

GIS-Based Assessment of Urbanisation Impacts on Flood Risk and Stormwater Infrastructure in Chennai Metropolitan Area

Rahul Debnath^{1*}, Prahallad Barman²

^{1, 2} Department of Geography, University of Madras, Guindy Campus, Chennai-600025, Tamil Nadu, India

¹ ORCID: <https://orcid.org/0009-0006-7671-4415>

*Corresponding Author: Rahul Debnath; debrahulnath981@gmail.com

Abbreviation: GESS

Website: www.maned.org/journals

Received: 10-07-2026

Revised: 27-08-2026

Accepted: 19-09-2026

Key Words:

Land-use change,
impervious surface,
GIS, flood hotspot,
KDE, DEM, TWI,
Chennai
Metropolitan Area,
urbanisation, flood
risk.

ABSTRACT

Urban flooding is a growing challenge in rapidly urbanising coastal cities, where intense monsoon rainfall interacts with expanding impervious surfaces, shrinking wetlands, and inadequate drainage capacity. The Chennai Metropolitan Area (CMA) has experienced major flood events, notably in 2005, 2015, and 2023, highlighting the need to understand the spatial drivers of flood risk. This study uses a GIS-based approach to examine the relationship between urban growth and flood susceptibility across CMA. Multi-temporal Landsat imagery (2000, 2010, 2015, 2020, and 2024) was used to assess LULC and impervious surface changes, while SRTM DEM data supported Flow Accumulation and Topographic Wetness Index (TWI) analysis. Historical flood locations were analysed using Kernel Density Estimation (KDE) to identify flood hotspots. Built-up area increased from 321.87 km² in 2000 to 346.33 km² in 2024 within the approximately 436.5 km² study area. Rainfall analysis using IMD gridded data showed that the 2015 event (349.63 mm/day) exceeded the estimated 100-year return-period rainfall of 330.19 mm/day, while the 2023 event (243.97 mm/day) was approximately associated with a 25-year return period. The combined spatial analysis indicates that flood-prone areas are concentrated in low-lying coastal zones, western and southern peri-urban areas, and the Adyar River floodplain, where urban expansion, high flow accumulation, and historical flood occurrences overlap. The findings highlight the importance of integrating land-use planning, terrain characteristics, and historical flood information for improving urban flood-risk management in Chennai.

INTRODUCTION

Urban flooding has become an increasingly important challenge in rapidly growing cities, particularly in tropical and monsoon-dominated regions where intense rainfall interacts with expanding built-up areas and limited drainage capacity. Urban development alters the natural hydrological response of catchments by replacing permeable surfaces with roads, buildings and other impervious structures. These changes reduce infiltration, increase surface runoff and shorten the time taken for rainfall to reach drainage channels, thereby increasing flood peaks and runoff volumes (Hollis, 1975; Ogden et al., 2011; Shuster et al., 2005). The distribution of impervious surfaces is therefore an important component of urban flood analysis, although recent studies also emphasise that topography, drainage configuration, rainfall characteristics and remaining pervious areas jointly influence urban hydrological response (Burns et al., 2012; Oswald et al., 2023).

The problem is particularly relevant to coastal cities in South Asia, where rapid urban expansion is occurring alongside intense seasonal rainfall and low-lying terrain. Previous studies have demonstrated that changes in land use and urban form can substantially modify rainfall–runoff processes and increase flood susceptibility (Huong and Pathirana, 2013; Fletcher et al., 2013). In Mumbai, Zope et al. (2015) demonstrated a strong association between long-term urban expansion and changes in runoff response in the Mithi River catchment.



Copyright: © 2026 by the authors

Licensee: ManEd Research Foundation

This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY 4.0) license.

Similarly, Suriya and Mudgal (2012) showed that increasing imperviousness in the Thirusoolam sub-watershed of Chennai altered streamflow behaviour and increased flood response. These findings highlight the importance of examining urban growth not only as a land-use process but also as a hydrological driver. Chennai presents a particularly important case because of its coastal setting, relatively low elevation, monsoon-dominated rainfall and long history of urban expansion. The city has experienced several major flood events, with the 2015 event becoming one of the most severe in recent decades. Studies of the Adyar basin have shown that both urban sprawl and changes in rainfall can influence future flood inundation, while the expansion of settlements into floodplains, wetlands and water bodies has modified the natural drainage system (Nithila Devi et al., 2019). More recent research has further demonstrated the importance of retaining Chennai's traditional water bodies, which provide natural storage and can reduce flood impacts (Nithila Devi et al., 2025). The loss and encroachment of such natural storage areas, together with increasing urbanisation, therefore remain important considerations in understanding Chennai's flood risk.

Geographic Information Systems (GIS) and remote sensing provide an effective framework for examining these interacting processes because they allow land-cover change, terrain characteristics, drainage patterns and historical flood information to be analysed within a common spatial framework. GIS-based flood studies have successfully integrated elevation, slope, drainage density, land use, rainfall and proximity to rivers to identify flood-prone areas (Tomar et al., 2021; Khosravi et al., 2016). In Chennai, GIS-based multi-criteria approaches have similarly demonstrated that low elevation, proximity to rivers, drainage conditions and land-use characteristics are associated with higher flood susceptibility (Mishra et al., 2023). Terrain-based indicators such as flow accumulation and the Topographic Wetness Index (TWI) are particularly useful for identifying areas where runoff is likely to concentrate, while historical flood inventories provide an empirical basis for examining the spatial distribution of observed flood occurrence.

Previous research has generally focused on individual components of the urban flood problem. Hydrological and hydraulic modelling studies have provided detailed simulations of flood depth and inundation, while land-use studies have examined urban expansion and its influence on runoff. Other studies have used GIS-based multi-criteria methods to produce composite flood susceptibility maps. For example, Tomar et al. (2021) integrated remote sensing, GIS and field information for flood-risk assessment in Delhi, whereas Ertan and Çelik (2021) examined different urbanisation and green-infrastructure scenarios using GIS and HEC-RAS. Their results demonstrate the importance of

linking urban development with hydrological processes and drainage conditions. However, relatively few studies for Chennai combine long-term urban land-cover change, impervious surface expansion, terrain-based flow characteristics and spatially explicit historical flood occurrence within a single analytical framework.

This study addresses this gap through a GIS-based assessment of urbanisation-related flood risk in the Chennai Metropolitan Area (CMA). Multi-temporal Landsat imagery is used to examine LULC and impervious surface changes between 2000 and 2024. SRTM DEM data are then used to derive flow accumulation and TWI, providing information on terrain-controlled runoff pathways and areas of potential water concentration. Historical flood incident locations are analysed using Kernel Density Estimation (KDE) to identify spatial concentrations of observed flooding. In addition, historical rainfall data are examined to place major flood events within their rainfall-frequency context.

The study therefore aims to move beyond a single-factor assessment of urban flood risk by bringing together urban expansion, impervious surface growth, terrain-driven hydrological behaviour and observed flood occurrence. The resulting spatial evidence provides a basis for identifying areas where multiple flood-generating factors overlap and can support more targeted urban drainage planning and flood-risk management in Chennai.

The study is guided by three interconnected aims: (i) to examine the spatial and temporal transformation of land use and impervious surfaces across CMA between 2000 and 2024; (ii) to investigate terrain- and rainfall-related conditions associated with potential flood-prone areas using DEM-based hydrological analysis and rainfall-frequency assessment; and (iii) to examine the spatial correspondence between existing stormwater drainage infrastructure and historically recorded flood hotspots, thereby identifying locations where urban development, natural flow concentration, and observed flooding overlap. By integrating these complementary sources of evidence, the study seeks to provide a spatially interpretable assessment of Chennai's changing flood-risk landscape that can support more informed urban drainage and land-use planning.

