Revealing the socio-economic vulnerability and multi-hazard risks at micro-administrative units in the coastal plains of Tamil Nadu, India

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ABSTRACT

Tamil Nadu (TN)'s South-Eastern coastal plain comprises of 5235 villages/wards, is densely populated (~2000/km²), and is highly vulnerable to multi-hazard events. Earlier vulnerability case studies carried out in TN utilized district as a unit of analysis, considering mostly the physical parameters. For the first time, the socio-economic vulnerability at the level of micro administrative units was analyzed for the entire stretch of the coastal plains of TN using ten census and household data-based indicators. All the indicators were used to determine the degree of vulnerability and summed up to determine the hot spots of socio-economic vulnerability. Public perception surveys carried out with 406 respondents from 363 villages were used to derive the likelihood-impact risk matrix. Results show that ~60% of the villages between the coastal stretch of Nagapattinam and Puducherry, including major parts of Cuddalore district are highly vulnerable (hot spots) to multi-hazard risks. The information retrieved at micro administrative units can be used by policymakers and coastal managers to develop effective plans for improving the resilience and preparedness of the community.

1. Introduction

The coast is a transitional zone between land and water, and is vulnerable to many natural hazards. In the coastal plains, there is a strong interaction between dynamic coastal processes, hazards and human activities. These interactions cause collateral...
damages and pose a serious threat to the physical and human environment (Panigrahi and Mohanty, 2012). The impacts and consequences of natural disasters in the coastal plains are severe, and continuously threaten the physio-socio-economic environment (Krishnamurthy et al. 2014). The coastal plains are of huge economic significance as they house one-third of the world population (Small and Nicholls, 2003; Mcgranahan et al. 2007; Murali et al. 2013; Balasundareswaran et al. 2019).

The coastal plains are ideal for human habitation as they support a wide variety of economic activities such as agriculture, fishery, industry, mining, trade and tourism. Altogether, these activities alter the existing physical processes and lead to numerous environmental hazards (Rani et al. 2015). Furthermore, in the past few decades, climate change has worsened the situation and has led to many adverse effects in the low-lying areas. Many coastal researchers across the globe have shown that the ecosystem of coastal regions is extremely vulnerable to disaster events, and many variables/factors need prior investigation under the changing climatic conditions (Appelquist and Balstrøm, 2015; Spalding et al. 2014; Kantamaneni et al. 2018; Koroglu et al. 2019).

In the Indian context, the livelihoods of 14.2 per cent of the total population of the country are dependent on the coastal resources, and are frequently facing severe natural and human-induced coastal hazards (Mahendra et al. 2011; Sahoo and Bhaskaran, 2018). Out of the 7,516 km Indian coastline, the State of TN has a coastline of 1,076 km, comprising one-third of the total population and most productive ecosystems. Studies have shown that all the highly populated coastal cities of TN viz. Chennai (Kumar and Kunte, 2012; Joerin et al. 2012), Puducherry (Murali et al. 2013), Cuddalore (Saxena et al. 2013; Thirumurugan and Krishnaveni, 2019; Parthasarathy et al. 2020), Nagapattinam (Muthusankar et al. 2013), Thoothukudi (Parthasarathy and Natesan, 2015) and Kanyakumari (Kaliraj et al. 2015) are vulnerable, and have experienced one or more major coastal hazards in the recent years. Implementation of effective mitigation measures and preparedness for future disasters is possible only through proper understanding of human habitations and their socio-economic conditions (Cutter et al. 2000; Mahendra et al. 2011; Appelquist and Balstrøm, 2015). As the coastal plain of TN is a primary human habitat, utmost attention has to be given to all aspects of disaster risk management to lessen the disaster impacts and improve the socio-economic conditions. Even though disaster risk is multi-factorial, and its assessment is highly complex, a proper understanding of vulnerability is imperative for preparedness planning and mitigating measures (Johnson et al. 2012).

The vulnerability of a community to the impact of hazards is determined by the physical, social, economic, and environmental factors or processes, and is also location and hazard-specific (UNISDR, 2017). Among the different dimensions of vulnerability, the socio-economic vulnerability is highly complex (Cutter et al. 2000). Many direct and proxy indicators have been used to assess the socio-economic vulnerability, and these indicators vary from place to place and time to time (Sherly et al. 2015; Mazumdar and Paul, 2016; Islam et al. 2016; Liu et al. 2016; Sahoo and Bhaskaran, 2018; Kantamaneni et al. 2019). A comprehensive analysis using multiple physical-socio-economic variables have also been attempted to identify the vulnerability
Coastal vulnerability index (Mujabar and Chandrasekar, 2013; Mahapatra et al. 2015; Priya Rajan et al. 2019), coastal sensitivity index (Shaj, 2014) and habitant vulnerability index (Nitheshnirmal et al. 2018; Balasundareshwaran et al. 2019) are examples of comprehensive attempts to analyse the physical and/or human vulnerability to individual/multi-hazards in India. However, there is very little knowledge/analysis on socio-economic vulnerabilities at micro (village/ward) level considering predominantly the socio-economic variables instead of the highly location-specific physical vulnerability parameters (Hoque et al. 2019).

