



Flood hazard mapping using geospatial techniques and satellite images—a case study of coastal district of Tamil Nadu

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Abstract In recent years, extreme rainfall events have resulted in several devastating floods especially in the east coast of Tamil Nadu, India. The main aim of this study is to identify the flood hazard zones in Cuddalore district by integrating spatial distribution of extreme rainfall events, slope, drainage density, soil, and geomorphology. Moderate Resolution Imaging Spectroradiometer satellite data was used to delineate the flood inundation area for the flood event which occurred in 2010 to validate the derived flood hazard zones by using geographical information system (GIS) and satellite images. The ground truth points were collected from the field to validate flood hazard zones, and it was identified that 92% of results were matched with hazard zones. Highly vulnerable blocks including Cuddalore, Kattumannarkoil, Keerapalayam, Kumaratchi, Kurinjipadi, Melbhunagiri, and Parangipettai were identified in Cuddalore district. From this study, it was also identified that nearly 45% of the total area of 3678 km² were inundated during the flood time. This present study will be a very useful tool and a resource for the policy planners and coastal planners to make effective decisions towards mitigation measures in flood-prone areas in the coastal districts.

Keywords Rainfall events · Spatial mapping · Weighted overlay analysis · MODIS and GIS

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Introduction

Flood is an overflow of water that submerges land areas due to excessive rainfall events within a short period of time. Flood is the most frequent natural disaster in the world which is widely distributed leading to significant damages to human lives (DMSG 2001), infrastructures, and livelihood, and also accelerates soil erosion. An extreme rainfall event may turn into a heavy flood in a short period of time. About 196 million people in more than 90 countries were exposed to catastrophic flooding, and 170,000 deaths were associated with floods worldwide between 1980 and 2000 (UNDP 2004). According to the National Oceanic and Atmospheric Administration (NOAA 1998), a flood is a flow of water above the carrying capacity of a channel. Worldwide, there is an estimation of about 1.5 billion people who were affected by floods in the past decades in 21 centuries (Khole and De 2001; De and Dandekar 2001; De et al. 2013). It has become extreme and widespread due to extreme weather events (Guhathakurta et al. 2011; Tongdi et al. 2008). Climate change is playing a significant role in inducing this extreme rainfall which is visible in the recent decades. Climate model simulations and empirical evidence confirm that warmer climates owing to increased water vapor lead to more intense precipitation events and therefore increase risks of floods (Hennessey et al. 1997; IPCC 2007). As per the Intergovernmental Panel investigation on Climate Change (IPCC 2007), the wet extremes are projected to become more severe in the future and mean precipitation is also expected to be on the rise. The findings of extreme rainfall events could be useful in

terms of flood management, as in the recent years, many places over India experienced heavy rainfall events. Recent examples would be events which happened due to multi-day cloud burst which was centered in the states of Uttarakhand, and Jammu and Kashmir during 2013 and 2015, respectively. Further, the consecutive flash floods in the three major metro cities in India experienced excessive rainfall in the year 2005 i.e. Mumbai in July 2005, Chennai in October and December 2005, and Bangalore in October 2005, which caused heavy damages to the loss of human lives, properties, livelihood, systems, infrastructures, and public utilities.

Floods have been a major reason for natural disasters in India because of its frequency, estimated to be around 41% of total disaster (De et al. 2005). ISMR (Indian Summer Monsoon Rainfall) report an average for the whole of India and found that there has been stable rainfall for the past hundred and more years, but in some places, there has been an increasing trend in heavy rainfall like > 65 mm/per day (Sinha and Srivastava 2000). Extreme rainfall events have been experienced in India for the last hundred years from 1901–2004, and severe floods have been caused by major rainstorms (De et al. 2005). There has been also an increasing trend in extreme rainfall events during ISMR, especially in the last 50 years (Goswami et al. 2006).

Some of the studies on extreme rainfall events show that the frequencies of extreme rainfall events may increase in the future over the central parts of India (Goswami et al. 2006). In this aspect, the geographical location of the state of Tamil Nadu makes it as one of the most vulnerable maritime states in India, particularly to tropical cyclones and their associated storm surges. It is also frequently subjected to extreme weather conditions of flooding in coastal districts (Bal et al. 2015). In this context, the Cuddalore district of Tamil Nadu state is experiencing these severe floods frequently due to its geographical location as it is situated near the coast of the Bay of Bengal. Several districts of the Tamil Nadu have battled floods during November and December 2015 when an area of the deep depression formed over the Bay of Bengal and dumped heavy rainfall across parts of the state. The El Niño effect, in particular, has played a vital role in this deep depression (Szynkowska 2015). The Cuddalore district in Tamil Nadu was particularly affected badly, and about 27 people died during the first few days of the heavy rainfall. A recent official report also says that Neyveli in Cuddalore district received 437 mm of rainfall on 9 November 2015 (Jesuraj et al. 2016).

Flood hazard mapping is a vital component for policy planners to identify the areas which are vulnerable to floods. Furthermore, flood hazard zone mapping will be significantly important for urban planning and risk management. Although it is impossible to evade the causes of floods, it is possible to reduce the impacts of events by taking prior efforts. Worldwide, weighted overlay analysis using GIS, a powerful and user-friendly tool in integrating many relative hazard thematic layers to map the flood hazard zone, is recognized. The utilization of remotely sensed data in GIS for the environment has proved to be one of the most resourceful approaches for flooding assessment and risk analysis (Jayasselan 2004; Ishaya et al. 2009; Irimescu et al. 2010). These parameters will also play a major role in the hydrological study.

This present study focuses on flood hazard zone mapping over the Cuddalore district through optical remotely sensed data combined with GIS techniques. In this aspect, elevation is one of the most important parameters, which determines the vulnerability of coastal lands to inundation from flooding events and SLR (Sea Level Rise). For all kinds of flood hazard mapping, the digital elevation model (DEM) is one of the key parameters to derive slope condition, drainage, and watershed. The coastal inundation impact assessments require DEM to identify low-lying lands which are at risk (Gesch 2009). There is a need to identify the areas which are under risk of flooding from sea level rise (SLR) through DEM for effective coastal management (Harry et al. 2018). DEM is a gridded geospatial data which can be used to model flood by combining with satellite data through GIS techniques to acquire the relationship between flood extent, elevation, and discharge with reasonable accuracy (Smith 1997; Younghun et al. 2014). For the lake Poyang at China, the study integrated two DEMs and 13 Landsat data to obtain the relationship between lake level and flood inundation area and revealed the estimation of water elevation at medium to high flow, showing higher accuracy (Qi et al. 2009). In this study, the parameters have been selected based on different case studies for multi-criteria analysis. Further, the drainage of water is very important in controlling the hazards in the ecosystem, as its density denotes the nature of the soil and its properties (Pareta 2004). The drainage density is defined as the total length of streams of all orders

