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Coastal Vulnerability Assessment: A case study of the Ratnagiri coast, Maharashtra, India

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Coastal Vulnerability Assessment: A case study of the Ratnagiri coast, Maharashtra, India

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Abstract. The coastal zone is a vulnerable habitat that needs extra caution to protect ecosystems. Coastal systems are increasingly threatened by possible climate change consequences, as evidenced by the Intergovernmental Panel on Climate Change's consecutive assessments . Increased tropical storm occurrences in recent years, in addition to the devastation caused by the tsunami in December 2004, have highlighted the necessity of analyzing the coast's susceptibility to flooding-induced hazards to get a better knowledge of the factors that generate various hazards and, as a result, reduce the after-effects of future occurrences. The Ratnagiri coast in Maharashtra is prone to erosional hazards, periodic land rehabilitation, and sudden rises in sea level. The main objective is to calculate the CVI (Coastal Vulnerability Index) for the Ratnagiri coast. To analyze the vulnerability of the coastal region, eight risk parameters were used, viz. shoreline change rate, coastal elevation, sea level change rate, coastal slope, tide range, significant wave height, coastal geomorphology, and tsunami arrival height. The coastal vulnerability map was created by categorizing the numerous coastal portions into three vulnerability groups: high, medium, and low, which will aid coastal residents in risk mitigation in the future.

Keywords: Coastal Vulnerability Index (CVI), DSAS, Ratnagiri, Coastal hazards.

1. Introduction

A vulnerability assessment is the procedure of finding, assessing, and monitoring risk. The coastal zone is a sensitive habitat that necessitates extra caution to protect ecosystems and human activities. As a result of various human activities, several coastal regions are experiencing severe environmental issues like coastal flooding, dune deterioration, and coastal erosion [1]. Inundation can worsen coastal erosion by moving submerged materials offshore, as well as prolong the impacts of coastal flooding by allowing storm waves to act. Increased tropical storm occurrences in recent years, as well as the terrible impact of the December 2004 tsunami. Cyclone Phyan (2009) caused massive damage to the property of coastal districts of Maharashtra. Also, since 1891, Cyclone Nisarga (2020) [2] has been the most severe and powerful tropical cyclone to hit the Maharashtra coast. These events have highlighted the necessity of analyzing the coast's susceptibility [3]. The Ratnagiri coastline, which stretches across India's west-central region, possibly vulnerable to rapid erosion. Most of the sites along the coast are already under threat from repeated storm floods and severe coastal erosion [4], [5].

CVI is the indicator of all the physical and geological risk factors in the coastal zone region (oceanic and landward hazard parameters). It synthesizes with individual parameters and creates a single Vulnerability Index, which leads to easy interpretation and identification of coastal risk zones along the coastline [6],[7]. It can help coastal managers, researchers, administrators, and industries for future infrastructure or other developments along the coastal area. Thieler and Hammar Klose's (2000) [8] approach is used to calculate CVI using geographical information systems (GIS). In India, a few attempts have been made to map the vulnerable areas along the Orissa coast [9], Ratnagiri coast [10], Andra Pradesh coast [11], and Mangalore coast [12]. The main aim of this work is to identify and prioritize the places on the Ratnagiri coast that are most susceptible to the adverse consequences of coastal hazards.

2. Study Area

The study was conducted along the coastline of Ratnagiri district, on the Arabian Sea coast of Maharashtra, India, which lies between 16.30°N - 18.0°N and 73.02°E - 73.53°E as shown in figure 1. The shoreline of the study area is about 276 km, which is distributed along five talukas, namely Ratnagiri, Dapoli, Guhagar, Rajapur, and Mandangad.

