Coastal Social Vulnerability and Risk Analysis for Cyclone Hazard Along the Andhra Pradesh, East Coast of India

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Abstract
People around the world are prone to frequent and intensive hazards due to the global climate change scenario and human interventions. Particularly, the coastal communities are always prone to various long-term coastal hazards like sea-level rise, shoreline changes, and short-term hazards like tsunami cyclone and storm surge. Coastal Andhra Pradesh state is consisting of 9 district and 670 villages and also having 3.43 Million Population (69.3%). Andhra Pradesh has a vast 972 km long coastline and total coastal area spread over 92,906 km² comprising the nine coastal districts. Andhra Pradesh state is prone to various natural hazards, especially cyclone and associated storm surges. There is an extreme loss of life and damage to properties caused by these cyclones. During the past 40 years Andhra Pradesh coast experienced more than 62 cyclones including depression, cyclone surge, and severe cyclone surges. Among these cyclones, there were 32 cyclones which affected the Krishna–Godavari region, comprising four districts, namely East Godavari, West Godavari, Krishna, and Guntur. Therefore, these four districts have been considered for this social vulnerability study to identify the cyclone vulnerable villages. Geospatial applications are used in this study for spatial and non-spatial data processing and spatial analysis. The study indicated that half of the study area (3121.07 km²) lying moderately risk zone and around 7% of the study area observed high vulnerability. This study revealed that the use of geospatial application is most reliable and cost-effective approach for vulnerability and risk mapping and analysis. The result obtained from the present study may serve the baseline information for disaster management planning in the area.

Keywords Climate change · Natural hazard · Tropical cyclone · Vulnerability · Risk · GIS

Küsten Soziale Anfälligkeit und Risikoanalyse für Zyklon Gefahr entlang der Andhra Pradesh, Ostküste von India

Zusammenfassung
Menschen auf der ganzen Welt anfällig aufgrund des globalen Klimawandels und menschlicher Eingriffe häufigen und intensiven Gefahren ausgesetzt. Insbesondere die Küstengemeinden sind immer verschiedenen langfristigen Küstengefahren ausgesetzt, z. B. dem Anstieg des Meeresspiegels, Änderungen der Küstenlinie und kurzfristigen Gefahren wie Tsunami-Wirbelstürmen und Sturmfluten. Der Küstenstaat Andhra Pradesh besteht aus 9 Distrikten und 670 Dörfern und hat 3.43 Millionen Einwohner (69.3%). Andhra Pradesh hat eine 972 km lange Küste und eine GesamtküsteKüstengebietfläche von 92,906 km², die die neun Küstenbezirke umfasst. Der Bundesstaat Andhra Pradesh ist verschiedenen Naturgefahren ausgesetzt, insbesondere dem Wirbelsturm und den damit verbundenen Sturmfluten. Durch diese Zyklone kommt es zu extremen Lebens- und Sachschäden. In den letzten 40 Jahren erlebte die Küste von Andhra Pradesh mehr als 62 Wirbelstürme, darunter...
Depressionen, Wirbelstürme und schwere Wirbelstürme. Unter diesen Wirbelstürmen befanden sich 32 Wirbelstürme, die die Region Krishna-Godavari betrafen und vier Distrikte umfassten, nämlich East Godavari, West Godavari, Krishna und Guntur. Daher wurden diese vier Bezirke für diese Studie zur soziale Verwundbarkeit in Betracht gezogen, um die Wirbelsturm gefährdeten Dörfer zu identifizieren. In dieser Studie werden georäumliche Anwendungen für die räumliche und nicht räumliche Datenverarbeitung und räumliche Analyse verwendet. Die Studie ergab, dass die Hälfte des Untersuchungsgebiets (3121.07 km²) in einer mäßigen Risikozone liegt und rund 7% des Untersuchungsgebiets eine hohe Verletzlichkeit. Diese Studie ergab, dass die Verwendung von georäumliche ist der zuverlässigste und kostengünstigste Ansatz für die Kartierung und Analyse von Schwachstellen und Risiken. Das Ergebnis dieser Studie kann Grundlinie für die Planung des Katastrophenmanagements in der Region dienen. Das Ergebnis dieser Studie kann Dienen als Grundlinie für die Planung des Katastrophenmanagements in der Region dienen.