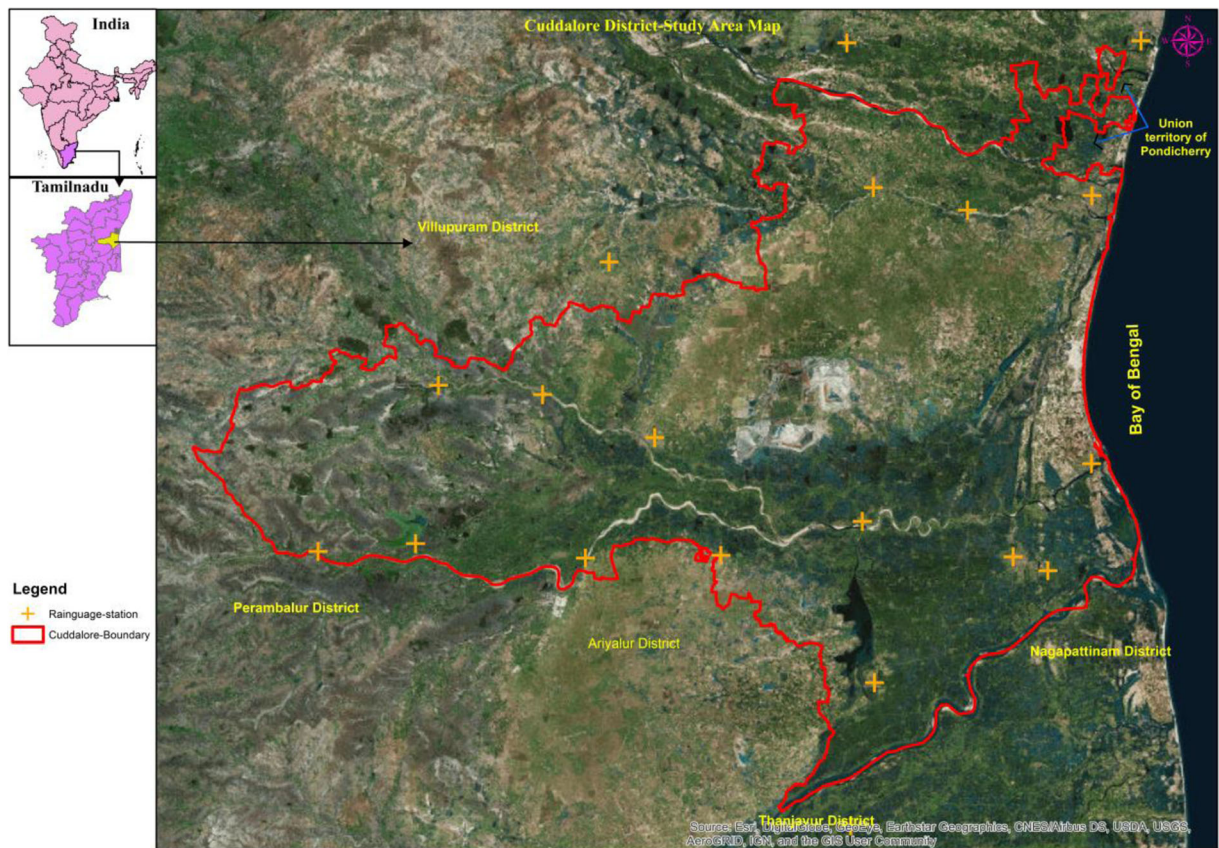


Fig. 1 Cuddalore district map

per drainage area (Horton 1945a). Also, soil types in an area control the amount of water that can infiltrate into the soil which becomes as flow (Nicholls and Wong 1990). The soil distribution can be derived from the spectral characteristics of remotely sensed data based on its spectra (Boettinger et al. 2008; Mohamed 2017). Several studies were conducted to map the soil distribution using IRS-1C, LISS III, and PAN data at 1:25,000 to 1:12,500 scales, which could be generated through the combination of these data (Kudrat et al. 2000). The reflectance spectra represent real physical properties on the earth surface. The quantitative relationships between soil and satellite measured reflectance can be used to predict soil distribution. Therefore, soil distribution can be derived from spectral data through various analysis methods such as principle component analysis, and unsupervised and supervised classification. Hence, the main objective of this present study is to assess the flood inundation area and the spatial impact of the flood which occurred during November 2010 in the district

of Cuddalore using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data and also to validate the derived flood hazard zone.

Study area

Cuddalore district is situated between 78° 52' 37" to 79° 46' 9" E longitude and 11° 52' 33" to 11° 9' 3" N latitude. It covers an area of 3678 km². It is one of the largest industrial districts in the state of Tamil Nadu. It is a low-lying coastal district having four major river basins namely Ponnaiyar, Paravanar, Vellar, and Cauvery and 23 rain gauge stations as shown in Fig.1. It is frequently subjected to extreme weather conditions of flooding mainly in coastal areas. The average annual rainfall ranges from 1050 to 1400 mm. The rainfall intensity is more towards eastern part and reaches a maximum rainfall of around 1051.3 mm over Virudhachalam, 1402.6 mm over Chidambaram, and 1347.1 mm over Parangipettai blocks.

Table 1 Historical extreme rainfall events (*NF-Not Functioning)

Years	Date	Annamalai Nagar	Chidambaram	Cuddalore	Kattumailur	Kattumannarkoil	Keelacheruvai	Kothavacheri	Kuppanatham	Memathur	Parangipettai	Panruti	Pelandurai
1983	23/12/1983	180.4	181	154	135.0	NF	180.0	NF	NF	100.0	NF	NF	22.0
1985	11/11/1985	165	148	177	NF	82	85.0	NF	NF	132.0	NF	NF	77.3
1988	06/11/1988	233.1	187	183	30.0	96	32.0	NF	31	30.0	NF	NF	58.0
1991	15/11/1991	145.0	158	69	199.0	270	150.0	NF	40	130.0	NF	NF	240.0
1991	16/11/1991	29.0	11	84	110.0	10	154.5	NF	61	39.0	NF	NF	162.0
1993	05/12/1993	109.0	40	8	120.0	72	125.0	NF	NF	66.0	NF	NF	202.0
1996	09/12/1996	178.5	184	134	35.0	135	50.0	NF	86	35.0	NF	NF	81.0
1996	11/12/1996	141.0	151	132	125.0	144	118.0	NF	143	100.0	NF	NF	109.0
1996	14/12/1996	69	71	124	160.0	137	230.0	NF	240	135.0	NF	NF	124.0
1996	15/12/1996	69	82	43	116.0	182	180.0	NF	86	92.0	NF	NF	85.0
1998	04/11/1998	161	185	134	126.0	162	222.0	NF	120	106.0	NF	NF	138.0
1999	21/11/1999	160	120	102	85.0	195	202.0	NF	180	100.0	NF	NF	180.0
2000	29/11/2000	141	15	16.2	85.0	15	442.0	12	3.9	75.0	42	7.5	184.0
2004	04/05/2004	150	114	148.4	58.0	90	113.0	182	146	35.0	55	110	133.0
2004	30/10/2004	160	152	49.7	120.0	87	126.0	93	105	155.0	70	112	96.0
2005	24/11/2005	140	102	154.2	130	164	243	114	134	136	110	374	168
2007	25/10/2007	247	203	95.3	65.0	195	28.0	185	88.6	75.0	138	138	97.0
2008	24/11/2008	134	100	94.7	118.0	72	115.0	121	130.6	121.0	150	59.2	95.0
2008	26/11/2008	271	284	217	92.0	235	56.0	250	44.2	63.0	277	110	91.0
2008	27/11/2008	71	189	104.8	125.0	243	115.0	201	115.2	89.0	168	16	101.0
2010	27/11/2010	191	202	203.8	102.0	NF	140.0	271.5	224.7	155.0	NF	159.6	223.0

Years	Perambalur	Sethiyathope	Srimushnam	Tholudur	Thuraiyur	Ulundurpettai	Vanamadevi Anaicut	Vembavur	Veppur	Virudhachalam	Virudhachalam	Virudhachalam	Anaicut
1983	197.2	120.7	72.2	159.0	148.6	163.6	113.2	NF	NF	178.4	NF	175.0	
1985	42.0	132.2	NF	84.0	33.6	79.6	168.4	NF	NF	96.2	NF	125.0	
1988	12.0	86.0	NF	30.0	8.2	36.6	170.4	NF	NF	48.0	NF	40.0	
1991	58.0	213.0	120.0	178.0	99.6	101.0	105.2	NF	NF	197.0	NF	255.0	
1991	26.2	19.0	30.0	146.0	27.2	61.0	12.2	NF	NF	152.0	NF	206.0	
1993	90.0	88.5	147.0	174.0	74.8	140.0	86.3	NF	NF	122.0	NF	135.0	
1996	29.0	158.5	95.0	205.0	21.4	50.0	93.0	NF	NF	120.0	NF	85.0	
1996	34.0	195.5	133.0	25.0	53.2	170.0	143.5	NF	NF	144.0	NF	120.0	
1996	38.0	196.0	127.0	NF	28.8	97.0	54.1	NF	NF	239.0	NF	246.0	
1996	35.0	115.0	89.0	NF	12.2	91.0	115.3	NF	NF	79.5	NF	86.0	
1998	99.2	287.0	110.0	116.0	82.6	134.5	149.3	NF	NF	127.0	NF	97.0	
1999	14.4	108.5	132.0	178.0	NF	0.0	104.2	NF	NF	92.0	NF	80.0	

Table 1 (continued)

Years	Perambalur	Sethiyathope	Srimushnam	Tholudur	Thuraiyur	Ulundurpettai	Vanamadevi Anaicut	Vembavur	Veppur	Virudhachalam	Virudhachalam Anaicut
2000	83.2	161.0	108.0	445.0	NF	2.5	45.2	NF	NF	256.0	240.0
2004	96.0	132.0	70.0	104.0	98.0	105.0	216.2	71	61	145.0	NF
2004	85.0	235.0	160.0	100.0	53.0	195.0	157.2	32.5	125	168.0	NF
2005	237	147	150	240	-	167	136	220	110	137	130
2007	74.0	242.0	60.0	144.0	66.0	50.0	96.2	15	26	62.0	NF
2008	37.0	113.0	45.0	145.0	42.0	60.0	90.2	48	115	129.0	NF
2008	32.0	270.0	120.0	62.0	10.0	55.0	164.0	36	86	92.2	NF
2008	139.0	210.0	150.0	134.0	37.0	45.0	94.4	95	122	87.8	NF
2010	46.0	217.5	205.0	205.0	34.0	168.0	233.2	NF	90	235.0	NF

Materials and methods

Flood hazard zone mapping

A study was conducted on flood hazard assessment in the Cuddalore district by integrating the following spatial distribution of extreme rainfall, slope, drainage density, soil, and geomorphology using GIS to propose a flood hazard zone. Based on this analysis, a flood hazard zone map was developed to identify very high, high, medium, low, and very low flood vulnerable zones. The developed flood hazard map was validated with MODIS satellite imagery flood inundation map. Thematic layers were derived from satellite imagery, and the data was processed through ArcGIS version 10.1 for on-screen digitalization. The detailed methodology is described as follows.

