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RESEARCH

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GIS based urban social vulnerability assessment for liquefaction susceptible areas: a case study for greater Chennai, India

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Abstract

Background The areas prone to geological hazards such as liquefaction need special attention with respect to social vulnerability. Though liquefaction by itself may not result in damage, it may trigger a series of ground failures such as ground oscillation, lateral spread, loss of bearing strength, etc., which cause heavy damage. Globally, during the past few decades liquefaction hazard analysis has become one of the important criteria in seismic risk analysis and mitigation management, especially for urban areas. Greater Chennai is one of the million-plus population cities in India. The city also felt earthquakes/tremors in the past history.

Method The present study aims to assess the social vulnerability of the population density of the Greater Chennai area due to liquefaction susceptibility using GIS technology. The liquefaction susceptibility map (hazard) for the Greater Chennai was prepared by integration of geological and geomorphological parameters and analyzed over socioeconomic parameters (exposure) using an integration of GIS and AHP.

Results The result showed that around 53% of Greater Chennai's households and population are very much exposed to liquefaction hazard.

Conclusions This study can be used as a base level study for decision-making during land use planning as well as disaster mitigation planning.

Keywords Earthquake, Liquefaction susceptibility, Hazard, Exposure, Urban sprawl, GIS

Introduction

Urban area expansion and growing complexity of the cities present new problems in attempting to understand the complex relationships between different forms of urban vulnerabilities. Recent disaster events manifest how societies are growing more susceptible to earthquake damages (Ganapathy 2011). The rapid and unchecked population growth signaled an increasing in the exposure (i.e. the elements at risk) which in turn will amplify the social vulnerability by taking built environment and the interaction among the community with the territory. One of the most important aspects of managing disaster risk reduction is understanding and measuring vulnerability. Only when effectively measured, vulnerability can give us an idea of the scale of the expected consequences and can targets be set in developing resilient urban space (CGWB 2017; Srinivasan et al. 2010). Since seismic hazard can't usually be reduced, vulnerability is one area where disaster risk reduction efforts can be made (Prasanna et al. 2010). Geomorphic settings of an area is a clue to seismic activities (Praseedha and Ganapathy 2020 a; b; Singh et al. 2016). One of the important factors of seismic vulnerability is the unprecedented growth of urban landscape. Due to rapid, uncontrolled

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sprawl of an urban area, even low to moderate seismological activities can trigger a great loss. 1960 Morocco earthquake (M = 5.8) and 1992 Dahshour earthquake (M = 5.7), even though both earthquakes were categorized as moderate earthquakes, geological settings along with the built environment triggered considerable social and economic damages and hundreds of life loss, thousands were injured (Pinto 2000). One the most significant seismic hazard that can create a great impact in urban disasters is soil liquefaction. It is also one of the major threats for civil structures under seismic loads, as deduced from the damage surveys performed after some strong earthquakes (Evangelista 2011).

The study area, Greater Chennai, the sixth largest metropolis in India and one of the densely populated urban centers in the word. It is one of the major economic hubs of India. By 2025, the Confederation of Indian Industry predicts Greater Chennai's GDPwill have increased by 1.5 times to a US$100 billion level. Greater Chennai's economy is mainly driven by IT services, automobile industries, healthcare sectors, banking & financial services and hardware manufacturing. As per the Global city GDP2014, Brookings Institution Report, Greater Chennai has an estimated GDPcontribution of $79 billion to $86 billion making it one of the most productive metros of India. As per Bureau of Indian Standards (BIS 2001) seismic zoning map of India, Greater Chennai has been classified under Zone III (Fig. 1). The majority of the city is covered in thick alluvium material, which might increase the soil amplification in the city during a seismological event. Also, most of the water bodies in the past century was filled and converted in to built environment. The filled-up soil will be easily liquefied during an earthquake of Magnitude more than 6.0. The aim of the present study is to prepare a vulnerability assessment of Greater Chennai due to soil liquefaction based on geological and geomorphological settings along with thematic integration of socio-economic parameters viz. population and number of households. This kind of vulnerability map can be used in all stages of disaster management, including prevention, mitigation, preparation, operations, relief, recovery, and lessons learned. When building places for residential, commercial, or industrial usage in the prevention stage, planners might use

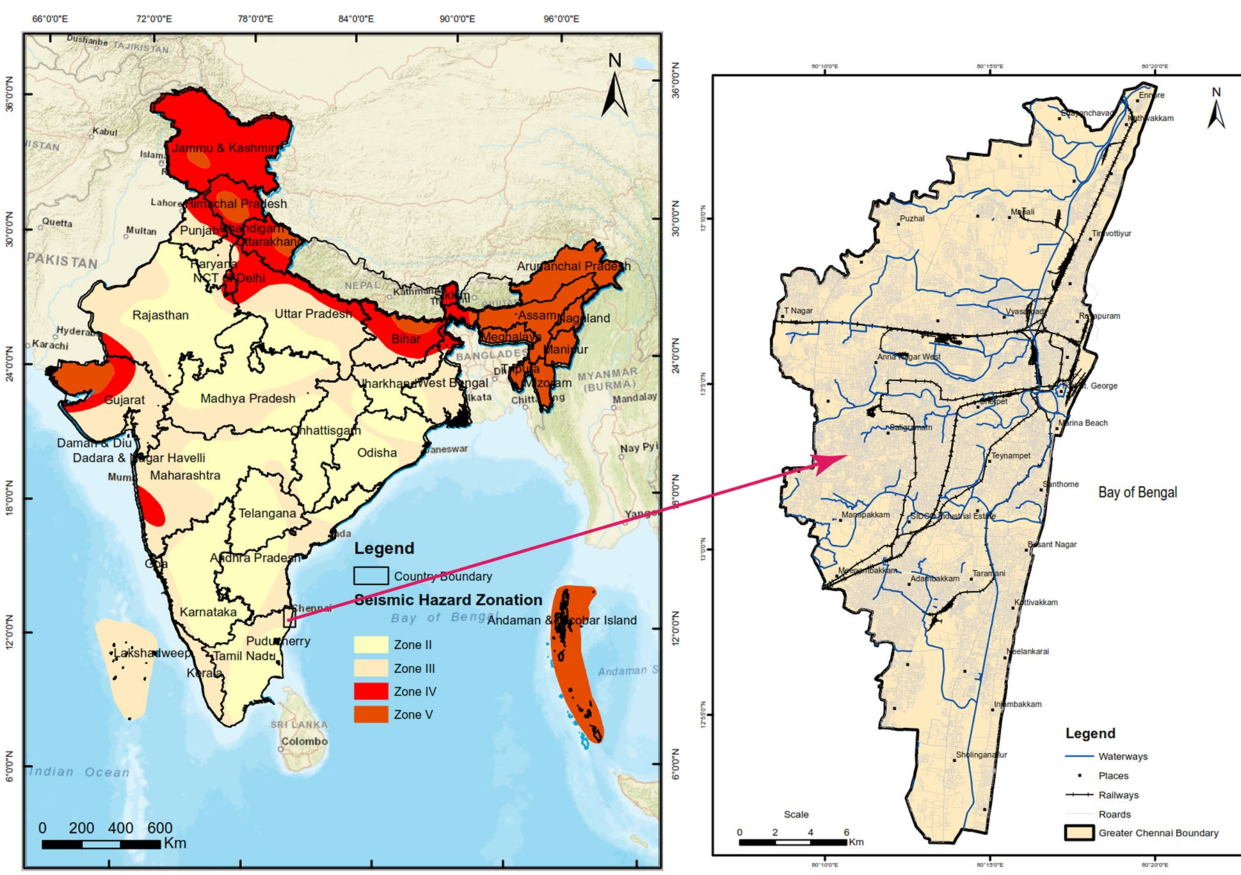

Fig. 1 Seismic hazard representation of the study area

vulnerability maps to avoid high risk zones (Edwards et al. 2007). Though seismic zonation studies and liquefaction susceptibility studies were being carried out for Chennai region, those studies are very much limited to seismicity and liquefaction susceptibility themes. Social vulnerability was hardly considered. Further, those studies were not carried out for the Greater Chennai region.

Materials and methods

Methodology

One of the major causes of structural damage during earthquakes is soil liquefaction. Soil liquefaction has historically been observed in moderate and strong earthquakes (Ambraseys 1988). Globally many research works have been carried out on seismic hazard and liquefaction assessment based on geological and geomorphological settings of an area (Ganapathy et al. 2018, 2019; Ganapathy and Rajawat 2012; El May et al. 2010; Iwasaki et al. 1982; Wakamatsu 1992; Vipin et al. 2009; Obermeier 1989). The present study was carried using the data published by the respective organizations, data published on journal papers and open source data. This study would not compensate for site-specific investigations, but can used as a tool for identifying an area which needs immediate attention and further detailed investigations. Four parameters with respect to geology and hydrogeology namely, lithology, age of deposits, depth to groundwater and depth to bedrock are utilized for the liquefaction susceptibility study. Exposure map was then prepared using two parameters namely, population density and density of households.

