Integrated Urban Flood Mitigation Framework- A Case of Lucknow

A Thesis

Submitted in partial fulfilment of the requirements for the award of the degree

of

Master of Planning (Urban Planning)

in

Department of Architecture and Planning

by

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under the supervision of

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JULY, 2026

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ACKNOWLEDGEMENT

I take this opportunity to express my profound gratitude to all those who have supported and guided me throughout the course of this dissertation.

I am deeply indebted to my research supervisor, **Dr. Manmohan Kapshe,** for his invaluable guidance, continuous encouragement, and scholarly insights into urban planning and infrastructure systems. His patient mentorship and constructive suggestions have been instrumental in shaping the quality, conceptual rigor, and analytical depth of this research. His expertise in evidence-based frameworks and commitment to grounding theoretical approaches in empirical Indian contexts have significantly enriched this work. It has been a privilege to work under his supervision.

I extend my heartfelt appreciation to my parents, whose unconditional love, constant motivation, and unwavering belief in my abilities have been my greatest source of strength throughout this demanding research process.

I would also like to thank my friends for their encouragement, assistance, and companionship throughout this academic journey. Their support both emotional and intellectual has helped me overcome challenges and stay committed to the completion of this work.

I am grateful to **Maulana Azad National Institute of Technology (MANIT), Bhopal** for providing the institutional resources and academic environment necessary to conduct this research.

Finally, I express my sincere gratitude to the researchers, practitioners, and scholars whose published work on urban flooding, DPSIR frameworks, system dynamics, and resilience have formed the foundation of this research. Their intellectual contributions have made this synthesis and analysis possible.

Kritika Pandey

ABSTRACT

Urban growth, surface imperviousness, and monsoon rains have come together to make pluvial floods the hallmark of Indian cities undergoing rapid urban growth. Traditional stormwater management focuses primarily on expanding the network of concrete drains, which has become increasingly inadequate. The current dissertation proposes an IUFMF (Integrated Urban Flood Mitigation Framework), wherein hydrological performance becomes one of the key considerations in statutory land use planning, with the case study being Lucknow in India.

The research employs both macro level geospatial analytics and hyper local field audit studies. On the macro level, geospatial terrain and flow accumulation analysis is used, coupled with historical data on waterlogging cases, in order to identify areas vulnerable to flooding. The three main hotspot locations under study for in-depth analysis are Faizullahganj (an informal, peripheral sprawl on a river terrace), Indira Nagar (a mature and planned neighbourhood), and Alamnagar (industrial and warehousing zone). The research concludes that urban flooding is a symptom of fragmented urban governance and landscape alteration rather than drainage inadequacy.

Hydrological evaluations reveal that when structural engineering enhancements are complemented with decentralized nature-based source controls, significant benefits are observed. The suggested local measures such as permeable streets, community wetlands, non-return flap gates, pumping sumps, and sunken parks are effective in ensuring the stabilization of peak flow and preventing backwater failure modes in diverse urban settings. The approach is adopted through a comprehensive city-wide strategy implemented along five main pillars: spatial, planning, governance, infrastructure, and ecological. Eventually, this model can be considered as a multi-level governance approach for making urban landscapes adaptable to climate change.

सारांश

शहरी विस्तार, अभेद्य सतहों में वृद्धि तथा मानसूनी वर्षा ने मिलकर तीव्र गति से विकसित हो रहे भारतीय शहरों में वर्षा जनित बाढ़ को एक सामान्य समस्या बना दिया है। पारंपरिक वर्षा जल निकासी प्रबंधन मुख्यतः कंक्रीट नालों के विस्तार पर केंद्रित रहा है, जो वर्तमान परिस्थितियों में लगातार अपर्याप्त सिद्ध हो रहा है। प्रस्तुत शोध में "एकीकृत शहरी बाढ़ न्यूनीकरण रूपरेखा" का प्रस्ताव किया गया है, जिसमें जलवैज्ञानिक प्रदर्शन को वैधानिक भू-उपयोग नियोजन का एक प्रमुख घटक माना गया है। इस अध्ययन का केस स्टडी क्षेत्र भारत का लखनऊ शहर है।

यह शोध व्यापक भू-स्थानिक विश्लेषण तथा सूक्ष्म स्तर के क्षेत्रीय सर्वेक्षण दोनों विधियों का उपयोग करता है। व्यापक स्तर पर भू-आकृतिक ढाल, प्रवाह संचयन तथा ऐतिहासिक जलभराव आंकड़ों का विश्लेषण करके बाढ़ संभावित क्षेत्रों की पहचान की गई। गहन अध्ययन हेतु तीन प्रमुख बाढ़ हॉटस्पॉट क्षेत्रों का चयन किया गया है– फैज़ुल्लागंज (नदी तट पर स्थित अनौपचारिक परिधीय विस्तार क्षेत्र), इंदिरा नगर (एक परिपक्व एवं नियोजित आवासीय क्षेत्र) तथा आलमनगर (औद्योगिक एवं गोदाम क्षेत्र)। शोध के निष्कर्ष दर्शाते हैं कि शहरी बाढ़ केवल निकासी तंत्र की कमी का परिणाम नहीं है, बल्कि यह विखंडित शहरी शासन व्यवस्था एवं भू-दृश्य परिवर्तन का भी परिणाम है।

जलवैज्ञानिक मूल्यांकन से यह स्पष्ट हुआ कि जब संरचनात्मक अभियांत्रिकी उपायों को विकेन्द्रीकृत प्रकृति-आधारित नियंत्रण उपायों के साथ जोड़ा जाता है, तब बाढ़ नियंत्रण में उल्लेखनीय लाभ प्राप्त होते हैं। प्रस्तावित स्थानीय उपायों– जैसे पारगम्य सड़कें, सामुदायिक आर्द्रभूमि, नॉन-रिटर्न फ्लैप गेट्स, पम्पिंग सम्प्स तथा अवनत उद्यान— के माध्यम से विभिन्न शहरी परिस्थितियों में अधिकतम प्रवाह को स्थिर करने तथा बैकवॉटर विफलताओं को रोकने में सहायता मिलती है।

इस दृष्टिकोण को शहर-स्तरीय समग्र रणनीति के रूप में पाँच प्रमुख स्तंभों– स्थानिक, नियोजन, शासन, अवसंरचना तथा पारिस्थितिकीय— के माध्यम से लागू किया गया है। अंततः, यह मॉडल जलवायु परिवर्तन के प्रति अनुकूलनशील शहरी परिदृश्य विकसित करने हेतु बहु-स्तरीय शासन व्यवस्था के रूप में उपयोगी सिद्ध हो सकता है।

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ABBREVIATIONS

1. AIDMI – All India Disaster Mitigation Institute
2. BBMP – Bruhat Bengaluru Mahanagara Palike
3. CAF – Climate Action Forum
4. CBOs – Community-Based Organizations
5. CWC – Central Water Commission
6. DPSIR – Driver-Pressure-State-Impact-Response
7. EEA – European Environment Agency
8. EOC – Emergency Operations Centre
9. GI – Green Infrastructure
10. GIS – Geographic Information Systems
11. HFL – Highest Flood Level
12. IMD – Indian Meteorological Department
13. IPCC – Intergovernmental Panel on Climate Change
14. IT – Information Technology
15. LED – Light Emitting Diodes
16. LEZ – Low Emission Zone
17. MLL – Maximum Water Level
18. MLD – Million Liters Daily
19. MoEFCC – Ministry of Environment, Forests and Climate Change
20. MoHUA – Ministry of Housing and Urban Affairs
21. NBS – Nature-Based Solutions
22. NDMA – National Disaster Management Compiled by Authority
23. OECD – Organisation for Economic Co-operation and Development
24. PSR – Pressure-State-Response
25. PWD – Public Works Department
26. SOPs – Standard Operating Procedures
27. SANDRP – Sustainable Development Goals Research Project Institute
28. ULB – Urban Local Bodies
29. UNESCO – United Nations Educational, Scientific and Cultural Organization
30. UN-Habitat – United Nations Human Settlements Programme

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Chapter I

INTRODUCTION & BACKGROUND

This chapter sets the stage for the discussion of the vulnerabilities, mechanisms, and mitigation strategies pertaining to modern urban flooding. With an increase in population and concretization in the urban environment altering hydrologic cycles, the existing drainage system in metropolitan cities has been under immense pressure. Through a discussion on the theoretical, environmental, and socio-economic background of the issue, Chapter I defines the problems being explored in this research and provides the structural path of the dissertation.

1.1 Understanding Urban Floods

In order to engineer specific solutions to address the problems posed by floods in the urban environment, it is important first to understand the multifaceted nature of the issue. Flooding in the city is a combination of local meteorological events and man-made changes to the land. This differs from flooding in a rural setting where long periods of flooding due to overflow from the river basin system cause the problem. The subsequent sections examine the various aspects of this crucial urban phenomenon.

1.1.1 Definition and Characteristics

Urban flooding has been defined as an unusual and uncontrolled accumulation of water in a developed area normally above ground level, caused by excess water from various sources overwhelming the capacity of the urban drainage systems (National Disaster Management Compiled by Authority [NDMA], 2010). Recent scholarly literature indicated that an urban flood may be caused by river overflow, high-intensity rainfall, high tides, surface runoff with sudden impervious area contribution, or the release of water from failed water retention structures or drainage facilities(Ali et al., 2025). If the structure of the urban facilities and the natural drainage system are unable to handle them, then the resulting overflow of streets, buildings, and public places disrupts regular urban functioning, causing massive destruction to property, causing obstacles in traffic flow, risking health through waterborne diseases, and is trailed by massive economic losses(Collins et al., 2025).

Complexity characterizes urban flooding, which is influenced by many factors that interactively include urban morphology, drainage network design, catchment characteristics, and hydrological conditions. Spatial concentration of economic activities, critical infrastructure, and dense populations in urban areas implies that flooding events immediately and severely affect regional and national economies beyond the flooded zones themselves.

1.1.2 How Urban Floods Differ from Other Flood Types

Fundamentally, urban floods differ from rural or riverine floods in several critical dimensions. Unlike natural floods, which are usually caused by widespread river overflow or rainfall in large catchment areas, urban floods are caused predominantly by anthropogenic factors such as land use changes, rapid and unplanned urbanization, and the resultant alteration of surface runoff patterns (NDMA, 2010; Sarmah et al., 2014). For instance, the conversion of permeable land to impervious surfaces, consisting of concrete pavements, asphalt roads, and building structures, causes drastic reductions in water infiltration into the soil and significantly higher and faster runoff volumes. For instance, studies have shown that flood peaks in urban catchments can rise between 1.8 and 8 times and the volumes as high as up to 6 times compared to natural catchments (NDMA, 2010), posing unwarranted situations for the drainage systems of cities and towns.

Moreover, the effects of urban floods tend to be more immediate and severe due to high population density, concentration of critical infrastructure, limited evacuation options, and the complexity of the built environment. Unlike the rural setting where hydrological interventions in the traditional sense may be enough, management of urban floods needs to be sophisticated, integrating urban planning, drainage engineering, disaster risk reduction, social aspects, and governance structures(Roy & Das, 2021). Because a large part of the surfaces in the urban landscape is covered by impervious covers, urban floods have become a ubiquitous threat in modern cities, occurring irrespective of proximity to designated floodplains or water bodies.

1.2 Background and Context

To get a clear idea as to why contemporary cities have become more susceptible to flash floods and floods, it is necessary to understand the wider context of geography and history within which city building takes place. The problem of urban flooding is not confined to a particular area or incident but is a problem which is part of global trends of climate change and migration on a macro scale. With the help of such a discussion, one will be able to understand how global environmental change interacts with regional planning to produce extremely risky zones. This section provides some background for the discussion below.

1.2.1 Global and Indian Urban Flooding Context

Urban flooding is becoming an increasing global issue due to rapid urbanization, increasing climate change effects, and increasing social and economic vulnerabilities. More cities and urban areas around the globe are at higher risk for flooding as a result of changes in rainfall from increased frequency and intensity of severe storms, as well as urban growth that is often unplanned (World Bank, 2020). Both developed and developing nations have significant impacts related to urban flooding that can include damage to public infrastructure, economic losses, disruption to society and loss of life.

Urban flooding is a result of climate change, which has changed rainfall patterns across the globe. With an increase in the number of severe storms, the amount of extreme rainfall is increasing at an alarming rate, exceeding the ability of many urban drainage systems to handle it (Zhao et al., 2024). Urban areas with high percentages of impervious cover combined with poor development of stormwater management systems are more prone to flooding events. Houston (USA), Jakarta (Indonesia), Venice (Italy), and London (UK) are examples of large population centres that have experienced catastrophic flooding events, demonstrating that flooding is a common threat experienced by many other cities and urban areas globally, regardless of their level of development.

Urban flooding has become an issue of growing concern in India due to rapid population growth, unplanned urban expansion, and infrastructure deficits in its major cities. India is highly prone to floods, especially within regions such as the National Capital Region, Maharashtra, Tamil Nadu, Gujarat, and Kerala, among others (NDMA, 2010). Compounding these effects are the progressive loss of natural drainage systems and water bodies, inadequate management of solid waste that blocks storm drains, climate variability, and insufficient investment in flood-resilient infrastructure.

Monsoon variability, accentuated by global climate change, further exacerbates the flood events that cause recurrent waterlogging and extensive damage in metropolitan areas such as Mumbai, Chennai, Hyderabad, Bengaluru, Delhi, and Lucknow. The economic costs of urban flooding within India are high and impact agricultural livelihoods, transport networks, health services, water supply systems, and urban ecosystems. High population density combines with inadequate infrastructure capacity and geographic exposure to multiple flood hazards to make Indian cities some of the most vulnerable in the world to urban flooding impacts.