The daily rainfall data was obtained from 23 rain gauge stations of Cuddalore district. The observed daily rainfall data for a period of 31 years (1980–2010) have been analyzed to identify the extreme rainfall events in Cuddalore district. The major extreme rainfall events recorded in each station are tabulated in Table 1.

The extreme rainfall event was varying from 124.4 to 244.4 mm/day. As per the various classifications of daily rainfall intensity provided by India Meteorological Department (IMD), if the rainfall amount was between 124.5 and 224.4 mm/day, it was considered as extreme rainfall events (Rajeevan and Bhate 2008). Flood happens when the precipitation occurs more than 100 mm in a few hours of the triggering rainfall (Gaume et al. 2009). In this context, this study is more focused on extreme rainfall events as one of the major parameters for flood hazard mapping. The IMD rainfall classification based on intensity is shown in Table 2.

The spatial distribution of one such extreme rainfall event was mapped for the year 2010, and the flood which occurred on 27 November 2010 shown in Fig. 2 indeed was one of the major flood events which caused huge damages in the whole district in terms of human loss, livelihood, infrastructure, and agriculture.

Three events in consecutive day extreme rainfall occurred in the mid of November 1991, end of December 1996, and mid of November 2008. Extreme rainfall events were high in November than in December in terms of occurrence. There was only one extreme rainfall event which occurred in 2004 during other seasons

Table 2 Rainfall classification intensity

S. No.	Range	Classes
1	0.0 mm	No rain
2	0.1 to 2.4 mm	Very light rain
3	2.5 to 7.5 mm	Light rain
4	7.6 to 35.5 mm	Moderate rain
5	35.6 to 64.4 mm	Rather heavy
6	64.5 to 124.4 mm	Heavy rain
7	124.5 to 244.4 mm	Very heavy rain

Source: India Meteorological Department

and 20 events occurred during the season of the north-east monsoon (October, November, and December) in the past 31-year period. De et al. (2005) also stated that 500 people were killed in Tamil Nadu due to the flood in November 1977. Districts including Madurai, Tiruchirappalli, and Pudukottai which were severely

affected and crops worth Rs. 42 crores were damaged, and it was also reported that severe damage was done to private and public properties worth Rs. 155 crores.

Soil types

The water-holding capacity and infiltration characteristics of an area are determined by two important factors, soil type and texture (Nyarko 2002). In this study, the whole Cuddalore district was divided into 11 soil types. The soil map was derived from LISS III image with the spatial resolution of 23.5 m. The soil map was obtained from the Disaster Management Cell, Government of Tamil Nadu. Based on the infiltration capacity, the weightage has been assigned to each soil type. Sand and clay types of soil are found along the Pennaiyar River. The coastal area of the district is covered by sand, sandy loam, sandy clay loam, and clay. Silty clay loam, sandy loam, is noted in Coleroon River. The western part of the district is