In addition to vulnerabilities, understanding disaster risk is of special importance when dealing with the many uncertainties of hazard events (Hao et al. 2012). To determine the nature and extent of risk, assessment of potential hazards and existing conditions of exposed livelihoods are essential (UNDP, 2010; Ahsan and Warner, 2014). Risk can be estimated using any one of the following approaches or its combination (Kappes et al. 2012): 1) Qualitatively by relative risk descriptions (high, medium, and low), usually based on expert appraisals or public surveys; 2) Semi-quantitatively on a relative ranking scale by weighing how much one scenario contributes in comparison to the other, and 3) Quantitative in terms of absolute risk values on a determined scale. Among these, the quantitative approach is preferred for accurate risk assessments, but an estimation of the social and environmental risk variables for a vast environmental region is very difficult. The severity-impact risk assessment matrix is one of the commonly used qualitative methods for systematic risk assessment (Dumbravă and Iacob, 2013); this matrix is very simple, considers both the hazard and vulnerability components on a matrix scale, and can be used to determine the likelihood and impact of multiple hazards. Here, multi-hazard risk mapping has been implemented through a public perception survey covering a wide geographic area at the micro level to analyse the individual’s perception of their socio-economic conditions in bearing the disasters. The present study also underscores the importance of combining the assessment of indicator-based socio-economic vulnerability and public perception of multi-hazard risk for developing appropriate mitigation and/or preparedness strategies.

2. Study area

TN is located in the southernmost part of India, and is bounded by Kerala on the west, Bay of Bengal on the east, Karnataka and Andhra Pradesh on the north and the Indian Ocean in the south. Earlier studies on coastal TN only considered either a narrow buffer region along the coast or broad administrative units such as the coastal districts. Here, the natural boundaries—the watersheds touching the coastline were considered for delineation of the coastal region. Some of the larger watersheds extending to the interior were trimmed to 40 m (above mean sea level) contour lines on the assumption that the places above 40 m contour rarely experience coastal hazards (Bukvic et al., 2020). The study area comprises of 40 watersheds extending from Kodyar (Kanyakumari district) to Pulicat (Thiruvallur district), and lies between 8° 04’ 39” – 13° 33’ 47”N latitudes and 77° 05’ 46” – 80° 20’ 58”E longitudes.
The total geographical area of the study region is \( \sim 26,000 \text{ km}^2 \). The administrative boundaries of these watershed areas were chosen for data compilation and micro-level analysis. Selected watersheds are administered by or covered under 5,235 villages/wards enclosed in 75 taluks of 16 districts. In order to have an effective visualization and regional comparison, the study area was broadly divided into northern (Coromandel Coast), central (Palk Strait region) and southern (Gulf of Mannar region) coastal plains which are shown in the boxes A, B and C respectively in Figure 1. The administrative boundary of the union territory of Puducherry (includes two geographical areas - Puducherry and Karaikal) along the Tamil Nadu coast were also included for comprehensive analysis of the coastal plains of TN.

Study of coastal plains should also include the characteristics of physiography, climate and hazard profiles. The study area comprised of vast stretches of plains with tidal flats, estuaries, lagoons and narrow fragmented beaches. The plains were mainly covered by Phanerozoic sedimentary rocks, fluviatile, fluvio-marine and marine sequences of the Gondwana Supergroup (Carboniferous to Permian and Upper Jurassic to Lower Cretaceous), marine sediments of the Cauvery basin (Lower Cretaceous to Paleogene), Cuddalore/Panambarai formation (Mio-Pliocene) and sediments of Quaternary and Recent age. The slope of the study area is very gentle to flat. Soil textures range from fine clay to loam, and is of very poor to moderate draining type. The climate is dry sub-humid hot, and the coastal plains receive most of the

Figure 1. Location of the southeast coastal region of India - Tamil Nadu coast plains (A: Coromandal Coast, B: Palk Strait and C: Gulf of Mannar). The base map shows the delineated coastal watersheds of Tamil Nadu along with the locations of major hazards during the past two decades (2000-2020). The background map represents the topography of land and sea.
rainfall from Northeast monsoons (October to December). The average temperature is \( \sim 27^\circ C \) and the average annual rainfall is \( \sim 990 \) mm.

The study area is comprised of 61 million households with a population of 24.3 million (one-third of TN’s population), and the average population density is \( \sim 2,000 \) persons per \( \text{km}^2 \). Nearly one-third of the population in the study area belongs to socially weaker sections, and are economically backward. An estimated 30 per cent of the total workers are engaged in primary activities such as agricultural (farming and daily wages) and fishing (large scale and small scale) activities. The average literacy rate of this region is 70%. The coastal plains are known for agricultural activities of the State, especially for paddy (rice) cultivation. About 75% of the State’s paddy production (~2.7 million Metric Tons annually) is from the coastal plains.

The physical and socio-economic settings of the study area make it vulnerable to natural disasters like tropical cyclones, floods, storm surges and earthquake-induced tsunamis. Eight cyclones, five floods, one drought, one tsunami and four man-made major accidents have occurred during the last two decades in the coastal plains of Tamil Nadu. The details of the disasters are represented in Table 1 and Figure 1. Among these, cyclones, floods, drought and tsunami are the major disasters, and also coastal erosion and earthquake in the study area have been documented for nearly 100 years (Figure 2). In the Northern coastal plains, cyclones are more frequent and severe (120 to 180 km/h), and usually occur during the months of October-November. Seasonal and cloudburst flooding are also frequently observed in this area. The low-lying parts of Cuddalore district and Chennai metropolitan area have witnessed widespread flood inundation in recent decades. Drought hazard, storm surge and coastal erosion are much pronounced in the Southern coastal plains. Even though the coastal region has not experienced any major earthquake events, peak ground acceleration (PGA) data show that the northern part of the Coramandel coast is prone to moderate damaging risks (Zone III). Among the recent natural disasters, the tsunami in 2004, flood in 2015, and very severe cyclonic storms (Vardah in 2016 and Gaja in 2018) caused most destruction to lives, properties and services.

