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GIS Based Integrated Vulnerability Assessment of Konkan Coastal Stretch between Bankot and Dabhol Creeks, Maharashtra

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Abstract

In the present research work, an attempt has been made to assess the coastal vulnerability of the Konkan stretch between Bankot and Dabhol creeks, Maharashtra, using GIS and various sources of geospatial data. The study area comprises the coast of Mandangad and Dapoli tahsils in the northern part of Ratnagiri district. The study area is bounded by two west flowing rivers debouching into the Arabian Sea viz.: Savitri River in the north and Vashishti River in the south. The study area is a part of Western Ghats and coastal plains agroecological region. The tropical cyclones in the Arabian Sea in recent years have stressed the importance of assessing the vulnerability of coastal areas to flooding and inundation. The coastline of Ratnagiri district, which has many beaches, tourism places, fishing villages, ports and towns, has been facing risk from cyclones, floods and erosion. The major objective of the present work is analysis and integration of physical variables with socio-economic variables to assess the coastal vulnerability. The physical coastal vulnerability index (PCVI) parameters are coastal geomorphology, shoreline changes, coastal slope, sea level rise rate, significant wave height and tidal range. The socio-economic coastal vulnerability index (SCVI) parameters are population density, coastal land use, coastal roads and economic activities. A composite coastal vulnerability index (CCVI) based on physical and socio-economic parameters has been calculated for every coastal segment, which reveals the overall coastal vulnerability. A coastal zone management action plan has been prepared to mark the coastal segments requiring higher priority for coastal protection viz.: Harnai-Paj Pandhari beach (No Development Zone under CRZ-IIIA), Murud village, Dabhol (Vashishti River mouth), etc. Ecologically sensitive areas viz. turtle nesting grounds, mangrove swamps, etc. have also been analyzed. The coastal vulnerability map is useful in decision-making for disaster management and integrated coastal zone management.

Keywords: *Erosion; PCVI; SCVI; CCVI; GIS*

1. Introduction

Coastal environments are under increasing pressure from predicted consequences of climate change, increasing coastal populations and rapid anthropogenic development. Coastal erosion and inundation pose a threat to human populations, activities and infrastructure. Tropical cyclones in the Arabian Sea in recent years - Nisarga (June 2020) and Tauktae (May 2021) striking the Konkan coast especially maritime districts - Raigad and Ratnagiri have stressed the importance of assessing the vulnerability of coastal areas to flooding and inundation.

Coastal vulnerability assessment is highly useful for identifying and prioritizing coastal areas that are vulnerable to impacts of climate change, natural hazards and coastal processes. The vulnerability of the coast to natural hazards needs to be analyzed by considering a number of parameters and a relative risk factor data needs to be generated for determining and mapping a vulnerability line for Integrated Coastal Zone Management (MoEF, 2005)[(1)].

Coastal vulnerability assessment[(2–4)] of the Indian coast has been completed by Dr. T. Srinivasa. CVI (Coastal Vulnerability Index) Atlas covering Indian coast with maps on 1:100000 scale has been prepared in 2012 by INCOIS, Hyderabad. Coastal vulnerability assessment of the Indian coast has been conducted at relatively smaller map scales using physical variables only by various researchers. There is a need for research on coastal vulnerability assessment at relatively larger map scale (1:5000 to 1:10000) or at village level. For decision-making at local level, there is a need to develop CVI at a relatively large scale which would be appropriate for local management, as local or regional variations in vulnerability could not be revealed if the analysis were performed at the national scale or state level (McLaughlin and Cooper, 2010)[(5)].

Coastal regions of India are facing tremendous population and developmental pressure for the last five decades (1971-2021). This has led to increase in demands of coastal resources as well as exposure of more people to coastal hazards. The Konkan coast of Maharashtra which has number of beaches, tourism sites, tourist resorts, hotels, fishing villages, ports and towns, has experienced threat from many disasters such as cyclones, floods and coastal erosion. The geo-environment of the stretch of Konkan coast between Bankot and Dabhol Creeks in Ratnagiri District, Maharashtra is changing and highly susceptible to such kind of natural and anthropogenic processes. Hence, it is necessary to identify and assess the vulnerability of coastal areas to erosion, flooding and inundation[(6–8)].

The present work analyses and integrates physical variables with anthropological variables to assess the coastal vulnerability and it is a crucial step towards identifying and prioritizing coastal areas for environmental protection. The present work has high interdisciplinary relevance and wider dimensions as it has availed the methods of Environmental Management, GIS (Geographic Information System), RS (Remote Sensing), Geology, Geomorphology, Oceanography, Population and Settlement Geography, etc.

Objectives

Specific objectives of the present research work are as follows:

1. To identify and study the coastal geomorphic features in the study area and their relative coastal vulnerability.
2. To analyze coastal geomorphology, coastal slope, rate of sea level rise, significant wave height and mean tidal range with reference to coastal vulnerability; and to estimate the physical coastal vulnerability index for the selected coastal stretch at a large scale.
3. To analyze density of population, coastal land use, etc. with reference to coastal vulnerability; and estimate the socio-economic coastal vulnerability index for the selected coastal stretch at a large scale.
4. To identify highly vulnerable coastal segments in the study area based on a composite coastal vulnerability index for integrated coastal zone management.

2. Study Area

1. Location: The study area is a part of the Middle Konkan coastal stretch of Maharashtra, between Bankot Creek (Savitri River) and Dabhol Creek (Vashishti River). The study area covers Mandangad and Dapoli Tahsils in the northern part of Ratnagiri District. Mandangad Tahsil is situated in the northern-most part of Ratnagiri District. Mandangad is surrounded by Shrivardhan and Mhasla Tahsils of Raigad District in the North, Mahad Tahsil of Raigad District in the East, Dapoli Tahsil in the South. Dapoli Tahsil is situated in the northern part of Ratnagiri District. Dapoli is surrounded by Guhagar Tahsil in the South; Khed Tahsil towards the East; Mandangad Tahsil in the North (Figure 1).

2. Geology: The geological formations found in Ratnagiri District include those of the Precambrian, Mesozoic, Tertiary and Quaternary ages. The geological formations observed in the study area near the coastal zone include alluvium or coastal sands, laterites and Diveghat formations (mainly aa or simple flows). Laterite, derived from the leaching process acting on the traps and Precambrian rocks, occurs over very large areas. It is found at different levels along the Konkan up to sea level. Large areas are also covered with secondary laterite. These laterites are considered to be of the Quaternary age. Geothermal springs, lineaments and dykes can also be observed in the study area.

3. Physiography: The major part of the study area falls in the low-lying Konkan coastal strip. Landforms of fluvio-marine origin and coastal landforms such as sandy beaches, wave cut platforms are common along the coast of the study

