Assessing the Extremes of Hydrological Disasters Through Analysing the Changes in the Spatial Growth

Total word count : 8312

Assessing the Extremes of Hydrological Disasters Through Analysing the Changes in the Spatial Growth

Ar. Shagun Sethi[1] ; Dr. Chetan R. Patel[2] & Ms. Jyoti Verma[2]
[1]Student at Sardar Vallabhbhai National Institute of Technology, Surat, shagunsethi97@gmail.com; 8780606099
[2]Associate Professor at Sardar Vallabhbhai National Institute of Technology, Surat, crp@ced.svnit.ac.in;
[2]Senior research specialist at National Institute of Urban Affairs, New Delhi, jverma@niua.org

Ar. Shagun Sethi, Dr. Chetan R. Patel & Ms. Jyoti Verma
Student at Sardar Vallabhbhai National Institute of Technology, Surat, shagunsethi97@gmail.com
Associate Professor at Sardar Vallabhbhai National Institute of Technology, Surat, crp@ced.svnit.ac.in
Senior research specialist at National Institute of Urban Affairs, New Delhi, jverma@niua.org

Abstract

Water has been central to the development of civilizations throughout history. The hydrological characteristics of Indian monsoons entails the necessity to store rainwater for utilisation in the dry stretches of the year, especially in the semi-arid regions of southern-India. Chennai, with no perennial source of drinking water, evolved around a cascading-system of water tanks called "Eri", which was used to sustain its requirements. Managed by community, it served as wetlands interconnected to each other to combat the hydrological vulnerabilities like droughts and floods by acting as reservoirs and flood control system and acting as habitats to diverse biodiversity. With the increasing rate of haphazard urbanisation and hydrological disasters, more number of people are becoming prone. The floods in 2015 and the droughts of 2019 converging city to "day zero", necessitates Chennai to plan and manage its waterbodies wisely to protect its growth and people.

Chennai lies in the southern part of the country with plainer topography and is experiencing decrease in waterbodies owed to rapid unplanned urbanisation leading to encroachments, changing socio-economic dynamics, political interventions and climate change. These factors have significantly impaired the city's capacity to recharge groundwater and manage hydrological disasters. With the increase in built-up areas from 12% to 48% coverage, this paper highlights the adverse effects of unplanned development on the city's waterbodies and wetlands. It underscores the urgent need to integrate sustainable practices into urban planning. The increasing frequency of hydrological disasters further necessitates incorporating risk and mitigation strategies into the city's planning process. This approach involves identifying prone and vulnerable areas and aligning development strategies with these risks, ensuring that mitigation practices are embedded within the broader scope of urban planning.

The research adopts a catchment-based approach to explore the cause-and-effect relationship between urban development and waterbody degradation, and the consequent increase in flood risk. The paper aims to identify the domino effect of Chennai's unplanned growth on its waterbodies and to highlight the necessity of incorporating mitigation practices into urban planning to safeguard the city's 11 million inhabitants.

Keywords— Hydrological extremes; climate change, natural disasters; Resilient cities; Urbanisation.

"Assessing the extremes of hydrological disasters through analysing the changes in the spatial growth "

I. Introduction

"There is a water crisis today. But crisis is not about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people — and environment suffer badly." (Kansal & Singh, 2022)

Water has always been the lifeblood of human civilization. Presently, approximately 80% of the global population continues to live near water bodies, underscoring water's essential role in human settlement and survival. The United Nations World Water Development Report 2020 (Water and Climate change: The United Nations World Water Development Report 2020 World Water Assessment Programme United Nations Educational, n.d.) highlights a significant increase in global water use, which has surged sixfold over the past century, growing at an annual rate of about 1%. This escalation is attributed to factors such as population growth, economic development, and evolving lifestyle patterns. Concurrently, the world grapples with the impacts of climate change, characterized by the increasing frequency and severity of extreme weather events such as heatwaves, unprecedented rainfall, thunderstorms, and storm surges. These phenomena have profound implications for water quality, leading to higher water temperatures, lower dissolved oxygen levels, and diminished self-purifying capacities of freshwater bodies. Moreover, water pollution and bacterial contamination exacerbate these challenges, particularly during floods and droughts.

The incidences of natural disasters and climate change represents two intricate and highly challenging issues, each with lasting impacts on a country's economic, environmental, and social well-being. (*Uttarakhand Action Plan on Climate Change "Transforming Crisis into Opportunity,"* n.d.) . Rivers and water bodies in India are not only vital for economic development, food security, and overall well-being but also represent productive and diverse ecosystems. (*Four Reasons to Protect Rivers*, n.d.)

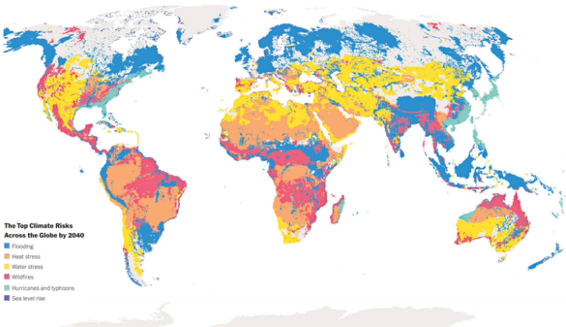


Figure 1.Countries with major climate risk index, Source:(Eckstein et al., n.d.)

India, the world's most populous country with a population of 1.3 billion, epitomizes these challenges. As the nation's economy rapidly develops it simultaneously faces severe environmental challenges resulting to disasters and hence exposing millions of people to them. India ranks high on the climate risk index, indicating its vulnerability to natural disasters that have the potential to impact millions of people. The rapid urbanization and population growth have led to the exploitation and degradation of urban water bodies, causing significant stress on these natural ecosystems. This disruption of water bodies' natural courses, compounded by climate change, have resulted in hydroclimatic extremes such as urban floods, water scarcity, groundwater overexploitation, stormwater runoff, and water pollution in many parts of the country. The increasing frequency of extreme natural disasters globally disrupts socio-economic structures, with urban areas facing significant threats from climate change and unplanned development (J. D. Miller & Hutchins, 2017). Chennai, home to 11 million people, experiences severe impacts from both flooding and water shortages.

As a major metropolitan city in Tamil Nadu, Chennai exemplifies the critical intersection of rapid urbanization, water management challenges, and climate change impacts. Situated on the Coromandel Coast in southeastern India, Chennai is traversed by three natural rivers—Kosathalaiyar, Cooum, and Adyar—and a man-made Buckingham Canal. Historically, the city boasted around 5000 water bodies that served as crucial sources of drinking water and supported a vibrant ecosystem. However, Chennai's rapid urbanization, coupled with poor urban planning, has led to the degradation and encroachment of these water bodies. Rivers that once nurtured the city have been reduced to polluted drains, significantly diminishing the city's capacity to manage water during heavy rainfall.

In the absence of a perennial river, Chennai has historically relied on a cascading network of water tanks known as "Eri." Functioning as wetlands, this system not only combated hydrological vulnerabilities such as droughts and floods but also served as vital habitats for diverse biodiversity. These eri were a part of the day to day lives of the people making them in- disposable and sensitive towards the management of these waterbodies, growing around them rather than on them.

The floods of October 2005 and December 2015, which submerged the entire city, underscored Chennai's vulnerability and compelled authorities to initiate measures for the restoration and maintenance of river bodies. In 2019, Chennai faced a severe drought, with all water resources drying up and the city relying on water tankers for basic needs. This paradox of simultaneous floods and droughts highlights the urgent need for sustainable water management strategies as well as their integration in the urban planning of the city with a sensitive approach to the wetlands and waterbodies which helps in mitigating the effects of these disasters.

The research delves deeper into finding the corelation of the rapid urbanisation on the waterbodies and the effects it have on them. While the sponge areas tends to decrese in the current scenarios, the increasing pace of diminishing waterbodies pose a great threat to Chennai.Analysing the trend of urbanisation in the city by taking the cactment based approach to detail out the effects of rapid unplanned growth on waterbodies becomes essential to find out the neighbourhood level approaches that the city can take to conserve and preserve its waterbodies. The study also examines the loss in the capacity of the city to absorb water and infiltrate it in the groundwater which satisfies approximately half of the water needs of the city's population by observing the pre and post monsoon scenarios of the city. Thus recharging the water and utilising the excess water received by the city is crucial for completing the water management cycle in Chennai.

II. Literature review

With the urban population reaching to an all-time high, the growth in urban areas have been happening at an exponential pace in an unsupervised manner raising an alarm to the ill-effects caused by the anthropological as well as the changing climatic conditions leading to intervention in the hydrological cycle of the city as a whole. Climate change exacerbates the vulnerability of urban areas to hydrological extremes. (Dash et al., 2019)indicate that altered precipitation patterns and increased frequency of extreme weather events are linked to climate change, posing significant challenges for water management. In Chennai, the 2015 floods and the 2019 drought underscore the city's increasing hydrological vulnerabilities (Bhagat et al., 2022)Globally, cities like Houston, USA, and Manila, Philippines, have faced severe flooding events attributed to changing climate patterns.(Lagmay et al., 2015) provide a detailed account of tropical cyclone-induced flooding in Manila, emphasizing the need for climate resilience in urban planning. Natural disasters have posed threats and challenges to the survival and welfare of mankind since ages.(Guo, 2021) .The monsoonal landscape as diverse as India is inherent to hydroclimatic extremes such as droughts and floods. `Although floods and droughts are generally regarded as opposites, they can co-occur as droughts tend to be long and cumulative as opposite to floods. (Kaaviya & Devadas, 2021a). Droughts, as defined by (*AR5 Synthesis Report: Climate Change 2014 — IPCC*, n.d.) is the prolongation of dry weather leading to unstable hydrological balance while floods are cumulative and short lived both of which exacerbates the need to develop resiliency in the city. Resilience is not only about how the environment responds to disturbances linked to climate changes but also about how effectively it can endure and adapt to the rising demands and requirements. (Kaaviya & Devadas, 2021b). Rapid urbanization has significant effects on hydrological systems, often leading to the degradation of natural water bodies and increased flood risks. In Chennai, the urbanisation led to expansion of the built-up area from 12% to 48%, causing severe impacts on the city's water bodies Unplanned urban growth leads to the encroachment of wetlands and water bodies, reducing their capacity to manage floodwaters and recharge groundwater (Ramachandra & Kumar, 2008)Although this pattern is not unique to Chennai but prevalent all over the world. (Krishna Kulkarni & Pratap Singh, 2023)discuss how land subsidence in Jakarta, Indonesia, exacerbates flooding, while Phien-wej et al. (2006) highlight the impacts of urban expansion on natural drainage systems in Bangkok, Thailand. These studies illustrate the widespread consequences of unplanned urbanization on urban hydrology and the need to manage water within any urban area.

Water management has historically been a cornerstone of civilization, particularly in regions dependent on seasonal rains. (Gould, 2015)describe rainwater harvesting techniques in Africa, which are crucial for water supply in arid regions. (Nasiri & Mafakheri, 2015)examines the qanat systems in Iran, ancient underground channels that provide a sustainable water supply in desert areas. In India, the traditional "Eri" system of interconnected water tanks have been vital for managing water resources in semi-arid regions like Chennai. (Manohar & Kt, n.d.) describes eri as "A cascading system of tanks" which has been implemented to supply water to distant villages, addressing challenges like drought and flooding. The author recognizes the ecological importance and role played by these water bodies which has contributed to their conservation, fostering a culture of respect and reverence. Mosse in his book "The rule of water" provides an in-depth analysis of how these tanks, managed by local communities, function as reservoirs and flood control systems while also supporting biodiversity. Similarly, (Anil Agarwal and Sunita Narain, n.d.) highlight the importance of traditional water harvesting systems across India, emphasizing their role in mitigating hydrological vulnerabilities such as droughts and floods. These examples underscore the global significance of traditional water management systems in addressing hydrological challenges.

Effective urban planning must incorporate sustainable practices to address the challenges posed by rapid urbanization and climate change. (Birkmann et al.,2016) argue that urban resilience can be enhanced through strategic planning that includes risk and mitigation strategies. This involves identifying vulnerable areas and aligning development with these risks. D(Douglas et al., 2008)emphasize the importance of integrating flood risk management into urban planning frameworks, particularly in developing countries where the urban poor are disproportionately affected by flooding. In the UK and the Netherlands, (Klijn et al., 2015) discuss the implementation of integrated water resource management practices to mitigate flood risks.