3. Data and methods

To assess the relative levels of socio-economic vulnerability in 5,235 villages/wards, census and household data of 2011 was used. After a thorough study of District Census Hand-Books (DCHB) and Primary Census Abstracts (PCA), all the possible direct and indirect parameters which affect the socio-economic vulnerability of the coastal regions were extracted and compiled into the following 10 indicators: Population Density(PD), Household Density (HD), Child Population Ratio (CPR), Female Population Ratio (FPR), Literacy Rate (LR), Primary Workers (PW), Socially Weaker Population (SWP), Sanitation Facilities (SF), Communication Facilities (CF) and Access to Health Care Facilities (AHCF). The methods used to compile these indicators are described in Table 2. All these indicators are incorporated in GIS (Geographical Information System) platform and the spatial distribution is visualized through choropleth mapping techniques.
Table 1. Major coastal disaster events in the coastal plains of Tamil Nadu during the last two decades (2000–2020).

| Major Disaster          | Month/Year | Geographical extent and Impact                                                                                                                                                                                                 | Reference                                      |
|-------------------------|------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------|
| Cyclone                 | November 2000 | Graded as an extremely severe cyclonic storm with a wind speed of around 180 kmph. Ten lives were lost due to this cyclone. The other major losses were crop damage and uprooting of trees. Major affected areas were Cuddalore, Nagapattinam and Puducherry | IMD http://www.rsmcnewdelhi.imd.gov.in/         |
| Fire Accident           | July 2004   | A fire at a government-aided school in Kumbakonam killed 93 children. It happened due to school’s narrow stairway, poor lighting, thatched roof and kitchen in the proximity of the school building | Walia & Satapathy, 2007                        |
| Tsunami                 | December 2004 | The tsunami from the 2004 M = 9.1 Sumatra-Andaman earthquake was primarily caused by vertical displacement of the seafloor in response to slip on the inter-plate thrust fault. The run-up height was 3 to 10 m and inundated 300 to 3000 m inland. In the coastal Tamil Nadu, 7,965 people lost their lives. Most of the fatalities were recorded in Nagapattinam (6,051), Chennai and Kanyakumari (206). The total damage is about one million USD. | EM-DAT 2020; Gopinath et al. 2014; Anandan & Sasidhar, 2011 |
| Flood                   | December 2005 | Two weeks of continuous rainfall caused flash floods in the low-lying areas of Tiruvarur, Nagapattinam, Cuddalore, Pudukottai, Ramanathapuram, Chennai and Karaikal. The death toll is about 490 |
| Cyclone Nisha and Flood | November 2008 | Heavy rainfall and gusty winds accompanied the cyclonic storm that gusted around 80 kmph. The highest rainfall was recorded at Vedaranayam (333 mm). In addition to more than 100 lives, 0.8 million acres of paddy were lost in Cuddalore, Nagapattinam, Karaikal, Thanjavur and Tiruvur districts | IMD http://www.rsmcnewdelhi.imd.gov.in/         |
| Cyclone Thane           | December 2011 | Thane was a very severe cyclonic storm with a wind speed of 140 kmph. It mainly affected the agricultural areas of Cuddalore, Puducherry, Thiruvur, Nagapattinam, and Thanjavur districts | IMD http://www.rsmcnewdelhi.imd.gov.in/ ; Punithavathi et al., 2012 |
| Building Collapse       | June 2014   | An eleven-story under-construction building at Moulivakkam in the suburb of Chennai collapsed, killing 61 construction workers | Radhakrishnan, 2017                            |
| Flood                   | December 2015 | The unprecedented rains in the first week of December 2015, the worst in 100 years, battered Chennai, Tiruvallur, Kanchipuram and Cuddalore districts. Chennai recorded over 33 cm of rain in 24 hours from December 1-2, resulting in widespread economic damage | Rajan, 2016                                    |
| Cyclone Vardah          | December 2016 | Vardah is a very severe cyclonic storm with a windspeed of 130 kmph. It severely affected the Chennai region. Twenty four lives were lost. The state government estimated the infrastructure damage to be ~3 billion USD. | IMD http://www.rsmcnewdelhi.imd.gov.in/         |
| Drought                 | 2017        |                                                                                                                                  | https://tnsdma.tn.gov.in                       |

(continued)
The values of exposure-related indicators such as population density, household density, child population ratio, female population ratio, primary workers and socially weaker population are grouped into very high, high, moderate, low and very low classes of vulnerability based on the assumption that higher values correspond to higher vulnerability. The values of capacity-related indicators - literacy rate, sanitation facilities, communication facilities and access to health care facilities were grouped, and higher values in these correspond to lower vulnerability. The intervals of all the vulnerability classes were determined based on the histogram distribution of each indicator. To determine a combined socio-economic vulnerability on a normalized scale, it is ideal to assign a rank to each vulnerability class of all indicators (Mclaughlin and Cooper, 2010). In the study, the five classes of vulnerability were