STUDY AREA

The study area, Chengalpattu District, is located in the southeastern part of India and covers an area of approximately 2659.4 km². It lies between latitudes 12°13'41"N to 13°01'42"N and longitudes 79°38'32"E to 80°15'19"E. The district is bounded by Chennai to the north, Kanchipuram District to the northwest, Tiruvannamalai District to the west, Villupuram District to the south, and the Bay of Bengal to the east. The region has an average elevation of about 30 m above mean sea

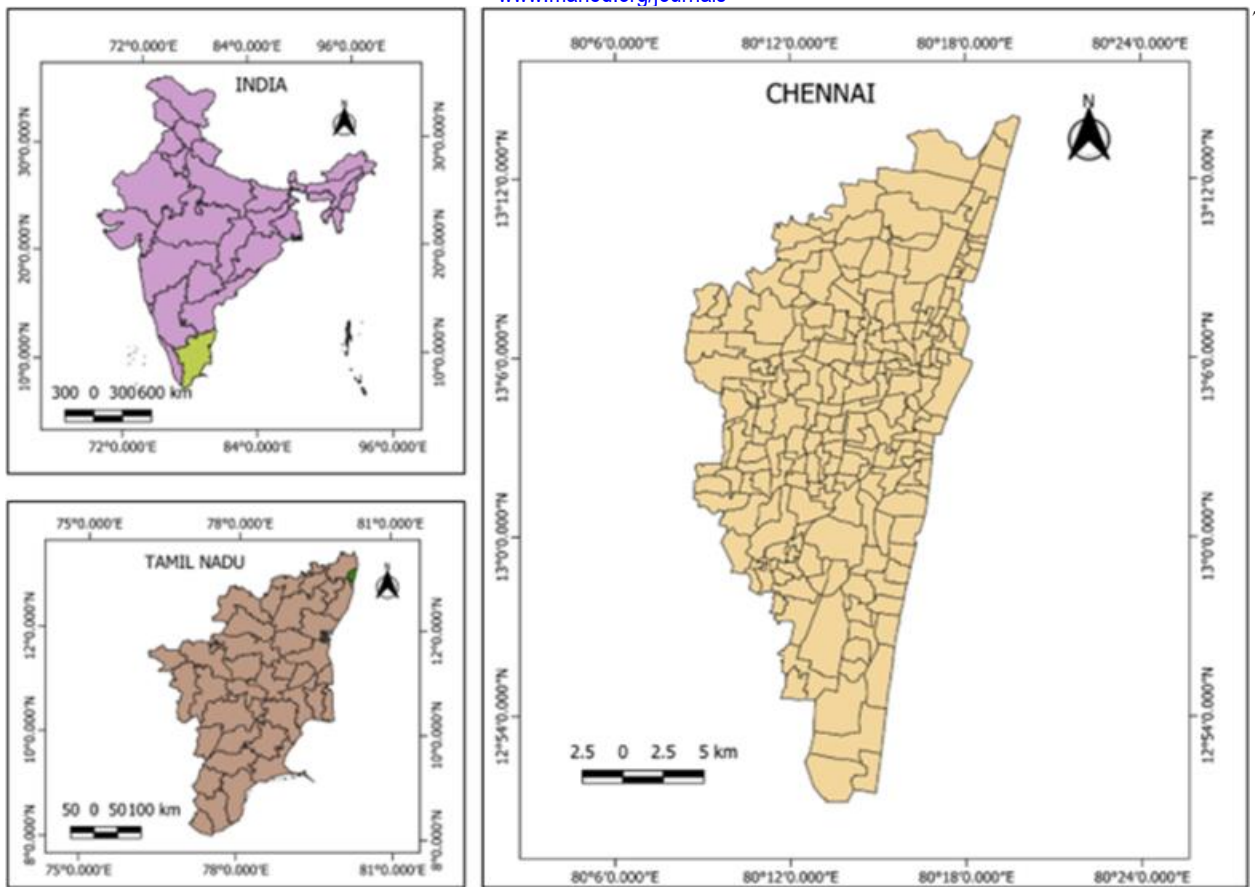


Fig.1: Study area- Chennai Metropolitan

level and shows a general west-to-east slope, influencing groundwater movement.

Geologically, the area consists of sedimentary and crystalline formations, including alluvium, Gondwana sandstones, and weathered rocks, forming multi-layered aquifer systems. Groundwater occurs mainly under unconfined conditions at shallow depths ranging from 5 to 10 m below ground level. The drainage network includes rivers such as the Palar River, along with Adyar and Ongur rivers, which are mostly seasonal and flow during monsoon periods. The district contains a large number of irrigation tanks and recharge structures that support groundwater replenishment.

The climate is tropical, with an average annual temperature of about 27.8°C and an average annual rainfall of approximately 1236.8 mm, mainly received during the northeast monsoon. Groundwater is the primary source of drinking water in the region. However, rapid urbanization, agricultural activities, and improper waste

disposal have increased the risk of groundwater contamination. These conditions make the study area suitable for groundwater quality assessment and human health risk analysis (Nagarathinam et al., 2025).

The study area is the Chennai Metropolitan Area (CMA), situated along the southeastern Coromandel Coast of Tamil Nadu, India. The metropolitan boundary used in this study spans from approximately 12°50'N to 13°15'N latitude and 79°52'E to 80°24'E longitude, enclosing an area of roughly 436.5 km² based on the classified LULC raster boundary. Chennai is the capital of Tamil Nadu and one of the most economically significant cities in South Asia, with a population estimated at over 10 million in the study period, projected to reach approximately 13.9 million by 2030 under current urbanisation trends (Nithila Devi et al., 2019).

Topographically, CMA is characterised by predominantly flat to gently undulating terrain with elevations mostly below 15 metres above mean sea level across the built-up urban core

and coastal belt. The principal river systems that provide drainage for the metropolitan area are the Adyar River, which drains the southern urban zones from the Chembarambakkam Reservoir to the Bay of Bengal, and the Cooum River, which traverses the northern urban districts. The Buckingham Canal — a historic navigational and drainage channel running parallel to the coastline — serves as an important interceptor drain for a large portion of the city's stormwater. Chennai's natural

landscape historically supported an extensive system of irrigation tanks (eries), many of which have been partially or fully encroached upon during the urbanisation process, with significant consequences for natural flood storage capacity (Sharma et al., 2024).

DATABASE AND METHODOLOGY

Database

The study draws on four primary categories of spatial and hydro-meteorological data. Landsat satellite imagery was sourced from the USGS EarthExplorer archive via Google Earth Engine, with five time steps selected: Landsat 5 TM for 2000, Landsat 7 ETM+ for 2010, and Landsat 8 OLI for 2015, 2020, and 2024. SRTM 30m Digital Elevation Model data was accessed through the Google Earth Engine data catalogue (dataset ID: USGS/SRTMGL1_003). Rainfall data covering 2000 to 2024 was obtained in gridded format from the India Meteorological Department (IMD) and processed as annual maximum daily values. Historical flood incident data was compiled from multiple sources - IMD flood impact reports, NDMA post-disaster situation reports, Greater Chennai Corporation (GCC) flood assessment records, and KML-format point datasets derived from field surveys and georeferenced media documentation — which were then used as input for the KDE flood hotspot analysis. Administrative boundary data for CMA was sourced from the GCC ward boundary dataset.

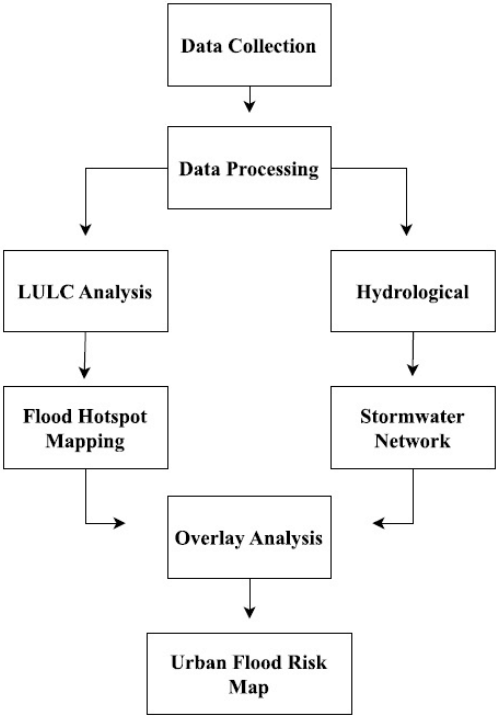


Fig .2: Methodological flow chart

Table 2: Summary of Data Sources

Data Layer	Source	Resolution / Period	Role in Study
Landsat 5/7/8/9 OLI Imagery	Google Earth Engine	30 m; 2000, 2010, 2015, 2020, 2024	LULC classification and impervious surface mapping
SRTM Digital Elevation Model v3	USGS via Google Earth Engine	30 m horizontal resolution	Flow direction, flow accumulation, TWI computation
IMD Gridded Daily Rainfall	India Meteorological Department	0.25°; daily; 2000–2024	Annual maximum rainfall, IDF curve analysis
Flood Incident Dataset	IMD, NDMA, GCC, KML field survey records	Point features; 2005–2023	Kernel Density Estimation flood hotspot analysis
CMA Administrative Boundary	GCC ward maps	1:50,000 scale; vector polygon	Study area boundary and spatial aggregation for all analyses

Methodology

Land-Use and Land-Cover Classification

LULC classification was performed in Google Earth Engine for five time steps using Landsat Surface Reflectance

composites. For each year, a cloud-free median composite was generated from dry-season scenes (January to March) to eliminate confounding seasonal vegetation effects. Collection 2

Level-2 Surface Reflectance corrections were applied to all Landsat images. Spectral indices were calculated from the composites: NDVI (Normalised Difference Vegetation Index) using NIR and Red bands, NDBI (Normalised Difference Built-up Index) using SWIR-1 and NIR bands, and MNDWI (Modified Normalised Difference Water Index) using Green and SWIR-1 bands. These indices were stacked with the six Landsat reflectance bands as a combined input feature set for classification.