A catchment-based approach can address the cause-and-effect relationship between urban development and water body degradation. This approach considers the entire hydrological cycle and the interconnectedness of water systems (Fletcher et al., 2013). In Chennai, recognizing the cascading system of water tanks and ensuring their functionality within the urban landscape is crucial (Srinivasan et al., 2013)).Internationally, cities like Melbourne, Australia, have successfully implemented integrated urban water management strategies to enhance water security and reduce flood risks (Mitchell et al., 2006). These strategies involve coordinated efforts across various sectors and scales, emphasizing the need for holistic approaches to urban water management.

The happenings of the disasters are a sum and co-relation of all the cognitive characteristics of the city. Sivakumar et al. (2020) used Multi-Criteria Decision-Making analysis for drought vulnerability by considering various parameters like annual rainfall, monthly rainfall, LULC, slope, soil type, NDWI, and population. (Suwandaru et al., 2020) performed an examination of Chennai's complex water governance network, stressing the need for improved collaboration and stakeholder awareness to address challenges effectively. Bremner (2019) investigates the relationship between spatial planning, capitalist urbanization, and monsoons in Chennai, advocating for inclusive planning and interdisciplinary collaboration. (Chundeli et. al., 2018) proposes using geospatial tools to map flood-prone areas in Chennai, while Shivakumar and Shanmuganathan (2023) recommend early flood forecasting systems and transdisciplinary approaches for effective flood management. Ramkumar et al. (2018) propose interlinking of rivers as a strategy to mitigate coeval floods and droughts.

(Kaaviya & Devadas, 2021b) emphasizes that current development practices contribute to the irrevocability of climate change, necessitating immediate mitigation and adaptation strategies. They highlight the drastic reduction in groundwater levels due to increased dependency and map various hydrological parameters to provide a comprehensive analysis of disaster-prone areas. (Abebe et al., 2018) underscores the importance of integrated water management strategies, identifying urban sprawl, land use changes, and inadequate flood management as key factors exacerbating urban pluvial flooding. The author highlights the drastic reduction in groundwater levels in Chennai due to increased dependency and other hydrological factors such as precipitation, runoff, evaporation, and infiltration. Parameters like slope, drainage density, land use/land cover, NDVI, NDWI, soil depth, geomorphology, sewage and water supply networks, per capita water supply, groundwater depth, rainfall, flood inundation depth, population density, and proximity to water bodies are mapped and overlaid. This comprehensive analysis identifies disaster-prone areas using analytical hierarchy and weighted overlay analysis.(Bremner, 2020) investigates the relationship between spatial planning, capitalist urbanization, and monsoons in Chennai, advocating for inclusive planning and interdisciplinary collaboration. Despite significant insights, many studies focus on either floods or droughts, highlighting a gap in comprehensive solutions addressing both phenomena, necessitating further research on integrated, long-term resilience strategies.

Overall, various papers address diverse perspectives to the multifaceted challenges faced by Chennai in managing its water resources, urging comprehensive approaches and stakeholder collaboration.

III. Study area: Chennai, Tamil Nadu

Chennai, formerly known as Madras, is the fourth most populous metropolitan city in India, sustaining a population of approximately 11 million. Established as a British trade port in the 1600s, it is the economic hub and state capital of Tamil Nadu. Located on the Coromandel coast, Chennai stretches 19 km along the Bay of Bengal and serves as a major commercial, cultural, economic, and educational centre in South India, attracting a large number of migrants. Geographically, Chennai is positioned in the northeastern part of Tamil Nadu, with coordinates spanning northern latitudes of 12°59'10" to 13°08'50" and eastern longitudes of 80°12'10" to 80°18'20". It has a population density of 26,553 people per square kilometre.

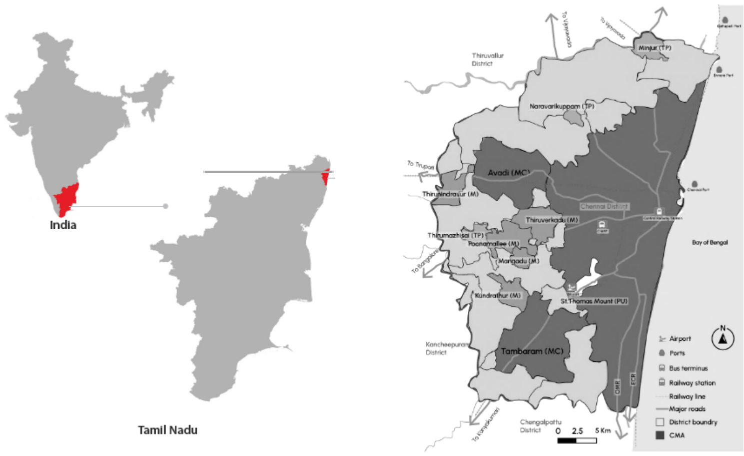


Figure 2.Chennai geographical location; Source: CMDA

Chennai has a tropical wet and dry climate, characterized by hot and humid conditions throughout most of the year. Peak temperatures range from 38 to 42°C, while minimum temperatures in January are around 18–20°C. The city's flat terrain, with an average elevation of 6 meters, creates significant drainage challenges, particularly during heavy monsoon rains. The city is governed by the Greater Chennai Corporation (GCC), and urban development and planning are managed by the Chennai Metropolitan Development Authority (CMDA). Over the years, their jurisdictions have expanded to cover 426 square kilometers and 5904 square kilometers, respectively. Urban development in Chennai has frequently disregarded the natural hydrological system, leading to construction over floodplains, marshes, lakes, and ponds. As a result, the city regularly faces periodic droughts and floods, struggling to meet its increasing water demand. According to the World Resources Institute's Aqueduct Water Risk Atlas, Chennai experiences extremely high baseline water stress, indicating a high ratio of total water withdrawals to the annual available renewable surface water supplies.

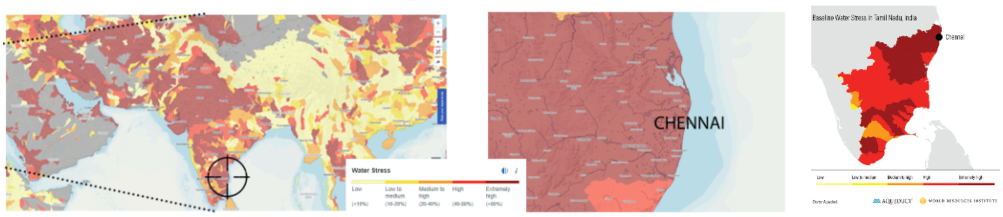


Figure 3. Water stressed Chennai and DEM model; Source: WRI,Aqueduct

The city is highly susceptible to tropical disturbances and cyclones, urban floods, overflow of major rivers, lakes, and drains, and frequently clogged drainage networks. Notable catastrophic floods in 1943, 1978, 1985, 1990, 2002, 2005, and 2015 have underscored the inadequacies in Chennai's drainage system. Despite frequent flooding, there remains a significant gap in understanding and methodologies to evaluate the impacts of climate change on urban flooding and the acute water crisis.

Chennai's rivers are facing the issues of constant encroachments and sewage and solid waste dump resulting in their reduction of area & effective width as well as the storage and carrying capacity.The lack of connectivity, or in some areas, the complete absence of storm sewers, has severely affected the city's ability to manage excess water during rainfall, resulting in flood-like situations. A performance audit report on flood management and response in the city highlighted that the increased discharge of 353.96 m^3/s of floodwaters in 2015 into the Buckingham Canal, which was designed to handle 254.85 m^3/s, led to the flooding of Velachery and surrounding regions. (Government of Tamil Nadu 2017, p. 69).

Top of Form

Bottom of Form

According to Aon Benfield's annual global climate and catastrophe report, the torrential rainfall and flooding in Chennai in November and early December of 2015 caused India's economy to incur a loss of 200 billion INR (USD 3 billion) (Aon Benfield 2015, p. 3,7). Additionally, it was the seventh-most fatal global disaster in 2015 (Aon Benfield 2016, p. 6).

While floods are short lived and droughts tend to be long and cumulative.(K. A. Miller & Belton, 2014). Chennai have a huge dependency on groundwater extratcted through dug borewells by individual households as in absence of any perneiil asource of drinking water, the city is dependent on the reservoirs in Poondi, Cholavaram, Red Hills and Chemabarambakkam, well fields in Arani—Kosasthaliyar basin, Veeranam, Kandaleru—the distant reservoirs. The city's water supply primarily relies

on an inconsistent rainfall pattern, leading to the drying up of reservoirs and lakes during periods of scant rainfall. Consequently, Chennai has struggled to provide adequate water to its increasing population. Despite the flood devastation in 2015, the reservoirs were completely dry the following year, resulting in a severe water crisis. Between 2016 and 2017, the average monthly water storage levels of the Chembarambakkam and Redhills reservoirs drastically decreased from 49.6 MCM to 11.25 MCM and 43.6 MCM to 12.01 MCM, respectively.(CMWSSB). The regular occurrence of draughts led by city's inability to supply water to only half of the population have increased the dependency of people on groundwater leading to overexploitation to meet the city's growing water demand (Ruet et al., 2007).
This is evident from the change from the figure 4 that the city has neglected its waterbodies in the due process of urbanisation. As per reports of National Institute for Disaster Management, Chennai had around 600 waterbodies in 1980 which have been reduced to 28 in 2017 scaling down its area of coverage from 12.6 Sq. km to 3.2 Sq.km. The unplanned growth of city, slowly vanished interconnected small tanks and lakes on which the city traditionally relied on to mitigate the floods by holding the excess water and retaining it to slowly allow for infiltration into groundwater mitigating draught scenarios and provide for their day to day use of water.

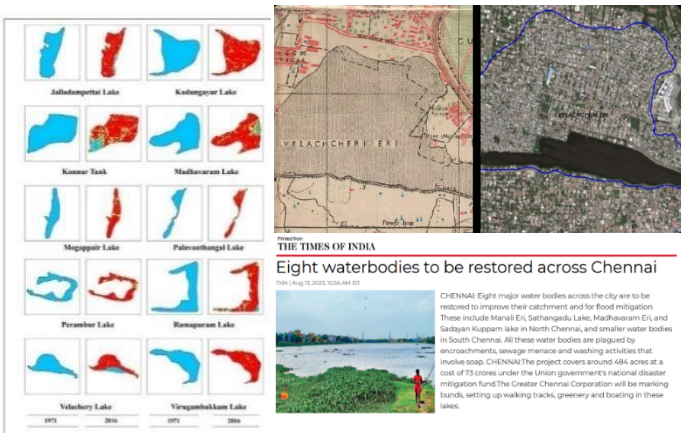
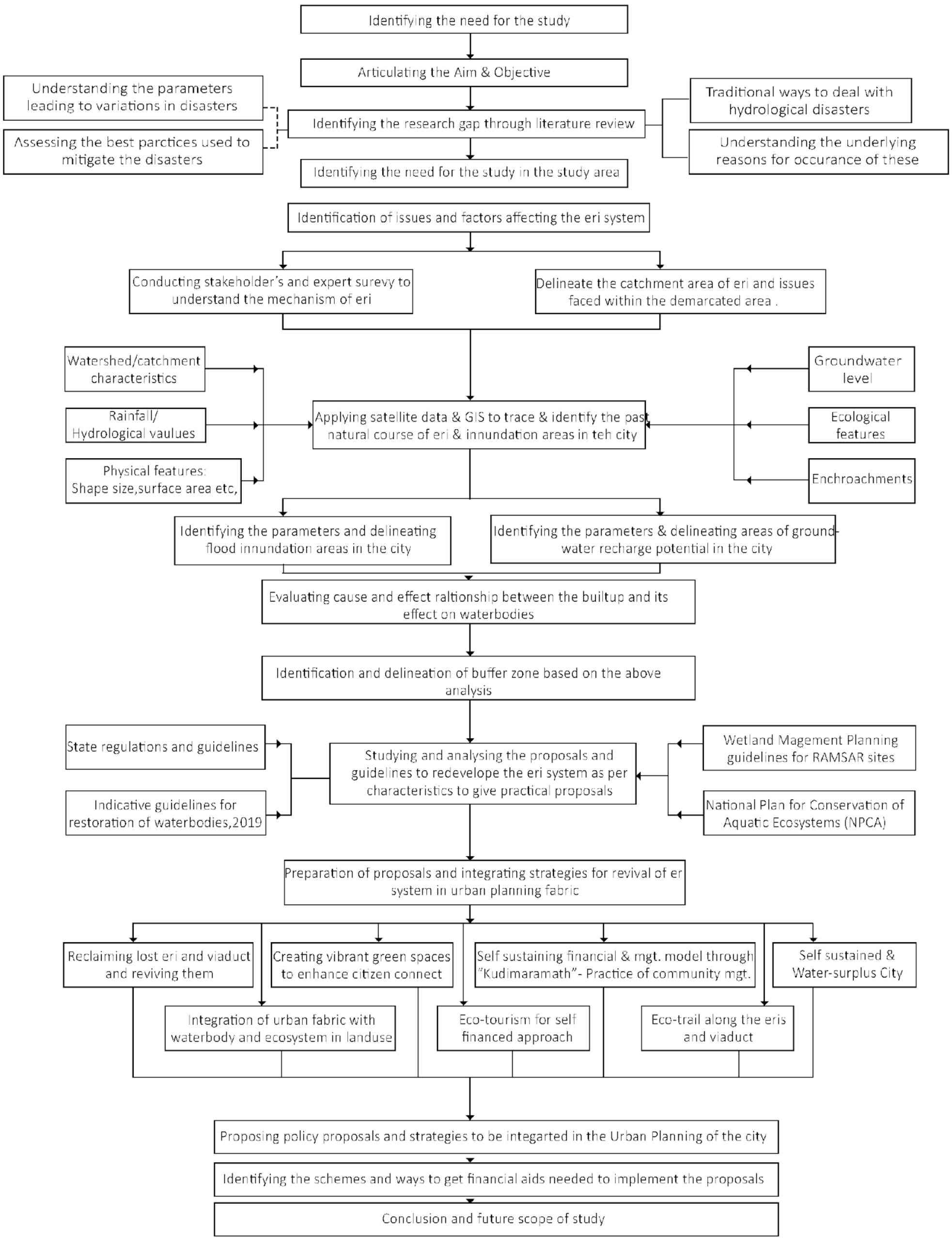