| Major Disaster | Month/Year | Geographical extent and Impact | Reference |
|---------------|------------|--------------------------------|-----------|
| Ennore Oil spill | January 2017 | Low rainfall coupled with irregular/erratic monsoons in the state lead to severe drought. Agricultural and drinking water sectors were adversely affected | ICMAM 2017 |
| Cyclone Ockhi | November 2017 | Ockhi was graded a very severe cyclonic storm (windspeed was around 85 kmph). Due to Ockhi, 199 Fishermen missing, 6,868 houses were damaged, 8,000 acres of rubber plantation were damaged, 25,000 coconut trees were uprooted, and 12,000 acres of banana plantations were damaged in Kanyakumari district. Inland flooding and inundation were experienced due to heavy to extremely heavy rainfall | IMD, http://www.rsmcnewdelhi.imd.gov.in/; Nivedita et al., 2019 |
| Cyclone Gaja | November 2018 | Gaja was a very severe cyclonic storm with a wind speed of 120 kmph. Major affected areas were Nagapattinam, Thiruvarur and Thanjavur districts. Of the 26,089 households affected, 10,512 houses were destroyed. Being a hub for perennial crops, 80% of the tree cover over 20 years old have been uprooted in the Cauvery delta region | IMD, http://www.rsmcnewdelhi.imd.gov.in/; Nivedita et al., 2019 |
| Industrial Accident | July 2020 | The boiler at Unit-5 in stage 2 of the Neyveli Thermal Plant (Cuddalore District) exploded early in the morning when workers were about to resume operations resulting in six killed and 17 injured | https://www.downtoearth.org.in/ |
| Cyclone Nivar / Flood | November 2020 | Nivar is a severe cyclonic storm with a wind speed of 90 kmph. Chennai, Puducherry, Villupuram and Cuddalore, districts were affected both by wind gusts and extreme rainfall | IMD, http://www.rsmcnewdelhi.imd.gov.in/ |
| Cyclone Burevi / Flood | December 2020 | Burevi is a cyclonic storm with a wind speed of 70-80 kmph. Southern and central coastal districts received very heavy rainfall and low-lying regions were inundated | IMD, http://www.rsmcnewdelhi.imd.gov.in/ |
ranked on a scale of 1-5, where 1 denotes very low vulnerability and 5 denotes very high vulnerability. The assigned ranks of all the indicators in each village were summed up to determine the composite socio-economic vulnerability. To group the similar levels of vulnerability, the resultant socio-economic vulnerability was further classified into five classes from very high to very low.

Then the cumulative rank values of each village were used to calculate Getis-Ord Gi* statistics for identification of hot spots of socio-economic vulnerability in the coastal plains. The optimized hot spot analysis tool in ArcGIS was used to correlate the neighbouring village rankings (Sánchez-Martín et al. 2019). This spatial autocorrelation tool works by looking at the rank of each village within the context of neighbouring villages’ ranks. The tool tests the hypotheses about the spatial concentration of the sum of x values associated with the j points within d of the i\textsuperscript{th} point (Getis and Ord, 1992). The statistic is denoted as

$$Gi(d) = \frac{\sum_{j=1}^{n} wij(d)xj}{\sum_{j=1}^{n} xj}$$  \hspace{1cm} (1)$$

where $wij$ is a symmetric one/zero spatial weight matrix with ones for all links defined as being within distance d of a given i; all other links are zero including the link of the point i to itself. $G_i(d)$ typically measures the concentration or lack of concentration of the sum of village ranks associated with the socio-economic vulnerability variables in the coastal plains. Based on computed Z-scores and p-values, the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure2}
\caption{Spatial distribution of hazard levels of the cyclone, coastal erosion, flood, drought and earthquake in the coastal plains of Tamil Nadu coast plains. The map is prepared with different data sources and grouped into five relative hazard levels. The legend of each natural hazard contains thresholds that limit values of each level. The green tints indicate a very low-low hazard, yellow tint indicates moderate hazard and red tints indicate high-very high hazard levels.}
\end{figure}
| Categories                        | Sub-categories                                                                 | Formula                                                                 | Sources                                                                 |
|----------------------------------|-------------------------------------------------------------------------------|------------------------------------------------------------------------|------------------------------------------------------------------------|
| Population Density (PD)          | Total Population                                                              | PD = \frac{\text{Number of Population}}{\text{Total Geographical Area}} | Balica et al. 2012; Johnson et al. 2012; Dondo Bühler et al. 2013; Rehman et al. 2020 |
| Household density (HD)           | Total Households                                                              | HD = \frac{\text{Number of Households}}{\text{Total Geographical Area}} | Cutter et al. 2000, Cutter et al. 2009; Dandapat and Panda, 2017; Aubrecht et al. 2013; Hagenlocher et al. 2013 |
| Female Population Ratio (FPR)    | Total Female Population                                                        | FPR = \frac{\text{Total Female Population}}{\text{Total Population}}   | Chakraborty et al. 2005                                               |
| Child Population Ratio (CPR)     | Total Child Population (0-6 Years)                                           | CPR = \frac{\text{Total Child Population}}{\text{Total Population}}    | Chakraborty et al. 2005                                               |
| Literacy Rate (LR)               | Total Literacy Population                                                     | LR = \frac{\text{Total Literates}}{\text{Total Population}}            | Yoon, 2012; Ahsan and Warner, 2014; BalaSundareshwaran et al. 2019     |
| Socially Weaker Population (SWP) | Scheduled Castes Population (SCP), Scheduled Tribes Population (STP)         | SWP = \frac{\text{SCP} + \text{STP}}{\text{Total Population}}            | Rehman et al. 2020                                                   |
| Primary Workers (PW)             | Main Cultivators (MC), Main Agricultural Labours (MAL), Marginal Cultivators (MrC), Marginal Agricultural Labours (MrAL) | PW = \frac{\text{MC} + \text{MAL} + \text{MrC} + \text{MrAL}}{\text{Total Working Population}} | Cutter et al. 2009; Das, 2012; Chakraborty & Joshi, 2016; Rehman et al. 2020 |
| Sanitation Facilities (SF)       | Tap Water Treated (TWT), Area Covered Under Total Sanitation Campaign (AUTSC), Community Toilet Complex Including Bath for General Public (CTCIB), Community Toilet Complex Excluding Bath for General Public (CTCEB), Community Waste Disposal System After House to House Collection (CWDS) | SF = \sum_{i=1}^{n} (\text{TWT} + \text{AUTSC} + \text{CTCIB} + \text{CWDS}) | Chakraborty & Joshi, 2016; Rehman et al. 2020 |
| Communication Facilities (CF)    | Telephone (T), Mobile Phone Coverage (MPC), Public Bus Service (PBS)         | CF = \sum_{i=1}^{n} (T + \text{MPC} + \text{PBS})                       | Chakraborty et al. 2005; Joerin et al. 2012; Rehman et al. 2020       |
| Access to Health Care Facilities (AHCF) | Community Health Center (CHC), Primary Health Center (PHC), Primary Health Sub Centre (PHSC), Maternity and Child Welfare Center (MCWC), Hospital Allopathic (HA), Hospital Alternative Medicine (HAM), Dispensary (D), Family Welfare Center (FWC) | AHCF = \sum_{i=1}^{n} (\text{CHC} + \text{PHC} + \text{PHSC} + \text{MCWC} + \text{HA} + \text{HAM} + \text{D} + \text{FWC}) | Chakraborty and Joshi, 2016; Rehman et al. 2020 |
villages are grouped and categorized into spatially significant hot or cold spots with different levels of confidence based on a high or low concentration of ranks. The villages with dissimilar rankings from their surrounding villages are considered as statistically not significant to form hot or cold spots.