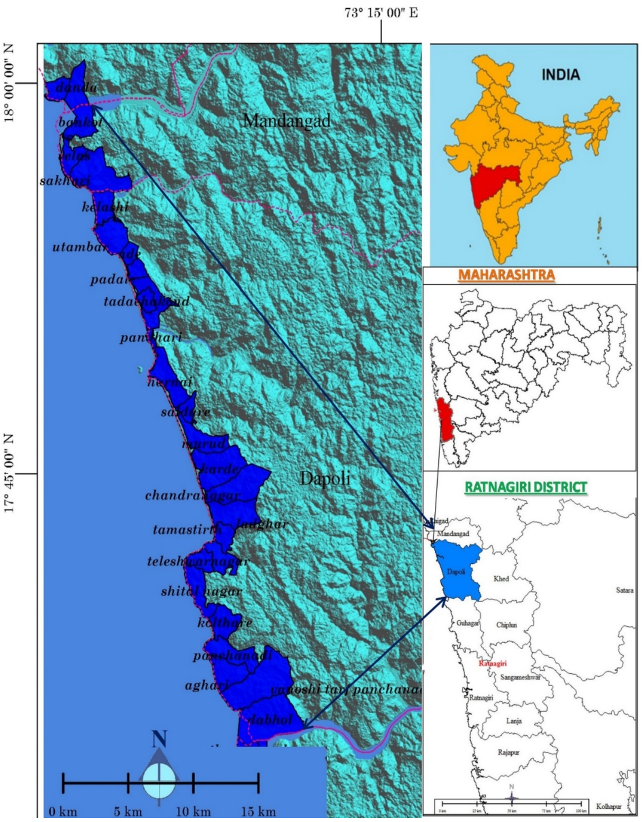


Fig. 1. Location Map of the Study Area

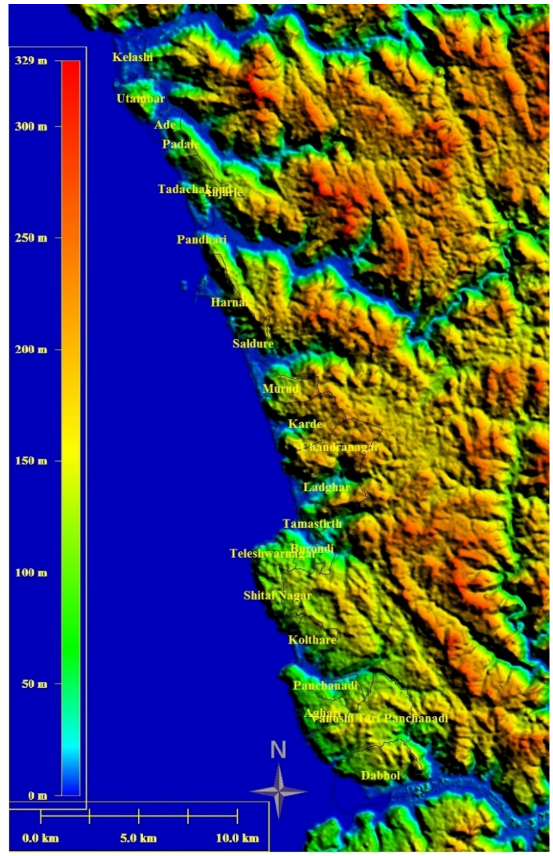


Fig. 2. Digital Elevation Model of the Study Area

area. The coastline is indented by number of creeks, small bays, headlands, pocket beaches, headlands, cliffs, etc.

4. Climate: The study area falls in the Tropical Monsoon climatic region (**AM**) as per Koeppen's climatic classification. The study area experiences a warm climate with very high humidity. The type of climate is tropical hot and humid in the study area. Heavy rainfall results in highly eroded landscape in the coastal region. The study area receives maximum amount of rainfall in the southwest monsoon season. Along the coastal region, the rainfall ranges from 3000 to 3200 millimeters. The rainfall decreases from mountainous area in the east to coastal plains in the west. During the pre and post monsoon months, the study area experiences very strong winds sometimes reaching gale force particularly near the coast and heavy rain in association with cyclonic storms which develop in the Arabian Sea and move in close proximity to the coast.

5. Drainage: The drainage network of the study area is dense and well-developed having dendritic drainage pattern. Various streams forming a dendritic drainage pattern are present. Drainage pattern is characterized by irregular branching of tributaries in many directions. The 1st, 2nd and 3rd order streams are seasonal in nature and remain dry in non-rainy seasons. The main source of water is numerous springs and a few perennial streams. Small amount of water is available only in the downstream portion of the main stream. The major rivers in the study area are Savitri, Bharja, Jog and Vashishti.

6. Soils: Soils of the study area have medium coarse texture. Lateritic soil having brick red colour are dominant in the study area. Alluvial soils are also found in the study area along the coast.

7. Natural Vegetation: The study area is a part of agro ecological region of Western Ghats and Coastal Plains Ecoregion and the forest type is tropical moist deciduous forest. Casuarina trees are found in abundance near the beaches. Casuarina plantation works as the first line of defence against coastal hazards. It helps to slow down winds and effects of extreme coastal hazards like cyclones. Littoral forests have mangroves which are highly significant for protection of the coastal environment. Mangroves occur along the intertidal region of estuaries and creeks viz. along Savitri Creek, Bharja Creek, Jog Creek, Vashishti Creek, etc.

8. Population: The population density of some villages near the coast is extremely high viz.: Pandhari, Harnai, Burondi, Kelshi, Ade, Dabhol Census Town, Bankot, etc. The village-wise data for the villages in the study area is outlined in the following table (Table 1):

Table 1. Population Density (PD) of selected villages along the coast

No.	Village	Tahsil	Location	Population	Area sq. km	PD per sq. km
1	Bankot	Mandangad	Savitri River HTL	2629	3.66	718
2	Kelashi	Dapoli	Bharja River HTL	3145	2.65	1186
3	Ade	Dapoli	Kesari River HTL	1718	1.46	1177
4	Juikar Mohalla	Dapoli	Jog River HTL	1447	1.79	810
5	Pandhari	Dapoli	Arabian Sea Coast	5780	0.57	10194
6	Harnai	Dapoli	Arabian Sea Coast	7274	5.91	1230
7	Burondi	Dapoli	Arabian Sea Coast	3966	3.30	1202
8	Dabhol Census Town	Dapoli	Vashishti River HTL	7038	8.95	786

9. Economic Activities: The dominant economic activities in the study area are agriculture, horticulture, fishing, animal husbandry, transport and tourism. Fishing is an important activity along the Konkan coast. There are certain industries such as animal husbandry, fruit processing industries, etc. in the study area. Tourism activity is growing along Velas, Kelshi, Anjarle, Harnai, Murud, Ladghar, Tamastirth and Kolthare beaches in the study area [9].

10. Transportation: Roads, Railways and Waterways are used for transportation in the study area. Maharashtra State Highway 4 passes through the study area and it is the most important road connecting the coastal areas to the interior places. National Highway 66 (Mumbai-Goa Highway) is also passing through the interior part of the study area. There is ongoing construction of bridge on Savitri River (Bankot Creek) near the mouth. Ferries are used for water transportation at Bagmandla to Bankot on Savitri River, and Dabhol to Dhopave on Vashishti River.

3. Database and Methodology [10]

Data Sources: Data for the present study is acquired from the following sources:

1. Toposheets: Survey of India (SOI) Topographical Map on 1:50000 scales are used as base maps. The area falls in Survey of India (SOI) Toposheet numbered 47G/1 and 47G/2.

2. Geological Quadrangle Map: Pune and Bombay, and Mahabaleshwar Geological Quadrangle Maps of Maharashtra, published by Geological Survey of India (GSI) have been used to analyze the geology of the study area.

3. GSI Geomorphology Map: Geomorphology map data (1:250000) by Geological Survey of India (GSI) has been used to analyze the geomorphology of the study area.

4. Digital Elevation data: Data of elevation has been acquired from ASTER GDEM (Advanced Space borne Thermal Emission and Reflection Radiometer – Global Digital Elevation Model) with a spatial resolution of 30 meters.

5. Bathymetric data: Data of bathymetry has been acquired from GEBCO (General Bathymetric Chart of the Oceans) gridded bathymetry data of 2022 on a 15 arc-second interval grid.

6. Ocean data: Data about the ocean waves has been acquired from Indian National Centre for Ocean Information Services (INCOIS) Maharashtra State Ocean Forecast and National Oceanic and Atmospheric Administration (NOAA) WAVEWATCH III wave model - global gridded data (30 arc-minute spatial resolution and 3 hours interval) of significant wave height from 2005 to 2019. Data about high tides and low tides has been extracted from tide tables (2010 to 2022).

7. Meteorological data: Long-term rainfall data (1992 to 2021) has obtained from IMD (India Meteorological Department) Gridded Dataset.

8. Shoreline Change data: Shoreline Change Atlas (Volume-II: Maharashtra and Goa) prepared by Space Applications Centre – Indian Space Research Organization (SAC-ISRO) have been used for obtaining data of shoreline change.

9. Google Earth Images: Historical as well as latest Google Earth Images of the study area have been used in the present study.

10. Land Use Land Cover data: Sentinel Land Use Land Cover data of 2021 (10 meters resolution) has been used for LULC analysis.

11. Census data: Indian Census data of 2011 for Raigad and Ratnagiri Districts has been used for calculating the population density and for analyzing other socio-economic parameters [11,12].

12. Open Street Maps: Open Street maps have been used to digitize transport network.

13. Hazard data: Building Materials and Technology Promotion Council (BMTPC), Ministry of Housing and Urban Affairs, Government of India - Vulnerability Atlas (3rd Edition) has been used to obtain wind speed hazard, landslide and probable maximum storm surge data.