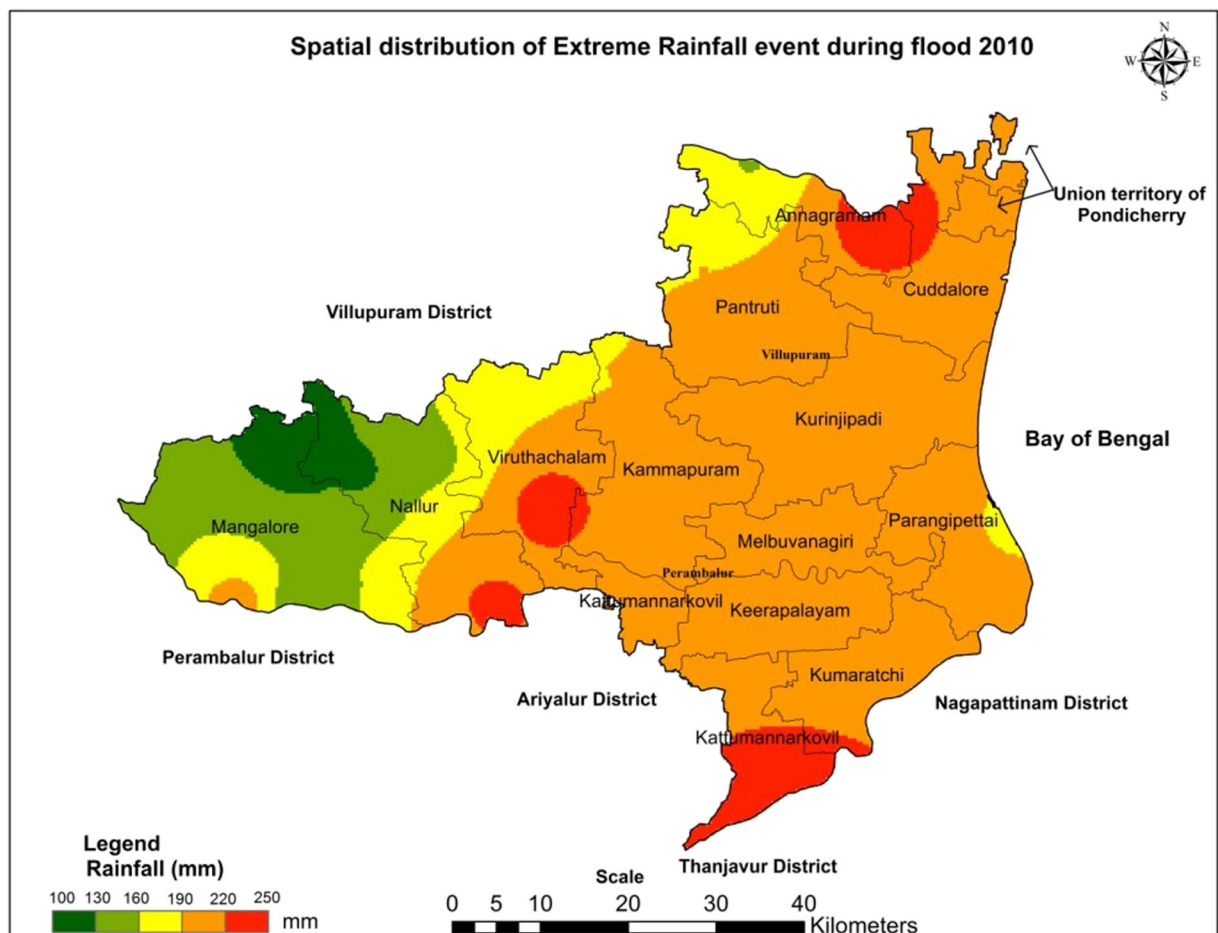


Fig. 2 Spatial distribution of extreme rainfall event during 2010

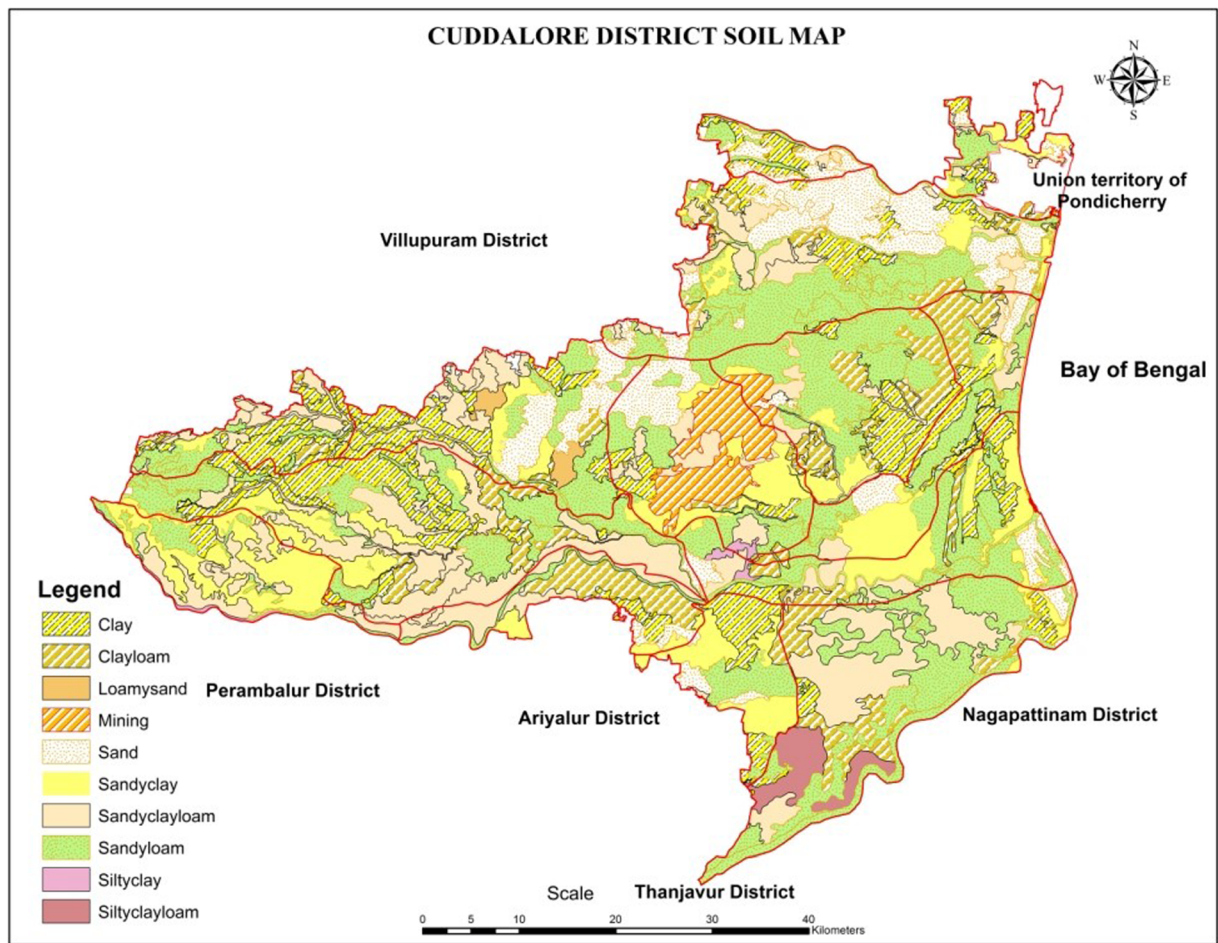


Fig. 3 Soil map of Cuddalore district

surrounded by a maximum of clay type, and the rest of the district is of other types (Fig. 3). The distribution of soil covered in the study area is given in Table 3.

Table 3 Different soil types details

S. No.	Types of soil	Area in km ²	Area of the soil %
1	Clay	460	12.5
2	Clay loam	271	7.3
3	Loamy sandy	21	0.5
4	Sand	320	8.7
5	Sandy clay	396	11.1
6	Sandy clay loam	635	17.2
7	Sandy loam	1420	38.6
8	Silty clay	13	0.3
9	Silty clay loam	43	1.1
10	Mines	99	2.6
Total		3678	100

Geomorphology

The damages are not only because of the amount of rainfall occurs but also a consequence of geomorphological factors and influences of human activity (Maruša et al., 2014). The geomorphological map was prepared for the study area using satellite images, and the entire Cuddalore district was broadly divided into 13 major geomorphic classes. It was found that the western part of the district was covered by a pediment, buried pediment shallow, buried pediment moderate, and buried pediment deep. In the lower part of the western region, floodplain was found along the river course. The most part of the northern district comprises interfluvial, alluvial plain, duricrust, deltaic plain, and buried channels. The northeastern part of the area was mainly covered by upland tertiary. Old deltaic plain, young deltaic plain, deltaic plain, old beach terrace, mud

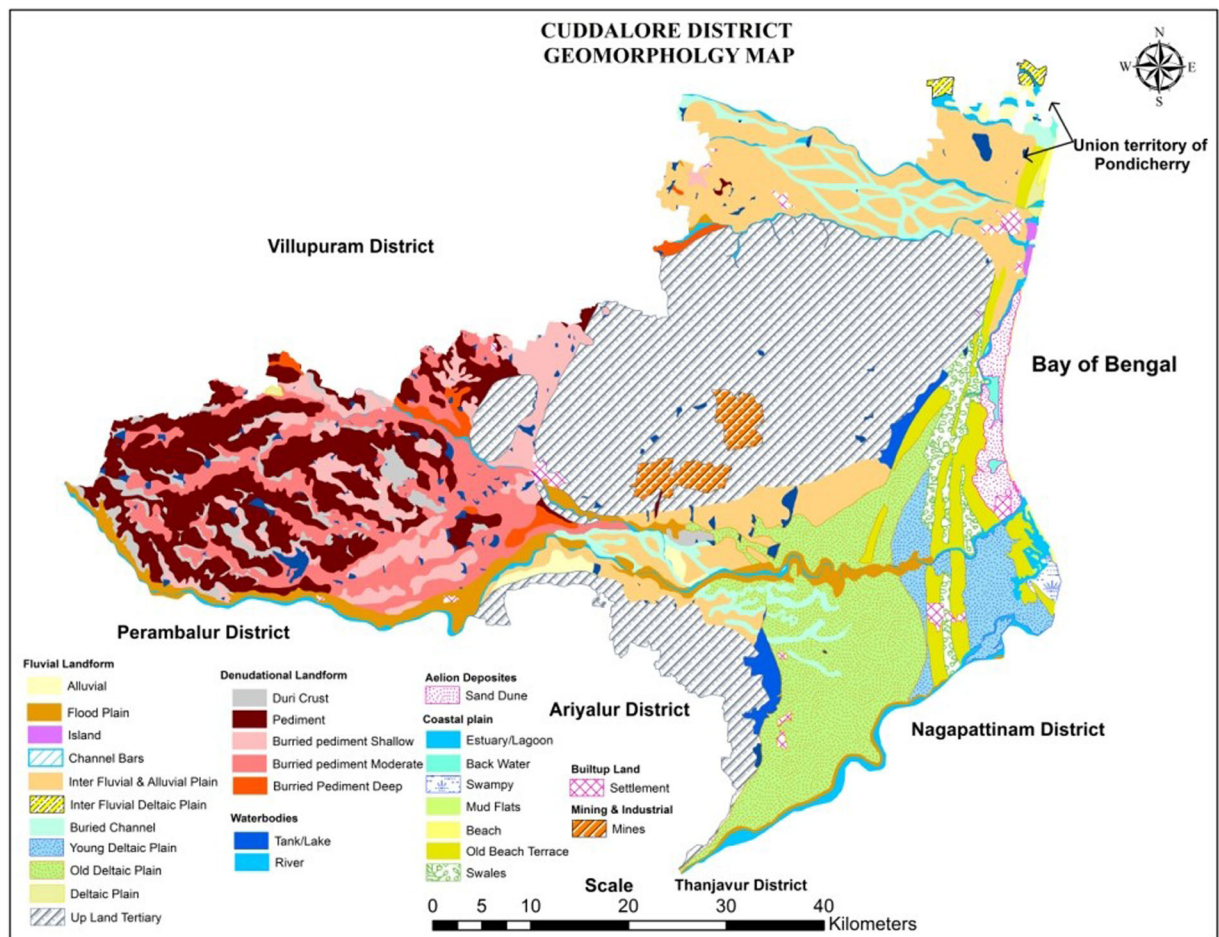


Fig. 4 Geomorphology of Cuddalore district

flats, estuary, lagoon, and sand dune are noted in several places of the eastern coastal area of the district (Fig. 4).

Weighted overlay analysis

The weighted overlay analysis was performed by integrating five thematic layers namely spatial distribution of extreme rainfall, slope, drainage density, soil, and geomorphology. The input criteria raster was weighted, and the influence of the raster compared to the other criteria was 100%. The values were rounded off to the nearest integer, and the sum of influences was equal to 100. The weighted overlay tools were scaled, and the input data on a defined scale (the default was 1 to 9) weighted the input raster and added them together. The rank on a scale of 1 to 9 was assigned to each class of the individual layer

which was depended on their potential hazard level for flood (Table 4). The more favorable locations for each input criterion were reclassified to a higher value of 9. In the weighted overlay tool, the weights assigned to the input raster must be equal to 100%. The layers were multiplied by the appropriate multiplier, and the resulting values were added together for each cell. The weighted overlay was assumed that the more favorable factors resulted in the higher values in the output raster, therefore identifying these locations as being the best.

