

Evaluating Flood Vulnerability with Remote Sensing and GIS: Urban Development Challenges in Chennai City Region, Tamil Nadu, India

Christinal J.¹, Richard Abishek S.¹, Antony Ravindran A.¹, Sakthi Priya R.¹, Karuthapandi K.¹, Rajalakshmi S.²

¹PG and Research Department of Geology, V.O. Chidambaram College, Thoothukudi, Tamil Nadu, India

²Department of Geology, Sir Isaac Newton College of Arts and Science, Nagapattinam, Tamil Nadu, India

*Corresponding Author: christinal.geo@voccollege.ac.in

(Received on 09 October 2024; In final form on 10 April 2026)

DOI: <https://doi.org/10.58825/jog.2026.20.1.192>

Abstract: This study evaluates flood vulnerability in the Chennai City Region, Tamil Nadu, using remote sensing and GIS techniques to guide urban development planning. With rapid urbanization and recurrent flooding, Chennai faces heightened risks from heavy monsoon rains, inadequate drainage, and encroachment on natural floodplains. Sentinel-2 and Landsat satellite imagery, combined with GIS data such as digital elevation models (DEM) and land-use maps, were used to classify land cover, map flood extents, and assess flood vulnerability. A multi-criteria evaluation using Analytical Hierarchy Process (AHP) identified key vulnerability factors, including population density, elevation, land use, and proximity to water bodies and drainage infrastructure. The study also conducted sensitivity analyses, including map-removal sensitivity analyses, to quantify the impact of individual parameters on flood vulnerability mapping. The findings reveal significant urban expansion (85% of the area) and widespread impermeable surfaces contributing to high surface runoff and limited infiltration. Topographic Wetness Index (TWI), drainage density, slope, and distance from streams were used to assess flood-prone zones further. The Normalized Difference Vegetation Index (NDVI) was calculated to evaluate the extent and health of vegetation affected by flooding. At the same time, DEMs and terrain analysis provided insights into low-lying areas with higher flood vulnerability. The research identified flood-prone zones classified into low, medium, and high-risk areas, covering 24.4%, 50.2%, and 25.4% of the study region, respectively. These results underscore the need for sustainable land-use management, improved drainage infrastructure, and climate-resilient urban development strategies to mitigate flood vulnerability in Chennai. The comprehensive assessment aims to support flood vulnerability management efforts and urban resilience planning in the region.

Keywords: Heavy flood, Remote sensing, GIS, Vulnerability assessment, Chennai city, Spatial analysis

1. Introduction

Global urbanization, climate change, and poor infrastructure make cities more vulnerable to natural disasters, particularly floods. Chennai has previously suffered devastating floods, such as the catastrophic 2015 floods, which submerged large areas of the city and caused extensive damage to infrastructure, livelihoods, and the environment. Furthermore, the Analytic Hierarchy Process (AHP) methodology provides a systematic framework for integrating multiple criteria and stakeholder preferences into flood risk management and adaptation decision-making. Flood risk assessment and management have emerged as critical research areas, particularly in regions prone to climate change and urbanization. This literature review examines several studies that use remote sensing, Geographic Information Systems (GIS), and other geospatial techniques to assess flood hazards, land use, and land cover changes across various geographical contexts. Sankhala and Singh (2014) used remote sensing and GIS techniques to assess urban sprawl, land use, and land cover changes in Jaipur City, India, focusing on the effects of rapid urbanization on flood risk. Similarly, Gashaw et al. (2014) used GIS and remote sensing to assess land use, land cover, and land degradation in Dera District, Ethiopia, and demonstrated the relationship between land-use changes and flood susceptibility. Flood vulnerability in Chennai has previously been evaluated using geospatial

techniques, highlighting the roles of terrain characteristics, land-use patterns, and drainage conditions in flood susceptibility (Ahmed and Kranthi, 2018). Murayama et al. (2015) investigated land-use and land-cover changes in major Asian and African cities, shedding light on their implications for flood risk mitigation.

Recent studies have applied machine learning methods integrated with geospatial data to assess flood vulnerability in coastal metropolitan cities, demonstrating improved prediction of flood-prone areas under complex urban conditions (Alabdan et al. 2025). A geospatial-based urban flood risk assessment for Chennai identified high-risk zones associated with rapid urbanization, impervious surfaces, and inadequate drainage infrastructure (Bagyaraj et al. 2023). Twumasi et al. (2017) investigated the use of remote sensing and GIS to visualize the impact of climate change-induced floods in Southern Africa, highlighting the significance of these technologies in flood risk assessment. Similarly, Wang and Xie (2018) examined the use of remote sensing and GIS in water resources and flood risk management, emphasizing the importance of integrated approaches for effective flood mitigation. Kundzewicz et al. (2014) presented global and regional perspectives on flood risk and climate change, emphasizing the importance of comprehensive assessment methodologies. Mahmoud and Gan (2018) examined the effects of urbanization and climate change on flood risk

management, emphasizing the importance of developing effective decision-support systems for flood-susceptibility mapping. Munawar et al. (2022) conducted a comprehensive review of remote sensing methods for flood prediction, highlighting advances in flood forecasting. Furthermore, Kabenge et al. (2017); Mojaddadi et al. (2017) proposed flood hazard assessment methodologies that employ remote sensing, GIS-based indices, and ensemble machine learning approaches, respectively. Cheng et al. (2022) demonstrated the use of satellite and UAV-based remote sensing to assess flooding risks and optimize relocation sites in Tibetan lake expansion areas.

Further research focused on specific regions, such as Saha and Agrawal (2020), who mapped and assessed flood risk in India's Prayagraj district, and Avand and Moradi (2021), who used machine learning models to investigate the effects of climate change and land-use changes on flood probability. Local-scale studies, such as those by Burayu et al. (2023), identify flood-vulnerable areas in the southern Oromia region using the analytical hierarchy process (AHP), GIS, and remote sensing, providing useful insights for targeted flood risk management strategies. In India's coastal regions, researchers such as Devi et al. (2019); George et al. (2022) used multi-data geospatial approaches to understand flood risk. In contrast, Natarajan et al. (2021); Thirumurugan and Krishnaveni (2019) used frequency ratios and geospatial techniques to conduct flood-susceptibility analysis and hazard mapping. Finally, Ramachandran et al. (2019); Selvam and Antony Jebamalai (2023) conducted studies on specific river basins in India, highlighting the effects of climate change on fluvial flooding and using the analytical hierarchy process for flood susceptibility mapping, respectively. Several studies have examined flood vulnerability in the Chennai region using remote sensing and GIS techniques. However, most of these studies focus on specific flood events, limited spatial variables, or individual analytical

approaches, with less emphasis on evaluating the combined effects of urban expansion, land-use change, and terrain-controlled hydrological factors. In addition, few studies have examined the relative contributions of different thematic layers through sensitivity analysis, limiting the applicability of their results for urban planning and flood mitigation.

The present study addresses these limitations by integrating multi-source satellite data with a GIS-based Analytical Hierarchy Process (AHP) framework to assess flood vulnerability in the Chennai City Region. A map removal sensitivity analysis is applied to evaluate the influence of key parameters, including land-use/land-cover, NDVI, Topographic Wetness Index, drainage density, slope, and distance from streams. By relating flood vulnerability patterns to recent urban development, this study provides practical insights for land-use planning and flood risk management in rapidly urbanizing coastal cities. This study aims to assess flood vulnerability in the Chennai City Region using remote sensing and GIS techniques, integrated with multi-criteria analysis, to identify spatial patterns of flood-prone areas. It will also examine how urbanization has influenced flood risk and apply sensitivity analysis to key parameters, such as NDVI, Topographic Wetness Index (TWI), and drainage density. The findings will provide actionable insights for urban planners to develop effective land-use management, flood mitigation, and resilience strategies for sustainable urban development.

2. Study Area

The Chennai City Region, located on India's southeast coast, is the focus of this investigation. The central city in this area is Chennai, the capital of the Indian state of Tamil Nadu. The Chennai City Region, which covers approximately 426 square kilometers, is home to a diverse range of environments, including urban areas, peri-urban zones, and coastal regions (Figure 1).