14. CZMP Data: Coastal Zone Management Plan (CZMP) Map of Maharashtra Coastal Zone Management Authority (MCZMA) as per the CRZ 2019 Notification, has been used to delineate the CRZ lines and zones as well as ecologically sensitive zones in the study area.

15. Other data sources: The Maharashtra Shoreline Management Plan, prepared by Sanctuary Beach (Singapore), Sustainable Coastal Protection and Management Investment Program – Tranche 1, Maharashtra Maritime Board, Mumbai, India and various socio-economic reports published by the Government of Maharashtra have also been used.

Methodology: The methodology of the present study involves determination of coastal vulnerability index using various physical and socio-economic variables (Figure 3). The methodology adopted for the present work can be divided into following major components:

1. Base Map Preparation: The base map has been prepared using SOI toposheets numbered 47G/1 and 47G/2 (on 1:50,000 map scale) covering the study area.

2. Digitization of Layers: Various point, line and area layers have been digitized in GIS software and these layers have been used for further analysis.

3. Estimation of CVI: Multi-criteria analysis technique has been used for estimating the CVI (Coastal Vulnerability Index) by using a combination of various physical and socio-economic parameters. PCVI (Physical Coastal Vulnerability Index), SCVI (Socio-economic Coastal Vulnerability Index) and CCVI (Composite Coastal Vulnerability Index) maps showing segment wise coastal vulnerability index have been prepared in GIS Software. Finally, the areas having very high, high and moderate vulnerability were identified.

4. Preparation of Coastal Zone Management Action Plan: After CVI analysis, a coastal zone management action plan has been prepared to mark the coastal segments requiring higher priority and those with action required or no action required for coastal protection.

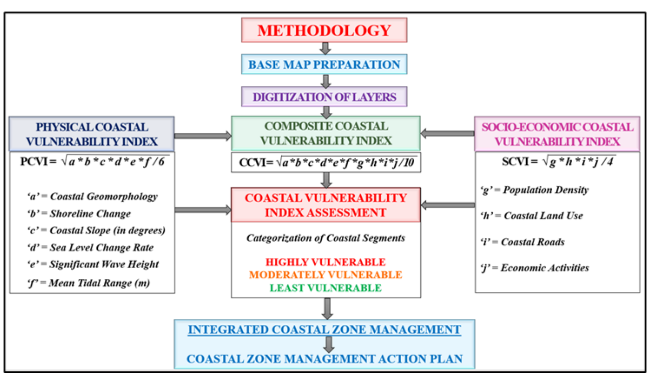


Fig. 3. Methodology Flow Chart

4. Results and Discussion

(A) Physical Coastal Vulnerability Index (PCVI): PCVI is a composite index expressed as square root of the product of ranked risk variables divided by the total number of risk variables. The formula of PCVI is:

$$PCVI = \sqrt{a * b * c * d * e * f \;/ 6}$$

Where,
'a' = Coastal Geomorphology
'b' = Shoreline Change (Erosion and Accretion)
'c' = Coastal Slope (in degrees)
'd' = Relative Mean Sea Level Change Rate (mm/yr)
'e' = Mean Significant Wave Height (m)
'f' = Mean Tidal Range (m)

Each of these six physical parameters are ranked for the physical vulnerability into one out of the three categories viz.: Low Risk = 1, Moderate Risk = 2 or High Risk = 3. High risk value is assigned to coastal segments having sandy beaches / mangroves / mudflats, gentle slope and coastal erosion. Low risk value is assigned to coastal segments having sea cliffs or rocky coast, steep slope and accretion or stable coast. Coastal segments are categorized as highly, moderately, and least vulnerable based on PCVI.

a. Coastal Geomorphology: Coastal geomorphology is a highly significant variable in determining the vulnerability level of a coastal segment to the sea erosion. This parameter indicates the relative erodibility as well as the degree of resistance of the different landforms and the materials that compose them. Geomorphology has been analyzed with the help of observations recorded during field visits, ASTER DEM, Google Earth Images (1985 to 2022), S.O.I. Toposheets and G.S.I. Geomorphology Map. Coastal landforms such as sand dunes, sandy beaches, spits, mudflats, etc. are extremely sensitive and least resistant to coastal erosion and sea-level rise. These highly vulnerable coastal landforms are assigned the highest risk rating. The least erodible features such as rocky sea cliffs, wave-cut platforms and lateritic residual cappings have highest degree of resistance to sea erosion. These landforms are less sensitive as well as less vulnerable, and they are assigned the lowest risk rating. Dominant geomorphic features along the coastal stretch are Moderately Dissected Plateaus (Structural Origin), Pediment Pediplain Complex (Denudational Origin), Mud Flats and Mangrove Swamps, Rocky Sea Cliffs and Wave Cut Platforms, Sand Dunes, Beaches and Beach Ridges. Highly Dissected Upper Plateaus (Structural Origin) are observed mostly along Mandangad Tahsil coast. Pocket Beaches, Headlands and Bays are common. Beaches are usually small and crescent shaped. Sandy Beaches which are long and linear beaches e.g., Murud beach. Gravel beaches in the study area are Ladghar, Tamastirth, Burondi, etc (Table 2).

b. Shoreline Changes: A change in the location of shoreline is an indication of the sensitivity of the coast to

Table 2. Beaches in the Study Area

No.	Beach	Location	Description
1	Velas	Mandangad Tahsil	Moderately low gradient beach. Turtle nesting ground sites for Olive Ridley turtles.
2	Kelshi	Dapoli Tahsil	Low gradient sandy beach with a roughly arcuate shape. Coastal sand dunes and Beach ridge-swale complex
3 4 5	Ade, Padale and Savane	Dapoli Tahsil	Low gradient sandy beaches, south of Utambar Creek. Ade and Padale beach form a continuous long stretch. Savane beach is to north of Tadacha Kond headland.
6	Anjarle	Dapoli Tahsil	Low-gradient beach adjacent to Jog River in the south with entrance sediment spit. Headland in the north at Tadacha Kond functions as natural coastal protection structure.
7	Harnai-Paj Pandhari	Dapoli Tahsil (south of Pandhari),	Low-gradient south facing beach - narrow in the north bordered by rocky coast and wide in the south. Naturally protected by an offshore island in the west.
8	Palande	Dapoli Tahsil (Harnai)	Wide and flat linear beach. Tidal inlet at Saldure between Palande and Murud beaches.
9	Murud	Dapoli Tahsil	Low gradient linear beach with fine sands
10	Karde	Dapoli Tahsil	Low gradient beach with Variable sand bars and resorts on the north side of the Karde River flowing in central part
11	Ladghar-Tamastirth	Dapoli Tahsil	Complex gravel beach with a river in the central part and another river near its southern part. Roughly Linear beach. Beach cusps are observed on the beach.
12	Kolthare	Dapoli Tahsil	Linear beach backed by dense vegetation cover. Panchanadi River flows near the southern part.

erosion. Coastal erosion is considered a risk not only because it threatens buildings and infrastructure, but also because it degrades and diminishes the extent of the beach. Shoreline Change Atlas (Volume-II: Maharashtra and Goa) prepared by SAC-ISRO have been used for shoreline change analysis. Shoreline change maps (changes between 2004-06- and 2014-16-time frames) representing eroding coast, stable coast and accreting areas have been used for assigning risk ratings for coastal segments. Shoreline changes maps (changes between 1989–1991 and 2004–2006 time frames) have also been used for reference. Extensive field checks have been conducted (2015-2022) and erosion hotspots have been identified in the study area. The coastal stretches experiencing significant sea erosion have been assigned high risk ratings (3), the coastal stretches with low erosion have been assigned moderate risk ratings (2) and the coastal stretches which are experiencing accretion or are stable in nature have been assigned low risk rating (1). Coastal stretches with rocky cliffs and headlands are stable shorelines, thereby limiting the major changes only along its pocket beaches, sandy spits and near mouths of rivers and creeks. Major areas of coastal erosion in the study area along Dapoli Tahsil coast are observed at Velas, Ade, Padale, Anjarle (southern part), Harnai (northern part), Murud, Kolthare and Dabhol. The northern part of Kelshi coast is experiencing accretion and its southern part is experiencing erosion. Karde coast is experiencing accretion. Ladghar coast is experiencing slight erosion. Severe erosion is noticed along a significant portion of coastal region at the northern bank of the Vashishti River mouth in Dabhol. This coastal area has been identified as a hot spot area of erosion (Figure 4).