Multi-hazard risk survey was planned based on the analysis of the socio-economic vulnerability. To study the socio-economic vulnerability in the field, to understand public’s perception about their exposure, and to determine the risks of multiple hazards, a risk perception survey was carried out throughout the coastal plains of Tamil Nadu, especially in the very high-high socio-economic vulnerability villages using the likelihood-impact risk matrix shown in Table 3 (Dumbravă and Iacob, 2013). Individual matrix was developed for 12 natural (cyclone, coastal erosion, storm surge, tsunami, flood, earthquake and drought) and human-induced (wetland loss, fire accident, transport accident, chemical accident and oil spill) hazards. A total of 406 respondents from 363 villages in the study area were interviewed during the months of March-May 2019. The respondents were randomly selected based on their prior exposure to natural or human-induced hazards prevailing in that region. All the respondents were asked about the likelihood-impact of natural and human-induced hazards in their villages. The matrix was developed under four likelihood possibilities (frequent, occasional, remote and improbable probabilities), and four impact levels (negligible, marginal, critical and catastrophic). The intersection of likelihood-impact levels was categorized into five classes of risks: very high, high, moderate, low and very low. The schematic representation of methods adopted in the study is shown in Figure 3.

4. Results

4.1. Socio-economic vulnerability

Ten direct and indirect socio-economic parameters that affect the vulnerability of the coastal plains were chosen and analysed. Each parameter is represented spatially with five classes, ranked on a scale of 1 (very low) to 5 (very high), and the interpretation is presented.
4.1.1. Exposure related indicators

The population and household density generally refer to the agglomerated human habitation, and is directly proportional to socio-economic vulnerability. The villages with more than 1,600 persons per km², and more than 400 households per km² were classified as highly vulnerable. There is a very high degree of vulnerability in the surrounding areas of the major coastal cities of Chennai, Puducherry, Thoothukudi and Kanyakumari. Besides, very high to high vulnerability is observed in the coastal stretch between Cuddalore and Nagapattinam (Figure 4A and 4B).

Women, children (0-6 years) and elderly are known to be highly vulnerable during the disasters. In this study, villages with >52% of the female population and >14% of child population were categorized as very highly vulnerable. The coastal villages of Thanjavur and Thoothukudi districts fall under very high vulnerability due to predominant female population (Figure 4C). Similarly, the villages situated around the major coastal cities viz; Chennai, Puducherry and Thoothukudi fall under very high vulnerability due to predominant child population (Figure 4D).

Primary workers constitute the most important part of rural development, and they are the most vulnerable section of society due to various insecurities (Pramanik, 2013). In the present study, the village with more than 60 per cent of the working population was categorized as very high vulnerability and 45-60 per cent as high vulnerability. These two classes were predominantly found in the villages located between the cities of Nagapattinam and Thoothukudi (Figure 5C).

The proportion of socially weaker sections to the total population is one of the important variables to understand socio-economic vulnerability. Even though, an accurate determination of socially weaker population in a village is challenging, the census of socially deprived castes such as Scheduled Caste (SC) and Scheduled Tribe (ST) provides a reasonable approximation in the Indian context. In this study, a proportion of more than 80 per cent of these deprived castes in a village was perceived.
as very high vulnerability, and 40 to 80 per cent as high vulnerability, and these villages are noticed mainly in the northern coastal plains, except in areas surrounding Chennai (Figure 5B).

4.1.2. Capacity related indicators

The literacy rate is associated with disaster preparedness, and is inversely proportional to the socio-economic vulnerability. It can be assumed that if the literacy rate of a village is more than TN’s average (70 per cent), then the village is relatively less vulnerable, and if the literacy is less than 50 per cent, it is considered as highly vulnerable. Villages with very high vulnerability are mainly located in the northern and southern peripheries of Chennai (Figure 5A).

The availability of sanitation facilities such as treated tap water, community toilet complex and community waste disposal system are good indicators of socio-economic development of a village. A village having all such facilities will maintain a better environment, and hence is considered as less vulnerable. In the present study, the vulnerability level has been graded based on the number of sanitation facilities. In general, the coastal plains of Tamil Nadu had proper sanitation facilities, and only a few scattered villages fell the under highly vulnerable class (Figure 6A).

The role of communication is very decisive in disaster preparedness and relief activities; without proper communications systems in a place disaster management will be a highly challenging task (Azad et al. 2019.) The communication indicators of

Figure 4. Spatial distribution of degree of vulnerability due to A) Population density, B) Household density, C) Female population ratio and D) Child population ratio in the coastal plains of Tamil Nadu. The legend of the map shows the range of values for each indicator and associated colour shade.
the household survey data such as telephone, mobile phone and public bus services were used in the study. Since all the households in the villages had one or more these communication facilities/services, the entire coastal plains show moderate to low vulnerability (Figure 6B).

