area is about 226 km and low risk area is 831 km of the coastline. Moderate risk area is about 730 km and high risk area is 306 km of the Gujarat coastline. Very low risk area constitutes Kachchh and the population density is 46 per km^2 (Fig. 7).

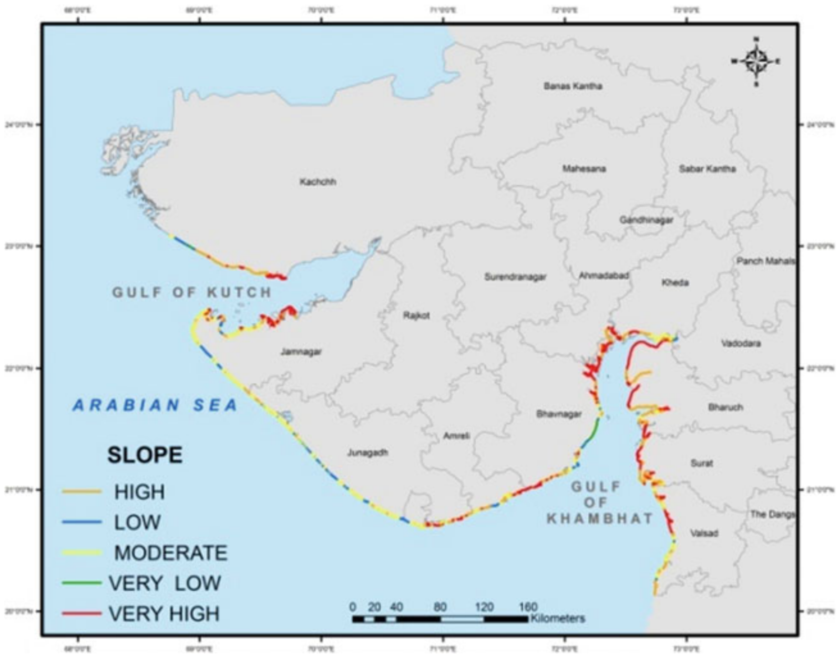

Fig. 5 Slope risk map

4.6 Significant Wave Height (SWH)

Majority of the coastline is under SWH risk index 1. It comes under very low risk class and it is about 1031 km. The length of coastline under very high risk class is about 353 km and under high risk it is 80 km. The low risk stretch is 434 km and moderate risk stretch is 435 km. The highest value of SWH is 2.69. According to the map prepared using the present work, Junagadh is under very high risk based on the significant wave height value. Most of the area of Gulf of Khambhat is under very low risk.

4.7 Sea Level Rise (SLR)

It is found from the present study that about 627 km of the Gujarat coastline is under low risk class and 545 km is under moderate risk class. The highest value of the sea level rise along the Gujarat coastline is 2.04 mm/yr. The stretch under high risk is 164 km, very low risk is 445 km, and very high risk is 552 km. The sea level rise along the Gulf of Kutch region is very high and this affects the geomorphology and population along that area.