Figure 4. Disappearing water bodies in Chennai Source: Chennai floods review-GCC , TOI article

This in turn have caused a social cohesion between the various income classes about their ability to access groundwater leading to a major drawback for the lower and vulnerable section of the society. Thus these extreme hydrological events requires deeper analysis of the reasons why the city fails to deal with manage excess water and yet suffer from the lack of it. Sturdy measures that integrate efforts to protect, restore and conserve water resources with efficient urban land-use planning, solid waste management and stringent monitoring and enforcement mechanisms are required. State officials have acknowledged this issue and have initiated efforts towards the restoration of certain waterbodies. A comprehensive restoration approach is required in Chennai which involves a base for water-sensitive urban planning practice as well as managing the excess and less water in the city.

IV. Materials and methods

Factors determining the scale of effect of hydrological disasters in a city were analysed through various secondary data which were collected and were determined by various research papers.. Preparation of geo database and the integration of these layers were done using Arc GIS software.The landform and landuse/ land cover (LU/LC) maps prepared by supervised classification validating them using Google earth imagery of the respective years. The parameters together were analysed to find out the collective effects of these parameters on the city's hydrological characteristics.



To assess the hydrologically vulnerable areas, flood and draught prone areas were delineated through weighted overlay analysis assigning weights to various parameters and the changing pattern of landcover was ascertained to delve deeper in the cause-and-effect relationship between the increased happenings of these events as a result of the anthropological factors.

Factors used in determining flood inundation areas and groundwater recharge potential areas are:

Table 1. Parameters and the source of data collected

Parameter	Source
DEM data	USGS earth explorer
Geomorphology	Bhukosh
LULC	USGS- Supervised classification
Lineament density	USGS- SRTM Data
Geology	GSI
Soil type	GSI
Drainage density	USGS- SRTM Data
Rainfall	Cru data

Slope	USGS- SRTM Data
Drainage density	USGS- SRTM Data
Distance to road	CMDA
Distance to river	CMDA
Slope	USGS- SRTM Data
Elevation	USGS- SRTM Data

DEM (Digital Elevation Model)

The Digital Elevation Model (DEM) map for the region indicates that the majority of areas in the city lying within the elevation range till 60 indicating the region with planer topography as indicated in the figure 5 below.

Table 2. DEM characteristics of Chennai; Source:Author

Range of elevation	Area (Sq. Km.)	Area (%)
-10 to 10	366.26	31%
10 - 20	436.41	36%
20 - 30	275.71	23%
30 - 60	116.70	10%
60 & above	2.48	0%

Geology

Geology is the scientific study of the Earth, including its materials, processes, physical characteristics, and history. This field encompasses the analysis of minerals, rocks, and fossils to understand the Earth's composition and the processes that have shaped its structure over geological time. Approximately 60% of the Chennai basin is characterized by sedimentary formations, while the remaining 40% consists of hard rock formations.The hard rock formations are predominant in the western and southeastern sectors of the basin. Biotite Hornblend gneiss and Epidote Hornblend gneiss are present in the western region, while charnockite is found in the southeastern part of the basin.

Table 3. Geological composition of Chennai; Source:Author

Type of Geology	Area (Sq.Km.)
Undiff.Fluvial / Aeolian / Coasta & Glacial Sediments,Quaternary	731.73
Upper Gondwana Gp. (Yerrapalli , Terani , Sriperumpudurf, Kota, Maleri, Fm.Etc),Triassic - Earl*	271.50
Lower Gondwana Gp.(Talchir,Barakar,Raniganj, Karharbari Fm.),Late Carboniferous - Permian	0.12
Charnockite Gneissic Complex (Southern Granulite Terrain),Archaean - Proterozoic	191.93

Rainfall

The rainfall map of the city indicates that the southern part of the city receives more rainfall as compared to the other parts of the city. On deeper analysis of the pattern of rainfall in the city, it is observed that the city receives majority of its rainfall from the north-east winds.

Geomorphology

Geomorphology is the study of the form of the earth and its evolution. The various types of geomorphological type found typically in the coastal regions of contains Older Deltaic plains, Active flood plain, Pediment Pedi plain complex, younger deltaic plain, younger coastal plain, older coastal etc. The geomorphology data was used in the analysis of type of flood inundation areas and groundwater recharge area delineation. The city geomorphological conditions indicate a major presence of older deltaic plains.

Table 4.Geomorphology of Chennai; Source:Author

Type	Area	Area(%)
Older Deltaic Plain	468.36	39%
Waterbodies - unclassified	119.73	10%
Active Flood Plain	33.82	3%
Pediment Pedi plain Complex	414.71	35%
Younger Deltaic Plain	7.93	1%
Younger Coastal Plain	106.67	9%
Older Coastal Plain	37.60	3%

Drainage density

Surface runoff is more prominent in areas with higher drainage density. These zones typically feature sparse to no vegetation, impermeable subsurfaces, and a high runoff potential (Kumar et al., 2007; Srivastava and Bhattacharya, 2006). The suitability of groundwater potential zones is inversely related to drainage density due to factors like permeability and runoff (Chowdhury et al., 2010). Higher drainage density indicates lower permeability, which reduces infiltration rates and increases surface runoff, especially in elevated regions. Consequently, areas with low permeability tend to have higher drainage densities, leading to less favorable conditions for groundwater potential.

As for the CMA, around 16% of the area majorly near the shore line and in central part is covered with the land having low drainage density whereas almost 52% is covered with region having low or moderate drainage density spread across all the city with appropriate distance from the waterbodies.

Table 5.Composition of drainage density in Chennai

Class of drainage density	**Area (Sq. Km.)**	**Area (%)**
Very low	186.49	16%
Low	314.14	26%
Moderate	312.11	26%
High	264.94	22%
Very High	117.61	10%

NDVI

NDVI parameter is related to the proportion of photosynthetically absorbed radiation. An NDVI value close to zero indicates the absence of green vegetation, while values nearing 0.8–0.9 suggest the presence of dense green leaves. NDVI is calculated on a per-pixel basis as the normalized difference (Patra and Mishra, 2018).

NDVI = (NIR−RED)/(NIR + RED)

The normalized difference vegetation index (NDVI) map indicates the extent of vegetation cover. Areas with negative NDVI values, which represent bare land, are more susceptible to flooding and have poor groundwater potential. Vegetation enhances infiltration capacity, so positive NDVI values correspond to areas with shrubs and forest cover. In Chennai city, most of the land is covered by settlements, leading to negative NDVI values. Observations show that over half of the study area (56%) has very low negative NDVI values, indicating very low water resilience.

Table 6. NDVI classification and area; Source:Author

NDVI Range	**Area(Sq. Km.)**	**Area(%)**
-0.20 - 0.07	108.62	9%
0.07-0.16	390.15	33%
0.16-0.27	504.51	42%
0.27-0.4	169.68	14%
0.4-0.72	22.36	2%

Lineament density

It represents the geological structures of an area and identify the faults and fractures which plays a key role in infiltartion of surface water into aquifiers thus increasing the groundwater recharge potentiality. It can be duly noted that majority of the high lineamnet density is found in the eastern side of the city depicting a higher recharge potential. This area also is validated with the acquifier region of the city.

Table 7.Composition of lineament density in Chennai

Lineament density cat.	Area (Sq. Km.)	Area(%)
Very Low	553.184667	46%
Low	191.947205	16%
Moderate	326.504692	27%
High	87.316404	7%
Very High	36.361421	3%

Slope

The slope plays an important role in demarcating the groundwater potential zones as it depicts the rise and fall in the land surface. For CMA, the slope ranges from 0 degrees to 39 degrees which is categorised in different classes as mentioned in the map. The angle between 1.5 to 3.1 degrees covers an area of almost 44% while slope ranging from 0 to 1.5 degrees is spread in the area with 36% coverage. This indicates the low slope the area possess which is suitable for the groundwater recharge potential and hence the preferential or the capacity of the city to absorb the water without discharging the water in runoff.

Table 8.Slope categories in CMA; Source:Author

Degree slope	Area(Sq. Km.)	Area(%)
0-1.5	424.79	36%
1.5 - 3.1	524.76	44%
3.1-5.6	218.91	18%
5.6-12.9	15.83	1%
12.9-39	3.48	0%

Distance from road and waterbodies

According to the regulations set by the Ministry of Environment and Forests, a 500-meter distance from water bodies and wetlands is classified as a sensitive zone. Approximately one-third of the total area (33.23%) falls within this sensitive zone as evident in the figure below. Additionally, nearly half of the area (48.88%) is considered to have moderate water resilience, while about one-fifth (17.90%) is classified as having high water resilience.

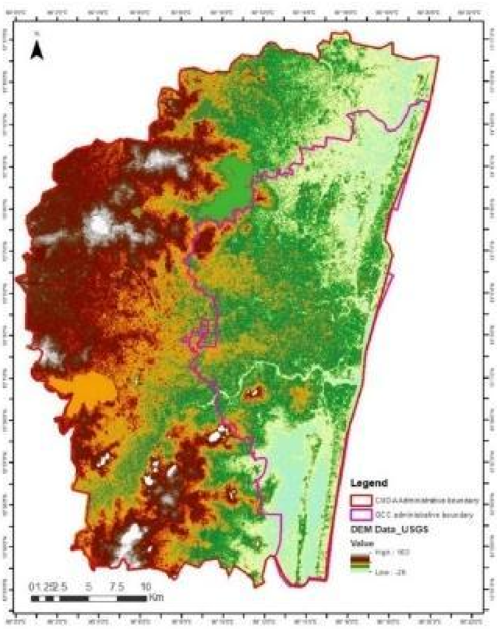
The distance from the road in a flood vulnerability map is an important parameter because it indicates the accessibility and impact of flooding on infrastructure and human activities. Proximity to roads can mean higher exposure to floodwaters due to impervious surfaces, leading to faster runoff and accumulation of water. This parameter helps in planning flood mitigation strategies, ensuring essential services and evacuation routes remain protected and accessible during floods.