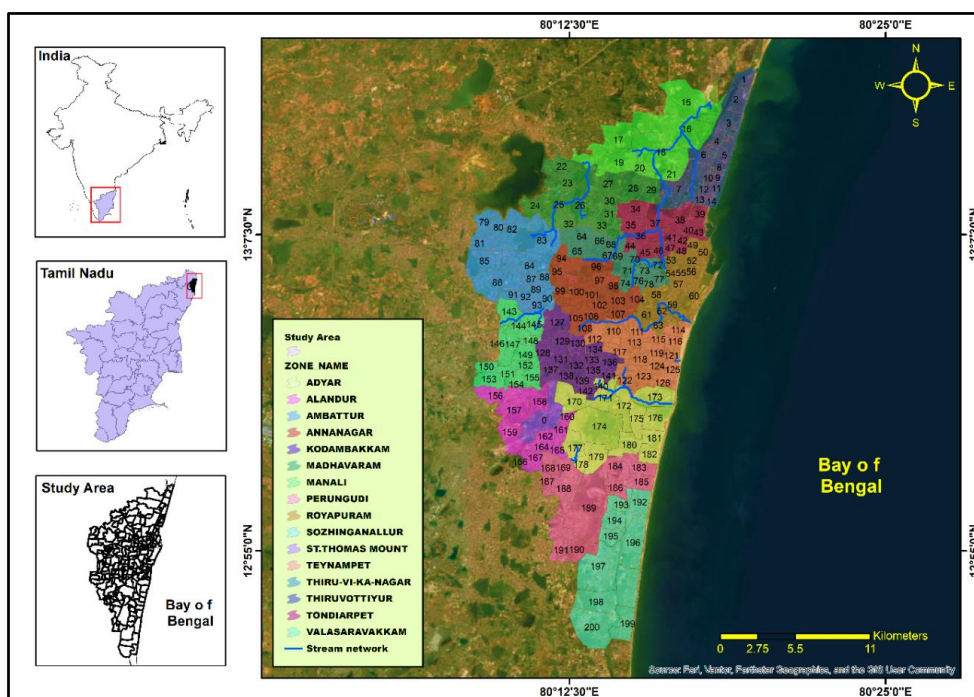


Figure 1: Location Map of the Study Area

Chennai is vulnerable to a variety of natural disasters, including heavy rains, cyclones, and flooding. These risks are exacerbated by the city's growing urbanization, inadequate drainage systems, and the effects of climate change. The city's topography ranges from undulating terrain to flat coastal plains, influencing drainage characteristics and surface water flow patterns. Numerous bodies of water, including lakes, ponds, rivers, and reservoirs, are spread throughout the city and play an important role in the regional hydrological system. However, pollution, siltation, and encroachment reduce their functionality and increase the risk of flooding. Chennai's proximity to the Bay of Bengal makes it vulnerable to storm surges and coastal flooding, particularly during cyclonic events. The city's coastal region is distinguished by mangrove ecosystems, beaches, and estuaries, all of which serve as natural barriers to erosion and flooding.

3. Materials and Methods

The study focuses on the Chennai City Region in Tamil Nadu, India, due to its vulnerability to severe flooding and the availability of relevant data, including Sentinel-2 and Landsat remote sensing imagery (Figure 2). Sentinel-2 Level-2A data, obtained from the Copernicus Open Access Hub, have a spatial resolution of 10 m for visible and near-

infrared bands and 20 m for red-edge and shortwave infrared bands, and were used for land use/land cover classification and NDVI analysis (<https://dataspace.copernicus.eu>). Landsat imagery was acquired from the United States Geological Survey (USGS) EarthExplorer portal at a 30 m spatial resolution and used to support land cover mapping and validation (<https://earthexplorer.usgs.gov>). Elevation-related parameters were derived from the Shuttle Radar Topography Mission (SRTM) Digital Elevation Model with a spatial resolution of 30 m (Youssef et al. 2011), obtained from the USGS EarthExplorer platform (<https://earthexplorer.usgs.gov>). The SRTM DEM was used to generate elevation, slope, flow accumulation, and Topographic Wetness Index (TWI) layers required for flood vulnerability assessment. Survey of India (SOI) topographic maps (1:50,000 scale) were used to extract contours, rivers, streams, and drainage networks (Jena et al. 2016). These layers were georeferenced and integrated with satellite-derived datasets to improve terrain representation and drainage accuracy. Daily rainfall data for the Chennai City Region were obtained from the India Meteorological Department (IMD) for the year 2023. The data were collected from the official IMD data portal (<https://mausam.imd.gov.in>) and used to analyze rainfall intensity and spatial variability contributing to flood events in the study area.

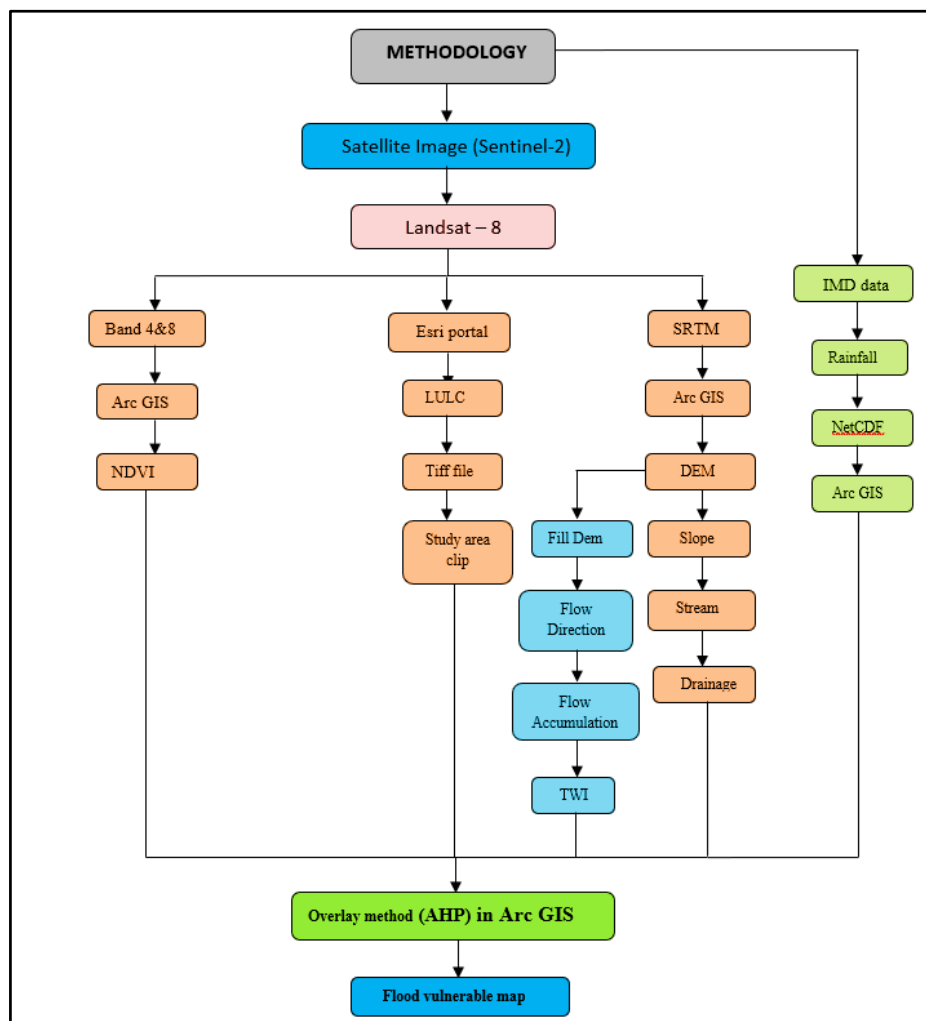


Figure 2: Methodological Framework Showing the Integration of Sentinel-2 and Landsat Satellite Data with GIS-based Thematic Layers for Flood Vulnerability Assessment

The thematic layer preparation includes calculating the Normalized Difference Vegetation Index (NDVI) from satellite imagery to assess vegetation health, classifying Land Use and Land Cover (LULC) using both supervised and unsupervised methods to ensure high accuracy through field validation and ground truth (Chanu et al. 2021), to maintain consistency, a uniform land-use/land-cover (LULC) classification scheme comprising built-up area, water bodies, vegetation, flooded vegetation, rangeland, and bare land was applied consistently across all satellite images, accuracy assessments, and flood vulnerability analyses. The Topographic Wetness Index (TWI) from the DEM by calculating slope and upstream contributing areas to evaluate water accumulation potential. All spatial data processing, thematic layer generation, and flood vulnerability mapping were performed in ArcGIS.

Additionally, the total length of drainage channels is mapped and calculated to determine drainage density, proximity analyses are performed to assess areas near water bodies for flood risk insights, historical rainfall data is compiled and analyzed to identify significant rainfall events contributing to flooding, and slope calculations derived from DEMs inform runoff potential in different areas. AHP is used to evaluate and prioritize factors influencing flood vulnerability (Tables 1 & 2). After consulting with stakeholders and reviewing the literature, the criteria are identified and weighted (Tables 3 & 4). These requirements include population density, elevation, land use and cover, and proximity to bodies of water and drainage infrastructure (Darko et al. 2019). Remote sensing/GIS layers and AHP-derived weights are combined with GIS-based spatial analysis to measure

flood vulnerability and generate vulnerability maps (Eq. 1 and 2).

Table 1: The Fundamental Scale of AHP (Saaty, 1980)

Intensity of Importance	Explanation
1	Two activities contribute equally to the objective
3	Experience and judgment strongly favor one activity over another
5	Experience and judgment strongly favor one activity over another
7	An activity is strongly favored and its dominance demonstrated in practice
9	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	When compromise is needed

Table 2: Saaty’s Ratio Index for Different Values of N

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.89	1.12	1.24	1.32	1.41	1.45	1.49

Table 3: The Resulting Weights for the Criteria Based on Pairwise Comparisons

S.No	Thematic layer	Priority	Rank
1	NDVI	26.50%	2
2	LULC	28.50%	1
3	TWI	22.50%	3
4	Drainage density	5.70%	5
5	Distance from the stream	7.50%	4
6	Rainfall	4.70%	6
7	Slope	2.20%	8
8	DEM	2.40%	7

$$\text{Consistency Index (CI)} = \frac{\text{Max principal Eigen value } (\lambda) - \text{Number of factors (n)}}{\text{Number of factors (n)} - 1} \tag{1}$$

$$\text{Consistency ratio (CR)} = \frac{\text{Consistency Index (CI)}}{\text{Random consistency Index (RI)}} \tag{2}$$

Table 4: The Resulting Weights Based on the Principal Eigen Vector of the Decision Matrix

Thematic layer	NDVI	LULC	TWI	Drainage density	Distance from the river	Slope	Rainfall	DEM
NDVI	1	2	3	4	5	6	7	8
LULC	1	1	1	2	6	5	4	9
TWI	2	1	1	2	7	6	5	9
Drainage density	3	0.5	0.5	1	8	7	6	5
Distance from the river	4	0.17	0.14	0.12	1	1	1	5
Slope	5	0.2	0.17	0.14	1	1	2	7
Rainfall	6	0.25	0.2	0.17	1	0.5	1	3
DEM	7	0.11	0.11	0.2	0.2	0.14	0.33	1

In AHP, the Consistency Ratio (CR) must be < 0.10 .