Sediment properties like lithology, age of deposit and hydrogeological conditions like depth to groundwater, depth to bedrock can make an area favorable to seismic wave amplification which in turn will make the soil prone to liquefaction upon seismic shaking. Also, the presence of different types of soil like clay, silty, sandy soil along with the shallow groundwater will increase

Table 1 Liquefaction Susceptibility of Sedimentary deposits present in Greater Chennai based on Geological and Geomorphological criteria (Youd and Perkins 1978)

Type of deposit	General distribution of cohesionless sediments in deposits	Likelihood that cohesionless sediments, when saturated, would be susceptible to liquefy (by age of deposit)			
		< 500 years	Holocene	Pleistocene	Pre-Pleistocene
River channel	Locally Variable	Very high	High	Low	Very low
Flood plain	Widespread	High	Moderate	Low	Very low
Alluvial plain	Widespread	Moderate	Low	Very low	Very low
Coastal delta	Widespread	Very high	High	Low	Very low
Estuarine	Locally Variable	High	Moderate	Low	Very low
Artificial compacted fill	Variable	Low			

Table 2 Liquefaction Susceptibility of the lithological units present in Chennai

Lithology type	Rank	Liquefaction
Sand fluvial-point bar deposit-sand and sandy clay	3	Possible
Sand marine-beach deposit-medium grey brown sand with leaves	3	Possible
Sand marine-strand flat deposit-medium grey brown sand	3	Possible
Sand paleo tidal flat	3	Possible
Black clay and sand tidal channel bar	2	Likely
Black clay marine-tidal flat deposit-black clay	2	Likely
Sand, silt and salt	2	Likely
Clay and sand marine-estuary deposit-sand and silty clay black mud with shells	2	Likely
Clay and silt flood plain deposit-black clay and sandy clay	2	Likely
Shale	2	Likely
Silt active levee deposit-sandy silt	2	Likely
Charnockite	1	Not Possible

the soil liquefaction during strong earthquakes (El May et al. 2009). The liquefaction susceptibility of a geological unit can be determined based on its depositional environment. For this study, the liquefaction susceptibility of geological and geomorphological deposits has been performed based on the Youd and Perkins (1978) criteria (Table 1).

The liquefaction susceptibility of lithological units was prepared by assigning ranks based on Iwasaki's (1982) classification as in Table 2. It is a well-known fact that soil layer will be liquefied when it is saturated. So, the depth of groundwater is one of the important criteria for the estimation of liquefaction potential. Liquefaction susceptibility decreases with increasing groundwater depth.

Obermeir's classification (1996) which related liquefaction susceptibility with the age of geology and depth of groundwater table was utilized (Table 3). Obermeir identified that liquefaction is typically observed at locations where groundwater is only a few metres below the ground surface. Ground characteristics play a key role in seismic activity of a region due to the amplification of seismic waves in different kind of deposits. Understandings of bedrock conditions are immensely useful in estimation and anticipation of seismic activity of a region (Ganapathy 2011). Depth to bedrock of Greater Chennai was assigned with ranks 1 to 5 with 5 being very high criteria and 1 being low criteria (Table 4). Liquefaction susceptibility map with all the four above said criteria was then prepared by thematic integration of those layers by multi-criteria weightage analysis.

Analytical Hierarchy Process (AHP) was then followed after assigning relative weightage to all the four layers depending upon its influences on the output. Highest weight was assigned to lithology as it has more effect on liquefaction. The different layers and their weights are listed in Table 5.

Then a pair-wise comparison matrix was prepared using 1–4 scale with 1, being least importance and 4 is of very high importance (Table 6). The resulting four thematic maps are then integrated in QGIS to obtain the liquefaction susceptibility map of Greater Chennai.

Table 3 Liquefaction Susceptibility of the near surface geological deposits present in Greater Chennai based on the ground water table depth during strong shaking (based on Obermeier 1996)

Depth to groundwater table	Age of deposit		
	latest Holocene	Earlier Holocene	Mesozoic
0–3 m	High	Moderate	Nil
3–10 m	Low	Low	Nil
> 10 m	Nil	Nil	Nil

Table 4 Depth to bedrock range of Greater Chennai with assigned ranks

Depth to bedrock (m)	Rank
5–15	1
15–30	2
30–50	3
50–70	4
70–90	5

Criteria's like population density, population density of children under age 6 years, building density, housing conditions with respect to each wards of Greater Chennai are considered to prepare the social vulnerability map. Population density along with building density is very vital in disaster preparedness and mitigation as both parameters directly deal with the social vulnerability in risk areas. Moreover, a region with more population and more buildings are greatly exposed to hazards. Using AHP method weightage is assigned to each theme. Assigned weightage along with the normalized values for the sub categories are given in Table 7. The four thematic maps generated are integrated in QGIS to attain social exposure map of Greater Chennai. For the four themes, range was classified using geometric interval claasification method due to the nature of the data and the geography of the study area (Francisci 2021). The respective thematic maps–liquefaction susceptibility and social exposure—were subjected to overlay analysis to generate the vulnerability assessment map following the flow shown in Fig. 2.

Study area and administration

Greater Chennai (Fig. 1), formerly known as Madras, is the capital of the state of Tamil Nadu. It is located on the coast of the Bay of Bengal. The district lies within the latitudes 12^0 58′ 10″ N to 13^0 09′ 50″ N and longitudes 80^0 11′ 16″ E to 80^0 18′ 20″ E. Chennai is bounded by Bay of Bengal on the east, Tiruvallur & Kancheepuram districts

Table 5 Thematic layers and weights assigned

Thematic layer	Weight
Lithology	4
Geomorphology	3
Depth to Groundwater	2
Depth to Bedrock	1

Table 6 Weighted comparison table for liquefaction susceptibility factors

	Lithology	Geomorphology	Depth to groundwater	Depth to bedrock	Normalized weightage
Lithology	4/4	3/4	2/4	1/4	0.4
Geomorphology	4/3	3/3	2/3	1/3	0.3
Depth to Groundwater	4/2	3/2	2/2	1/2	0.2
Depth to Bedrock	4/1	3/1	2/1	1/1	0.1

Table 7 Weighted comparison table for social exposure indicators

Theme	Weightage	Normalized values			
		4	3	2	1
Population Density: < 6yrs	0.35	Very dense	Dense	Moderate	Average
Population Density	0.25	Very dense	Dense	Moderate	Average
Building Density	0.20	Very high	High	Moderate	Average
Housing Condition	0.20	Very high	High	Moderate	Average

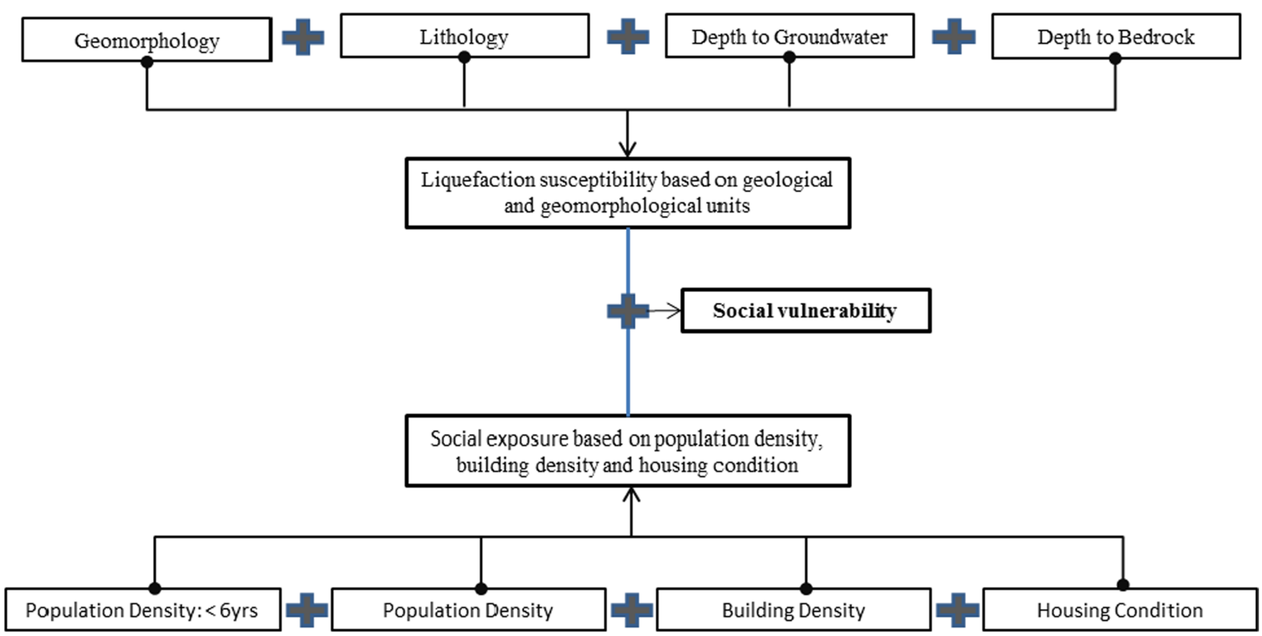

Fig. 2 Methodology for Vulnerability Assessment

on all of the other sides. Greater Chennai is a city district covering an area of over 426 km^2.

Greater Chennai Corporation is the governing body of Greater Chennai. The corporation was established in 1688. It is the oldest municipal corporation in India and the second oldest corporation in the world after London. In 2011, Chennai Corporation has expanded the city limits from an area of 174 km^2 to 426 km^2 and renamed it to Greater Chennai. Greater Chennai is classified into three major regions: North Chennai, South Chennai and Central Chennai. It is further divided into 15 zones, consisting of 200 wards. Greater

Chennai falls under the Chennai Metropolitan Area (CMA).

Physiography

Surface Topography plays a significant role in amplifying the ground motion when the wavelength of the incoming seismic waves is smaller than the topographical irregularities (Pallav K et al. 2007). Greater Chennai is a low-lying area and major part of the city is having a very flat topography. The elevation of the greater Chennai's land surface varies from 6 to 10 m above msl in the west to sea level in the east. The average elevation of Greater Chennai is 6.7 m. In the city during the monsoons, flooding and water stagnation occur due to the city's flat geography and partial storm water drain coverage of its roads (ISWD 2014). Amplification effects due to surface topography were not considered for this study as the surface topography of the study area is flat.