c. Coastal Slope: Loss of land due to inundation depends on the coastal slope, as locations with gentle slope values retreat faster than steeper ones and are more prone to flooding from storm surges and tsunamis. Thus, coastal areas having gentle slopes are considered as highly vulnerable while areas of steep slope as least vulnerable. The coastal slope has been analyzed by profile analysis at 500 meters distance interval using 240 ASTER DEM (Advanced Spaceborne Thermal Emission and Reflection Radiometer - Digital Elevation Model) profiles and 225 GEBCO (General Bathymetric Chart of the Oceans) gridded bathymetry data profiles of 2022. Coastal segments having low slope are assigned high risk ratings and those having high slope are assigned low risk ratings (Figures 5 and 6).

d. Relative Mean Sea Level Rise (SLR) Rate: With respect to vulnerability, coasts that are subject to a high rate of SLR are considered as highly vulnerable and vice versa. The NASA (National Aeronautics and Space Administration) Sea Level Projection Tool (based on IPCC's Sixth Assessment Report has been used to obtain the predicted values of sea level change rates in future in the study area. According to the IPCC Assessment Report from Working Group I - 'Climate Change 2021: The Physical Science Basis', the sea

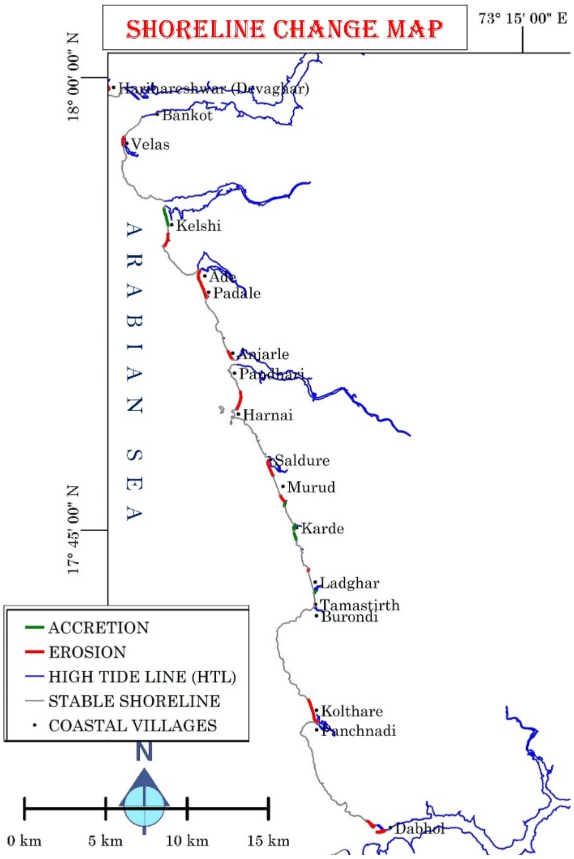


Fig. 4. Shoreline Change Map

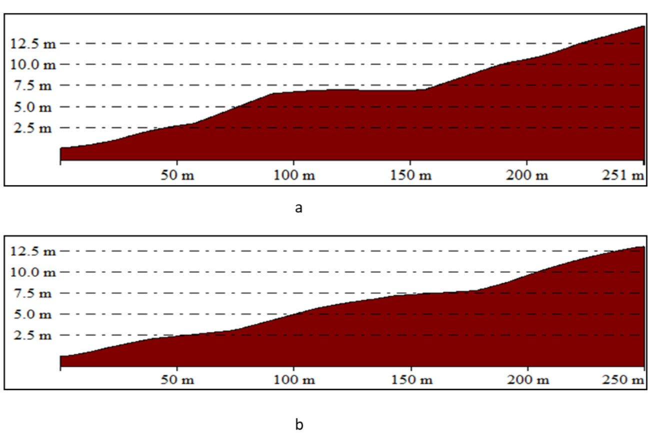


Fig. 5. (a) ASTER DEM PROFILE–40: Anjarle (Coastal Slope = 4.1 °), (b) ASTER DEM PROFILE–50: Harnai (Coastal Slope = 3.1 °)

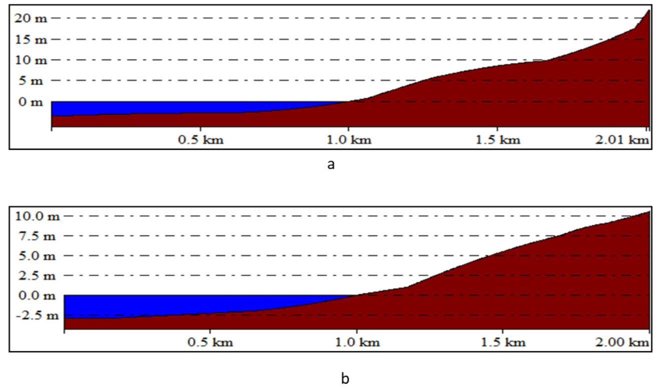


Fig. 6. (a) GEBCO DTM PROFILE–48: Padale (Coastal Slope = 0.7 °), (b) GEBCO DTM PROFILE–48: Harnai (Coastal Slope = 0.4 °)

level along the Konkan coast has risen to 3.7 millimeters per year from 2006 to 2018, which is highest since 1971 due to rising temperatures. Sea levels along Maharashtra's coast may rise by about 0.38 meters by 2050, as predicted by a State Government study. In case of mean sea level change rate, all coastal segments have been assigned moderate risk values, as there are not much variations. Total sea level rise and sea level rise rate projections along the study area are almost uniform. In the possible best-case scenario (SSP1-1.9: net-zero emission by mid-2050), the estimated median value of total sea level rise along the coast: 0.09 meter by 2030, 0.17 meter by 2050, 0.33 meter by 2100 and 0.50 meter by 2150. In the worst possible scenario (SSP 5-8.5: highest greenhouse gas emission levels and no additional climate policy), the estimated median value of total sea level rise along the coast: 0.22 meter (medium confidence) to 0.23 meter (low confidence) by 2050; 0.77 meter (medium confidence) to 0.90 meter (low confidence) by 2100; 1.33 meters (medium confidence) to 2.04 meters (low confidence) by 2150. Low-lying areas such as Velas, Kelshi, Ade, Padale, Anjarle, Pandhari, Harnai, Murud, Ladghar, Tamastirth, Kolthare, Dabhol, etc. are relatively prone to coastal inundation in long-term future as compared to the rocky steep sloping coasts in the study area (Figure 7).

e. Significant Wave Height: Significant wave height gives an indication of the amount of beach materials that may be moved offshore and thereby influencing coastal erosion. Coastlines experiencing high wave heights are considered more vulnerable than those exposed to low wave heights. The United States Department of Commerce's NOAA (National Oceanic and Atmospheric Administration) WAVEWATCH III Wave Model has been used to acquire global gridded data of Significant Wave Height from 2005 to 2019. Grid operations have been performed to determine the Mean Significant Wave Height along the coastal segments.

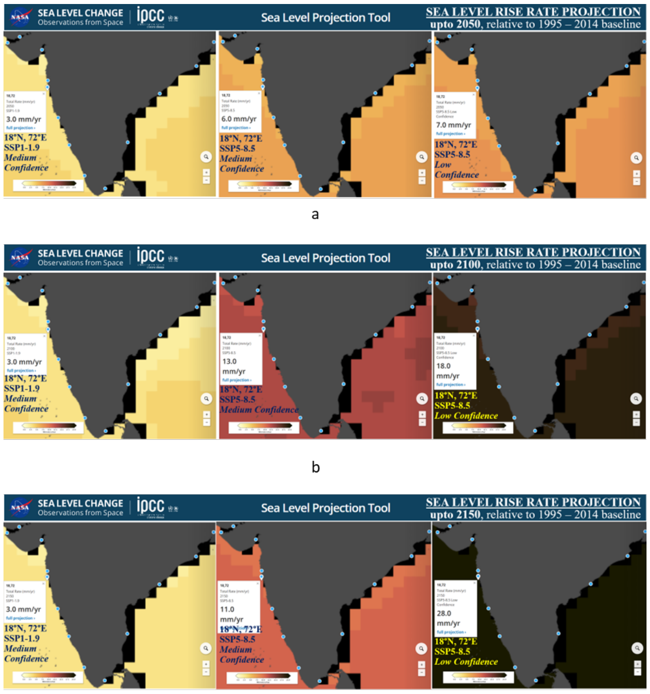


Fig. 7. (a) Sea Level Rise Rate Projection up to 2050, relative to 1995-2014 baseline, for the study area, (b) Sea Level Rise Rate Projection up to 2100, relative to 1995-2014 baseline, for the study area,(c) Sea Level Rise Rate Projection up to 2150, relative to 1995-2014 baseline, for the study area

Forecasted Significant Wave Height data of 2021-2022 has been obtained from INCOIS (Indian National Centre for Ocean Information Services). In case of mean significant wave height, all coastal segments have been assigned moderate risk values, as there are not much variations (Table 3 and Figures 8 and 9).

