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Coastal Vulnerability Assessment for Climate Change Adaptation: A Case Study of Bapatla District, Andhra Pradesh, India

Sreerama Naik S. R.*, T. K. Prasad, and Jayapal G.

Department of Geography, Swami Anandatheertha Campus, Kannur University, Kerala, India

ABSTRACT

This study assessed the vulnerability of Bapatla district to multiple environmental, social and climate stresses using the Coastal Vulnerability Index (CVI). The study computed the Socio-Economic Vulnerability Index (SEVI), the Physical Vulnerability Index (PVI) and the Climate Hazard Index (CHI) as inputs to the conceptual model for estimating the CVI of the study area. With regard to SEVI, the study observed that 32.7% of the district falls in the high and very high socio-economic vulnerability classes, owing to a higher proportion of dependent age groups, female population, sex ratio and built-up density. The PVI results indicate that 34.86% of the area of the district falls in the high and very high vulnerability classes with respect to coastal hazards, and the highest priority for mitigating their impacts is the eastern low-lying coastal belt of the district, which includes Repalle mandal, among others. On the other hand, CHI showed that 25% of the district experiences high to very high climate hazard, caused by temperature variations, high rainfall intensity and high wave energy along the coastal stretches. Overall, the study estimates that 45.7% of the Bapatla district falls within the high and very high CVI classes, with only 9% falling within the moderate class. Notably, this study shows that vulnerability to coastal hazards crosses administrative boundaries and is not confined to the coastal fringe but extends to the interior parts of the district, highlighting the need for coastal zone management interventions for effective disaster management and climate change adaptation planning in the area.

Keywords: *Coastal Vulnerability Index; Climate Hazard; Socio-Economic Vulnerability; Physical Vulnerability; Bapatla District; Geospatial assessment.*

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Corresponding Author: *Sreerama Naik S. R.*

E-mail Address: *rs_sreeramanaik@kannuruniv.ac.in*

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1. Introduction

Among Earth's most dynamic environments, coastal zones are home to nearly a third of humanity. They deliver a broad array of ecosystem functions, stabilizing shorelines, cycling nutrients, sequestering carbon, and sustaining habitat for a wide range of land and marine species [2,31]. Yet, despite the ecological and economic importance of these systems, they are under serious threat from climate change, rising sea levels, storm surges, coastal erosion, and human activities. These problems undermine the resilience of coastal ecosystems and threaten the communities that depend on them [15,26]. Recent assessment reports indicate that low-lying coastal areas are highly exposed to climate-related hazards and that sea-level rise is projected to intensify coastal flooding, increase shoreline erosion, and damage infrastructure during this century [14]. This poses a significant risk to developing countries, which are characterized by extensive coastal habitation and a heavy reliance on coastal agriculture and fisheries [5,25]. India is among the countries that experience the adverse impacts of climate change in its coastal areas. The expected rise in sea level will combine with non-climate factors (land subsidence, decreased sediment supply and changing land use) to increase coastal inundation, erosion and saltwater intrusion [24].

India has a coastline of about 7517 km, which is vulnerable to climate change impacts such as cyclones, storm surges, shoreline erosion, and rising sea levels. The coastal areas of Andhra Pradesh are especially prone to cyclones that originate in the neighbouring Bay of Bengal [19,23]. Historical cyclone paths within the Bay of Bengal indicate the Indian East Coast suffers repeated impacts from tropic cyclones making landfall [27]. The impacts of these hazards pose a risk to coastal ecosystems, fisheries, agriculture, infrastructure, and human health. There is a need to conduct coastal vulnerability assessments to guide disaster management and adaptation strategies. Coastal vulnerability is a function of exposure, sensitivity, and adaptive capacity to climate change impacts [13]. It is a measure of the susceptibility of coastal systems to the negative effects of climate change and variability. Vulnerability assessments of coastal areas to climate change impacts have been carried out using different approaches. Most of the methods have evolved from purely geographical and geomorphological analyses to include socio-economic variables in the assessment [1,16,22].

Coastal vulnerability indices (CVIs) are among the methods used to evaluate vulnerability. The method is convenient to use and provides vulnerability scores based on physical parameters [11,30].

Some researchers have modified the CVI by including socio-economic variables in the assessment process. The modified CVI can be used to evaluate the exposure, sensitivity, and adaptive capacity of coastal communities to climate change impacts [3,20]. Coastal vulnerability assessments have been conducted along most of the Indian coastlines. The vulnerability of coastal areas in Odisha, Karnataka, Chennai, and Puducherry has been evaluated using the coastal vulnerability index [7,17,18,20]. The studies highlight the usefulness of vulnerability indices in coastal management, disaster management, and adaptation planning. Recent work has extended the index approach to multivariate, composite and multiple hazard indices using physical, social and ecological indicators [9,28,29,34]. For the newly formed Bapatla district, there is a need to develop a composite index of the physical, socio-economic and climate hazards at the district scale. Therefore, the purpose of this study is to develop an integrated CVI for the newly formed Bapatla district using Google Earth Engine and GIS technologies to identify the priority areas for coastal management and climate change adaptation.

2. Study Area

The research has been conducted in a district known as Bapatla. This district is located in the central coastal area of Andhra Pradesh, a state in India that borders the Bay of Bengal. Overall, this district covers an area of 3,829 km^2. In terms of coordinates, Bapatla is located between the parallels of 15°43′ and 16°18′ N and the meridians of 79°50′ and 81°30′ E. The district is divided into 25 administrative units called mandals, including Bapatla, Chirala, Addanki, Inkollu, Karlapalem, Pittalavanipalem, Nagaram, Cherukupalli, Repalle, Bhattiprolu, Kollur, Vemuru, Amruthalur, and Tsundur (Fig. 1). The landscape of this district is characterized by a vast coastal plain with low hills and a lake-rich area. Moreover, the district lies in the Krishna delta region and has an extensive system of irrigation canals.