In addition to sanitation and communication indicators, the study also included the presence of health care facilities in a village as an indicator. Proximity to primary health care is very important for effective emergency management, and also for risk reduction (Redwood-Campbell and Abrahams, 2011). Unlike other facilities, most of the villages in the coastal plains are highly dependent on district headquarters or nearby cities for health care services, which make most of the plains highly vulnerable (Figure 6C).

4.1.3. Composite socio-economic vulnerability

The vulnerability classes of all the indices (in the scale of 1-5) were summed up to show composite socio-economic vulnerability in the study area. The summed up ranks were categorized as very high (above 33), high (29-32), medium (24-28), low (21-23), and very low (16-20) vulnerability levels based on the histogram distribution. The result shows that the Northern coastal plains (Coromandel coastal) fall under high-very...
high vulnerability (Figure 7A), while the central coastal stretch (Palk Strait), and the southern plains (Gulf of Mannar) fall under moderate and low vulnerability classes respectively. The district-wise distribution of the number of villages/wards falling under different classes of composite socio-economic vulnerability is presented in Table 4.

4.2. Multi-hazard risk perception survey

The risks of coastal hazards vary from place to place mainly due to the differences in the occurrence of hazards and associated impacts. To visualize the risks of different hazards, a wide public perception survey was attempted, particularly along the coastline. The likelihood-impact matrix presented in Table 3 was used for qualitative risk assessment. The spatial distribution of responses is presented in Figure 8 (natural hazards) and Figure 9 (human-induced hazards).

4.2.1. Risks of natural hazards

The risk survey revealed that cyclone and tsunami are the most destructive natural hazards in the coastal Tamil Nadu. The majority of the respondents living in the coastal
villages of the Northern coastal plains perceived that they are under very high cyclonic risk. The respondents living in the districts of Cuddalore and Villupuram feared very high cyclonic risk, which is also observed in the hazard assessment (Figure 2). Very high level of tsunami risk is perceived by respondents mostly in the northern coastal districts, especially in Cuddalore and Nagapattinam districts. The survey showed that respondents living in the low lying areas of the major cities perceived very high risks of the flood. Storm surge and coastal erosions are constant threats to the environment and economic activities of the coastal villages of the Southern coastal plains. In recent history, the coastal community were not exposed to any major earthquakes events except for a few tremors in Chennai and Pondicherry, and hence the very low risk is perceived throughout the coast of TN. The risks of drought perceived by respondents in the southern plains as these regions are comparatively dry and, most of their agricultural activities depend on rainfall. The residents surrounding the major wetlands of Cuddalore, Pudukkottai and Thoothukudi districts were feared high risk due to wetland losses.

4.2.2. Risks of human-induced hazards

The risk of fire, transport, chemical and oil spill accidents were surveyed. High risk of transport accidents is perceived throughout the coastal regions, and very high risk is perceived in the surrounding regions of Chennai and Thoothukudi, the major industrial cities (Figure 9). Respondents from Chennai and Thoothukudi perceived high risk of fire and chemical-related accidents due to the presence of power plants and chemical industries. The risk of the oil spill is perceived around Chennai.
4.3. Hot spots of vulnerability and multi-hazard risks

The composite socio-economic vulnerability ranking of villages along with risks surveys was used to determine the hot spots in the coastal regions. The optimised hot spot analysis tool was used to statistically aggregate villages with a very high socio-economic vulnerability rank (Figure 10A). The major hot spot with 99 per cent confidence level is formed by the villages of Cuddalore, Nagapattinam, Thiruvarur, and

| District       | Very low | Low | Moderate | High | Very high |
|----------------|----------|-----|----------|------|-----------|
| Ariyalur       |          |     |          |      |           |
| Chennai        | 3        | 16  | 128      | 8    |           |
| Cuddalore      |          | 2   | 54       | 261  | 219       |
| Kancheepuram   | 5        | 13  | 159      | 362  | 98        |
| Kanniyakumari  | 5        | 26  | 90       | 12   | 1         |
| Karaikal       | 1        | 1   | 26       | 2    |           |
| Nagappattinam  | 1        |     | 34       | 308  | 158       |
| Puducherry     |          |     | 44       | 24   |           |
| Pudukkottai    | 2        | 3   | 76       | 129  | 31        |
| Ramanathapuram | 3        | 16  | 172      | 160  | 8         |
| Sivagangai     |          | 3   | 47       | 68   | 2         |
| Thanjavur      | 1        | 3   | 78       | 351  | 163       |
| Thiruvallur    | 1        | 4   | 76       | 232  | 122       |
| Thiruvarur     |          | 2   | 59       | 351  | 138       |
| Thoothukkudi   |          | 13  | 124      | 150  | 14        |
| Tirunelveli    | 1        |     | 21       | 22   | 4         |
| Viluppuram     |          | 1   | 33       | 170  | 89        |
| Viruthunagar   |          |     | 4        | 4    | 1         |
| Total villages | 23       | 103 | 1228     | 2636 | 1058      |
Thanjavur districts. A minor hot spot with 99 per cent confidence level is found in Thiruvallur district, south of Chennai.

Multi-hazard risk assessment shows that the respondents living in the coastal villages of Cuddalore, Nagapattinam, Thiruvarur, Thanjavur and Thiruvallur districts perceived very high multi-hazard. These districts fall under more than four very high risk classes (Figure 10B). Thoothukudi district is categorised under very high risk of human-induced hazards. The coastal villages of the Southern plains, especially Ramanathapuram and Kanyakumari districts, fall under very low socio-economic vulnerability and multi-hazard risks.