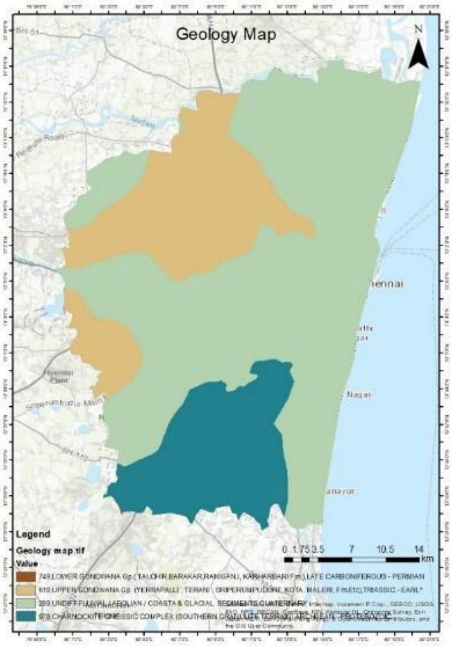
LULC data

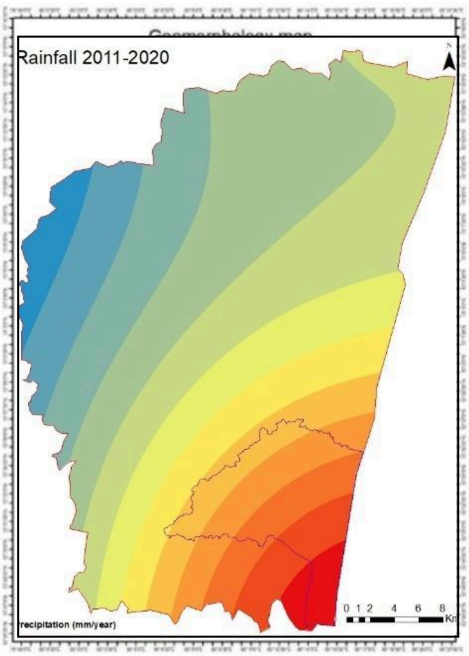
The landcover data was acquired from USGS (U.S. Geological Survey) which monitors, analyzes, and predicts interactions within the Earth's systems, providing actionable information at scales and timeframes that are relevant to decision makers. The LULC produced used Sentinel-2 satellite data. Supervised classification was done in which the LULC were classified into five major categories namely- Water surface, Builtup, bareland,dense vegetation, Agricluture.The data so used is derived after filtering out the cloud cover percentage to 18-20%. Since the study involves analysing the data during pre and post monsoon scenarios from 1990 to 2024, all the data used were from Landsat satellite from different versions.

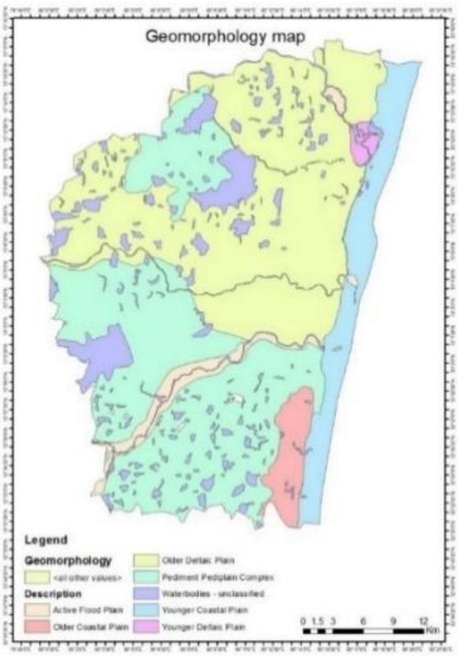
Table 9. LULC data collection; Source:Author

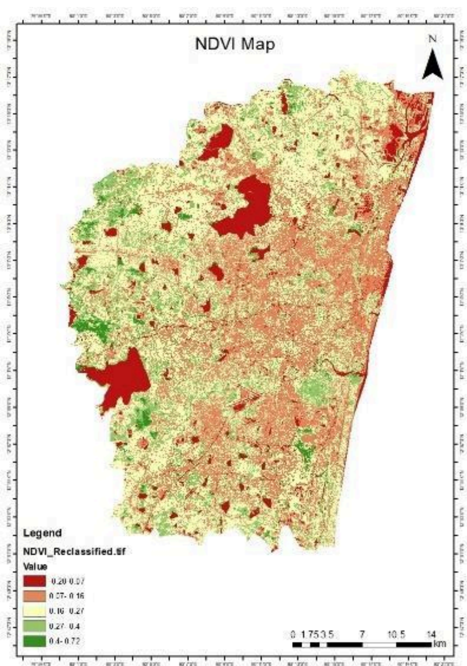
Sr. No.	Satellite/ Sensor ID	Spatial resolution/ Cell size(m)	Path/Row	Source
1.	Landsat 1-5 MSS C2 L1	30	142/51	USGS (C2 L1)
2.	Landsat 4-5 TM C2 L1	30	142/51	USGS (C2 L1)
3.	Landsat 8-9 OLI	30	142/51	USGS(C2 L1)

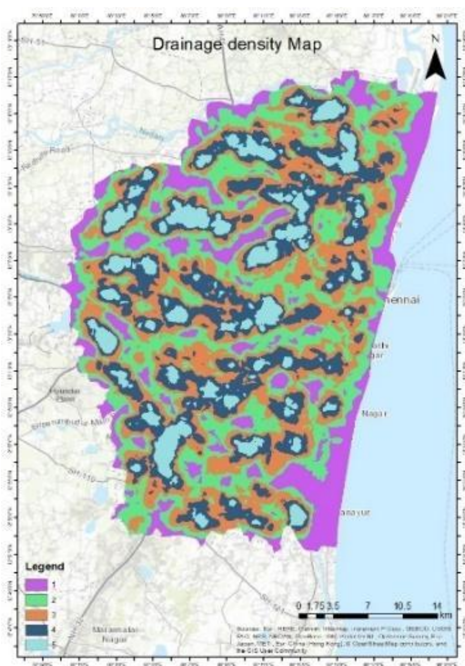

Legend
CMDA Administrative boundary
GCC administrative boundary
DEM Data_USGS
Value
High : 903
Low : -26
0 1.25 2.5 5 7.5 10
Km

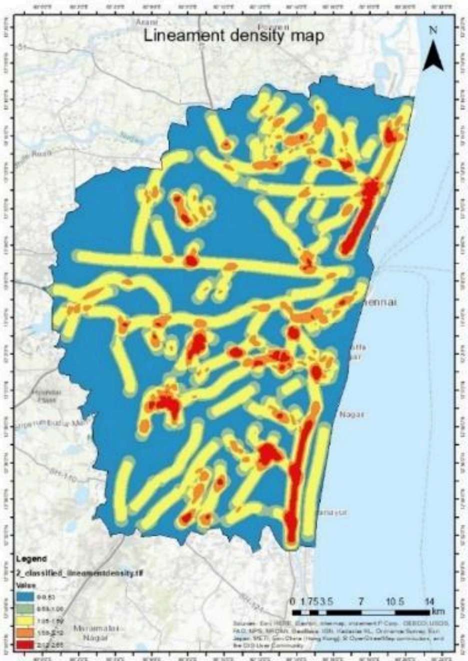

Geology Map
Legend
Geology map.tif
Value
0 1.75 3.5 7 10.5 14
km

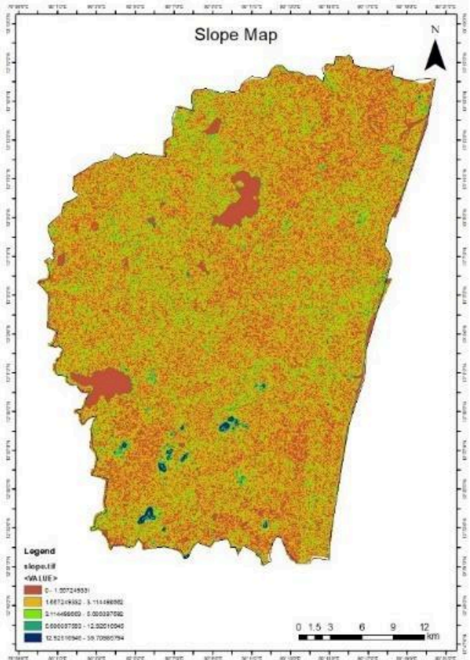

Rainfall 2011-2020
recipitation (mm/year)
0 1 2 4 6 8
Km

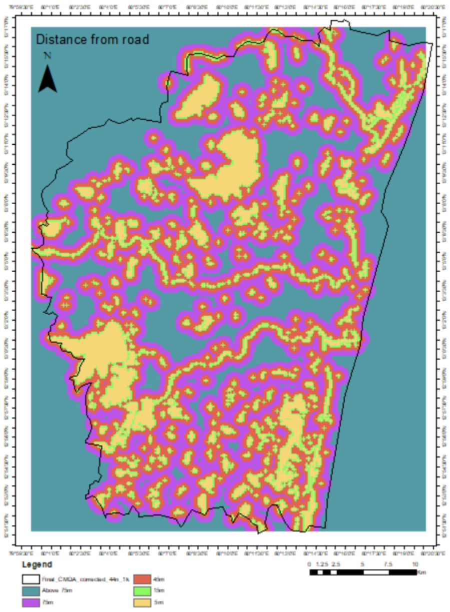

Geomorphology map
Legend
Geomorphology
<all other values>
Description
Active Flood Plain
Older Coastal Plain
Older Deltaic Plain
Pediment Pediplain Complex
Waterbodies - unclassified
Younger Coastal Plain
Younger Deltaic Plain
0 1.5 3 6 9 12
Km

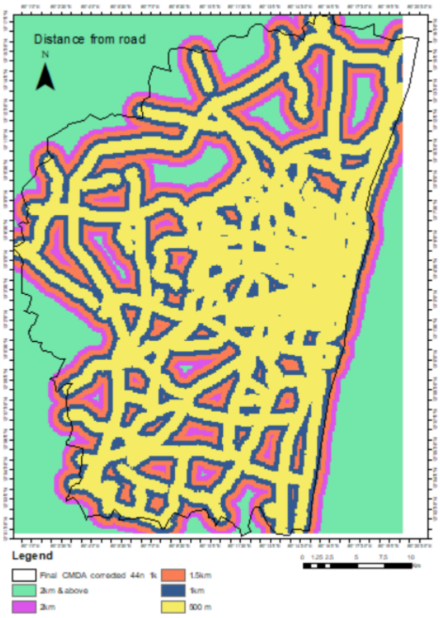

NDVI Map
Legend
NDVI_Reclassified.tif
Value
0 1.75 3.5 7 10.5 14
km

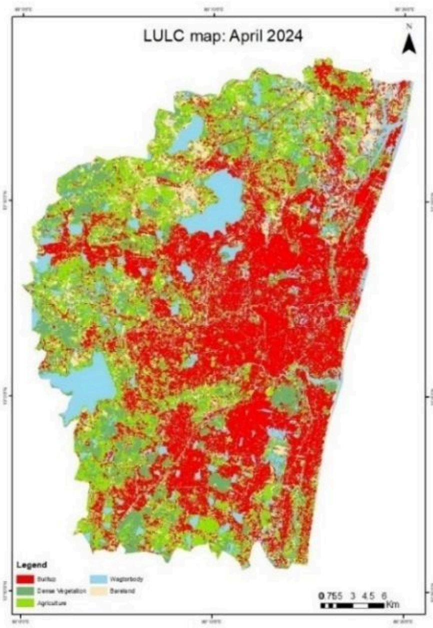

Drainage density Map
Chennai
Legend
1
2
3
4
5
0 1.75 3.5 7 10.5 14
km


Lineament density map
N
Chennai
Legend
2_classified_lineamentdensity.tif
Value
0 1.75 3.5 7 10.5 14
km


Slope Map
N
Legend
slope.tif
<VALUE>
0 1.5 3 6 9 12
km


Distance from road
N
Legend
Final_CMDA_corrected_44n_1k
Above 75m
75m
45m
15m
5m
0 1.25 2.5 5 7.5 10
Km


Distance from road
N
Legend
Final_CMDA corrected 44n 1k
2km & above
2km
1.5km
1km
500 m
0 1.25 2.5 5 7.5 10
Km


LULC map: April 2024
N
Legend
Builtup
Dense Vegetation
Agriculture
Wagterbody
Bareland
0.75 1.5 3 4.5 6
Km

V. Data Analysis

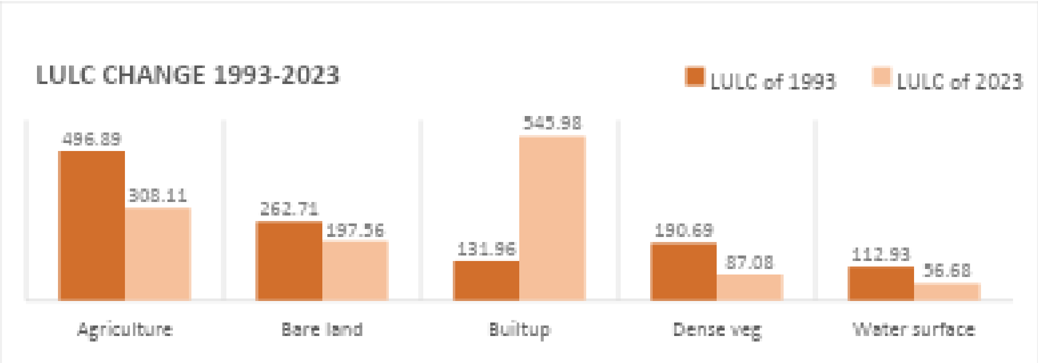
Land use landcover change of Chennai over the years

To analyze the causes and the gravity of the hydrological issues in the city, a proper understanding of the city's natural and man-made characteristics are evaluated. This includes analysing the LULC changes of the city over the years and the way it affected the city's capability to deal with the hydrological aspects and eventually its resilience.

