A Multi-Data Geospatial Approach for Understanding Flood Risk in the Coastal Plains of Tamil Nadu, India

Rasme Allat V

Central University of Tamil Nadu

Leo George Sekar

Central University of Tamil Nadu

Arun Prasad Kumar

Central University of Tamil Nadu

Balasubramani Karuppusamy (✉ geobalas@cutn.ac.in)

Central University of Tamil Nadu <https://orcid.org/0000-0003-0671-1033>

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Abstract

The coastal plains of Tamil Nadu (India) are highly vulnerable zone for coastal floods, the most common disaster, experienced every year. In the study, the coastal plain is delineated through a watershed approach with 5020 micro-administrative units covering an area of about 3,000 sq.km. A comprehensive flood risk assessment was carried out by preparation of hazards, vulnerability, and exposure layers using multiple data sources including from field surveys, satellite data and secondary data sources. The flood prone regions are delineated initially from Sentinel-1 Synthetic Aperture Radar data coupled with SRTM-DEM on a probability scale (0–1) and validated with the District Disaster Management Plans of 13 coastal districts. In addition, National Resources Conservation Service – Curve Number (NRCS-CN) method was adopted to estimate surface runoff potential for flood risks. The vulnerability and exposure of the population to the flood hazards was determined using census and household data based indicators. A focused group interview was conducted at 514 locations targeting deprived communities of all major settlements of the study area. The public perceptions were used to understand the flood risks and to validate the hazard and vulnerability layers. To estimate location-specific flood risks within the micro-administrative units, built-up areas with different categories were delineated and intersected with the flood hazard. The amalgamation of results shows that very high flood risk prevails in the northern parts of coastal Tamil Nadu, especially the stretch between Chennai and Cuddalore. In addition to provide a baseline datasets for the first time at micro-administrative units for entire coastal plains of Tamil Nadu, the study offers a pragmatic methodology for sustainable development measures in general and flood risk management in particular.

1. Introduction

Coastal floods are one of the most common natural disasters, which affect lives and the environment. Coastal areas are prone to extreme weather events as it is highly dynamic and has geo-morphologically complex systems (Balica et al., 2012; Khan and Chatterjee, 2018). It has been estimated that about 23 percent of the world's population lives both within 100km distance from and 100m above sea level (Small and Nicholls, 2003). Coastal cities are much vulnerable to floods and the impact is high because the land use of the area is altered i.e. agricultural fields to buildings, parking lots, and others (Suriya et al., 2012). Coastal zones with dense populations, low altitudes, high rates of land subsidence, and little adaptive capability are the places most in danger. According to OFDA/CRED (International Disaster Data, Office of Foreign Disaster Assistance/ Centre for Research on the Epidemiology of Disasters) data, flood is the most common disaster as the annual global number of deaths is very high by the flood. Statistically stated, India ranks the third position, next to China and the United States of America, for the loss due to flood disaster for the timeline 1990 to 2021 and estimated about 93,727,634,000 USD economic loss (EM-DAT).

India is one of such countries that have been seriously affected by floods on multiple occasions. Due to the topographic situation, India's east coastal areas are often prone to tropical cyclones/depressions and associated floods, where the bulk of India's population is also concentrated (Dhar and Nandargi, 2003).

With no exception, coastal districts of eastern Tamil Nadu and Puducherry usually bear heavy rains during the northeast monsoon which becomes prone to flooding with numbers of swelling rivers and wetlands (Singh et al., 2019). Identifying flood-prone areas at micro-level unit in the coastal Tamil Nadu is important for effective mitigation and management of flood risks. Although various studies attempted for flood risk assessment, but all of them either covered conducted for smaller region with micro-units or covered entire plains with district as unit. In addition, there are global flood risk assessment system based on global hydrological models and global impact assessment models for river floods (Winsemius et al., 2013) with no scope of downscaling to micro-levels. The availability of microwave satellite data sets and GIS based modeling approaches now offers better environment for quantifying the severity of flooding, the damage to the built environment, mapping flood-vulnerable areas, and eventually mitigation and management of flood-prone areas (Faiz Ahmed and Kranthi, 2018). The public availability of