5. Discussion

The coastal plains of TN are considered to be one of the most vulnerable regions in India due to high population density and exposure to multi-hazards. In the recent decades, this region has encountered multiple coastal hazards (Table 1), and faces a serious threat of changing climatic conditions (Krishnamurthy et al. 2014) necessitating the need for a comprehensive assessment of multi-hazard vulnerabilities and risks. Even though a systematic assessment of vulnerability using micro-administrative units and delineation of most vulnerable regions could help planners and emergency managers to devise better disaster management strategies (Yoon, 2012), such assessment covering the entire coasts at village level has not been carried out earlier in TN as well as in India.

Unlike physical vulnerability assessment, which is widely and frequently studied, assessment of socio-economic vulnerability is complex. The common approach to assess social or economic vulnerability is to employ direct or indirect indicators based
on prior knowledge from existing literature (Cutter et al. 2009). This proxy approach has been used to understand the socio-economic vulnerability of different regions (Yoon, 2012). However, the set of indicators used in one region does not uniformly apply to other regions due to wide variations in social and economic conditions. Even though many studies have been carried out to measure socio-economic vulnerability (Birkmann, 2007; Fekete, 2009; Yoon, 2012; Koks et al. 2015; Lung et al. 2013; Wu et al. 2016; Maanan et al. 2018; Kantamaneni et al. 2018; Tragaki et al. 2018; Gomez et al. 2020), there are no widely agreed set of socio-economic indicators that could be uniformly used in all regions. Even if certain indicators/approach of one region may be highly relevant to the study of another similar region, the lack of data-sets from authentic sources greatly limit the applicability. For example, per capita

![Figure 10. Hot spots of socio-economic vulnerability (left) and spatial distribution of multi-hazard risks (right) in coastal plains of Tamil Nadu. Left: The hot (red shades) and cold (blue shades) spots of socio-economic vulnerability are represented with different levels of confidence intervals. The villages that not formed either under hot or cold spots are depicted with yellow colour. Right: The different colour of the circle designates medium (green), high (yellow) and very high (red) risk categories. The size of the circle denotes the number of risk classes with different risk categories. For instance, the largest red circle denotes more than four different risks (natural and/or human-induced) observed with very high risk category.](image)
Income is one of the most important variables for the assessment of economic vulnerability but such data at the village level in India is not available in the public domain. After carefully considering these facts and limitations, 10 indicators under five vulnerability classes were chosen to assess the socio-economic vulnerability in the coastal plains of TN.

The population and household density are two most frequently used parameters in vulnerability assessments, and are critical to assess the vulnerability of the population to coastal hazards. Studies have shown that a higher proportion of children and females in the total population indicate increased vulnerability of the administrative units (Cutter et al., 2000; Koroglu et al. 2019). In the present study, the northern coastal plain (Coromandel region) has a higher population density, and hence the vulnerability is very high. The class-1 cities of Chennai and Puducherry (also referred to as Pondicherry), and their surrounding areas in the Northern coastal plain have very high population density, and these regions are most exposed to coastal hazards. However, higher literacy rate, better sanitation, health care and communication facilities reduce their vulnerability status to moderate to low levels. Similarly, most of the villages in Kanyakumari district have very high population density but other socio-economic indicators fall under low to very low vulnerability. Thoothukudi district and its surroundings in the southern coastal plain (Gulf of Mannar region) have a higher proportion of children and female population, with moderate to high population density, making this region highly vulnerable. However, the other socio-economic parameters fall under moderate to low vulnerability, and therefore Thoothukudi district is classified as a moderate to high vulnerability region in the composite socio-economic vulnerability assessment. On the other hand, the risk survey carried out to understand the perception of the population shows that this region is highly vulnerable to coastal erosion and human-induced industrial hazards. Several earlier studies have documented the vulnerability of the population to coastline erosion in this region (Mujabar and Chandrasekar, 2013; Kaliraj et al. 2015; Parthasarathy and Natesan, 2015).

The study identified most of the villages between the stretch of Nagapattinam and Puducherry, including major parts of Cuddalore district to be a hot spot of socio-economic vulnerability. The risk survey also shows that the people of this region are highly aware of the risks due to natural hazards. In addition to high population density, a high proportion of primary workers, female and socially weaker population make this region most vulnerable. Furthermore, this region is highly prone to cyclones, storm surges and floods (Mazumdar and Paul, 2016; Thirumurugan and Krishnaveni, 2019). Many physical vulnerability analyses have documented this stretch to be a highly vulnerable zone (Nitheshnirmal et al. 2018; Balasundareshwaran et al. 2019; Priya Rajan et al. 2019). Several multi-hazard vulnerability studies have also reported that coastal parts of Cuddalore district are very vulnerable to coastal hazards (Mahendra et al. 2011; Murali et al. 2013; Muthusankar et al. 2013; Saxena et al. 2013; Parthasarathy et al. 2020) Recently, Rehman et al. (2020) developed a composite vulnerability index for the coastal districts of India using exposure, sensitivity and adaptation to coastal hazards as factors, and showed that Cuddalore district has very high sensitivity and very low adaptation index, and is in agreement with our study where we report this region to be highly vulnerable. Rehman et al. (2020)’s units of analysis of are at the level of district and sub-
district, and the limitation is that spatial variations within the vast coastal stretch could have been generalized. Here we have presented the spatial variations in this region at micro-level which would help the administrators to prepare a local level plan for community awareness, preparedness and also setting up of emergency response centres. This would greatly help to reduce future disaster impacts.