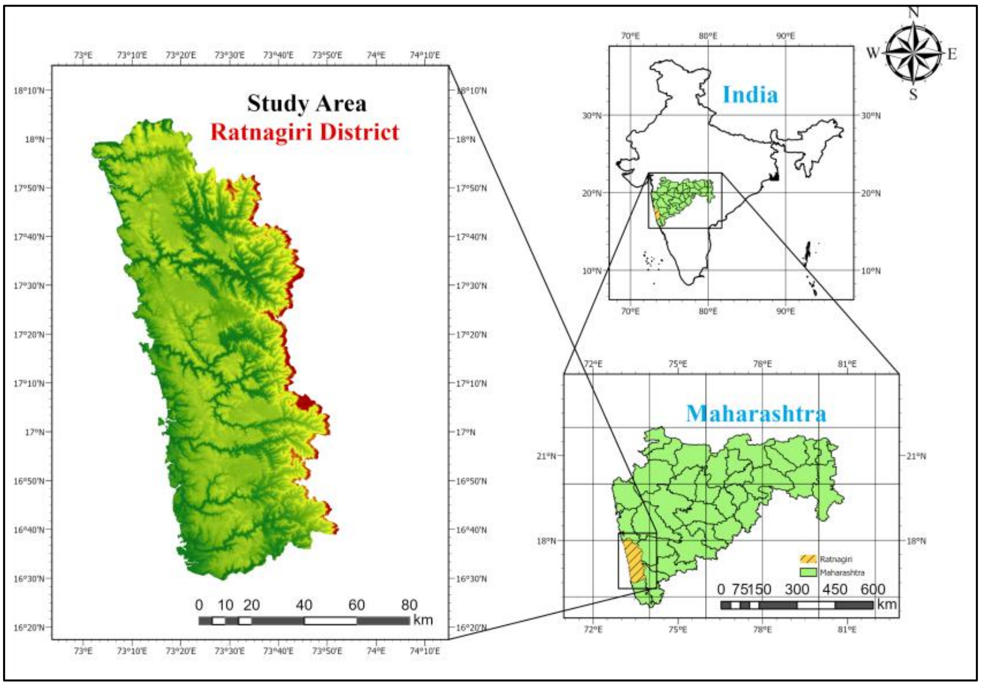

Figure 1. Study Area Map

3. Materials and Methodology

3.1. Data Collection

The majority of these parameters are dynamic along the coast and necessitate a large amount of data from various sources (Table 1). They are based upon data from geographic information systems, remote sensing, and numerical models.

Table 1. Data-sets and their respective sources.

Sr. No	Datasets	Sources
1.	Shoreline Change rate	USGS Earth Explorer, Landsat 7 and Landsat 8
2.	Sea level change rate	AVISO Altimetry
3.	Coastal slope	GEBCO (General Bathymetric Chart of Oceans)
4.	Coastal regional elevation	SRTM DEM
5.	Tidal range	WXTide Software
6.	Coastal Geomorphology	Geological Survey of India (GSI) Bhukosh web service
7.	Significant wave height	INCOIS
8.	Tsunami arrival height	INCOIS

A Landsat picture (path147-row 48) encompasses the whole Ratnagiri coastline, and data were gathered from ETM+ and OLI/TIRS sensors with 30 m resolution from 2001 to 2021. While downloading data, tidal levels were taken into consideration. To eliminate the influence of the tide, all satellite images taken for this study correspond to approximately equal tide levels (±0.5).

3.2. Methodology

The methodology adopted in this study is based on Gornitz's [13] Coastal Vulnerability Index and the work of Thieler and Hammer-Klose (2000) [8] and Doukakis (2005) [14]. Vulnerability is an internal risk factor that relates to a subject's or system's intrinsic predisposition to be impacted or prone to damage when exposed to a hazard [11]. As a result, eight geophysical parameters were used to compute the CVI: shoreline change rate, coastal slope, coastal regional elevation, sea-level change rate, tidal range, significant wave height, coastal geomorphology, and tsunami arrival height. The factors were categorized into three categories based on their risk level: low, moderate, or high. The flow chart (figure 2) below depicts the complete methodology used in the calculation of CVI.