A supervised Random Forest classifier with 100 trees was trained on digitised training samples for four land-cover classes: Built-up, Vegetation, Water, and Open Land. Training samples were digitised by on-screen visual interpretation with reference to Google Earth historical imagery for each year. The classifier was applied to the stacked band-plus-index composite for each time step. Post-classification accuracy was assessed using stratified random validation samples per year, and a 3×3 majority filter was applied to remove isolated misclassified pixels. Change detection between all consecutive time steps was carried out by pixel-by-pixel raster subtraction on the Built-up class, generating the Impervious Surface Growth maps.

DEM-Based Hydrological Analysis

The SRTM 30m DEM was processed in ArcGIS Pro using the Spatial Analyst Hydrology toolset. The standard D8 flow routing processing chain was applied: Fill (to remove spurious sinks), Flow Direction, and Flow Accumulation. The flow accumulation raster was classified into five categories (Low, Moderate, High, Very High, Extreme) to produce the DEM-Derived Runoff Flow Accumulation Map. The Topographic

Wetness Index (TWI) was computed as the natural logarithm of the ratio of flow accumulation to the tangent of slope angle ($TWI = \ln(A / \tan \beta)$), providing a spatially continuous index of terrain-driven flood susceptibility. The TWI raster was classified into five categories (Very Low, Moderate, Moderate-High, High, Very High) using natural breaks.

Rainfall Trend and IDF Analysis

Annual maximum daily rainfall values were extracted from IMD gridded data for the period 2000 to 2024. IDF (Intensity-Duration-Frequency) curves were developed using Gumbel extreme value (Type I) distribution fitting to the annual maximum series, following the methodology applied by Sharma et al. (2024) for Chennai. Return period rainfall intensities were computed for 2, 5, 10, 25, 50, and 100-year events, providing a design return period reference

frame for interpreting observed flood event intensities.

KDE Flood Hotspot Analysis

A flood incident dataset was compiled from IMD flood reports, NDMA post-disaster situation reports, GCC flood damage records, and KML-format point data from field surveys and georeferenced media documentation covering the 2005, 2008, 2010, 2015, 2021, and 2023 flood events. Each incident point was georeferenced to sub-kilometre precision using the GCC ward address database. Kernel Density Estimation was applied to the compiled point layer in ArcGIS Pro using the Spatial Analyst Kernel Density tool. A quartic kernel with a search radius (bandwidth) of 1,500 metres was applied based on the documented spatial scale of neighbourhood-level inundation in Chennai's 2015 flood.

The output resolution was set to 30 metres to match the LULC and DEM layers. The resulting density surface was classified into five hotspot intensity categories: Very Low, Low, Moderate, High, and Very High.

RESULTS AND DISCUSSION

Land-Use and Land-Cover Change (2000–2024)

The classified LULC maps reveal a clear and sustained trajectory of built-up expansion across the Chennai Metropolitan Area over the 24-year study period. Built-up area increased from 321.87 km² in 2000 to 346.33 km², representing a net gain of 24.46 km² or 7.60 percent over the period. This increase, while modest in percentage terms relative to the total study area boundary, is significant when considered in the context of what it displaced: the water body class declined by 22.54 percent (from 33.10 to 25.64 km²), and vegetation cover fell by 26.14 percent (from 45.94 to 33.93 km²). These losses of permeable and water-retaining land covers are hydrologically consequential far beyond what the raw area figures suggest, because natural water bodies and vegetated land play a disproportionately important role in attenuating flood peaks and sustaining infiltration (Sharma et al., 2024; Bronstert et al., 2002).

Table 3: LULC Class Areas (km²) for 2000–2024

LULC Class	2000 (km ²)	2010 (km ²)	2015 (km ²)	2020 (km ²)	2024 (km ²)
Built-up	321.87	327.36	332.85	335.29	346.33
Vegetation	45.94	41.01	46.79	48.79	33.93
Water	33.10	30.65	32.98	28.63	25.64
Open Land	35.61	37.53	23.93	23.84	30.64
TOTAL	436.52	436.55	436.55	436.55	436.54

The most pronounced single-period built-up expansion occurred between 2020 and 2024, when 11.04 km² was added to the built-up class - more than the combined increase of the preceding 15 years from 2005 to 2020. This acceleration coincided with the largest single period vegetation loss in the dataset (-14.86 km² between 2020 and 2024), suggesting that the most recent phase of urban expansion has been particularly aggressive in converting vegetated peri-urban land. From a flood risk perspective, this

Table 3: Net Change in LULC Class Area from 2000 to 2024

LULC Class	2000 (km ²)	2024 (km ²)	Net Change (km ²)	% Change
Built-up	321.87	346.33	+24.46	+7.60%
Vegetation	45.94	33.93	-12.01	-26.14%
Water	33.10	25.64	-7.46	-22.54%
Open Land	35.61	30.64	-4.97	-13.96%

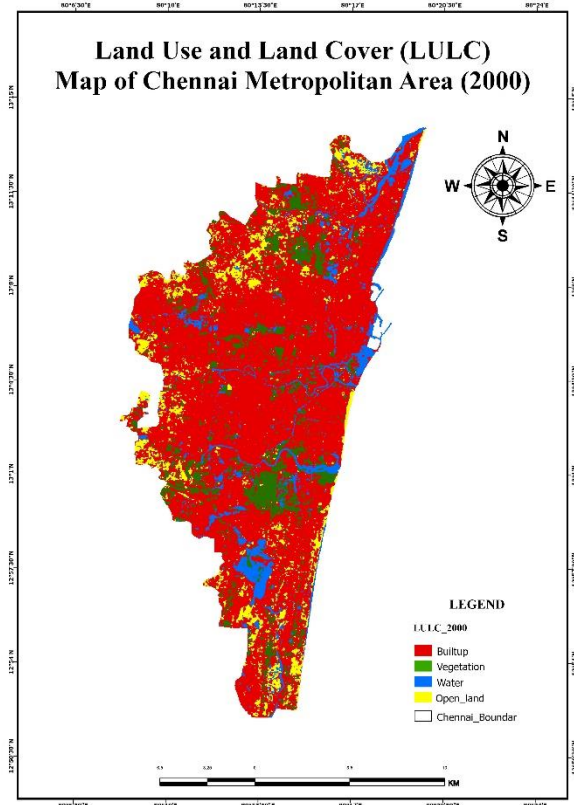


Fig. 3: LULC Map 2000

is the most concerning period in the dataset, as it represents the ongoing conversion of land that still had meaningful hydrological buffering capacity. The maps for individual years are presented in Figures 3 through 7.