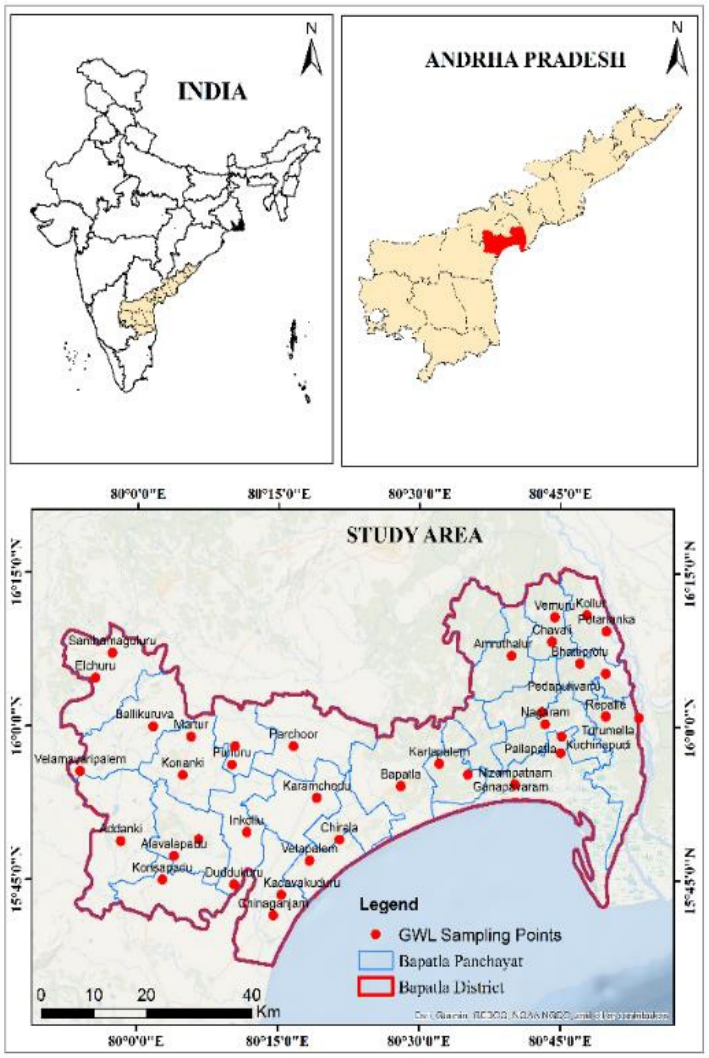


Figure 1: Location Map of the Study Area

To the east of the district lies the Bay of Bengal, while the interior has alluvial soil, which is fertile and suitable for intensive cultivation. The climate is generally tropical monsoon, which is characterized by a significant amount of rainfall throughout the year, mostly brought by the southwest and northeast monsoon winds. On average, it rains around 800–1000 mm per year, and the temperature rarely falls below 25 °C or rises above 35 °C. The main type of land use in the region is connected to agriculture, where farmers grow rice, cotton, chilli, black gram, maize, and other crops.

The aquaculture industry, along with inland fishing, contributes significantly to the district's economy. Apart from this, groundwater plays a significant role in the district as it is an important source of irrigation as well as drinking water. Many mandals depend on groundwater for domestic use and agriculture. The district has a geology of Quaternary alluvium, coastal sediments, and crystalline rocks of varying thicknesses in places, which makes the groundwater storage inconsistent throughout the region. Moreover, coastal aquifers have been under pressure from saltwater intrusion, intensive agricultural activities, urbanization, and over-exploitation, which has led to their degradation.

These pressures, together with its low-lying coastal setting, make the Bapatla district a suitable candidate for coastal vulnerability assessment using geospatial techniques.

3. Data and Methodology

To assess vulnerability to climate change in Bapatla district, Andhra Pradesh, this work developed a Coastal Vulnerability Index (CVI) using a combination of the cloud-based Google Earth Engine (GEE) and a geographic information system (GIS). GEE provides a cloud-based platform with a multi-petabyte catalog of satellite imagery and geospatial datasets, which allows large raster collections to be processed without local downloads [10]. The methodology consisted of ten steps: i) delineating the study area, ii) collecting the input data, iii) pre-processing the data, iv) developing input variables for the vulnerability model, v) calculating the vulnerability indices, vi) aggregating the indices to derive the overall vulnerability, vii) classifying the aggregated values into vulnerability categories, viii) producing end-user-ready information, ix) exporting the final outputs, and x) using the results for adaptation planning purposes.

Table 1: Data used for Vulnerability Analysis

Sl. No.	Dataset	Source	Spatial Resolution	Purpose
1	Cartosat DEM	Bhuvan	30 m	Elevation and Slope
2	Sentinel-2 MSI Level-2A	Copernicus	10 m	NDWI and NDBI
3	Sentinel-2 MSI Level-2A	Copernicus	10 m	Land Use/Land Cover
4	Population	GEE Census Asset	Non-spatial	Population Density
5	Female Population	GEE Census Asset	Non-spatial	Social Vulnerability
6	Population (<6 years)	GEE Census Asset	Non-spatial	Social Vulnerability
7	Population (>59 years)	GEE Census Asset	Non-spatial	Social Vulnerability
8	Sex Ratio	GEE Census Asset	Non-spatial	Demographic Sensitivity
9	CHIRPS Rainfall	UCSB	5 km	Rainfall Intensity
10	MODIS LST (MOD11A2)	NASA MODIS	1 km	Land Surface Temperature
11	MODIS SST (Aqua)	NASA MODIS	4 km	Sea Surface Temperature
12	ERA5 Wave Height	ECMWF	0.25°	Wave Climate