1 Introduction

Majority of the coastlines in the world are at threat from various cyclone and storm surges. The term ‘Cyclone’ is used globally to cover tropical weather systems, in which winds equal or exceed the minimum of 34 knot (62 km/h) (Mohapatra 2015). These are intense low-pressure systems of the earth atmosphere coupled system and are extreme weather events of the tropics. Tropical cyclones are known by many names the world over like cyclones, typhoons, hurricanes, etc. Indian subcontinent is one of the most cyclone-affected regions in the globe. Although, 80% of the cyclones affected in India made its history in the eastern coast alone (Fitchett and Grab 2014). These coastal regions are already stressed with extreme habitants, who are responding in various ways to extreme weather events. Its need to study about frequent but intensive cyclones and its impact on socioeconomic condition of the living population, for that better research has to rise up with development of the concept of vulnerability and involve varying magnitudes depending upon the coping capacity of people (Cutter et al. 2000). East coast of India is experienced nearly 308 cyclones affected in the east coast between 1891 and 2000; among them, 103 cyclones were severe (Rao et al. 2007; Mohapatra 2015; Suchitra 2015). Recurring cyclones account for large number of deaths, loss of

Fig. 1 The location map. a East Godavari, b West Godavari, c Krishna, and d Guntur
livelihood opportunities, loss of public and private property, and severe damage to infrastructure, thus seriously reversing the developmental gains at regular intervals. Broad scale assessment of population at risk suggests that an estimated 32 Cr people, who accounts for almost third of the country’s total population, are vulnerable to cyclone related hazards. Climate change and its resultant sea-level rises can significantly increase the vulnerability of coastal population (Ravishankar et al. 2004; Mukhopadhyay et al. 2011; Kumar and Kunte 2012).

Geospatial applications have functions and tools required to efficiently capture, store, analyze, and display the information about places and features (Basheer Ahammed et al. 2016). Its helps to prepare multi-layer information and spatial relationships between natural hazards and exposure. The techniques of remote sensing, GIS, and GPS have been proven to provide extremely valuable data for analysis of the scenario and develop management action plans (Basheer Ahammed and Pandey 2019a). Studies showed that satellite remote sensing offered high temporal resolution for monitoring of land-use change at lower costs than those associated with the use of traditional methods (Mahendra et al. 2011; Fang et al. 2014; Basheer Ahammed and Pandey 2019b). However, geospatial applications handle spatial information by linking location with its attribute information. Therefore, GIS-based decision support system will work effectively even in the worst situations. The present study was focused on social vulnerability analysis for cyclone along the coastal Andhra Pradesh. There are five major parameters which are used to assess the vulnerability including historical cyclone tracks, population density, population growth, settlement density, and transportation network.

Table 1 Vulnerability and risk classes for hazard, social vulnerability, and infrastructure vulnerability

|                                | Very high | High  | Moderate | Low   | Very low |
|--------------------------------|-----------|-------|----------|-------|----------|
| Cyclonic storm surge (km/h)    | > 90      | 60–90 | 50–60    | 30–50 | < 30     |
| Population growth (%)          | > 24      | 16.1–24 | 8.1–16 | 0.1–8 | < 0      |
| Population density (p/km²)     | > 1000    | 500–1000 | 250–500 | 100–250 | < 100   |
| Household density (hh/km²)     | > 400     | 200–400 | 100–200 | 50–100 | < 50     |
| Cyclone shelter (km)           | > 20      | 20-Oct | 10-May  | 2.5–5 | < 2.5    |
| Transportation (km)            | > 5       | 5-Jan | 0.5–1   | 0.25–0.5 | < 0.25 |

Fig. 2 Schematic diagram of the methodology formulation
2 Study Area

In India, eastern coastal region between West Bengal and Tamil Nadu has been affected tremendous coastal hazards, such as storm surge, cyclone, tsunami, etc. (Mukhopadhyay et al. 2011; Kumar and Kunte 2012; Basheer Ahmed et al. 2016). In the state of Andhra Pradesh, tremendous population living in the coastal region, especially Krishna Godavari deltaic Plain, and also the region are prone to various hazards. In the last decades, there are number of hazards which are affected this region. The present study is conducted along the Andhra Pradesh coast, east coast of India, and consists of four districts, viz., East Godavari, West Godavari, Krishna, and Gundur (Fig. 1). The area lays between 15°46'53" to 17°16'10" North Latitude and 80°23'30" to 82°34'40" East Longitude. The most part of study area exhibits low elevated topography within relief of 0–10 m, rendering it highly sensitive to coastal floods and sea water intrusion. The present study carried out in the 4838.47 km² area consisting 369 coastal villages laying within 10 km buffer zone along the coastline between East Godavari and Gundur.