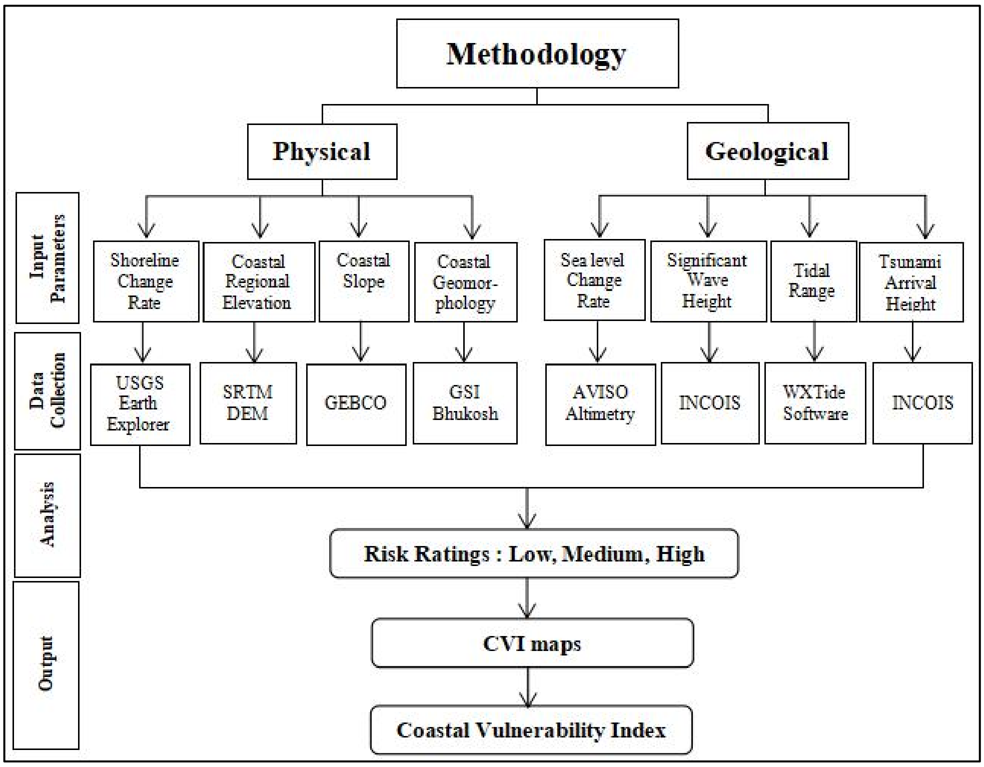

Figure 2. Methodology flowchart

3.2.1. Shoreline Change Rate. The shoreline change rate is obtained using the Digital Shoreline Analysis System (DSAS) toolbar, which is an extension of ArcGIS. The Landsat images obtained from the USGS Earth Explorer were projected to UTM WGS-1984 zone 43N. The extension includes three main aspects. The first step is to define the baseline, then to create transects at precise intervals along the coastline, and finally to determine the change rate using various statistical approaches. Shorelines were digitized manually using ArcGIS 10.5 for each year. The latest digitized shoreline was used to establish a baseline using a 100 m buffer. More than 2000 transects were created using a baseline at a 100 m interval. Each transect has a unique ID. Transects emerging from the baseline intersect all coastlines. Finally, the linear regression method was used to estimate the shoreline change rate throughout the entire coast of Ratnagiri. DSAS determines whether the shoreline change involves accretion or erosion, which depends upon the locations of coastlines with respect to the baseline. DSAS calculates the rate in numerical form. It's erosion if it has a negative value or accretion if it has a positive value.

3.2.2. Coastal Slope. The ratio of the change in height to the lateral distance measured between any two points along the shore is referred as coastal slope. The coastal slope is an important component in determining how vulnerable a coastal region is to inundation from severe storms and tsunamis [15]. A line's slope represents the steepness. The slope was calculated using GEBCO data with one-minute grid resolution. The study area's slope values are determined in degrees, and risk ratings are given. The slope values are computed in degrees, and risk ratings are assigned.

3.2.3. Coastal Regional Elevation. It is the average elevation of any region above the mean sea-level. It is crucial to study this parameter in detail to determine and quantify the amount of land affected by future rising sea levels. High-elevation coastal regions will be classified as less vulnerable areas, whereas low-elevation areas will be highly vulnerable. The Shuttle Radar Topography Mission (SRTM) data with a resolution of 30 m is used to compute elevation values.