The weightage was assigned by taking opinion from Public Works Department Engineers, and Hydrology and Flood Experts. The questionnaire survey was also conducted at a household level in the study area, and it was used to assign weightage for each class of all the parameter for the multi-criteria analysis. Hence, based on the expert knowledge and

Table 4 Scale and weightages for thematic layers of the flood hazard zone

Thematic layer	Attribute data	Scale value (Rank)	% of influence
Rainfall	70–124.5 mm	7	30
	124.5–244.4 mm	8	
	> 244.5 mm	9	
Slope	0–0.5%	9	15
	0.5–2%	8	
	2–5%	7	
	5–10%	6	
	> 10	5	
Drainage density	0.2–0.6 km/km ²	9	20
	0.6–1.0 km/km ²	8	
	1.0–1.4 km/km ²	7	
Soil	Sand	1	15
	Loam sand	2	
	Sandy loam	3	
	Loam	4	
	Sandy clay	5	
	Clay loam and sandy clay loam	6	
	Silty clay loam	7	
	Silty clay	8	
	Clay	9	
Geomorphology	Sand dunes and pediment	2	20
	Upland tertiary	3	
	Buried channel, buried pediment (deep, moderate, and shallow)	4	
	Swampy, swales	5	
	Sand dunes, channel bars, duricrust	6	
	Mudflat	7	
	Beach, old beach terrace	8	
	Flood plain, river, tank, lakes, estuary, lagoon, backwater, alluvial, inter-fluvial, alluvial and deltaic plains, and old and young deltaic plains	9	

by understanding the influence of different thematic layers to flood, the different weightage was assigned to each layer. The thematic layers were converted into raster grids and integrated through GIS. The cell size assigned was 30 m × 30 m. Finally, the flood hazard zone map was derived by comprising of different vulnerable zones. The output map was validated in the field at 72 places over the area, and out of which, 92% of the area was matched. Further, the comparison was performed between the flood hazard map and real-time flood inundated map derived from MODIS by using Normalized Difference Water Index (NDWI).

Flood inundation mapping using MODIS satellite data

It is essential to monitor the flooded area on site using real-time or near-real-time satellite data for appropriate flood disaster management and to minimize the risk of the event. There is a need to provide a quick flood inundation map during the flood event which in turn can provide essential information for decision makers to put relief measures in the area (Amarnath 2013). In Cambodia, the flood inundated area was detected during the flood season using MODIS-based vegetation cover product (Zhang et al. 2002). To analyze the flood inundation mapping, MODIS satellite image was acquired

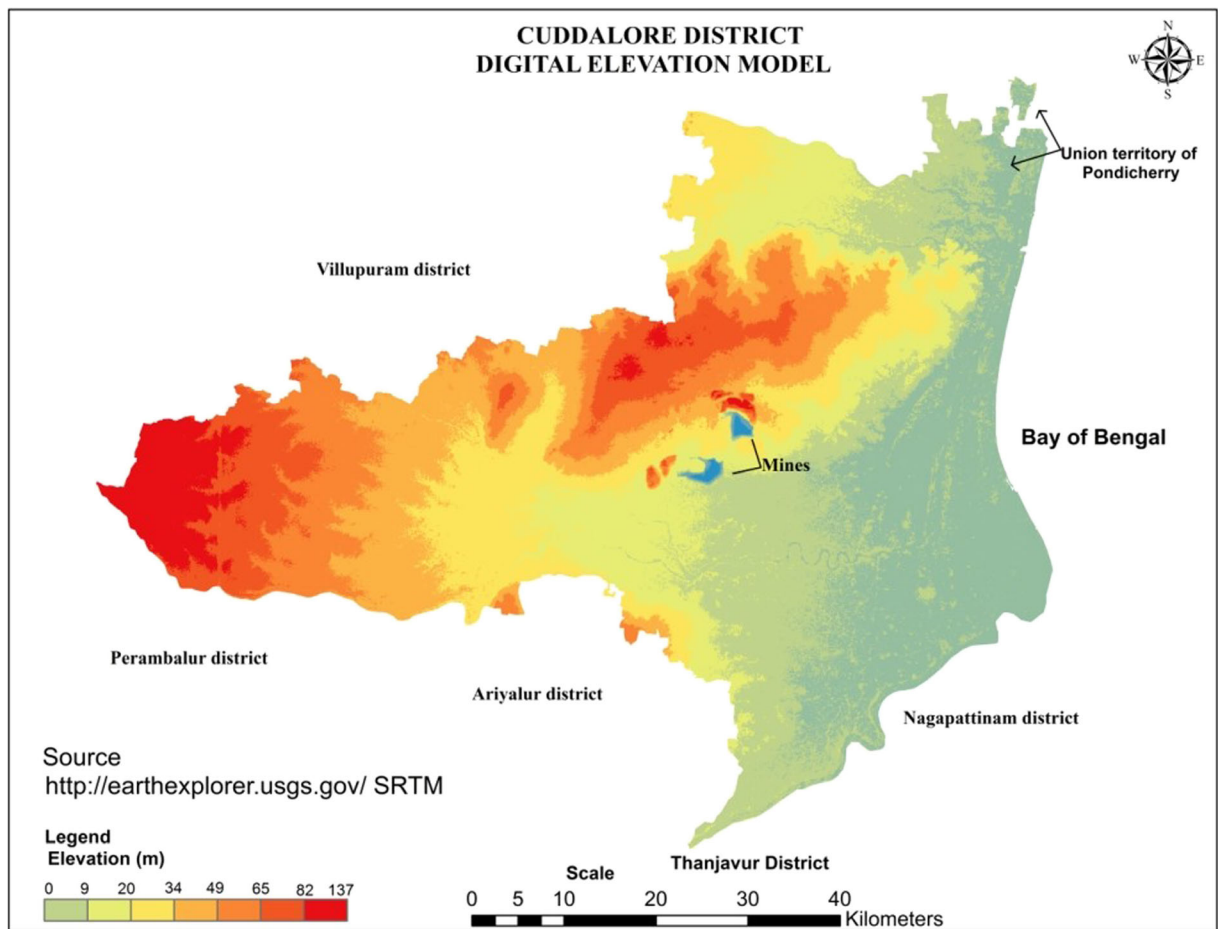


Fig. 5 Digital elevation model of Cuddalore district

through remote sensing technique and was downloaded from the NASA’s website <http://earthexplorer.usgs.gov> (LP DAAC) for the year 2010 when the flood disaster hit the district. The data type was MOD09A1 with 250-m spatial resolution. MODIS data were used to derive flood inundation map using the Normalized Difference Water Index (NDWI) from the combinations of the near-

infrared (NIR) and shortwave-infrared (SWIR) bands to detect the water surface (Gao 1996). NDWI was calculated as per the following equation:

$$NDWI = \rho_{NIR} - \rho_{SWIR} / \rho_{NIR} + \rho_{SWIR}$$

where ρ_{NIR} and ρ_{SWIR} are the reflectances of MODIS bands 2 (841–876) and 7 (2105–2155 nm), respectively. The final inundation map was used to validate the derived flood hazard zone map. The flood hazard zone and inundation map were derived for the same event which occurred in 2010.