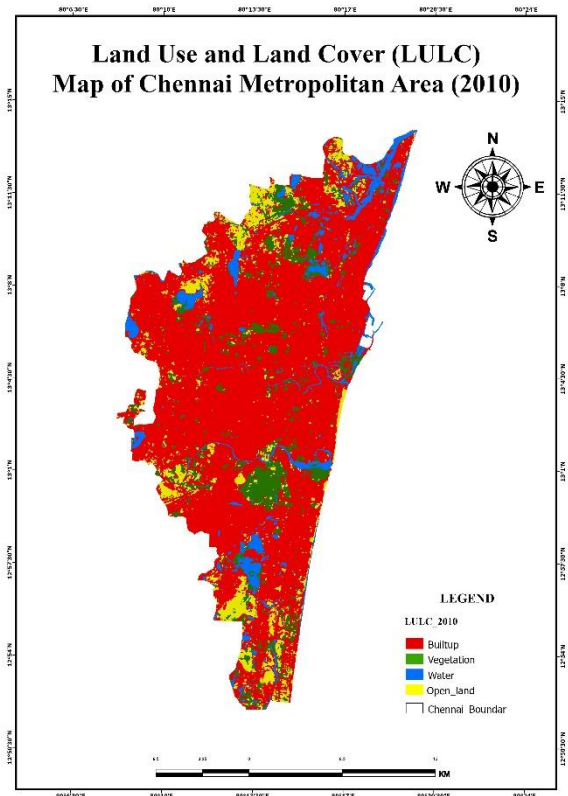


Fig. 4: LULC Map 2010

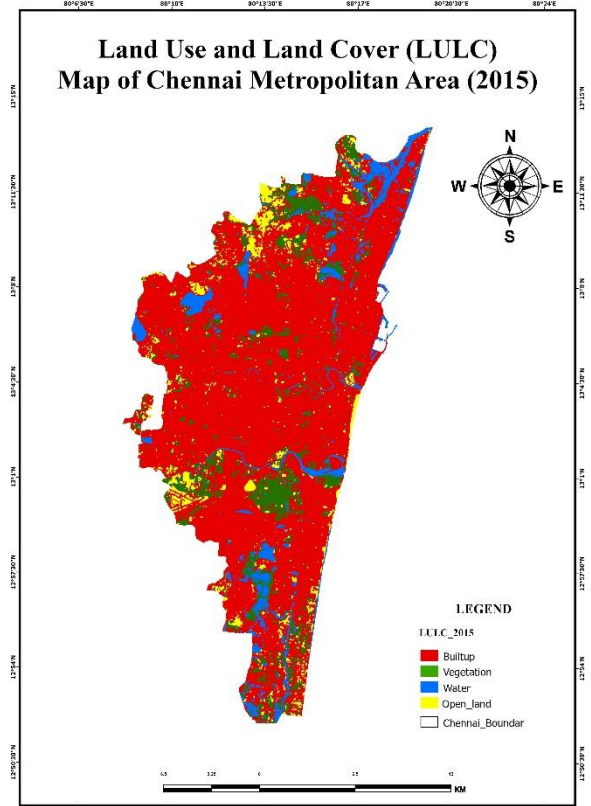


Fig. 5: LULC Map 2015

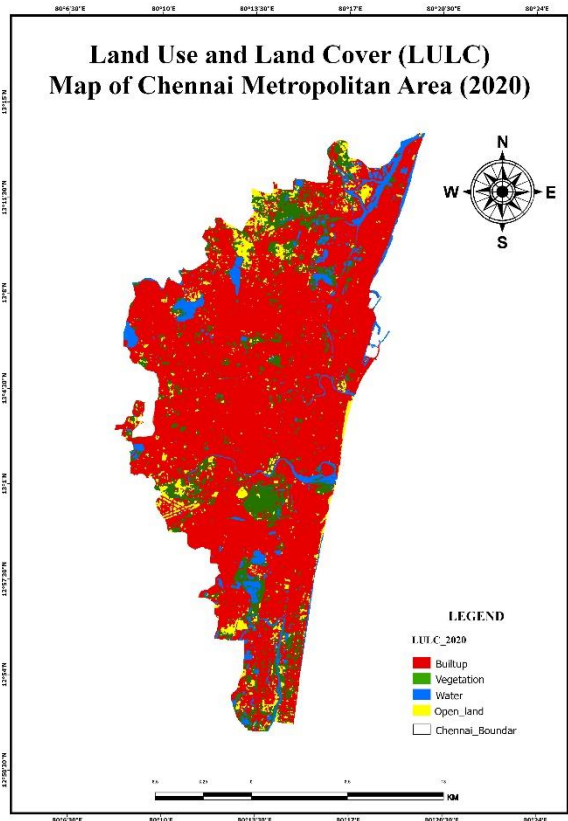


Fig. 6: LULC Map 2020

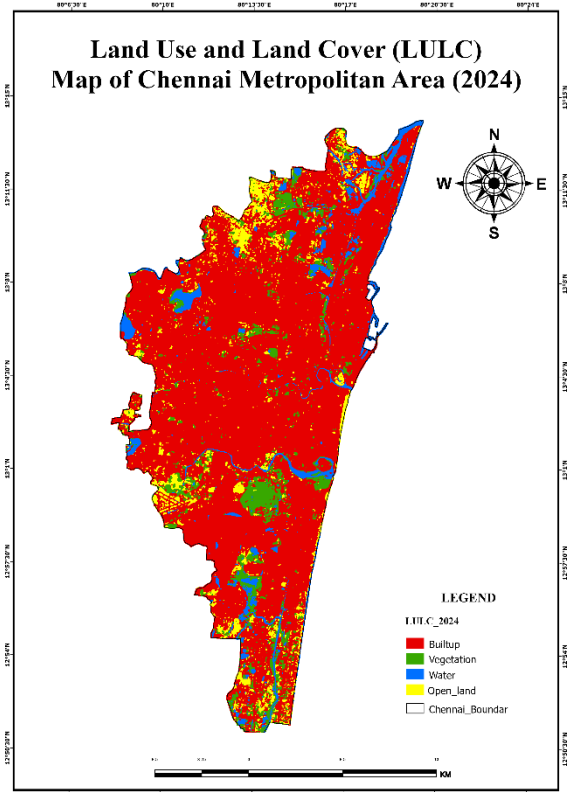


Fig. 7: LULC Map 2024

Impervious Surface Growth Maps

The four Impervious Surface Growth maps- covering 2000–2010, 2010–2015, 2015–2020, and 2020–2024 - show the spatial distribution of built-up expansion and recession across the metropolitan area during each period. The maps use a three-class classification: Increase (red), Decrease (blue), and No Change (white background). The 2000–2010 period (Fig.8) shows the most spatially widespread pattern of impervious surface increase, with significant red patches concentrated in the western peri-urban zones (around Ambattur, Villivakkam, and Koyambedu) and extending into the southern fringe. The concurrent presence of blue decrease patches reflects real land-use dynamics where previously classified built-up pixels shifted to open land or were reclassified, partly reflecting classification uncertainty at the edges of development fronts.

The 2010–2015 period (Fig.9) shows a tighter spatial pattern of increase, concentrated in the northern fringe around Madhavaram and the southern coastal fringe around Sholinganallur and Perungudi — areas that were rapidly incorporated into the IT corridor and residential real estate market during this period. By the 2015–2020 period (Fig.10),