3.2.4. Sea-Level Change Rate. Sea level changes are differences in mean sea level that are estimated by tide gauging stations. According to the IPCC, every millimeter increase in mean sea level results in a 1 m recession of the shoreline. According to Unnikrishnan et al. (2007) [16], there are two types one is global (mean sea level change), while the second is local sea level rise. As a result, sea-level rise is a significant phenomenon that, by combining global and localized processes, influences climate change-induced coastal hazards.The SLR data was acquired from AVISO altimetry data. Sea level anomaly (SLA) time-series data from 1993 to 2020 was obtained. The graph was plotted between SLA and the year and the slope was calculated in mm/yr.

3.2.5. Coastal Geomorphology. The scientific study of landforms is referred to as geomorphology. Geo implies "earth," morpho denotes "shape," and Logy means "discourse" or "science." The morphological structure of the coastal area is essential in evaluating the consequences of susceptibility. Coastal geomorphology studies give a fundamental knowledge of the coastal region. Coastal geomorphology was obtained using 1:250 K geomorphological maps from the Geological Survey of India (GSI) Bhukosh web services. The regions obtained in the study area were highly dissected plateaus, moderately dissected plateaus, a pediment pediplain complex, and coastal plains.

3.2.6. Tidal Range. The height difference between high and low tide is referred to as the tidal range. It is compelled by the moon's and sun's gravitational pull. One year of data for 2021 was acquired from the Windows Unix Programme for Tides (WXTide 32) software, which represents projections about the tidal range for tide stations around the study area. From the standpoint of vulnerability, there is an evident tendency to categorize coastal regions with a higher tidal range as extremely susceptible, while coastal regions with a lower tidal range are deemed less susceptible. The maximum and minimum tide amplitudes were calculated for the Rajapur river entry and Bassein.

3.2.7. Significant Wave Height (SWH). Significant wave height is used to assess the susceptibility of shorelines as an alternate option to wave energy. An increase in wave height results in land loss due to increased erosion and flooding along the coast. The higher the wave height, the more the region is vulnerable and vice-versa. The maximum value of significant wave height data was extracted from wave watch III at 0.5-degree spatial resolution during the 2018 to 2021 period.

3.2.8. Tsunami Arrival Height (TAH). The wave characteristics are affected by seismic source factors, bathymetry, seashore morphology, and coastal land elevation. These surges produce an inundation of seawater into land for up to 1 km or more, leading to damage to infrastructure and human life. The maximum value of tsunami wave height is simulated from all the historical tsunami-generated focal mechanism parameters for your academic project work. A risk rating will be provided for the entire study region based on the run-up values.

Table 2. Criteria for Risk Assessment

Datasets	Risk Ratings		
	Low (1)	**Moderate (2)**	**High (3)**
Shoreline Change Rate (m/y)	> 1	1 to -1	< -1
Coastal Slope (degree	>1	0.2 to 1	≤ 0.2
Coastal regional elevation (m)	> 6	3 to 6	≤ 3
Sea Level Change Rate (mm/yr)	-	0.64-0.68	-
Significant wave height (m)	-	0.47-0.74	-
Tidal range (m)	< 2	2 to 3.5	> 3.5
Tsunami arrival height (m)	< 2.3	2.3 to 3	> 3
Coastal Geomorphology	Highly dissected plateaus	Moderately dissected plateaus	Pediment pediplain complex and coastal plain

3.2.9. Coastal Vulnerability Index (CVI). It is computed by integrating different risk variables into a single index, as shown in equation (1). Each risk parameter is classified into one of three risk categories. A rating of 3 is given if the risk is severe, a rating of 2 is assigned for moderate risk, and a rating of 1 is given for low risk for a certain shoreline. Risk ratings are provided for each of the variables listed above. Table 2 shows the risk ratings that have been assigned to each variable. The CVI is determined by dividing the square root of the ranking variable by the total number of variables [17]. The CVI is calculated using the field calculator in ArcGIS based on the risk value provided as input parameters. The CVI value was determined for several stretches of the shoreline based upon its percentile value. If the value is less than the 25^{th} percentile, it is considered low risk; if it is between the 25^{th} and 50^{th} percentile, it is considered moderate risk; and if it is more than the 50th percentile, it is considered high risk.

$$\mathbf{CVI} = \sqrt{[(\boldsymbol{P} * \boldsymbol{Q} * \boldsymbol{R} * \boldsymbol{S} * \boldsymbol{T} * \boldsymbol{U} * \boldsymbol{V} * \boldsymbol{W})/\mathbf{8}]} \quad (1)$$

where, P = Shoreline change rate, Q = Coastal slope, R = Coastal regional elevation, S = Coastal geomorphology, T = Sea level change rate, U = Significant wave height, V = Tidal range, W = Tsunami Arrival Height.

