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Flood Vulnerability Assessment using Geospatial Techniques: Chennai, India

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Abstract

Timely and accurate damage assessment due to floods is crucial for the authorities to respond. Damage assessment and vulnerability mapping of Chennai flooding 2015 is presented. **Objectives**: The key objective of the paper is to quantify the extent of inundation, the damage incurred to the built environment, road and railway networks by mapping the flood vulnerable areas based on watershed analysis. **Methods/Analysis:** Landsat-8 OLI, Sentinel-1 and CartoDEM-3 R1 data of the study area during the flooded period were analyzed using geospatial techniques such as Normalized Difference Water Index, Normalized Difference Vegetation Index, Normalized Difference Built-up Index, Iso-Cluster Unsupervised Classification and Spatial Analyst tool. **Findings**: The results showed that 18% of the Chennai Metropolitan Area (CMA) (including 56 sq.km of the built fabric, 3742 km road length) was inundated directly affecting 21% of the total population. **Novelty/Improvement**: Based on the results, the study area is classified into low, medium and high vulnerable areas. Suitable directions for effective disaster management are recommended.

Keywords: Disaster Management, Inundation, Vulnerability Mapping, Watershed Analysis

1. Introduction

In recent past, more and more people around the world are exposed to extreme natural disasters disrupting socio-economic and built fabric[1] and the trend continues to rise, especially in the case of floods[2–5]. Floods are one of the most significant disasters in the world, more than half of it occurs in Asia[6]. Climate change and urbanization patterns have increased the recurrence of floods across the globe with significant change in characteristics of flood-return period[7,8]. About 13% of Asia's population live in Low Elevation Coastal Zones (LECZ)[9] which are exposed to extreme weather events like floods. Flash flood is a result of heavy rain followed by massive discharge within five or six hours of heavy rain[10–12] and it is classified as hydro-meteorological hazard[13]. Flash floods indicate the city's vulnerability to natural disasters and the need for spatial planning and policy interventions to manage the risks[14,15].

In the 1990s, the term 'vulnerability' was first used in the context of disasters[16,17], however quantification of vulnerability is a complex task[18]. According to[19], there are four dimensions of vulnerability assessment i.e., physical, economic, social and environment. Among them, only

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the physical dimension of vulnerability is explored in this paper.

The recent trends and advancement in geospatial technology for mapping flood prone area have given the leverage to monitor[20,21], assess the damage incurred[22,23] and reduce the risk caused by floods[24]. Geographical Information System (GIS) together with Remote Sensing (RS) data offer variety of techniques such as flow direction, watershed delineation[25] and information about terrain. Real-time management of floods can be monitored through integration of geospatial techniques[26].

In this research the established application of geospatial techniques are used to achieve the following objectives. First, to quantify the extent of inundation, the damage incurred to the built environment, road and railway networks. Second, to map the flood vulnerable areas based on watershed analysis. Third, to propose structural and non-structural mitigation measures and to improve the urban disaster governance. Fourth, to recommend suitable directions for more effective disaster management in Chennai.

Historically expensive flood control structural measures have also been failed[27–30]. These structural measures promote false sense of security, thereby encouraging further developments in areas prone for floods[4]. However, controlling floods larger than 10-year by spatial planning has been observed to be ineffective[31]. Flow regulating storage-based feature in urban watersheds have proven to be significantly effective in reducing the flood magnitude[32,33].

2. Study Area: Chennai Metropolitan Area (CMA)

2.1 Setting of CMA

CMA is located between 12°50'49" and 13°17'24" North and between 79°59'53" and 80°20'12" East, with a population of 8.6 million[34]. The total administrative area of CMA is 1189 sq.km including the corporation area of 426 sq.km (old corporation area was 176 sq.km) Figure 1. It comprises of Chennai corporation area, 16 municipalities, 20 town panchayats and 214 villages[35]. Chennai, the capital city of Tamil Nadu state is the fourth largest metropolitan city in India, with major cultural, economic, educational and administrative base of south India. It is often referred to as the gateway to south India. It is the fourth most densely populated city in the country with 26,401 persons per sq.km[34].