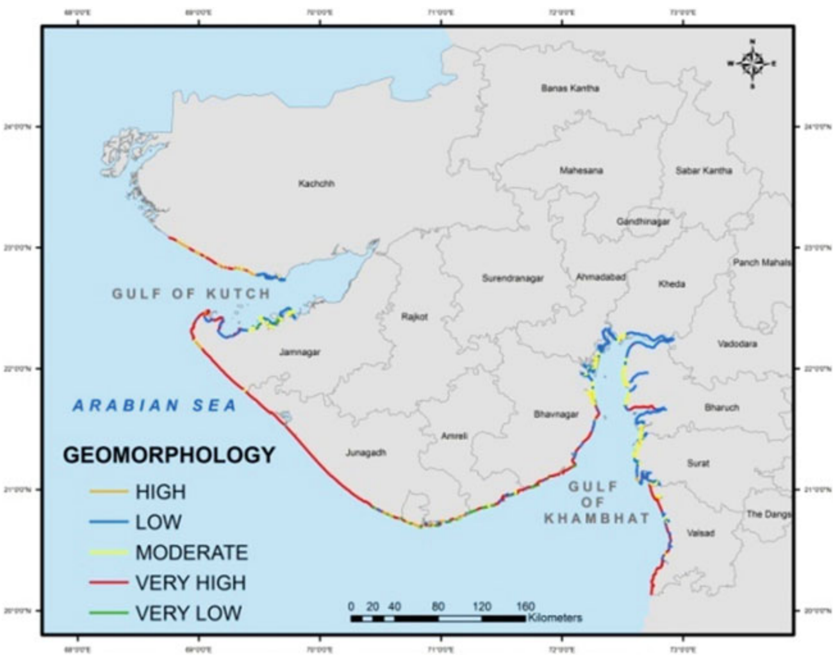

Fig. 6 Geomorphological risk map

4.8 Tidal Range

The coastline under very high vulnerability is about 718 km based on tidal range. The highest tidal range along the Gujarat coastline is 9.04 m and the lowest tidal range is 1.57 m. Tidal range is high along Gujarat coastline, while considering the other coastline states. Stretch of very low vulnerability is about 274 km and of low risk is 295 km. The moderate risk stretch is 405 km, and high risk stretch is 638 km (Figs. 8 and 9).

4.9 Coastal Vulnerability Index (CVI)

Based on the vulnerability values obtained by calculating using the equation, the coastline is divided into four classes, i.e., low, moderate, high, and very high risk class. Majority of the coastline is under high risk, i.e., about 1017 km of 2333 km is under high risk class and about 20 km is under very high risk. The very high risk region is in Valsad and it is one of the developed areas of the coastline. There are many built-ups in the very high risk region; hence, steps should be taken by the coastal zone management departments to protect those areas. The stretch under low CVI is about 428 km and moderate CVI is about 868 km (Figs. 10 and 11).

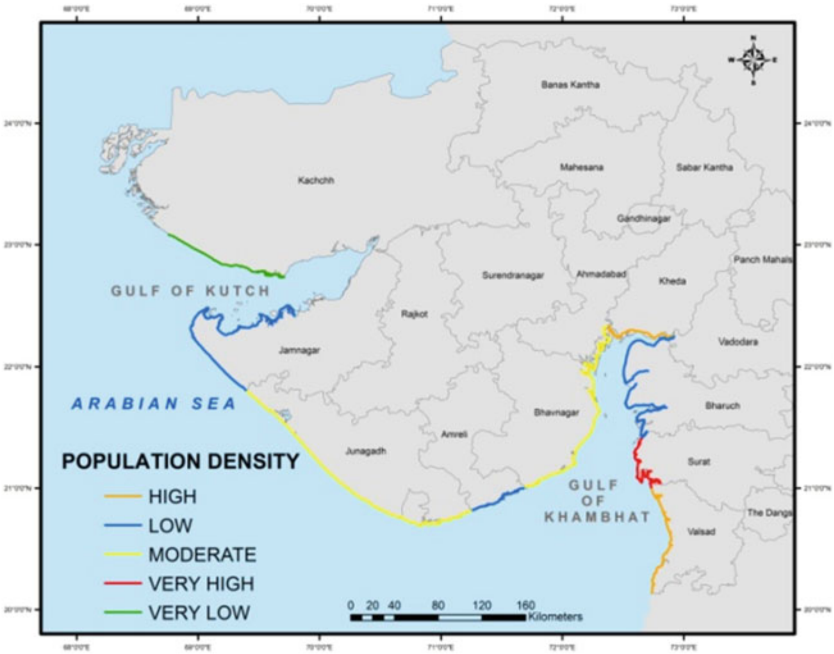

Fig. 7 Population density risk map

5 Conclusion

The present study found that remote sensing and GIS can be depended where field survey is not available. The spatial data can be effectively utilized to scrutinize the study area. This also saves a lot of time and money. The present work estimated the risk values for seven physical parameters and one socio-economic parameter. Table 3 shows the values of each parameter and its classification to each risk class.

Sea level rise is the main issue along Gujarat coastline; hence, there is a chance that in the future the erosion rate may increase more than 3%, which is estimated by this study. Hence, the present study is useful for the coastal zone managers as the estimation is more precise compared to the previous studies. The latest year data is used to find the shoreline change rate and also that almost 4.3 decades data (from 1973 to 2016) of the shoreline is studied. From Fig. 12, it can be seen that only 1% of the coastline is under very high risk toward natural hazards, while considering all the parameters. About 44% of the coastline is under high risk toward natural hazards. The scopes for future works are that more parameters can be utilized to determine the CVI, like storm surge and historical events. These factors are not considered in the present work.