SENTINEL 1 images for extracting flood inundation has made possible to harness the satellite technology for detailed flood assessments (Uddin et al., 2019). In addition to optical satellite datasets, microwave data based approaches are now most commonly exists to identify the flood inundation at various levels/scales (Joshi, 2012; Patel & Dholakia, 2010; A. K. Singh & Sharma, 2009; Zope et al., 2015). Due to its thick cloud penetration capability during the rainy seasons, microwave data offers unique opportunity for the identification the flood inundation region. It can also be used to understand the probability and magnitude of flooding (depth, velocity, and intensity) by combining multi-temporal datasets with DEMs and other datasets (Demirkesen et al., 2007; Van de Sande et al., 2012; Ehrlich et al., 2018).

Surface runoff is the key factor for any flood event and understanding runoff coefficient using empirical equations would greatly assist flood inundation mapping (Jariwala & Samtani, 2012). The National Resources Conservation Service - Curve Number (NRCS-CN) was widely used to evaluate floodwater retarding projects in the early years (1950–1980) due to its simplicity, predictability, stability, applicability for ungauged watersheds (Williams et al., 2012). The comparison of surface runoff potential and average seasonal rainfall would forms sound basis for characterizing the flood prone regions.

Flood risk assessment methods mainly consist of four steps, including hazard assessment, exposure assessment, vulnerability assessment, and risk assessment (Kvočka et al., 2016). Although the satellite data based assessment is necessary for accurate delineation of flood prone regions, vulnerability of exposed population can be assessed mainly through census based or sample based indicators. Vulnerability has multiple dimensions (physical, social, economic, and environmental) and increase the susceptibility of the exposed elements to the impact of flood hazards (UNISDR, 2009; De Brito et al., 2018). Vulnerability is an essential component of flood risk analysis and, as such, it has to be deeply investigated (Papathoma-Köhle et al., 2019). Due to its complex nature, vulnerability is always assessed in terms of indirect indicators. The census and other published household survey reports can be utilized to generate vulnerability indicators. However, structural field survey and direct interview of exposed population is precautionary before concluding anything on the basis of vulnerability indicators. The direct impacts and economic loss caused by floods can be better estimated by comparing vulnerability indicators and field surveys (Bahinipati et al., 2015). It is also imperative that survey of individuals is not

wise option although the sample designing is sound as individuals often biased with their own judgments on flood risks. Therefore, group survey of deprived communities is advisable to understand the perceptions of the public (Xia et al., 2011), as the risk of personal danger to people caused by a flood varies both in time and place across a flood-prone area. By cognizing all above facts, we attempted a comprehensive analysis of flood risk in the coastal plains of Tamil Nadu to generate firsthand baseline datasets and to demonstrate the integrative methods for flood risk assessment which would help in all phases of disaster management ranging from preparedness to long-term planning strategies.

2. Methodology

2.1 Study area

Tamil Nadu is the southernmost state of India situated with 1076 km length coastline stretches along the Bay of Bengal, the Arabian Sea, and the Indian Ocean that constitutes about 15% of the total coastal length of India. For the present study, we have used the micro-watershed boundaries for demarcating the coastal plain regions of Tamil Nadu. All the coastal watersheds were considered for delineation of coastal plains where the larger coastal watersheds were trimmed with 40m contours above mean sea level. The delineated study area extends between the latitude of 8°4' 39.183"N to 13°32'56.875"N and longitude of 77°6'8.831"E to 80°20'54.37"E and covers an area about 3,000 sq.km with 13 districts, 75 taluks and 5,020 villages/wards (micro-administrative units of India). The Union Territory Puducherry is also considered for the profound understanding of the study area. The coastline extended from Thiruvallur to Kanyakumari districts are highly vulnerable to frequent tropical cyclones, floods, and storm surge events (Fig. 1). The slope of the study area is very gentle to flat and covered by dominant sediments of Quaternary-Recent age. The riverine landforms are the product of the major rivers and laterite landforms are probably the oldest erosion surface. Soil textures range from fine clay to loam with moderately shallow to very deep depths. The average annual temperature and rainfall are 27°C and 990 mm respectively. The coastal region is mainly dependent on monsoon rains from October to December. The study area has one-third of state population with an average population density of 2,000 persons/sq.km. The most of the people are economically disadvantaged and socially marginalized. About 52% of the coastal plains of Tamil Nadu are used for agriculture, particularly for paddy cultivation. The physical setting of the study area makes it vulnerable to floods. Flooding includes annual flooding, cloudburst flooding, monsoonal flooding, and cyclonic floods. Seasonal and cloudburst floods are also common in this region. In the recent decades, the Chennai metropolitan area has seen widespread flood inundation and floods that occurred in the years 2005 and 2015 are recent examples of devastating flooding.