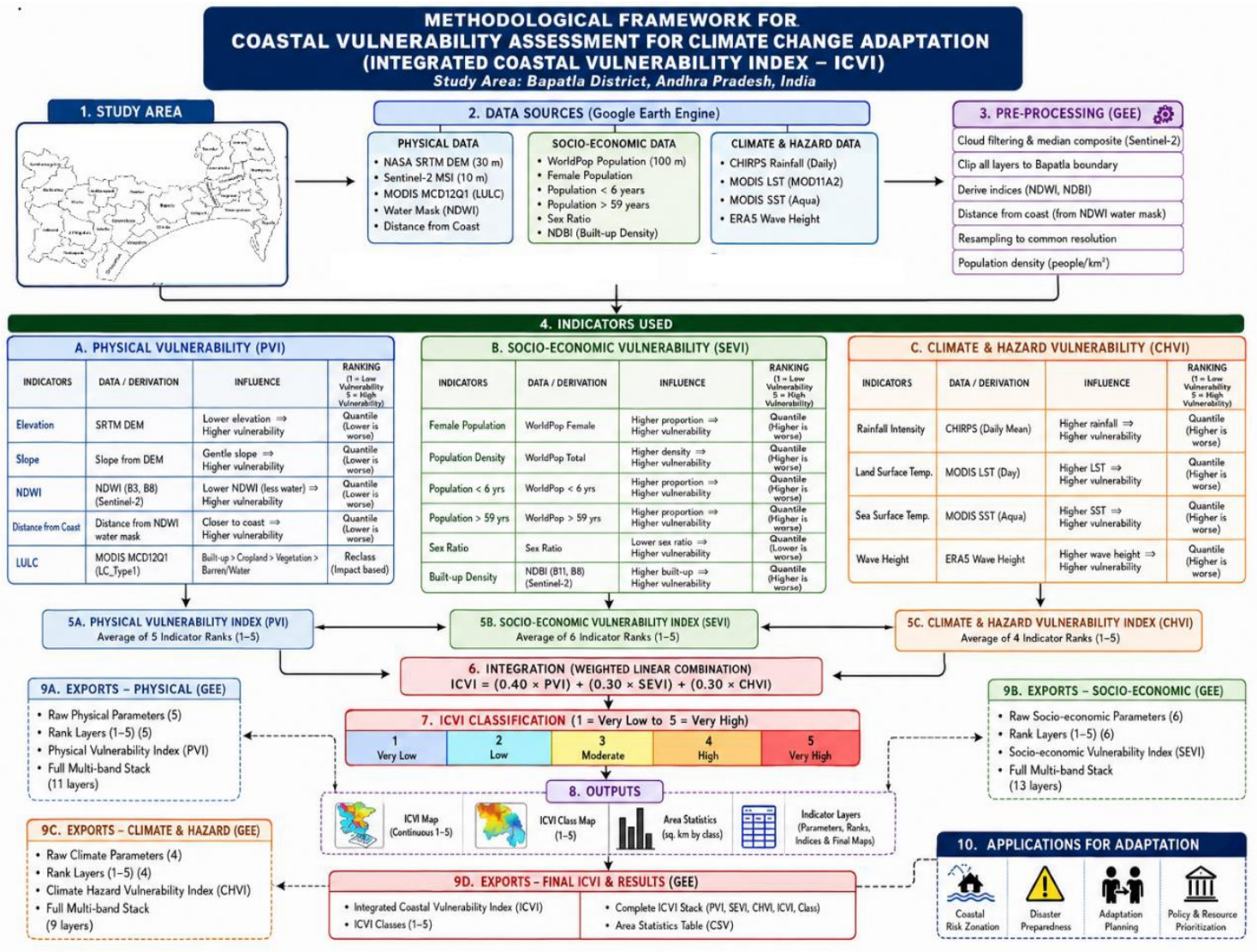


Figure 2: Methodological Framework

Spatial data on topography, land cover, climate, oceanic state, and socio-economic parameters were gathered from public databases. These databases included, but were not limited to, the Cartosat Digital Elevation Model, Sentinel-2 MSI Level-2A [6], specific MODIS products [32], CHIRPS rainfall data [8], ERA5 wave heights [12], and census data on demographics. Before analysis, all data were pre-processed to ensure consistency in spatial resolution. First, clouds were masked from the Sentinel-2 scenes and a median composite was created, from which spectral indices were calculated.

All raster files were subsequently clipped to the district boundary, resampled to a common pixel size, and projected to a common coordinate system.

The Normalized Difference Water Index (NDWI) [21] and Normalized Difference Built-up Index (NDBI) [33] were calculated from the composite Sentinel-2 data. Using the NDWI, a water mask was created, which was used to calculate the distance to the coast from each cell in the raster. Population data were taken from the Census of India and used to calculate population density. The three main vulnerability indices were the Physical Vulnerability Index (PVI), Socio-Economic Vulnerability Index (SEVI), and Climate Hazard Index (CHI).

For each index, individual factors were grouped, standardized, and assigned scores from 1 to 5, based on either quantile or impact thresholds, or a combination of both. The 1 to 5 scale is used to follow the original method of the CVI [11,30]. This allows comparison between variables of varying units.

The PVI was calculated using elevation, slope gradient, NDWI, distance to coast, and land cover. The SEVI combined female population percentage, population density, percentage of children under six, percentage of the population above 59 years of age, sex ratio, and built-up density. Finally, the CHI grouped rainfall, land surface temperature, sea surface temperature, and significant wave height. These factors were aggregated in separate calculations to form the final PVI, SEVI, and CHI surfaces. These three indices were then combined through a weighted linear sum, with PVI contributing 40% of the final score and SEVI and CHI each contributing 30%. The Coastal Vulnerability Index (CVI) was calculated as

CVI = 0.40 (PVI) + 0.30 (SEVI) + 0.30 (CHI)

The resulting composite index values were reclassified into five vulnerability categories to produce the final spatial vulnerability maps. Outputs from the analysis comprised the individual parameter layers, ranked indicator surfaces, the three component indices, the integrated composite vulnerability map, class-wise area statistics, and GIS-compatible datasets suitable for supporting coastal adaptation planning and management decisions.

4. Results and Discussion

4.1 Inputs for Socio-Economic Vulnerability Index

The following analysis illustrates the thematic maps prepared for the Bapatla District Vulnerability Assessment study. This includes the percentage of the population above 59 years of age, children below 6 years of age, female percentage, built-up percentage, water index, population density, and sex ratio. Understanding the pattern of the individual factors will help the Bapatla authorities to identify the major contributors to the Socio-Economic Vulnerability Index and to take the necessary measures to improve disaster response and coastal management. Studies on social vulnerability have shown that demographic characteristics such as age profile, gender and population density greatly affect the ability of a community to prepare, respond and recover from hazards [4].