The calculated Consistency Ratio (CR) was 0.078, which is within the acceptable threshold of 0.10, indicating satisfactory consistency in the pairwise comparison matrix.

3.1 Sensitivity Analysis

A dependable method for quantifying the variability and uncertainty associated with model-based results is sensitivity analysis, as described by Saltelli et al. (2008). This study used a sensitivity analysis to examine the overall effect and how different classes and parameters on the Flood Vulnerable Map were affected by different rankings and weights. To carry out the sensitivity analysis, the following method was used.

3.2 Map Removal Sensitivity Analysis

They used the map removal technique to determine how different input parameters affected the delineation of the flood-vulnerable map (Lodwick et al. 1990). Following this method, the flood-vulnerable map was progressively stripped of its input parameters and layers, and the effect of each removal on the remaining layers was described (Eq. 3).

$$S = \frac{\left(\frac{FH}{N}\right) - \left(\frac{FH'}{N}\right)}{FH} \times 100 \dots \quad (3)$$

Where S represents the sensitivity index linked to the elimination of a single parameter or layer, FH stands for the flood hazard index derived with all parameters, FH' for the flood hazard index obtained by eliminating each input parameter one after the other, and N and n denote the number of input parameters or layers used to calculate FH and FH' , respectively.

4. Results and Discussion

4.1 Normalized Difference Vegetation Index (NDVI)

The Normalized Difference Vegetation Index (NDVI) classification is a valuable tool for analyzing vegetation distribution and health during flooding in the Chennai region (Narayani et al. 2023). Areas with dense vegetation can be identified from non-vegetated surfaces and water

bodies by calculating the NDVI from satellite imagery. When assessing the effects of flooding on ecosystems and agricultural lands, the NDVI classification can be used to pinpoint areas where vegetation has been severely damaged or submerged (Eq. 4). Calculate NDVI using the following formula:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)} \quad (3)$$

Where NIR is the near-infrared band, and Red is the red band. Furthermore, NDVI classification can help assess vegetation resilience to flooding and guide post-disaster recovery efforts, such as prioritizing restoration projects in areas with significant vegetation loss. In general, the NDVI classification provides valuable information for flood risk management and environmental monitoring in the Chennai region by revealing the spatial extent and severity of changes in vegetation cover induced by floods (Figure 3). In terms of topography, the area is mostly land (74.6%), followed by shrubland (35%), water (7.4%), and vegetation (39%).

4.2 Land Use and Land Cover

High-density residential, commercial, and industrial areas are proliferating due to rapid urbanization, population growth, and economic expansion. Chennai's built environment comprises a range of structures, including residences, shopping centers, factories, transportation networks, and green areas. Urban growth has led to the conversion of natural land cover, including wetlands, agricultural fields, and vegetation, into impermeable surfaces, thereby profoundly altering the area's hydrological regime. Built-up areas in Chennai are frequently submerged to a significant extent during flooding events due to the high concentration of impermeable surfaces, the scarcity of green spaces, and insufficient drainage infrastructure. According to Brema (2020), dense concentrations of roads, buildings, and pavements increase surface runoff and decrease infiltration capacity, leading to rapid water accumulation and a heightened risk of flooding. Furthermore, built-up areas now face increased flood hazards due to urban expansion and encroachment into natural floodplains.