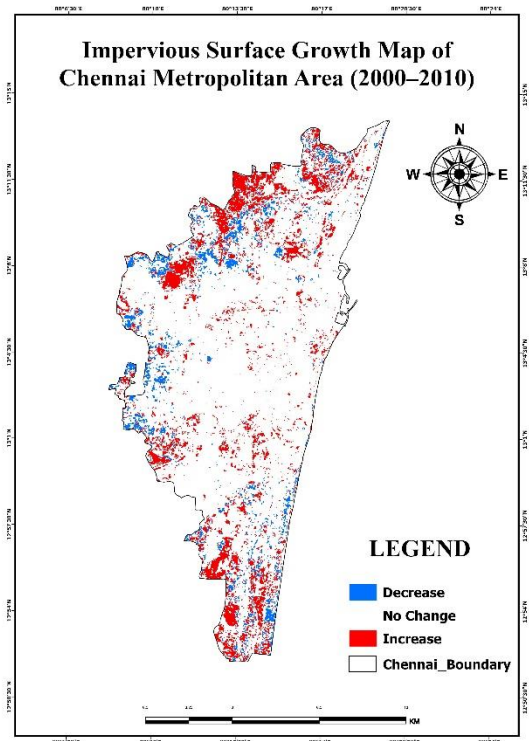


Fig. 8: Impervious Surface Growth Map 2000 to 2010

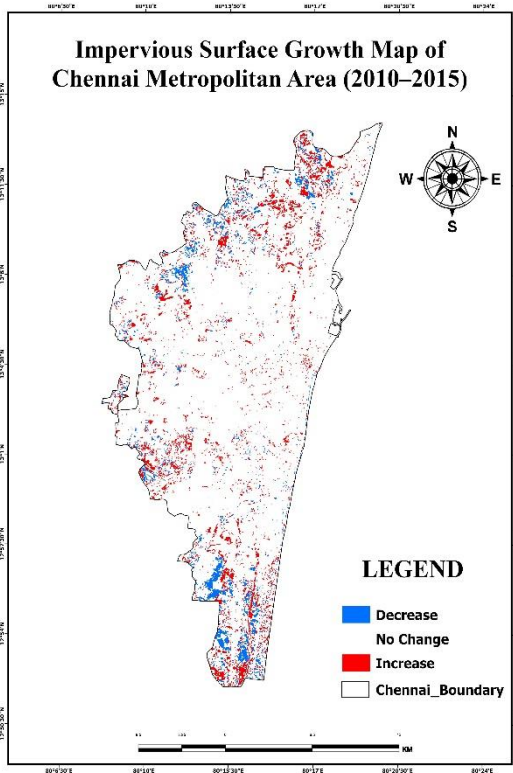


Fig. 9: Impervious Surface Growth Map 2010 to 2015

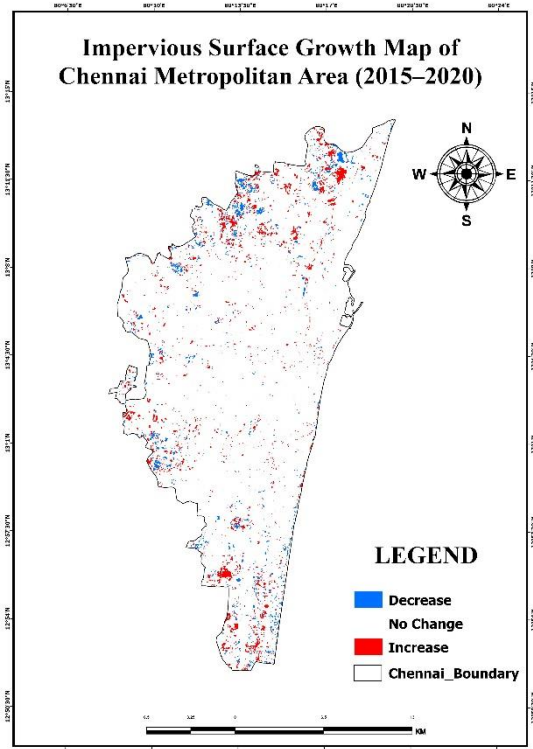


Fig. 10: Impervious Surface Growth Map 2015 to 2020

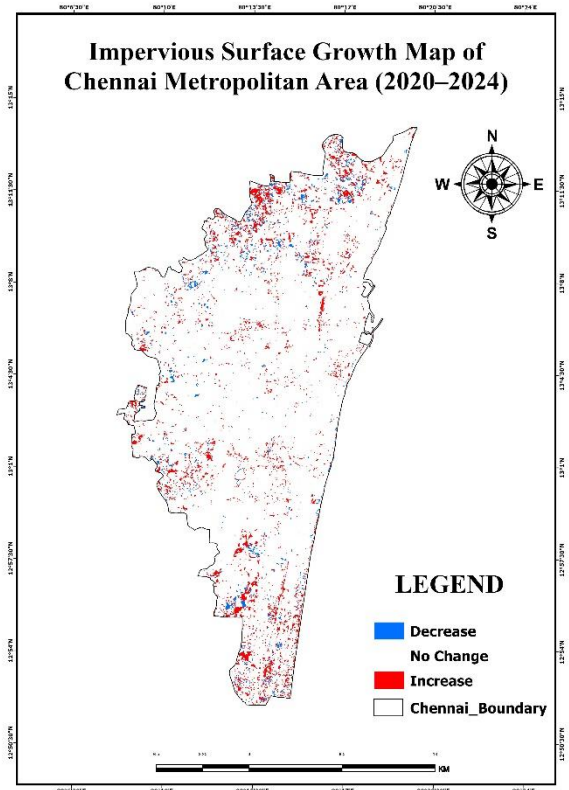


Fig. 11: Impervious Surface Growth Map 2020 to 2024

the spatial footprint of increase patches narrows further, consistent with the smaller net built-up gain of only 2.44 km² recorded in Table 3 for this period. The 2020–2024 period (Fig. 11) shows concentrated increase patches in the southwestern fringe and southern coastal zone, consistent with the observation from the LULC tables that this most recent period recorded the highest net built-up expansion in the study record. Taken together, the four maps show how the spatial frontier of urban expansion has progressively shifted from the northern and western peri-urban fringes in the earlier period toward the southern coastal and southwestern zones in the more recent period (Hollis, 1975; Bronstert et al., 2002).

DEM-Derived Runoff Flow Accumulation and TWI Maps

The DEM-Derived Runoff Flow Accumulation Map (Fig. 12) presents the terrain-driven drainage pathway network of CMA as derived from the SRTM 30m elevation data. The dominant background of Low Accumulation (dark purple) reflects the broad sheet-flow character of the flat urban terrain, where most cells contribute individually small amounts to downstream flow rather than concentrating into defined channels.

The higher accumulation classes (Moderate through Extreme) are visible as fine linear features that trace the natural drainage

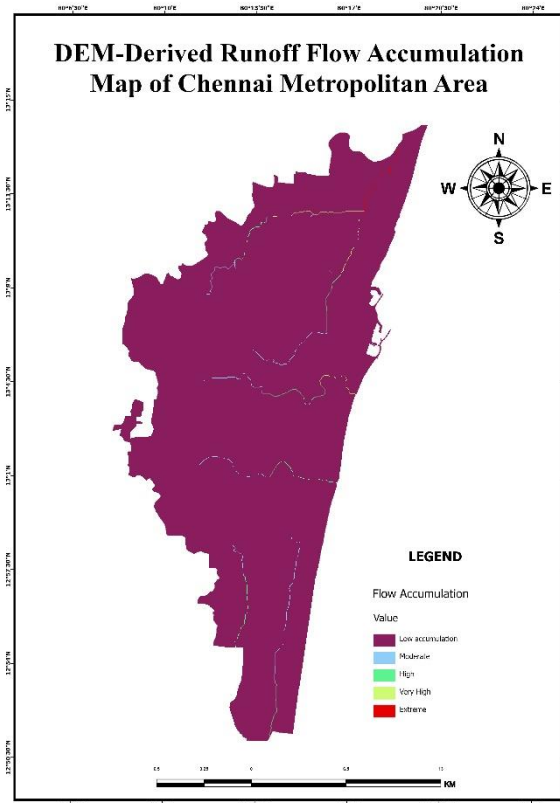


Fig.12: Flow Accumulation Map

pathways — primarily the Adyar River corridor running from northwest to southeast, the Cooum River corridor crossing the northern urban area, and smaller tributary channels draining toward the Buckingham Canal along the coast. The Extreme accumulation class, though very limited in spatial extent, identifies the highest-order flow concentration zones where the greatest volumes of upstream runoff converge and where terrain-driven flood risk is structurally highest.

The TWI Map (Fig.13) provides a complementary terrain perspective, expressing at each cell the combined influence of upstream contributing area and local slope on the tendency for water to accumulate. High and Very High TWI values (dark blue) are concentrated along river channels and low-lying coastal areas, confirming that these zones have the greatest natural propensity for water logging and sustained inundation following a rainfall event. The broad spatial coverage of Moderate TWI values (green and cyan speckle pattern) across the urban fabric reflects the relatively flat nature of CMA's urban terrain, where even areas distant from defined channels can experience saturated soil conditions when rainfall is intense or prolonged. This pattern is consistent with the documented spread of inundation across large parts of the urban core during the 2015 event (Nithila

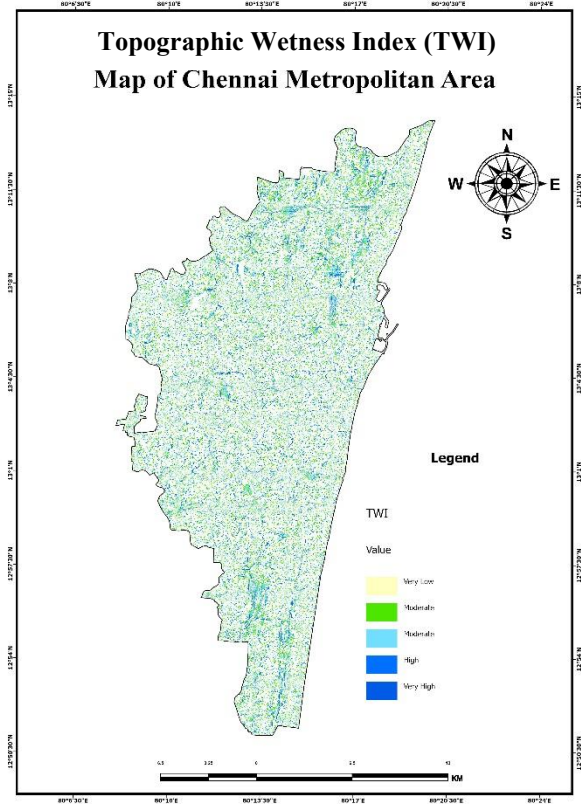


Fig.13: Topographic Wetness Index (TWI) Map

Devi et al., 2019) and with the flow pathway findings of Tomar et al. (2021) in a comparable flat urban setting in Delhi.