2.2 Chennai Flooding 2015

Chennai is highly sensitized to flooding and is a rapidly developing city in the Indian LECZ[36]. Every five to ten years large fluvial floods occur in Chennai and because of the low frequency, flood management plans or mitigation measures are less prioritized. However, even the slightest rainfall leads to substantial flooding of roads and streets across the city. This is despite Tamil Nadu being the first state in the country to implement mandatory rainwater harvesting techniques at every individual plots across the state[37]. Inadequate drains, deficient capacity of drains, blockages, encroachments of flood plains are the most common reasons for flooding in Chennai. The primary way of dealing urban floods in Chennai is through improving Storm Water Drain System (SWDS) and reviving the *ery* system[36].

CMA receives an average annual rainfall of 1100 mm (700 mm rainfall during northeast monsoon and 400 mm rainfall during southwest monsoon)[35]. In November 2015, the south-eastern coast of India was hit by a deep tropical depression through the Bay of Bengal causing heavy rain and floods. Chennai witnessed the heaviest rainfall in the last 100 years causing massive flooding across the city and resulting in disruption of normal life. The first spell of intense rain was between 8-9 November

2015; minor floods across the city were observed. This was followed by the second spell of intense rainfall between 15-17 November 2015. The third spell of intense rainfall was between 1-5 December 2015, causing major floods across the city. The rains and subsequent overflow of Chembarapakkam, Pondi and Puzhal lakes, River Coocum, River Adyar and Buckingham Canal, within the city caused severe flooding and a significant damage to the inhabitants, existing built fabric and infrastructure of the city[38]. Following this, the Government of India declared Chennai, a National Disaster zone. Road and rail access was cut off in several parts of the city. The runways at Chennai airport were flooded and remained closed for three days, severely hampering the day-to-day activities. The rescue and relief operations were stranded leaving the affected people unattended. Decadal rainfall data reveal the consistent recurrence of major floods in Chennai. The city had witnessed major floods in 1943, 1976, 1985, 1996, 2005[35] and the recent one in 2015.

2.3 Overlapping Competencies

Chennai is a highly sensitized city in Indian LECZ to flooding due to the Tsunami and massive flooding in 2004 and 2005 respectively. The state government agencies retain the management of urban affairs (including the flood management). Apart from the local government, a number of other agencies or departments are also involved in planning and management of urban services. Chennai's flood management is split across six government departments viz.1. Public Works Department (PWD), 2. Water Resource Department, 3. Corporation of Chennai - Storm Water Drainage Department (SWDD), 4. Corporation of Chennai (Zonal Office), 5. Chennai Metropolitan Development Authority (CMDA) and 6. Chennai Metropolitan Sewerage and Water Supply Board (CMWSSB) – Sewerage Department and Water Supply Department[36]. Effective planning and management of floods are practically challenged by overlapping competencies and clash of authorities[39].

3. Data Acquisition and Analysis Methods

3.1 Data Acquisition

Flood mapping and vulnerability assessment demand extensive list of data pertaining to the study area, required for informed interpretations and decision making. This includes physical, topological, infrastructural datasets from various agencies across the disciplines. Administrative boundary showing the extent of CMA, with major roads, railway networks, water bodies (existed during 1970s) were procured from Chennai Master Plan II[35]. Population and population density details from Census of India 2011[34] were used to assess the extent of vulnerability. Further, to analyze the spatio-temporal changes of built-up, water bodies and open spaces (before and after the flood), satellite imagery Landsat-8 OLI (dated October 14, 2015) and flood inundation map prepared by UNITAR – UNOSAT (Sentinel-1 Satellite Data Acquired 24 November, 12 November, 01 September 2015) and Indian Institute of Remote Sensing (IRS) (CartoDEM-3 R1) were used. Four tiles of CartoDEM-3 R1 PAN (2.5m) stereo data downloaded from Bhuvan, National Remote Sensing Centre (NRSC), and Indian Geo-Platform of Indian Space Research Organization (ISRO) were mosaicked and analyzed.