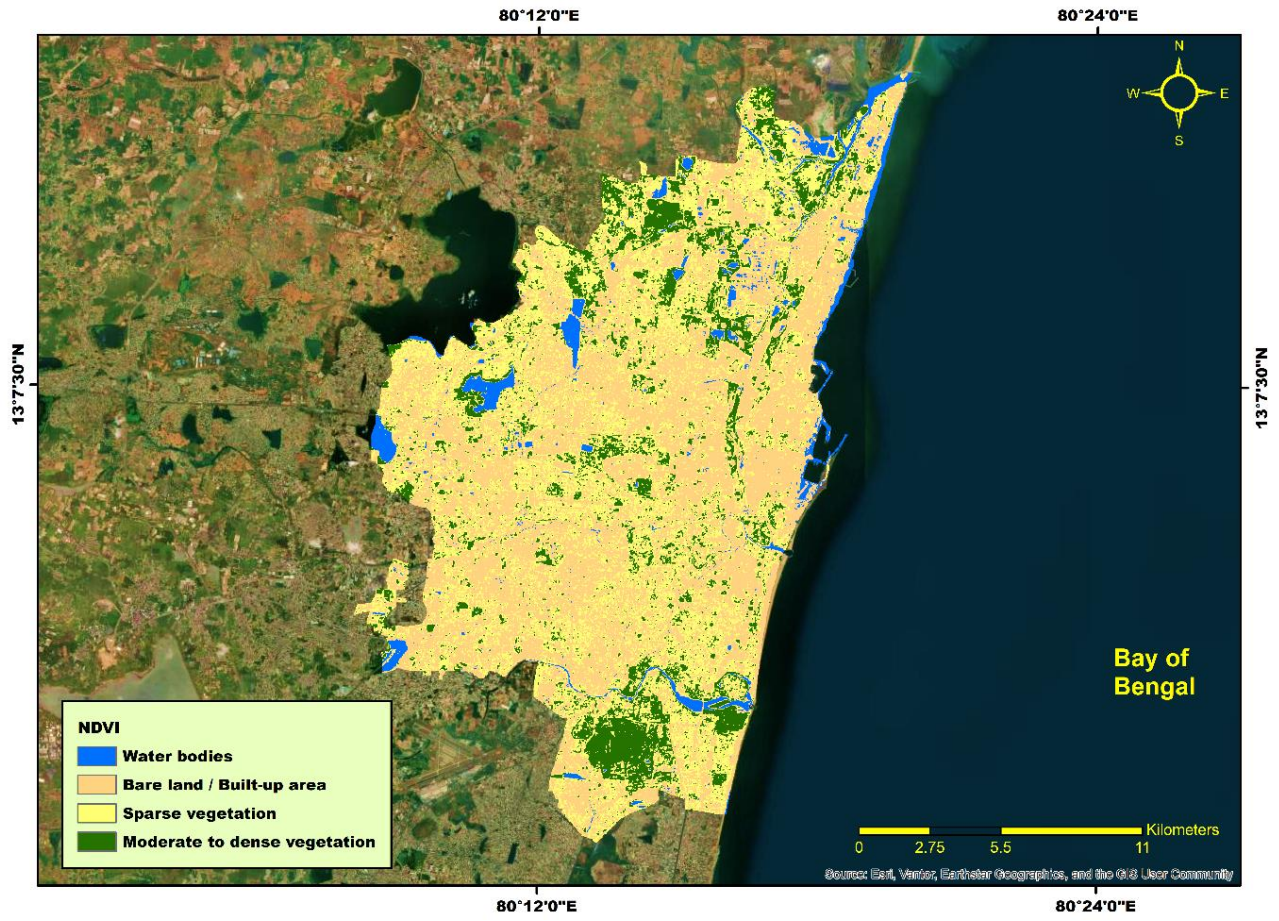


Figure 3: NDVI Map of the Study Area

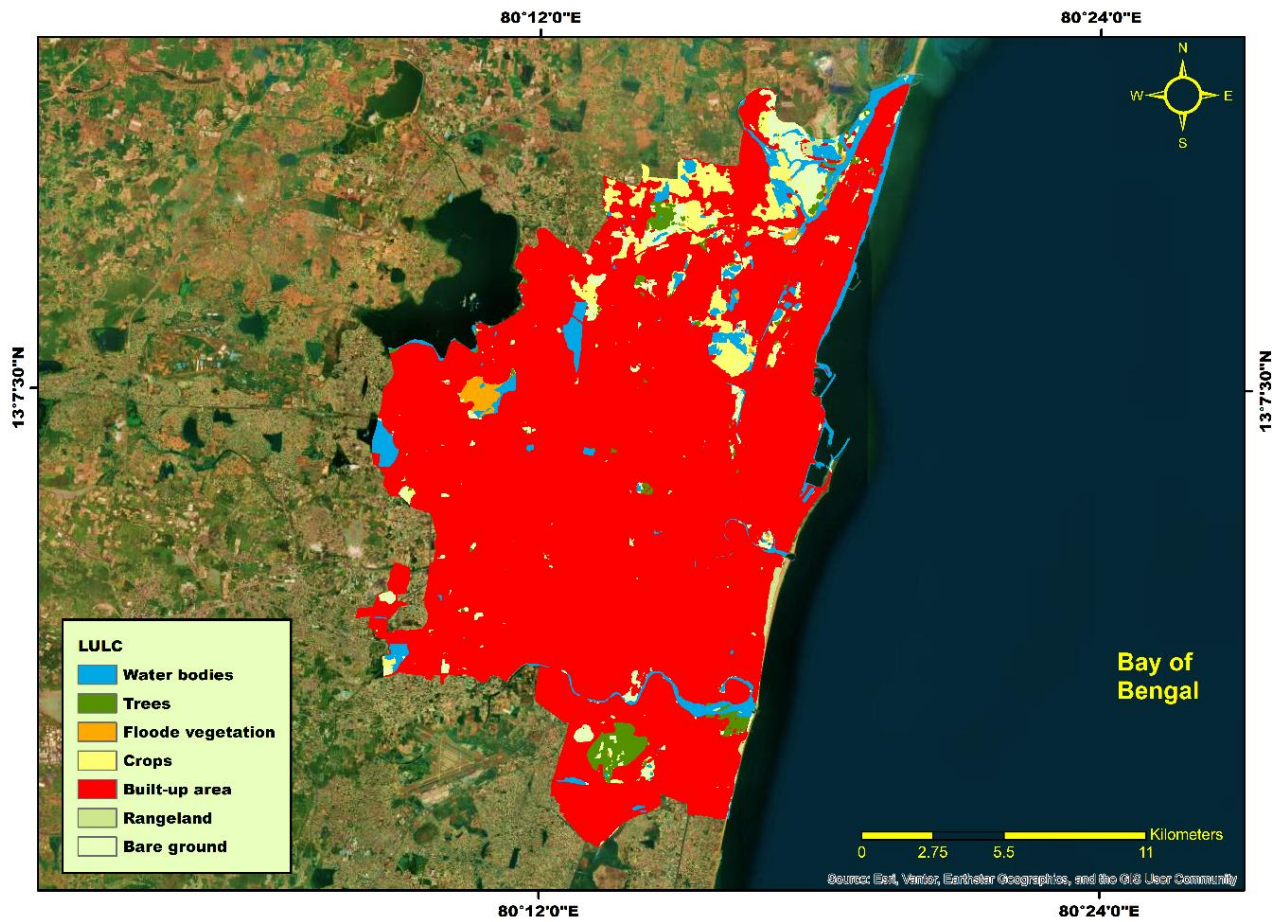


Figure 4: Land Use and Land Cover Map of the Study Area

This emphasizes the need for sustainable urban planning and flood mitigation strategies. Therefore, to improve resilience and reduce vulnerability in built-up areas, addressing flooding challenges in Chennai requires comprehensive land-use management practices, creative infrastructure solutions, and community engagement. A large portion of the land is covered by buildings, accounting for 85% of the total (Figure 4). The remaining areas comprise water, trees, flooded vegetation, rangeland, and bare ground, with percentages of 7%, 0.9%, 4%, 0.1%, and 3%, respectively.

4.3 Topographic Wetness Index (TWI)

By assessing terrain features and water-flow patterns, the Topographic Wetness Index (TWI) was applied in the Chennai region to provide relevant insights into flood vulnerability. TWI is determined by calculating the slope and upstream contributing area of each cell in a Digital Elevation Model (DEM), which represents a location tendency to retain moisture and accumulate water (Eq. 5). TWI analysis revealed low-lying topography, shallow depressions, and inadequate drainage capacity in Chennai flood-prone areas, indicating increased vulnerability to flooding during intense rainfall events or cyclonic disturbances.

$$TWI = Ln \frac{a}{\tan(\beta)} \quad (5)$$

Adding the area (a) and the length (L), where L is the slope in degrees, yields the catchment area. The slope angle of the location is given by tan, and the entire upslope region drains through a point (per unit contour length) (Figure 5). High TWI values indicate less adequate drainage and a higher risk of waterlogging, especially in populated or urbanized areas where impermeable surfaces prevent natural infiltration of water. Flood management authorities can reduce flood risk and improve resilience in vulnerable zones by prioritizing mitigation measures, such as

enhanced green infrastructure, improved stormwater management infrastructure, and targeted land-use planning, by identifying areas with elevated TWI values.

4.4 Drainage Density

In Chennai, drainage density analysis is critical for flood mapping and assessing flood vulnerability. Drainage density is the total length of streams or drainage channels per unit area. It provides information about how well surface water drains in a particular area (Figure 6). High drainage densities in flood-prone areas of Chennai indicate a well-developed network of streams and channels that quickly convey storm water, reducing the risk of flooding and waterlogging. On the other hand, areas with low drainage density may experience slower drainage and be more vulnerable to flooding, especially during periods of heavy precipitation or cyclonic disturbances. Flood management authorities can use drainage density mapping to identify areas with inadequate drainage infrastructure and prioritize targeted interventions, such as dredging, sedimentation, and the construction of new drainage channels, to improve flood resilience and reduce flood risk in the Chennai region.

4.5 Distance from Streams

In the context of flood mapping in Chennai, calculating distances to streams helps assess flood vulnerability and delineate flood-prone areas. When nearby water bodies experience high water levels or heavy rainfall, areas near streams are more vulnerable to flooding, which raises the risk of inundation and property damage. Flood management authorities can identify areas at higher risk of flooding and prioritize targeted flood mitigation measures, such as flood defenses, land-use planning regulations, and early warning systems, to minimize flood impacts and enhance community resilience (Figure 7). Mapping distances from streams across the Chennai region does this.