1.2.2 Historical Evolution of Urban Flood Management in India

In the past, Indian cities were flooded primarily due to the seasonal monsoon rains and rivers overflowing. Urban flooding was less frequent and occurred over a smaller area. Because of the presence of natural drainage systems, a large percentage of permeable land and floodplains that absorbed excess water, there was less water caused by flooding to run off into urban areas (NDMA 2010). Historical records indicate that there were significant flooding events earlier than floods like the Gomti River Flood of Lucknow in 1923 and the Flood of Chennai in 1943 as a result of extreme rainfall and water bodies overflowing (Gupta, 2020).

After the birth of India as an independent nation, urbanization ramped up dramatically, and the nature of and how to manage floods changed significantly. Urban sprawl and unplanned growth in urban areas led to the degradation of lakes, wetlands and floodplains by blocking the natural drainage systems of cities and disrupting the natural ability of the land to retain and absorb water (Collins et al., 2025). Disasters caused by urban flooding, such as the deadly floods in Mumbai in 2005 and the devastating floods in Chennai in

2015, are good examples of how poor drainage infrastructure, encroachment of water bodies and uncontrolled urban sprawl have caused urban flooding (Roy & Das, 2021).

The historical development of flood management in India has transformed from a paradigm of utilizing traditional grey infrastructure (i.e. hardened drainage systems built for quick removal of stormwater) to employing many nature-based systems and processes to be part of the sustainable way to manage urban flooding. This evolution reflects growing understanding that purely engineered approaches without integration of planning, governance, and natural systems are insufficient for managing contemporary urban flood challenges exacerbated by climate change and rapid urbanization.

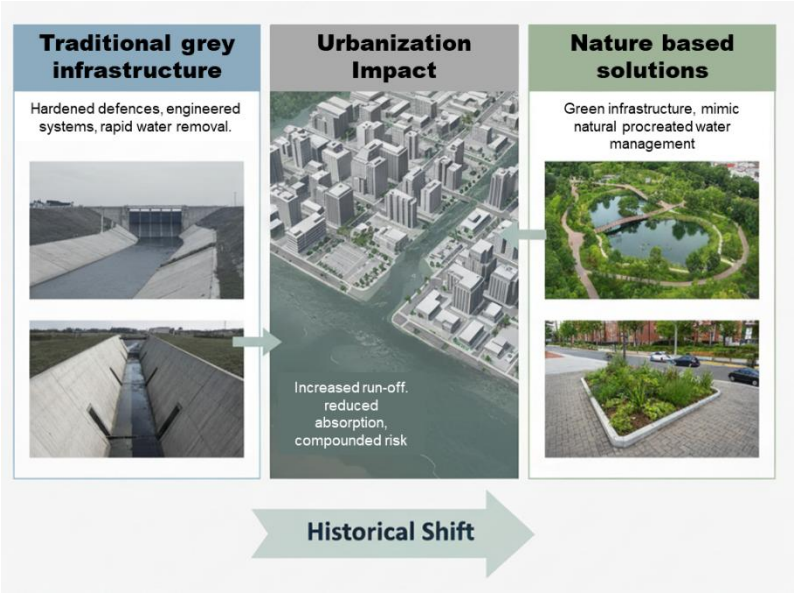


Figure 1 Historical development of flood management *Source - Compiled by Author*

The evolution of urban flood management demonstrated in fig:1 shows the compounded effects of climate change and unplanned urban growth, underscoring the necessity for integrated, multidisciplinary, and adaptive approaches to urban flood governance in the Indian context (Zhao et al., 2024).

1.2.3 Recent Urban Flood Incidents in India (2025)

Recent urban flood events across major Indian cities in 2025 have been predominantly triggered by extreme rainfall, inadequate and aging drainage infrastructure, urban planning deficiencies, blocked natural watercourses, and the cascading effects of climate variability. These flood episodes have resulted in severe waterlogging, disruption of transportation networks, extensive property damage, and loss of human life in multiple cities including Mumbai, Lucknow, Kolkata, Bengaluru, Delhi, and Gurugram (NDMA, 2023; MoEFCC, 2024).

The following table: 2 presents key data points from recent 2025 flood incidents, including rainfall quantities, event durations, predominant causes, and documented impacts:

Table 1 Recent flood incidents *Source - IMD and NDMA reports*

City	Date (2025)	Rainfall	Main Cause	Key Impacts
Mumbai	Aug 15-18	150-185 mm (21 hrs)	Extreme rainfall + aging drainage network	Mithi River peak; 300+ evacuated; transport disrupted; major traffic gridlocks
Lucknow	Aug 3-4	61.5 mm (24 hrs)	Prolonged rain + insufficient stormwater drains	Severe waterlogging; stalled vehicles; power outages; drainage gaps highlighted
Kolkata	Sep 24	251.4 mm (24 hrs)	Record rainfall + high tide in Hooghly River	12 deaths; waist-deep street flooding; transport halted; schools closed
Bengaluru	May 21, Sep 19	130 mm (12 hrs), 66 mm	Heavy showers + poor drainage; monsoon rain + blocked watercourses	3 deaths; 500+ homes flooded; flyovers submerged; traffic snarls
Delhi	Sep 1-3	64.5-204.4 mm (3 days)	Monsoon surge + Yamuna overflow	Yamuna at 206.03 m; low-lying areas flooded; thousands displaced to relief camps
Gurugram	Sep 1	133 mm (4 hrs)	Urban planning flaws + inadequate drains	2-3 ft water submergence; NH-8 jams over 4 km; infrastructure inundated

These collective incidents underscore the recurring vulnerabilities of urban systems to intense precipitation coupled with inadequate stormwater management, encroachment on floodplains and water bodies, poor maintenance of drainage infrastructure, and governance coordination gaps. The incidents highlight the urgent necessity for improvements in municipal drainage systems, comprehensive urban planning reforms, and anticipatory flood risk governance.

1.3 Significance of the Study

Analysis of the structural and spatial aspects of urban flooding is vital for the formulation of resilient models in fast-growing cities. This research is very significant as it links the broad scale of hazard mapping to practical engineering and nature-based designs. Through an analysis of the weaknesses that exist in various urban forms, from slums to planned cities, this study offers a framework that can be replicated by city councils to address the problem of flooding, protect human life, and save money. Below are the reasons why this research is highly relevant today.

1.3.1 Contemporary Relevance

Urban flooding has emerged as a critical hazard in India's rapidly growing cities, precipitated by the combined effects of rapid urbanization, climate variability, and insufficient drainage infrastructure (NDMA, 2010). The increasing frequency and intensity of extreme rainfall events combined with expansive impervious surfaces have progressively overwhelmed traditional stormwater systems in major urban centres, leading to frequent inundation, substantial economic losses, and significant human suffering (NDMA, 2023). A comprehensive understanding and strategic approach to urban flood management are urgently required to safeguard lives, protect urban infrastructure, and ensure sustainable urban development.

Rising Urban Flood Events in India

Major cities including Mumbai, Chennai, Bengaluru, Kozhikode, Delhi, Hyderabad, and Lucknow have witnessed increasingly frequent flood episodes in recent years, exacerbating vulnerabilities caused by aging and inadequate drainage systems, solid waste clogging storm drains, and systematic encroachment on natural floodplains and water bodies (NDMA, 2023). Monsoon rains in the 2024-2025 period have reinforced this concerning pattern, with record-breaking precipitation events resulting in widespread disruption, emergency evacuations, and extensive infrastructural damage (NDMA, 2023). These recurring floods reveal systemic lapses in urban planning, governance, and flood

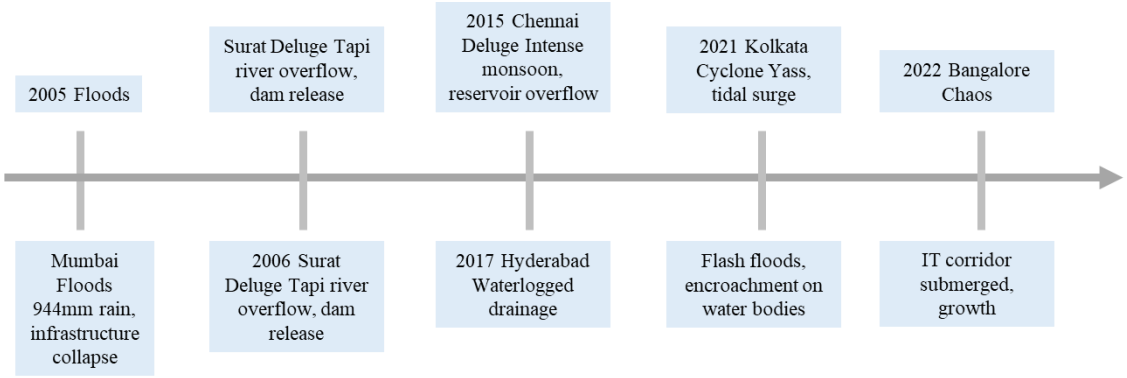


Figure 2 Urban Flooding Timeline

Source - Compiled by Author

management requiring urgent strategic interventions. The Figure 2 shows how the great impact urban flooding events have occurred over time.

Vulnerabilities in Indian Urban Context

It is evident from previous studies that urban floods in India have disproportionately damaged urban areas that are densely populated and contain important infrastructure assets such as hospitals, power systems, transportation systems, water supply facilities, and communication systems (Vazhuthi & Kumar, 2020). The configuration of buildings, i.e., ground slope, density of buildings, street/pavements lay out, and drainage porosity of cities, has a large impact on the designation of flood risks. Therefore, cities will require flood mitigation plans that take into account local geographic features (Zhao et al., 2024). As climate change continues to evolve, so does the likelihood of urban floods and the unexpected patterns of extreme weather. In order for cities to plan for adaptive and forward-thinking, adaptive and future-oriented urban governance strategies are necessary.

1.3.2 Policy and Knowledge Gaps

Gaps in Current Mitigation Approaches

Current approaches to mitigating the effects of flooding on cities are largely focused on traditional structural flood mitigation strategies, such as: expanding drainage systems, building new pumping stations, and building new embankments. These flood mitigation techniques are reactive and do not consider integration with land use planning, early flood warning systems or with community-based flood preparedness (Collins et al., 2025). There are large gaps in the use and implementation of non-structural flood mitigation strategies, such as flood zoning, flood hazard mapping, flood education programs, and policy reforms to improve flood preparedness, in the majority of Indian municipalities (World Bank, 2020). Flood risk data and assessment at the urban scale is another important gap in the provision of adequate flood mitigation design, planning and resource allocation at the local level for most cities.

Governance and Coordination Challenges

The governance of urban flooding in the Indian context involves several agencies: the National Disaster Management Compiled by Authority (NDMA), the Ministry of Housing and Urban Affairs, the Central Water Commission, the State Water Resources Departments, and the urban local bodies. Yet, coordination gaps, capacity constraints, and division of roles among sectors remain persistent, compromising the effective mitigation of flood risks. In most Indian cities, the integration of flood management with urban planning, regulation of water resources, environmental protection, and disaster management remains fragmentary.

Need for a Strategic Framework

Consequently, responding effectively to the growing complexities of urban flooding in India requires a multidimensional framework that synthesizes the best of structural and non-structural measures, spatial flood risk zonation, climate adaptation strategies, nature-based solutions, and participatory governance (NDMA 2023; MoHUA 2023). Such a framework should be explicitly rooted in the Indian urban planning context with the integration of city-level flood risk indicators, spatial zoning requirements, and planning-centric solutions aligned to national policies and local governance structures.

1.4 Aim and Objectives

1.4.1 Research Aim

The overarching aim of this thesis is to identify flood-prone areas in Lucknow, analyse the key factors contributing to urban flooding, and propose planning-oriented strategies for effective flood management.

The objective of the present thesis is to find out the flood prone areas of Lucknow and the significant causes of urban floods through a spatial planning analysis approach. The purpose of conducting this research includes studying the relationship between geographical parameters such as physiography, topography, drainage and watershed features and urbanization processes and imperviousness in causing urban flooding. The research also intends to evaluate the vulnerabilities of selected urban flood hot spots through GIS based analysis and on ground observations in an attempt to comprehend the causes of urban flooding.

In view of the above-mentioned findings regarding urban flood vulnerability, the research intends to design suitable mitigation measures for sustainable urban flood management in Lucknow using integrated planning approach combining both structural and non-structural, nature based and policy-based interventions.

1.4.2 Objectives

Phase 1 Objectives (Dissertation)

1. To understand causes and drivers of Urban Flooding.

2. To study impacts of urban flooding through case examples.

3. To synthesise existing structural and non-structural urban flood mitigation strategies through systematic literature Review.

4. To organize findings into a strategic Urban flood management matrix in Indian context.

Phase 2 Objectives (Thesis)

1. *To comprehend the spatial and physical aspects that lead to urban flooding in Lucknow by carrying out a GIS-based analysis of terrain, drainage, watershed, land use, and flows.*
   Understanding the spatial and physical attributes involved in urban flooding in Lucknow by using geographical information system techniques is the primary purpose of this research. In this regard, the research will focus on the examination of spatial attributes such as topography, elevation, slope, drainage pattern, watersheds' performance, flow accumulation, and land usage. Through the identification and analysis of such spatial factors, the research hopes to examine the role played by the natural and urban landscape in relation to the occurrence of floods in Lucknow.

2. *To identify and analyse major urban flood hotspots in Lucknow in relation to their topographic, infrastructural, and planning vulnerabilities.*
   The second objective of this research is to pinpoint the major flood hotspot zones of the city of Lucknow, and to analyse them based on the vulnerabilities they possess in terms of geography, infrastructure, and planning. This is done by identifying those parts of the city where the flood vulnerability occurs, and then studying why they are vulnerable to flooding. The process of analysing the vulnerabilities would include looking at factors like low lying areas, poor drainage network, encroachment on natural water flows, unplanned urbanization, and increasing imperviousness.