Most of the attempts in India to study coastal risks have considered only the physical and demographic parameters, and have ignored individuals' perceptions of their vulnerability to coastal hazards. Here, a risk perception survey was carried out throughout the coastal plains. The survey results are in agreement with indicator based socio-economic vulnerability analysis, and show that the northern coastal stretch is most vulnerable to multiple natural hazards. Among the hazard-specific risk perceptions, a tsunami is considered a serious threat to coastal societies. The people of TN were not aware of the impacts of the tsunami until they witnessed massive destruction due to the huge surge of sea waves in 2004 (TNSDMA, 2005). Unlike the Asia-Pacific region, the coastal region of TN does not experience the impacts of tsunami often (Roshan et al. 2016). The 2004 tsunami created huge panic among the people living in the coastal plains of TN, especially along the Coromandel coasts, as the State accounted for 80% of the total death toll in India (official estimate of India’s death toll is 9,995 persons), and Rs. 47 billion (63 million USD/52 million EURO) economic loss (TNSDMA, 2005). The massive loss and pain caused by the tsunami have left a deep scar in their minds, and is reflected in the survey where many respondents perceived risks of tsunami to be very high compared to all the other coastal hazards. Implementation of proper early warning systems, mitigation measures and mock drills in the most affected regions would create confidence among the people to tackle the situation in future.

The other very high risk hazards perceived by most of the community are cyclones and transport accidents. The state has experienced eight cyclones in the last two decades (Table 1), and five of them are very severe cyclonic storms. Except for cyclone Ockhi, all other recent cyclones crossed northern coastal regions of TN, and have caused huge economic loss and > 100 deaths. The transport accidents are likely to occur in the coastal plains due to the presence of ports and harbours, associated trading activities, and poor road infrastructure (Krishnan et al. 2018). Out of the 16,157 fatalities due to road accidents in 2017, ~50% fatalities were reported in the coastal districts (https://tnsta.gov.in/tnsta/information.jsp). Floods are common in the Eastern coastal plains of India due to its physiographic structure, drainage system and seasonal rainfall character (Mirza, 2011). Even though floods are frequent in the coastal plains of TN, and five widespread flood events were reported in the last two decades, people have adapted to survive the impact of floods as noticed in many parts of the world (Svetlana et al. 2015). The survey showed that only a few respondents living in the low lying areas of Chennai and Cuddalore perceived a very high risk of flood. Flood risk is perceived highly in Chennai, mainly due to the catastrophic 2015 floods, and this could be attributed to improper management of drainage and illegal constructions in the low lying areas.

Overall, the northern coastal plains of Tamil Nadu, especially from Nagapattinam to Puducherry and North of Chennai, form a hot spot of socio-economic vulnerability due to higher population density, female ratio and socially weaker sections, and
people here have a very high perception of multi-hazard risks mainly due to cyclone, tsunami, flood and transport accidents. As large number of villages in the northern plains fall under very high vulnerability and multi-hazard risks, conservation efforts and coping strategies have to be prioritized in this region to overcome the hazard impacts, and strengthen the resilience of the community. The UN’s Sendai Framework and Sustainable Development Goals (SDGs) urges the local governance to take up a proper roadmap for reducing human and economic loss from disasters and make human settlements safe, resilient and sustainable (https://www.undrr.org). Such a roadmap should consider a comprehensive long-term mitigation and preparedness plan that requires a detailed assessment at a micro-level. In this context, the study comprehensively details the hazard-prone regions, the most vulnerable micro-units and multi-hazard risks for the coastal plains of TN. The composite socio-economic vulnerability index, and associated hot spot identification will serve as a knowledge-base and resource for formulating effective disaster risk management plans in the coastal areas of TN. As the study has generated baseline data at the village level, the findings of this study would greatly help the administrators in establishing evacuation/aid assistance zones and emergency planning. The perceptions about the multi-hazard risks have ensured the validity of hot spots and affirm the selection of indicators for vulnerability assessment. Therefore, these indicators can be used as a proxy to identify and implement hazard awareness and education programmes.

6. Conclusion

The study has comprehensively assessed the socio-economic vulnerability and multi-hazard risks in the coastal plains of Tamil Nadu at the village level through authentic Census data and field surveys. The physiographic form of the coastal plains of TN is susceptible to multiple natural hazards, especially cyclone, flood, tsunami and storm surges. In addition to population exposure (~2,000 persons per km$^2$), the high proportion of the socially weaker population, the dominance of primary workers and female ration make this region most vulnerable. The spatial variations in socio-economic vulnerability and multi-hazard risks in the coastal plains of TN have not been comprehensively assessed at village level earlier. As risk assessment with the district as a unit does not convey any meaningful information to formulate micro-level plans, here the study utilized data obtained at village/ward level. The hot spot analysis of socio-economic vulnerability and spatial overlay of multi-hazard risk surveys has identified three major coastal regions for immediate policy intervention: 1) The stretch between Puducherry and Nagapattinam covering the major parts of Cuddalore district 2) Northern part of Thiruvallur district (North of Chennai) and 3) Surrounding villages of Thoothukudi industrial belt. Prompt disaster mitigation measures (structural and non-structural measures) and effective disaster preparedness plans should be implemented in these regions to reduce disaster risks and achieve sustainable socio-economic development.

The information generated in this study can be used as a baseline data to identify the micro administrative units, to be prepared locally to prevent the devastating disaster impacts, and to increase the resilience of the community. As the results are shown
on a relative scale, a detailed assessment of hazard-specific socio-economic vulnerability has to be carried out first before executing disaster risk management plans. Quantitative assessments considering all major risk elements have to be conducted to understand the absolute risks in these regions. Even though the study used limited socio-economic parameters due to the lack of authentic and vital data sources at the village level, the results reveal a spatial pattern of disaster risks comprehensively. The methodology adopted for this study can be extended throughout the coastal plains of India at the village level. Additional micro-level indicators and stratified sampling procedures can be considered to further improve the socio-economic vulnerability assessment. Inclusion of indicators of economic (public and private assets, poverty, unemployment, per capita income etc.), financial strategies (insurance schemes, debt to revenue ratio of local governments etc.) and social mobilization (migration, illegal occupation etc.) will make the socio-economic vulnerability assessment more accurate, and effective for policy formulation.

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