2.2 Delineating flood prone areas

The methodology adopted for this study is illustrated in Fig. 2. Flood hazard depends on factors such as flood inundation and the topography of the area. The flood prone areas are extracted from Sentinel 1 Synthetic Aperture Radar (SAR) and rainfall data used from the year 2015–2020, which is depicted in

Table 1. Sentinel-1 constellation consists of currently two satellites (Sentinel-1A and Sentinel-1B) with a Synthetic Aperture Radar (SAR) instrument operating on-board at C-band of 5.5 GHz frequency and provides data at the resolution of 10 m at 12 days repeat cycle. In this study, we used all available VH polarized SAR data in the default Interferometric Wide-Swath (IW) mode and Ground Range Detected High Resolution (GRDH) format acquired for pre-flood and post flood periods as mentioned in Table 3.1. The pre-processing of the Sentinel-1 data and the calculation of temporal median image for each of the seasons were done in Google Earth Engine platform. The SRTM Digital Elevation data was used for terrain filtering to eliminate areas of radar shadow and areas of unlikely flooding using the slope information. The Change Detection and Thresholding methodology was adopted, where the difference in sigma naught values between the pre-flood and post-flood datasets were calculated (Clement et al., 2018; Long et al., 2014). Following that, based on the global threshold, threshold filter is determined to extract the potentially flooded zone in the study area.

Table 1
Window periods for Sentinel-1 median images extraction before
and after the major floods

Year	Before flood	After flood
2015	10-10-2015 to 23-10-2015	10-11-2015 to 15-12-2015
2018	10-10-2018 to 23-10-2018	01-11-2018 to 18-12-2018
2020	10-11-2020 to 23-11-2020	24-11-2020 to 10-12-2020
2021	10-11-2020 to 23-11-2020	06-01-2021 to 17-01-2021

In this study, we have utilized the daily rainfall data collected from State Water Resources Data Centre and Indian Meteorological Department (IMD) reports. The daily rainfall data is grouped into heavy (64.5 -115.5 mm), very heavy (115.6-204.4mm), and extremely heavy (above 204.4 mm) classes. Based on these classes, the dates for satellite datasets is determined (Table 1). The extracted flood inundation layers for multiple rainfall events were overlaid and cumulative flood inundation layer was prepared with frequency of flood events. The cumulative layer was overlaid with SRTM (Shuttle Radar Topography Mission) Digital Elevation Model and flood rise scenarios were modeled with varying depth levels (1 to 5 feet) in Global Mapper software. By comparing the Sentinel 1 SAR based inundation data and DEM based modeling, flood probability layer was generated. The District Disaster Management Plan (DDMP) reports collected from 13 coastal districts of Tamil Nadu were considered and used as validation for flood prone regions. After the validation, the micro-administrative units such as villages and wards were classified on 0–1 scale, where 0 denotes very low and 1 is for very high.

2.3 Surface run-off potential

Numerous hydrologic methods have been used for estimating surface runoff. These models vary from simple to complex and differ in structures and data requirements. The NRCS-CN is more widely used for estimating the surface runoff due to its simplicity, predictability, stability, applicability for ungauged

watersheds (Kumar et al., 2017; Singh et al., 2011). The NRCS-CN method proved to be an effective method for estimating surface runoff of flood risks in prone regions, which does not have runoff records (Bharathi and Balasubramani, 2015). The Land Use/Land Cover (LU/LC) map prepared using LANDSAT 8 and Google Earth images, and Soil data of the National Bureau of Soil Survey and Land Use Planning (NBSS-LUP) obtained through the European Digital Archive of Soil Maps (EuDASM) were used to prepare layers for NRCS-CN method. The weighted values were calculated based on the curve number and the land use – soil group units. The overlay technique in GIS has been used for intersecting the soil map and LU/LC map and to generate the surface runoff potentials (Curve Numbers) for different land-use-soil group. To cognizance the risk of floods due to seasonal rainfall activity, long-term rainfall data extracted through the POWER (Prediction of Worldwide renewable Energy Resources) web services was used to prepare seasonal rainfall distribution map.