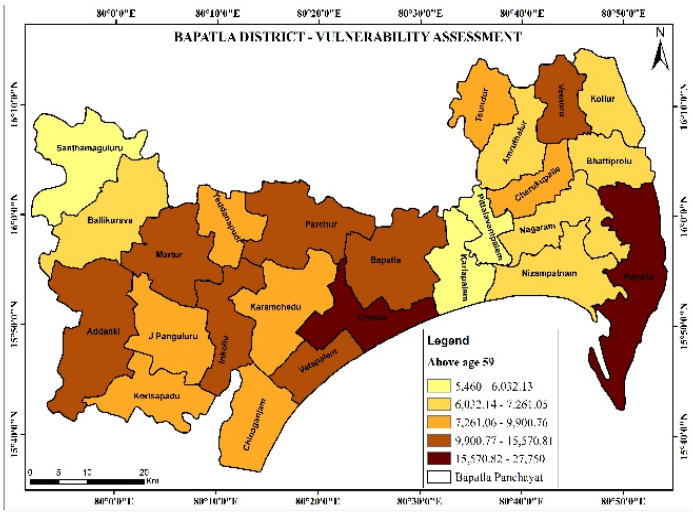


Figure 3: Age group above 59

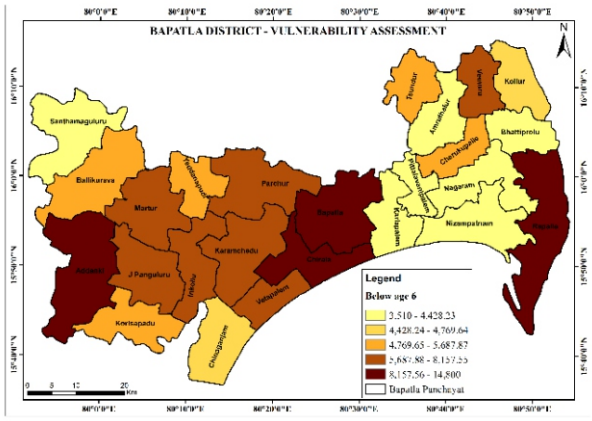


Figure 4: Age group below 6

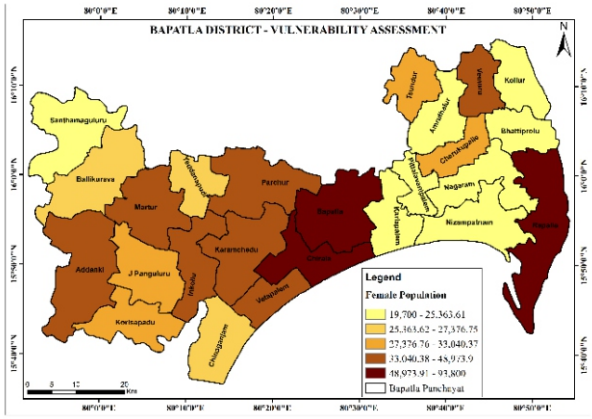


Figure 5: Female Population

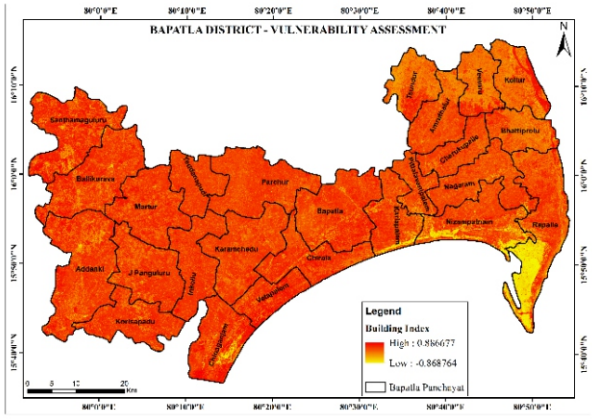


Figure 6: Built-up Index

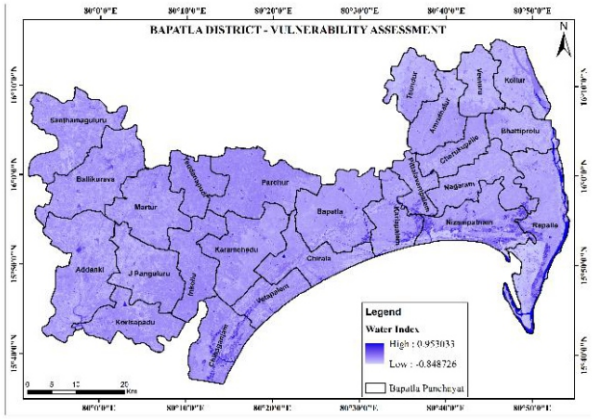


Figure 7: Water Index

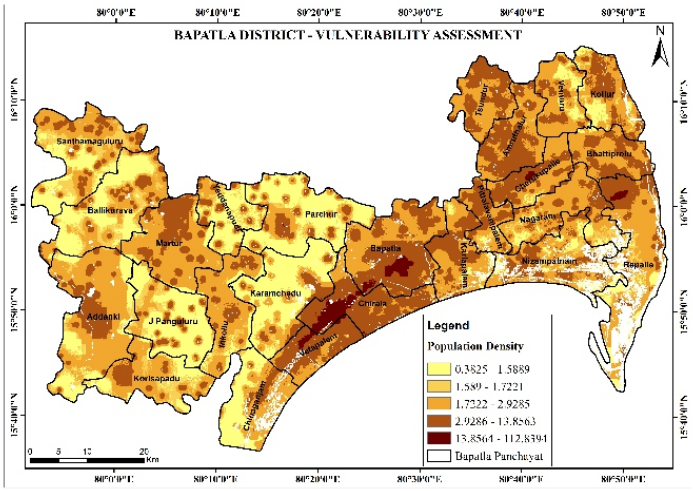


Figure 8: Population Density

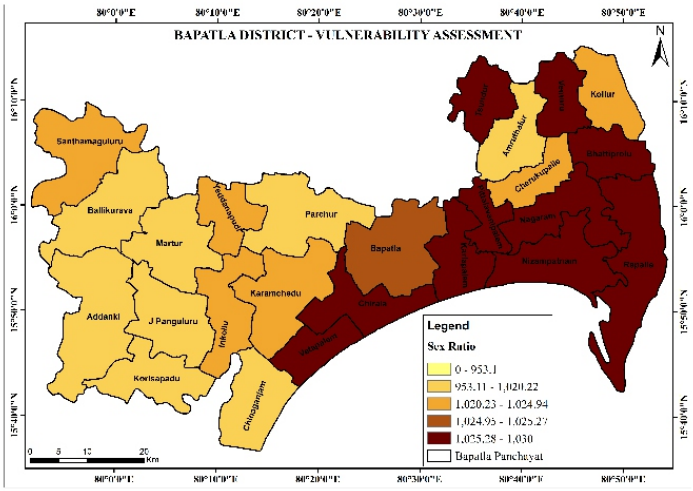


Figure 9: Sex Ratio

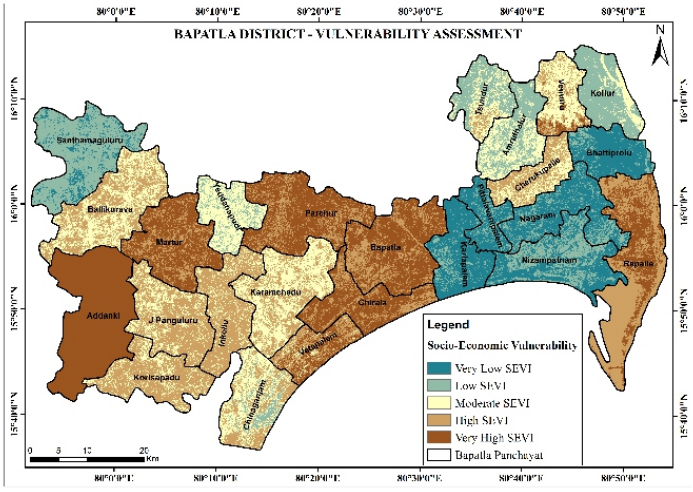


Figure 10: Socio-Economic Vulnerability

4.1.1 Population above Age 59: The map of the population "Above age 59" represents the number of elderly people in the district. It can be seen that the majority of the dark red areas (higher values) are distributed along the eastern and south-eastern coastal mandals of the district, especially in Repalle and Chirala. These mandals have higher social vulnerability to disasters than the western inland ones, such as Santhamaguluru.

4.1.2 Population below Age 6: Similarly, the "Below age 6" map represents the number of young children in the district. It can be seen that the majority of dark red areas (higher values) are distributed along the south-eastern coastal mandals, such as Chirala, Repalle, and Bapatla. Moreover, another dark red area is present in the inner western mandal of Addanki. Thus, it can be suggested that these areas are more socially vulnerable to disasters than others because of the large number of young children who depend on adults during emergencies.

4.1.3 Female Population: The "Female population" map displays the number of women in the district. It can be seen that the largest number of females is concentrated along the eastern coastal mandals, especially in Repalle, Chirala, and Bapatla. The female population is especially vulnerable to disasters because of potential social and economic disadvantages. Therefore, the eastern coastal areas are more vulnerable to disasters than others.

4.1.4 Building Index: The "Building index" map displays areas with the highest number of buildings by using the NDBI (Normalized Difference Built-up Index). Dark red colors indicate high values and are usually distributed along the coastlines or within the cities. It can be seen that most of the buildings are distributed within the district along the coastlines, especially in eastern and southeastern parts. Therefore, the areas with the highest value of building index are more vulnerable to disasters as a result of potential damage to the building structures.

4.1.5 Water Index: The "Water index" map displays areas with the highest amount of water by using NDWI (Normalised Difference Water Index). Similar to the building index, dark blue colors indicate high water concentration along the coastlines, estuaries, internal water areas, and wetlands. The identified areas are more vulnerable to disasters and especially to coastal disasters, such as saltwater flooding.

4.1.6 Population Density: The "Population density" map displays areas with the highest number of people per square kilometre. Most of the dark red areas are distributed along the coastlines in the eastern part of the district (Chirala, Bapatla), as well as some inland areas within the district. Therefore, it can be suggested that these highly populated areas will be more vulnerable to any disaster due to the high number of people at risk.

4.1.7 Sex Ratio: The "Sex ratio" map displays areas with the highest ratio of females to males. Dark red colors indicate a higher proportion of females than males and are usually distributed along the eastern coastal areas of the district, such as Repalle, Bhattiprolu, Nagaram, and Chirala. It might suggest that these areas are more vulnerable to disasters because of the high number of females, depending on the socio-economic characteristics of these populations.

4.1.8 Socio-Economic Vulnerability Index: Finally, the "Socio-economic vulnerability" map displays a special type of social vulnerability that considers different aspects, such as population groups (younger and older), sex ratio, building density, and water index. It can be seen that a considerable part of the district is represented by "High" and "Very High" socio-economic vulnerability (SEVI).