Geological and geomorphological units of greater Chennai

The geological formations of the area can be grouped into three units, namely (1) the Archaean crystalline rocks (2) recent alluvium (3) consolidated Gondwana and tertiary sediments. Except for a few exposed crystalline rock formations such as charnockites in the Guindy area and the Adyar riverbed at Saidapet, the most of the geological formations are obscured since they are covered by alluvial sediments (Ganapathy and Rajawat 2014a, b; Ganapathy 2011). Charnockites, which form the major rock types in can be seen as residual hills around Pallavaram, Tambaram, Vandalur, St.Thomas Mount. The Gondwana series which comprises massive pile of lacustrine and fluvial deposits represent the upper Gondwanas of Jurassic to lower cretaceous rocks and the marine beds of the cretaceous age (CGWB 2017). These Gondwanas and Cretaceous sedimentary rocks occur particularly along the coastal area of basal sediments, wherein these are overlained by quaternary sediments (Srinivasan et al. 2010). Also, the outcrops of Gondwana rocks are seen outside the city and as sub-crops within the city. The occurrence of the tertiary in Greater Chennai is not clearly demarcated (CGWB 2017).

Geomorphology of Greater Chennai (Fig. 3) mainly consists of alluvial plain, delta plain, coastal plain. Delta plains can be found along the coastal region stretch. North—Western part of the city is almost entirely covered by alluvial plain and delta plain. Flood plains consisting of sand clay are found along the boundaries of Araniar and Kosasthalaiyar rivers (Sivaraman and Thillaigovindarajan 2004). Two types of alluvium formations can be seen in the city. River and coastal alluvium. The thickness of the alluvium is highly variable spatially. The difference is about 10 m to 28 m in most part of the city. The beach sands and alluvial aquifers of the Adayar River in the Adayar and Besant Nagar regions were a good potential area in the past. But due to the indiscriminate extraction of groundwater from this potentially rich aquifer, the groundwater level has dropped below mean sea level and faces a serious risk of seawater intrusion (Prasanna et al. 2010).

Lithological units of greater Chennai

Lithology of Greater Chennai (Table 8) comprises hard rock (Charnockite), clay formation, clay over hard rock, clay–sand formations and clay-silt formations (Fig. 4). The south-western part of the city is covered by hard rock of Charnockites. The outcrops exposed over few meters in St. Thomas mount area near Guindy as residual hills (Prasanna et al. 2010). Black clay formation starts from northern part of the city near Kathivakkam and extends till Uththandi, approximately a 40 km stretch. Sand formation can be seen on either side of the clay formation linear stretch. Clay—silt formation is found in the North-Western part the city. Clay—sand formation can be found in patches near the Cooum and Adayar estuaries. Most of the city is covered by sand formation followed by clay—sand formation (Ganapathy and Rajarathnam 2011a, b). The Gondwana sediments are represented by sandstones, shales and clays. The shales and clays are highly consolidated and dense. The dark grey Gondwana shales are jointed/fractured (CGWB 2017).

Depth to groundwater

Depth to groundwater is an important criterion for liquefaction susceptibility. An area is more susceptible to liquefaction when the ground water table is less than 10 m (Youd and Idriss 2001). There have been few instances of liquefaction in areas with groundwater that is deeper than 20 m (Prasanna et al. 2010). Based on the two reports that were taken in to consideration (CGWB 2008, 2017), the depth to ground water level in the city generally varies from 2 to 8 m (Fig. 5). Depth to groundwater map was prepared using the pre—monsoon and post—monsoon groundwater table reports published by Greater Chennai corporation's metro water board (CMWSSB 2020) between the years 2016 to 2020.

Depth to bedrock

The basement is relatively shallow in the southern side of the city (5–15 m) and average in the central part of the city (15–50 m). Basement depth of more than 50 m (Fig. 6) can be observed in Western to Northern stretch of the city. Table 9 shows the five zones demarcated in

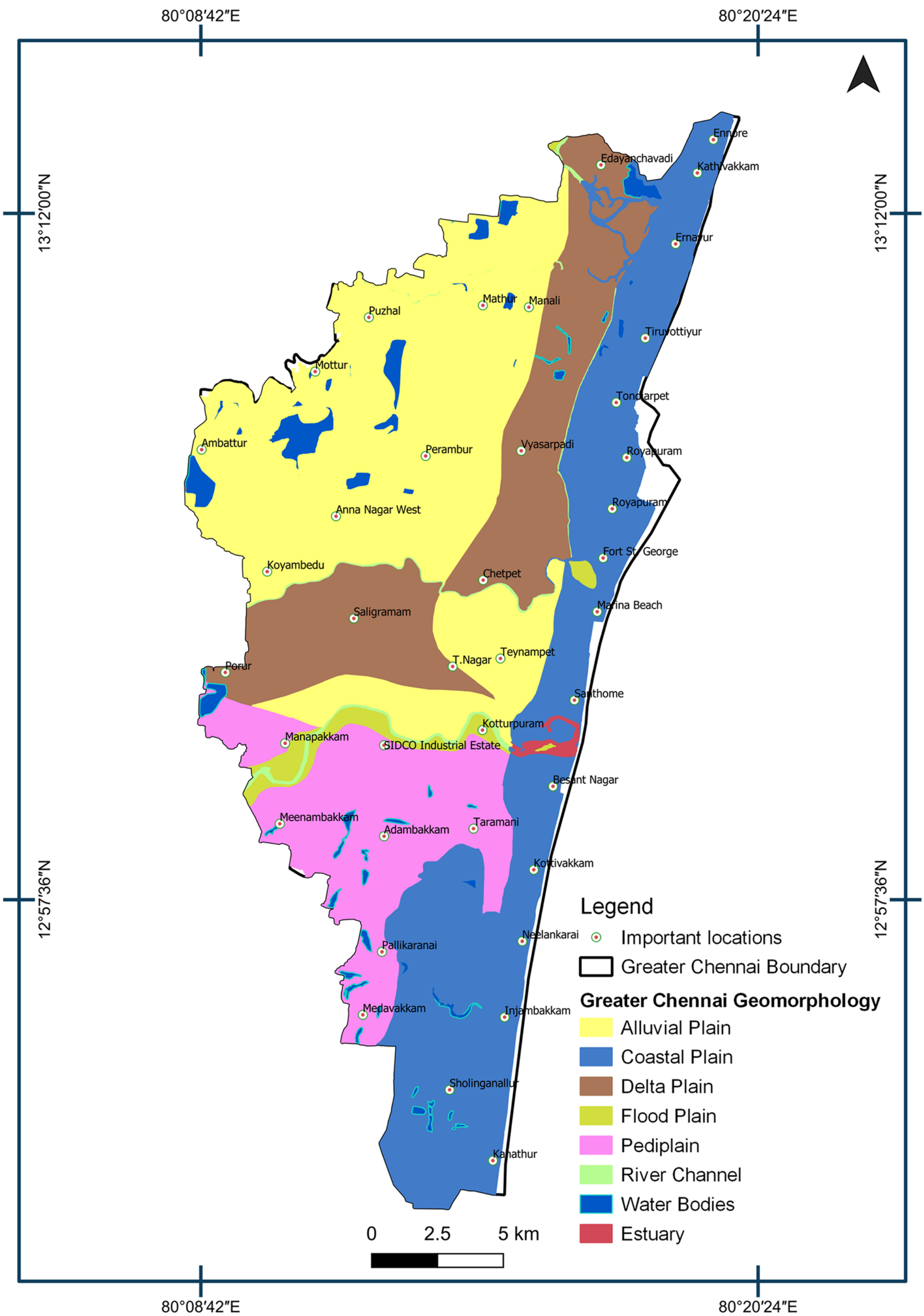

Fig. 3 Geomorphological map of the study area

Table 8 The geological formation of Greater Chennai

No	Period	Epoch	Formation	Lithology
1	Quaternary	Holocene to Pleistocene	Cuddalore	Soils, Alluvium (River/Coastal), Coastal sand, Black clay, Laterite, Fine to coarse sand
2	Tertiary	Eocene to Pliocene		Sandstone, Shale, Green Shales, Marine sediments
3	Upper Gondwana	Cretaceous	Satyavedu, Sriperumbudur	Black shale, Grey shale, Sandstone, Siltstone
4	Azoic	Archaean		Granites, Charnockites, Schist, Gneisses, Dolerite

the Chennai city and the general nature of hydrogeology and its composition (Vutla 2011).

Population of greater Chennai

Chennai is the sixth largest metropolitan area in India and is experiencing rapid growth in population. Chennai grew in stages both in land area and population. The transition occurs from rural to urban in terms of employment, social security, living environment and industry structure (Aithal and Ramachandra 2016). Chennai is not an exception to this phenomenon. In fact, available data indicate that till the beginning of nineteenth century population growth was slow and steady. But due to migration of population from other parts of Tamil Nadu for reasons like employment, environment etc. from earlier decades of nineteenth century population density of Chennai is changing drastically. The population, which was 0.019 million in 1646, expanded to 0.04 million in 1669. The surroundings of the fort area spreads over nearly 69 km^2 and contains 16 hamlets within its boundary in a location were the city of Madras is constituted in 1798. Later on, the city extended over an area about 73 km^2 and had a population of 0.54 million in 1901 (Jothilakshmy 2011).

Table 10 clearly shows the phenomenal growth of population in Chennai city. After the city limit was expanded to 426 km^2 in 2011, the population of Greater Chennai is 6.67 million. Greater Chennai is the most densely populated city in Tamil Nadu, very far ahead of the next most dense city–almost twenty times—Kanyakumari which has density of 1,111 per square kilometer. Population data was extracted from reports published by Greater Chennai Corporation which is the governing body of Greater Chennai. Report provides an average number of persons per ward.

Population density map of Greater Chennai (Fig. 7) was generated by calculating population w.r.t area of the wards using census data published by both Greater Chennai corporation (2017) and Census of India (2011). Similar methodology was followed for calculating population density of children under age 6 (Fig. 8) after taking the total population into consideration. Central part of Greater Chennai is densely populated and the trend continues towards northern parts. Distribution of population density of children under age 6 is concentrated in the central part of the region along with patches of northern and southern region.