3. *To assess the primary reasons behind floods in selected hotspots using spatial analysis and field observation and current urban scenario.*
   The third objective of the research is to find the main reasons for floods occurring in select hotspots using spatial analysis techniques and observations in the field. It includes examining the flood vulnerability hotspots with regards to drainage, land use practices, roadways, behaviour of water flow, and physical obstacles present there. By observing these sites and analysing spatially, this research will try to understand how urban infrastructure inadequacies and lack of proper maintenance increases flood vulnerability in those areas.

4. *To develop holistic urban flood management strategies for hotspots using structural, non-structural, natural, and policy-based approaches.*
   Fourthly, the study seeks to provide a framework for developing integrated and planning oriented flood mitigation strategies for the hotspots that have been identified through integrating structural, non-structural, natural, and policy-based approaches. Context specific strategies are to be developed through this research with a view to addressing urban flooding from two perspectives –physical perspective and planning perspective. Some of the strategies will involve

upgrading drainage systems, developing SUDS, implementing natural-based measures and also devising some measures for policy development.

1.4.3 Scope

1. Systematic Literature Review on Indian Urban Flooding

The present research is informed by a systematic review of literature through academic articles, policy documents, namely by NDMA, MoHUA, and CWC, and reports from both government and international sources. It synthesizes multidisciplinary knowledge on hydrology, urban planning, social sciences, and governance to identify patterns, evidence gaps, and best practices applicable to Indian contexts.

2. Development of Framework Suited for Indian Urban Areas

The research thus explicitly attempts to develop a strategic framework for evidence-based urban flood management for Indian urban contexts. The framework integrates Indian policy structures, drainage standards, urban morphologies including informal settlements, regulatory frameworks, financing constraints, and climate characteristics rather than generic international principles.

3. Comprehensive Multi-Dimensional Analysis

The research addresses urban flood causes in a structured way, taking into consideration natural/hydrological drivers, anthropogenic drivers from urbanization, governance drivers; multidimensional impacts including social, economic, environmental; and a portfolio of mitigation strategies such as structural, non-structural, and nature-based solutions, linking identified causes to applicable interventions.

1.4.4 Limitation

1. Theoretical Framework Does Not Go Through Field Tests

The end product from the research is a theoretical framework, as opposed to having developed a field-tested model ready for real-world implementation. Until then, the use of this framework in real-life situations will be determined through empirical validation of an actual implementation within urban Indian environments.

2. Emphasis on Present-Day Conditions Leave the Future Unaccounted

The framework has been developed primarily for use in analysing urban flooding between the years of 2005-2025. Therefore, the framework does not incorporate future climate change forecasts or future urban development. Furthermore, it will likely need to be updated and revised regarding Assumptions related to rainfall increases or future development patterns.

3. Low Transferability of Framework-Attempted Solutions Across the Entire Merged Urban Population

The proposed solutions that work for large metropolitan cities may not apply to smaller cities or the rural-urban fringe. Therefore, the proposed framework needs to be significantly modified to work in the unique conditions of different urban areas across India since all documentation has focused on the four major metropolises of Mumbai, Delhi, Bangalore and Chennai. The recommendations may not meet the needs for secondary cities or municipalities with limited resources.

1.5 Methodology

The methodology adopted in the research has been segmented into two stages. The first stage comprised the dissertation phase, wherein the research involved gaining theoretical knowledge about urban flooding and formulating a strategy framework for mitigating urban floods using literature research. The second stage will comprise the thesis phase wherein the formulation framework will be applied to the city of Lucknow. Figure 3 shows the flow of work in schematic format.

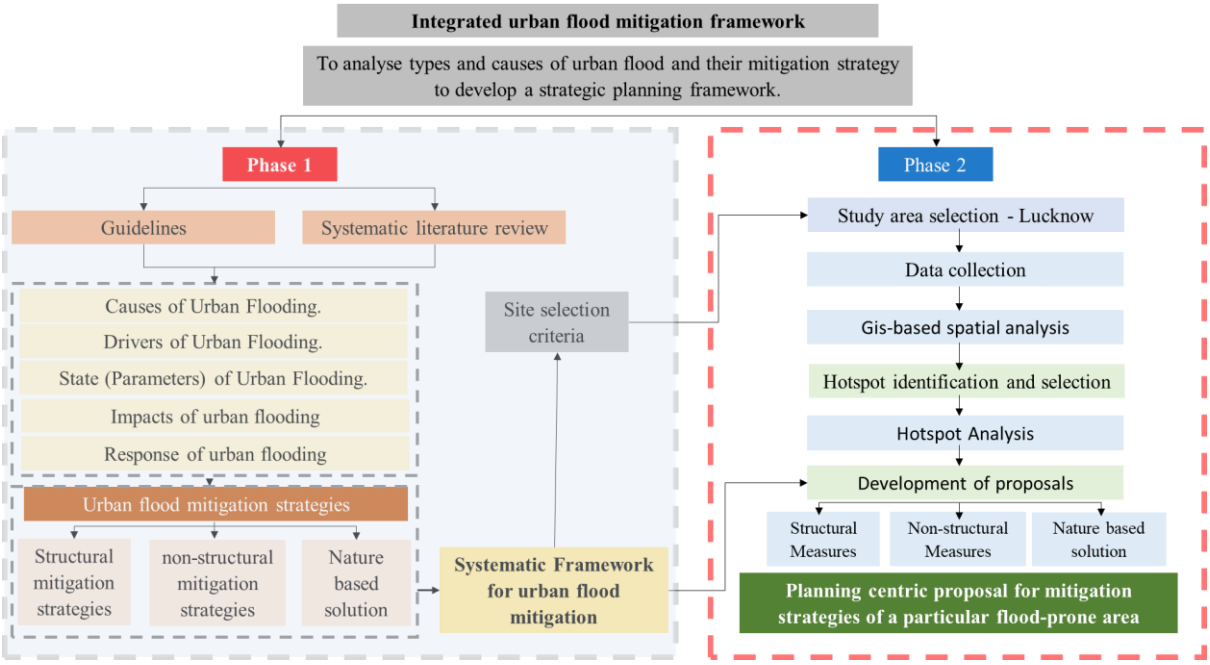


Figure 3 Methodology chart *Source - Author*

Stage 1: Dissertation Stage – Formulation of Urban Flood Mitigation Framework

The initial phase of the research involved gaining insights into theoretical and conceptual aspects of urban flooding by undertaking a comprehensive literature review and policy analysis. Pertinent national and international literature; government guidelines, journal

papers, case studies, and reports in relation to urban flooding were examined with a view to identifying causes, drivers, impacts, and mitigation of urban floods.

The literature review entailed understanding types of urban floods; physical and anthropogenic causes of urban floods, issues related to governance of flooding, impacts of urban flooding on infrastructure, environment, economy and society and different structural, non-structural and nature-based approaches used in mitigating urban flooding. Besides, various policy frameworks and guidelines related to urban flood mitigation including NDMA guidelines and urban planning policies were reviewed to comprehend current approaches towards mitigating urban flooding in India.

On the basis of findings from this review of literature and policy, a cause-mitigation matrix was developed relating urban flood causes and mitigation approaches. The findings emerging from this phase helped in formulating an integrated urban flood mitigation framework, which would form the basis of the thesis phase. Selection criteria of sites for implementation of the developed framework were determined at this phase.

Phase 2: Thesis Phase - Spatial Analysis and Proposing Solution for Lucknow

The second phase involved application of the developed framework on a selected urban city, which is Lucknow in this case. The choice of Lucknow for conducting the research has been made because of its increasing urban floods, poor drainage system, rapid urbanization, and occurrence of water logging zones repeatedly in the area.

Data collection was started first, involving both primary and secondary sources. The collection of primary data was in the form of field visits, visualizing the actual scenario at site level, photography, and on-ground situation regarding the areas identified for flooding problem. The secondary sources involved Digital Elevation Model (DEM) data, satellite imagery, drainage maps, land use map, precipitation details, history of floods in Lucknow, planning documentations etc.

A number of spatial parameters were analysed to identify the factors causing urban flooding through GIS based approach. Parameters such as DEM, slope, flow accumulation, watershed identification, drainage networks, land use land cover, and imperviousness were analysed to comprehend terrain behaviour, run-off pattern, drainage efficiency, and areas prone to water logging.

The flood prone areas were identified using the spatial analysis and historical floods information in Lucknow. The identified hotspots which included the areas such as Faizullahganj, Alamnagar, and Indira Nagar sector 25 area were assessed and analysed extensively considering their geographical, drainage, land use features, infrastructural inadequacies, and planning concerns.

The hotspot assessment included the identification of factors and causes of floods in the hotspot through observations, spatial analysis, and evaluation of the current urban status. The assessment was mainly based on issues such as inadequate drainage network, low-lying geographical characteristics, obstruction to natural drainage channels by human activities, high impervious surface coverage, poor solid waste disposal and management, and uncontrolled urban growth.

Mitigation planning proposals for the hotspot areas under assessment were made according to the identified weaknesses and vulnerabilities. The proposal incorporated both structural measures such as improved drainage and storm water management structures, non-structural measures such as flood zoning and control strategies, and natural solutions such as bioswales, rain gardens, permeable pavement, and green buffers.

Lastly, the results of spatial analysis, hotspots detection, and suggestion generation were incorporated into a flood management strategy for urban settings geared towards sustainable and planning-based flood reduction in Lucknow.

Chapter 2

LITERATURE REVIEW

Using a systematic method, we searched the literature to find all the ways researchers have studied urban flooding, mitigation actions against it, risk assessments for urban flooding, the causes of floods in cities, the effectiveness of how cities manage their wastewaters / urban drainage systems, and Integrated Flood Management from a global perspective.

Urban flooding is a multi-disciplinary crisis affecting areas of interest such as Climate Change, Hydrology, Urban Planning, Government Policies, Infrastructure Systems, and Socio-economic Vulnerability. Therefore, it was extremely important that a scientifically credible screening method was used that was also repeatable.

A suitable method to accomplish this research task was to perform a comprehensive bibliometric search of the Scopus database by designing a well-thought-out and appropriate search string, focusing on the TITLE, ABSTRACT, and KEYWORD fields while applying both inclusions and exclusions based on the year (2010-2025), document type/language/subject area, and specifically the keyword "urban flooding." The goal of the search was to compile a thorough and comprehensive collection of peer-reviewed literature containing material that contributes to understanding the causes, consequences, and mitigation strategies of urban flooding.

This approach was designed to ensure the final dataset consisted of the most significant and relevant global academic contributions relating to Urban Flood Management. The detailed process used to screen through the search string as well as the total number of articles screened at each step is represented in the following flowchart and table, respectively.

The process of bibliometric screening followed, as shown in the table:3 a five-stage sequential methodology in order to refine the dataset from the initial search to the final list of relevant documents. The first stage generated all the publications that matched the complete search query and yielded 412 documents. A preliminary language filter was then applied to include only English-language publications; the number reduced to 395.

Next, filters of subject areas were applied in order to exclude biomedical and chemical sciences domains, areas that are not relevant for the subject of research on urban floods. That refinement narrowed the dataset further to 284 publications. The third stage was then to retain only Articles, Review Papers, and Conference Papers, which represent academically valid and peer-reviewed research.

Exclusions were then made on a keyword basis to eliminate documents whose contexts were mismatches with urban flood management, such as hydrological protein modelling and medical simulations. These exclusions finally narrowed down the dataset to 201 papers. Finally, manual screening of titles and abstracts was done to identify thematic relevance, duplicates, and substantive core alignment with dissertation objectives. This final refinement led to 118 high-quality publications that formed the basis for the literature review and bibliometric analysis using VOS viewer. Table 2 summarizes the bibliometric screening process at each stage.

Table 2 Bibliometric screening process

Source - Author

Screening Stage	Criteria Applied	Documents (n)
Initial Search	TITLE-ABS-KEY ("Urban Flood*" AND (“Mitigation”, “Types”, “Reasons”, “Causes”, “Management”)) + Filters for OA, 2010–2025	670
Preliminary Screening	Language limited to English	450
Subject Area Refinement	Excluded IMMU, PHAR, NEUR, CHEM, CENG, MEDI, BIOC	352
Document Type Selection	Included Article, Review, Conference Paper	276
Keyword Exclusion	Removed non-urban, medical, biochemical modelling papers	267
Manual Screening	Relevance check of titles & abstracts, removal of duplicates	190
Final Dataset	Papers used for Literature Review & Bibliometric Analysis	106

2.1 Introduction to Urban Flooding

The Development of Urban Flood is a large-scale concern in the current time with rapidly growing cities. Developing countries tend to lag behind on stormwater management and infrastructure development(Ali et al., 2025; Nanda et al., 2025) Urban Flood is very different than river (or Pluvial) flood in rural areas, as it is much more complicated than that; one of urban floods’ complications is the fact that the hydrology, weather, and human

effects are combined and impact densely populated areas. A significant portion of many cities' critical infrastructure is located within the area of impact of a urban flood event, meaning there is a massive increase in vulnerability to those most impacted by urban flood and a significant economic impact on the community (Tillermuir et al., 2025).

Climate Change has increased the frequency, severity, and overall occurrence rate of extreme precipitation events resulting in rapid urbanization substantially modifying surface hydrology by creating larger areas of impervious surface and removing natural drainage systems from the urban environment (Kim & Kim, 2025). There has been a significant increase in the amount of attention directed to research that focuses on urban flood reduction/modulation, as evidenced by a current bibliometric review that demonstrated a shift away from the traditional hydrologic/engineering-based academics to a more integrated socio-ecological (as a result of the understanding that urban flood risk is multidimensional) perspective (Kim & Kim, 2025; Nanda et al., 2025).The imperative for systematic examination of urban flooding drivers, impacts, and mitigation strategies is underscored by the escalating frequency and magnitude of catastrophic flood events in major cities. This chapter synthesizes literature across these three critical dimensions: first, the natural and anthropogenic drivers underlying urban flood genesis; second, the multi-faceted impacts spanning social, economic, and environmental domains; and third, the portfolio of mitigation strategies ranging from structural infrastructure interventions to nature-based solutions and governance frameworks.