3 Data and Methodology

3.1 Parameters for Vulnerability and Risk Analysis

In this section, discussing about data and methods adopted for the social vulnerability studies. There are varieties of tools and techniques which are used to analyze social vulnerability in all over the globe (Cutter et al. 2000; Cutter and Emrich 2006; Basheer Ahmed and Pandey 2019a).

Tropical cyclone and associated flood are major concern to the global population and environment. Temperature, atmospheric pressure, cyclonic cycles, and ocean circulation are the major contributor leading towards accelerating vulnerability in the coastal region (Kumar et al. 2010; Ali and Narayana 2015; Rani et al. 2015). Besides, the intensity of the cyclone in the east coast is increased in the recent decades. In this crucial situation, it is need to be studied on social vulnerability to cyclones. The present study carried out with five major parameters, viz., cyclone intensity, population density, population growth, household density, transportation accessibility, and accessibility to cyclone shelter to estimate the vulnerability and risk to cyclone.

![Cyclone Track Map](image)

**Fig. 3** Historical cyclone track map; tracks show between 1970 and 2014 along the Andhra Pradesh coast. a Severe cyclonic storm. b Cyclonic storm. c Deep depression

| District          | No. of cyclones |
|-------------------|-----------------|
| Nellore           | 16              |
| Krishna           | 15              |
| West Godavari     | 5               |
| East Godavari     | 8               |
| Srikakulam        | 14              |
| Visakhapatnam     | 9               |
| Prakasam          | 7               |
| Guntur            | 5               |
| Total             | 79              |

**Table 2** District-wise historical cyclone events in the Andhra Pradesh State
Fig. 4 Variable for social vulnerability. a Village-wise spatial distribution of the population density under different vulnerability classes. b District-wise distribution of the vulnerability classes for population density
Table 3  District-wise distribution of the population density under different vulnerability classes

|                  | East Godavari | West Godavari | Krishna | Guntur | Total | Percentage |
|------------------|---------------|---------------|---------|--------|-------|------------|
| Very low         | 12            | 5             | 12      | 8      | 37    | 10.03      |
| Low              | 10            | 30            | 11      | 51     |       | 13.82      |
| Moderate         | 40            | 6             | 35      | 7      | 88    | 23.85      |
| High             | 101           | 8             | 7       | 7      | 123   | 33.33      |
| Very high        | 59            | 1             | 5       | 5      | 70    | 18.97      |
| Total            | 222           | 20            | 89      | 38     | 369   | 100        |

Fig. 5  Variable for social vulnerability. a Village-wise spatial distribution of the population growth under different vulnerability classes. b District-wise distribution of the vulnerability classes for population growth
Table 4 District-wise distribution of the population growth under different vulnerability classes

| Vulnerability  | East Godavari | West Godavari | Krishna | Guntur | Total | Percentage |
|----------------|---------------|---------------|---------|--------|-------|------------|
| Very low       | 87            | 15            | 73      | 22     | 197   | 53.39      |
| Low            | 77            | 3             | 11      | 11     | 102   | 27.64      |
| Moderate       | 38            | 1             | 3       | 3      | 45    | 12.2       |
| High           | 9             |               | 1       | 1      | 10    | 2.71       |
| Very high      | 11            | 1             | 2       | 1      | 15    | 4.07       |
| Total          | 222           | 20            | 89      | 38     | 369   | 100        |