Building density of greater Chennai

Planetscope imagery which comprises four bands—Red, Green, Blue, NIR with the spatial resolution of 3 m—of the Greater Chennai region, acquired on 19th of June, 2018 is considered (Planetscope 2018). Using object based image segmentation (OBIA) tool in SAGA software, clusters are created and individual classes like buildings, water, road, etc. are assigned. By using zonal statistics method for the 200 wards of Greater Chennai with respect to the building class raster which was obtained as mentioned in the above step—building density map is prepared. The obtained building density map's pattern is in accordance with the Planetscope imagery (Fig. 9). Majority of Greater Chennai area is overwhelmed with building density (Fig. 10). Especially the entire south to west region of the city is densely packed with buildings. It can be noted that Greater Chennai's households are expanding rapidly along the outskirts.

Housing condition of houses in greater Chennai

Using the 2011 census data published, 200 wards of Greater Chennai are mapped with the building conditions namely—good, liveable, dilapidated. Almost the entire stretch of the coastal area has more houses which fall under the category liveable. Similarly, the northern part of the city is predominantly under liveable category. Southern and packets of central region of the city, which are historically known for well-established infrastructures are in general good to very good condition (Fig. 11).

Results and discussions

Liquefaction susceptibility of greater Chennai

The resultant liquefaction susceptibility map (Fig. 12) of Greater Chennai—which was prepared by integration of geological and geomorphological parameters such as lithology, geomorphology, depth to groundwater and depth to bedrock after assigning normalized weightage values (Table 6)—was divided in to three classes namely