Chennai, one of the most populated cities in South India, has experienced significant land use and land cover (LULC) changes between 1993 and 2023. These years are chosen due to absence of any hydrological event in its previous years which would help ascertain a true picture. Both the years 1992 and 2022 oversaw normal average rainfall. During the span of 3 decades, agricultural land decreased by 188.78 km², and bare land diminished by 65.15 km², indicating urban expansion into previously unused areas. Concurrently, the built-up area increased by 414.02 km², driven by population growth and industrial and commercial development. This urbanization led to a reduction in dense vegetation by 103.61 km² and a decrease in water surface area by 56.25 km².

The correlation between the increase in built-up areas and the reduction in green and water spaces suggests a pattern of unplanned development that has compromised natural landscapes. This encroachment on water bodies and vegetative areas is particularly concerning as it exacerbates the city's vulnerability to hydrological disasters. The loss of natural buffers such as vegetation and wetlands reduces the city's capacity to manage stormwater, leading to increased flooding risks. Furthermore, the reduction in water surfaces impacts the natural drainage systems, contributing to waterlogging and urban floods.

In conclusion, the LULC changes in Chennai over the past three decades, marked by increased unplanned built-up areas at the expense of agricultural, vegetative, and water surfaces, have significantly heightened the city's susceptibility to hydrological disasters.



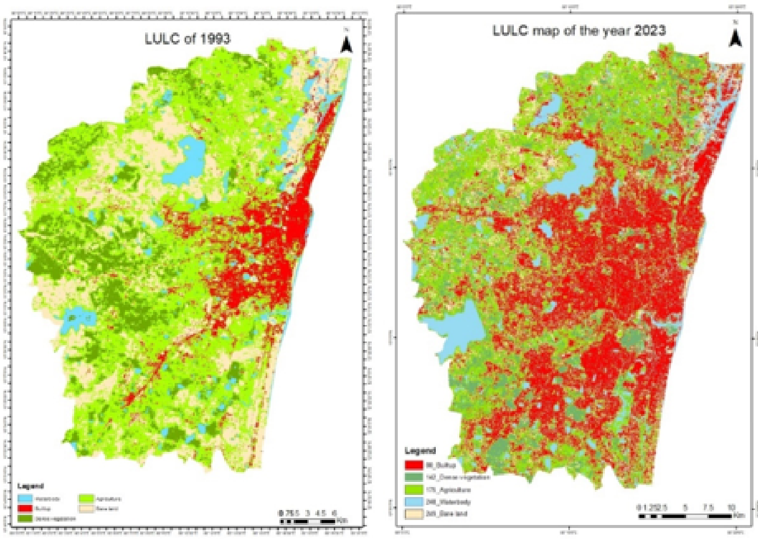


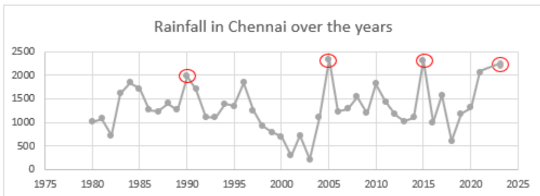
Figure 7. LULC of 1993(L) & 2023(R)

The city's expansion has been directed towards the west and south, incorporating various villages and altering the natural topography, often encroaching on water bodies and floodplains. These changes underscore the extensive urban growth at the cost of agricultural land, vegetation, and water bodies, highlighting the need for balanced urban planning to mitigate environmental impacts.

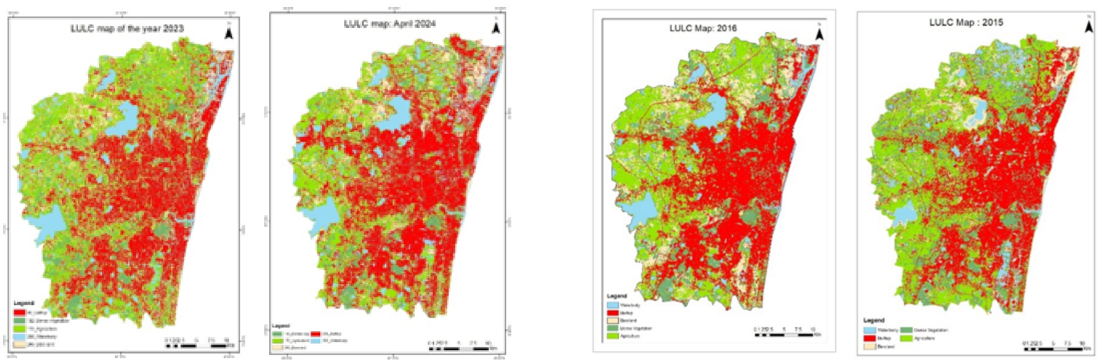
Pre- monsoon and post monsoon LULC changes

Chennai, with its flat terrain, typically receives an average annual rainfall of about 1300mm. However, uncertainties in the northeast monsoon winds, exacerbated by climate change from September to December, heighten the city's flood risk, especially with additional rainfall from southwest winds in August and September. To understand the impact, rainfall data from flood years, both pre-monsoon and post-monsoon, were analyzed, highlighting the correlation between high rainfall and flooding in the city.The years taken for detailed pre and post monsoons includes:

1. 2023 & 2024 for floods of Nov-Dec 2023
2. 2015 & 2016 for floods of Dec 2015
3. 2005 & 2006 for floods of Nov-Dec 2005
4. 1990 & 1991 for floods of Dec. 1990



The figure below illustrates the temporal changes in Land Use Land Cover (LULC) across various periods in Chennai, segmented by specific months and seasons (pre- and post-monsoon) from 1990 to 2024. The categories include Agriculture, Bare Land, Built-up, Dense Vegetation, and Waterbody. Analyzing this data reveals significant trends that underscore the impacts of unplanned urban development on the city's hydrology and environmental health. The data provides valuable insights into the complex dynamics of LULC changes in the CMDA area over time, reflecting the multifaceted interactions between natural processes and human activities.



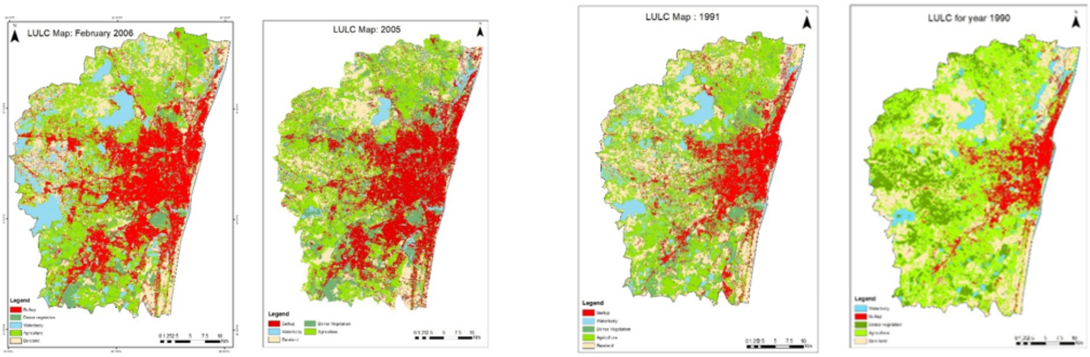
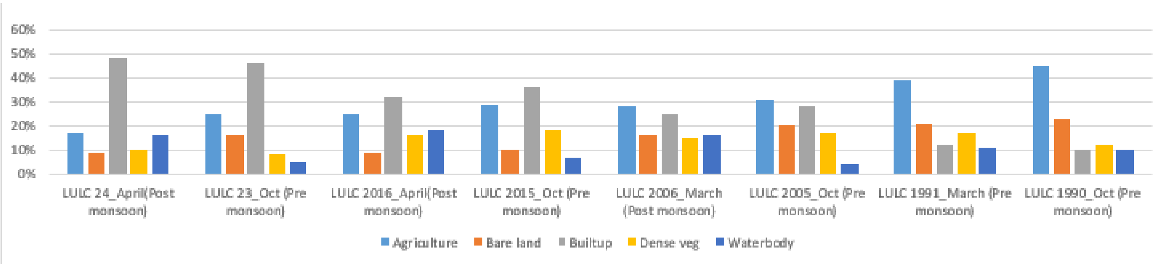


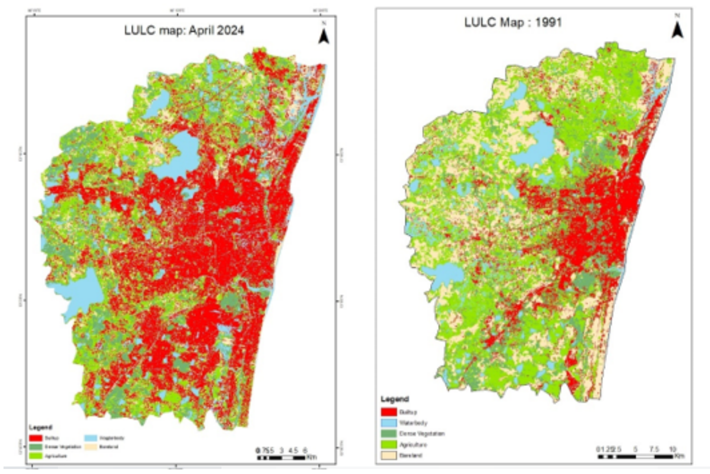
Figure 8.LULC change over the years pre and post monsoons for the years 2024&2023, 2016&2015, 2006&2005, 1990 & 1991; Source: Author



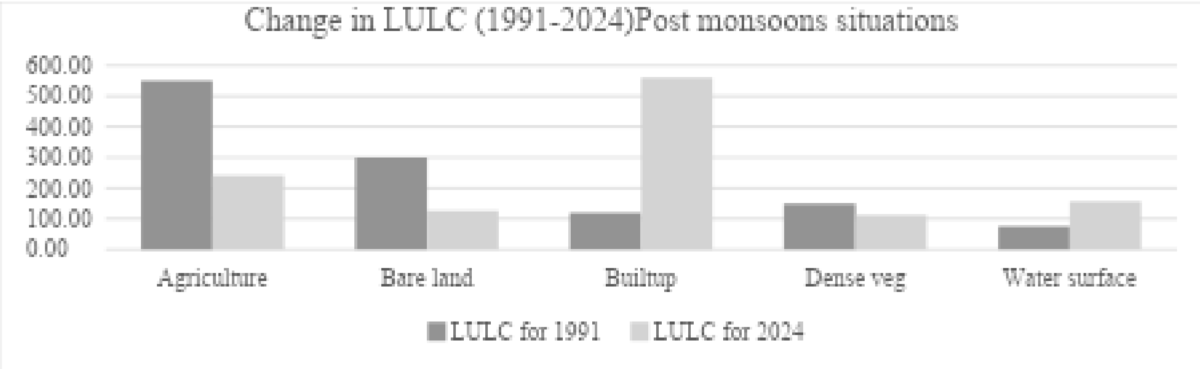
The analysis of Land Use and Land Cover (LULC) in Chennai from 1990 to 2024 shows significant shifts in land utilization. Agricultural land decreased from 537.83 km² (45%) in 1990 to 203.18 km² (17%) in 2024, indicating a shift towards urban development. Bare land declined from 274.89 km² (23%) to 107.57 km² (9%), suggesting extensive land development. Built-up areas dramatically increased from 119.52 km² (10%) in 1990 to 573.69 km² (48%) in 2024, reflecting rapid urbanization. Dense vegetation decreased from 203.18 km² (17%) in 1990 to 119.52 km² (10%) in 2024 due to urban encroachment. Water surfaces fluctuated, initially at 119.52 km² (10%) in 1990, peaking at 215.13 km² (18%) in 2016, and reducing to 191.23 km² (16%) by 2024, highlighting water management issues and urban spread.Hence it can be seen that whereby in 1990 (October), agriculture and waterbodies occupied a substantial proportion of the land, by 2024 (April), built-up areas dominate, with noticeable reductions in both waterbodies and dense vegetation.

This trend highlights the encroachment of green and blue spaces due to unplanned urban expansion. The significant reduction in waterbodies indicates compromised natural drainage and retention systems, while the decline in dense vegetation further disrupts ecological balance and groundwater recharge, increasing flood risks. The conversion of agricultural and vegetative land to urban areas reduces rainfall absorption, leading to higher surface runoff and flooding, particularly evident in post-monsoon periods where built-up areas have replaced natural landscapes, diminishing resilience to heavy rains and hydrological events.

1991-2024 LULC Changes during post monsoon scenarios with similar rainfall.