2.2 Causes and Drivers of Urban Flooding

Urban flooding emerges from a complex constellation of causes that can be categorized into three interconnected systems: natural or hydrological drivers, anthropogenic drivers rooted in urbanization processes, and system-level or governance-related drivers (Sarmah et al., 2014). Understanding these causes is essential for designing targeted mitigation strategies that address root drivers rather than merely treating symptoms. Figure 4 shows the direct and indirect causes of urban floods in flowchart format.

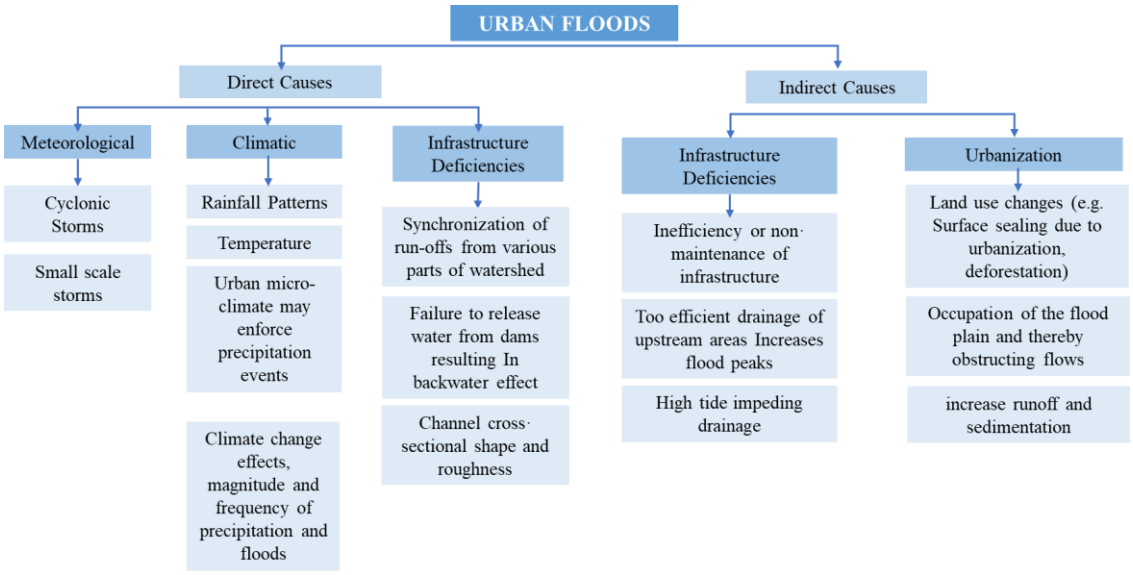


Figure 4 Causal Analysis

Source - Compiled by Author from NDMA Reports

2.2.1 Natural and Hydrological Drivers

Natural or hydrological causes of urban flooding include meteorological and watershed conditions that produce excessive water for which urban drainage systems must be designed. Examples of drivers include heavy rainfall, snowmelt, high water tables, and riverine over-topping mechanisms processes that would occur in the absence of urbanization (NDMA, 2010).

Extreme Rainfall and Precipitation Intensity: The most important natural factor causing flooding in urban areas is extreme rainfall, or events of high-intensity precipitation concentrated over periods of time. Due to climate change, the frequency and magnitude of extreme rainfall events in urban and small catchments are increasing (Tyndall Centre for Climate Change Research, 2025). The physical mechanism behind this intensification is simple: a warmer atmosphere can hold about 7% more water vapor per degree of temperature rise, which may increase available moisture for precipitation (Tyndall Centre for Climate Change Research, 2025). Hence, flood peaks in urban areas can rise as high as 1.8 to 8 times compared to natural catchments, while runoff volumes can increase up to 6 times (NDMA, 2010).

Evidence of this escalation can be seen in Indian cities. Mumbai received about 950 mm rainfall on July 26, 2005, against the normal pattern of the monsoon. In Bengaluru, it rained 130 mm in one day in May 2025, against the normal of 4.5 mm a day during that month. Kolkata received 251.4 mm precipitation in 24 hours in September 2025-a sign of growing intensity in extreme precipitation events.

High Tides and Storm Surges: Coastal urban centres face distinct hydrological drivers related to oceanographic phenomena. Storm surges driven by cyclonic activity and high tides can inundate low-lying coastal areas, particularly when coinciding with heavy

rainfall—a phenomenon termed "compound flooding" (Ministry of Environment, Forests and Climate Change [MoEFCC], 2024). Climate change projections indicate accelerating sea-level rise, amplifying coastal flood risk over coming decades.

2.2.2 Anthropogenic Drivers

Human activity and the process of creating cities are the dominant manmade reasons why flood risks continue to grow and are managed primarily through policy and planning. Human-made drivers also don't just coexist with natural causes; they work hand in hand with natural causes or processes, and increase the flood vulnerability of you and your urban community (Collins et al., 2025).

The large rise in impervious surfaces as a result of converting natural surfaces to impervious materials such as concrete in roadways and pavements, rooftops, and buildings drastically changes the hydrology of the area (Sarmah et al., 2014). As mentioned previously, the soils of a natural catchment have various infiltration capabilities based on vegetation, soil type, and terrain, and vegetated surfaces also provide a place for rainwater to fall and eventually soak into the groundwater system, thus providing a reduction in surface runoff. Impervious urban surfaces are designed so that nearly all precipitation lands on the surface and runs off very quickly.

The amount of change to the hydrology caused by the increased area of impervious surfaces is large; an increase in impervious surfaces results in High Runoff Volumes and Fast Rates of Runoff. As urbanization increases without sufficient infrastructure for controlling stormwater runoff such as drainage systems, the gap between the capacity to generate floods and a system's ability to handle those floods must increase (Collins et al., 2025).

Loss of Natural Drainage Systems and Water Body Encroachment: The rapid, often informal, urbanization has led to systematic encroachment upon and elimination of natural drainage corridors and water bodies including lakes, wetlands, floodplains, and stream channels (NDMA 2010; Roy & Das 2021). These natural systems provide a host of hydrological functions: they absorb excess precipitation, attenuate peak flows, facilitate infiltration, and temporarily store flood waters, thereby distributing flood risk spatially and temporally. Their removal eliminates these functions, concentrating flood risk downstream and accelerating flow velocities.

For example, the Dakshina Pinakini River in Bengaluru, which was declared extinct due to many decades of reduced flows and encroachment, became a source of destructive floods during heavy rainfall events as water rushed through areas that had previously been developed on its historic bed. The natural flood buffer capacity that normally typifies most Indian cities has also been destroyed through systematic lake encroachment. Analyses of data from Bengaluru's Municipal Corporation showed that BBMP had

identified 2,626 encroachments around water bodies and had removed less than 714-a clear indication that this driver persists despite regulatory recognition.

Inadequate and Aging Drainage Infrastructure: Urban drainage systems, consisting of surface stormwater networks, underground sewers, and treatment facilities, must be designed to have capacity to handle design storm events—rainfall of specified return period, for example, 25-year or 50-year storms. Given that most Indian cities' drainage systems were designed several decades ago based on historical rainfall statistics, those no longer represent current or future precipitation patterns (NDMA, 2010). The aging infrastructure suffers from reduced capacity due to sediment accumulation, structural deterioration, and maintenance deficits.

Urban development is often accompanied by inadequate drainage capacity in most Indian cities. In many instances, due to rapid population growth and construction, the drainage infrastructure has not kept pace with the required investment. For example, Mumbai's flood event in 2005 resulted partly from the inability of its drainage network to accommodate the extreme rainfall amounts combined with the high tides at the time. A similar problem occurred in August 2025 when Lucknow experienced flooding near the PGI due to inadequate capacity of its stormwater drainage system to handle the intensity of the monsoon.

Urbanization contributes to the Urban Heat Island Effect, which causes elevated temperatures in urban settings when compared to adjoining rural settings. The reduced vegetation, large amounts of dark impervious surfaces, and the release of heat from vehicles and buildings contribute to the Urban Heat Island Effect. The increase in temperature has an effect on atmospheric instability, which contributes to the enhancement of convective activity. Therefore, the Urban Heat Island Effect will create greater intensity of rainfall on urban areas than on rural areas. The increase of urbanization and the Urban Heat Island Effect will contribute to the increased risk of flooding. In summary, the Urban Heat Island Effect (due to urbanization) and climate change (due to urbanization) work together to further increase flooding risks beyond what either would do alone.

A third factor contributing to flooding in Indian cities is the accumulation of plastics and other debris in drainage systems caused by inadequate solid waste management in informal settlements and during major monsoon events. The accumulation of plastic waste and debris reduces drainage capacity because of blockages, creating localized areas of waterlogging, and has also contributed to urban flooding in several cities in India. The obstructions to effective drainage caused by inadequate solid waste management have been documented by the National Disaster Management Compiled by Authority (NDMA) and have been a major factor contributing to flooding in India.

2.2.3 System-Level and Governance-Related Drivers

In addition to direct physical drivers, urban flood risk is conditioned by institutional, policy, and governance factors which determine how the natural and anthropogenic drivers interact and whether mitigation efforts will be effectively implemented.

Uncoordinated Urban Planning and Development Control: Urban growth in most Indian cities has occurred without due coordination on stormwater management planning, environmental impact assessment, or correlation among permissions for development and investment in drainage infrastructure. Development often occurs in flood-prone areas-historical floodplains, riparian zones, and low-lying depressions-where the cost of development is comparatively lower but flood vulnerability is inherently higher. Without integrated land use and stormwater planning, such development dramatically increases exposure to flood hazards.

Fragmented Governance and Inter-Agency Coordination Gaps: Urban flood management at the national, state, and municipal levels encompasses a number of agencies, such as the National Disaster Management Compiled by Authority, the Ministry of Housing and Urban Affairs, the Central Water Commission, state water resources departments, urban local bodies, and specialized agencies like traffic police and utility providers. Inadequately defined responsibilities and coordination gaps often lead to uncoordinated responses, duplicated efforts, inadequate resource allocation, and unmitigated vulnerabilities. Besides, the capacity constraints at the municipal levels often restrict the implementation of policy and framework regarding flood management.

Inadequate Investment in Drainage Infrastructure: Limited public financial resources, particularly in developing countries, result in insufficient investment in flood-resilient drainage infrastructure relative to urbanization rates and climate change intensification (World Bank, 2022). This infrastructure deficit perpetuates reliance on aging systems inadequate for contemporary flood pressures, perpetuating vulnerability.

Policy Implementation Deficits: Even where regulatory frameworks exist to protect natural drainage systems and restrict development in flood-prone areas, implementation gaps frequently allow encroachment, uncompiled by Authorized development, and environmental degradation to proceed (NDMA, 2010). Weak enforcement of building bylaws, inadequate environmental monitoring, and insufficient penalties for violations undermine policy effectiveness.

2.3 Types of Urban Flooding

Urban flooding manifests through distinct typologies, each with different causative mechanisms, spatial-temporal characteristics, and implications for mitigation strategies. Understanding these types is essential for designing appropriately targeted responses. Figure 5 shows illustration of different types of Urban Floods.

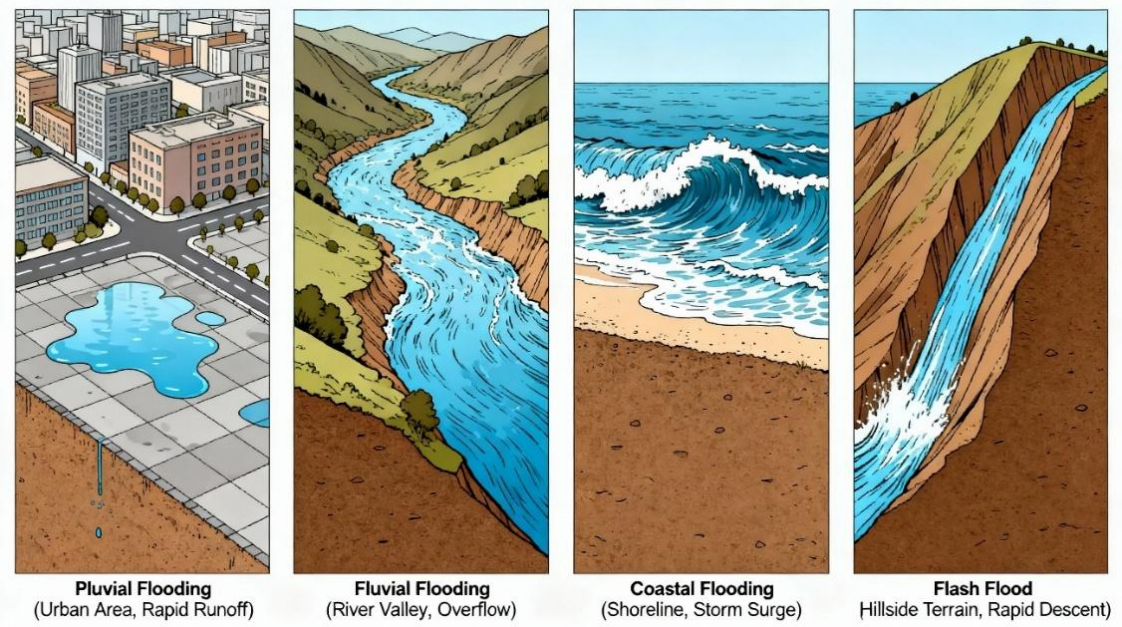


Figure 5 Illustration of different types of Urban Floods *Source - Compiled by Author*

2.3.1 Pluvial Flooding

Pluvial flooding, also termed "cloudburst" or "rainfall flooding," occurs when intense precipitation exceeds both the infiltration capacity of urban soils and the discharge capacity of stormwater drainage systems, resulting in accumulation of water on urban surfaces (NDMA, 2010). This type of flooding has become particularly common in rapidly urbanizing areas with much impervious surface coverage.