However, the central and western inland areas, such as Addanki, Parchur, and Martur, are characterized by "High" SEVI. On the contrary, the easternmost areas, such as Repalle, Nizampatnam, and Pittalavanipalem, are ranked as "Low" and "Very Low" in SEVI. It might suggest that these eastern coastal areas (Repalle, Nizampatnam, and Pittalavanipalem), with a high number of younger and older people, as well as a high number of females, have better access to resources, opportunities, and especially to building structures that resist disasters, such as buildings made of concrete and improved drainage systems.

Table 2: Area-wise Socio-Economic Vulnerability Index

Sl. No.	SEVI - Level	Area (sq. km.)	Area (%)
1	Very Low Vulnerability	771.146	19.598
2	Low Vulnerability	762.787	19.386
3	Moderate Vulnerability	1113.375	28.296
4	High Vulnerability	720.202	18.303
5	Very High Vulnerability	567.296	14.417
Total		**3934.805**	**100**

The Socio-Economic Vulnerability Index (SEVI) was grouped into five classes based on kernel density estimation. According to Figure 10, the moderate class had the largest share of the district (1113.375 sq. km.), covering 28.3%. The very low and low classes covered 771.146 sq. km. (19.6%) and 762.787 sq. km. (19.4%) of the district, respectively. This suggests that most of the district has a relatively better socio-economic status. The high and very high classes covered 720.202 sq. km. (18.3%) and 567.296 sq. km. (14.4%), respectively. Overall, the high and very high classes covered 1287.498 sq. km. (32.7%) of the entire study area (3934.805 sq. km.). This suggests that almost a third of the entire district has a high SEVI and requires special attention for disaster response and management to minimise the adverse impact on the local community.

4.2 Inputs for Physical Vulnerability Index

Coastal hazard indices are significant in identifying the vulnerability of coastal areas to different climate change impacts such as an increase in sea level, coastal erosion, storm surges, and flooding. This study analyzed the Coastal Vulnerability Index (CVI) of Bapatla district based on the Exposure component of the Index, comprising distance to coast, elevation, Land Use Land Cover (LULC), and slope. Using the exposure component and its implications for the study area, a Physical Vulnerability Index (PVI) was developed by considering the sensitivity of each of the geographical parameters of the CVI. This will help in prioritising vulnerable coastal zones for coastal zone management and disaster response.

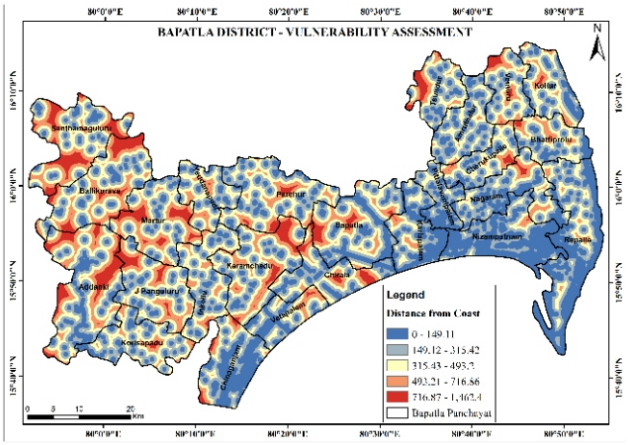


Figure 11: Distance from Coast

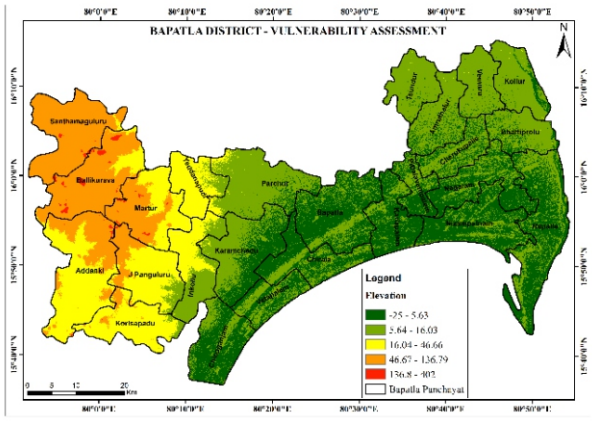


Figure 12: Elevation

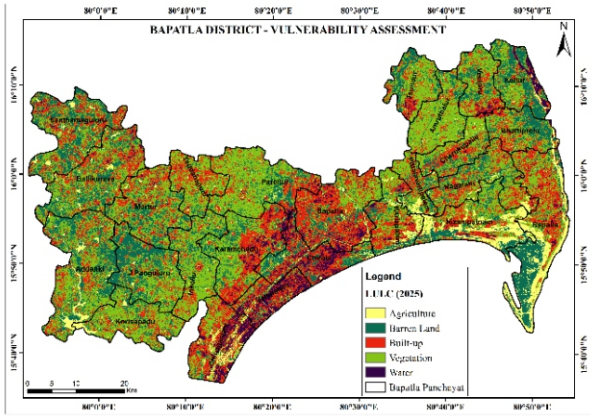


Figure 13: Land use/land cover

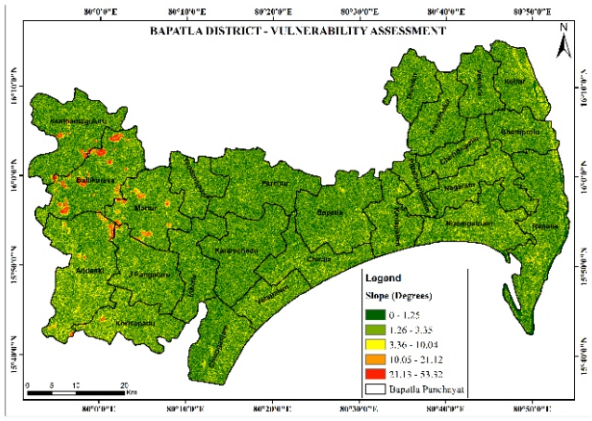


Figure 14: Slope

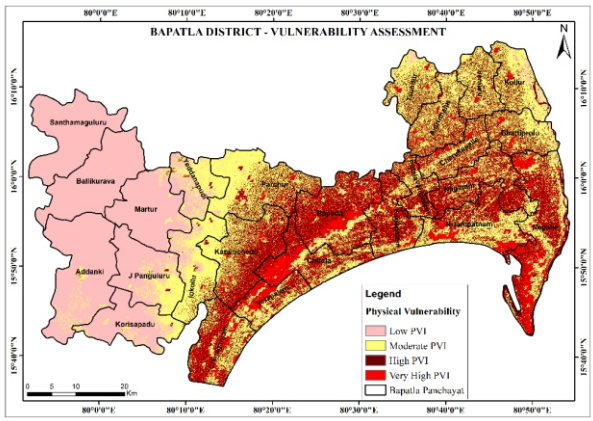


Figure 15: Physical Vulnerability

4.2.1 Distance from Coast: The Distance from Coast map shows the pattern of distance from the coast, and accordingly, the study area has been categorized into 0 – 1,462.4 m. It was observed that the coastal mandals, specifically Repalle, Nizampatnam, Chirala, and Chinaganjam, are highly exposed to coastal flooding, surge, and shoreline erosion because their distance from the coast ranges between 0 – 149.11 m. On the contrary, the western inland mandals, Santhamaguluru and Addanki, are less exposed to marine hazards because their distance from the coast is far (> 820.17 m). Overall, it can be concluded that the distance from the coast influences the physical vulnerability of the study area.