2.4 Vulnerability assessments

Vulnerability is a multi-dimensional complex subject and an attainment of composite vulnerability combining all major social and economic indicators at micro-level units is difficult task (McLaughlin and Cooper, 2010). It is preferable then to compare the available indicators on a relative scale. Therefore, the social repercussions of floods in 5,020 villages/wards are examined using census and household data (2011) to determine the relative degrees of socio-economic vulnerability. All the available direct and indirect indicators that impact the socio-economic vulnerability of coastal regions were retrieved after a comprehensive examination of District Census Hand-Books (DCHB) and Primary Census Abstracts (PCA). The indicators used in the study and methodology of the arriving composite socio-economic vulnerability is explained in Balasubramani et al., (2021). Overall, in this study, the vulnerability is classified into five classes from very low to very high, which corresponds to the scale of 1 to 5, where 1 denotes very low vulnerability and 5 denotes very high vulnerability.

2.5 Focused group interview of deprived communities

A community-based interviews are essential for realizing the disaster impacts and challenges (Mohapatra, 2009). A focused group interview of deprived communities is carried throughout the entire coastal plains of Tamil Nadu covering the villages at a radial distance of every 5 to 10 kilometers and all major towns. A total of about 514 responses were collected during 2020-21 across the coastal Tamil Nadu. The locations of conducting group interviews in each selected villages/towns were decided on the basis of built-up structures (mainly the poor structures), socio-economic fabrications of the locality and susceptibility to floods. Pre-determined questions in online/offline form were used to ask in the group of people and based on the majority responses appropriate options were picked-up from the pre-filled responses for uniformity. Although the field study consists of many questions related to flood risks, the major questions considered in the study are flood frequency, flood exposure, flood impacts, flood challenges, average time to recover, government assistance, and average economic loss. All the responses were scaled 1 to 5 and categorized into five classes from very low to very high.

2.6 Built-up area flood risk assessment

The built-up area of the study area is extracted from high resolution ArcGIS and Google Earth images. Based on visual interpretations, built-ups were classified into 30 different categories based on the type of built-ups, density, floor, and planning. The categorized built-ups were compared with flood hazard layer and a matrix was formed, where very dense buildings in high flood prone region were given higher rank (5) and sparse buildings in low flood prone region were given lower rank (1). The ranks were normalized by built-up area and rescaled into 0–1 scale.

3. Results

3.1 Hazard analysis

The purpose of flood hazard mapping is to determine the area and probability of inundation. In the study the probability of flood inundation is determined on a scale of 0–1 and the distribution is represented in Fig. 3. Out of 5,020 villages/wards, 1,464 villages/wards reported with varying probability of flood inundation. The southern zone which comprises Kanniyakumari, Thoothukudi, and Thirunelveli districts comes under low to very low inundation probability, except some parts of the Kanniyakumari district and surrounding regions of Thoothukudi where the inundation probability is moderate. The central zone is marked with absence of major flood events in the past due to low seasonal rainfall and presence of numerous flood management tanks. In the northern region, probability of flood inundation is very high in parts of the Cuddalore, Kancheepuram, Chennai and Thiruvallur districts.

3.2 Surface run-off potential

The surface run-off potential was assessed on the basis of Curve Number where higher value (> 90) denotes more potential risks exists for flood events during heavy rainfall events (Fig. 4). In the southern coastal regions, especially in the Teri sands of Thoothukudi and Thirunelveli districts, the risks of peak surface runoff is very low. Such very low run-off risks can also be noted almost all along the shorelines, especially where beaches are prominent. In contrast, the Cauvery deltaic system and northern areas of Thoothukudi observed with high runoff potentials due to the presence of fine clayey soils. Rainfall is the primary input for the surface runoff. From the long-term rainfall distribution map presented in Fig. 5, it is observed that rainfall is comparatively is high in the Cauvery delta and northern areas of Thoothukudi. Therefore, these regions also have the risk of floods every year.