Fig. 6 Variable for social vulnerability. a Village-wise spatial distribution of the household density under different vulnerability classes. b District-wise distribution of the vulnerability classes for household density
Table 5  District-wise distribution of the household density under different vulnerability classes

| District          | Very low | Low | Moderate | High | Very high | Total | Percentage |
|-------------------|----------|-----|----------|------|-----------|-------|------------|
| East Godavari     | 16       | 23  | 81       | 66   | 36        | 222   | 15.99      |
| West Godavari     | 5        | 0   | 8        | 6    | 1         | 20    | 17.08      |
| Krishna           | 25       | 32  | 24       | 3    | 5         | 89    | 32.53      |
| Guntur            | 13       | 8   | 7        | 7    | 3         | 38    | 22.22      |
| Total             | 59       | 63  | 120      | 82   | 45        | 369   | 100        |

Fig. 7  Social vulnerability of the study area. a Village-wise spatial distribution of the social vulnerability under different vulnerability classes. b District-wise distribution of the vulnerability classes for social vulnerability
3.1.1 Cyclone Intensity

Cyclone and storm surges are not common process to coastal degradation; however, it can be damage entire coastal region within shot span. Cyclone and storm surge cause to coastal flood, sea-level rise, and coastal inundation into the low laying areas and loss of life and wealth. In Indian scenario, cyclone and storm surge are mostly get affected in the eastern coast than the west. Vulnerability and impact depend upon the intensity of the cyclone which is experienced in the coastline. To analyze the cyclone track and its intensity, Historical cyclone data were collected from Global Risk Data Platform (GRDP) and IMD Cyclone atlas for the period 1975–2014. Further study area is categorized into five different risk classes based on the value assigned. Speed of the cyclones comes below 30 km/h is considered as very low risk, 30–50 km/h is considered low, and flowingly 50–60 km/h moderate, 60–90 km/h high, and above 60 km/h are considered as very high risk. Furthermore, these data processed and analyzed using geospatial tools in Arc GIS environment and generated final outputs (Table 1).

3.1.2 Population Growth

The rate of population growth is higher in the coastal zone than the inland region. Availability of the resource and rapid developmental activities are the major drivers for population growth in the coastal zone. Population growth was calculated using the Census of India population database. Data were collected for the year 2001 and 2011 and the data further classified into five different risk classes between very high and very low. Below 0% population growth falls in very low population growth, flowingly 0.1–4% falls in low, 4.1–8% as moderate 8.1–16% in high, and above 16.1% of the population growth falls in very high sensitivity class (Table 1). Furthermore, these results of the study processed and analyzed using geospatial tools in Arc GIS environment and generated final outputs.

3.1.3 Population Density

Population density is directly related with the disaster impact. The impact of the coastal hazard will be much higher in densely populated regions. Vulnerability of those people will be in higher. Population density is calculated using census of India population database for the year 2011. Based on the vulnerability, population density classified into five classes varying from 0 to 100 person/km² as very low vulnerability, 100–250 p/km² as low vulnerability, 250–500 p/km² as moderate vulnerability, 500–1000 p/km² as high vulnerability, and above 1000 p/km² as very high vulnerability (Table 1).

3.1.4 Household Density

Household density is the one of the major parameters for the social vulnerability studies. Household density refers to the number of the houses within the km². The damage and impact is directly related to the density of the household. The higher density of the households will get effected higher rate of damages, whereas low-density area will become low economic loss or property loss. The vulnerability to the household density divided into five categories based on the number of houses present in a km². Below 50 house/km² is considered as very low vulnerability, following that 50–100 h/km² falls in low vulnerability, 100–200 h/km² in moderate vulnerability, 200–400 h/km² falls in high, and above 400 h/km² falls in very high vulnerability (Table 1). Further villages categorized based on the vulnerability class for the calculation of the social vulnerability.

3.1.5 Cyclone Shelter House

Cyclone shelter plays an important role during the extreme events, and it gives shelter for thousands of people during and post-disaster. Cyclone shelter houses reduce the loss of life and prevent the impact of the disaster after effects such as epidemics, food shortage, homelessness, etc; however, the availability and accessibility of the cyclone shelter is major concern in the disaster prone areas. Spatial distribution of the cyclone shelter houses was collected from the AP space application. Vulnerability to cyclone shelter house has classified into five classes based on the accessibility to the cyclone shelter house, area nearest to the cyclone shelter house is very low vulnerability, i.e., within 2.5 km from the cyclone shelter house, following low vulnerability falls