The onset of pluvial flooding is sudden, usually with little warning; it has a spatially distributed impact over the urban area rather than being concentrated along water courses. It is the low-lying topographic areas within cities that are usually the most badly affected—depressions, underpasses, parking areas, and streets in low-lying localities. Even critical infrastructure, including underpasses at major roads such as NH-8 in Gurugram, which witnessed 4 km-long traffic jams due to rainfall of 133 mm in September 2025, and electronic corridors of technology hubs, such as Electronic City in Bengaluru, are prone to inundation.

2.3.2 Fluvial Flooding

Fluvial flood (or riverine flood) is where rivers and streams overflow due to discharges which have exceeded their channel capacity because of heavy precipitation upstream, or

rapidly melting snow, which will usually occur at the same time in the spring (Roy & Das, 2021; Singh, 2020). All urban settlements that are located within a river's floodplain and valley areas are susceptible to this type of flooding indicating that those areas would also experience flooding on the floodplain adjacent to their riparian corridors. The increased severity of fluvial flooding is particularly evident within those metropolitan cities that have moved into previously undeveloped natural floodplains and eliminated riparian buffer zones through land development. The metropolitan cities of Lucknow and Agra and several others along the Gomti and Yamuna River systems are examples of this type of vulnerability. An example of severe fluvial flooding occurred in the month of September 2025 in Delhi when the Yamuna River reached critical flood levels (206.03 m) which caused thousands of people to evacuate their homes located in low-lying areas adjacent to the river to relief camps.

2.3.3 Coastal Flooding

Coastal cities around the world, particularly the cities along the east coast of India, such as Mumbai, Chennai, Kolkata, and Kochi experience flooding from several oceanographic processes, including storm surges resulting from cyclones, seasonal high tides, and a rapid rise in sea levels, are all related to climate change (MoEFCC, 2024). In many instances, tsunami flooding is the result of the coinciding effects of wave action and heavy monsoon rainfall that occur together to intensify the severity of the flooding.

Based on climate change projections, global average sea level rise is expected to occur faster than in the past and thus this represents a threat to coastal cities in India. The three combined, storm surge, high tide and extreme rainfall, illustrate the synergistic interaction of multiple driving forces that create a flood risk that exceeds the flood risk associated with any one driving force acting independently.

2.3.4 Flash Floods

Flash floods occur with little warning and are a high-velocity flood caused by heavy rainfall over small, steep, narrow valleys and highly responsive small watersheds *(*Zhao et al., 2024*)*. Flash floods can occur quickly and produce extremely high peak flows that can cause considerable damage and loss of life. An urban area with hilly or sloped terrain or that is close to small rivers that respond quickly to rainfall is particularly vulnerable to flash flooding. Table 3 shows the classification of urban flood types discussing primary causes , spatial pattern, magnitude etc..

Table 3 Classification of Urban Flood Types *Source: Compiled from Zhao et al. (2024), NDMA (2010), and Singh (2020)*

Flood Type	Primary Cause	Temporal Characteristics	Spatial Pattern	Magnitude	Affected Areas
Pluvial	Extreme rainfall exceeding drainage and infiltration capacity	Hours to <1 day	Distributed across urban areas; concentrated in low points	Highly variable; moderate to severe	All urban areas; highest in poorly drained zones
Fluvial	River/stream overflow due to upstream runoff and watershed saturation	Hours to days	Along river/riparian corridors; extends into floodplain areas	Depends on watershed size and precipitation	Cities in river valleys; low-lying adjacent areas
Coastal	Storm surges, high tides, sea-level rise; often compound with pluvial	Hours to 1-2 days	Coastal zones and low-lying inland areas near coast	Severe; extent increasing with climate change	Coastal metropolitan areas; deltaic regions
Flash Floods	Intense rainfall on small catchments; slope terrain; debris flows	Minutes to hours	Localized in small catchment areas; often in valleys or slopes	Very high peak flows; destructive	Hilly/sloped urban terrain; cities near small rivers

2.4 Impacts of Urban Flooding

Urban flooding generates multifaceted negative impacts spanning social, economic, and environmental dimensions. These impacts extend beyond immediate property damage to encompass longer-term disruptions to livelihoods, health, social cohesion, and environmental integrity.

2.4.1 Social Impacts

Loss of life and injuries: Urban flooding is one of the main hazards that people will face immediately; death will be among the first impacts, especially in the cases of the most vulnerable populations that are not even warned and are without escape capacity. Flash floods along with rapid onset pluvial flooding, in most cases, cause the highest death tolls than slow-rising riverine floods due to the limited time for warning and evacuation. Drowning, electrocution due to the existence of flooded electrical infrastructures, and injuries caused by debris are the main reasons for deaths that are directly related to floods.

Displacement and Livelihood Loss: When the flooding is severe, the Compiled by Authorities have no choice but to evacuate residents, and sometimes they may even have to stay away for a long time until the repair and restoration of infrastructure are completed. For the most vulnerable groups residing in informal settlements or marginal urban areas, evacuation is often a loss of income time. Daily-wage workers who are not able to reach their works during floods and recovery phases do not get paid; hence the disruption of income generates multiple economic and social vulnerabilities.

Health impacts: Flooding leads to the public health hazards like the transmission of waterborne diseases such as cholera, typhoid, and diarrheal diseases due to the contamination of drinking water supplies and the mixing of sewage with flood waters (NDMA, 2010). Moreover, flood-related injuries, health impacts, and psychological trauma among the flood survivors have been documented quite extensively. The mental health-related issues like depression, anxiety, and post-traumatic stress disorder are developed among the flood victims, especially after the very fierce incidents with a large number of deaths.

Psychosocial Effects and Social Disruption: Urban flooding not only affects the physical health but also causes huge psychosocial impacts such as trauma from very close to death experiences, sorrow from losing people who are dear to one, and anxiety caused by the loss of property and the need to move, among others.

2.4.2 Economic Impacts

Property Damage and Infrastructure Loss: Immediate financial effects encompass damage to structures, personal belongings, automobiles, and public infrastructure such as roads, bridges, drainage systems, and utility networks. The extent of such destruction can amount to billions of rupees in large cities; flood damages in India averaged Rs. 1,800 crores per year (1953-2010) with total estimated losses from 1953-2011 amounting to around Rs. 812,500 crores (around USD 97 billion) (Bardhan, n.d.).

Business Disruption and Economic Output Loss: Flooding interrupts commercial operations via various means: direct flooding of business locations, damage to inventory and equipment, transportation disruption hindering employee commuting and customer access, and interference with supply chains for both inputs and output distribution. The

time frame for business shutdown stretches far beyond the flooding incident, as the recovery of facilities, replenishment of stock, and rebuilding of trust take weeks to months.

Destruction of Productive Assets: Livelihoods reliant on agriculture in areas near urban settings experience damage to crops and loss of livestock. Industrial sites facing flooding suffer losses in equipment and production capability. Small and medium enterprises that are especially susceptible to flood effects often do not have financial reserves to handle losses or the capital needed to resume operations, which can lead to permanent business shutdowns and joblessness.

Decreased Investment and Economic Development: Frequent flooding deters sustained public and private investment in areas susceptible to floods, as investors view it as a high-risk situation with uncertain returns. Investments in infrastructure are shifted away from productive development to emergency aid and recovery, limiting the capital accessible for growth-focused investments. Flood-prone areas, over time, face diminished economic growth, decreased investment in health and education, and growing development disparities compared to regions not affected by floods.

Inflation and Increased Cost of Living: Post-flood recovery requires substantial public and private investment in reconstruction, often financed through reallocation from other budgets or public borrowing, potentially contributing to inflation. Disruption to supply chains raises prices of essential commodities. For low-income households with limited financial buffers, such price increases reduce purchasing power and nutritional intake.

2.4.3 Environmental Impacts

Ecosystem Disruption and Biodiversity Loss: Flooding disrupts urban and peri-urban ecosystems through submersion, erosion, siltation, and chemical contamination. Wetlands and riparian ecosystems, which are increasingly rare in urbanized areas, are particularly vulnerable to flooding-related disturbance. However, the systematic elimination of natural flood buffer areas-wetlands, floodplains, and riparian zones-for urban development has already eliminated much ecosystem capacity, while remaining ecosystems are under pressure from flood-related damage and degradation.

Soil Degradation and Contamination: The sediment and silt carried by the flood waters are deposited on agricultural and urban land, changing the structure and properties of the soil. Mixing of sewage, industrial effluent, and hazardous materials into flood waters causes chemical and biological contamination of the soils, groundwater, and any remaining surface water bodies. It may take many years to recover the contaminated soils and water with remediation and investment.

Groundwater and Water Quality Impacts: The infiltrated polluted surface water contributes to the contamination of groundwater aquifers during urban flooding. This

complicates the restoration of the water supply and can affect public health for years. Surface water bodies get highly contaminated with sewage, solid waste, and pollutants, reducing utility for drinking, irrigation, and ecosystem support.

Increased Solid Waste and Environmental Burden: Flooding generates enormous quantities of solid waste through damaged buildings, household contents, and debris. Urban waste management systems, already stressed in many Indian cities, become overwhelmed during and after major flood events, resulting in accumulation of waste and associated environmental and public health hazards.

2.5 Parameters of Urban Flooding in Indian context

Urban flooding in India is characterized through multiple measurable parameters that define the severity, extent, and nature of flood events. These parameters serve as indicators for identifying flooded areas, assessing vulnerability, and designing mitigation interventions appropriate to Indian urban conditions. The following section details key parameters used in Indian flood classification systems, their threshold values, and their application in urban flood management contexts.

2.5.1 Hydrological and Meteorological Parameters

Rainfall Intensity and Duration

Rainfall intensity is the key meteorological factor that causes urban flooding in Indian cities. The Indian Meteorological Department (IMD) categorizes rainfall into various severity levels: light spells (10–20 mm/hr), moderate spells (20–30 mm/hr), intense spells (30–50 mm/hr), very intense spells (50–100 mm/hr), extremely intense spells (>100 mm/hr), and cloudbursts (>100 mm/hr with high localization). The threshold of 30–50 mm/hr signifies the critical level at which the majority of urban drainage systems in Indian cities are unable to cope, leading to localized waterlogging and flooding on streets. In practical terms, short bursts of rainfall intensities surpassing 30 mm/hr generally exceed the design capacity of the majority of Indian urban drainage systems, which were historically designed for lower intensities.

Total rainfall accumulation during 24–48-hour intervals offer another essential factor for evaluating the severity of urban flooding. Rainfall amounts between 100–150 mm led to moderate urban flooding, causing considerable waterlogging in low-lying regions; totals from 150–250 mm result in severe, extensive inundation accompanied by infrastructure damage; and amounts surpassing 250 mm led to catastrophic urban floods that cause mass dislocation and economic devastation. Recent flooding incidents in India demonstrate this connection: Mumbai's 2005 disaster, which saw around 950 mm in 24 hours, resulted in catastrophic city-wide flooding; Kolkata's September 2025 event with 251.4 mm in 24 hours led to significant flooding impacting millions; Bengaluru's 130 mm in a single day in May 2025 interrupted transport systems.

The Impact-Based Forecast (IBF) system implemented by IMD applies rainfall intensity thresholds with a four-level warning structure: Stage 1 (3-4 days prior) issues a Heavy Rainfall Watch for notification; Stage 2 (48 hours) advances to an Alert demanding vigilance; Stage 3 (24 hours) provides a Warning that triggers emergency measures; Stage 4 (12 hours) delivers updates on imminent threats facilitating evacuations. This system converts technical rainfall parameters into practical administrative choices, demonstrating the understanding that parameter thresholds hold value only when incorporated into decision-making processes.

Flood Depth (Water Level)

Flood depth is the vertical distance between the ground level and the water surface elevation and is considered a main parameter in differentiating flooded and non-flooded areas, as well as different classes of severity. International standards, adapted in modified form by Indian practice, define water depth of 0.3 m (30 cm) and above as indicating flooded conditions. This 0.3 m threshold, while somewhat arbitrary, reflects a degree of hydrological significance: below 0.3 m, while this can cause considerable inconvenience and hazard, it usually does not lead to structural damage in buildings or make transport systems impassable.

The higher the depth threshold, the more severe the hazard: 0.5-1.0 m depths cause moderate damage to structures, force evacuation of ground-floor populations, and prevent vehicle passage; depths greater than 1.0 m cause severe structural damage, create life-threatening conditions for adults, and pose extreme hazard requiring emergency response. The CWC river flood classification system, applied in Indian contexts to fluvial flooding, defines hazard levels by water level relative to established warning thresholds: Warning Level, or WL (above-normal conditions requiring alert); Danger Level, or DL (typically 0.5-1.0 m above normal), "severe flood" with orange bulletin issuance and emergency mobilization; and proximity to the Highest Flood Level, or HFL, indicating extreme hazard.

The flooding in Delhi on September 2025 caused the Yamuna River to reach 206.03 meters, which is one of the highest levels seen in many years, causing thousands of people living in low-lying areas next to the river to evacuate from their homes. This flood event shows us how depth parameters become humanitarian issues and how they activate emergency response mobilization when they exceed a designated threshold.