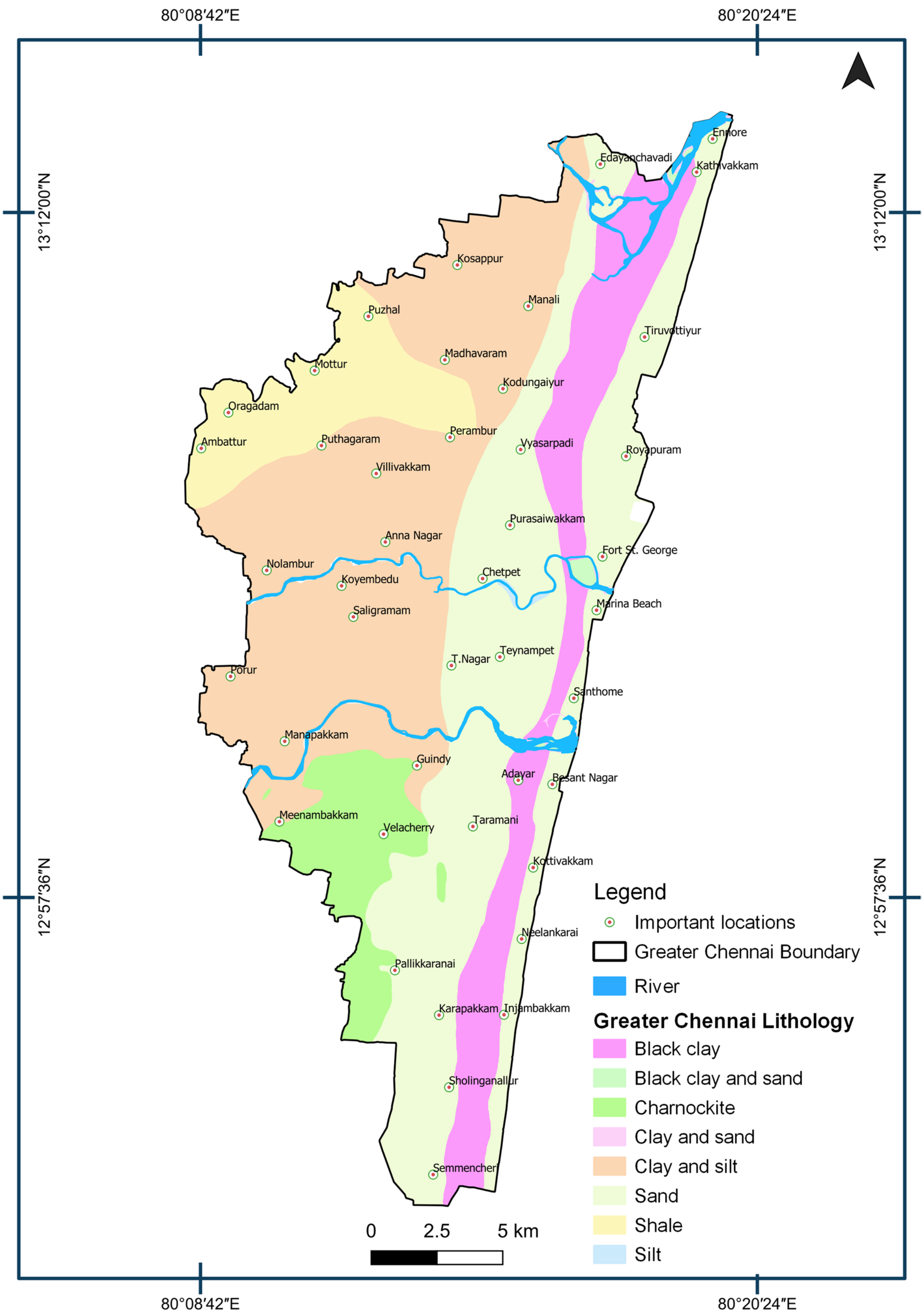

Fig. 4 Lithological units of the study area

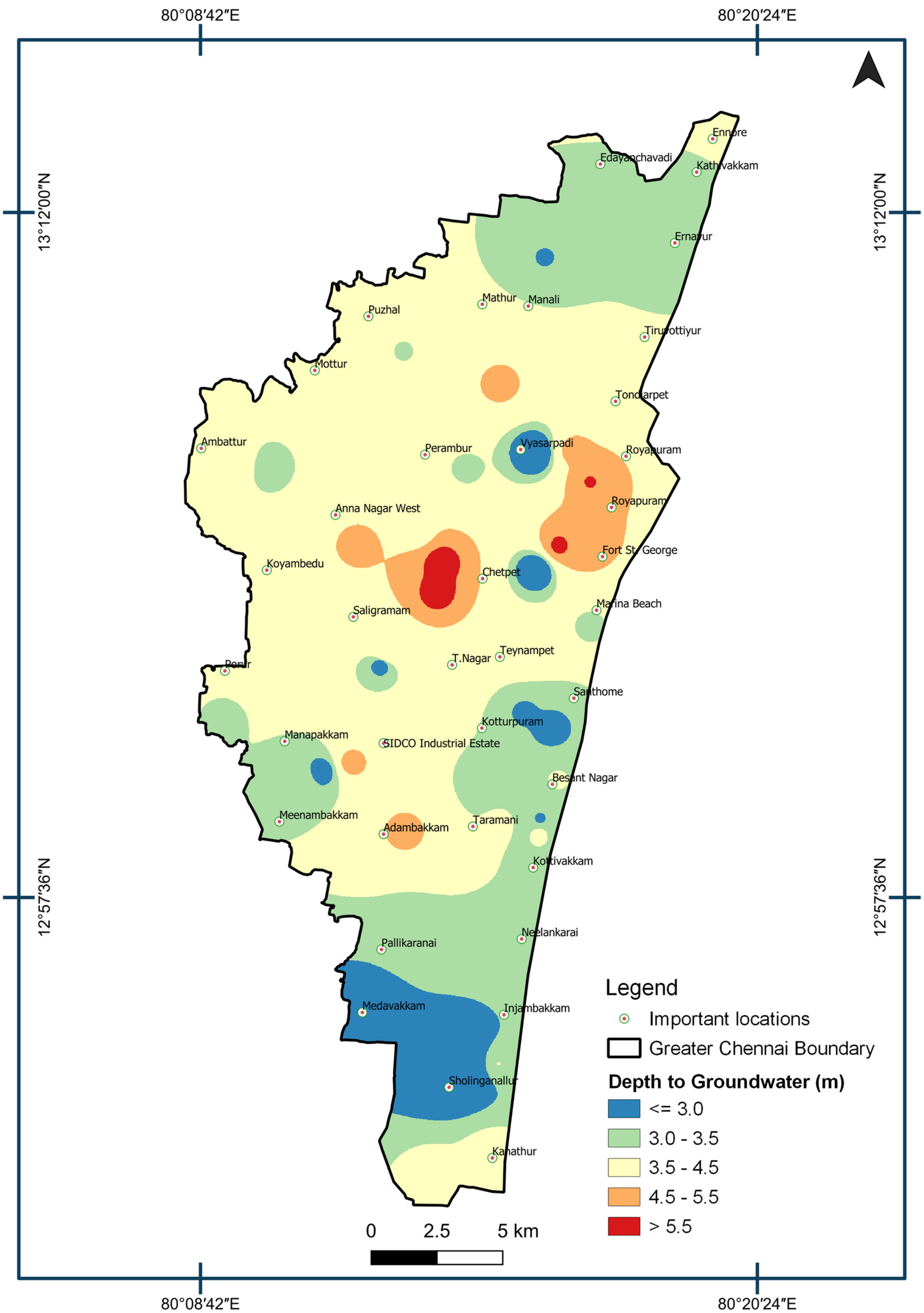

Fig. 5 Depth to ground water level

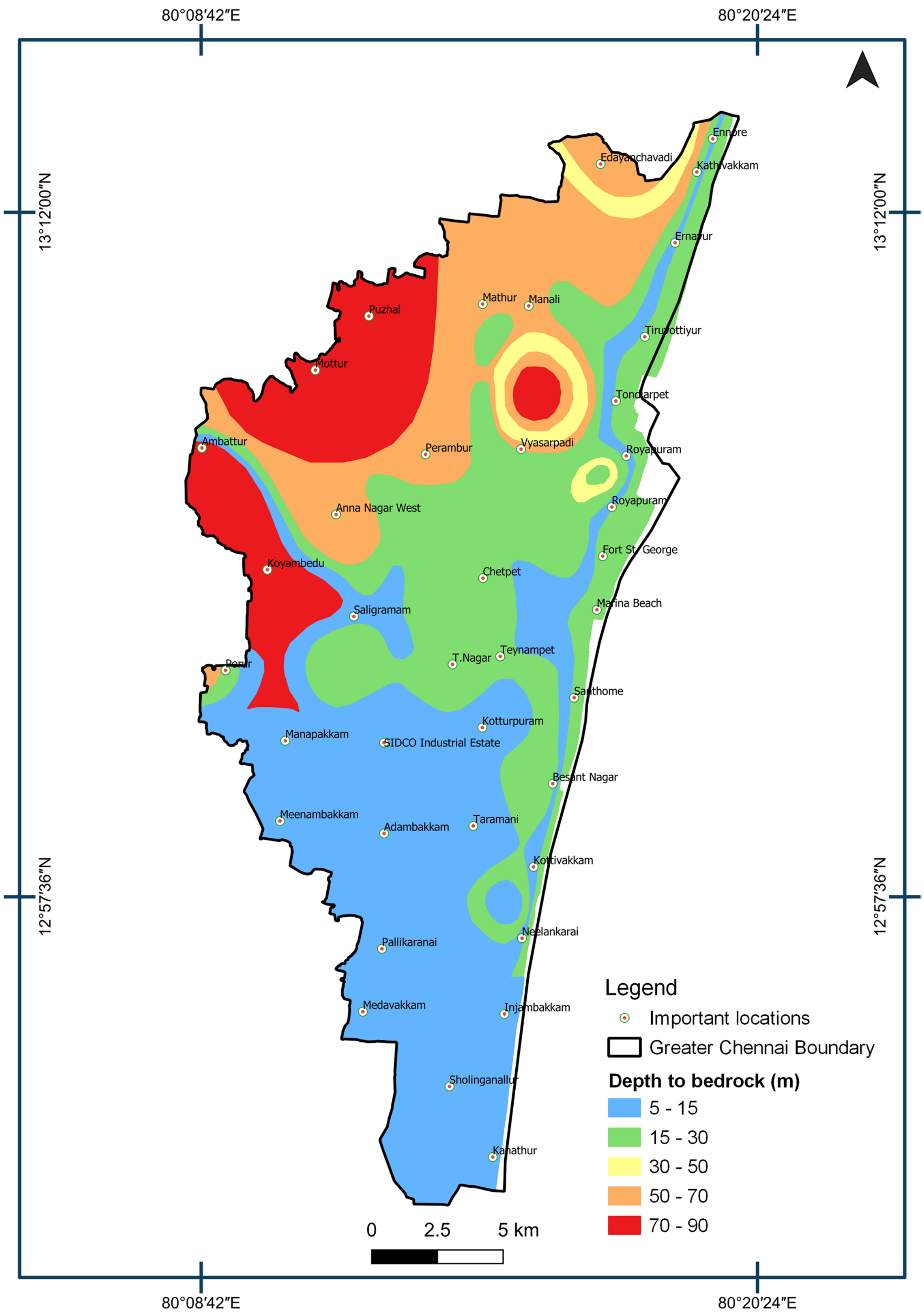

Fig. 6 Depth to bedrock map of the study area

Table 9 Depth to Bedrock in Greater Chennai

No	Zone	Nature	Bedrock depth	Composition
1	North	Coastal alluvium followed by Gondwana clay	28–90	Recent alluvium Sand-silt, Shale, Sedimentary rocks
2	South	Crystalline rocks with top soil cover	25	Silt–clay, Charnockites, Weathered rocks
3	West	Alluvium followed by Gondwana clay, Shales, Crystalline rocks	24–90	Mixed alluvium Clay Shales, Sand stones
4	Central	River alluvium followed by Crystalline rock	30	Alluvium Silt–clay, Gondwana shales
5	East	Coastal alluvium followed by Crystalline rock	5–30	Sand / Silt, Sand dunes, Marine fluvial clay Crystalline rocks

liquefaction—likely, possible, not possible. 35% of Greater Chennai was identified as areas wherein which liquefaction is possible. Those areas were observed along the coastal region and areas which are underlained by delta plain. Around 25% of the city falls under liquefaction may occur category due to underlying soil conditions. Areas with archean crystalline rock formations were identified as very low to low susceptible categories.

Social exposure of greater Chennai based on social vulnerability indicators

Social exposure indicators, namely–population density, building density and housing conditions for the 200 wards were fused together after assigning proper weightage (Table 7). 16% of Greater Chennai has been normally exposed to vulnerable factors based. 40% has been highly exposed and 44% of Greater Chennai has been under very highly exposed category (Fig. 13). Almost all of the coastal line of the city falls under either highly exposed or very highly exposed category due to rapid expansion of the city which in turn results in dense built environment and high population density. Central part of Greater Chennai is also heavily exposed due to population density, building density and housing conditions.

Table 10 Population of Greater Chennai

Year	Population (in millions)	Area (in Sq.kms)	Population density/Sq. kms
1901	0.541	68.17	7936
1911	0.556	68.17	8156
1921	0.578	68.17	8479
1931	0.713	68.17	10459
1941	0.865	77.21	11203
1951	1.427	128.83	11077
1961	1.749	128.83	13576
1971	2.469	128.83	19165
1981	3.285	176	18665
1991	3.843	176	21835
2001	4.344	176	24682
2011	4.681	176	26597
2011(After Expansion)	6.672	426	15662

Social vulnerability assessment of greater Chennai

The resulting exposure map (Fig. 13) was then processed with liquefaction susceptibility map as per the equation Risk = Hazard x Exposure (Cardona et al. 2012) which has yielded the social vulnerability map of Greater Chennai based on liquefaction hazard (Fig. 14). The highest vulnerability is shown to exist along the coastal corridor and in areas of Santhome, Vyasarpadi, Purasaiwakam (Table 11). Areas like T.Nagar, Chetpet which are famous for shopping areas and buzzing crowd falls under highly vulnerable category. It has to be noted that, Greater Chennai is expanding along the coastal zone which is already creating a lot of problems with respect to coastal zone management and disaster mitigation. In addition, as per Greater Chennai corporation's 2026 master plan for the city, so many IT corridors and industrial developments are planned along the coastal corridors which clearly fall under the moderate to high category in terms of vulnerability.

Conclusions

The aim of this study is to assess the social vulnerability of Greater Chennai with respect to seismic hazard risk, namely soil liquefaction as liquefaction studies are crucial for disaster mitigation planning especially in urban areas which are transforming so rapidly. Out of 426 km^2 19.4% of the area falls under high category and 33.5% fall in moderate to high category. It has to be noted that northern and north–east parts of the city falls under moderate category where economic activities are catching up. Altogether from moderate to high–53% of Greater Chennai's population is very much vulnerable to liquefaction hazard. Given the rapid growth along the coastal stretch of the study area, this paper exhibits the need for better urban planning and disaster management framework. This is a first