| Table 6 District-wise distribution of the social vulnerability under different vulnerability classes |
|---------------------------------------------------------|---------------|-------------|--------------|--------------|----------|-------------|
| District       | East Godavari | West Godavari | Krishna     | Guntur       | Total     | Percentage |
|----------------|---------------|---------------|-------------|--------------|----------|-------------|
| Very low       | 10            | 3             | 7           | 7            | 27       | 7.31        |
| Low            | 15            | 0             | 43          | 13           | 71       | 19.24       |
| Moderate       | 98            | 11            | 30          | 9            | 148      | 40.11       |
| High           | 79            | 6             | 4           | 8            | 97       | 26.29       |
| Very high      | 20            | 0             | 5           | 1            | 26       | 7.05        |
| Total          | 222           | 20            | 89          | 38           | 369      | 100         |


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Fig. 8 Variable for infrastructure vulnerability. a Village-wise spatial distribution of transportation accessibility under different vulnerability classes. b District-wise distribution of the vulnerability classes for transportation accessibility.
between 2.5 and 5 km, moderate vulnerability falls between 5 and 10 km, and high vulnerability falls between 10 and 20 km; above 20 km area falls in very high vulnerability (Table 1). Long distance put to the habitant into the trouble during extreme events.

### 3.1.6 Transportation Accessibility

Road network is the most efficient and simplest economical asset that has a major role in disaster mitigation and management process (Holzmann and Jørgensen 2001; Van Wassenhove 2006). Locations with well-connected road networks are comparatively low vulnerable and the less road network area becomes high vulnerability. The road network data were collected from the SOI topographical sheet and Google earth and then vectorised using geospatial tool in Arc GIS. The classification of the road network has been done by the buffer distance from the road network. Area within the 250 m from the road network falls in very low vulnerability, following that, vulnerability class divided by 500 m, 1 km, and 5 km as low to high, and above 5 km as very high vulnerability (Table 1).

### 3.2 Coastal Social Vulnerability and Risk Assessment

Vulnerability is made of the characteristics of a person or group and their situation that influence their capacity to outlook, to cope with, resist and recover from the impact of a natural hazard (Cutter et al. 2009; Sahoo and Bhaskaran 2017). In past decades, there have been extensive studies carried on the potential and observed impacts of climate change on natural and social systems (McCarthy et al. 2001). The study focused on coastal zone management particularly impacts and adaptation of climate change and sea-level rise as well as the sustainable coastal management. In the present study, adopted Coastal Social Vulnerability Index (CoSVI) method is developed by Cutter et al. (2003) to experiment the spatial pattern of the social vulnerability to coastal multi-hazards at the village level in the Krishna Godavari deltaic plain with selected coastal villages, to describe and understand the physical and social burdens of risk. There are five consecutive steps are to be followed to reach the final result. They are: spatial data processing and future extraction, non-spatial data collection and geo spatial analysis, integration of spatial and non-spatial data, weighted indexing of the physical and social parameter, and coastal social vulnerability analysis. CoSVI calculated with combination of social vulnerability and infrastructure vulnerability and risk assessment for cyclone is analyzed using hazard and vulnerability, and the detailed structure of the methodology is described in the form of equations below (Eqs. 1–4). The comprehensive methodology of the present study is shown by the following (Fig. 2):

\[
\text{Risk} = \text{hazard} \times \text{vulnerability}.
\]  

The above equation can also written as follows:

\[
r = h \times v,
\]

where \( h \) indicates hazard intensity and \( v \) indicates coastal social vulnerability (CoSVI).

The intensity of the hazard, \( h \), can be calculated as follows:

\[
h = (c w_1 + c w_2 + c w_3 + c w_4 + c w_n),
\]

where \( c \) indicates the event and \( w_n \) indicates the weighted rank.

Vulnerability, \( v \), can be calculated as follows:

\[
v = \text{CoSVI} = (SV + IV)/2,
\]

where SV indicates social vulnerability and IV indicates infrastructure vulnerability.

Further various spatial analysis and geo-statistical tools are used for mapping and analyzing of the outputs. Then, the outputs are used to calculate vulnerability and risk of the coastal villages.