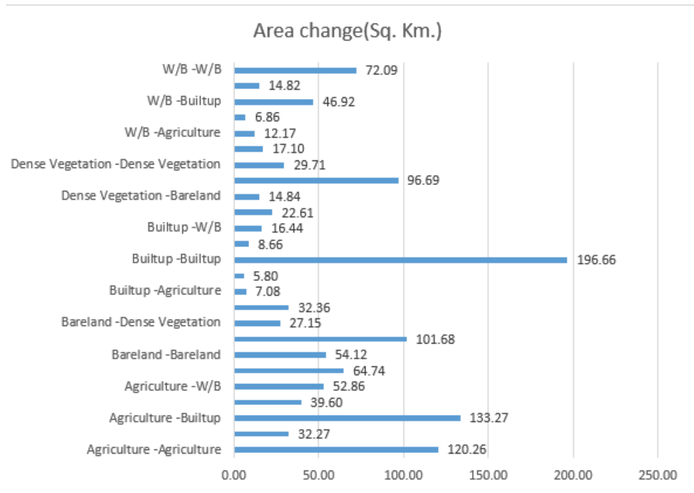
The post-monsoon scenarios of 1990 and 2023, with equivalent rainfall, were compared to analyse changes in Chennai's capacity to absorb rainfall of same amount and intensity. Complex flood situations occurred in November and December of both years, so data for 1991 and 2024 were assessed. The land use and land cover analysis of 1991 and 2024 over 1194.74 Sq. Km revealed significant transformations. There was substantial urbanization, a reduction in water bodies, and a shift from agriculture and bare land to built-up areas, reflecting the city's adaptation to rising population demands.



CMDA	LULC 24_April (Post monsoon)		LULC 1991_March (Post monsoon)	
	Area	%	Area	%
Agriculture	203.18	17%	466.12	39%
Bare land	107.57	9%	250.99	21%
Builtup	573.69	48%	143.42	12%
Dense veg	119.52	10%	203.18	17%
Water surface	191.23	16%	131.47	11%

Despite similar rainfall in both years, the post-monsoon water-covered area differed greatly. Research and surveys show a significant reduction in water bodies, yet an increase in water surface area. This rise is due to water accumulating outside original water bodies, caused by more non-porous surfaces and encroachment on water channels connecting Chennai's drainage system. Consequently, the city's capacity to absorb water has diminished, even though nearly 50% of its water demand is met by groundwater from borewells.

The analysis of land use changes in Chennai from 1991 to 2024 reveals significant shifts primarily driven by urbanization. A notable 133.26 sq. km of agricultural land converted to built-up areas, reflecting rapid development. The transformation of 52.85 sq. km of agricultural land to water bodies, primarily due to increased non-porous surfaces from urban expansion, suggests inadequate drainage leading to water accumulation and flooding. Additionally, built-up areas expanded significantly, while dense vegetation and water bodies decreased, indicating a loss of natural resources. These changes underscore the need for sustainable urban planning to balance development and environmental conservation, ensuring the protection of water bodies and natural habitats amidst urban growth.



Flood Inundation map

For a more detailed analysis of the effect of built-up over the waterways and waterbodies, flood inundation map for the year of 1990 and 2023 were made using several parameters such as elevation, rainfall, slope, distance from road, distance from waterbody, drainage density, Land use Landcover. The maps so generated was then overlayed through assigning weights, each category having its own weightage. The weightage given to each of the parameters are:

Table 10. Parameters and its weightage for flood inundation map; Source: (Kaaviya and Devadas, 2021)

Parameter	Type	Risk value	Weightage
LULC	Water surface	5	10
	Built-up	4	
	Bare land	3	
	Dense vegetation	1	
	Agriculture	2	
Slope	0-1.5	5	10
	1.5 - 3.1	4	
	3.1-5.6	3	
	5.6-12.9	2	
	12.9-39	1	
Drainage Density(km/km2)	0.004–0.663	1	15
	0.663–1.1022	2	
	1.102–1.554	3	
	1.554–2.122	4	
	2.122–3.296	5	
Elevation	-10 to 10	5	15
	10 - 20	4	
	20 - 30	3	
	30 - 60	2	
	60 & above	1	
Rainfall	280-366 mm	1	25
	366-452	2	
	452- 539	3	
	539- 625	4	
	625- above	5	
Distance from road	0.5km	5	5
	1km	4	
	1.5 km	3	
	2km	2	
	2km & above	1	
Distance from waterbodies	5m	5	20
	15m	4	
	45m	3	
	75m	2	
	75m & above	1	

The flood inundation maps for 1991 and 2024 reveal a significant increase in vulnerable zones experiencing flood inundation, despite consistent rainfall levels. With urbanization and changing rainfall patterns due to climate change, the city now faces flash floods with heavy rainfall over short periods, exacerbated by encroachment on drainage channels.

The table below compares flood risk assessments for 1991 and 2024, showing a stark increase in high-risk zones. In 1991, 225 sq. km were in the low inundation zone, 943 sq. km (80% of CMDA) were in low-risk areas, and only 16 sq. km (1%) faced moderate inundation. By 2024, almost half the city fell into high-risk zones, with 209.82 sq. km (18% of CMDA) in very high-risk areas. The low inundation zones decreased from 80% to 6%, highlighting the city's growing flood vulnerability.

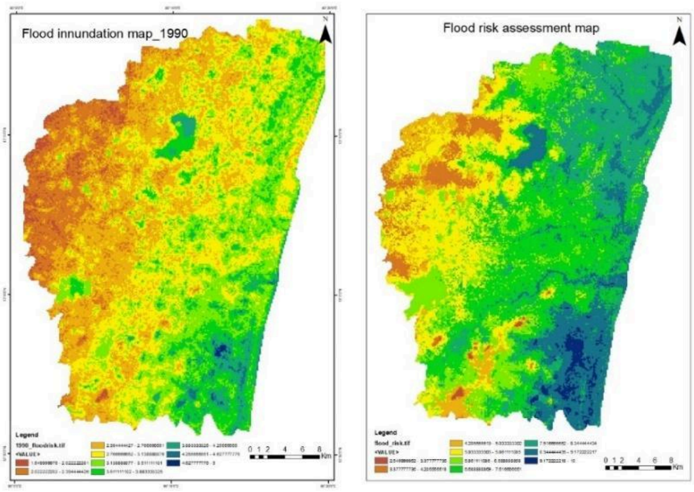
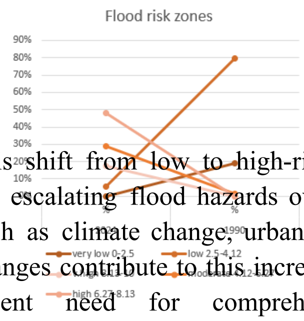


Figure 6. Flood inuundation map for 1990 and 2024

Table 11. Change in the flood innundation zones in Chennai; Source:Author

Risk category zone	Range (m)	1991		2024	
		Area	%	Area	%
Very low	0-. 25	225.01	19%	0	0%
Low	.25-.412	943.62	80%	67.08	6%
Moderate	.412-.627	16.29	1%	340.49	29%
High	.627-.813	0	0%	565.17	48%
Very high	.813-1.0	0	0%	209.82	18%



This shift from low to high-risk areas underscores the escalating flood hazards over 33 years. Factors such as climate change, urbanization, and land use changes contribute to this increased risk. There is an urgent need for comprehensive flood risk management strategies, including improved infrastructure, better drainage systems, and proactive planning to mitigate flood risks and protect vulnerable areas.

Groundwater recharge potential zone

Groundwater potential recharge zones were demarcated through help of AHP by assigning weightage to different parameters such as given in the table below. The weightage for these parameters were obtained through various research papers on the same regions with the plain terrain and geology and geomorphological conditions.

Table 12. Weightage of parameters for groundwater map; Source: Sajil.L.and Elango, 2022)

Parameter for recharge zone	Type	Potentiality	Ranking	Weightage
LULC	Water surface	Vert high	5	20
	Built-up	Low	2	
	Bare land	Medium	3	
	Dense vegetation	High	4	
	Agriculture	High	4	
Slope	0-1.5	Very high	5	3
	1.5 - 3.1	Very high	5	
	3.1-5.6	Medium	3	
	5.6-12.9	Medium	3	
	12.9-39	Low	1	
Drainage Density(km/km2)	0.004–0.663	Very low	1	6
	0.663–1.1022	low	2	
	1.102–1.554	Medium	3	
	1.554–2.122	High	4	
	2.122–3.296	Very high	5	
Geomorphology	Older Deltaic Plain	Very high	5	28
	Waterbodies	Very high	5	

	Active Flood Plain	Very high	5	
	Pediment Pedi plain	Medium	3	
	Younger Deltaic Plain	Very high	5	
	Younger Coastal Plain	Very low	1	
	Older Coastal Plain	Low	2	
Geology	Charkonite	Medium	3	13
	Upper Gondwana	Low	2	
	Lower Gondwana	Low	2	
	Aluvial	Very high	5	
Soil type	Sand	Very high	5	8
	Laterite and sandstone	High	4	
	Shale	Low	2	
	Hard rock	Medium	3	
	Clay and Shale	Very low	1	
	Clay	Very low	1	
Lineament density	0–0.70	Very low	1	17
	0.70–1.40	Low	2	
	1.40–2.11	Medium	3	
	2.11–2.81	High	4	
	2.81–3.52	Very high	5	
Rainfall	280-366 mm	Very low	1	4
	366-452	Low	2	
	452- 539	Low	2	
	539- 625	Medium	3	
	625- 711	High	4	

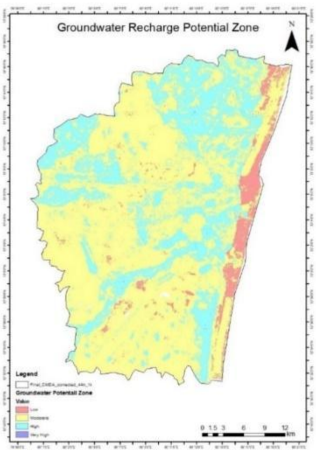
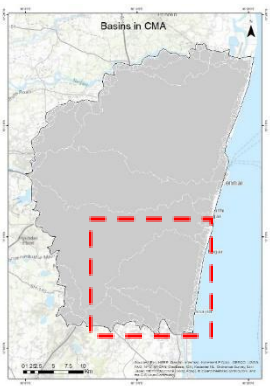


Figure SEQ Figure * ARABIC 9. Groundwater potential recharge zone in Chennai; Source: Author

The shoreline area has low recharging capacity, covering 58 sq. km (5% of CMA). In contrast, the central, western, northern, and southern areas, with varied soil and geological conditions, have moderate recharging capacity, totaling 770 sq. km (65% of CMA). High recharging potential is found in the western and southern regions, covering 331 sq. km (28% of CMA), including the southwestern floodplains and the Pallikarnai marshland.

Category	**Area (Sq. Km.)**	**Area (%)**
Low	58.20	5%
Moderate	770.80	65%
High	331.20	28%
Very high	20.22	2%

To analyse in a more detailed manner the effect of LULC changes on water handling capacity of the lakes and basin a whole, Pallikarnai basin was taken for the further studies. This approach deals with the Macro to micro level approach. The Pallikaranai marshland basin covers an area of 116.22 Sq. Km. and is located in the southern part of Chennai near the shore. Anchored with IT hubs and SEZ, the area encloses marshland declared as RAMSAR site of 7.2 Sq. km (remaining). The drainage pattern shows that the flow of all the water in the basin drains into the marsh.



Premonsoon and post monsoon scenarios of the basin was analysed to find out the reason for frequent occurrence of floods and water scarcity in the area.