River and Water Level Parameters

When forecasting and issuing the early warning phases of flood events for cities that are susceptible to fluvial floods, the water level recorded at the Gaging Station is a significant parameter. The Central Water Commission has established the National Flood Forecasting Network, which uses stream gages located at several locations to monitor the water levels of rivers through comparison of the measured water levels to three reference levels: Bank

full Level (normal channel capacity); Warning Level (WL); and Danger Level (DL). Bank full Capacity levels of rivers exceed the capacities of banks and overflow into flood plain areas; when the water level exceeds WL, an alert to prepare for flooding will be generated; when the water level exceeds DL, an activation for emergency response will occur. The Bank full Level, WL, and DL were developed using hydrological studies of historical flood events that provided governance actions based on evolving water levels.

2.5.2 Urban Morphology and Infrastructure Parameters

Impervious Surface Coverage Percentage

The amount of land that urban areas contain that has no impermeability, including concrete and asphalt surfaces as well as building rooftops and paved surfaces, is the basis for determining the level of flood level that can occur from urbanized areas. Since impermeably (or impervious) surfaced areas are incapable of allowing the pervasion of rainfall to become absorbed into the soil, this creates a rapid flow of water (surface runoff) into the rivers and creeks instead of allowing water to enter the groundwater strata. Past studies indicate that once impervious surface area coverage exceeds 35% of the urbanized area, the chance of flooding is greatly increased; if the amount of impervious area exceeds 50% of the urbanized area, the chance of flooding is extremely high and severe drainage problems are foreseeable. Mumbai's central business district (CBD) and other urban centres with a high density of buildings generally exceed the 70% mark for coverage, making them extremely vulnerable to flooding from a moderate rain event since the drainage systems cannot handle the volume of water generated from these areas of coverage.

The amount of coverage for the impervious surface parameter should have planning implications with regard to zoning, in that zoning should restrict the density of development in designated flood plain areas to reduce the total coverage of impervious surfaces; as well as through development regulations requiring the incorporation of green space and permeable surface areas to lower the overall amount of impervious surface coverage; while also through retrofitting existing development areas with both green infrastructure and permeable pavement to effectively decrease the total amount of impervious surface coverage and enhance the resiliency of the area to flooding events.

Drainage System Capacity

Urban drainage infrastructure comes with a designed capacity, generally expressed in terms of millimetres of rainfall per hour that the system can handle without overflowing. Storm drainage systems in most Indian cities were designed several decades ago for 25 mm/hr capacity, based on historic rainfall statistics. However, extreme rainfall events of today have started surpassing such design limits fairly regularly; current events that produce 50–100 mm/hr rainfall are 2–4 times the historic design capacity and thus lead to system overflows and localized flooding.

The parameter "deficit between design capacity and actual rainfall events" directly determines the frequency of flooding: where design capacity is adequate for events of expected frequency, flooding is minimal; where design capacity is exceeded by routine events, flooding becomes chronic. The drainage system in Mumbai, nominally designed for 25 mm/hr but facing rainfall events of 50+ mm/hr, experiences floods following monsoon rains that would have been manageable decades ago. This infrastructure adequacy parameter is crucial to determining modernization needs and whether expansion alone will suffice, or fundamental redesign incorporating climate change projections is called for.

Green Space and Natural Water Body Coverage

The share of the urban area that consists of parks, open spaces, water bodies, and vegetated areas is another crucial parameter. Green spaces and water bodies yield a natural drainage function because of infiltration, evapotranspiration, and temporary storage capacity. Urban areas with less than 30% green space coverage lack adequate natural infiltration capacity and are thus more vulnerable to flooding, while urban areas with green spaces over 30% will show improved resilient drainage.

Systematic loss of a water body due to urban encroachment-lakes, tanks, wetlands-represents especially grave parameter degradation. For example, the removal of one 10-hectare lake eliminates its flood storage capacity of millions of cubic meters. The documented loss of more than 90% of lakes in Bengaluru in recent decades-from about 1,400 water bodies to fewer than 150-directly correlates with escalation in flood frequency and severity. Restoration of water bodies, even partially, acts to improve flood resilience directly through the recovered storage and infiltration capacity.

2.5.3 Temporal and Duration Parameters

Urban Flood Duration

The duration that regions stay flooded after overflow events is a key factor influencing health consequences, economic disruption, and recovery needs. Flooding that endures for less than 12 hours results in minor disturbances aside from immediate dangers; flooding that persists for 24–48 hours raise health risks due to exposure to waterborne illnesses and prolongs disruptions to livelihoods; flooding that lasts over 48 hours leads to serious health issues, potential disease outbreaks, and significant economic damages. According to NDMA guidelines, if flooding lasts more than 2 days, emergency public health measures and extensive relief efforts are necessary.

Duration is affected by various factors: drainage efficiency (higher capacity systems remove floodwaters more quickly); topography (in basins with inadequate drainage, water lingers longer); rainfall continuation (if heavy rain persists, water levels stay high);

and management of drainage efforts (the operation of sluice gates and pumps impacts the drainage speed).

Flood Event Frequency and Return Period

The rate at which flood events of particular sizes take place is another essential factor. Hydrology typically defines floods by their return period: a "25-year flood" is a magnitude anticipated to happen once every 25 years on average; a "100-year flood" occurs once every 100 years on average. Nonetheless, climate change is changing precipitation patterns, rendering historical frequencies irrelevant: incidents once considered "100-year floods" now happen more often.

Recent urban flooding in India illustrates this trend: major cities have seen a significant rise in the occurrence of "extreme" rainfall events (>100 mm/day) in recent decades. Delhi encountered several similar occurrences in 2025, indicating a significant change in return intervals that necessitate revised design standards.

2.5.4 Vulnerability and Exposure Parameters

Population Exposure in Flood-Prone Areas

The population numbers and population proportions of individuals who live within flood prone areas is a vulnerability statistic of utmost importance. Any city where more than 30% of the total population resides within flood-prone areas will have a high degree of social vulnerability; this statistic is particularly critical when those populations also include those deemed vulnerable (e.g., children, the elderly, the disabled, and/or low-income households) and therefore possess minimal capability to adapt to or cope with flooding incidents. Areas of informal settlement usually contain high areas of spatial exposure (floodplains/low-lying lands) and high areas of demographic exposure (e.g., low-income), therefore being doubly vulnerable.

Protective infrastructure likely exists in flood prone locations, i.e., hospitals; power sub-stations; water treatment facilities; transportation terminals; and communication systems. Flood incidents from the flooding of one hospital will adversely affect the health care delivery system of the entire City; flooding of a power substation will interrupt electricity for hundreds of thousands of people. By overlaying flood hazard maps over critical infrastructure location maps, municipalities will identify the areas of critical infrastructure requiring the greatest level of intervention. To establish resilience for critical infrastructure located in the highest flood risk areas, these municipalities will establish protective measures, relocate or enhance resilience of responsible infrastructure to an acceptable level.

2.5.5 Quantitative Threshold Summary

The following Table 4 shows parameters and thresholds are directly applicable to Indian urban flood management:

Table 4 Parameters of Urban flooding

Source - Author

Parameter	**Threshold Value**	**Classification**	**Reference**
Rainfall Intensity	30–50 mm/hr	Urban drainage overwhelmed	IMD; NDMA
Rainfall Intensity	>100 mm/hr	Extreme; cloudburst threshold	IMD
24-hr Total Rainfall	100–150 mm	Moderate urban flooding	Indian city cases
24-hr Total Rainfall	150–250 mm	Heavy urban flooding	Indian city cases
24-hr Total Rainfall	>250 mm	Severe/catastrophic flooding	Indian city cases
Flood Depth	≥0.3 m	Flooded area threshold	UNESCO; adopted practice
Flood Depth	0.5–1.0 m	Moderate hazard	International standards
Flood Depth	>1.0 m	Severe hazard	International standards
Drainage Design Capacity	25 mm/hr	Historical Indian standard	CWC; NDMA
Impervious Surface	>35%	Flood risk escalation	Research

Integrated Urban Flood Mitigation Framework- A Case of Lucknow, Kritika Pandey (24209011113)

Parameter	Threshold Value	Classification	Reference
Impervious Surface	>50%	Very high flood risk	Research
Flood Duration	>24–48 hrs	Health and economic impact threshold	NDMA
Population Exposure	>30% in flood-prone	High social vulnerability	Vulnerability assessment
Green Space Coverage	<30%	Reduced infiltration capacity	Urban ecology research

These parameters, rooted in Indian standards (NDMA, CWC, IMD) and international practice adapted to Indian contexts, provide quantitative basis for classifying areas as flooded, assessing severity, prioritizing interventions, and evaluating mitigation effectiveness. Their measurement and monitoring constitute essential foundation for evidence-based urban flood management in Indian cities.

2.6 Urban Flood Governance and Policy Framework

Urban flood management effectiveness is substantially determined by governance structures, policy frameworks, and institutional arrangements shaping how multiple actors coordinate and implement mitigation strategies.

2.6.1 Governance Structures for Urban Flooding

Effective urban flood governance requires coordination across several organizational levels and sectoral domains. The organizational landscape comprises the following:

1. National Level: National Disaster Management Compiled by Authority (NDMA), Ministry of Housing and Urban Affairs (MoHUA), Central Water Commission (CWC), Ministry of Environment, Forests and Climate Change (MoEFCC), and Indian Meteorological Department (IMD)
2. State Level: State Disaster Management Compiled by Authorities, state water resources departments, state urban development Compiled by Authorities, and state environmental agencies

3. Local/Municipal Level: Urban Local Bodies (ULBs), municipal corporations, municipal health and sanitation departments, specialized agencies of traffic, utilities, fire, emergency services
4. Community Level: Resident associations, civil society organizations, and community-based organizations

Such coordination across levels and sectors is necessary but often lacking, leading to service gaps and fragmented responses. -NDMA, 2023. A comprehensive framework for managing urban floods in informal settlements identifies five interrelated themes: governance or institutional arrangements and clarity of roles; community capacity or knowledge, resources, and organizational ability; resilience or adaptive capacity and recovery speed; perception of floods or community understanding and behaviour; and future thinking or anticipatory planning. -Tillermuir et al., 2025. The framework argues that the application of these dimensions to informal settlements necessitates pragmatic recognition of the socioeconomic constraints, the limited presence of formal institutions, and land tenure insecurity that characterizes the informal urban areas. -Tillermuir et al., 2025.

2.6.2 Indian Policy Context

NDMA's Guidance/Documents Standards: The National Disaster Management Compiled by Authority has produced Urban Flood Guidance/Standard Operating Procedures that offer detailed guidance and process definitions for all urban local bodies operating in India to effectively manage urban flooding (NDMA, 2010, 2023). These guidance documents stress the importance of establishing Emergency Operations Centres (EOCs) within each city, which will consist of representatives from all relevant agencies working together to define their roles with respect to coordinating efforts during a flood event, developing new public policy for responding to urban flooding, monitoring and tracking urban flooding within their jurisdiction, managing information related to urban flooding and communicating with residents about urban flooding (MoHUA, 2023).

MoHUA Flood Management Policies for Urban Areas: The Ministry of Housing and Urban Affairs (MoHUA) has created frameworks to develop a comprehensive integrated urban flood risk management system that consists of a combination of structural and non-structural strategies and identifies and supports nature-based solutions to manage urban flooding (MoHUA, 2023). In recent years, the frameworks developed by MoHUA have increasingly focused on building climate resilience through urban planning. This is due to the fact that historical trends of rainfall do not accurately reflect the impact of future climate change and that urban planning must take climate resilience into account from the initial planning stages of the process.

There are several issues related to the implementation of these policy frameworks, including:

1. The capacity and skillset of municipalities to adequately implement urban flooding policies is very limited
2. Funding for urban flooding management policies is insufficient when considering all of the required infrastructure needs (finance versus infrastructure already constructed)
3. There is a lack of clear demarcation of responsibility among agencies
4. The enforcement of land use and environmental regulations is weak
5. The lack of community involvement in the development and implementation of flooding management plans is a major issue and
6. The lack of consideration for the informal settlements and vulnerable populations affected by flooding (NDMA, 2023; World Bank, 2022).

2.7 Urban Flood Mitigation Strategies

Literature identifies a portfolio of mitigation strategies spanning structural (Gray infrastructure) approaches, non-structural measures, nature-based solutions (green-blue infrastructure), and integrated frameworks combining multiple approaches. The effectiveness and appropriateness of specific strategies depend on local conditions, institutional capacity, and available financing.

2.7.1 Structural Measures

Structural measures consist of constructed systems intended to control flood waters via transport, retention, or prevention. Historically, urban flood management has been primarily governed by these "grey infrastructure" methods, although they are now more often combined with non-structural and nature-based strategies.

Development and Expansion of Drainage Systems: Enhancing stormwater drainage systems involves the enlargement of surface channels and underground sewers, engineered to handle design storm events, which is a crucial structural strategy (NDMA, 2010; Kumar & Singh, 2018).

Sure, please provide the text you would like me to paraphrase. A well-designed drainage system takes into account:

1. selection of design storms (usually events with a 25-year or 50-year return period),
2. network setup reducing travel time to outfalls,
3. choosing materials for strength and hydraulic performance, and
4. upkeep procedures guaranteeing functional capability.

Nevertheless, the expansion of drainage systems encounters numerous challenges: substantial capital costs limit coverage, especially in developing nations; continuous maintenance needs create ongoing budget strains; design storms could prove insufficient due to climate change-related extreme rainfall intensification; and swift urbanization frequently surpasses drainage expansion, perpetuating or widening the disparity between runoff generation and conveyance ability.

Pumping Facilities and Flood Management Reservoirs: In regions where gravity drainage to natural discharge locations is not feasible (low-lying zones, enclosed basins), mechanical pumping facilities facilitate the transfer of water from lower regions to elevated discharge points (NDMA, 2010). Although effective, pumping stations depend on a dependable power source, consistent upkeep, and operational oversight—issues prevalent in developing nations.