### Table 7: District-wise distribution of the transportation accessibility under different vulnerability classes

|          | East Godavari | West Godavari | Krishna | Guntur | Total | Percentage |
|----------|---------------|---------------|---------|--------|-------|------------|
| Very low | 441.08        | 88.72         | 255.10  | 148.12 | 933.00| 19.28      |
| Low      | 313.24        | 74.12         | 199.52  | 118.24 | 705.10| 14.57      |
| Moderate | 433.22        | 95.70         | 293.08  | 173.98 | 995.96| 20.58      |
| High     | 394.22        | 106.70        | 457.73  | 263.00 | 1221.63| 25.25      |
| Very high| 585.98        | 40.94         | 263.44  | 92.42  | 982.76| 20.31      |
| Total    | 2167.72       | 406.16        | 1468.94 | 795.81 | 4838.47| 100        |
4 Results and Discussion

Disaster risk is determined by the intensity and frequency of hazards, as well as its exposure and vulnerability to these hazards (Peduzzi et al. 2009; Sharma et al. 2009; Hoque et al. 2017). According to the IPCC report (2014), drivers of hazards, exposure, and vulnerability include many factors, like climatic and societal changes along with adaptation and mitigation measures that combine to form overall risk or potential impacts (Fang et al. 2014). In the present

![Image of a map showing Cyclone Shelter House, West Godavari, East Godavari, Krishna, and Guntur with a Bay of Bengal. The map includes a legend for vulnerability with classes: Very High, High, Medium, Low, and Very Low.](image)

**Fig. 9** Variable for infrastructure vulnerability. a Village-wise spatial distribution of the social vulnerability under different vulnerability classes. b District-wise distribution of the vulnerability classes for social vulnerability.
study, discuss cyclone intensity and frequency, exposure, and vulnerability.

### 4.1 Hazard

India is highly vulnerable to natural hazards, especially cyclones and storm surges; however, eastern coast of India is more vulnerable to cyclone disasters than the west (Basheer Ahammed and Pandey 2019a). Studies indicate that natural disaster losses equate to up to 2% of India’s Gross Domestic Product (GDP) and up to 12% of Central government revenue (Lester and Gurenko 2003). In India, around 40% of the total population lives within 100 km of coastline. In the present study, understanding cyclone intensity and frequency, around 44 year data for the period 1970–2014 were analyzed. Reports also indicated that on average, annually 370 million people are exposed to cyclones in India (Lester and Gurenko 2003). Cyclones generally affected in the month of May–June and October–November in the eastern coast. Nearly 300 cyclones were affected in the eastern coast during the 44 years. During the past 40 years, Andhra Pradesh coast experienced more than 62 cyclones including depression, cyclone surge, and severe cyclone surges. Among these cyclones, there were 32 cyclones which affected the Krishna–Godavari region (Fig. 3, Table 2), comprising four districts namely East Godavari, West Godavari, Krishna, and Guntur. During 1970–1989, frequency of the cyclone was 2/year, whereas during 1990–2010, it increased to 3/year. The present study also observed that the intensity of cyclone is very high in all over the study (Fig. 3). Based on the empirical cyclone track, it is observed that the entire 4838.4 km² of study area is under very high vulnerability (Fig. 3).

### 4.2 Vulnerability

Population density and population growth are higher in the coastal region than the inland, not only in India but over the globe (Kumar and Kunte 2012; Fang et al. 2014). Evidencing that vulnerability of assets and population in the eastern coastal regions is increasing rapidly. In the present study, investigate the vulnerability for cyclone in the east coast depict that the area highly vulnerable to cyclone. There are two vulnerability criteria used to identify the CoSVI, such as social vulnerability and infrastructure vulnerability.

#### 4.2.1 Social Vulnerability

Social vulnerability for the eastern coast is calculated using the three major parameters such as population density, population growth, and household density. Human deaths and injuries due to cyclones and associated storm surges are one of the major concerns in global level as well as India. The impact and damage of the cyclone will be very high where dense population lives. In this contest, it is need to analyze the population density along the cyclone potential zones.