3.3 Composite vulnerability assessment

The vulnerability is assessed using exposure and capacity related vulnerability indicators and categorized into very low to very high, which is represented in Fig. 6. The vulnerability is very high in the northern parts and is most commonly noticed in Thiruvallur, Villupuram, Cuddalore and Cauvery delta regions. The low level of vulnerability is noticed in most of the villages of Ramanathapuram, Thoothukudi, Thirunelveli, and Kanniyakumari districts.

3.4 Perceptions of deprived communities

The large area public perception survey revealed that the flood risks in the coastal plains are highly localized, owing to variances in the frequency of flood hazards and socio-economic conditions. According to the group interviews in the coastal plains and observations, residents in low-lying areas of large cities experiences flood threats with extremely high level. The flood challenges that include challenges like shortage of food and water, transportation cutoff, dysfunction of economy, crop loss, disease outbreak, and sanitation issues are very high in the parts of Chennai and delta regions (Fig. 7). The flood damage is calculated based on the damage caused to the people, their buildings, properties, and livestock. Except dry regions of Ramanathapuram, Thoothukudi and Triunelveli districts, most of the community perceived that there is a high risk of flood damage and exposure. The major loss due to the flood is lost lives/disabled, complete building damage, partial damage to houses, crop damage, livestock or poultry lost, property/vehicles lost, and vegetation/wetland loss. The reporting of major loss is frequently noticed in the delta regions. Except a few localities, most of the community perceived that the frequency of the flood is moderate to low.

The other details obtained from the group interview of deprived communities are the average time for recovery, government assistance, and average loss. About 56 % have responded that they have recovered within a week from the disaster and 10% takes more than six months to recover completely from the flood impacts. More than half of the population responded that they received compensation from the government. The average loss due to the flood is determined in the study by summing up economic loss due to house, property, crop, and livestock damages. The majority (41%) of people responded that the economic loss is less than 10,000 INR due to flood events.

3.5 Built-up area flood risk assessment

The built-up risk assessment detects the settlements which are at flood risk within the villages on a scale of very high to very low. The result of detailed built-up is grouped into A to G zone, from Chennai to Kanniyakumari for better visualizations and comparisons (Fig. 8). Zone A is Chennai where the risk is very high due to denser settlements. Zone B comprises Villupuram and Kanchipuram districts where the overall risk is moderate to low. Zone C is observed with very high risks that falls under Cuddalore district and Puducherry. All other zones are noticed with low to very low risks.

4. Discussion

Due to its physiographic structure, drainage system, and seasonal rainfall character, floods are frequent in India's eastern coastal plains (Mirza, 2011). The coastal plains of India are much prone to flood events and thousands of people are affected each year, a few hundred lives are lost, thousands are displaced, and many hectares of crops are devastated (Dube and Rao, 2005). Being a most populous part of Tamil Nadu, the coastal plains of Tamil Nadu are considered to be one of the most vulnerable regions in southern India. In the recent years, the northern parts of the coastal Tamil Nadu encountered multiple coastal hazards mainly the flood events. About two weeks of continuous rainfall caused floods in the

low-lying areas of Chennai-Cuddalore-delta region in 2005. The exceptional rains in the first week of December 2015, the worst in last 100 years, inundated heavily Chennai-Cuddalore region. In very recent, the cyclones Nivar and Burevi brought heavy rainfall to Chennai-Cuddalore and the delta region and made miseries to the low lying communities. The satellite based estimation, the landuse-soil based runoff potential, socio-economic indicators based vulnerability assessments, average seasonal rainfall studies, and even public perceptions on flood exposure are all reflected that the northern coastal plains of Tamil Nadu stretching from Nagapattinam to Chennai is threatened by floods. Floods occurred in the year 2015 in the Chennai region considered to be the worst-hit disaster in the century. Improper urban planning, change in land use, the encroachment of wetlands, improper drainage design, and structures are considered to be the causes. It made an impact on around 2 million people and costed around 421 lives (Ramaswamy et al., 2018). After Chennai, Cuddalore is the most affected and where around 60000 hectares of agricultural land were inundated. In contrast to Chennai metropolitan region, Villupuram-Cuddalore-delta region is modestly covered by agriculture land use and even inundation of water less than a feet for few days led to flood (crop) loss. This is evidenced in surface runoff potential layer and flood loss reported by deprived communities. Many studies on flood hazards attempted for this region but most of them focused on physical flood modeling of selected portion of this region rather than covering the whole stretch with all dimensions of flood risks.