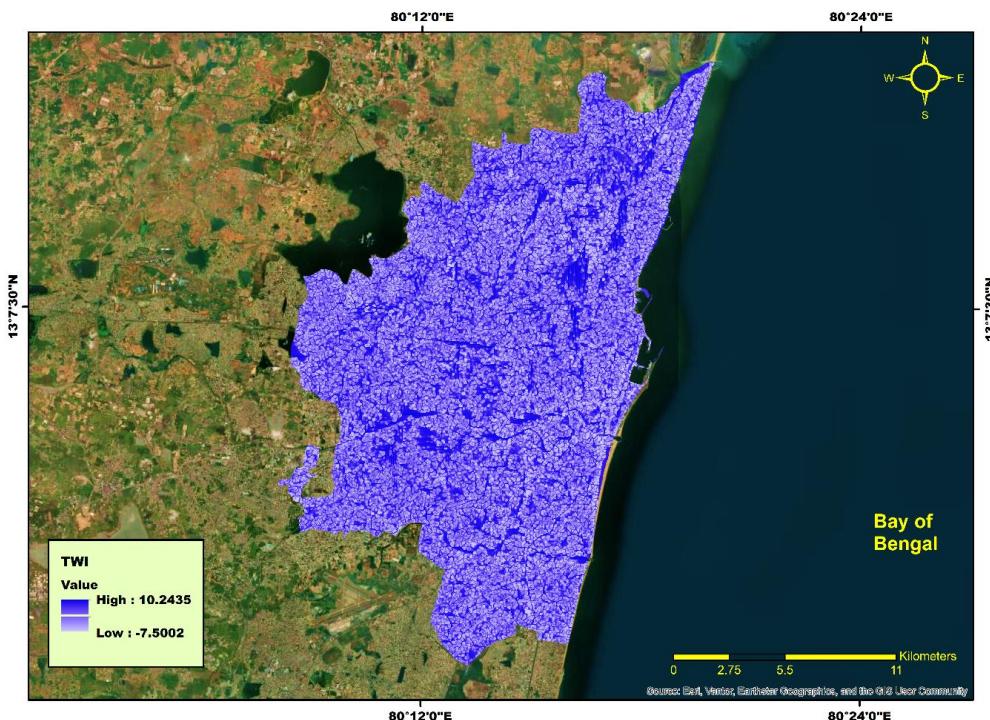


Figure 5: TWI (Topography Wetness Index) Map of the Study Area

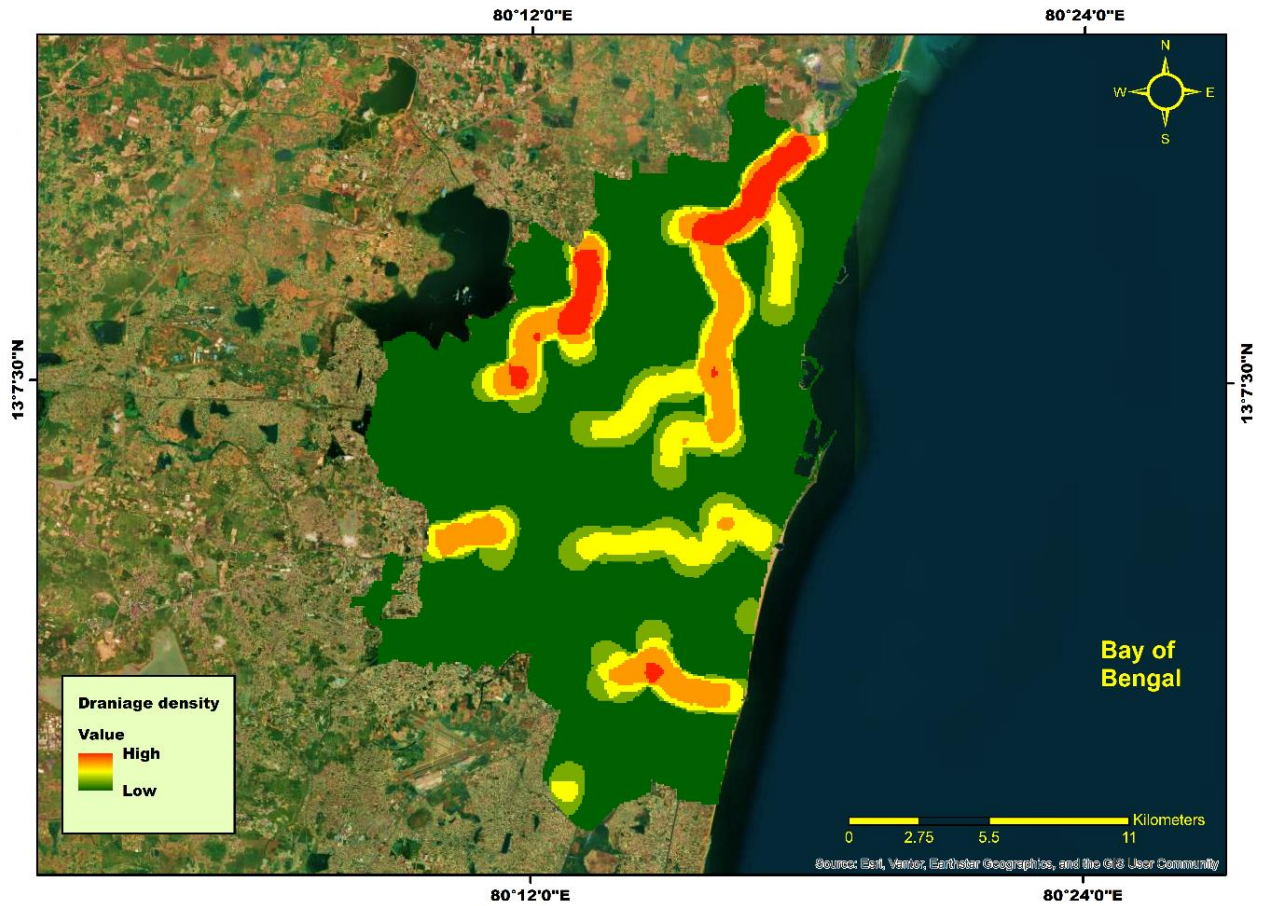


Figure 6: Drainage Density Map of the Study Area

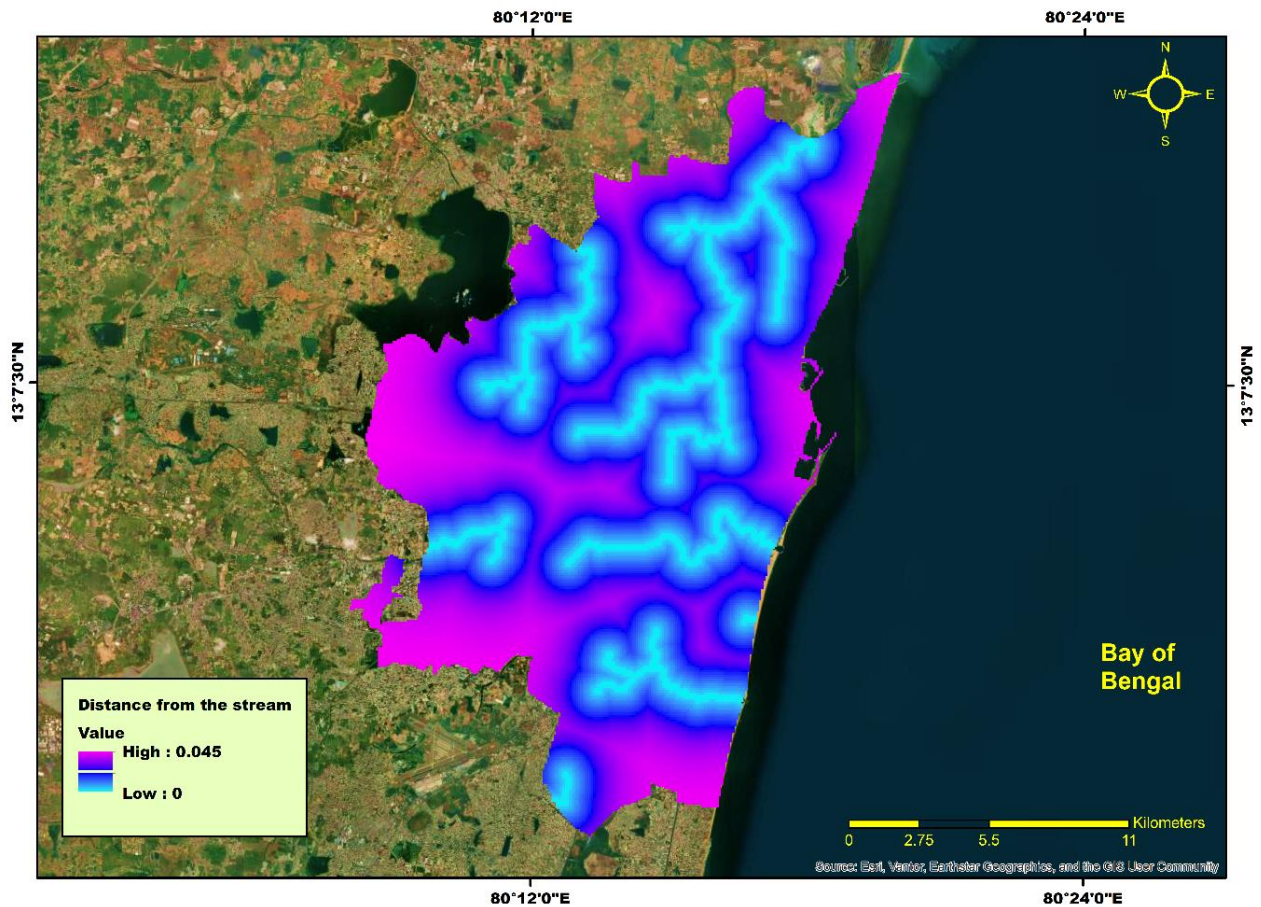


Figure 7: Distance from the Stream Map of the Study Area

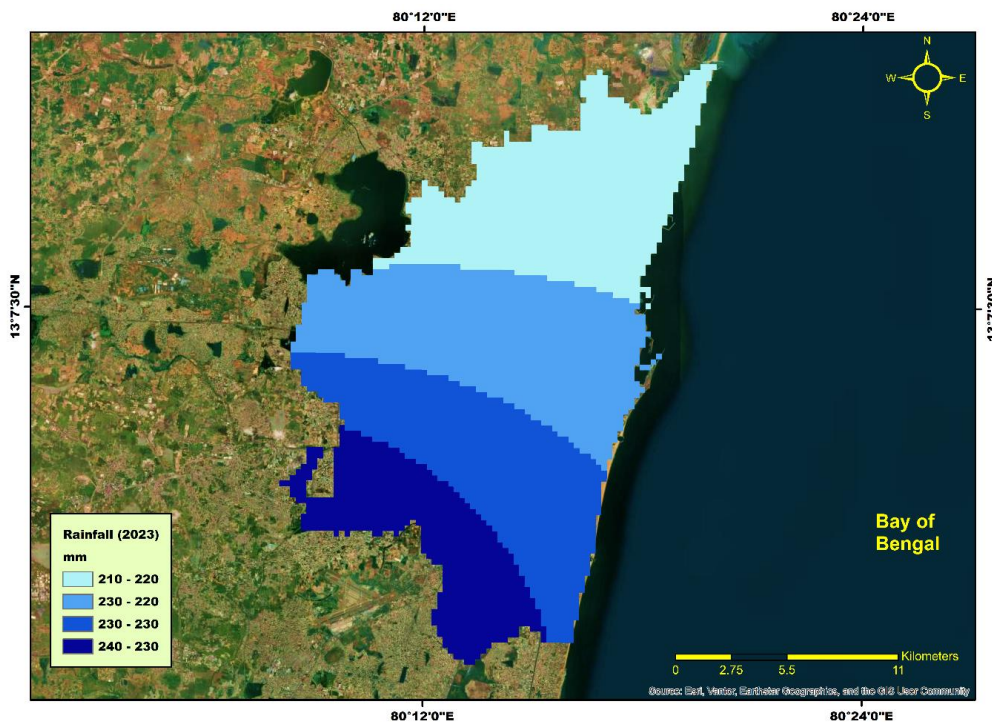


Figure 8: Rainfall (2023) Map of the Study Area

4.6 Rainfall

Rainfall events of 211-234 mm in the Chennai region can have a significant impact on water management and flooding. Such heavy downpours can cause flash floods in low-lying areas, excessive runoff, and overwhelmed drainage systems. Because impermeable surfaces reduce infiltration and increase surface runoff, they increase the risk of flooding in urban areas that experience heavy rainfall. Furthermore, the Chennai region's topography, characterized by flat terrain and inadequate natural drainage, can exacerbate flooding during periods of heavy rainfall. Therefore, reducing the impacts of heavy rainfall and boosting resilience in the Chennai region (Figure 8) requires effective flood preparedness and mitigation measures, such as improved stormwater management, infrastructure upgrades, and early warning systems.

4.7 Slope

The slope of the land is an important factor in flood mapping and flood vulnerability assessment in the Chennai region. The slope is the steepness or gradient of the land surface, which affects drainage capacity and the rate at which surface water runs off. Higher slopes usually result in faster runoff and less infiltration, increasing the risk of flooding, especially during periods of heavy precipitation (Jain et al. 2019). Conversely, regions with lower slopes typically experience better drainage and slower runoff, which reduces their vulnerability to flooding. Flood management authorities can identify areas with steep slopes that are vulnerable to rapid runoff and surface water accumulation by mapping slope gradients across the Chennai region (Figure 9). This information can then be used to guide targeted flood mitigation efforts, such as soil conservation measures, erosion control, and vegetation management, to lower the risk of flooding and increase resilience.

4.8 DEM

Digital Elevation Models (DEMs) are essential for identifying flood-prone areas and evaluating flood vulnerability in the Chennai region. Digital elevation models (DEMs) provide comprehensive data on terrain topography and elevation, enabling identification of low-lying areas vulnerable to flooding during heavy rainfall or storm surges. Flood management authorities can identify regions with limited natural drainage capacity and depressions or valleys that might serve as natural water collection points during flooding by analyzing DEMs. As a result, precise DEM are essential for efficient flood mapping and mitigation planning in the Chennai area (Figure 10), guiding infrastructure planning and decision-making to improve resilience and reduce flooding risk.