3.2 Analysis

Open water (inundated area), green and built-up features of the study area were extracted by adopting the following established geospatial procedures (Figure 1). The Normalized Difference Water Index (NDWI) calculation was used: (Green – NIR)/(Green + NIR), where Green and NIR (Near Infra-Red) corresponds to band 3 and band 5 respectively. For this, NIR and green channels of Landsat-8 OLI were used to delineate and enhance open water features[40,41]. Further, the Normalized Difference Vegetation Index (NDVI) defined as (NIR – Red)/(Red + NIR) was used to delineate and enhance green features of the study area[42-44]. Also, the Normalized Difference Built-up Index (NDBI) defined as [Short Wave Infra-Red (SWIR) – Infra Red (IR)]/(SWIR + IR) of Landsat-8 OLI was used to delineate and enhance built-up features of the study area.

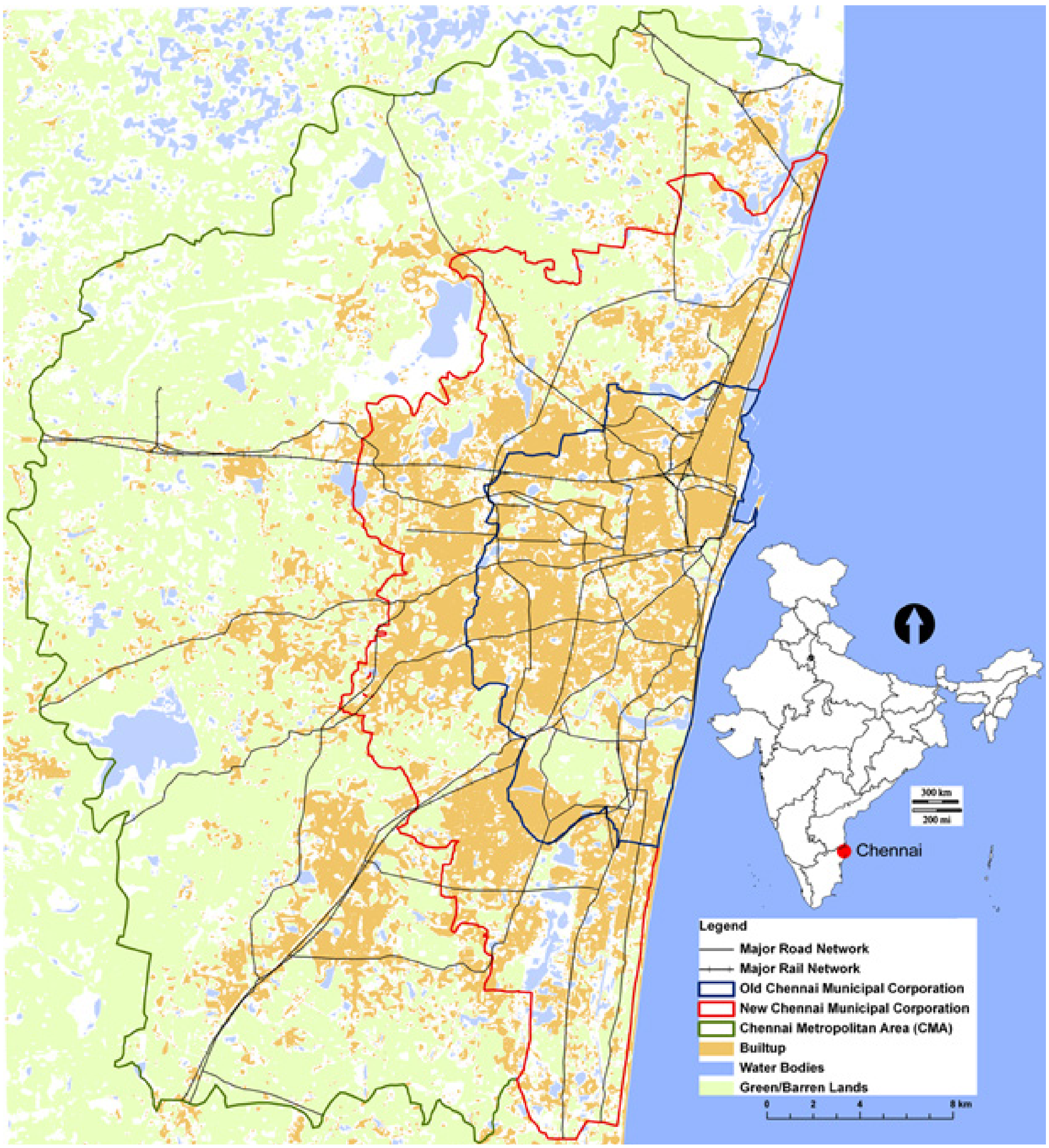

Figure 1. Chennai Metropolitan Area base-map.

Various tools in ArcGIS Desktop (version 10.1) were used to analyze the built-up area, water bodies and green cover. Iso-cluster unsupervised classification tool was used for extracting barren lands of the study area using Landsat-8 OLI data. This tool is an iterative process for computing the minimum Euclidean distance in a cluster using migrating means technique[45]. Intersect tool was used to extract the inundated built-up area and physical infrastructure (roads and railway network). This was used to compute geometric intersection of the input the overlapping features. Besides, Spatial Analyst tool (hydrology) was used to extract watershed area using CartoDEM-3 R1 data. This tool was used for delineating the watersheds. Finally, dot density map of inundated area was superimposed on extracted watershed area and the water bodies (that once existed) to demarcate zones of vulnerability.