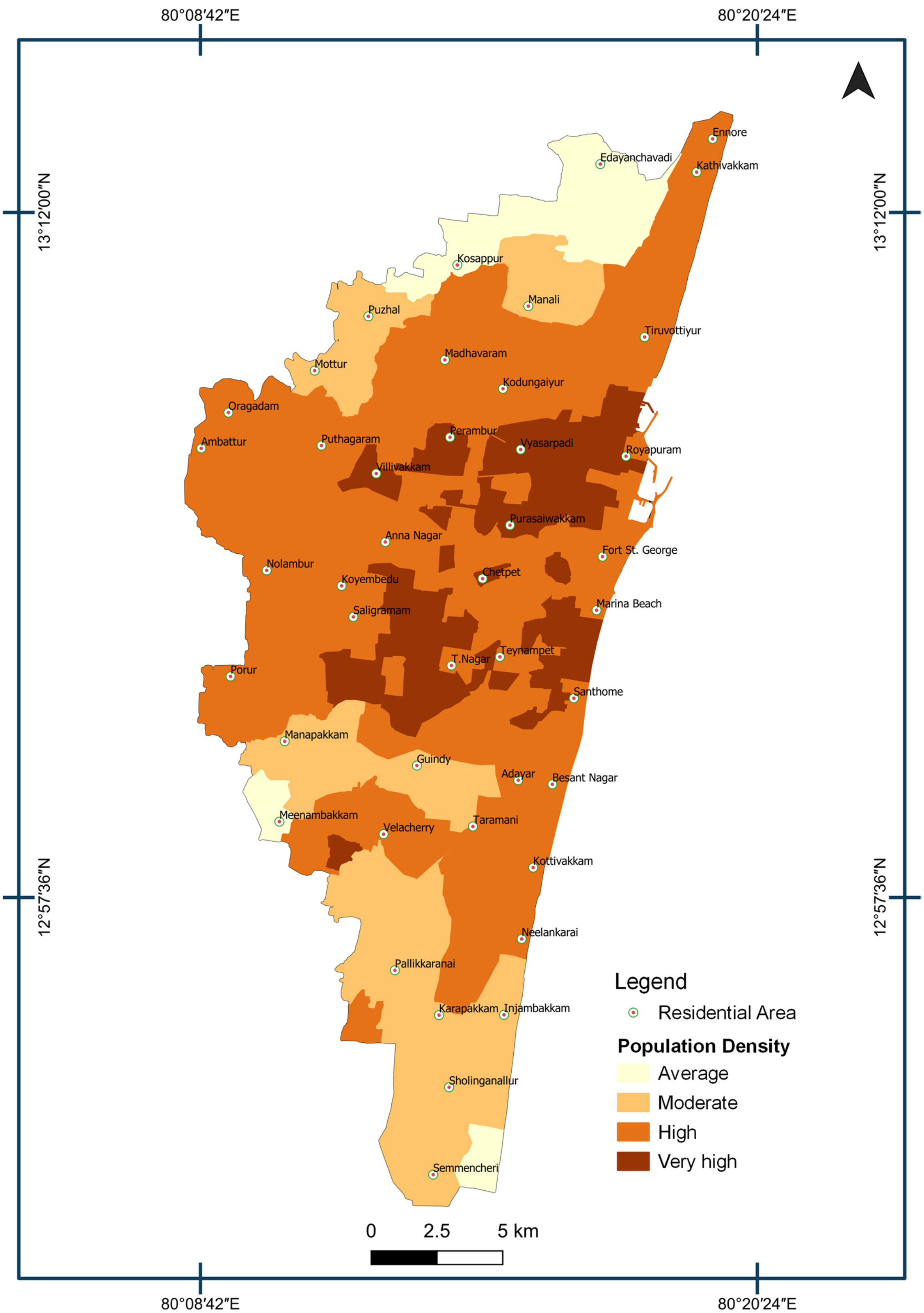

Fig. 7 Population density of the study area

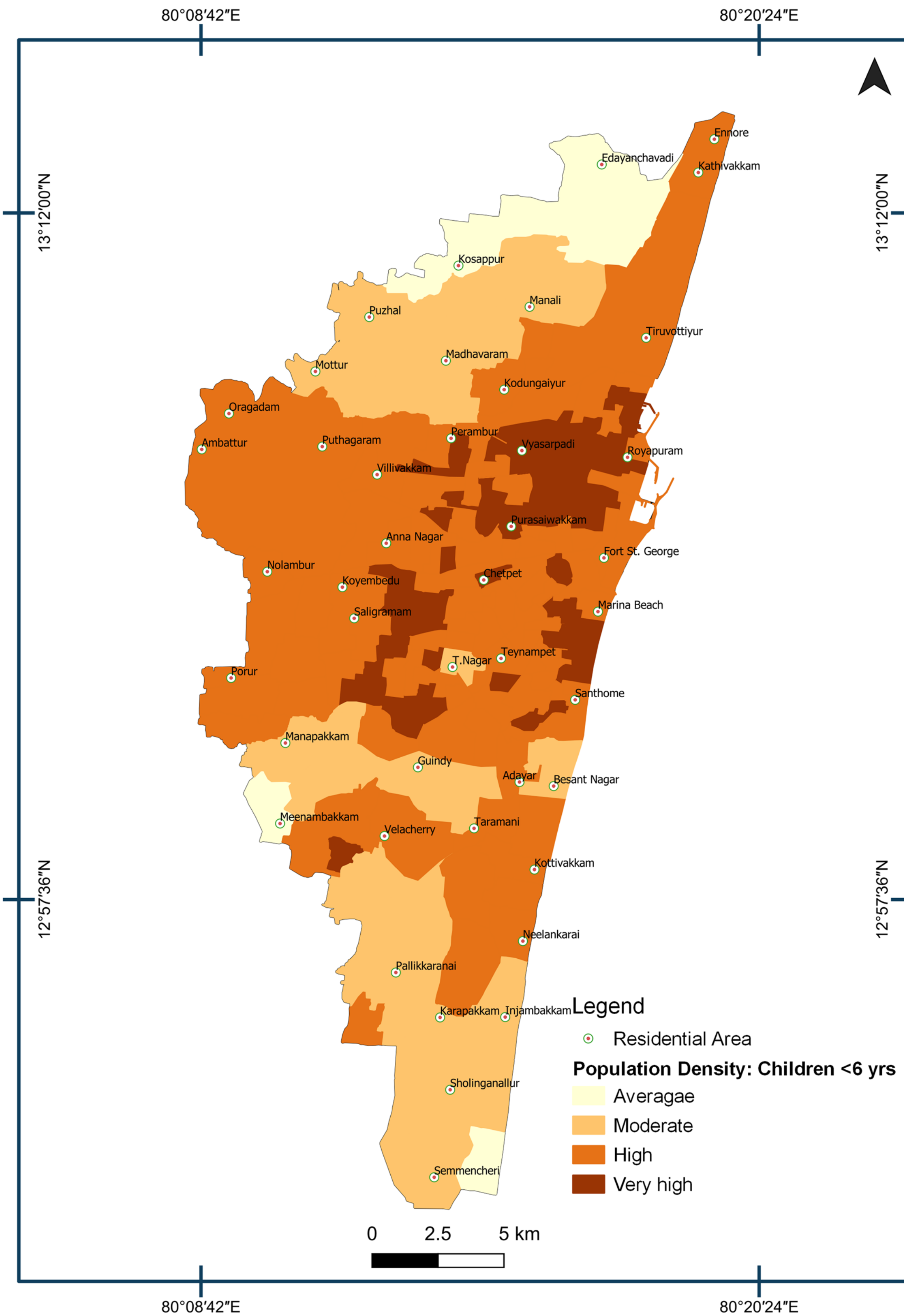

Fig. 8 Population density of children less than 6 Years

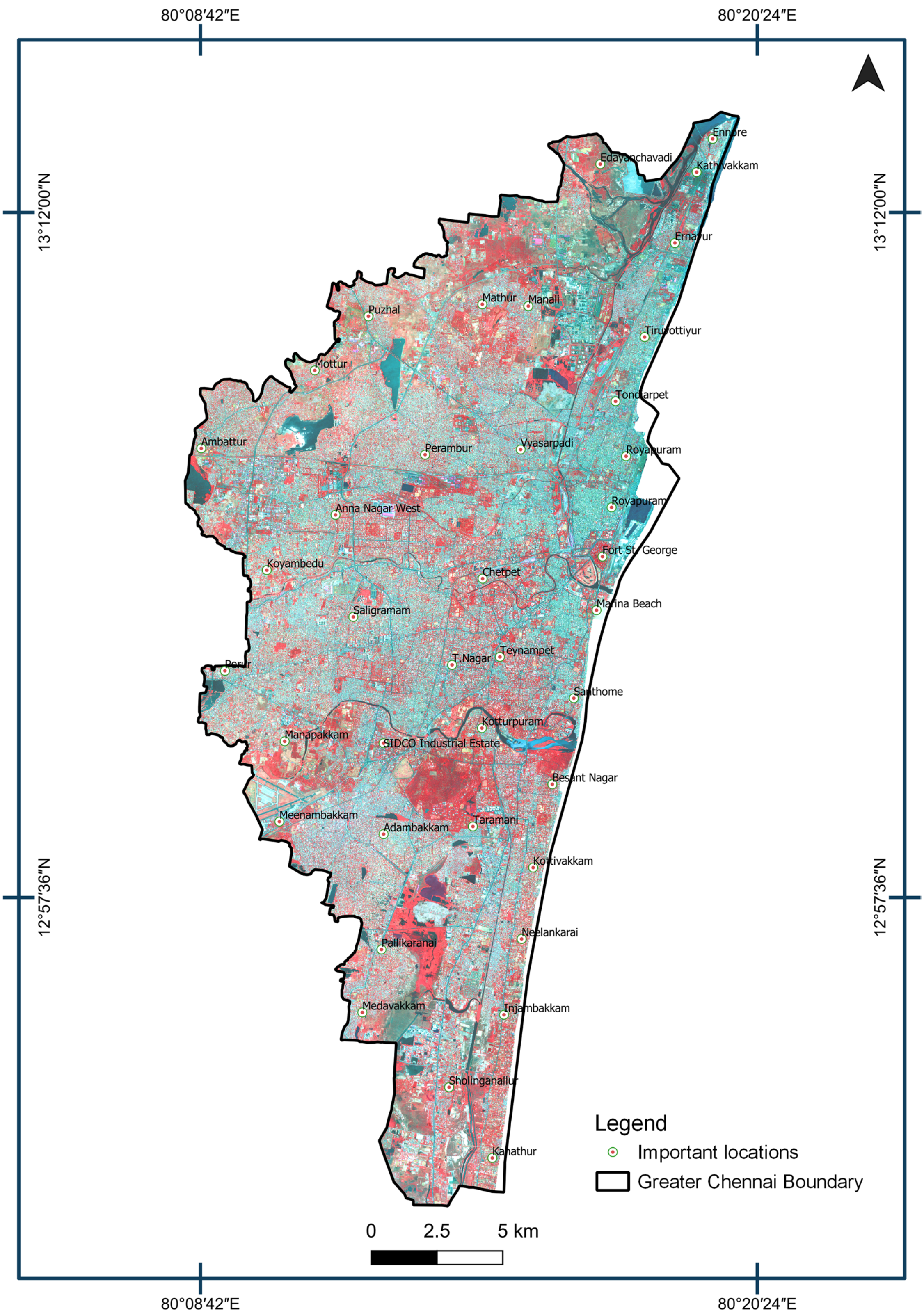

Fig. 9 Planetscope false color composite (432) of Greater Chennai