4.9 Map Removal Sensitive Analysis

A sensitivity analysis was conducted to evaluate the influence of various thematic data layers-such as NDVI, Land Use Land Cover (LULC), Topographic Wetness Index (TWI), drainage density, distance from streams, rainfall, slope, and Digital Elevation Model (DEM) on flood vulnerability in Chennai, essential for understanding the significance of each parameter in determining the spatial distribution of flood risk and informing effective management strategies. Descriptive statistics were calculated for each thematic layer, revealing that NDVI values ranged from 1 to 4, with an average of 2.5 and a standard deviation of 1.29, indicating significant variability in vegetation density across the region; higher NDVI values correlate with healthier vegetation, which can mitigate flooding by absorbing excess rainfall (Table 5). The LULC analysis highlighted urbanization trends, with a significant increase in impervious surfaces that contributed to increased surface runoff.

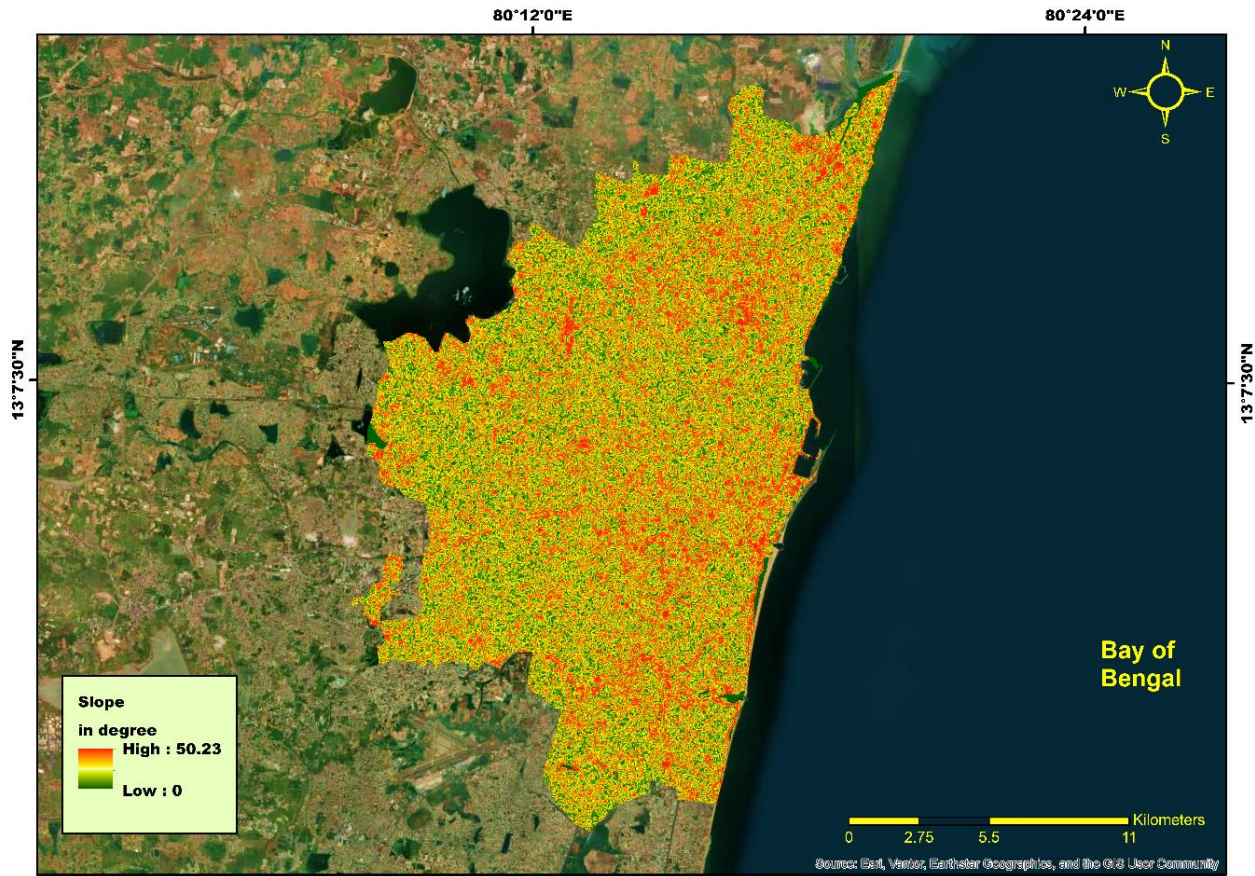


Figure 9: Slope Map of the Study Area

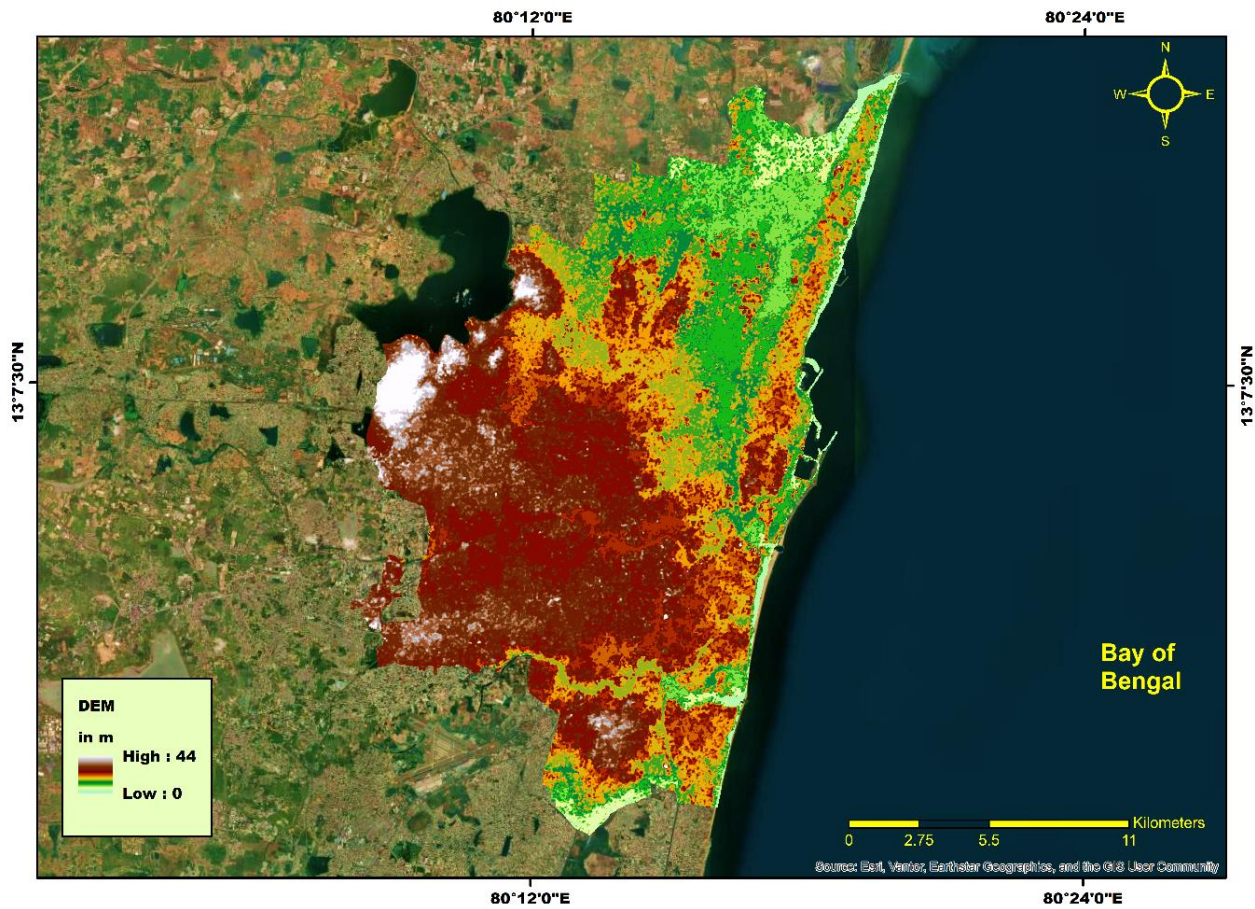


Figure 10: Digital Elevation Map of the Study Area

At the same time, higher drainage density indicated a greater concentration of drainage networks, which may enhance flood resilience. Conversely, areas with lower drainage density exhibited greater flood vulnerability, underscoring the need for infrastructure improvements. Proximity analysis revealed that areas located near water bodies were at higher risk, particularly during heavy rainfall events. In contrast, rainfall data illustrated the frequency and intensity of precipitation, providing a temporal context for understanding flood dynamics. Slope analysis indicated that steeper areas are less prone to flooding due to faster runoff, whereas flatter regions are more susceptible to water accumulation. DEM analysis provided crucial information on elevation changes across Chennai, identifying low-lying areas particularly vulnerable to flooding. A validation procedure comparing model predictions with observed flood events ensured the robustness and reliability of the findings (Figures 11a and b) by cross-referencing historical flood records and satellite imagery, thereby establishing confidence in the model's predictive capabilities. By sequentially removing each thematic layer, the degree to which each parameter influences flood susceptibility was determined, elucidating the interdependencies among various factors affecting flood vulnerability. This comprehensive analysis provides valuable insights for effective flood management and urban planning in Chennai, enabling policymakers and urban planners to prioritize interventions, enhance resilience, and develop targeted strategies for flood risk reduction, while also shaping future research directions and community engagement initiatives to foster sustainable urban environments.