DEM

The Shuttle Radar Topographic Mission (SRTM) data was downloaded (data source <http://earthexplorer.usgs.gov/>), which is used to prepare DEM and slope map using

Table 5 Classification of slopes

S. No.	Classes	Quantitative procedure
1	Level	0–0.5%
2	Nearly level	0.5–2%
3	Very gentle slope	2–5%
4	Gentle slope	5–10%
5	Moderate slope	10–15%

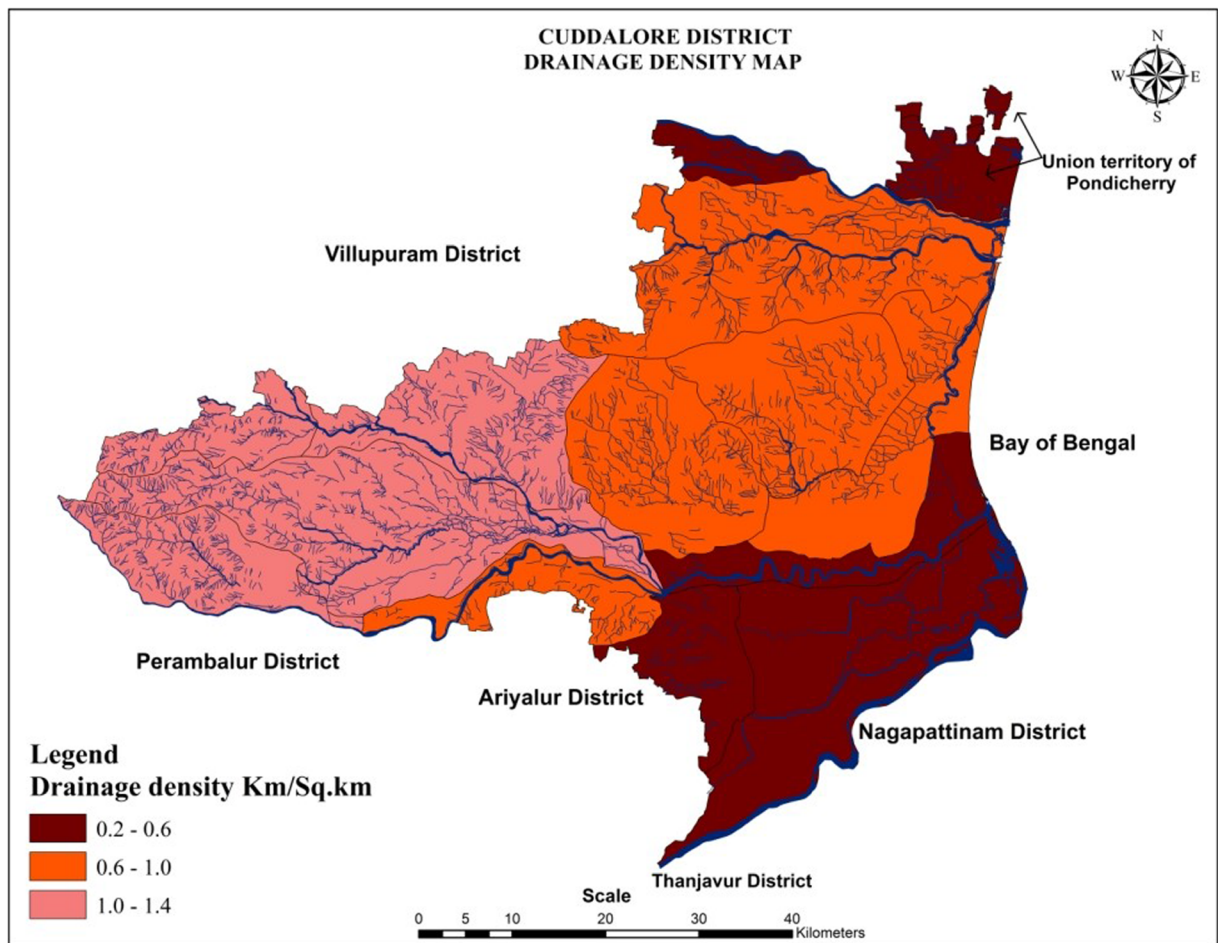


Fig. 6 Drainage density map

ERDAS and Arc Map 10.1 software. NASA (National Aeronautics and Space Administration) released free SRTM data for some region at 90-m resolution (approximately 3 arcsec) in 2003, presently 30-m data (approximately 1 arcsec) is available at <https://earthexplorer.usgs.gov/>. The contour map at 30-m interval was prepared from the Shuttle Radar Topographic Mission (SRTM) data, which is used to prepare DEM and slope map using the ERDAS software. A 30-m contour-based DEM produced slightly better results than the Shuttle Radar Topography Mission DEM (Shuhua et al. 2009).

A DEM is a physical model of the ground using a numerical array to represent a set of orderly ground elevations; it is also a branch of the digital terrain model (DTM) (Gao et al. 2018). In Cuddalore district, the large parts of the coastal zone are low lying and with a gentle slope, resulting in large inundation, and therefore increased the vulnerability of the

region (Saxena et al. 2012). There were some holes in the downloaded SRTM data. The potential of hydrological analysis may be hindered due to holes. An algorithm can be used to fill the holes through spatial analysis techniques such as interpolation method (Reuter et al. 2007; Jarvis et al. 2008). The inverse distance weighted (IDW) interpolation method was used to fill the holes to 30×30 -m pixel. The elevation values were varying from 0 to 137 m above mean sea level (MSL) as shown in Fig. 5. Slope is one of the primary and important parameters for effective flood study. Flood-related studies worldwide consider that slope is an important parameter to define flood. For the constructions of flood mitigation structures and rainfall harvest structure, the slope is the major criterion among others. A set of five slope classes has been provided for flood hazard zone from DEM as given in Table 5.

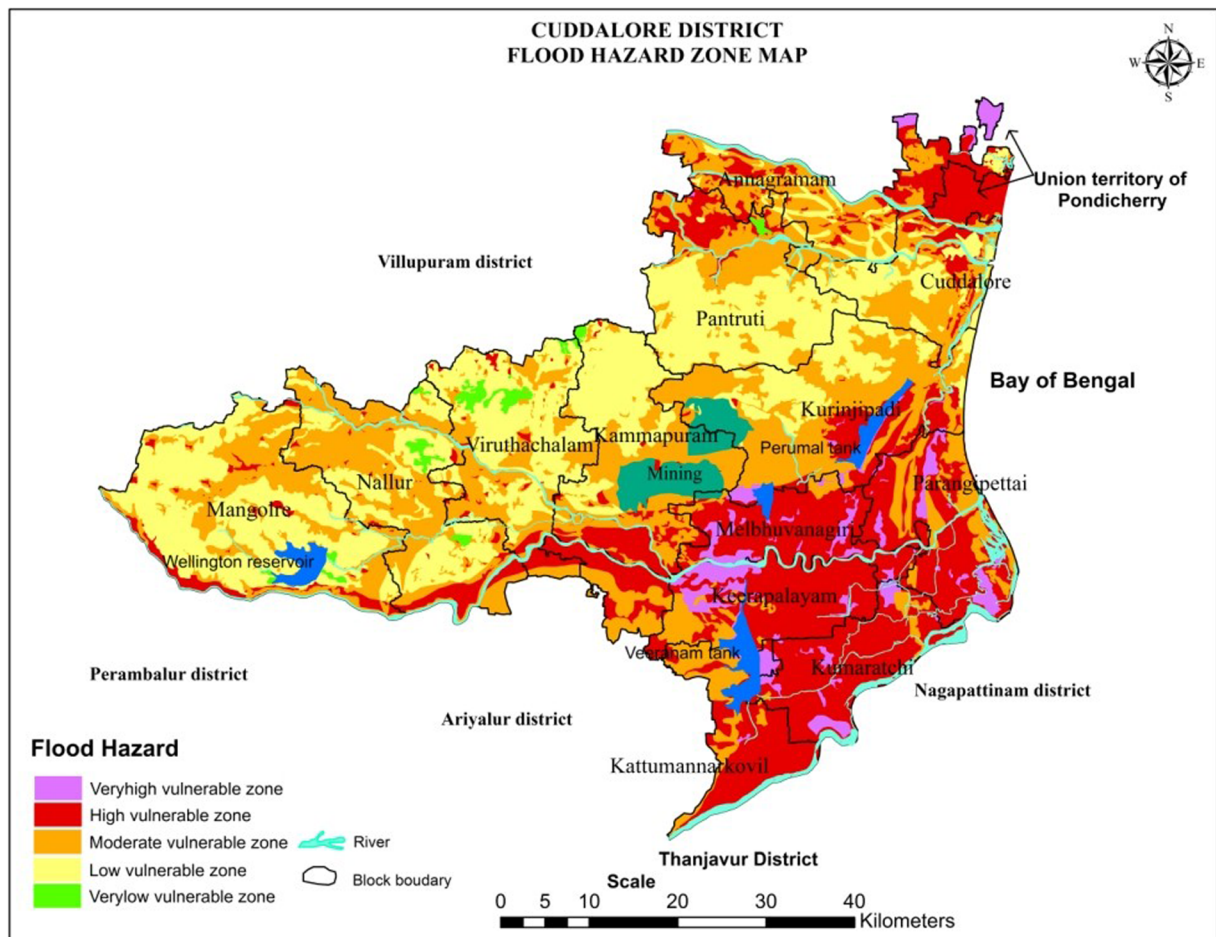


Fig. 7 Flood hazard zone map

Results and discussions

Rainfall distribution

Usually, Tamil Nadu receives more rainfall during the northeast monsoon season (October, November, and December) when compared to other seasons. Extreme rainfall events occurred mainly during the northeast monsoon which was triggered by cyclones in Cuddalore district in the last 30 years. The extreme rainfall event which was realized between 124 and 244 mm/day has been identified according to the Indian Meteorological Department of rainfall classification for the year 1980–2010. The group interview was conducted with PWD engineers and public in Cuddalore district to identify the intensified flood event occurred between 1980 and 2010. From the interview, it was concluded that the 2010 flood event had resulted in a huge loss of human lives, agriculture, and property than other events in

31 years. Finally, the 2010 extreme rainfall event was considered for flood hazard zone, and for the same event, the flood inundation map also was derived from the MODIS satellite data by adopting NDWI.