4. Result and Discussion

The current study's findings suggest a high risk of vulnerability along the Ratnagiri coast's low-lying sections and a low risk along rocky beaches for all CVI criteria. The assessment and ranking are discussed below.

4.1. Shoreline Change Rate

The Ratnagiri Coast's change rate was analyzed using a DSAS technique. The shoreline change analysis for the entire Ratnagiri coast for the study duration shows that around 48 km (18%) of coastline falls into a high-risk category, with an erosion rate of 5.32 m/yr and around 150 km (54%) remaining steady. Around 78 km (28%) of coastline recorded accretion falls under the low-risk category, with an accretion rate of 2.43 m/yr (figure 3a).

The research also identified high-risk vulnerable places along the beaches, creeks, and estuaries of Kelshi, Jaigad, Gavakhandi, Bhatye, Guhagar, Jaitapur, and Harnai, whereas low-risk zones such as cliffs and shoals are geologically exposed. As a result, the pace of change along the Ratnagiri coast indicates a moderate risk of coastal vulnerability.

4.2. Coastal Slope

According to the findings, approximately 222 km of coastline have low-risk ratings with a coastal slope greater than 1.0°, 52 km of coastline have moderate risk ratings, with values between 0.2° and 1.0°, and the remaining 3 km of coastline have low-risk ratings, with a slope less than 0.2° (figure 3b).

4.3. Coastal Regional Elevation

According to the current study, 178 km of coastline have high-risk ratings, with coastal elevations ranging from 0 to 3 m. A medium-risk rating of between 3 and 6 m has been observed along a 27-km stretch of shoreline. A total of 70 km of shoreline has low-risk ratings, with elevations exceeding 6 m (figure 3c).

4.4. Coastal Geomorphology

The present study shows 213 km of the study region is made up of coastal plain and pediment pediplain complexes with high-risk ratings. A total of 62 km of coastline has a medium risk rating, having moderately dissected plateaus. About 1 km of shoreline has a low-risk rating due to highly dissected plateaus (figure 3d).

4.5. Significant Wave Height

The mean significant wave height was found to be between 0.47 - 0.74 m in the current study. The entire coastline is categorized as moderately vulnerable (figure 4a).

4.6. Tidal Range

The current study shows 141 km of shoreline stretch have a moderate risk of tide ranges greater than 2 m. With a tide range of less than 2 m, about 135 km of coastline has low-risk ratings (figure 4b).

4.7. Tsunami Arrival Height

According to the current study, around 4 km of shoreline has a high-risk rating of greater than 3 m. A total of 9 km of shoreline stretch has a moderate risk of value ranging from 2.3 to 3.0 m. A total of 264 km of coastline has low-risk ratings ranging from 0 to 2.3 m (figure 4c).

4.8. Sea Level Change Rate

According to the current study, the 276 km of Ratnagiri coastline is at moderate risk, with sea-level change rates ranging from 0.64 to 0.67 mm/yr (figure 4d).