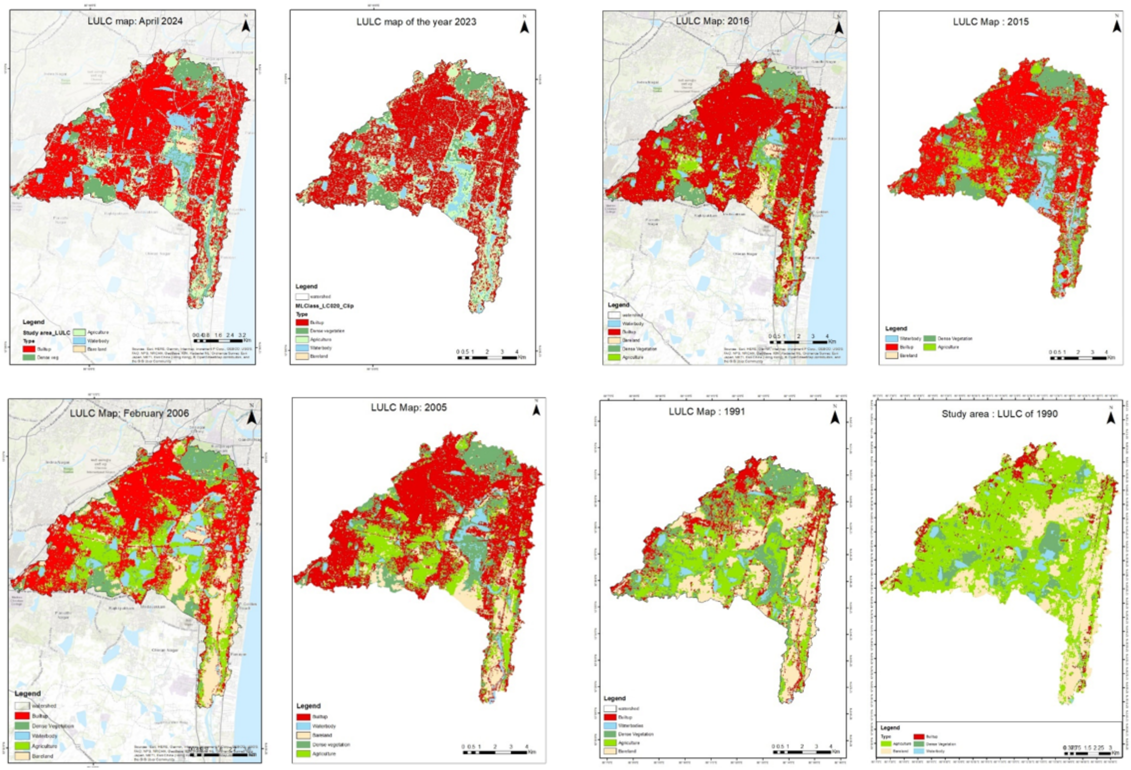


Table 13. LULC changes pre and post monsoon scenarios in Pallikarnai Basin; Source:Author

Study Area	LULC 24_April (Post monsoon)		LULC 23_Oct (Pre monsoon)		LULC 2016_April (Post monsoon)		LULC 2015_Oct (Pre monsoon)		LULC 2006_March (Post monsoon)		LULC 2005_Oct (Pre monsoon)		LULC 1991_March (Pre monsoon)		LULC 1990_Oct (Pre monsoon)	
	Area	%	Area	%	Area	%	%	%	Area	%	Area	%	Area	%	Area	%
Agriculture	6.00	5%	13.68	12%	13.08	11%	19.94	17%	25.33	22%	28.64	25%	53.89	46%	61.36	53%
Bare land	11.22	10%	13.39	11%	5.65	5%	10.25	9%	13.00	11%	16.14	14%	24.244	21%	29.00	25%
Built up	72.18	62%	76.19	65%	59.93	52%	63.48	54%	45.53	39%	49.37	42%	13.288	11%	8.01	7%
Vegetation	12.10	10%	9.36	8%	21.65	19%	16.20	14%	21.52	18%	16.98	15%	14.831	13%	9.00	8%
Water Surface	15.68	13%	4.03	3%	16.02	14%	6.62	6%	11.19	10%	5.40	5%	10.255	9%	9.20	8%

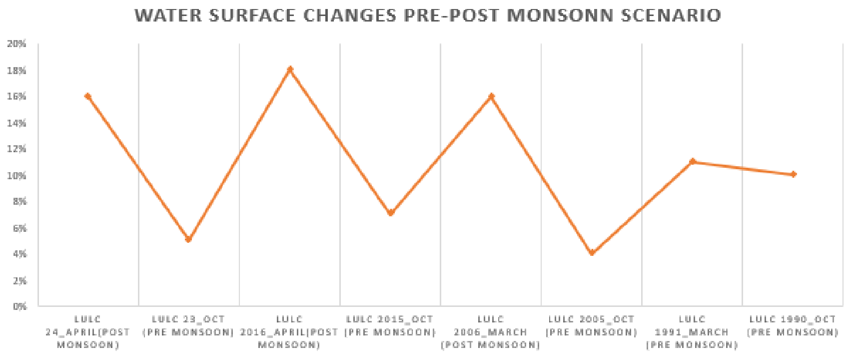
The Land Use and Land Cover (LULC) analysis of Chennai from 1990 to 2024 reveals significant shifts, particularly driven by rapid urbanization and its impact on natural resources.

Agricultural Land:There was a notable decrease in agricultural land post-monsoon, from 53% (61.36 Sq. km) in October 1990 to 46% (53.89 Sq. km) by March 1991, continuing to 12% (13.68 Sq. km) in October 2023 and further reducing to 5% (6.00 Sq. km) by April 2024. This reduction is due to urban encroachment and conversion for extracting groundwater, which gets flooded during monsoons.

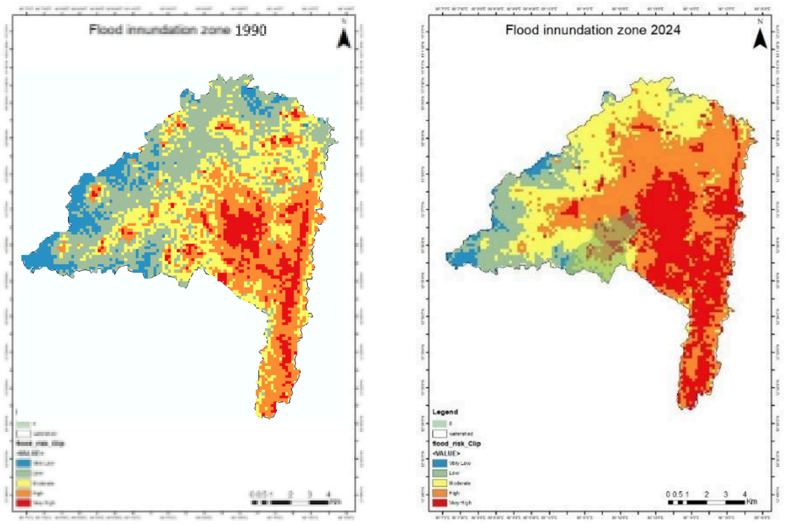
Bare Land:Bare land also saw a decrease post-monsoon, from 25% (29.00 Sq. km) in October 1990 to 21% (24.244 Sq. km) by March 1991, and from 14% (16.14 Sq. km) in October 2005 to 11% (13.00 Sq. km) in February 2006. The trend continues to 11% (13.39 Sq. km) in October 2023 to 10% (11.22 Sq. km) in April 2024. This reduction indicates the conversion of bare land to vegetative or agricultural land due to flooding.

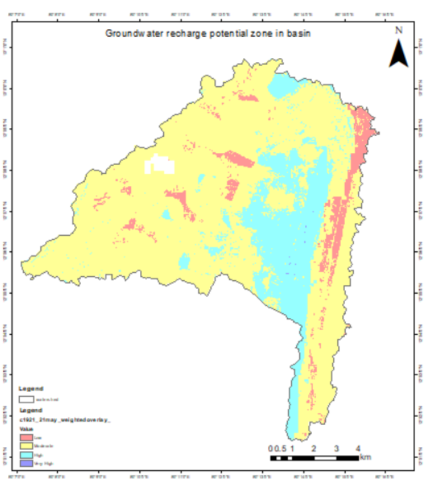
Built-up Areas: Built-up areas showed rapid urban growth despite flood damage. From 7% (8.01 Sq. km) in October 1990 to 11% (13.288 Sq. km) by March 1991, and from 42% (49.37 Sq. km) in October 2005 to 39% (45.53 Sq. km) in February 2006, the trend continued to 65% (76.19 Sq. km) in October 2023, reducing slightly to 62% (72.18 Sq. km) in April 2024. This rapid urbanization, largely unplanned, has led to significant flooding in areas where construction has encroached on water bodies.

Dense Vegetation: Dense vegetation increased post-monsoon, indicating regrowth. From 8% (9.00 Sq. km) in October 1990 to 13% (14.831 Sq. km) by March 1991, and from 15% (16.98 Sq. km) in October 2005 to 18% (21.52 Sq. km) in February 2006, the trend continued to 8% (9.36 Sq. km) in October 2023 to 10% (12.10 Sq. km) in April 2024.
Water Bodies: Water bodies experienced significant reductions, with a large portion converted to built-up areas and agriculture. From 46.92 Sq. km converted to built-up areas and 12.16 Sq. km to agriculture, it highlights the pressure of urban expansion on natural water resources. Additionally, 6.85 Sq. km became bare land, indicating potential environmental degradation.



The Land Use and Land Cover (LULC) analysis of Chennai from 1990 to 2024 reveals significant trends in different categories. Agricultural land consistently decreased post-monsoon, highlighting adverse flooding effects and urban encroachment. Bare land also saw a reduction post-monsoon, indicating its conversion to vegetative or agricultural land. Built-up areas showed rapid urban growth but faced flood damage, reflecting unplanned expansion. Dense vegetation increased post-monsoon due to regrowth. These changes emphasize the need for better urban planning and sustainable development to mitigate flooding and preserve natural resources.
This overall scenario have led to the shift of the resiliency of area from low flood risk zone to area with high inundation.



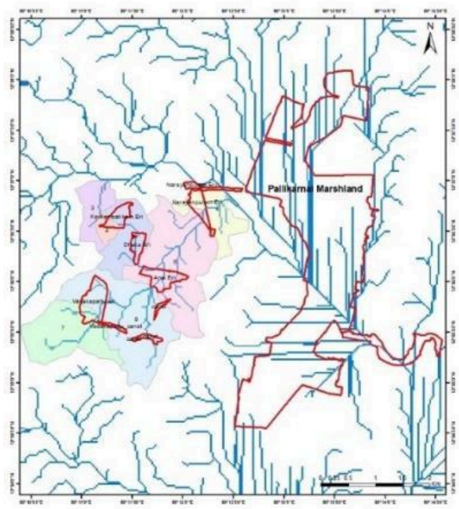


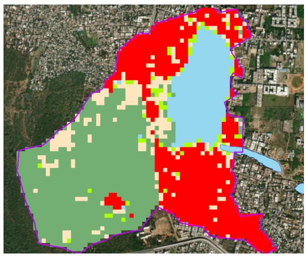
This above scenario is happening whereby majority i.e almost 88 Sq. Km. of the whole basin area of ground which amounts to 116 Sq. Km is covered with moderate zone to absorb and recharge the groundwater.

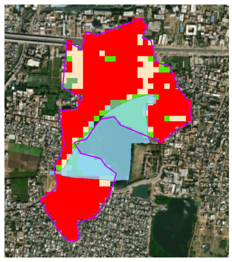
Table 14. Groundwater potential recharge zone in basin

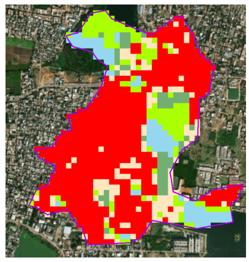
Potential zone	Area	Area %
Low	6.9	6%
Moderate	88.18	75%
High	22.4	19%
Very high	0.5	.42%

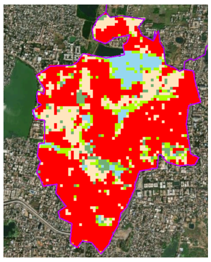
Lake catchment scenario

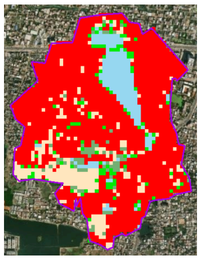












Type of landuse	**Vadakapaatu Eri catchment**		**Kovilambakkam Eri catchment**		**Dhaka Eri catchment**		**Anai Eri catchment**		**Narayanpuram Eri catchment**	
	Area (km2)	**%**	**Area**	**%**	**Area**	**%**	**Area**	**%**	**Area**	**%**
Agriculture land	0.085	7%	0.0492	11%	0.096	11%	0.518	20%	0.276	14%
Builtup	0.743	64%	0.0301	70%	0.505	60%	1.754	65%	1.427	72%
Dense vegetation	0.145	13%	0.008	2%	0.013	2%	0.063	2%	0.043	2%
Hyacinth/ Light vegetation	0.08	7%	0.048	11%	0.047	6%	0.092	3%	0.060	3%
Water	0.104	9%	0.020	5%	0.183	22%	0.249	9%	0.176	9%

Taking a case example of one waterbody among the various waterbodies that sustains the city of Chennai, it is evident the waterbodies are being encroached upon within its reserve of the revenue boundaries in Chennai. This have increased the flooding as well as the vulnerability index of Chennai as a whole in view of its ability to mitigate the floods as well as the water scarcity with the continuous increasing impervious surfaces.