Table 5: Statistical Analysis of Sensitivity Data in the Study Area

Thematic layer	Min	Max	Avg	St dev
NDVI	1	6	2.5	1.29
LULC	2	5	4	0.82
TWI	1	4	2.5	1.29
Drainage density	1	4	2.5	1.29
Distance from the stream	1	4	2.5	1.29
Rainfall	1	5	2.5	1.29
Slope	1	4	2.5	1.29
DEM	1	4	2.5	1.29

5. Flood Vulnerability Index

Chennai's vulnerability to flooding is influenced by several interrelated factors, including its geographical location, rapid urbanization, inadequate drainage infrastructure, climate change, and increasingly extreme weather events. Located on India southeastern coast, the city experiences heavy monsoon rains from October to December, which frequently lead to significant flooding due to aging and insufficient drainage systems, as well as encroachment on natural water bodies that historically acted as buffers. Rapid urbanization and population growth have transformed open spaces, wetlands, and other natural flood buffers into built-up areas, significantly increasing the city's flood risk. The conversion of these areas into impermeable surfaces, such as roads, buildings, and parking lots, diminishes the land's natural ability to absorb rainfall and manage stormwater, leading to increased surface runoff during heavy rainfall (Saravanan and Abijith, 2022). Additionally, Chennai flat terrain and low soil permeability hinder effective water drainage, further exacerbating vulnerability during intense rainfall events. Climate change predictions indicate that extreme weather occurrences, including heavy rainfall and cyclonic disturbances, are likely to become more frequent and severe, compounding flood risks. Current urban planning strategies inadequately address these vulnerabilities, with poor land-use planning, insufficient early warning systems, and a lack of proactive flood mitigation measures disproportionately affecting informal settlements with limited access to essential services. To effectively address Chennai's flood vulnerability, a multifaceted approach is essential, incorporating improvements to drainage infrastructure, sustainable urban planning, and community engagement. The classification of flood-prone areas into low-, medium-, and high-vulnerability zones (Figure 12) provides crucial insights for urban development strategies. Low-vulnerability areas (80.2 square kilometers, or 24.4%) can serve as models for sustainable practices. In comparison, medium-vulnerability areas (164.2 square kilometers, or 50.2%) require targeted interventions such as green infrastructure and enhanced drainage systems. High-vulnerability areas (84 square kilometers, or 25.4%) require immediate action and investment in comprehensive flood mitigation strategies (Table 6), including the restoration of natural floodplains, the

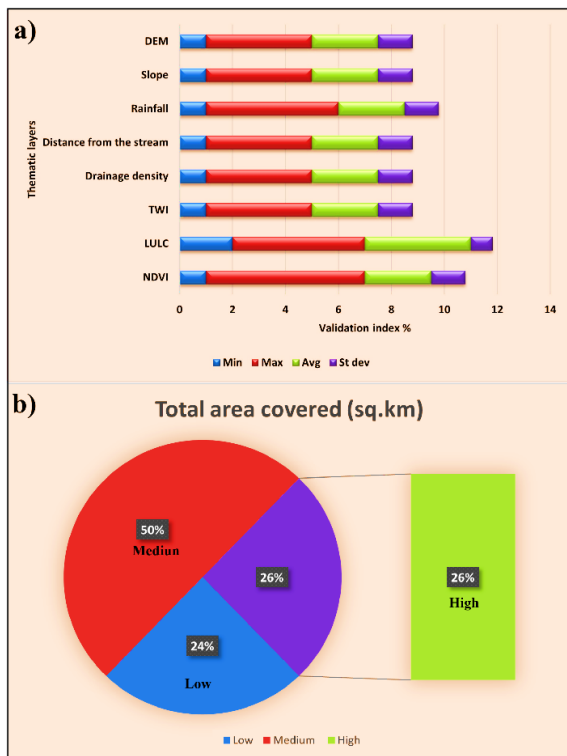


Figure 11: a) Validation Index Statistics for Thematic Layers, b) Percentage Area Covered by Flood Vulnerability Classes

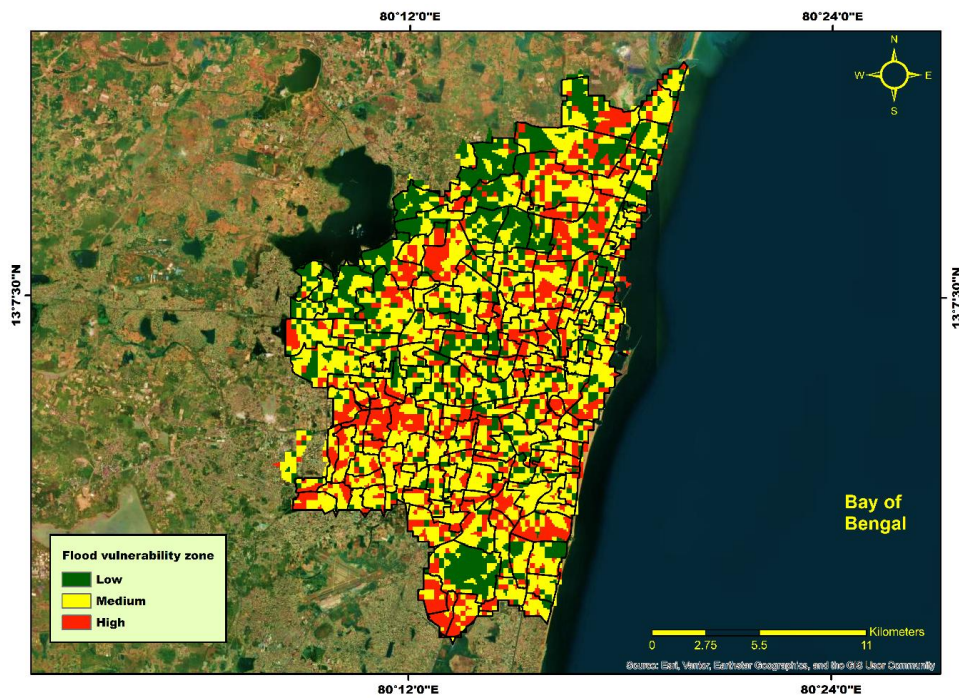


Figure 12: Flood Vulnerability Zone Map of the Study Area

Table 6: Classification of Flood Vulnerable Zone in the Study Area

Classification	Total area covered (sq.km)	Area percentage (%)
Low	80.2	24.4
Medium	164.2	50.2
High	84	25.4

creation of wetlands for stormwater management, and the development of effective emergency response systems. Community engagement is vital to creating and implementing flood resilience strategies, ensuring that local needs and insights are integrated and fostering a sense of ownership in flood risk management.

6. Conclusions

Chennai's vulnerability to flooding is a complex interplay of geographical, infrastructural, and socio-economic factors that collectively hinder effective flood management. The city's low-lying terrain, inadequate drainage systems, and rapid urbanization have significantly increased flood risks, particularly during the monsoon season. Climate change further exacerbates this vulnerability, with predictions of more frequent and severe weather events. The existing urban planning framework has proven inadequate, particularly in addressing the needs of informal settlements, where the impact of flooding is most acutely felt. As the city continues to grow, the necessity for robust flood management strategies becomes increasingly urgent. To enhance Chennai's resilience to flooding, several key recommendations should be implemented: invest in upgrading and expanding drainage infrastructure to accommodate increased rainfall and runoff; adopt comprehensive urban planning strategies that prioritize the preservation of natural water bodies and green spaces while limiting construction in high-risk flood zones; foster community participation in flood risk

management through education and awareness programs; develop a holistic approach that incorporates various stakeholders for coordinated flood risk reduction; establish and enhance early warning systems using advanced meteorological data and satellite imagery; implement regular monitoring and assessment of flood vulnerability and the effectiveness of strategies; and promote research and innovation in flood risk management technologies. By adopting these recommendations, Chennai can significantly reduce its vulnerability to flooding, ensuring the safety and well-being of its residents while promoting sustainable urban development.

Acknowledgments

The First author expresses his grateful acknowledgment to Shri. A.P.C.V. Chockalingam, Secretary, and Dr. C. VeeraBhahu, Principal, V.O. Chidambaram College, Thoothukudi, for their support and guidance. The help was extended by our department professors and research scholars, PG and Research Department of Geology, V.O. Chidambaram College, Thoothukudi.

Author's Contribution Statement

The authors confirm their contributions to the paper as follows: study conception and design, Christinal J and Antony Ravindran A; Data collection, Richard Abishek S and Karuthapandi K; analysis and interpretation of results, Rajalakshmi S and Sakthi Priya R; Map and reference preparation.

Funding

There is no funding source for this study.

Conflict of Interest

The authors declare that they have no conflict of interest.