4. Results and Discussion

4.1 Damage Assessment

In[46] categorized the flood damage assessment into four aspects: 1. Direct tangible impacts i.e. quantification of the extent of damage, 2. Business interruption and indirect tangible impacts, 3. Impacts on infrastructure and 4. Intangible impacts. This paper limits discussion to direct tangible impacts on built-fabric and the road and railway networks. Business interruption and intangible impacts are beyond the scope of this study.

4.1.1 Impact on Built-fabric, Road and Rail Infrastructure

Around 18% of the CMA i.e. 217 sq.km was inundated directly affecting 21% of the total population, while around 75% of population was indirectly affected[38] as shown in the Table 1. Around 56 sq.km of the built fabric, 3742 km of road and street length was inundated. Also, more than 13.5 km length of railway lines and the airport were flooded causing major disruptions. Response and rescue operations were severely hampered, as access to road and railway network was inundated and as a result, the city remained disconnected for a good number of

Table 1. Damage assessment of population, built-up road and rail network

Administrative Area	Area (sq. km)	Population	Density (persons per sq.km)	Inundated area (sq. km)	Affected settlements (sq. km)	Affected Population	Affected Population in %	Affected Road and Street (km)	Affected Railway lines (km)
Chennai Municipal Corporation *	176	464 732	26401	106	31	818431	18	1810	11.5
Rest of CMA area	769	404-9278	3997	111	25	99925	3	1932	2
Total CMA	1189	8,69-6,010	7314	217	56	918356	21	3742	13.5