4.2.2 Elevation: The Elevation map shows the variation in relief in Bapatla District. The eastern coastal plain is characterized by having very low elevations ranging from −25 to 5.63 m, whereas the western inland areas have high elevations ranging from 136.8 – 402 m above sea level. Accordingly, the low-lying eastern coastal areas are highly vulnerable to coastal flooding, and their vulnerability is moderate to high in the Physical Vulnerability Index (PVI). Moreover, the high-elevation western inland areas are less likely to be affected by coastal hazards and therefore have low vulnerability in PVI.

4.2.3 Land Use and Land Cover (LULC): Generally, the LULC map shows that most parts of the district are used for agricultural purposes, whereas some parts are covered by vegetation, barren land, water bodies, and built-up structures. The pattern of LULC shows that a significant percentage of the coastal belt is utilised as farmland and settlement, while a few water bodies are found distributed along the eastern coastal areas. Since water bodies can act as conduits for inland floodwater, the eastern coastal areas can experience extensive inland flooding during surge or coastal flooding. Notably, the high percentage of farmland along the coastal belt is at high risk of being damaged during flooding events. Therefore, the LULC pattern indicates high physical vulnerability for the coastal belt.

4.2.4 Slope: The Slope map shows the distribution pattern of gentle and steep slopes in Bapatla District. The majority of the district has a gentle slope of 0 – 1.25°, while only a few western parts have a slope ranging from 1.25 – 53.32°. The eastern coastal plain, having flat slopes, is highly exposed to extensive flood inundation during storm surges. On the other hand, the western inland areas that have moderate to steep slopes are resistant to flood surges and therefore have less physical vulnerability. Overall, the western inland areas are less exposed to coastal hazards than the eastern coastal areas.

4.2.5 Physical Vulnerability Index (PVI): The PVI map shows that the vulnerability of Bapatla District is mainly high and very high, except for some parts of the western inland mandals. It was observed that the eastern coastal mandals, including Chinaganjam, Vetapalem, Chirala, Nizampatnam, and Repalle, were highly exposed to marine hazards such as surge and coastal flooding, as shown by the PVI analysis. On the contrary, the western inland mandals such as Addanki, Ballikurava, and Santhamaguluru were less exposed to flooding and had the lowest vulnerability in PVI. Overall, the PVI indicated that the eastern coastal belt is the most physically vulnerable region to future coastal hazards. Hence, it is critical to implement coastal zone management policies and ensure sustainable development practices to minimise potential damage in the future.

Table 3: Area-wise Physical Vulnerability Index

Sl. No.	PVI - Level	Area (sq. km.)	Area (%)
1	Low Vulnerability	1271.2365	32.307
2	Moderate Vulnerability	1291.9707	32.834
3	High Vulnerability	884.5308	22.480
4	Very High Vulnerability	487.0674	12.378
Total		**3934.8054**	**100**

The distribution pattern of the PVI indicates that moderate vulnerability was the majority class, covering 1,291.97 sq. km (32.83%) of the 3,934.81 sq. km. study area. Low vulnerability ranked second, covering 1,271.24 sq. km (32.31%). This suggests that most of the inland and moderately elevated part of the western side of the district have low PVI values. High vulnerability covers 884.53 sq. km (22.48%), whereas very high vulnerability covers 487.07 sq. km (12.38%) of the district. Very high and high vulnerability classes were found to be dominant along the eastern coastal and low-lying belt of the district. Taken together, high and very high vulnerability classes cover 1,371.60 sq. km (34.86%) of the study area. This implies that more than one-third of the district is highly vulnerable to coastal hazards. Hence, there is a need to give special attention to coastal zone management and develop strategies to minimize physical vulnerability and climate risk in the study area.

4.3 Inputs for Climate Hazard Index

Climate hazard vulnerability plays a significant role in the Coastal Vulnerability Index (CVI) as it determines the level of exposure of the coastal region to various climatic events. The factor can be identified using several geographical features that include extreme temperatures both on land and sea, high precipitation rates, and high-energy waves, among others. In this regard, evaluating the climate hazard vulnerability of the selected coastal region contributes immensely towards understanding the relationship between coastal processes and climate change. This is because the area under review is characterized by low-lying coastal areas that are vulnerable to a wide range of climate change and human impacts, which threaten the stability of the adjacent groundwater and the coastal system itself. Therefore, identifying and mapping climate hazard vulnerability is critical in the establishment of the appropriate countermeasures that can be adopted to address the threat. Ultimately, it provides a baseline against which other factors affecting coastal vulnerability can be compared.