KDE-Based Flood Hotspot Intensity Map

The Kernel Density Estimation flood hotspot map (Fig.14) provides the most direct empirical evidence of where flooding has historically concentrated across the Chennai Metropolitan Area, based on the compiled incident dataset from multiple flood events between 2005 and 2023. The KDE surface has been classified into five intensity categories from Very Low to Very High. The spatial pattern of Very High and High hotspot zones is immediately striking: rather than forming a continuous zone concentrated in one part of the city, the high-intensity hotspots appear as discrete and spatially distributed clusters across the metropolitan area, reflecting the multi-event and multi-area character of flooding in CMA.

The largest single Very High intensity hotspot cluster is located in the southern part of the study area, roughly corresponding to the Velachery and Pallavaram–Chromepet zone — an area that has experienced severe inundation in both the 2015 and 2023

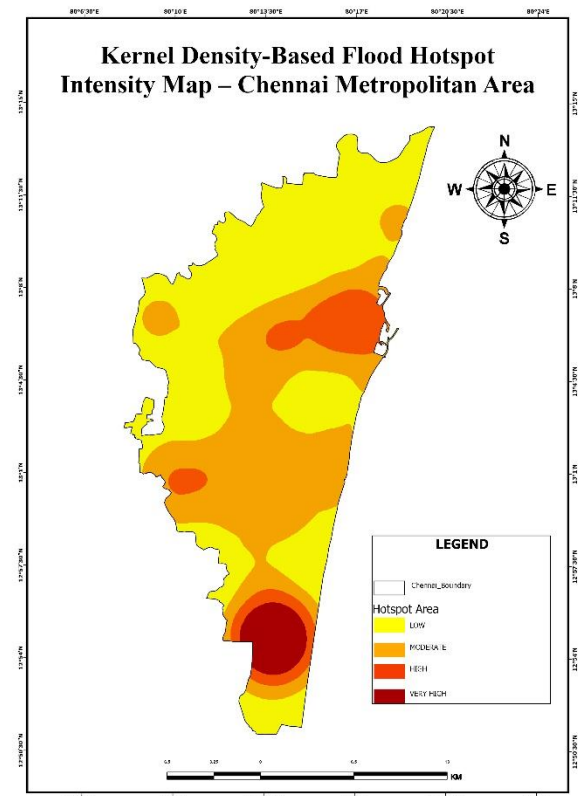


Fig.14: Kernel Density-Based Flood Hotspot Intensity Map

flood events and where the drainage network has historically been inadequate relative to the rapid pace of urban development. Additional Very High and High zones are visible in the northern coastal fringe near Tondiarpet, in the central areas around Koyambedu and Villivakkam, and at several locations in the western peri-urban belt. The spatial pattern is consistent with the inundation extents documented by Nithila Devi et al. (2019) for the 2015 Adyar basin event and corroborates the KML-derived field survey incident data used as input for the KDE analysis.

Critically, comparing the spatial distribution of Very High KDE hotspot zones with the Impervious Surface Growth maps (Figures 8–11) and the DEM accumulation analysis (Fig.12) reveals a notable spatial correspondence. Several

of the western peri-urban hotspot clusters fall in areas that also recorded the largest impervious surface increases in the 2000–2010 and 2020–2024 periods, suggesting that the emergence of these as flood hotspots is at least partly attributable to recent land conversion. Similarly, the southern hotspot cluster corresponds to a zone of both high recent built-up expansion and relatively high flow accumulation values in the DEM analysis. This spatial convergence of all three independent risk indicators provides the strongest analytical evidence in the study for a causal link between urbanisation-driven imperviousness, terrain-driven runoff concentration, and actual flood occurrence in specific zones of CMA (Zope et al., 2015; Ogden et al., 2011).

Rainfall Analysis and IDF Results

Annual maximum daily rainfall data for the period 2000 to 2024 was extracted from IMD gridded records and subjected to Gumbel extreme value distribution fitting to develop IDF curves for the Chennai study area. (Table.4) presents the annual maximum daily rainfall values, and (Table.5) presents the IDF return period results. The data shows clearly the exceptional character of the 2015 event (349.63 mm/day) relative to the full 25-year record, followed by the 2005 event (280.34 mm/day) and the 2023 event (243.97 mm/day) as the next most extreme values. Most years record annual maxima in the range of 75 to 165 mm/day, consistent with standard heavy monsoon rain, but well below the extreme event threshold.

The IDF analysis yields a finding of direct relevance to interpreting the 2015 flood event. The 100-year return period daily rainfall intensity for the Chennai study area is 330.19 mm/day based on the 25-year annual maximum series. The observed 2015 annual maximum of 349.63 mm/day therefore exceeded even the 100-year design threshold — confirming the characterization of the 2015 event as a once-in-a-century or rarer extreme. The 2005 event (280.34 mm/day) falls between the 50-year and 100-year return period thresholds, while 2023 (243.97 mm/day) approximates the 25-year return period. The 2008 event (268.70 mm/day) similarly approaches the 50-year threshold. These results support the argument made by Sharma

Table 4: Annual Maximum Daily Rainfall -Chennai 2000–2024 (IMD Gridded Data)

Year	Max RF (mm)	Year	Max RF (mm)	Year	Max RF (mm)	Year	Max RF (mm)
2000	135.70	2007	143.05	2014	116.72	2021	161.80
2001	162.56	2008	268.70	2015	349.63 ★	2022	111.33
2002	96.75	2009	131.78	2016	146.48	2023	243.97
2003	57.67	2010	101.45	2017	164.15	2024	126.83
2004	76.64	2011	74.41	2018	75.00		
2005	280.34	2012	112.67	2019	80.86		
2006	139.06	2013	117.78	2020	141.72		

et al. (2024) that Chennai's flood risk cannot be attributed to rainfall trends alone — the infrastructure and urban surface condition that determines how the city responds to even a 10-year or 25-year event is equally critical

Table 5: IDF Return Period Rainfall Intensities -Chennai (Gumbel Distribution)

Return Period (Years)	Rainfall Intensity (mm/day)
2	132.32
5	185.29
10	220.37
25	264.68
50	297.56
100	330.19

Cross-Map Spatial Analysis

When the four map outputs are read together, they describe a spatially coherent picture of flood risk in CMA that is greater than the sum of its individual parts. The western and southern peri-urban zones of the metropolitan area consistently appear as elevated risk areas across all three indicator maps. They show the highest cumulative impervious surface increase across the 24-year study record, they contain flow accumulation pathways and moderate-to-high TWI zones that indicate terrain-driven runoff concentration, and they correspond to several of the Very High and High KDE flood hotspot clusters. This triple spatial coincidence — which is not the result of a single analysis but the product of three independent datasets and methods — provides the strongest evidence in the study that these zones have experienced a genuine and measurable increase in flood risk as a direct consequence of their rapid urbanization.

A second distinct risk cluster, characterized by a different combination of factors, is visible in the low-lying coastal areas and along the Adyar River floodplain. Here, the KDE hotspot intensity is high because these areas have been repeatedly and severely flooded. The flow accumulation map confirms that they are the terminal collection points for runoff from large upstream contributing areas, and the TWI map shows high intrinsic wetness. While the impervious surface growth in these areas is more limited — because much of the central urban core was already substantially built-up at the start of the study period — the persistence of these zones as flood hotspots reflects a structural hydrological vulnerability that predates recent urban expansion and will not be resolved without direct

infrastructure intervention.