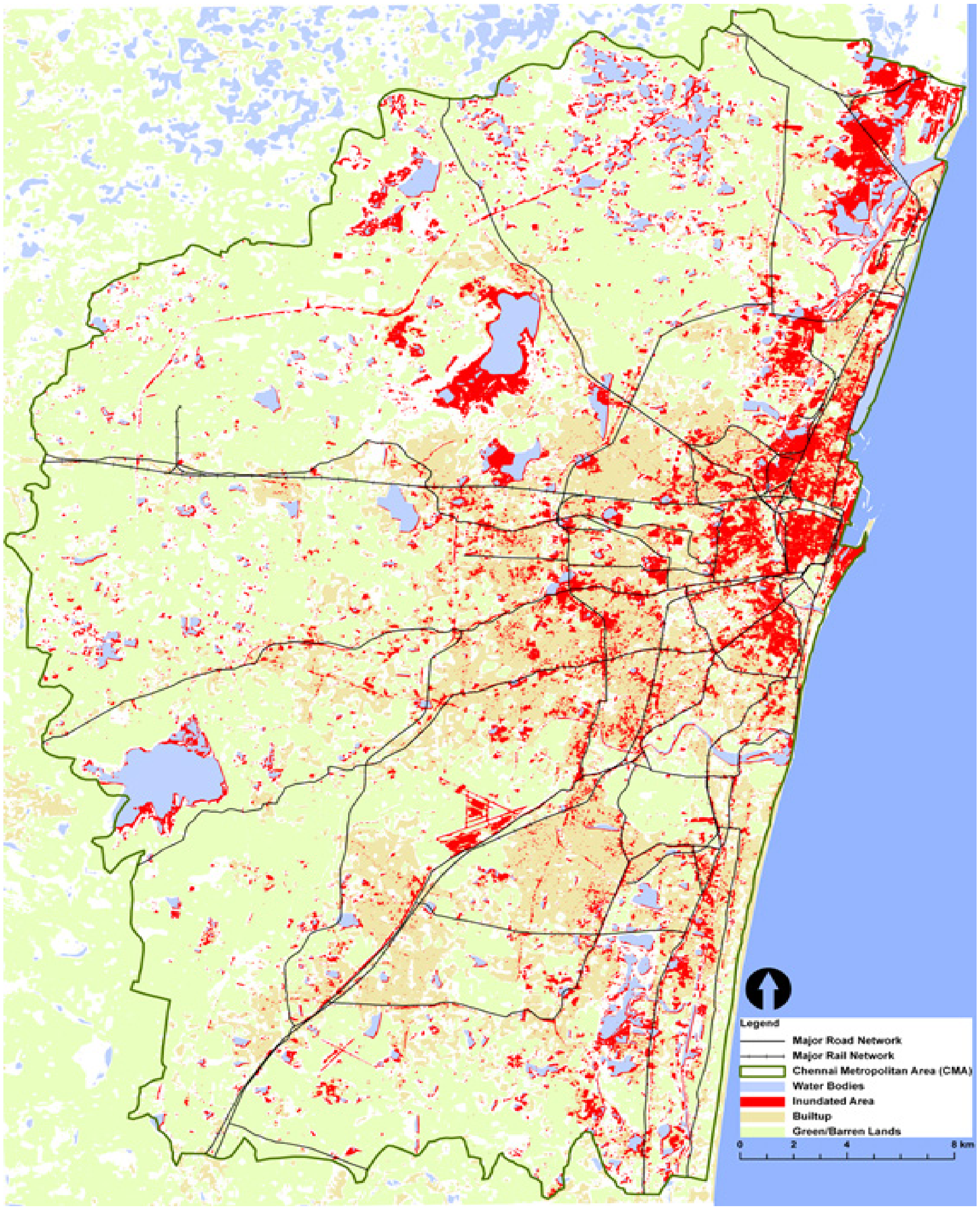

Figure 2. Cumulative inundation map (validated with Landsat-8 OLI, Sentinel-1, CartoDEM-3 R1dataset).

days. The impact of flood on built-fabric, roads and railway line is shown in Figure 2.