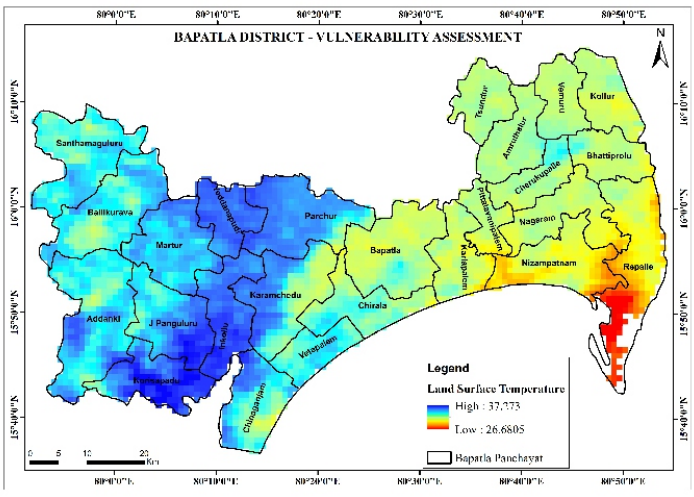


Figure 16: Land Surface Temperature

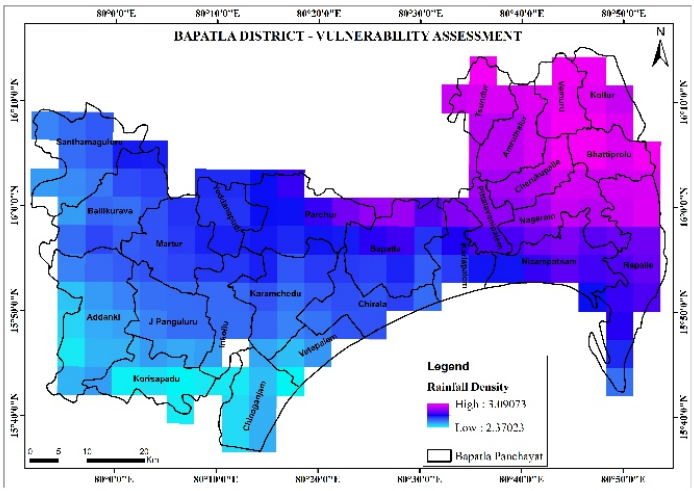


Figure 17: Rainfall Density

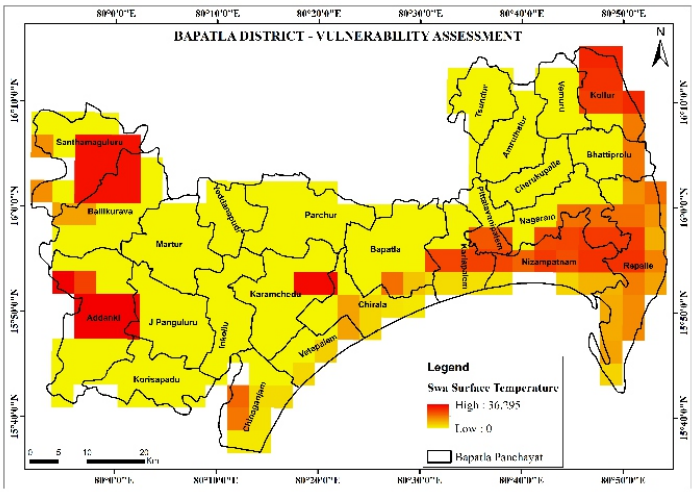


Figure 18: Sea Surface Temperature

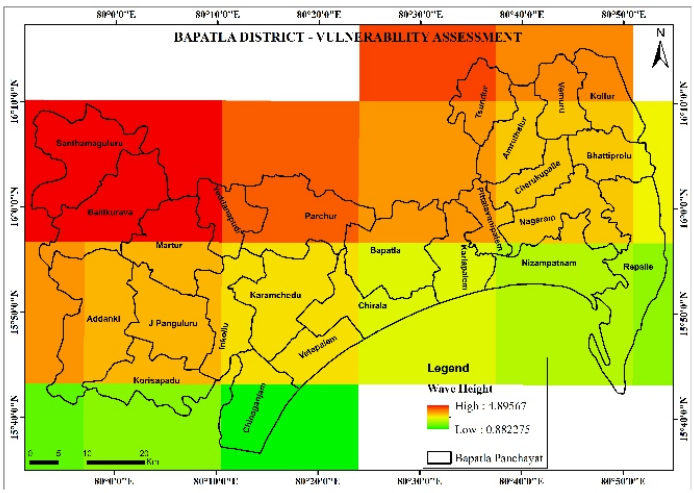


Figure 19: Wave Height

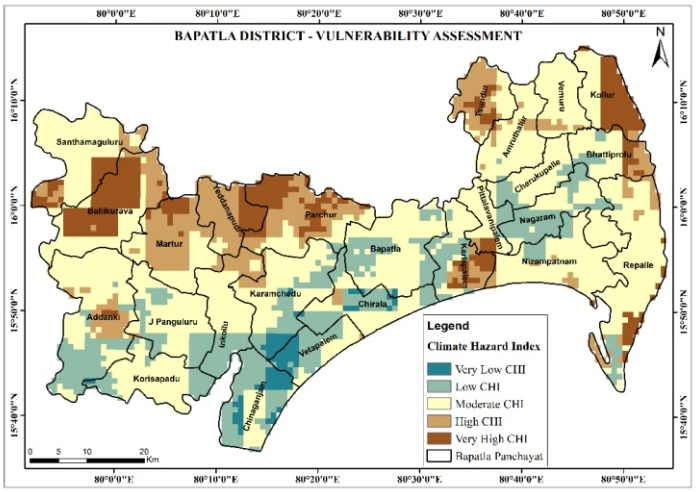


Figure 20: Climate Hazard Index

4.3.1 Land Surface Temperature (LST): The Land Surface Temperature (LST) map below indicates the extensive variation in temperature in degrees Celsius over the Bapatla district, with a maximum of 37.27 °C found in the eastern coastal region. The surface temperature threatens the coastal region as the extreme heat adversely affects the coastal vegetation and inland mangroves vital in stabilising the region against erosion and flooding. Additionally, the surface temperature affects other coastal processes such as surface evapotranspiration and circulation, resulting in increased vulnerability levels. Consequently, the eastern coastal region of Bapatla is the most vulnerable to climate change impacts, with high temperatures being the main cause.

4.3.2 Rainfall Density: The rainfall density map shown below indicates the variation in the amount of rainfall received by the coastal district. The study area receives highly intense rainfall, which is hazardous to the local vegetation and threatens the ecological security of the coastal region. Generally, rainfall is a significant factor that affects most of the coastal processes. For instance, extremely heavy rainfall causes waterlogging in coastal communities, especially during high tides, as water from the floodplains becomes trapped in the coastal lowlands, causing prolonged inundation. Further, heavy rainfall accelerates erosion and increases the amount of sediments transported to the coastal region, which are detrimental to the neighboring communities.

4.3.3 Sea Surface Temperature (SST): The Sea Surface Temperature (SST) map below indicates the variations in temperature in the coastal region with respect to the deep sea. As observed in the map, the eastern coastal region experiences relatively higher temperatures compared to the rest of the area.

The coastal temperature is a vital factor in determining the vulnerability levels of coastal areas as it facilitates the development of tropical cyclones that threaten coastal communities. Moreover, hot surface temperatures increase erosion rates, destroying coastal structures and flooding nearby inland communities. Therefore, the eastern coastal region is the most vulnerable as it experiences high surface temperatures that promote cyclones and floods.

4.3.4 Wave Height: The wave height map indicates the variation in the wave heights along the coastal region, with the eastern coastal area experiencing the highest wave energy. In general, wave height is the most critical process in determining the vulnerability of the coastal area as it influences most of the other coastal processes. For instance, it can be observed that the wave height promotes erosion along the coastal region, removing vital structures such as sandbanks, spits, and bars that protect the inland communities from flooding caused by high waves. Additionally, high wave heights increase the transportation of sediments along the coastline, affecting the delicate coastal ecosystem. Therefore, wave height is considered the primary factor in coastal vulnerability assessment as it often determines the extent to which other coastal processes will affect the nearby coastlines and communities.

4.3.5 Climate Hazard Index: The climate hazard index (CHI) shows the distribution pattern of various climate hazards in the Bapatla district, including land surface temperature, rainfall, sea surface temperature, and wave height. There are five categories of climate hazard in the Bapatla district, ranging from Very Low to Very High. According to the climate hazard map, the eastern coastal belt of the district, especially around Repalle and the neighboring coastal mandals, is exposed to High and Very High hazard levels. The coastal areas are severely affected by high temperature, heavy rainfall, rising sea levels, and high wave energy, leading to coastal flooding, erosion, and storm surges. On the other hand, the interior western region has lower and moderate levels of climate hazard than the coastal areas. This is because the interior parts of the district are relatively less exposed and vulnerable to climate change effects.

Table 4: Area-wise Climate Hazard Index

Sl. No.	CHI - Level	Area (sq. km.)	Area (%)
1	Very Low Vulnerability	813.685	20.679
2	Low Vulnerability	1288.787	32.753
3	Moderate Vulnerability	840.651	21.364
4	High Vulnerability	800.587	20.346
5	Very High Vulnerability	191.136	4.858
Total		**3934.845**	**100**

The area statistics help to assess the extent of climate hazard in the district. Thus, out of 3934.85 sq. km. of the study area, 25% (991 sq. km.) falls in the High and Very High CHI classes. These 991 sq. km. are exposed to climate-related risks that are severe and can aggravate the overall impacts of coastal hazards. It is vital to note that almost a quarter of the study area has high CHI, which threatens its climate condition and adds to the impacts of coastal vulnerability. By combining the data on the Climate Hazard Index and Coastal Vulnerability Index, it will be possible to prioritize the areas that need attention. Therefore, the regions with a high CHI need to prioritize climate adaptation, disaster prevention, infrastructure improvement, preservation of coastal ecosystems, and sustainable development of areas exposed to climate change.