Table 3. Mean Significant Wave Height and Mean Tidal Range

Sr. No.	Tidal Station	Mean Significant Wave Height (m)	Mean Tidal Range (m)
1	Bankot	1.09	1.82
2	Velas	1.11	1.81
3	Kelshi	1.11	1.80
4	Anjarle	1.12	1.78
5	Harnai	1.12	1.76
6	Saldure	1.13	1.76
7	Ladghar	1.14	1.73
8	Kolthare	1.16	1.71
9	Dabhol	1.17	1.68

f. Mean Tidal Range: Mean Tide Range is linked to both permanent and episodic inundation hazards. Coastal areas experiencing high tidal range have relatively higher risk. Mean tidal range values (in meters) for nine tidal stations in the study area have been calculated using monthly tidal tables data from 2010 to 2022. In case of mean tidal range, all coastal segments have been assigned moderate risk values, as there are not much variations.

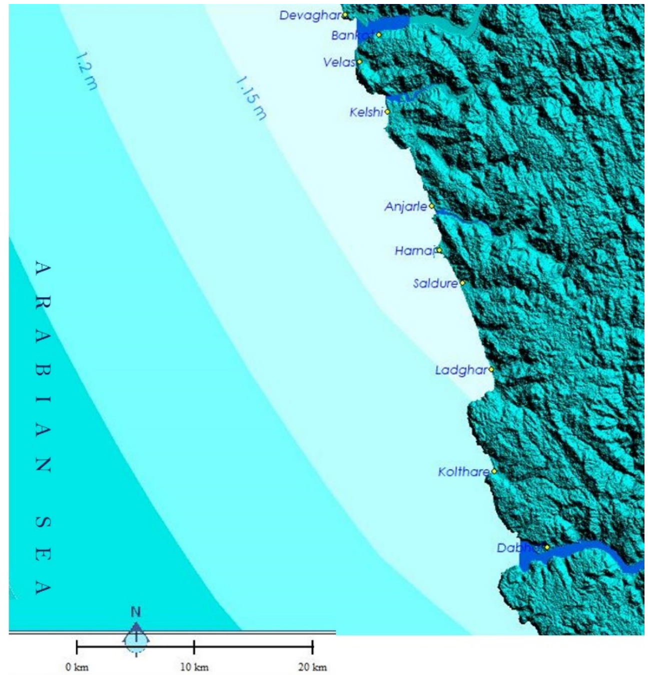


Fig. 8. Mean Significant Wave Height Map (Mean Significant Wave Height Values in meters)

Physical Coastal Vulnerability Index Analysis: Highly vulnerable coastal segments with high PCVI (index value more than 4) are beaches at Velas, Kelshi, Ade-Padale, Anjarle, Harnai, Murud, Ladghar, Kolthare, Panchnadi River mouth segment and Vashishti River mouth segment near Dabhol. Moderately vulnerable coastal segments have PCVI value between 2 and 4. Least vulnerable coastal segments with low PCVI (index value less than or equal to 2) are mostly rocky / steep coastal segments of Bankot to Sakhari, Utambar, Tadachakond, Chandranagar, Burondi to Shital Nagar, Panchnadi to Northern Dabhol. The results of PCVI analysis and INCOIS CVI map are shown in Figure 10. The detailed PCVI map produced from the present research highlights the highly vulnerable areas which are not shown in small scale INCOIS CVI map (1:100000 map scale).

Socio-economic Coastal Vulnerability Index (SCVI) : The SCVI is equally important when compared with the PCVI. The SCVI has been computed by using four socio-economic and demographic variables: population density, coastal land use, coastal roads and economic activities in the study area. Each variable is ranked for vulnerability

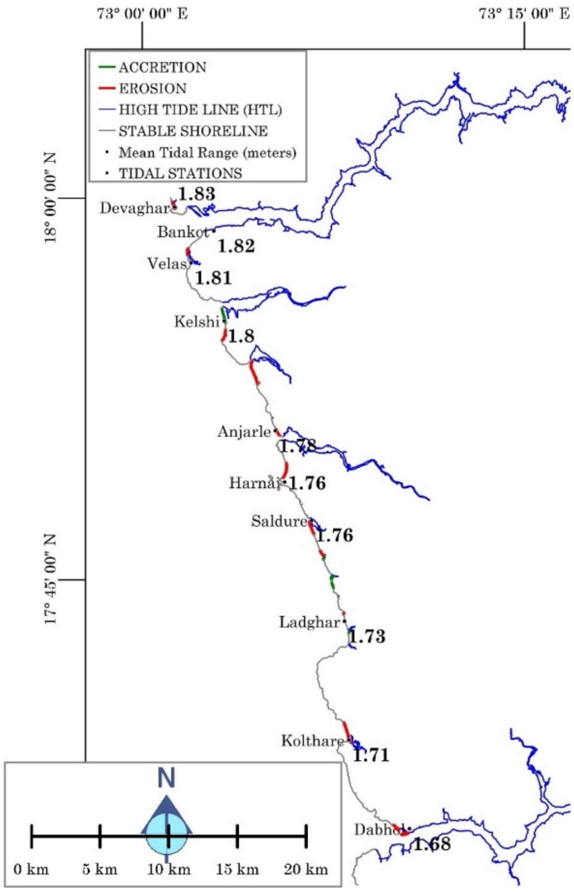
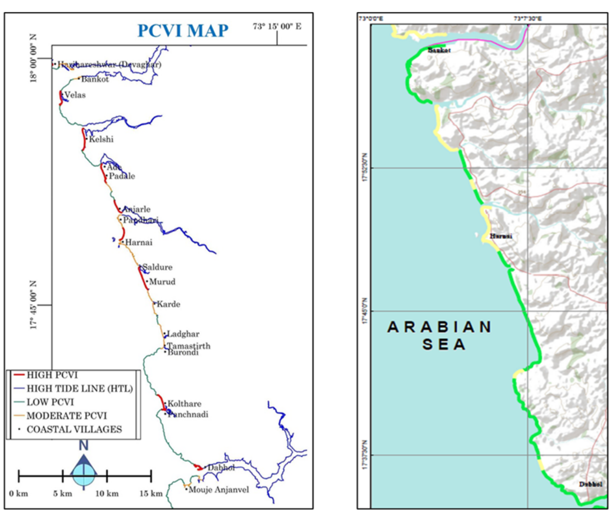


Fig. 9. Mean Tidal Range Map



a b

Source: INCOIS CVI Atlas, 2012

Fig. 10. (a) PCVI Map, (b) CVI Map - INCOIS (2012)

into: high (3), moderate (2) or low (1) category. High risk values are given to segments having very high density of population, closely spaced settlements, intensive land use, presence of coastal roads and tourism activity. Low risk values are given to segments having low density of population, few or no settlements near the coast, barren lands or rocky areas, absence of coastal roads and no major economic activities. All coastal segments were assigned a risk value for every variable and the SCVI is calculated as the square root of the product of the ranked variables divided by the total number of variables.

$$SCVI = \sqrt{g * h * i * j / 4}$$

Where, 'g' = population density; 'h' = coastal land use; 'i' = coastal roads; 'j' = economic activities

Coastal segments are classified as highly vulnerable, moderately vulnerable and least vulnerable, according to SCVI (Table 4).