Stormwater Drainage Network and Gap Analysis

The stormwater drainage network of the Chennai Metropolitan Area was analysed using a distance-based buffering approach to evaluate the spatial coverage and service efficiency of the existing drainage infrastructure. A multiple ring buffer was generated around the drainage network at distances of 300 m, 500 m, and 1000 m, representing zones of high, moderate, and low drainage service accessibility respectively. Areas beyond the 1000 m threshold were identified as drainage-deficient zones using an Erase operation between the Chennai boundary and the outermost buffer.

The resulting drainage gap map (Fig.15) clearly highlights the spatial distribution of areas that fall outside the effective service range of the stormwater drainage network. These gap zones are predominantly concentrated in the peripheral regions of the metropolitan area, particularly in the western and southern extents. Several discontinuous patches are also observed within the central urban fabric, indicating localised deficiencies in

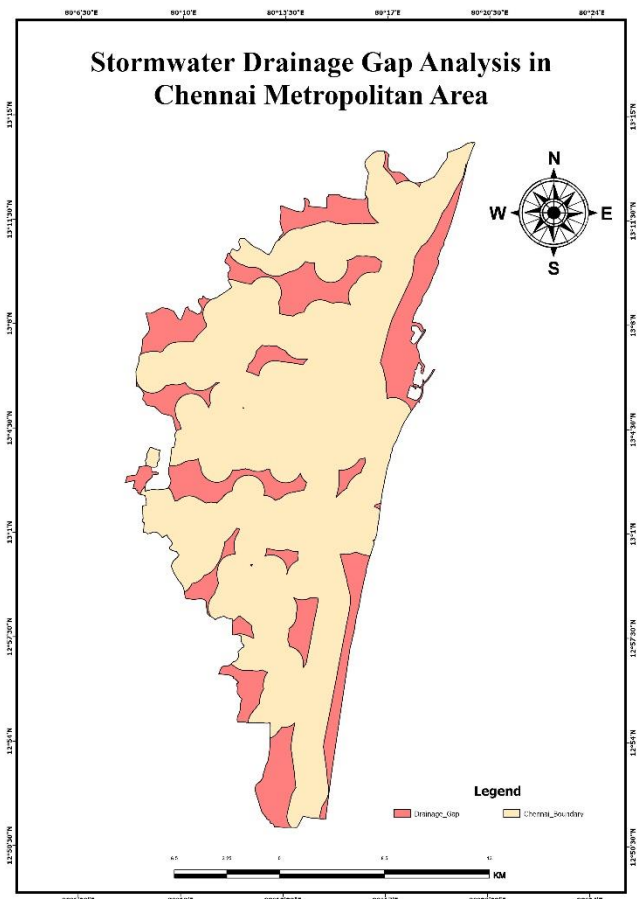


Fig .15: Stormwater Drainage Gap Analysis Map

drainage coverage even within relatively developed zones.

The spatial pattern of drainage gaps corresponds closely with areas of recent urban expansion identified in the impervious surface growth maps, particularly in the 2020–2024 period. This suggests that the expansion of built-up areas has not been matched by a proportional extension of stormwater drainage infrastructure. As a result, these newly urbanized zones exhibit reduced capacity for surface runoff conveyance, making them more susceptible to waterlogging during intense rainfall events.

Furthermore, the coastal fringe and low-lying southern zones, which already exhibit high terrain-driven wetness and flow accumulation characteristics, are also identified as drainage-deficient in several segments. This overlap of natural hydrological vulnerability and infrastructural deficiency significantly increases the likelihood of persistent inundation in these areas. Overall, the drainage gap analysis provides critical insight into the infrastructural dimension of urban flood risk in Chennai. It demonstrates that flood vulnerability is not solely a function of rainfall intensity or

terrain conditions, but is strongly influenced by the spatial adequacy of stormwater drainage systems relative to urban growth patterns.

Integrated Flood Risk Zonation Map

The final flood risk zonation map (Fig.16) was generated by integrating flood hotspot intensity derived from Kernel Density Estimation with drainage network accessibility derived from the multiple ring buffer analysis. A rule-based classification approach was applied, where flood intensity (gridcode) and distance from drainage network (distance field) were combined to assign risk levels ranging from Low to Very High.

The resulting spatial pattern reveals a clear differentiation of flood risk zones across the Chennai Metropolitan Area. Very High-risk zones are concentrated primarily in the southern part of the study area, particularly in regions corresponding to Velachery, Pallavaram, and surrounding localities. These areas exhibit a combination of high flood hotspot intensity and poor drainage accessibility, indicating that both hydrological and infrastructural factors are contributing to elevated flood risk.

High risk zones are distributed across parts of the central and eastern regions, where moderate-to-high flood intensity coincides with intermediate drainage accessibility (typically 500–1000 m from drainage lines). These zones represent areas where the drainage network exists but may be insufficient in capacity or poorly maintained to effectively handle peak runoff conditions. Moderate risk zones form a broad transitional belt across the metropolitan area, particularly in the central urban region. These areas are characterized by moderate flood intensity and relatively better drainage accessibility (within 300–500 m), suggesting that while flooding may occur, it is generally less severe and more manageable. Low risk zones are predominantly located in the northern and some peripheral regions, where flood hotspot intensity is low and drainage accessibility is relatively high. These areas benefit from a combination of lower runoff generation and better drainage coverage.

The integrated risk zonation map demonstrates a strong spatial correspondence with the patterns observed in the LULC change analysis, DEM-derived hydrological indicators, and KDE hotspot distribution. In particular, the southern and southwestern zones emerge consistently as high-risk areas across multiple independent analyses. This convergence provides robust evidence that these regions represent critical flood vulnerability zones within the Chennai Metropolitan Area.

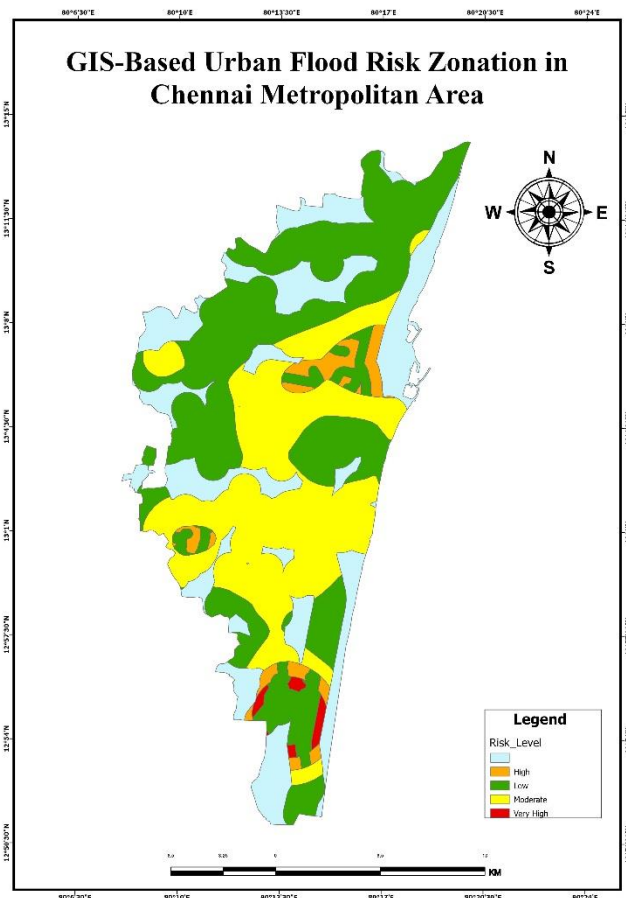


Fig.16: GIS-Based Urban Flood Risk Zonation Map

CONCLUSION

This study examined the spatial dimensions of urbanisation-related flood risk in the Chennai Metropolitan Area (CMA) using a GIS and remote-sensing-based approach. Four complementary spatial outputs were developed to represent major components of the flood-risk landscape: long-term LULC change, impervious surface expansion, terrain-driven flow accumulation, and the spatial concentration of historical flood incidents. These analyses integrated Landsat imagery, SRTM DEM, IMD rainfall data, and georeferenced flood records to provide a spatially explicit assessment of changing flood conditions across CMA.

The results indicate a clear spatial correspondence between areas of rapid impervious surface expansion, high flow accumulation, and concentrated historical flood occurrence. This pattern is particularly evident in parts of the western and southern peri-urban areas, low-lying coastal zones, and the Adyar River floodplain. The findings suggest that urban expansion and changes in surface characteristics are important factors to consider alongside extreme rainfall when assessing flood risk in Chennai. Rainfall-frequency analysis further showed the exceptional nature of the 2015 event, which exceeded the estimated 100-year return-period rainfall, while the 2023 event was associated with a substantially lower return period but still resulted in widespread flooding. This contrast highlights the importance of considering both rainfall extremes and the changing characteristics of the urban landscape in flood-risk assessment.