References

- Ahmed, C. F., and N. Kranthi. 2018. "Flood Vulnerability Assessment Using Geospatial Techniques: Chennai, India." *Indian Journal of Science and Technology* 11(6):215–223. <https://dx.doi.org/10.17485/ijst/2018/v11i6/110831>
- Alabdian, R., C. Sharmila, N. Alruwais, H. M. Alshahrani, S. Anbukkarasi, M. Sujatha, and S. Vivek. 2025. "Assessment of Flood Vulnerability in a Coastal Metropolitan City for Sustainable Environment Using Machine Learning Methods." *Scientific Reports* 15(1):24796. <https://doi.org/10.1038/s41598-025-08912-4>
- Avand, M., and H. Moradi. 2021. "Using Machine Learning Models, Remote Sensing, and GIS to Investigate the Effects of Changing Climates and Land Uses on Flood Probability." *Journal of Hydrology* 595:125663. <https://doi.org/10.1016/j.jhydrol.2020.125663>
- Bagyaraj, M., V. Senapathi, S. Y. Chung, G. Gopalakrishnan, Y. Xiao, S. Karthikeyan, et al. 2023. "A Geospatial Approach for Assessing Urban Flood Risk Zones in Chennai, Tamil Nadu, India." *Environmental Science and Pollution Research* 30(45):100562–100575. <https://doi.org/10.1007/s11356-023-29132-1>
- Brema, J. 2020. "Flood Modelling and Mapping: Case Study on Adyar River Basin, Chennai, India." Pp. 104–139 in *Decision Support Methods for Assessing Flood Risk and Vulnerability*. Hershey, PA: IGI Global. <https://doi.org/10.4018/978-1-5225-9771-1.ch006>
- Burayu, D. G., S. Karuppannan, and G. Shuniye. 2023. "Identifying Flood Vulnerable and Risk Areas Using the Integration of Analytical Hierarchy Process (AHP), GIS, and Remote Sensing: A Case Study of the Southern Oromia Region." *Urban Climate* 51:101640. <https://doi.org/10.1016/j.uclim.2023.101640>
- Chanu, C. S., L. Elango, and G. R. Shankar. 2021. "A Geospatial Approach for Assessing the Relation between Changing Land Use/Land Cover and Environmental Parameters Including Land Surface Temperature of Chennai Metropolitan City, India." *Arabian Journal of Geosciences* 14(2):132. <https://doi.org/10.1007/s12517-020-06409-0>
- Cheng, J., C. Song, K. Liu, C. Fan, L. Ke, T. Chen, et al. 2022. "Satellite and UAV-Based Remote Sensing for Assessing the Flooding Risk from Tibetan Lake Expansion and Optimizing the Village Relocation Site." *Science of the Total Environment* 802:149928. <https://doi.org/10.1016/j.scitotenv.2021.149928>
- Darko, A., A. P. C. Chan, E. E. Ameyaw, E. K. Owusu, E. Pärn, and D. J. Edwards. 2019. "Review of Application of Analytic Hierarchy Process (AHP) in Construction." *International Journal of Construction Management* 19(5):436–452. <https://doi.org/10.1080/15623599.2018.1452098>
- Devi, N. N., B. Sridharan, and S. N. Kuiry. 2019. "Impact of Urban Sprawl on Future Flooding in Chennai City, India." *Journal of Hydrology* 574:486–496. <https://doi.org/10.1016/j.jhydrol.2019.04.041>
- Gashaw, T., A. Bantider, and A. Mahari. 2014. "Evaluations of Land Use/Land Cover Changes and Land Degradation in Dera District, Ethiopia: GIS and Remote Sensing Based Analysis." *International Journal of Scientific Research in Environmental Sciences* 2(6):199.
- George, S. L., K. Kantamaneni, R. A. V., K. A. Prasad, S. Shekhar, S. Panner, et al. 2022. "A Multi-Data Geospatial Approach for Understanding Flood Risk in the Coastal Plains of Tamil Nadu, India." *Earth* 3(1):383–400. <https://doi.org/10.3390/earth3010023>
- Jena, P. P., B. Panigrahi, and C. Chatterjee. 2016. "Assessment of Cartosat-1 DEM for Modeling Floods in Data Scarce Regions." *Water Resources Management* 30(3):1293–1309. <https://doi.org/10.1007/s11269-016-1226-9>
- Kabenge, M., J. Elaru, H. Wang, and F. Li. 2017. "Characterizing Flood Hazard Risk in Data-Scarce Areas Using a Remote Sensing and GIS-Based Flood Hazard Index." *Natural Hazards* 89:1369–1387. <https://doi.org/10.1007/s11069-017-3024-y>
- Kundzewicz, Z. W., S. Kanae, S. I. Seneviratne, J. Handmer, N. Nicholls, P. Peduzzi, et al. 2014. "Flood Risk and Climate Change: Global and Regional Perspectives." *Hydrological Sciences Journal* 59(1):1–28. <https://doi.org/10.1080/02626667.2013.857411>
- Lodwick, W. A., W. Monson, and L. Svoboda. 1990. "Attribute Error and Sensitivity Analysis of Map Operations in Geographical Information Systems: Suitability Analysis." *International Journal of Geographical Information System* 4(4):413–428. <https://doi.org/10.1080/02693799008941556>
- Mahmoud, S. H., and T. Y. Gan. 2018. "Urbanization and Climate Change Implications in Flood Risk Management: Developing an Efficient Decision Support System for Flood Susceptibility Mapping." *Science of the Total Environment* 636:152–167. <https://doi.org/10.1016/j.scitotenv.2018.04.282>
- Mojaddadi, H., B. Pradhan, H. Nampak, N. Ahmad, and A. H. B. Ghazali. 2017. "Ensemble Machine-Learning-Based Geospatial Approach for Flood Risk Assessment Using Multi-Sensor Remote-Sensing Data and GIS." *Geomatics, Natural Hazards and Risk* 8(2):1080–1102. <https://doi.org/10.1080/19475705.2017.1294113>
- Munawar, H. S., A. W. Hammad, and S. T. Waller. 2022. "Remote Sensing Methods for Flood Prediction: A Review." *Sensors* 22(3):960. <https://doi.org/10.3390/s22030960>
- Murayama, Y., R. C. Estoque, S. Subasinghe, H. Hou, and H. Gong. 2015. *Land-Use/Land-Cover Changes in Major Asian and African Cities*. Annual report on the multi-use social and economy data bank, 92.

http://giswin.geo.tsukuba.ac.jp/capital-cities/data/2015_capital_project_report.pdf

Narayani, A. R., R. Nagalakshmi, and D. Pakrasi. 2023. "Application of Geoinformatics to Classify Landcover from Satellite Imagery Using NDVI: A Case of Peri-Urban Regions of Southern Chennai." *IOP Conference Series: Earth and Environmental Science* 1210(1):012034.

Natarajan, L., T. Usha, M. Gowrappan, B. Palpanabhan Kasthuri, P. Moorthy, and L. Chokkalingam. 2021. "Flood Susceptibility Analysis in Chennai Corporation Using Frequency Ratio Model." *Journal of the Indian Society of Remote Sensing* 49:1533–1543. <https://doi.org/10.1007/s12524-021-01331-8>

Ramachandran, A., K. Palanivelu, B. V. Mudgal, A. Jeganathan, S. Gunganesh, B. Abinaya, and A. Elangovan. 2019. "Climate Change Impact on Fluvial Flooding in the Indian Sub-Basin: A Case Study on the Adyar Sub-Basin." *PLOS ONE* 14(5):e0216461. <https://doi.org/10.1371/journal.pone.0216461>

Saha, A. K., and S. Agrawal. 2020. "Mapping and Assessment of Flood Risk in Prayagraj District, India: A GIS and Remote Sensing Study." *Nanotechnology for Environmental Engineering* 5:1–18. <https://doi.org/10.1007/s41204-020-00073-1>

Saltelli, A., M. Ratto, T. Andres, F. Campolongo, J. Cariboni, D. Gatelli, et al. 2008. *Global Sensitivity Analysis: The Primer*. Chichester: John Wiley & Sons.

Sankhala, S., and B. Singh. 2014. "Evaluation of Urban Sprawl and Land Use Land Cover Change Using Remote Sensing and GIS Techniques: A Case Study of Jaipur City, India." *International Journal of Emerging Technology and Advanced Engineering* 4(1):66–72.

Saravanan, S., and D. Abijith. 2022. "Flood Susceptibility Mapping of Northeast Coastal Districts of Tamil Nadu, India Using Multi-Source Geospatial Data and Machine Learning Techniques." *Geocarto International* 37(27):15252–15281. <https://doi.org/10.1080/10106049.2022.2096702>

Selvam, R. A., and A. R. Antony Jebamalai. 2023. "Application of the Analytical Hierarchy Process (AHP) for Flood Susceptibility Mapping Using GIS Techniques in Thamirabarani River Basin, Southern India." *Natural Hazards*. <https://doi.org/10.1007/s11069-023-06037-3>

Thirumurugan, P., and M. Krishnaveni. 2019. "Flood Hazard Mapping Using Geospatial Techniques and Satellite Images: A Case Study of Coastal District of Tamil Nadu." *Environmental Monitoring and Assessment* 191:1–17. <https://doi.org/10.1007/s10661-019-7327-1>

Twumasi, Y. A., E. C. Merem, T. Ayala-Silva, A. Osei, B. M. Petja, and K. Alexander. 2017. "Techniques of Remote Sensing and GIS as Tools for Visualizing Impact of Climate Change-Induced Flood in the Southern African Region." *American Journal of Climate Change* 6(2):306–327. <https://doi.org/10.4236/ajcc.2017.62016>

Wang, X., and H. Xie. 2018. "A Review on Applications of Remote Sensing and Geographic Information Systems

(GIS) in Water Resources and Flood Risk Management." *Water* 10(5):608. <https://doi.org/10.3390/w10050608>

Youssef, A. M., B. Pradhan, and A. M. Hassan. 2011. "Flash Flood Risk Estimation along the St. Katherine Road, Southern Sinai, Egypt Using GIS-Based Morphometry and Satellite Imagery." *Environmental Earth Sciences* 62(3):611–623. <https://doi.org/10.1007/s12665-010-0551-1>