4.2 The Case of Depleted Water Bodies

Since 1970, more than one-fifth area of the water bodies within the CMA limits has been reduced. NDWI results derived out of Landsat-8 OLI (October 14, 2015) detected a reduction in the area of the water bodies i.e. from 267 sq.km to 56 sq.km[35] as shown in Figure 3. As pointed out

Table 2. Flood prone areas in CMA

Categories	Identified flood prone areas in CMA
Low Flood Prone	Alwarpet, Teynampet, Gopalapuram, Nandanam, CIT Colony, Mylapore, Mandaveli, Ashok Nagar, Santhome, Villivakkam, Besant Nagar, Little Mount, Guindy, Thiruvanmiyur, Pallavaram, Madambakkam, Kannadasan Nagar, Nandambakkam, Madhavaram, Alandur, Nemilichery, Perungudi, Thuraipakkam,
Medium flood prone	Anna Nagar,Chetpet, Perumbakkam, Ambattur, Vepery, Moolakadai, Valasaravakkam, Red Hills, Vanagaram, T Nagar,Taramani, Tambaram
High flood prone	Nungambakkam, Royapettah, Triplicane, Kottur Gardens, Thousand Lights, Pudupet, Egmore, Chepauk, Perambur, Sowcarpet, Saidapet,Vallalar Nagar, Kilpauk, George Town, Park Town, Kotturpuram, Royapuram, Vyasarpadi, Basin Bridge, Washermanpet, Mannady, Flower Bazaar, Tondiarpet, Pulianthope, Purusawalkam, Ennore, Periamet, Chintadripet, Doveton, , Choolai, Otteri, Kellys, Tiruvottiyur, Zam Bazaar, Jafferkhanpet, Adayar, Velachery, Pallikaranai

by[36], these 'naturally low lying areas' instead of acting as flood sink, pose a greater risk due to urban development. Comprehensive flood management could be worked out by re-inventing the depleted urban water bodies[47].

4.3 Mapping of the Flood Prone Areas

Mapping of the flood prone areas is a primary step involved in reducing the risk of the region. For this purpose, a modified version[48] was adopted for demarcating the flood prone areas. A historical record of DEM data i.e. watershed areas extracted from CartoDEM-3 R1 were superimposed with dot density inundation map to identify the flood prone areas. This has enabled to identify the critical spread of the affected areas for undertaking vulnerability analysis, flood plain prediction, etc. Further, this can act as a base for all post flood relief measures and also in turn can have a better control over the post flood works. The basic inundation map was combined with land use, built-fabric and infrastructure data to form a complete image of the flood plain. Based on the intensity of inundation and extent of watershed area, flood prone areas were categorized into: 1. Low Flood Prone (LFP), 2. Medium Flood Prone (MFP) and 3. High Flood Prone (HFP), as shown in Figure 3 and tabulated in Table 2.

4.4 Mitigation Strategies

Mitigation strategies are classified into: 1. Structural measures and 2. Non-structural measures.

4.4.1 Structural Measures

As observed by[4], that constructing short-term protective structures create false sense of security and have failed historically, long-term urban planning interventions must be explored. No construction must be permitted in the HFP areas. Also, buildings in LFP and MFP areas must be constructed with stilts or on raised platforms. In addition to clearing the encroachment along the river edges, de-silting of River Coocum and River Adyar must be carried out. Lakes like Chembarapakkam, Poondi and Puzhal lakes must be improved in terms of capacity and structural safety.

4.4.2 Non-Structural Measures

In the demarcated HFP areas, built-up density should be reduced curtailing further developments. Relocation of residents of HFP areas to alternate safer sites must be considered. Necessary steps to revive the already depleted water tanks and water bodies across the CMA must be carried out. Construction of community facilities in the LFP areas must be encouraged. These facilities can be used as make-shift places during floods. Reforestation of banks of the River Coocum and River Adyar must be carried out to reduce the flood damage and increase the retention capacity. In line with the National Disaster Management Plan 2016, a comprehensive spatially integrated flood inundation and risk management plan must be prepared to deal with disasters of similar scale in future[49].