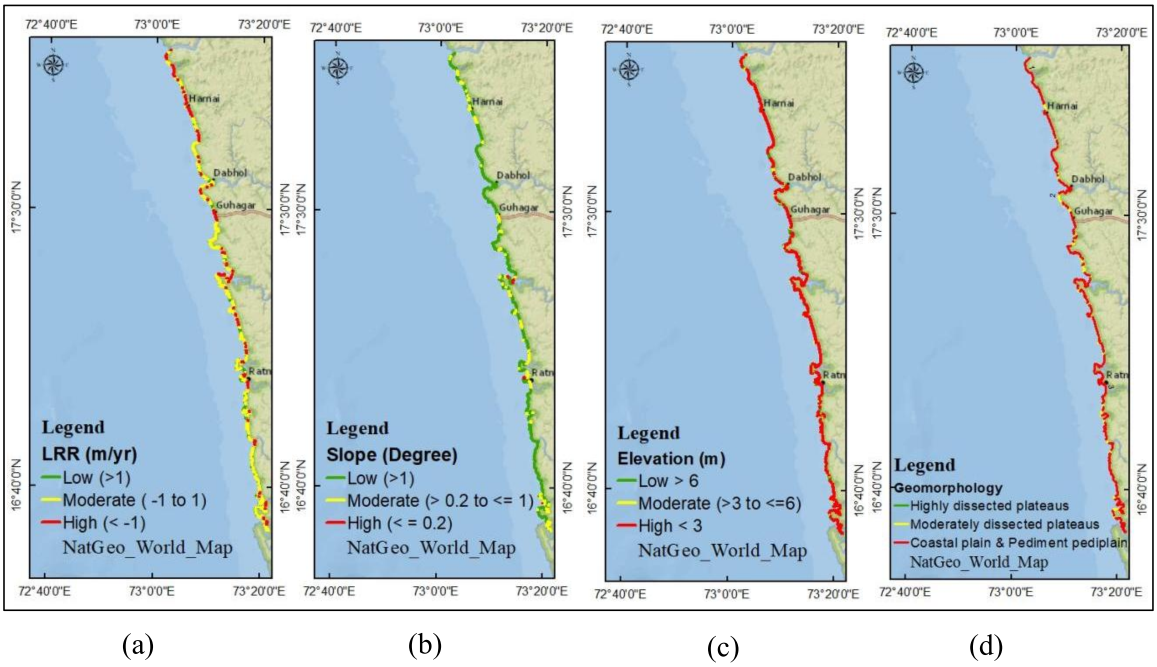

Figure 3. (a) Risk categories for the Shoreline change rate (LRR), (b) Risk categories for the Coastal Slope, (c) Risk categories for the Coastal Regional Elevation & (d) Risk categories for the Geomorphology