Table 4. Ranking Criteria for SCVI

Variables	Parameter's Vulnerability rank		
	Low	Moderate	High
	1	2	3
Population Density	Less than 150 per sq.km	151 to 300 per sq.km	More than 300 per sq.km
Coastal Land Use	Bare rocks, barren land or sparsely vegetated areas No or Few Settlements	Agricultural areas and settlements with Wadis	Clustered or compact settlements, urban places and industrial areas
Coastal Roads	No roads along the coast	Roads of local importance along the coast	State highways passing along the coast
Economic Activities	No major economic activities	Agriculture and tourism are observed to a limited extent	Tourism as the dominant economic activity

g. Population density: Coastal villages which are densely populated are generally regarded as highly vulnerable, as there is a relatively higher risk and damage when a disaster occurs. Pandhari has the highest population density among all the coastal villages of the study area. The population density of Pandhari is 10,194 persons per square kilometer land area, which is extremely high. Pandhari is also the third most populated coastal village of Dapoli Tahsil having a total population of 5780 (2011). The population density of four coastal villages viz.: Harnai, Burondi, Kelshi and Ade is more than 1100 persons per square kilometer land area, which is very high. The population density of Harnai is 1229 persons per square kilometer land area. Harnai has the highest population (7274) among all the coastal villages of the study area. The Census Town of Dabhol situated along the north bank of Vashishti River near its mouth is also categorised as coastal area having high density of population as this area has 786 persons per square kilometer land area. Dabhol has the second highest population (7038) along the Dapoli Coast (Figure 11).

h. Coastal Land Use: The coastal villages having very closely spaced compact settlements, urban places and industrial areas near the coast have been assigned high risk rating. These areas have been considered as having relatively high vulnerability. These coastal villages are Pandhari, Harnai, Burondi and Dabhol (CT) (Figure 12).

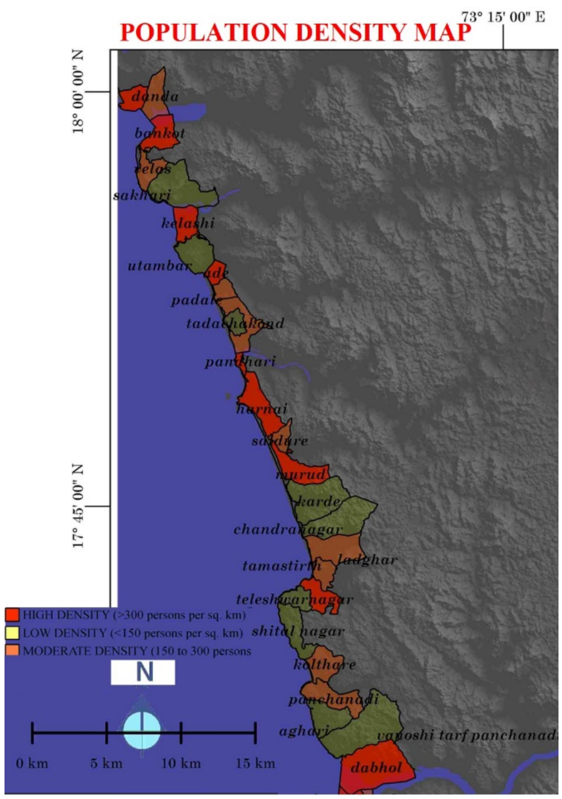


Fig. 11. Population Density Map

i. Coastal Roads: The coastal villages through which state highways are passing along the coast have been assigned high risk rating. These villages are Harnai, Saldure and Ladghar. The Maharashtra State Highway number 4 passes very closely from the coast of these villages.

j. Economic Activities: The coastal villages in which tourism is the dominant economic activity have been assigned high risk rating. These villages are Anjarle, Harnai, Murud and Karde along the northern coast of Dapoli Tahsil; Ladghar and Tamastirth along the central coast of Dapoli Tahsil and Kolthare along the southern coast of Dapoli Tahsil (Figure 13).

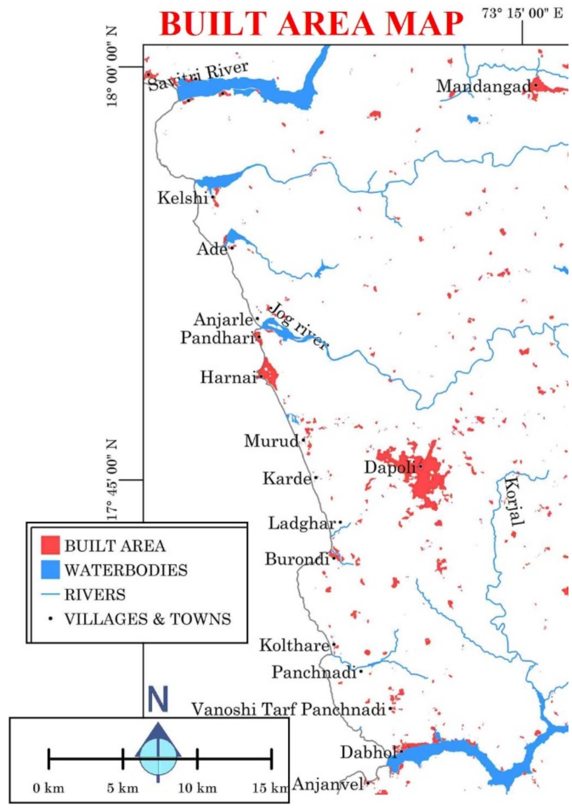


Fig. 12. Built Area Map

Socio-economic Coastal Vulnerability Index Analysis: Highly vulnerable coastal segments with high SCVI (index value more than 2.5) are Harnai, Murud and Dabhol. Coastal segments of Bankot, Kelshi, Anjarle, Pandhari, Tamastirth, Burondi and Kolthare, were also highly vulnerable. Coastal segments having SCVI index value between 1 and 2.5 have been considered as moderately vulnerable coastal segments. Least vulnerable coastal segments having low SCVI (index value less than or equal to 1) are Sakhari, Utambar, Tadachakond, Chandranagar, Teleshwarnagar, Shital Nagar, Aghari, Vanoshi Tarf Panchanadi (Figure 14).

Composite Coastal Vulnerability Index (CCVI) Analysis : CCVI gives a comprehensive idea regarding coastal vulnerability by combining physical and socio-economic parameters. CCVI has been calculated by using ten variables: six physical variables (coastal geomorphology, shoreline change, coastal slope, relative mean sea level change rate, mean significant wave height and mean tidal range), and four socio-economic variables (population density, coastal land use, coastal roads and economic activities). All the coastal segments were assigned a risk value for every variable and the CCVI (Composite Coastal Vulnerability Index) is calculated as the square root of the product of the ranked variables divided by the total number of variables.