Increasing population is one of major problems in the coastal region, availability of the resources and rapid industrial developments lead to migration from inlands, and it may trigger the growth of population. Therefore, population growth can be considered as major variable for assessing social vulnerability. Thus, the present study also considered population growth rate as a variable. The present study observed very low population growth rate in the study area. Higher rate (very high vulnerability) of population growth is observed in 15 villages (4%), whereas high vulnerability to population growth is observed only ten coastal villages.
Fig. 10  Infrastructure vulnerability of the study area. a Village-wise spatial distribution of the infrastructure vulnerability under different vulnerability classes. b District-wise distribution of the vulnerability classes for infrastructure vulnerability
(2.71%). Around 50% of the villages comes under very low vulnerable to population growth (197 villages), following that 102 villages come under low vulnerability, a significant amount of villages (45 villages) also observed in moderate vulnerability (Fig. 5, Table 4). The result of the study indicates that the Krishna–Godavari region is well maintained the population growth as compared to the global population growth.

Cyclones and associated coastal flooding are spreading a huge loss for property and livestock’s within a short span (Rao et al. 2009; Sharma et al. 2009). The impact and damage of the cyclone will be high in the high-density regions. Higher density of the households indicates the higher rate of population as well as the settlements. Thus, very high household density villages will be the higher rate of damage and loss of life.

The present study observed that 12.2% (45 villages) of the coastal villages have very high household density, and 22.22% (82 villages) of the village have high household density. However, 32.5% (120 villages) of the total villages observed moderate household density. Low and very low household density observed in 17% (63 villages) and 16% (59 villages), respectively (Fig. 6, Table 5). This report shows that a significant amount of villages are under high threat due to cyclone impact.

Using these vulnerability variables, social vulnerability is calculated and observed higher rate vulnerability in the study area. The study observed 26 villages (7.05%) under very high vulnerability, whereas 97 villages (26.29%) exhibit high vulnerability. Moderate vulnerability zone exhibited in 148 coastal villages (40.11%). 71 (19.24%) villages exhibit low vulnerability zone and 7.31% (27) of the villages exhibit in very low vulnerability zone (Fig. 7, Table 6).

### 4.2.2 Infrastructure Vulnerability

Infrastructure development and facilities are reducing the hazed impact on the habitant. Within the perspective of accessibility of basic infrastructure, highly developed regions such as cities and urban regions are always go with less loss of life in compare to rural regions. Assessing infrastructure vulnerability, road network, and cyclone shelters are used in the present study. Transportation and communication facilities are always playing keen role in evacuation and disaster mitigation process. In this contest, the study observed that a significant amount of area exhibit in very high vulnerability to transportation accessibility. Around 20.31% (982.76 km²) and 25.25% (1221.63 km²) of the total area observed under very high and high vulnerability, respectively. Moderate vulnerability observed in 20.58% (995.56 km²) area. However, low and very low vulnerability was observed in 14.57% (705.10 km²) and 19.28% (933 km²) of the total area, respectively (Fig. 8, Table 7).

The study observed that the urban environments like Kakinada, Nizampatnam are well connected with road and rail network, whereas developments for the rural areas still need to consider.

Tropical cyclones are one of the dangerous hazards that comprise storm surge. When a storm surge arrives on top of a high tide, the resulting inundation can reach areas that above sea level. It is critical and difficult to plan for the safety before the cyclone season. Evacuation plan and the distance to the cyclone shelters are very important for disaster management. Habitant will be under threat such people who far away from the cyclone shelter house.

The study analyzed the proximity of the coastal area with cyclone shelter houses and observed that no area exhibit under very high vulnerability. However, 12.25% (592.57 km²) of the area exhibit high vulnerability zone, and further half of the study area (2356 km²) exhibit moderate vulnerability. Flowingly, 27.68% (1339.13 km²) and 11.38% (550.71 km²) of the study area exhibit low and very low vulnerability zone (Fig. 9, Table 8).

Combined infrastructure vulnerability has been calculated using the above parameters, viz, transportation accessibility and cyclone shelters depict that the area lying moderate vulnerability. The study observed that 5% (241.76 km²) of the area exhibit very high vulnerability, and flowingly, 30.45%
(473.22) of the area depicts high vulnerability, whereas 37% (1790.13 km²) of the area lying under moderate vulnerability. Although, 23.95% (1158.75 km²) of the area exhibit low vulnerability and 3.61% (174.60 km²) of the area depicts very low vulnerability (Fig. 10, Table 9). High and very high vulnerable area need to more development for future climate change adaptation; in addition, the rest of the areas
also need some basic infrastructure development to improve the existing facilities.