4.4.3 Urban Disaster Governance

The Disaster Management Act (DMA) 2005, gives the legal authority to the state to frame policies and prepare Disaster Management and Mitigation Plan (DMMP) with the help of national disaster management authority. But the mandated role for the state level authorities is relatively limited[50]. DMA also emphasizes the creation and updating DMMP to assess disaster risk and to prepare for mitigate, respond to and recover from disaster[49]. DMMP in Tamil Nadu is not comprehensive enough, as only mere listing of flood prone areas and contact information during disaster is usually carried out. The task of preparing DMMP must be taken up at the earliest by adopting established scientific techniques, so as to reduce the risk of exposures to disasters such as flooding[36].

5. Recommendations

5.1 Awareness and Participation

Dissemination of information through newspaper and digital media to the general public in advance, about the impending disaster/imminent floods/unfavorable and hazardous weather conditions must be carried out. Precautions must be taken-up by the individual residents/community of city in general and people living in the identified MFP and HFP areas in particular (Figure 3).

5.2 Training/Capacity Building

Necessary training to the concerned officials of all the six departments viz. Public Works Department (PWD) - Water Resource Department, Corporation of Chennai-Storm Water Drainage Department (SWDD), Corporation of Chennai (Zonal Office), Chennai Metropolitan Development Authority (CMDA), Chennai Metropolitan Sewerage and Water Supply Board (CMWSSB) – Sewerage Department and Water Supply Department[36] on flood map reading, interpretation for timely response during the emergency situations must be carried out.