4.4 Coastal Vulnerability Index (CVI)

The CVI map of the Bapatla district shows the spatial distribution pattern of coastal vulnerability, determined by using the Physical Vulnerability Index (PVI), Socio-Economic Vulnerability Index (SEVI) and Climate Hazard Index (CHI). It could be observed that the vulnerability pattern is far from being homogeneous, as it is determined by several factors, which do not necessarily correspond to the distance from the coast. It could be seen that the vulnerability levels in Bapatla district varied from very low to very high. The study area was classified into five categories based on the calculated vulnerability index.

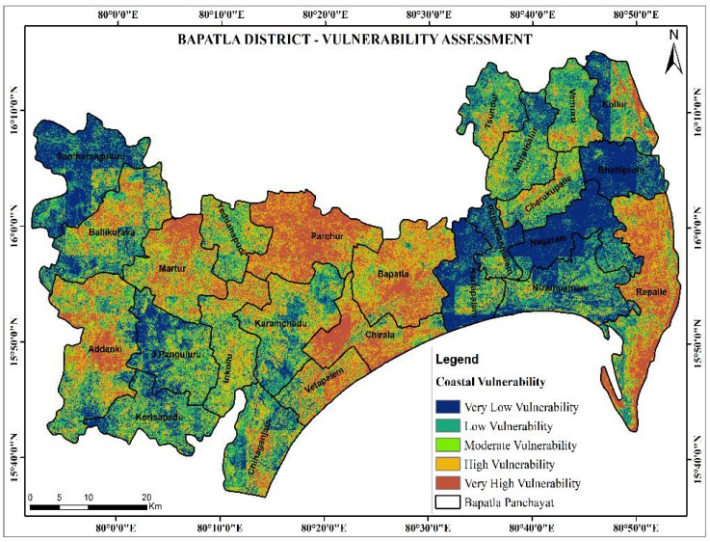


Figure 21: Coastal Vulnerability Index

It was revealed that coastal areas such as Repalle, Nizampatnam, Chirala, Vetapalem, and Chinaganjam, located mainly in the eastern part of the district, had high and very high vulnerability levels. This fact could be explained by the fact that those areas were directly exposed to several coastal hazards. The presence of multiple coastal hazards, especially high climate hazard and high physical vulnerability, accounts for the high vulnerability levels. They are associated with low relief, low slope, coastal location, climate hazards, and high population and economic density. On the other hand, the CVI map also indicates several areas with high vulnerability scores located in the interior parts of the district, such as Parchur, Martur, and Yeddanapudi. Thus, it could be concluded that vulnerability was not determined solely by the distance from the coast, as one might expect.

The general pattern of vulnerability could be explained by the combination of different factors, including the coastal hazard index, low-lying terrain with low slope, inland water bodies, hydrology, and social and economic factors. In contrast, the western part of the district was characterized by very low and low vulnerability scores due to higher elevation, a considerable distance from the coast, and lower social and economic importance. Generally, the eastern part of the district was more vulnerable to climate change and other natural hazards than the western part.

Table 5: Area-wise Coastal Vulnerability Index

Sl. No.	CVI - Level	Area (sq. km.)	Area (%)
1	Very Low Vulnerability	754.772	19.182
2	Low Vulnerability	1027.185	26.105
3	Moderate Vulnerability	354.317	9.005
4	High Vulnerability	1031.357	26.211
5	Very High Vulnerability	767.174	19.497
Total		**3934.805**	**100**

The statistics of area distribution also confirm this pattern, as low and very low vulnerability scores were found to occupy 45.3% of the whole study area (3934.805 sq. km). At the same time, the high and very high vulnerability levels account for approximately 45.7% of the district. It was found that only 354.317 sq. km. (9.005%) was associated with the moderate level of coastal vulnerability, which makes up only 9% of the total study area. Thus, it could be concluded that approximately 45.7% of the Bapatla district has a high or very high level of coastal vulnerability. Consequently, it requires urgent measures, such as coastal conservation, climate change adaptation measures, disaster management planning, and ecological security conservation.

5. Conclusion

The coastal vulnerability assessment performed for the Bapatla district shows that multiple factors determine the extent of hazard. According to the study, the most vulnerable areas to coastal hazards are not always those located near large bodies of water but rather depend on a combination of socioeconomic, physical, and climate factors. Altogether, the analysis revealed that almost half of the Bapatla district is highly vulnerable to climate change impacts requiring immediate measures. When considering the influence of socioeconomic parameters on coastal vulnerability in the Bapatla district, this study identified critical points with high concentrations of children below six years of age and people above 59 years of age.

Overall, the analysis revealed that 32.7% (1,287.498 sq. km) of the area has high and very high socio-economic vulnerability. While coastal mandals of Repalle and Chirala have a considerable proportion of the population belonging to vulnerable groups, other inland mandals such as Addanki, Parchur, and Martur score high on the overall SEVI due to a combination of several factors. On the other hand, some of the easternmost mandals have low vulnerability due to the presence of resilient buildings. The analysis of the physical vulnerability in the Bapatla district showed contrasting results for coastal and inland areas. The results indicate that 34.86% of the district is highly physically vulnerable. These regions were found to be concentrated in the eastern coastal mandals of Chinaganjam, Vetapalem, Chirala, Nizampatnam, and Repalle, which are characterized by low-lying features with dip slope coastal landforms facing the ocean. On the other hand, the western inland mandal of Santhamaguluru is highly elevated and have steep slopes, making them physically less vulnerable. Overall, the eastern coastal areas are the most physically vulnerable in the Bapatla district.

Climate hazard factors influencing coastal vulnerability in the Bapatla district are severe, particularly in the eastern part of the district, where the high and very high hazard classes are concentrated. The analysis revealed that 25% (991 sq. km) of the Bapatla district is exposed to high and very high climate hazards. The eastern coastal areas once again emerge as the most affected region due to high surface temperatures (37.27°C) contributing to increased incidents of cyclones and storm surges. The northeastern part of the district is at risk of pluvial flooding due to exceptionally high rainfall, while the eastern coastal areas experience high wave heights impacting coastal ecosystems and structures. Meanwhile, the interior western part of the district is largely unaffected by any climate hazards. The final Coastal Vulnerability Index, revealing the extent of coastal vulnerability in the Bapatla district, is a combination of all three analyses conducted for the study.

The research findings revealed that 45.7% (1,798.53 sq. km) of the district has a high or very high vulnerability to coastal hazards. The study's results exhibited that most of the vulnerable areas were not necessarily located in the closest vicinity to the coast but were rather controlled by several local factors. For instance, even though the coastal mandals like Nizampatnam and Repalle were found to be highly vulnerable to coastal hazards due to their exposure to coastal, climatic, and physical factors, the interior drylands of Parchur and Yeddanapudi also reported very high vulnerability due to the prevalence of multiple adversities.

Conclusively, the study revealed that coastal vulnerability in the Bapatla district was a multifaceted process determined by various factors, thus necessitating multidisciplinary assessments for effective coastal hazard management. It was found that only 9% of the study area has moderate vulnerability and 45.3% has low or very low vulnerability, whereas 45.7% has high or very high vulnerability and therefore needs urgent management attention. Therefore, it can be opined that management practices that are site-specific are more efficient than generalized approaches in managing coastal hazards in the Bapatla district.

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