It was identified that this district has faced severe floods in the year 2010 (27 November 2010). The spatial distribution of the rainfall in Cuddalore district was mapped for the abovementioned years and presented in Fig. 2. The spatial range of rainfall was distributed between 100 and 250 mm/day for the year 2010, and more than 80% of the Cuddalore district has received 160–250 mm/day. Maximum rainfall was observed over Katturmanarkoil and anagram blocks within the range 220–250 mm/day, which comes under the very heavy rainfall to extremely heavy rainfall categories as per the classifications given by IMD. Parangipettai, Sethiyathope, Srimushnam, Chidambaram, and Annamalai Nagar received more than 250 mm. During the 2010 flood, the amount of rainfall received was 100 to 250 mm in a day.

Table 6 Flood vulnerable zone block-wise

Sl. No.	Name of the block	Vulnerable area in hectare					Total area
		Very high	High	Moderate	Low	Very low	
1	Annagramam	–	3547.83	11,121.81	2622.02	–	17,291.66
2	Cuddalore*	1319.28	7187.83	10,861.10	6906.13	–	26,274.34
3	Kammapuram	1.94	7958.02	13,776.20	12,372.84	186.75	34,295.75
4	Kattumannarkoil*	1275.13	14,822.63	7956.71	–	–	24,054.47
5	Keerapalayam*	3916.83	13,493.99	2789.26	–	–	20,200.08
6	Kumaratchi*	2041.89	16,630.31	935.52	–	–	19,607.72
7	Kurinjipadi*	2143.60	6922.98	21,729.80	10,608.45	–	41,404.83
8	Mangalore	–	4369.32	16,057.75	26,595.09	343.95	47,366.11
9	Mel Bhuvanagiri*	2877.18	13,554.55	1325.44	–	–	17,757.17
10	Nallur	–	3286.76	19,732.13	11,753.22	777.69	35,549.8
11	Panruti	–	4102.73	10,795.35	18,101.43	210.29	33,209.8
12	Parangipettai*	2707.82	14,705.21	5872.51	–	–	23,285.54
13	Virudhachalam	–	2333.53	11,179.10	15,903.31	1356.57	30,772.51

*Very high vulnerable block

Drainage density

Drainage density can be integrated with other parameters in GIS environment to identify the areas which are more likely to get flooded. The drainage network information can be taken from the topographic maps, but the development of satellite image-based elevation information for drainage networks have more accuracy (Forte and Strobl 2006). The drainage data was derived from DEM by using a hydrology tool in GIS. Further drainage density was analyzed by following a simple method developed by Horton (1945b) as expressed in the formula below:

$$Du = (El)/Au$$

where Du is the drainage density in km per square kilometer, (El) is the sum of the total length of streams in kilometer, and Au is the total area of drainage watersheds in square kilometer.

The drainage density was calculated for 14 watersheds present in the district. It was found that the drainage density value varies between 0.2 and 1.4 km/km². The lower Vellar, Coleroon, and upper Pennaiyar watersheds showed a very low drainage density, and flat slope areas are more likely to get flooded, indicating that these watersheds are highly vulnerable to flood whereas the remaining watersheds fall under the range of 0.6 to 1.4 km/km² (Fig. 6).

Flood hazard zone

Flood hazard mapping is a vital component in identifying and prioritizing the flood-prone areas, which would help in planning long-term mitigation strategies by the decision and policymakers. GIS techniques are found to be useful for integrating the various factors and generating a flood hazard map for the district. The different vulnerable zones of the Cuddalore district ranges from very low to very high as shown in Fig. 7.

Validation of the flood hazard zones was carried out in the field at 72 locations, and the ground truth points have been collected. The derived flood hazard was validated with the collected ground truth points which matched 92% of the area flooded in 2010 floods. The highly vulnerable blocks were identified, and they are Cuddalore, Kattumannarkoil, Keerapalayam, Kumaratchi, Kurinjipadi, Melbhunagiri, and Parangipettai. Fund allocation for flood relief and flood mitigation measures can be done based on the degree of flood-prone areas. Also, the block-wise vulnerable zones are furnished in Table 6.

Flood inundation mapping

The result of the analysis shows that NDWI was ranging from – 1 to 1. The flood inundated areas were identified when the values are ranging from 0.6 to 1. Figure 8 shows that about 45% of the total area was inundated