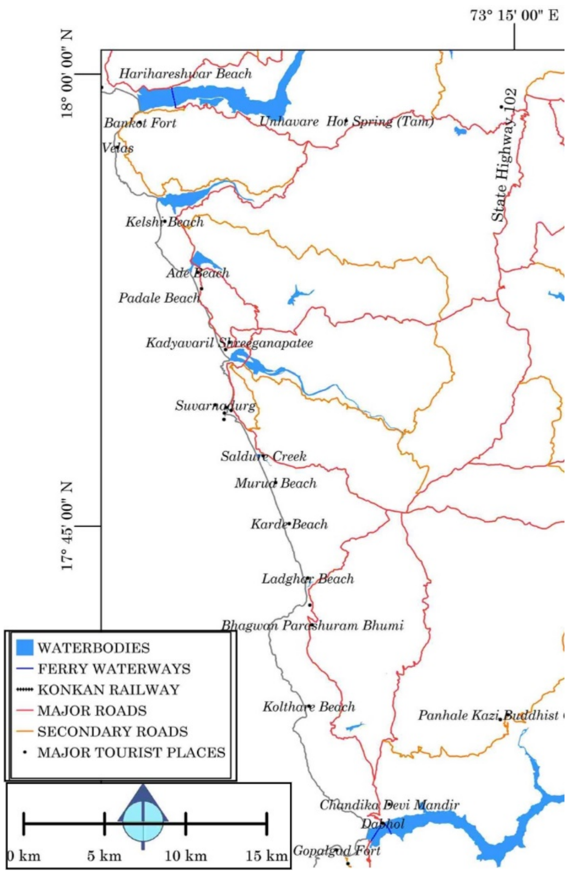


Fig. 13. Transport Network and Tourist Places Map

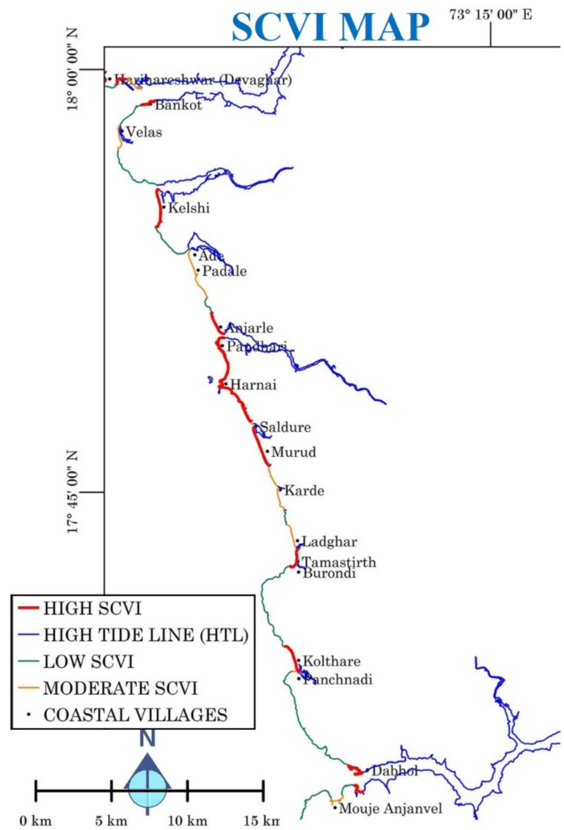
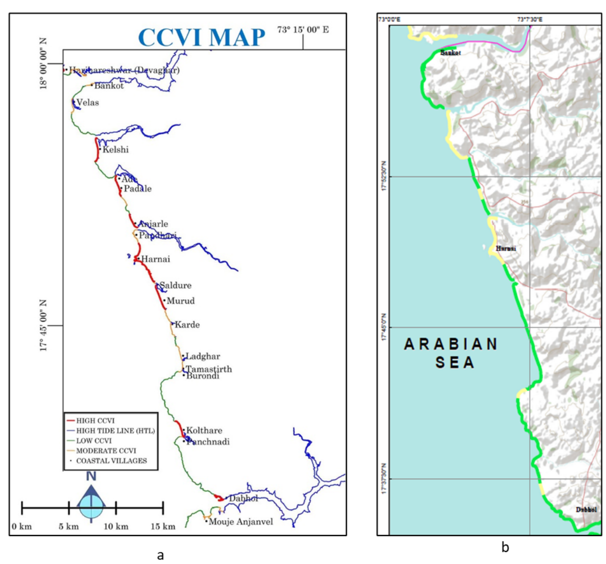


Fig. 14. SCVI Map

Coastal segments are classified as highly vulnerable, moderately vulnerable and least vulnerable, according to CCVI. CCVI Index analysis revealed coastal segments which are naturally as well as socio-economically vulnerable. Highly vulnerable coastal segments with high CCVI (index value more than 20) are Harnai-Paj Pandhari beach, Murud village, Dabhol (Vashishti River mouth), Kelshi, Ade-Padale, Anjarle, Palande, Kolthare. Coastal segments having index value between 7.5 and 20 are categorized as moderately vulnerable segments. Least vulnerable coastal segments with low CCVI (index value less than or equal to 7.5) are rocky and steep coastal segments of Bankot to Sakhari, Utambar, Tadachakond, Chandranagar, Burondi to Shital Nagar, Panchnadi to North Dabhol. The results of CCVI analysis and INCOIS CVI map are shown in Figure 15. The CCVI map produced from the present research highlights the highly vulnerable areas which are not shown in small scale INCOIS CVI map (1:100000 map scale) prepared used physical variables only.



Source: INCOIS CVI Atlas, 2012

Fig. 15. (a) CCVI Map, (b) CVI Map - INCOIS (2012)

Integrated Coastal Zone Management: Integrated Coastal Zone Management (ICZM) is a coastal management process for the management of the coast using an integrated approach, regarding all aspects of the coastal zone, including geographical and political boundaries, in an attempt to achieve sustainability. HTL (High Tide Line), LTL (Low Tide Line), Hazard Line and various CRZ lines and areas as demarcated by the National Centre for Sustainable Coastal Management (NCSCM) on CZMP (Coastal Zone Management Plan) of Maharashtra State Coastal Zone Management Authority (MCZMA) as per CRZ Notification (2019), have been digitized, in order to prepare a comprehensive CRZ and CZMP Maps for the entire study area. Coastal Zone Management Action Plan has been prepared for the study area. Coastal Zone Management Action Map shows coastal segments which need high priority and coastal protection measures. Ecologically sensitive areas (turtle nesting grounds, mangrove swamps etc.) also need to be monitored and suitable measures should be undertaken and implemented for their protection and conservation by concerned authorities. Turtle nesting grounds identified by the Maharashtra Government shall be protected as per Wildlife (Protection) Act of 1972. All the five marine turtle nesting grounds (at Bankot, Velas, Kelshi, Kolthare and Dabhol) need to be monitored and suitable measures and management plans should be undertaken and implemented for their protection and conservation by the concerned authorities, as per CRZ Notification, 2019. Mangroves occur along the intertidal region of Bankot Creek (Savitri River), Sakhari Creek (Bharja River), Utambar Creek (Kesari River) Anjarle Creek (Jog River), Dabhol Creek (Vashishti River) need to be protected. Geomorphologically important zones such as coastal sand dunes, sandy beaches and biologically active mudflats should be protected and managed, as per the CRZ Notification 2019. Areas or structures of archaeological importance and heritage value sites also need conservation viz.: Suvarnadurg Fort near Harnai (Table 5 and Figure 16).

Coastal Zone Management Action Plan: Coastal Zone Management Action Map shows coastal segments which need high priority and coastal protection measures. Three coastal segments have overall extremely high vulnerability: Harnai-Paj Pandhari beach segment, Murud village segment, and Dabhol segment (Vashishti River mouth) need high priority for planning and successful implementation of suitable coastal protection structures such as anti-sea erosion bunds because coastal erosion is observed along these segments. Harnai-Paj Pandhari beach segment is a No Development Zone (NDZ) under CRZ-IIIA. Action is required for coastal segments having high coastal vulnerability viz.: coastal segments of Kelshi, Ade, Padale, Southern Anjarle, Palande (Harnai), Kolthare. Coastal areas along these six segments need attention and certain suitable coastal protection measures as sea erosion is witnessed along these segments (Figure 18).

5. Conclusion

Coastal Vulnerability Index (CVI) assessment is highly crucial for prioritization of coastal segments for coastal zone

Table 5. Marine Turtle Nesting Grounds in the Study Area

Sr. No.	Site	Length	Description
1	Bankot, Mandangad Tahsil	0.6 km	Turtle nesting ground on an intertidal flat
2	Velas, Dapoli Tahsil	1.7 km	Velas beach is one of the most important turtle nesting grounds along the Konkan coast.
3	Kelshi, Dapoli Tahsil	2.8 km	Kelshi beach is a major turtle nesting ground in the northern part of the Dapoli Tahsil.
4	Kolthare, Dapoli Tahsil	1.5 km	Kolthare beach is a major turtle nesting ground in the southern part of the Dapoli Tahsil
5	Dabhol (North of Vashishti River mouth), Dapoli Tahsil	-	Turtle nesting ground on a depositional sand bar which has been experiencing erosion.