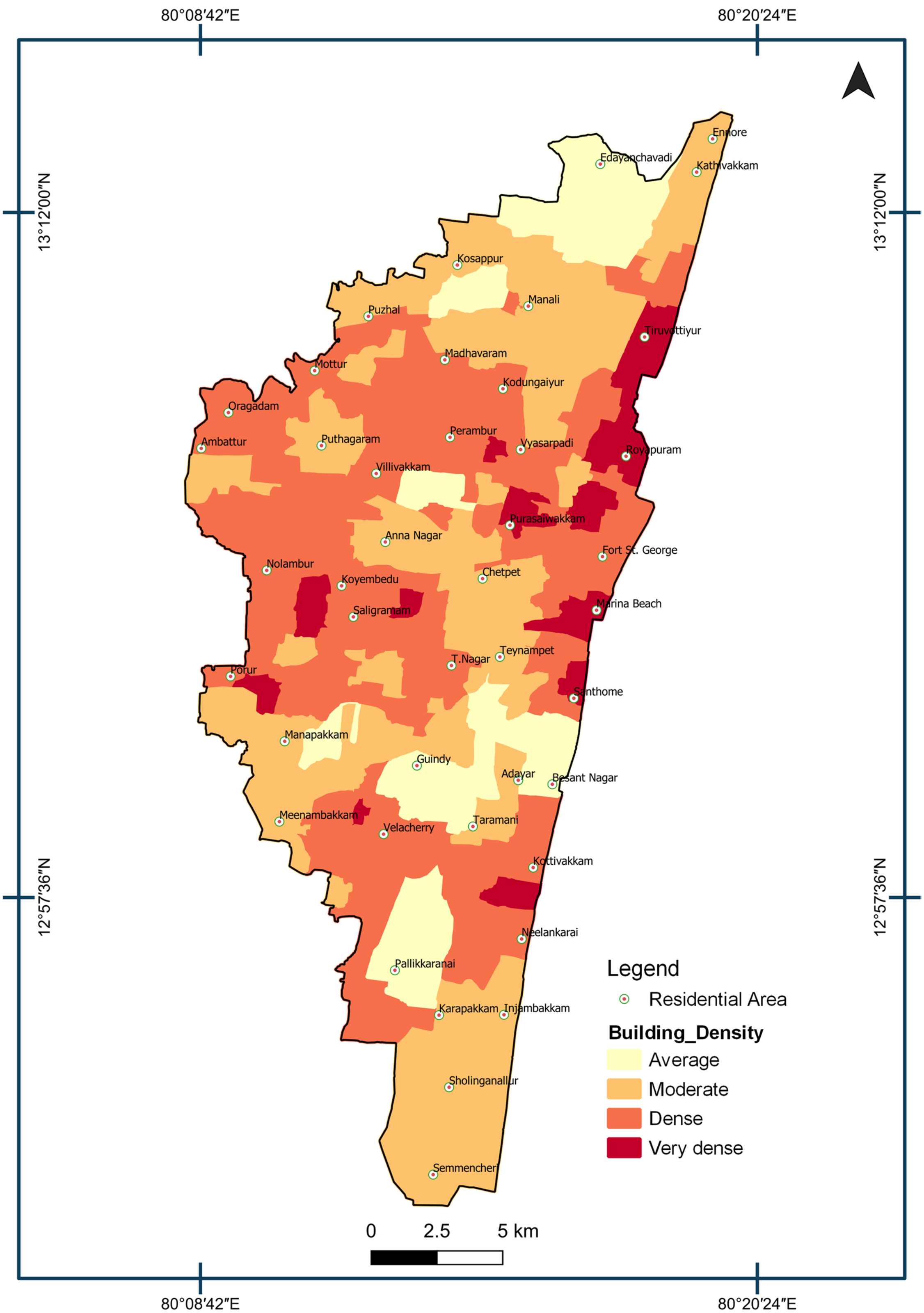

Fig. 10 Building Density of Greater Chennai

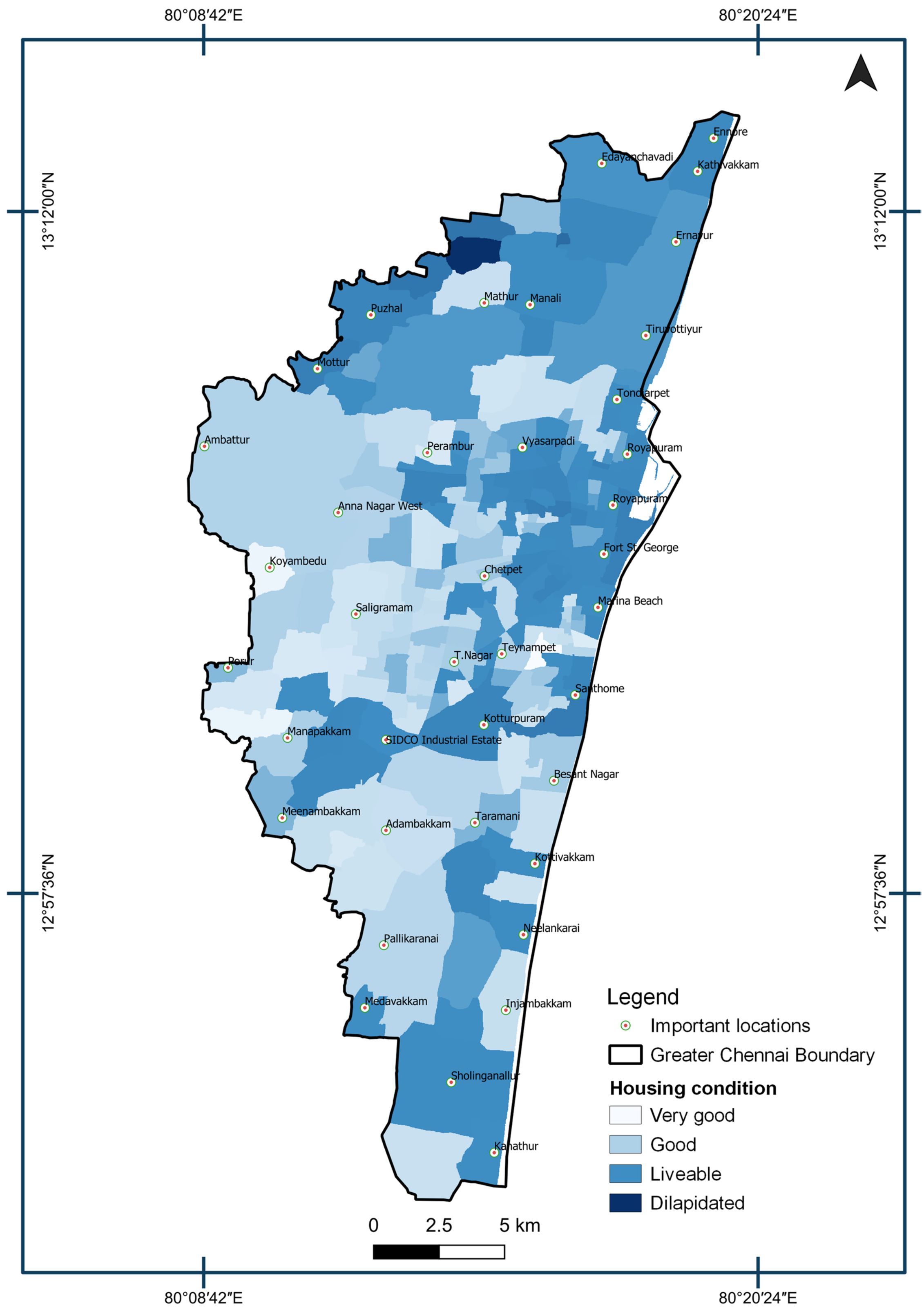

Fig. 11 Housing condition of houses in Greater Chennai

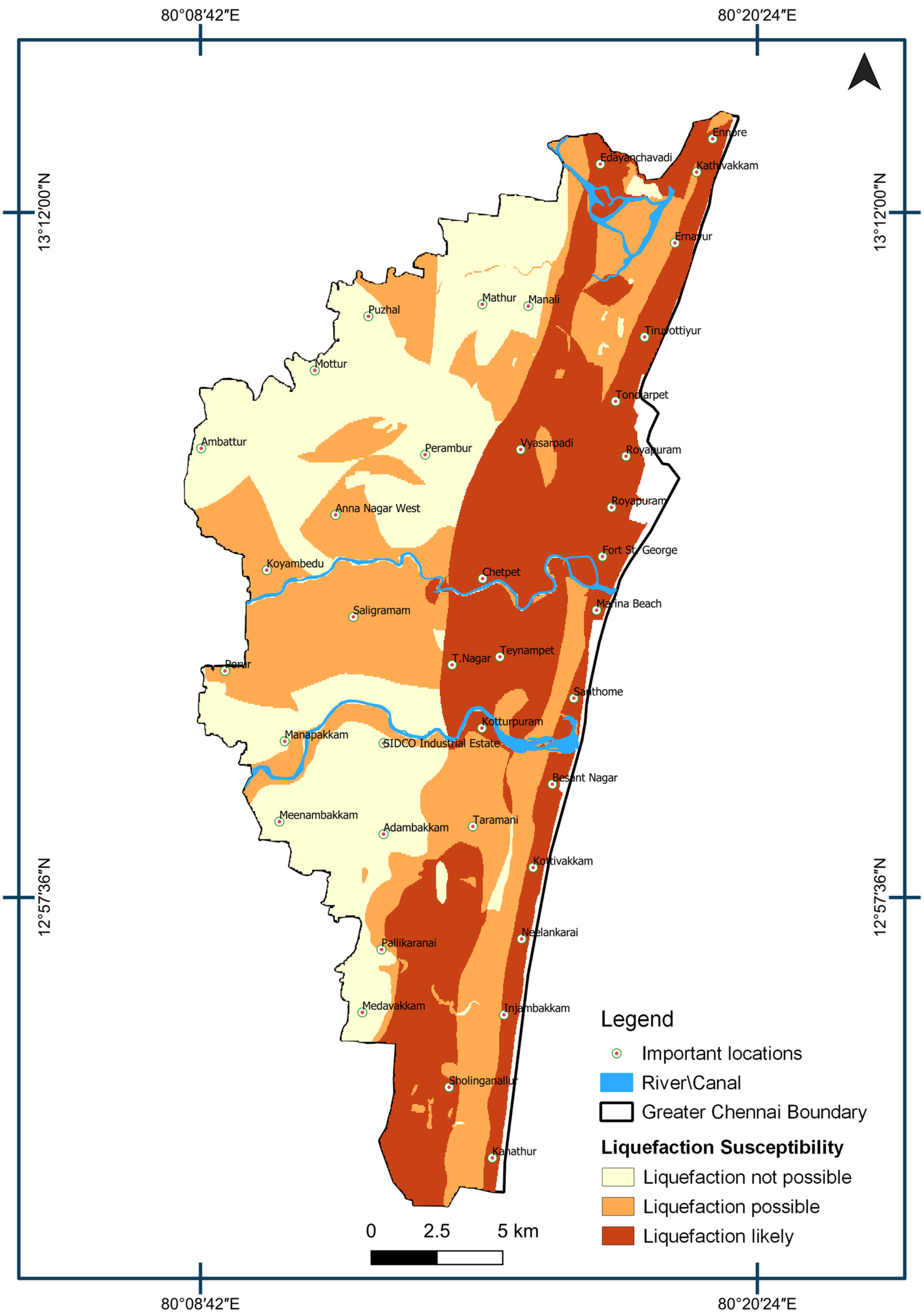

Fig. 12 Liquefaction susceptibility of Greater Chennai based on geological and geomorphological units