Flood control reservoirs and retention basins, situated in key areas of watersheds, temporarily hold floodwaters, lessening peak flows and mitigating downstream flood intensity (Singh, 2020). Reservoir management demands expert coordination with other water users (irrigation, water supply, hydropower), and advantages are constrained when extreme rainfall events exceed storage limits.

Embankments and Flood Defences: The construction of embankments along the banks of rivers and elevated drainage channels offers protection to areas behind defences but concentrates and accelerates flood waters, thereby often increasing the magnitude of flooding downstream. This "hard defence" paradigm has traditionally been the approach but is increasingly recognized as being inadequate when used in isolation, particularly under climate change scenarios with increased extreme precipitation.

Integrated 1D-2D urban drainage modelling: Advances in computational modelling, in particular the integration of 1D (network model) and 2D (surface inundation model) hydrodynamic simulations, have enabled detailed assessment of urban flood risk and evaluation of proposed interventions (Bardhan, n.d.). High-performance computing techniques, including GPU acceleration, now allow simulation of high-resolution models comprising millions of elements that represent the real urban geometry at a fine resolution, thereby allowing more detailed planning and design. Such modelling helps optimize the drainage system design, identify critical bottlenecks, and assess the performance under climate change scenarios.

2.7.2 Non-Structural Measures

Mitigation that is non-structural uses Institutional/regulatory/planning/awareness approaches as a means to decrease vulnerability without primarily relying on engineered infrastructure for risk/mitigation. Non-structural mitigation methods typically allow for the most cost-effective reduction in risk with a special focus on developing countries where resources are limited (Bardhan, n.d.).

Land Use Planning/Flood Risk Zoning: The implementation of strategic land use planning will significantly reduce the number of people and assets at risk of flooding (e.g., historical floodplains; areas below dam(ridge) outlets; low-lying areas with poor drainage) by restricting developments that are in high-risk flood zone(s) (NDMA, 2010; Roy & Das, 2021). Zoning regulations are an effective tool for providing guidance on

development away from the highest-risk flood areas by establishing allowable use, allowable density, and development standards.

The implementation of flood zoning in developing countries typically fails due to intense political pressure to develop, a lack of resources/resources for the enforcing of regulations, and competing demands from a limited supply of urban land. Informal settlements are typically found in areas where demand for land is lowest (e.g., most affordable) and enforcement of building regulations is weak, and the population residing in these areas is vulnerable and also dependent on proximity to urban centres for their livelihoods, making relocation complex and difficult to achieve.

Building Code/Flood-Proofing Standards: Building Codes may incorporate elements of flood-proofing such as elevated building plinths, flood-resistant building materials, elevated utilities, and emergency access provisions (NDMA, 2010; MoHUA, 2023). Flood-proofing elements will help to mitigate property loss and increase the level of safety for occupants during a flood.

Flood Forecasting and Early Warning: Real-time rainfall monitoring, hydrological forecasting, and early warning systems development enable advance notice of impending floods, allowing evacuations and the positioning of emergency responses (Young et al., 2025). High-resolution rainfall forecasts have been combined with hydrological and hydraulic models to assist decisions by flood responders. Limitations involve the demands on technical capacity and availability of data in data-scarce regions, as well as adequacy of lead times for action to be effective (Young et al., 2025).

Disaster Preparedness and Community Awareness: Public education on flood risks, appropriate responses, evacuation procedures, and post-flood recovery increases resilience in the community. Community preparedness minimizes mortality, hastens recovery, and spreads knowledge that reduces risk in a wide manner. Nevertheless, awareness programs capture variable audiences, and effectiveness depends on the behavioural response towards awareness.

Institutional Coordination and Emergency Response Planning: Establishment of EOCs at city levels with multiple agency representatives from municipal corporations, health, police, fire, utilities, etc., assists in coordinating disaster response and mobilization of resources. Standard operating procedures spell out role and responsibilities and sequence of actions required during emergencies, thereby saving time and reducing confusion due to coordination delays.

Flood Insurance and Financial Protection Mechanisms: Insurance mechanisms can transfer flood risk from property owners and government to broader risk pools, enabling faster recovery post-flood (Bardhan, n.d.). However, insurance uptake remains limited in many developing countries due to cost barriers for low-income populations and

inadequate policy design for small-scale properties. Government-backed insurance schemes can extend coverage but require substantial public investment.

2.7.3 Nature-Based Solutions

Nature-based solutions (NBS) or green-blue infrastructure integrate natural ecosystem processes into urban water management, providing flood mitigation benefits while generating co-benefits including water quality improvement, ecosystem habitat provision, urban cooling, and enhanced liveability. (Ali et al., 2025; Roy & Das, 2021)

Green Infrastructure Elements:

The use of plants on the exterior surfaces of buildings by installing vegetated roof systems (also known as green roofs) and vertical gardens (also known as green walls) provides rainwater control, evaporate excess moisture from inside the building, and reduce the amount of stormwater runoff from the building site (Ali et al., 2025). Modelling research of the performance of green roofs in New Cairo, Egypt showed that when individually installed, the stormwater volume effective capture for a green roof's only stormwater volume was only 9.9%. This is considerably lower than the stormwater volume capture for all other NBCs and suggests that although green roofs provide many benefits for buildings in cities, when they are installed as single structures, they may have less impact than when compared with other natural solutions for arid/semi-arid locations (Ismaeel & Mustafa, 2025).

Both rain gardens and bioswales are vegetated depressions or channels used to pull stormwater from a site, allow for merging stormwater into the soil and utilizing the natural filtering through the foliage of selected native plants in conjunction with the soil (Ali et al., 2025). Both of these solutions can be built on a limited budget and can be easily scaled to all urban environments to provide stormwater control by creating a distributed application for multiple urban landscapes. For the research completed in New Cairo (Egypt), rain gardens produced the greatest volume of stormwater capture, producing a stormwater volume capture of 43.6%, significantly greater than green roofs and comparable to other NBS options.

In comparison to asphalt and concrete, permeable pavements are made with porous surfaces allowing for stormwater to infiltrate rather than rolling off the surface due to impervious surfaces (Ali et al., 2025). As a result of installing permeable pavement throughout most of New Cairo, the simulation scenarios for this geographical area showed that permeable pavement provided the greatest amount of volume capture from stormwater.

Urban parks, green spaces, and tree canopy provision enhance infiltration, reduce surface runoff through vegetation interception, and provide multiple co-benefits including

reduced urban heat island effect, improved air quality, and enhanced community well-being (Roy & Das, 2021).

Blue Infrastructure Elements:

Wetland restoration and construction establish or rehabilitate natural wetland systems in urban environments, offering water storage capabilities, infiltration chances, and habitats for ecosystems (Ali et al., 2025; Green Infrastructure Hub, 2023). Rehabilitated wetlands enhance biodiversity and offer recreational and educational benefits.

Stream channel restoration eliminates channelization and reinstates natural channel shape, riparian plants, and floodplain connections, allowing natural flood mitigation processes (Roy & Das, 2021). Reconnecting floodplains with channels reinstates the natural ability of systems to temporarily hold floodwaters, lessening peak flows downstream.

Built ponds and detention basins offer temporary water retention during flooding, enabling gradual release during non-flood times (Roy & Das, 2021). These attributes blend into cityscapes as both leisure and visual components, offering additional advantages aside from flood control.

Efficiency and Efficacy of Nature-Inspired Solutions:

Recent studies indicate the effectiveness of NBS varies significantly based on:

1. particular kind of intervention and extent,
2. characteristics of climate and precipitation,
3. geological and hydrological conditions,
4. distribution in space and strength of execution, and
5. quality of design and maintenance (Ali et al., 2025; Kim & Kim, 2025).

A study conducted in Melbourne, Australia, found that the effectiveness of NBS is limited by several factors, such as insufficient real-time monitoring data, challenges in regional parameterization that need site-specific calibration, financial limitations affecting the scale of implementation, poorly developed maintenance protocols, and knowledge deficiencies concerning long-term performance in climate change scenarios (Ali et al., 2025). Professionals applying GI encountered obstacles related to design and performance modelling unpredictability, higher construction costs compared to traditional grey infrastructure, and the allocation of maintenance responsibilities between public and private organizations (Ali et al., 2025).

The bibliometric analysis of GI research (2015-2024) reveals that while research has increasingly adopted multifunctional and socio-ecological perspectives recognizing GI's broader benefits, persistent knowledge gaps remain regarding:

1. longitudinal performance evaluation under climate change,
2. governance frameworks for maintenance and operation,
3. scalar integration from site-specific interventions to watershed-level outcomes, and
4. inclusive design ensuring equitable benefits across income and demographic groups (Kim & Kim, 2025).

Roof Rainwater Harvesting for Flood Mitigation: Roof rainwater harvesting systems, capturing rainfall from building surfaces for non-potable uses (toilet flushing, landscape irrigation, cleaning), effectively reduce surface runoff generation. Analysis in Hamadan, Iran (an arid region), using hydrological connectivity indicators, demonstrated that roof rainwater harvesting implementation substantially reduced flood severity through decreased runoff connectivity between upstream and downstream areas (Lu et al., 2025). Areas with very high hydrological connectivity in the absence of harvesting systems decreased to 11.4%, while moderate and low connectivity categories increased substantially (Lu et al., 2025). However, success depends on adequate technical infrastructure, regulatory frameworks permitting non-potable water reuse, and community acceptance of alternative water sources (Lu et al., 2025).

Blue-Green Infrastructure Integration: Integrated approaches combining green infrastructure (vegetated systems, permeable surfaces) with blue infrastructure (water bodies, detention systems) create multifunctional landscapes managing stormwater while providing habitat, recreation, and cooling benefits (Blue Infrastructure Working Group, 2025). Blue-green infrastructure mimics natural hydrological processes, capturing and filtering water, increasing infiltration, and reducing burden on conventional drainage systems. Examples including Los Angeles's green streets (capturing and recharging 13 million gallons annually into groundwater) and San Francisco's Urban Watershed Assessment Framework demonstrate practical implementation pathways (Blue Infrastructure Working Group, 2025).

2.7.4 Integrated Approaches and Adaptive Management

Recent scholars increasingly support integrated spatial strategies that draw from, incorporate or build upon, structural, non-structural, and nature-based approaches, whilst tailoring the strategies to the needs of specific local settings through the adoption of Adaptive Management Frameworks that are flexible enough to adapt to a constantly evolving situation in a community (NDMA, 2023; MoHUA, 2023; Collins et al., 2025). Table 5 provides Integrated Urban Flood Management Strategies listed against Cause; as many of the strategies used for managing floods are based on causes and environmental behaviours and effect of climate impact.

Table 5 Integrated Urban Flood Management Strategies *Source: Compiled from NDMA (2010), MoHUA (2023), World Bank (2020), Fang et al. (2023), and O'Donnell et al. (2020)*

Cause	**Primary Strategy**	**Supporting Strategies**	**Integration Logic**
Impervious Surfaces	Green infrastructure (green roofs, rain gardens, permeable pavements)	Drainage expansion for extreme events; density planning	Address root cause through infiltration while providing conveyance backup
Water Body Encroachment	Land use planning protection + riparian restoration	Wetland restoration; stream daylighting; community monitoring	Prevention (stop further encroachment) + restoration (recover capacity)
Inadequate Drainage	Drainage modernization to contemporary standards	Green infrastructure reducing demand; planning preventing further growth	Upgrade infrastructure + reduce burden through distributed green solutions + planning
Extreme Rainfall Intensification	Forecasting & early warning	Emergency planning; community preparedness; shelter identification	Cannot prevent but can enable response
Planning/Development Coordination Gaps	Integrated urban planning incorporating flood risk	Building codes for flood-proofing; zoning enforcement; inter-agency protocols	Systematic integration addressing governance root cause
Governance Fragmentation	Multi-level coordination mechanisms; institutional reform	Cross-sectoral planning; clear responsibilities; resource mechanisms	Address institutional root cause enabling all other strategies

The defining characteristics of an Integrated Urban Flood Management Framework includes;

1. A structured and systematic understanding on the causes and drivers of Urban Flood risk.

2. An Inclusive and comprehensive flood impact, hazard and risk assessment at a local government level.

3. Coordination and collaboration between the all related and collective stakeholder participants (urban planning professionals, architects, engineers, emergency management professionals, community representatives)

4. Combines Intervention for Prevention (avoiding exposure), Preparedness (managing unavoidable risks), Response (managing flood events), recovery (building back better);

5. Promoting equity and inclusion, giving the most vulnerable population priority in terms of risk reduction;

6. Providing Adaptive Management that advocates monitoring outcomes and adjusting strategies according to changing conditions; 7. Incorporating with broader Urban Development and Sustainability (NDMA, 2023; MoHUA, 2023; World Bank, 2022).

2.8 Case Studies and Contemporary Examples

Urban flooding in Indian cities presents complex, multi-causal challenges requiring integrated mitigation approaches. Contemporary flood events in major Indian metropolitan areas—Delhi, Bengaluru, Kolkata, and Mumbai—illustrate how inadequate drainage infrastructure, unplanned urbanization, loss of natural water bodies, and intensifying rainfall due to climate change interact to create severe urban flood impacts. This section examines four case studies: three from major Indian cities experiencing recent severe flooding, and one demonstrating integrated nature-based solution implementation applicable to Indian urban contexts.

2.8.1 Delhi-NCR September 2025 Yamuna River Flooding

In September 2025, the Yamuna River in Delhi reached its highest water level in recent years, attaining 206.03 meters—exceeding the evacuation threshold of 206 meters and approaching the Highest Flood Level (HFL) (NDMA, 2025). This extreme flood event resulted from compound hydrometeorological factors: excessive rainfall in the Yamuna catchment across nine upstream districts in Haryana and Uttar Pradesh, combined with significant rainfall in Delhi itself during the first week of September 2025, generated unprecedented runoff into the river (Sustainable Development Goals Research Project Institute [SANDRP], 2025).