The main contribution of this study is the integration of three complementary spatial perspectives—urban growth, terrain hydrology, and observed flood occurrence—within a consistent GIS framework. Rather than relying on a single flood-susceptibility indicator, the study compares independently derived spatial evidence to identify areas where multiple flood-related factors overlap. This provides a practical basis for understanding the changing flood-risk pattern of CMA and can support subsequent planning of drainage infrastructure, land-use management, and flood-mitigation measures.

The present study represents the first stage of a broader flood-risk assessment framework. The next stage will integrate the four spatial indicators through a weighted-overlay approach to develop a composite Urban Flood Risk Zonation Map for CMA. The analysis will also incorporate stormwater drainage infrastructure and drainage-gap assessment to examine whether areas of high flood occurrence and terrain-

based susceptibility are adequately served by the existing drainage network. Together, these subsequent analyses will provide a more comprehensive basis for identifying priority areas for urban flood-risk reduction in Chennai.

Acknowledgements

The authors acknowledge the United States Geological Survey (USGS) for providing Landsat satellite imagery, which was accessed and processed through the Google Earth Engine platform. Rainfall data used in this study were obtained from the India Meteorological Department (IMD). The authors acknowledge the support of the University of Madras during the course of this research. The authors declare no conflict of interest.

REFERENCES:

1. Bronstert, A., Niehoff, D., & Burger, G. (2002). Effects of climate and land-use change on storm runoff generation: Present knowledge and modelling capabilities. *Hydrological Processes*, 16(2), 509–529. <https://doi.org/10.1002/hyp.326>
2. Ertan, S., & Celik, R.N. (2021). The assessment of urbanisation effect and sustainable drainage solutions on flood hazard by GIS. *Sustainability*, 13(4), 2293. <https://doi.org/10.3390/su13042293>
3. Sharma, A., Poonia, M., Rai, A., Biniwale, R.B., Tiwari, A., Lachure, S., Tuegel, F., Holzbecher, E., & Hinkelmann, R. (2024). Impact of land use and rainfall change on runoff and flood resilience of an urban environment: A case study of Chennai City, India. *Arabian Journal of Geosciences*, 17(6), 208. <https://doi.org/10.1007/s12517-024-11985-6>
4. Bagyaraj, M., Senapathi, V., Chung, S.Y., Gopalakrishnan, G., Xiao, Y., Karthikeyan, S., Nadiri, A.A. and Barzegar, R. (2023) 'A geospatial approach for assessing urban flood risk zones in Chennai, Tamil Nadu, India', *Environmental Science and Pollution Research*, 30(45), pp. 100562–100575. doi:10.1007/s11356-023-29132-1.
5. Bremner, L. (2020). Planning the 2015 Chennai floods. *Environment and Planning E: Nature and Space*, 3(3), 732–760. <https://doi.org/10.1177/2514848619880130>
6. Burns, M.J., Fletcher, T.D., Walsh, C.J., Ladson, A.R. and
7. Hatt, B.E. (2012) 'Hydrologic shortcomings of conventional urban stormwater management and opportunities for reform', *Landscape and Urban Planning*, 105(3), pp. 230–240.

- doi:10.1016/j.landurbplan.2011.12.012.
8. De Risi, R., Jalayer, F., de Paola, F. and Lindley, S. (2018) 'Delineation of flooding risk hotspots based on digital elevation model, calculated and historical flooding extents: the case of Ouagadougou', *Stochastic Environmental Research and Risk Assessment*, 32(6), pp. 1545–1559. doi:10.1007/s00477-017-1450-8.
 9. Ertan, S. and Çelik, R.N. (2021) 'The assessment of urbanization effect and sustainable drainage solutions on flood hazard by GIS', *Sustainability*, 13(4), 2293. doi:10.3390/su13042293.
 10. Fletcher, T.D., Andrieu, H. and Hamel, P. (2013) 'Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art', *Advances in Water Resources*, 51, pp. 261–279. doi:10.1016/j.advwatres.2012.09.001.
 11. Green, D., O'Donnell, E., Johnson, M., Slater, L., Thorne, C., Zheng, S., Stirling, R., Chan, F.K.S., Li, L. and Boothroyd, R.J. (2021) 'Green infrastructure: The future of urban flood risk management?', *WIREs Water*, 8(6), e1560. doi:10.1002/wat2.1560.
 12. Hamel, P., Daly, E. and Fletcher, T.D. (2013) 'Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review', *Journal of Hydrology*, 485, pp. 201–211. doi:10.1016/j.jhydrol.2013.01.001.
 13. Hollis, G.E. (1975) 'The effect of urbanization on floods of different recurrence interval', *Water Resources Research*, 11(3), pp. 431–435. <https://doi:10.1029/WR011i003p00431>.
 14. Huong, H.T.L. and Pathirana, A. (2013) 'Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam', *Hydrology and Earth System Sciences*, 17(1), pp. 379–394. doi:10.5194/hess-17-379-2013.
 15. Khosravi, K., Nohani, E., Maroufinia, E. and Pourghasemi, H.R. (2016) 'A GIS-based flood susceptibility assessment and its mapping in Iran: a comparison between frequency ratio and weights-of-evidence bivariate statistical models with multi-criteria decision-making technique', *Natural Hazards*, 83(2), pp. 947–987. doi:10.1007/s11069-016-2357-2.
 16. Leopold, L.B. (1968) *Hydrology for urban land planning: A guidebook on the hydrologic effects of urban land use*. U.S. Geological Survey Circular 554. Washington, DC: U.S. Geological Survey. doi:10.3133/cir554.
 17. Nithila Devi, N., Ganapathy, A., Silva, A.F.R., Vorogushyn, S., Apel, H., Kreibich, H., Oostwegel, L.J.N., Kuiry, S.N. and Sairam, N. (2025) 'Lost water bodies and a flooded city – Counterfactual scenarios of the extreme Chennai flood highlight the potential of nature-based solutions', *Urban Climate*, 61, 102454. doi:10.1016/j.uclim.2025.102454.
 18. Nithila Devi, N., Sridharan, B. and Kuiry, S.N. (2019) 'Impact of urban sprawl on future flooding in Chennai city, India', *Journal of Hydrology*, 574, pp. 486–496. doi:10.1016/j.jhydrol.2019.04.041.
 19. Ogden, F.L., Pradhan, N.R., Downer, C.W. and Zahner, J.A. (2011) 'Relative importance of impervious area, drainage density, width function, and subsurface storm drainage on flood runoff from an urbanized catchment', *Water Resources Research*, 47(12), W12503. doi:10.1029/2011WR010550.
 20. Oswald, C.J., Kelleher, C., Ledford, S.H., Hopkins, K.G., Sytsma, A., Tetzlaff, D., Toran, L. and Voter, C. (2023) 'Integrating urban water fluxes and moving beyond impervious surface cover: A review', *Journal of Hydrology*, 618, 129188. doi:10.1016/j.jhydrol.2023.129188.
 21. Shuster, W.D., Bonta, J., Thurston, H., Warnemuende, E. and Smith, D.R. (2005) 'Impacts of impervious surface on watershed hydrology: A review', *Urban Water Journal*, 2(4), pp. 263–275. doi:10.1080/15730620500386529.
 22. Suriya, S. and Mudgal, B.V. (2012) 'Impact of urbanization on flooding: The Thirusoolam sub watershed – A case study', *Journal of Hydrology*, 412–413, pp. 210–219. doi:10.1016/j.jhydrol.2011.05.008.
 23. Tomar, P., Singh, S.K., Kanga, S., Meraj, G., Kranjčić, N., Đurin, B. and Pattanaik, A. (2021) 'GIS-Based Urban Flood Risk Assessment and Management—A Case Study of Delhi National Capital Territory (NCT), India', *Sustainability*, 13(22), 12850. doi:10.3390/su132212850.
 24. Zope, P., Eldho, T.I. and Jothiprakash, V. (2015) 'Impacts of urbanization on flooding of a coastal urban catchment: a case study of Mumbai City, India', *Natural Hazards*, 75(1), pp. 887–908. doi:10.1007/s11069-014-1356-4.