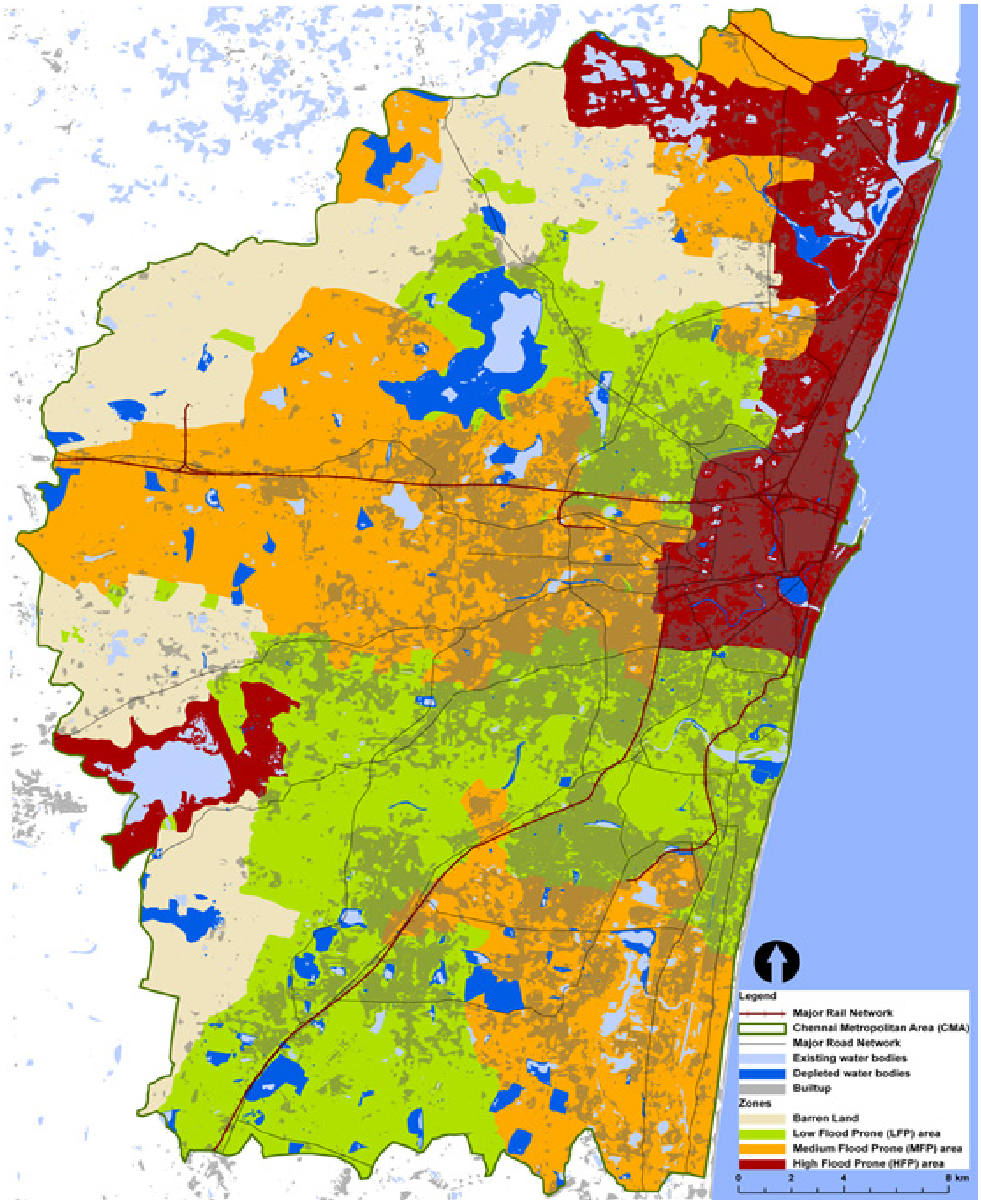

Figure 3. Flood prone map and depleted water bodies.

5.3 Improved Forecasting Techniques

Disaster Management Authority in Chennai must adopt improved forecasting and early warning system for preparation of comprehensive disaster management plan. For this, a three tier action plan i.e. Immediate Measures (1 year), Medium Term Measures (1-3 years) and Long Term Measures (more than 3 years) for disaster management as recommended by the NDMP[49] must be prepared.

5.4 Use of Social Media

During Chennai flood 2015, the city dwellers and the administrators witnessed a more powerful force pounding the city than rains, i.e. social media. When a major part of the city remained disconnected physically due to inundation, the city dwellers and volunteers resorted to social media for support and rescue operations. Hence, further research in this area is required for capitalizing social media during unforeseen situations.

5.5 Integrated Geospatial Technologies/ Spatial Data Infrastructure

Geospatial data infrastructure technologies must be integrated with disaster management plan, so as to facilitate informed analysis and decision making. This can enable sharing and delivery of geospatial data, in advance for effective pre and post flood measures. Access by the communities and concerned authorities to such geospatial data must be created through the use of online/digital technology. This can be helpful in emergency situations in minimizing the loss of life and assets.

5.6 Evacuation Plan/Strategies

Identification and creation of evacuation centers at the suitable locations in proximity to the MFP and HFP areas must be prepared. Besides, an evacuation plan with a provision of alternate routes may be taken up in the MFP and HFP areas.

6. Conclusion

The devastation caused by Chennai flood 2015 was a result of unprecedented rain, coupled with mismanagement of water bodies within the city limits and the lack of comprehensive disaster management plan. The results of damage assessment and mapping of flood prone areas reveals 56 sq.km of the built fabric was inundated directly affecting 21% of the population. Due to inundation of the major rail and road infrastructure, the northern and eastern access to the city was severely affected and remained disconnected. It was alarming to note that more than 211 sq.km of water bodies were depleted over a span of three decades. LFP, MFP and HFP areas within the CMA limits are mapped to deal with the future disasters of similar nature. Further research is required on area specific structural and non-structural measures to mitigate the floods through the use of geospatial technologies in the future. Steps for the preparation of disaster management and mitigation plan must be carried out at the earliest. There is an urgent need to address issues relating to data duplication, overlapping competencies of the government department, etc. so as to streamline the disaster management. The findings of this paper can be an initial step towards preparation of comprehensive disaster management and mitigation plan for Chennai.

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