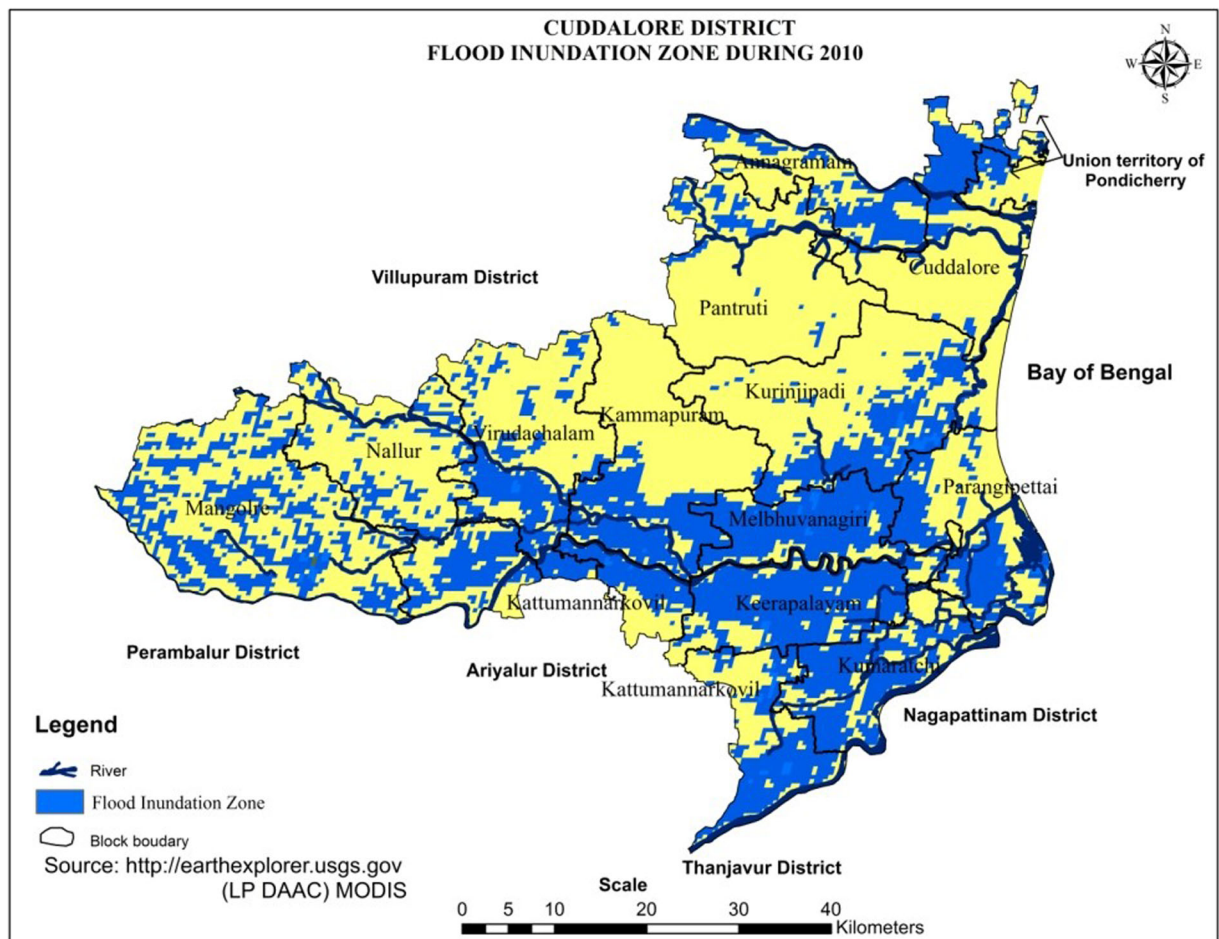


Fig. 8 Inundation map

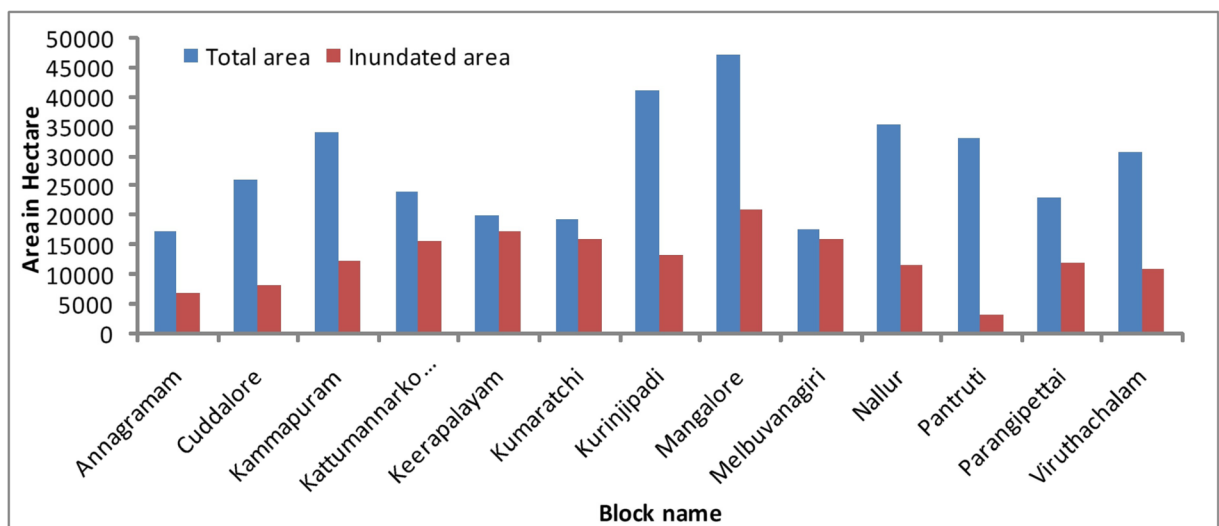


Fig. 9 Total area inundated due to flood

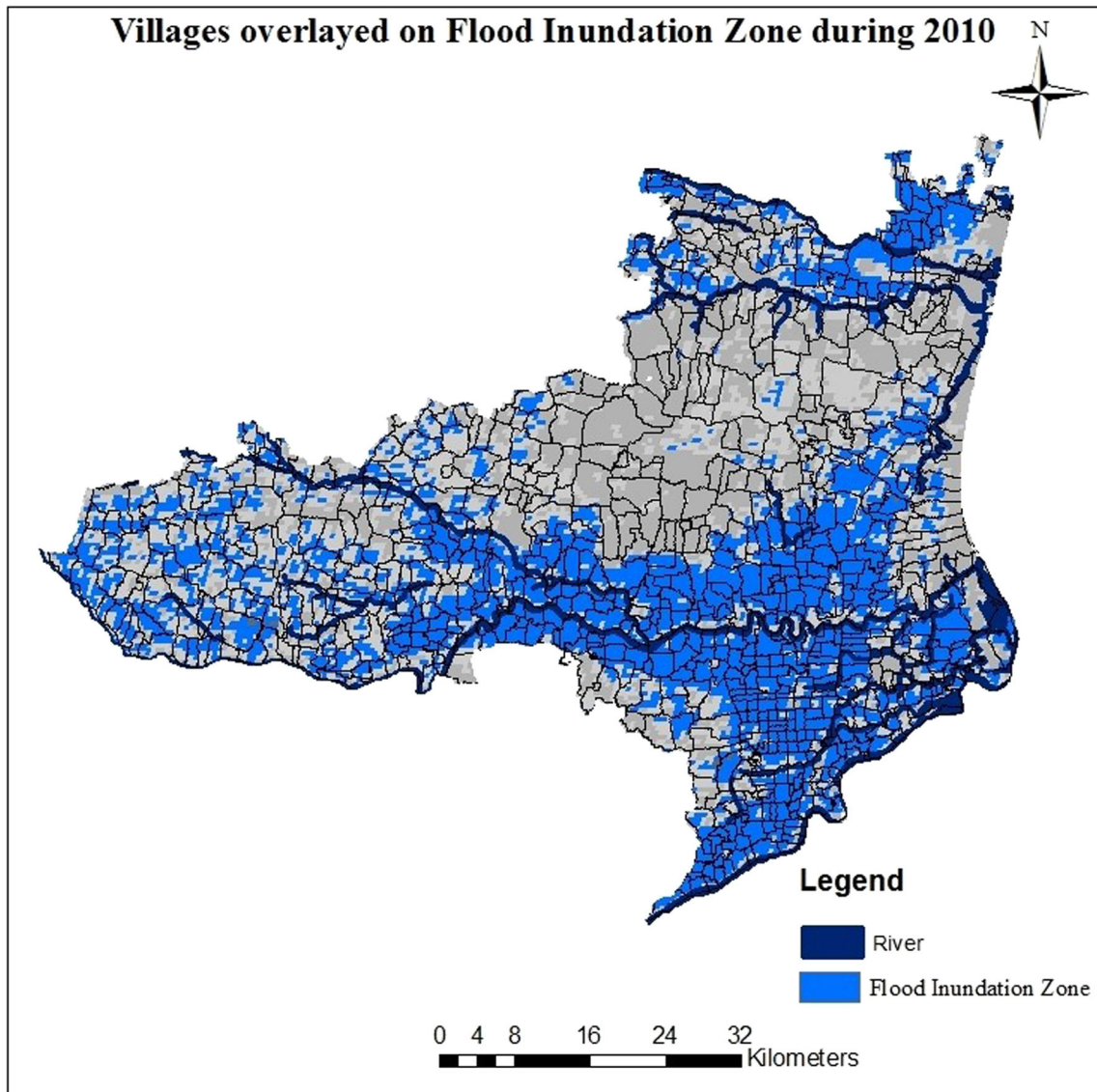


Fig. 10 Villages under inundation

due to the flood in 2010. The flood inundated area was extended up to 60 km from the coast towards the west region of the Cuddalore. The result from the previous analysis of a derived flood hazard zone map shows a good agreement with the flood inundation map extracted from the MODIS satellite data which in turn shows the coastal areas along the lower Vellar and lower Gadillam rivers which are highly inundated due to flood. Further, Keerapalayam, Kumaratchi, and Mel Bhuvanagiri which are the coastal blocks of the district show that 83%, 86%, and 91% of their total area have been inundated during the flood, respectively, as shown in Fig. 9. Also, the

result shows that, out of the 858 numbers of total villages of the district, 475 villages fall under the inundated area during the 2010 flood event (Fig. 10).

Conclusion

In this present study, an attempt was made to prepare the flood hazard zone map using ArcGIS and ERDAS software tools to study the district of Cuddalore which is one of the low-lying coastal districts in Tamil Nadu. Flood hazard map was used to identify the flood-prone

areas in the Cuddalore district with block-wise distribution. It was observed that 45% of the study area was identified as inundated area due to the flood in 2010, and these inundated areas were extended up to 60 km from the coastal area towards the land region. By considering this aspect, the government can implement rainwater harvesting systems to the nearby drought-prone districts namely Permbalur and Ariyalur. Check dams can also be constructed along the river to store rainwater and can be supplied to the nearest low- and high-elevated areas by pumping the water. Meanwhile, the integration of extreme rainfall events, DEM, drainage density, soil types, and geomorphology data are found to be effective in determining the flooding hazard along the coastal areas. Furthermore, the MODIS data has assisted in producing an inundation map of the spatial distribution of the typical November 2010 flood event. The methodology developed in this study with a series of maps generated can also be adapted to study the flood hazard for some other coastal areas. This study will enable various policy planners in the district as well as in the Government of Tamil Nadu for appropriate planning and implementation of mitigation measures and developmental works in the flood-prone areas. Finally, such flood vulnerability analysis and mapping may help the urban planners and stakeholders for assessing flood risk and preparedness to mitigate the impact of the flood.

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