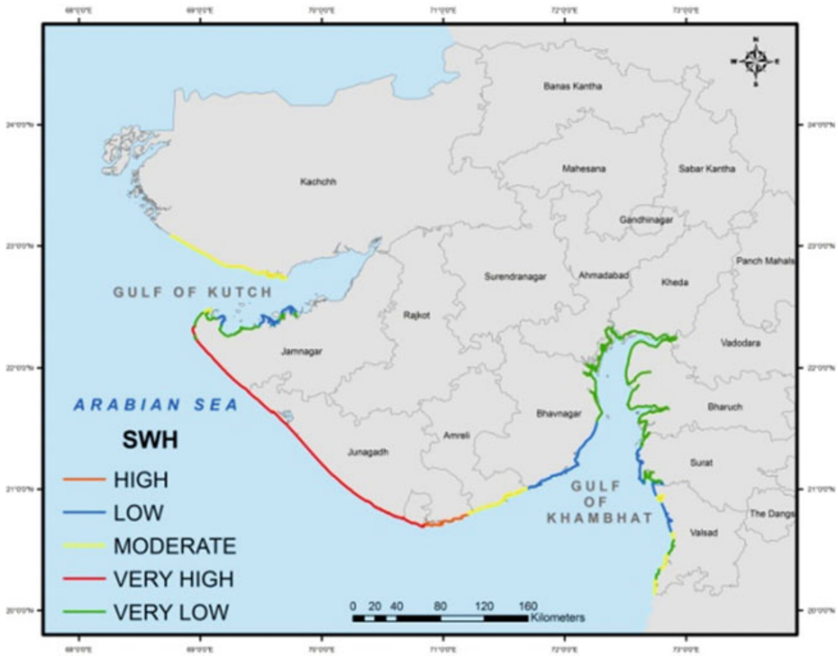

Fig. 8 SWH risk map

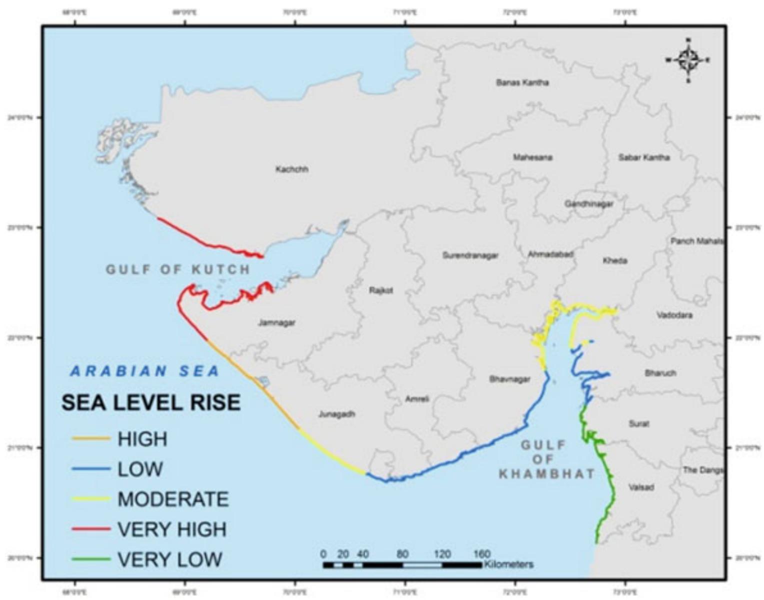

Fig. 9 Sea level rise risk map

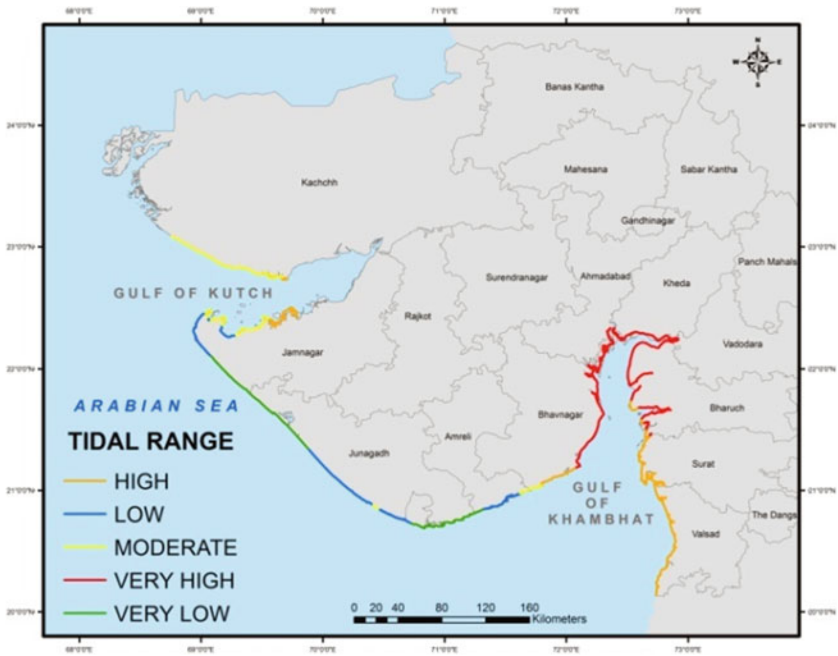

Fig. 10 Tidal range risk map

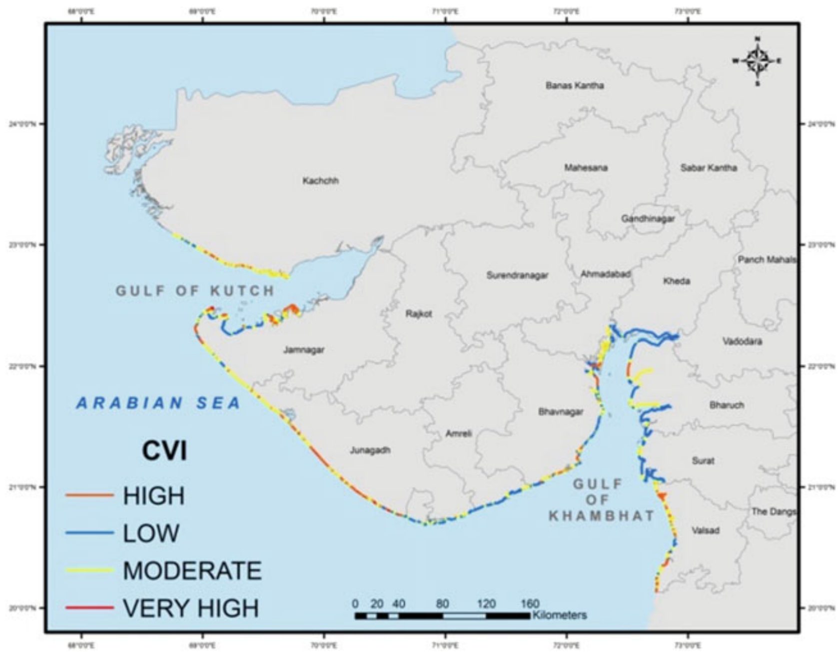

Fig. 11 CVI risk map

Table 3 Data ranking

Parameter	Data ranking				
	Very low (1)	Low (2)	Medium (3)	High (4)	Very high (5)
Shoreline change rate (m/y)	>1 (accretion)	−1 to 1 (no change)	−1 to −5 (low erosion)	−5 to −10 (moderate erosion)	<−10 (high erosion)
Coastal slope (degree)	>0.47	0.31–0.46	0.18–0.30	0.092–0.17	0–0.091
Elevation (m)	>38	26–37	19–25	10–18	<9
Geomorphology	Rocky coasts	Mudflats/tidal flats, vegetation	Estuaries, mangroves, spit/estuary	Sea wall, wide beach	Built-ups, harbor, narrow beach
Sea level change rate (mm/y)	1.10–1.34	1.35–1.52	1.53–1.68	1.69–1.89	1.9–2.04
Mean significant wave height (m)	0–0.32	0.33–0.83	0.84–1.43	1.44–2.14	2.15–2.7
Tidal range (m)	1.56–2.50	2.51–3.32	3.33–4.53	4.54–6.48	6.49–9.04
Population density (no/km^2)	0–46	47–238	239–310	311–561	562–1376

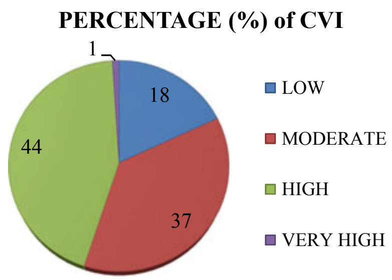

Fig. 12 CVI risk percentage

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