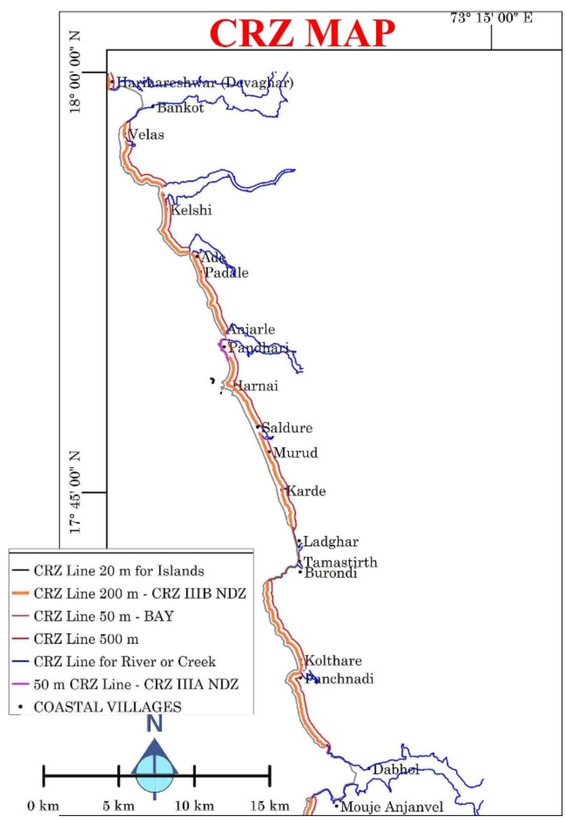


Fig. 16. Coastal Regulation Zone Map

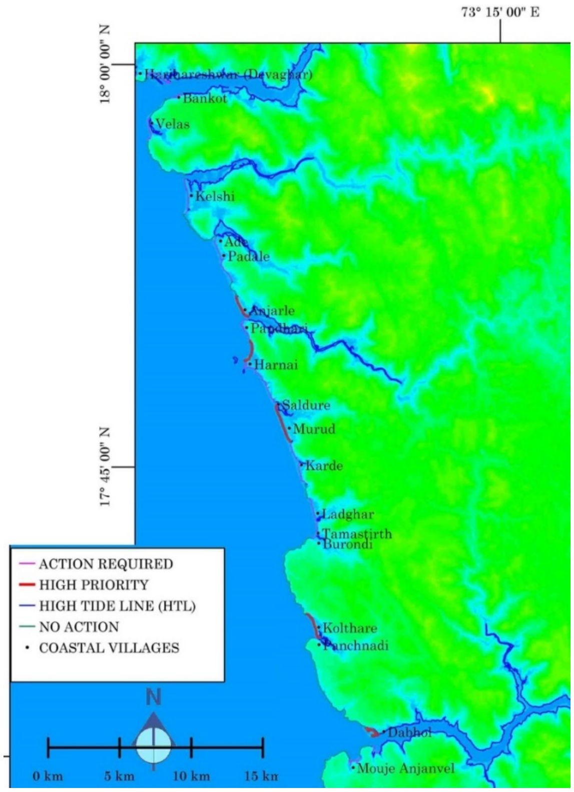


Fig. 18. Coastal Zone Management Action Plan

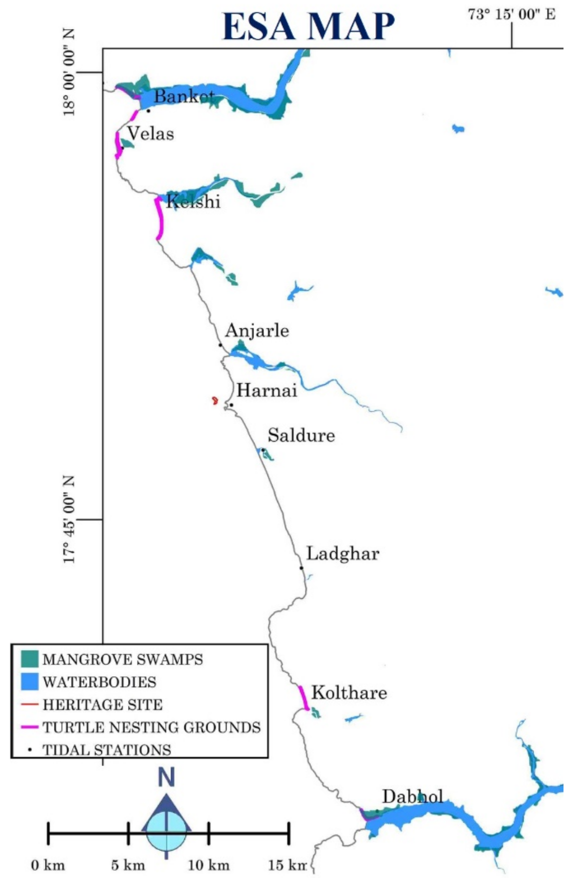


Fig. 17. Ecologically Sensitive Areas

management and disaster management. Coastal vulnerability assessment purely based on physical parameters only does not give a comprehensive idea of coastal vulnerability. Hence, Composite Coastal Vulnerability Index (CCVI) assessment is highly appropriate as it gives results based on assessment of physical as well as socio-economic parameters. The results of PCVI analysis closely matched with those of CCVI analysis. Similarly, the results of SCVI analysis were in line with those of CCVI analysis. The use of Geoinformatics and geospatial data in coastal vulnerability assessment has proved to be fruitful. Variety of datasets pertaining to sea level, wave height, etc. are available online from different satellites and models which have proved to be immensely useful for future predictions. The coastal vulnerability maps prepared for the study area at relatively large map scale can prove highly useful for the local administration in decision-making for Integrated Coastal Zone Management as well as management and mitigation of disasters. There is an increasing need for mapping coastal vulnerability at relatively larger scales by following a multidisciplinary scientific approach through integration of various physical, geological, biological, social, economic and demographic parameters into the coastal vulnerability index.

References

1) Dwarakish GS, Vinay SA, Dinakar SM, Pai JB, Mahaganesha K, Natesan U. Integrated coastal zone management plan for Udupi coast using remote sensing, geographical information system and global position system. In: Remote Sensing of the Ocean, Sea Ice, and Large Water Regions 2007; 67430D (2007);vol. 6743 of SPIE Remote Sensing. SPIE-Intl Soc Optical Eng. 2007. Available from: https://doi.org/10.1117/12.737528.
2) Duriyapong F, Nakhapakorn K. Coastal vulnerability assessment: a case study of Samut Sakhon coastal zone. *Songklanakarin Journal of Science and Technology*. 2011;33(4):469–476. Available from: https://www.researchgate.net/publication/266439568_Coastal_vulnerability_assessment_A_case_study_of_Samut_Sakhon_coastal_zone.
3) Kumar AA, Kunte PD. Coastal vulnerability assessment for Chennai, east coast of India using geospatial techniques. *Natural Hazards*. 2012;64:853–872. Available from: https://doi.org/10.1007/s11069-012-0276-4.
4) Kumar TS, Mahendra RS, Nayak S, Radhakrishnan K, Sahu KC. Coastal Vulnerability Assessment for Orissa State, East Coast of India. *Journal of Coastal Research*. 2010;26(3):523–534. Available from: http://indiaenvironmentportal.org.in/files/Coast%20Orissa.pdf.
5) McLaughlin S, McKenna J, Cooper JAG. Socio-economic data in coastal vulnerability indices: constraints and opportunities. *Journal of Coastal Research*. 2002;36:487–497. Available from: https://www.researchgate.net/publication/291771990_Socio-economic_data_in_coastal_vulnerability_indices_Constraints_and_opportunities.
6) Tragaki A, Gallousi C, Karymbalis E. Coastal Hazard Vulnerability Assessment Based on Geomorphic, Oceanographic and Demographic Parameters: The Case of the Peloponnese (Southern Greece). *Land*. 2018;7(2):1–16. Available from: https://doi.org/10.3390/land7020056.
7) Cutter SL. Vulnerability to environmental hazards. *Progress in Human Geography*. 1996;20(4):529–539. Available from: https://doi.org/10.1177/030913259602000407.
8) Gornitz VM, Beaty TW, Daniels RC. A coastal hazard database for the U.S. West Coast. Oak Ridge, Tennessee, USA. Oak Ridge National Laboratory. 1997. Available from: https://www.osti.gov/servlets/purl/661514.
9) Tourism Survey for the State of Maharashtra, Final Report. 2019. Available from: https://tourism.gov.in/sites/default/files/2020-04/Maharashtra_0.pdf.
10) Gornitz VM, Daniels RC, White TW, Birdwell KR. The development of a coastal risk assessment database: Vulnerability to sea-level rise in the U.S. southeast. *Journal of Coastal Research Special Issue No*. 1994;(12):327–338. Available from: https://www.jstor.org/stable/25735608.
11) Census of India 2011 - Maharashtra - Series 28 - Part XII A - District Census Handbook, Ratnagiri: Village and Town Directory. Maharashtra, India. Directorate of Census Operations. 2011. Available from: https://censusindia.gov.in/nada/index.php/catalog/824.
12) Census of India 2011 - Maharashtra - Series 28 - Part XII A - District Census Handbook, Ratnagiri: Village and Town wise Primary Census Abstract. Maharashtra, India. Directorate of Census Operations. 2011. Available from: https://censusindia.gov.in/nada/index.php/catalog/824.