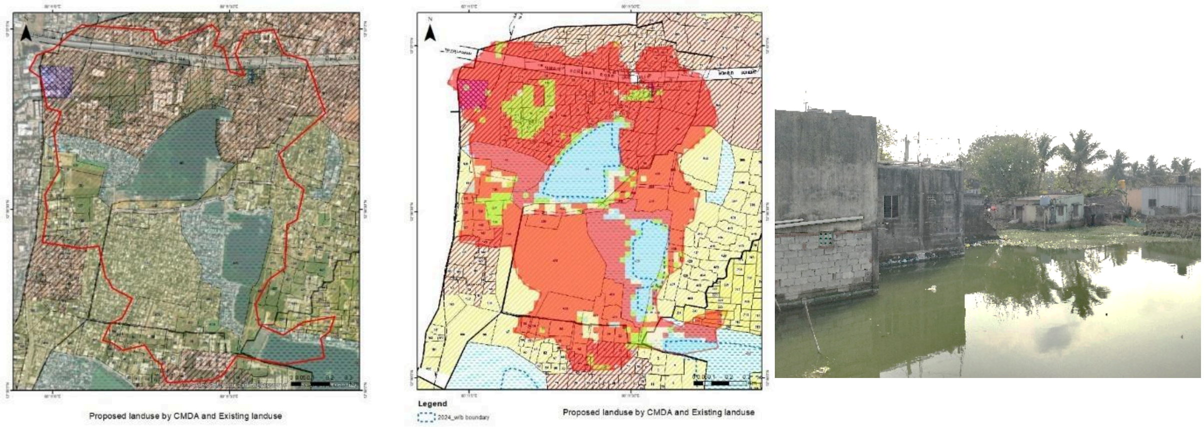


Figure 14.The proposed landuse by the CMDA and the existing landuse

Upon detail observation of the past connection of this waterbody, it was observed that the eri shared a same past whereby the 2 distinct eri with road in between them was previously one huge waterbody holding not only water but supporting the biodiversity of many aquatic and other species as a whole.

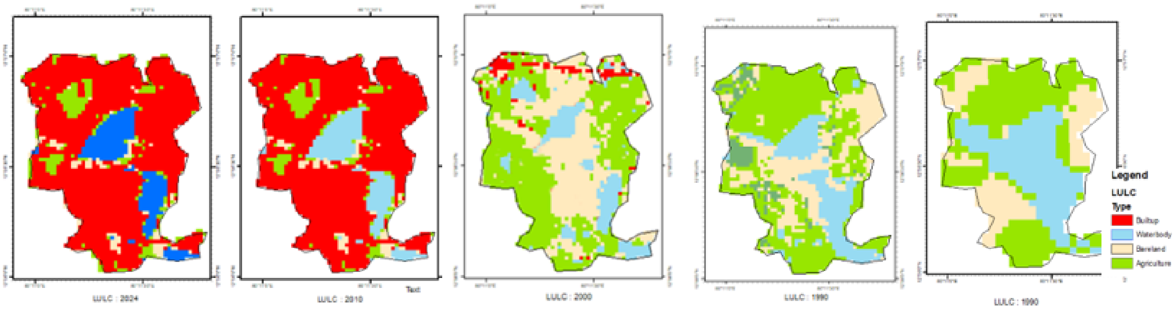


Figure 15Changes in the waterbody area over the years; Source:Author.

VI. Conclusion

The research underscores the critical impact of unplanned urbanization on the hydrological features of Chennai, particularly focusing on the encroachment of waterbodies and green areas. The analysis reveals that rapid urban expansion has significantly transformed the city's land use, reducing agricultural land, bare land, dense vegetation, and water surfaces while dramatically increasing built-up areas. This shift has compromised natural drainage and retention systems, leading to heightened flood risks and decreased groundwater recharge potential.

Chennai's historical reliance on a cascading network of water tanks, known as the "Eri" system, once provided a resilient framework for managing hydrological extremes. However, the neglect and encroachment of these water bodies due to urban sprawl have diminished their effectiveness. The city's capacity to handle heavy rainfall and recharge groundwater has been severely affected, as evidenced by the increased frequency and severity of floods and droughts.

The comparative analysis of LULC changes from 1990 to 2024, particularly in pre- and post-monsoon scenarios, highlights the urgency of integrating sustainable urban planning with effective water management strategies. The transformation of natural landscapes into impermeable surfaces has reduced Chennai's resilience to hydrological events, necessitating a comprehensive approach to restore and manage its waterbodies.

The study advocates for a catchment-based approach to reviving the interconnected Eri system, emphasizing the need to trace and restore lost water bodies and their connections. This approach aims to mitigate the adverse effects of unplanned growth and enhance the city's ability to manage both excess and scarce water resources. Sustainable urban development, combined with effective risk and mitigation strategies, is essential for creating a resilient Chennai capable of withstanding future climatic and hydrological challenges.

All the above highlights the negative relationship between unplanned growth and hydrological disasters. Climate change is a global phenomenon which calls for a global effort to reduce the negative impacts of human activities but at the same time cities especially in the global south of which Chennai is a part of should brace themselves to face the external as well as internal impacts and results of it.

In conclusion, the research highlights the domino effect of unplanned urbanization on Chennai's hydrological systems, pressing the need for integrated planning and management practices to restore the city's natural water management capabilities and ensure long-term resilience against hydrological disasters.As Chennai continues to develop, it must adopt these strategies to ensure it becomes a model of urban resilience and sustainability, capable of withstanding the challenges posed by a changing climate.

VII. Recommendations and way forward

To address the complex challenges of Chennai's urban water management and enhance the resilience of the Eri system, a strategic and integrated response is essential. Establishing a unified water management authority will consolidate responsibilities across departments, ensuring cohesive and effective water management. Strengthening and enforcing legal frameworks to protect water bodies from encroachment and pollution, alongside implementing stricter penalties for non-compliance, are crucial steps. Improving data collection and analysis through continuous monitoring mechanisms and modern technologies like remote sensing and GIS will enable real-time data analysis and informed decision-making. Leveraging IoT and AI technologies can optimize water use and enhance disaster response strategies.

Community engagement and education are vital components, involving residents in conservation efforts through programs like 'Adopt a Lake' initiatives and educational workshops to raise awareness about water conservation and the impacts of climate change. Restoring degraded water bodies and developing new green spaces will enhance groundwater recharge and flood mitigation. Regular maintenance of existing infrastructure, such as desilting and repairing drainage channels, will ensure efficiency, particularly during monsoon seasons.

Shifting to localized, catchment-based management practices will better address the unique characteristics of each area, and integrating climate adaptation measures into all urban development plans will prepare the city for future risks. Sustainable funding mechanisms, including public-private partnerships, international grants, and central government schemes, will support large-scale infrastructure projects. Collaborations with academic and research institutions will bring scientific insights into planning and policy-making, ensuring that solutions are evidence-based and innovative.

Implementing these recommendations will require a commitment to adaptive management, where policies and practices are continuously refined based on ongoing research and the evolving urban and climatic landscape. By adopting these strategies, Chennai can not only mitigate its current environmental challenges but also pave the way for a sustainable and resilient urban future.

References:

Abebe, Y., Kabir, G., & Tesfamariam, S. (2018). Assessing urban areas vulnerability to pluvial flooding using GIS applications and Bayesian Belief Network model. *Journal of Cleaner Production*, *174*, 1629–1641. https://doi.org/10.1016/J.JCLEPRO.2017.11.066

Anil Agarwal and Sunita Narain. (n.d.). http://www.cseindia.org

AR5 Synthesis Report: Climate Change 2014 — IPCC. (n.d.). Retrieved December 9, 2023, from https://www.ipcc.ch/report/ar5/syr/

Bhagat, C., Misra, A., Mohapatra, P. K., Babu, D. S. S., & Kumar, M. (2022). Salinity and temperature profiling for the submarine groundwater discharge simulations: Quantification through heat and solute transport model. *Science of the Total Environment*, *807*. https://doi.org/10.1016/j.scitotenv.2021.151888

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

Dash, S., Shakyawar, S. K., Sharma, M., & Kaushik, S. (2019). Big data in healthcare: management, analysis and future prospects. *Journal of Big Data*, *6*(1). https://doi.org/10.1186/s40537-019-0217-0

Douglas, I., Alam, K., Maghenda, M., Mcdonnell, Y., Mclean, L., & Campbell, J. (2008). Unjust waters: Climate change, flooding and the urban poor in Africa. *Environment and Urbanization*, *20*(1), 187–205. https://doi.org/10.1177/0956247808089156

Four reasons to protect rivers. (n.d.).

Gould, J. (2015). Rainwater harvesting for domestic supply. In *Rainwater Harvesting for Agriculture and Water Supply* (pp. 235–268). Springer Singapore. https://doi.org/10.1007/978-981-287-964-6_8

Guo, R. (2021). Cross-border natural disaster and crisis management. *Cross-Border Resource Management*, 371–400. https://doi.org/10.1016/B978-0-323-91870-1.00012-4

Kaaviya, R., & Devadas, V. (2021a). Water resilience mapping of Chennai, India using analytical hierarchy process. *Ecological Processes*, *10*(1). https://doi.org/10.1186/s13717-021-00341-1

Kaaviya, R., & Devadas, V. (2021b). Water resilience mapping of Chennai, India using analytical hierarchy process. *Ecological Processes*, *10*(1). https://doi.org/10.1186/s13717-021-00341-1

Kansal, M. L., & Singh, S. (2022). Flood Management Issues in Hilly Regions of Uttarakhand (India) under Changing Climatic Conditions. *Water (Switzerland)*, *14*(12). https://doi.org/10.3390/W14121879

Krishna Kulkarni, I., & Pratap Singh, T. (2023). *Vulnerability and Impact Assessment of Land Subsidence using Persistent Scatterers Interferometry (PSI) for Chennai, India*. https://doi.org/10.21203/rs.3.rs-2719169/v1

Lagmay, A. M. F., Agaton, R. P., Bahala, M. A. C., Briones, J. B. L. T., Cabacaba, K. M. C., Caro, C. V. C., Dasallas, L. L., Gonzalo, L. A. L., Ladiero, C. N., Lapidez, J. P., Mungcal, M. T. F., Puno, J. V. R., Ramos, M. M. A. C., Santiago, J., Suarez, J. K., & Tablazon, J. P. (2015). Devastating storm surges of Typhoon Haiyan. *International Journal of Disaster Risk Reduction*, *11*, 1–12. https://doi.org/10.1016/j.ijdrr.2014.10.006

Manohar, L., & Kt, | Muthaiah. (n.d.). *Lakshmi Manohar | Muthaiah KT towardsresilienceinchennai wastelandterritoriesintransitiontowardsasustainablecross-borderMetroPolitancore TOWARDS RESILIENCE IN CHENNAI Lakshmi Manohar | Muthaiah KT towardsresilienceinchennai wastelandterritoriesintransitiontowardsasustainablecross-borderMetroPolitancore*. 251. https://doi.org/10.7480/iphs.2016.3.1266

Miller, J. D., & Hutchins, M. (2017). The impacts of urbanisation and climate change on urban flooding and urban water quality: A review of the evidence concerning the United Kingdom. *Journal of Hydrology: Regional Studies*, *12*, 345–362. https://doi.org/10.1016/J.EJRH.2017.06.006

Miller, K. A., & Belton, V. (2014). Water resource management and climate change adaptation: a holistic and multiple criteria perspective. *Mitigation and Adaptation Strategies for Global Change*, *19*(3), 289–308. https://doi.org/10.1007/s11027-013-9537-0

Nasiri, F., & Mafakheri, M. S. (2015). Qanat water supply systems: a revisit of sustainability perspectives. *Environmental Systems Research*, *4*(1). https://doi.org/10.1186/s40068-015-0039-9

Ramachandra, T. V., & Kumar, U. (2008). Wetlands of Greater Bangalore, India: Automatic delineation through pattern classifiers. *Electronic Green Journal*, *26*. https://doi.org/10.5070/g312610729

Srinivasan, V., Seto, K. C., Emerson, R., & Gorelick, S. M. (2013). The impact of urbanization on water vulnerability: A coupled human-environment system approach for Chennai, India. *Global Environmental Change*, *23*(1), 229–239. https://doi.org/10.1016/j.gloenvcha.2012.10.002

Uttarakhand Action Plan on Climate Change "Transforming Crisis into Opportunity." (n.d.).

WATER AND CLIMATE CHANGE The United Nations World Water Development Report 2020 World Water Assessment Programme United Nations Educational, Scientific and Cultural Organization Sustainable Development Goals water and sanitation United Nations Educational, Scientific and Cultural Organization. (n.d.).