4.3 Costal Social Vulnerability (CoSVI)

Coastal social vulnerability refers to the ability and coping capability to the extreme events such as cyclone and associated surges. The present study analyzed CoSVI, and the combination of the social vulnerability and infrastructure vulnerability depicts that 64% (3121.07 km²) of the total study area in moderate vulnerability. However, a remarkable area also depicts in high and very vulnerable area. Around 17.06% (835.45 km²) of the area observed high vulnerability and 1.65% (79.97 km²) of the area observed very high vulnerability. Low and very low vulnerable area observed 15.30% (1158.75 km²) and 1.48% (71.53 km²), respectively (Fig. 11, Table 10). High vulnerability area is distress with density of the population and lack of infrastructure. Therefore, the area laying in the high and very high vulnerability classes needs an attention in the terms of development.

4.4 Integrated Cyclone Risk Assessment

Cyclone risk assessment was calculated using the potential hazard zone and the vulnerability of the same location. Based on the analysis conducted, the study depicts the most area lying under moderate risk zone. However, significant area was also observed in the high-risk zone. The study observed that the half of the study area (3121.07 km²) lying moderately risk zone; however, considerable area was also observed in high-risk zone. Around 7.06% of the area was observed in high-risk zone following a small area which shares 1.65% of the total area also observed very high risk to cyclone. Low-risk zones are observed in 15.31% of the total area, whereas 1.46% of the area observed very-low-risk zone (Fig. 12, Table 11). The study observed that the districts Guntur and East Godavari are under higher risk with reference to the cyclone and associated hazards. The study observed areas like Suryalanka, Kannuru, Nizampatnam, Kalipatnam, Part of Machilipatnam, Uppada, etc. are the major places which exhibit in the high- and very-high-risk zone.

5 Conclusion

Cyclones are one of the most destructive natural hazards along highly populated coastlines all over the world. Presently, 40% of the global population lives within 100 km of the coast. Density of the population and the pressure on the coastal ecosystem are increased in the last decades. The multi-criteria decision support system alerts in the team of expected potential impacts due to tropical cyclones in the future. Regular risk assessment is important to support the development of effective cyclone mitigation policies and implementation of specific measures. Results of the present study will contribute to improve the adaptation and mitigation strategy, such as increasing the infrastructure, building new coastal embankments and construction of new cyclone shelters, and development of coastline roadways. New developments in the terms of embankments, cyclone shelters, and roadways should be in the places with high- and very-high-risk zone. On the other hand, the successful early warning system reduced the loss of life; however, false information and lack of awareness claimed many human lives. Incorporating the spatial distribution of vulnerable people in warning messages may increase trust of people to the warning signals. Impact of the cyclone will not be same in all over the region; impact may be severing where high population lives. Therefore, the early warning system should improve among the vulnerable people. The study recommended to increase the infrastructure like coastal roads and cyclone shelter houses in particularly high and very high vulnerability zones. The produced vulnerability and risk maps will give baseline information to the decision-makers to develop action plans, result of which will give guidance to the policy makers and governmental and non-governmental authorities to develop long-term action plans, disaster preparedness, and mitigation strategies. Furthermore, the study can be improved with micro-level study using additional physical and social vulnerability parameters.
Fig. 12  Spatial distribution of the cyclone risk analysis.  
(a) Village-wise spatial distribution of the cyclone risk under different vulnerability classes.  
(b) District-wise distribution of the risk classes of the cyclone risk analysis
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Table 11 District-wise distribution of the Cyclone risk area under different risk classes

| District | Very Low | Low | Moderate | High | Very High | Total | Percentage |
|---------|---------|-----|----------|------|-----------|-------|------------|
| East Godavari | 17.90   | 16.86 | 18.75    | 17.20 | 70.70     | 2167.56 |            |
| West Godavari | 207.13  | 58.02 | 352.73   | 122.79 | 740.65    | 4838.47 | 1.46       |
| Krishna  | 982.55 | 484.16 | 3121.69  | 795.81 | 406.16    | 406.16 | 15.31      |
| Guntur   | 93.74  | 147.78 | 234.87   | 79.03  | 17.52     | 1468.94 | 64.52      |
| Total    | 2167.56 | 406.16 | 1468.94  | 795.81 | 4838.47   | 406.16 | 100        |