Considering the vulnerability parameters, the majority of the villages in the northern coastal region fall under high to very high socio-economic vulnerability. A very high population density is noticed in this region with high proportion of primary workers, female population and socially weaker sections (Balasubramani et al. 2021). Despite the widespread flood occurrences in northern coastal plains and high socio-economic exposure, the local communities have learned to adapt to the impact of floods (Svetlana et al. 2015). This tendency is clearly noticed in the group interview responses that most of the people in this region perceived low to moderate flood exposure and challenges. However, the extreme rainfall events in future will create havoc in this region overnight if suitable precautionary measures are not in place. Since built-up is the surface expressions for economic/human activities and associated losses, the detailed built-up mapping with different categories was compared with flood hazard layer. The results clearly show that the northern coastal plains extending from Thiruvallur district in the north to Nagapattinam district in the South is covered by dense settlements and prone to flood hazard. For an instance, settlements in ten villages of Cuddalore district Pinnattur, Tillaividangan, Kundiyamallur, Sirupalaiyur, Tirttanagari, Tanur, Adinarayanapuram, Alappakkam, Puvanikuppam, Kambalimedu that are located near Kadilam river and Thenpennai river are categorized under very high hazard level. Therefore the outcomes of this study will substantially assist micro-level to state level administrators to frame suitable planning measures to mitigate the effects of flood hazard in the coastal plains of Tamil Nadu.

5. Conclusion

The physiographic form of the coastal plains of Tamil Nadu is susceptible to coastal floods. In this context, this study has comprehensively assessed the flood risks in the coastal plains of Tamil Nadu at micro-level scale through field surveys, satellite data, and published data sources. The hazard analysis

shows the most flood-prone region is found in Chennai-Cuddalore region. The surface runoff potentials and socio-economic vulnerability hint that Cauvery delta region is also susceptible to flood risks. The high proportion of denser settlements and the dominance of primary activities are further aggravated the situation and makes the northern coastal plains of Tamil Nadu as severe flood prone regions. To reduce disaster risks and ensure sustainable socio-economic development, these regions should undertake disaster mitigation measures and effective disaster preparedness strategies. The information generated through this study can be used as baseline data to identify the micro administrative units that to be prioritized for undertaking preventive measures. A much localized flood mitigation measures should be implemented in northern coastal plains of Tamil Nadu to reduce disaster risks and achieve sustainable socio-economic development. The methodology proposed in the study can be extended to all flood prone regions of the country for effective flood risk management.

Declarations

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Author contribution:

Rasme Allat V – Writing original draft and data collection

Leo George - Data collection and GIS analysis

Arun Prasad K. – Satellite data processing and methodology

K. Balasubramani: Conceptualization, methodology, supervision, and revision

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Figures

Figure 1

Location of the study area with micro-level administrative divisions and major disaster events. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country,

territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

Schematic representation of the methodology adopted in the study

Figure 3

Flood hazard in the coastal plains of Tamil Nadu. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 4

Surface runoff potential in the coastal plains of Tamil Nadu. Higher the curve number denotes more the surface runoff potential. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 5

Average seasonal rainfall (1980-2017) in the coastal plains of Tamil Nadu. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Spatial distribution of composite socio-economic vulnerability in the coastal plains of Tamil Nadu (after Balasubramani et al., 2021). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 7

Spatial distribution of perceptions on A) flood challenges B) flood damage C) flood exposure D) flood loss and E) flood frequency. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 8

Spatial distribution of built-up area flood risk assessment. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

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