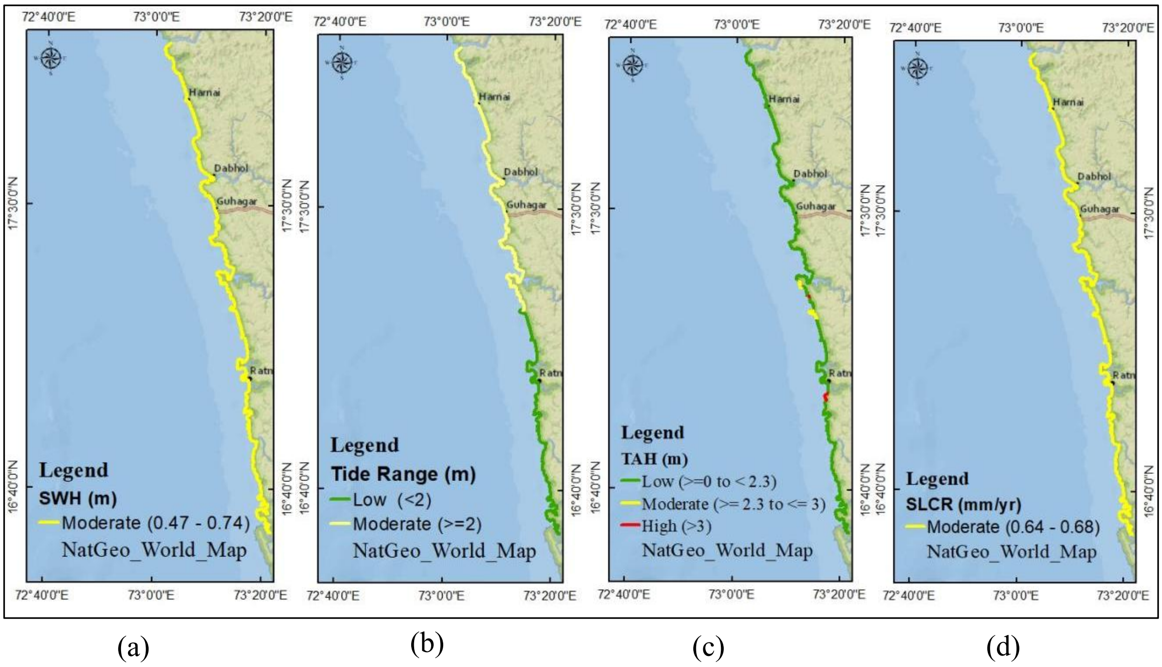

Figure 4. (a) Risk categories for the significant wave height (SWH), (b) Risk categories for the Tide Range, (c) Risk categories for the Tsunami Arrival Height (TAH) & (d) Risk categories for the Sea level change rate (SLCR)

4.9. Coastal Vulnerability Index

The coastal lengths of Ratnagiri are categorized from low to high based on the vulnerability of risk parameters. The CVI is computed, and the vulnerable regions along the coastline are highlighted on the map (figure 5). The CVI ranged from 1 to 9 throughout the Ratnagiri coastline. The CVI values are 2.5 and 5, respectively, in the 25^{th} and 50^{th} percentiles. Regions of the shoreline with an index value of between 1 and 2.5 are considered less vulnerable, those between 2.5 and 5.0 are regarded as moderately vulnerable, and those with a value greater than 5.0 are considered extremely vulnerable. As a result, around 114 km of Ratnagiri's coastline stretch are less susceptible. About 143 km of Ratnagiri's shoreline are at medium risk, while 20 km are at high risk. The coastline stretch along Velas, Kelashi, Aade, Anjarle, Harnai, Guhagar, Palshet, Velneshwar, Jaigad shows a highly vulnerable area.

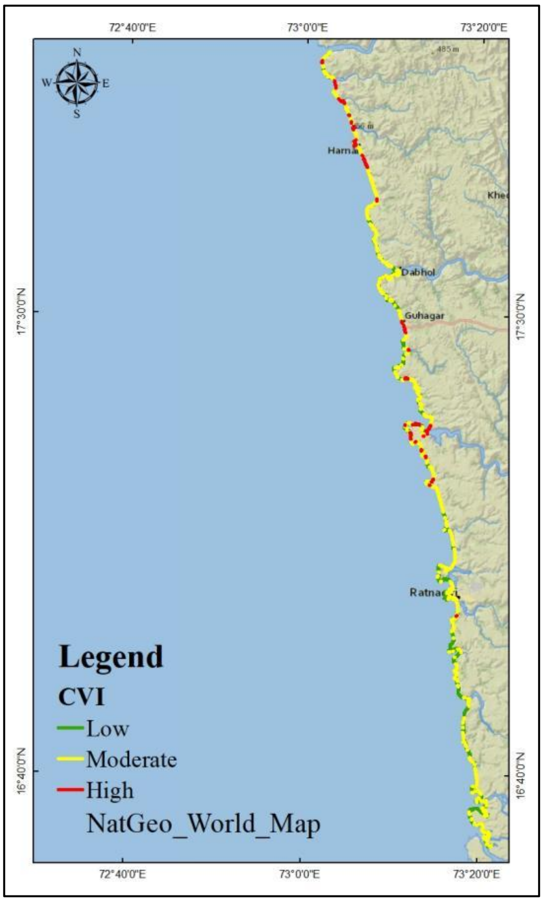

Figure 5. Risk classes for the Coastal Vulnerability Index

5. Conclusion

These coastal vulnerability maps serve as an indicator of risk to coastal geomorphic landforms along the Ratnagiri coast. The study area's segmentation aids in determining the degree of vulnerability on a regional scale. This study demonstrates comprehensive approaches to guide the adaptation process, as well as visualizations that will improve local government decision-making in response to climate change[18]. The study yielded new insights into the concept of vulnerability, which consists of three risk rating factors: low, medium, and high. Geophysical data were combined to create a single indication that can help prioritize and focus adaptation actions. The studies illustrate and propose larger implications for other groups and circumstances confronting comparable issues outside of the case study location.

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