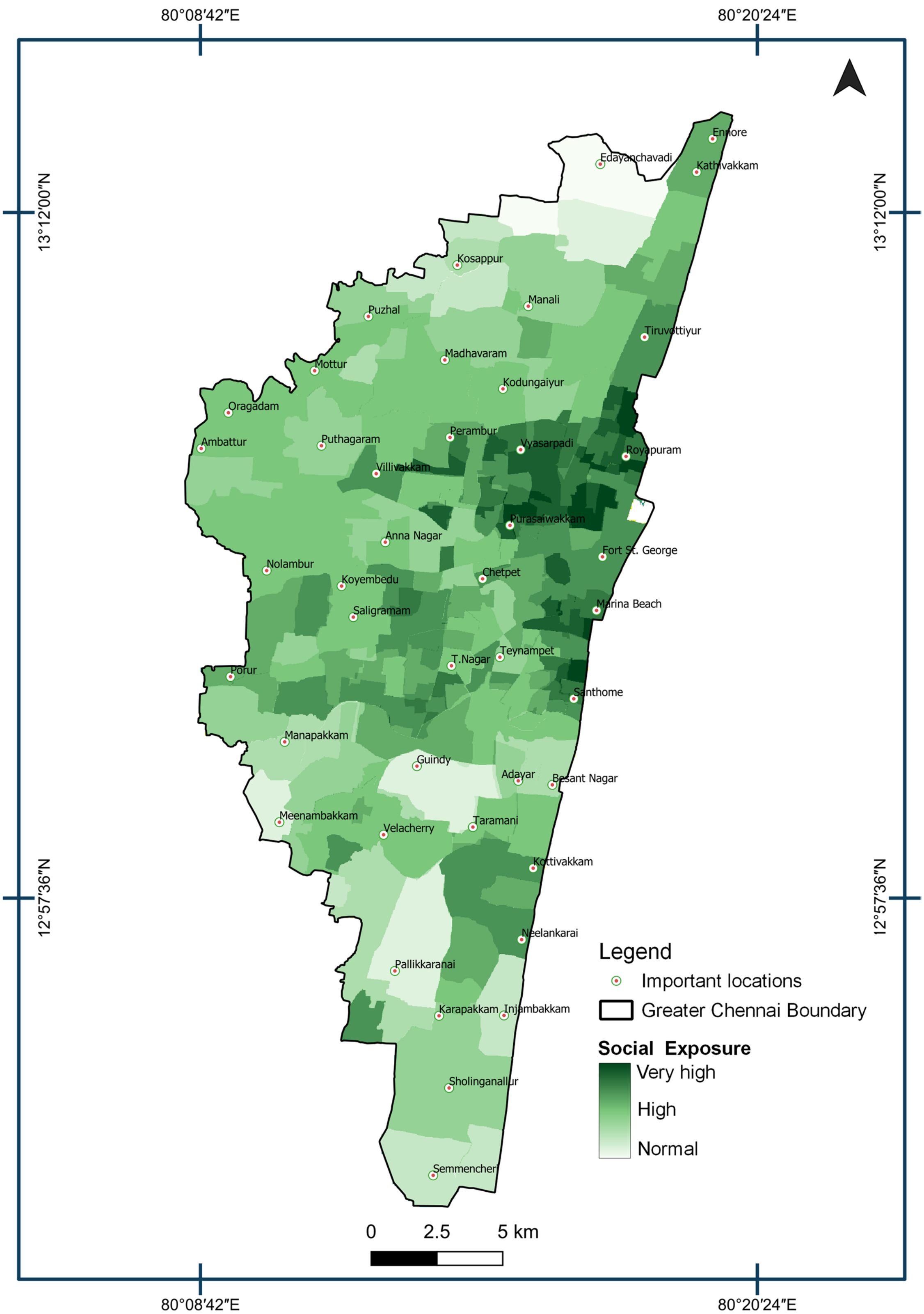

Fig. 13 Social exposure of Greater Chennai based on population density, building density, household condition

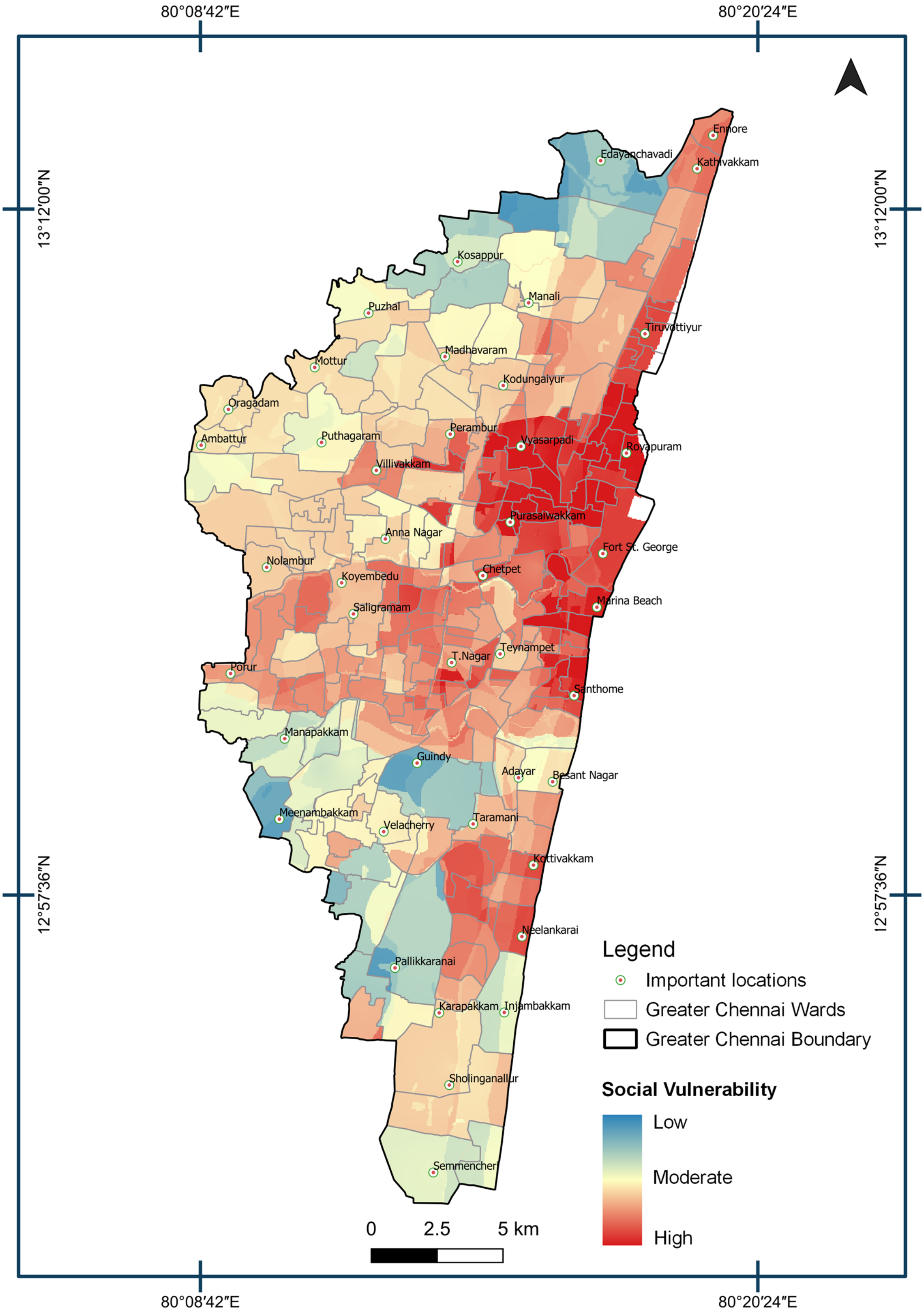

Fig. 14 Social vulnerability map of Greater Chennai

Table 11 Social vulnerability severity percentage

Social vulnerability	Percentage	Important locations
Low	7.4	Guindy, Meenambakkam, Pallikkaranai
Low to moderate	12.9	Semmencheri, Edayanchavadi
Moderate	26.8	Velachery, Ambattur, Manali
Moderate to high	33.5	Anna Nagar, Porur, Taramani
High	19.4	T.Nagar, Santhome, Vyasarpadi, Royapuram, Chetpet

level study to ascertain the regional liquefaction hazard and social exposure for an urban area. This paper has not considered factors which affect liquefaction like shear wave velocity, PGA, plasticity index. Further site specific studies depends on requirement can be done for detailed assessment and the hazard maps can be significantly refined.

Abbreviations

GIS	Geographic information systems
GDP	Gross domestic product
AHP	Analytical hierarchy process
OBIA	Object based image segmentation

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Declarations

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