The causative rainfall pattern represented extreme conditions: multiple districts upstream of Delhi received excess to large-excess rainfall during September 1-4, 2025, while Delhi itself experienced persistent, heavy precipitation. The Indian Meteorological Department

(IMD) rainfall data indicated rainfall intensities and volumes that substantially exceeded historical patterns, triggering the extraordinary Yamuna response (SANDRP, 2025). Figure 6 shows the visual expression of urban flooding scenario of Delhi.

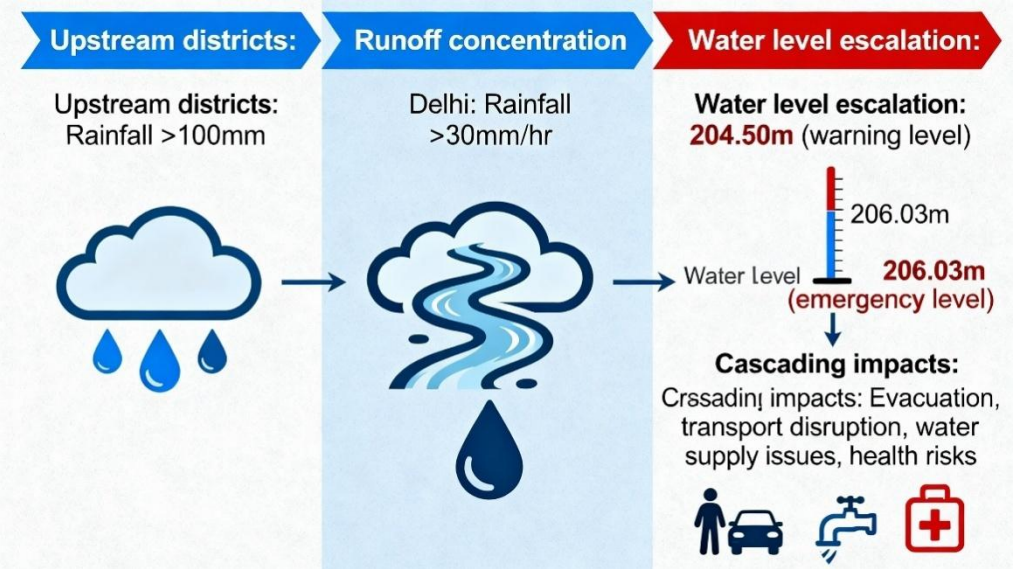


Figure 6 Urban Flooding Scenario of Delhi *Source - Compiled by Author*

Impacts and Vulnerability Manifestation

The elevated water level necessitated evacuation of thousands of residents from low-lying areas adjacent to the Yamuna floodplain, particularly in east Delhi neighbourhoods including Mayur Vihar, where flood relief camps were established to shelter displaced populations (NDMA, 2025). The event demonstrated that despite policy frameworks, institutional structures, and planning guidelines developed since previous major floods, implementation gaps persist, leaving populations in floodplain areas highly vulnerable to extreme events (NDMA, 2025).

The September 2025 event directly paralleled July 2023 flooding, when the Yamuna similarly reached extreme levels, indicating that within a two-year interval, the river reached extreme flood status twice—a pattern suggesting either increased frequency of extreme rainfall generation in the Yamuna catchment or potential shift in baseline precipitation regimes. This frequency escalation has profound implications for flood risk management design standards, which historically assumed longer return periods for such extreme events (SANDRP, 2025).

Governance and Institutional Response

The flood response revealed both institutional capacity and critical limitations: evacuation procedures were activated at appropriate water level thresholds, early warning systems functioned, and disaster management agencies coordinated relief operations. However,

the persistence of large populations in high-risk floodplain areas, despite decades of awareness and planning, underscores fundamental disconnects between policy intent and ground reality. Many floodplain residents lack alternatives—alternative housing options in safer locations are inaccessible due to economic constraints, and relocation programs remain incomplete (NDMA, 2025).

Implications for Framework Development

The Delhi case demonstrates that infrastructure capacity thresholds, institutional coordination structures, and emergency response systems, while necessary, remain insufficient without addressing root causes: continued occupation of high-risk floodplain zones, climate-driven intensification of rainfall, and inadequacy of drainage systems designed for historical rainfall statistics. Future mitigation requires integration of long-term land-use planning restricting floodplain occupation, climate-adaptive drainage design, and restoration of natural storage areas (floodplain wetlands, green spaces) that would accommodate extreme rainfall runoff (NDMA, 2025).

2.8.2 Bengaluru May 2025 Pre-Monsoon Cloudburst and Systematic Urban Flooding

Event Overview and Hydrometeorological Catastrophe

On May 18, 2025, Bengaluru experienced a pre-monsoon cloudburst delivering 130 mm of rainfall within a 12-hour period, representing an extreme rainfall intensity of approximately 10.8 mm/hr—well above the city's drainage design capacity and exceedingly even IMD's "extremely intense spell" classification threshold of 5-10 cm/hr. This single rainfall event pushed cumulative May 2025 rainfall to 278 mm, representing 157 percent above normal seasonal rainfall and nearly one-fifth of Bengaluru's annual average precipitation.

Cascading Urban Flooding and Infrastructure Failure

The extreme rainfall triggered cascade failures across multiple urban systems simultaneously. Over twenty urban lakes overtopped, exceeding storage capacity and inundating surrounding developed areas; three lives were lost to direct flood impacts, and more than 500 dwellings were submerged. Critically, many of the 20+ lakes that overtopped existed in degraded condition, having lost much of their natural storage and infiltration capacity through decades of encroachment and ecosystem degradation. The flooding demonstrated that even restoration efforts remain insufficient when rainfall intensity vastly exceeds system design capacity.

The May 2025 event revealed structural vulnerabilities compounding the immediate rainfall response. Critical infrastructure failures included IT corridor flooding (notably

Whitefield area), stranding workers and disrupting business operations; widespread power outages from electrocution and equipment damage; and potable water system disruptions. Social impacts included displacement of vulnerable populations, damage to informal dwellings, and disruption of informal economy livelihoods dependent on daily mobility.

Root Cause Analysis: Urbanization and Ecosystem Degradation

Bengaluru's extreme vulnerability to the May 2025 event reflects decades of uncontrolled urbanization without corresponding infrastructure upgrades or ecosystem preservation. The city's fundamental hydrological challenge—lacking a major river system for gravity-based drainage, unlike Delhi (Yamuna) or Chennai (Coum)—necessitates reliance on interconnected lake and valley systems for natural drainage and flood retention.

However, systematic destruction of this natural infrastructure has eliminated the city's inherent flood mitigation capacity. Between 1972 and 2025, Bengaluru's lakes declined from approximately 1,452 documented lakes to fewer than 190 remaining—a loss representing approximately 87% of urban water bodies. A 2016 assessment indicated that 80% of Bengaluru's lakes have been lost or degraded, severely reducing urban flood absorption and groundwater recharge capacity. Remaining lakes face severe degradation through encroachment, with lake beds and interconnecting valley zones illegally occupied, disrupting natural water flow patterns. Figure 7 shows the strong contrast as described.

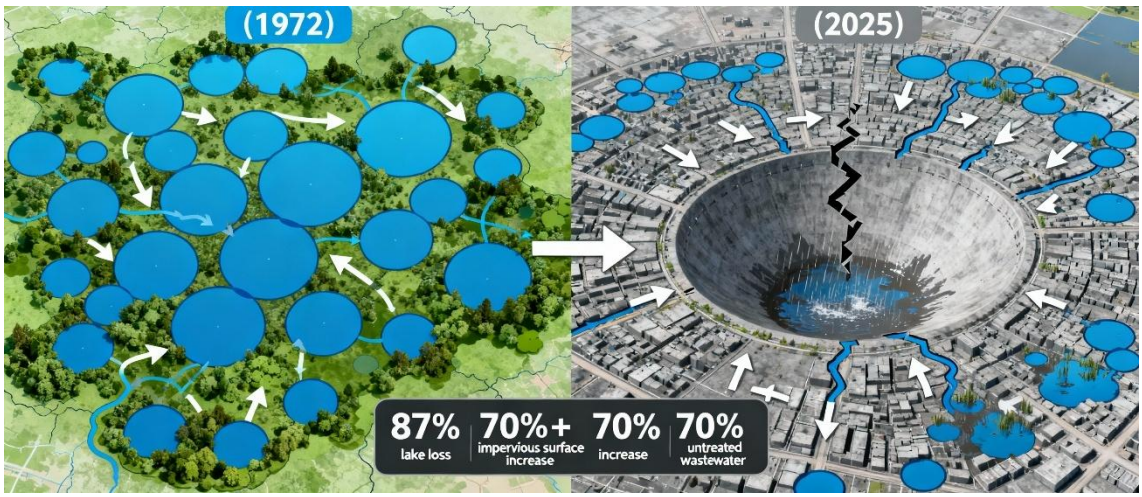


Figure 7 Illustration comparison of Drainage of Bangalore from 1972 to 2025 *Source - Compiled by Author*

Concurrently, drainage infrastructure has failed to scale with urban population growth. Bengaluru's stormwater drains, designed for a smaller population and lower rainfall intensity, operate far below required capacity for current urban area and contemporary rainfall extremes. The Bruhat Bengaluru Mahanagara Palike (BBMP), the municipal Compiled by Authority responsible for stormwater management, has struggled to upgrade drainage infrastructure, with repeated clogging from solid waste exacerbating drainage

failure. Bengaluru treats only 30% of its 1,800 million litres daily wastewater generation, with untreated sewage clogging drains and entering lakes, further degrading water body functionality.

Topographical constraints compound these anthropogenic factors. At 900 meters elevation and lacking gradient-based gravity drainage, Bengaluru's drainage depends entirely on lake systems and valley interconnections. Elevation changes directing runoff toward low-lying zones, combined with lake loss and encroachment, create "saucer" effects—topographical depressions where water accumulates without gravity-based drainage outlet, necessitating mechanical pumping for water removal. When pumping capacity is overwhelmed by rainfall intensity, these depressions become persistent waterlogging zones.

The May 2025 rainfall represented not merely an extreme individual event, but indicator of intensifying climate dynamics affecting Indian monsoon and pre-monsoon rainfall patterns. IMD data indicates systematic rise in rainfall intensity over recent decades, with Bengaluru receiving nearly 20% of annual precipitation in compressed 20-day periods, compared to more distributed rainfall historically. Cyclonic circulations, troughs, and pre-monsoon thundershowers triggering extreme rainfall have intensified substantially.

Critically, the frequency of such extreme rainfall events appears to be increasing. If May 2025 represents a "once-in-50-year" event under historical climate statistics, yet occurs with increasing regularity under current conditions, this suggests fundamental non-stationary shift in precipitation regimes requiring upgraded design standards and mitigation strategies.

Institutional and Policy Response Gaps

Despite Bengaluru's status as a major IT centre, national icon of economic development, and Smart City initiative participant, the May 2025 event demonstrated that urban development continues without corresponding hydrological infrastructure or ecosystem protection. Flood mitigation measures have focused primarily on drainage system upgrades, yet these address only symptoms rather than root causes: without lake restoration, the city remains structurally dependent on rainfall infiltration capacity that has been systematically eliminated. Without limits on urban density and impervious surface expansion, runoff generation rates continue escalating.

Encroachment of water bodies has continued despite formal designation as protected areas, indicating governance failure—Compiled by Authorities possess regulatory Compiled by Authority to prevent encroachment, yet tacit approval of violations continues due to political economy of development prioritizing property development over water security. Restoration of the few remaining lakes and halting ongoing encroachment represent necessary but insufficient interventions; regenerating even half

of Bengaluru's lost water bodies would require acquisition of developed property—extremely expensive and politically unfeasible.

Implications for Integrated Mitigation Framework

The Bengaluru case demonstrates that isolated technical infrastructure upgrades cannot substitute for ecosystem restoration and development density management. The city requires integrated approach encompassing:

1. systematic restoration of priority water bodies to create flood retention capacity;
2. enforcement of restrictions on further lake/valley encroachment;
3. comprehensive wastewater treatment to eliminate sewage contamination of drainage systems;
4. green infrastructure in developed areas to increase infiltration and reduce runoff;
5. land-use planning restricting development density to sustainable levels; and
6. climate-adaptive design standards reflecting contemporary rainfall extremes rather than historical statistics (AIDMI, 2025).

2.8.3 Lucknow Urban Flooding: River Constraints and Drainage Infrastructure Failures

Overview and Geographic Context

Lucknow, the capital of Uttar Pradesh with approximately 4 million residents, has emerged as a notable urban flooding case study despite historical classification as a non-flood city. The Gomti River, a tributary of the Ganga flowing 30 km through urban Lucknow, represents the city's primary drainage outlet (Hindustan Times, 2025). The city's transition from non-flood to flood-prone status within 3-4 years reflects rapid urbanization paired with inadequate infrastructure scaling.

Emergence of Flooding Vulnerability

Lucknow was historically not associated with waterlogging; however, since 2021, the city has experienced recurrent flooding events previously considered anomalous. September 2023 witnessed flooding in over two dozen localities including Hazrat Ganj, Janki Puram, Ashiana, Chinhat, and Gomtinagar (Times of India, 2023). The geographic distribution revealed systemic drainage inadequacy affecting both low-lying and high-value areas (Times of India, 2023).

Root Causes: Rapid Urbanization and Infrastructure Lag

Urban sprawl has eliminated natural drainage features including wetlands and lakes. Existing drainage systems, designed for smaller urban populations and historical rainfall statistics, remain inadequate for contemporary urbanization. Research documents that "expansion of the city's spatial limit has led to a surmounting pressure on both natural and

built drainage systems" (International Scholars Journals, 2023). Major drain projects—Faizullahganj (9 km, Rs 45 crores), Gomtinagar drain expansion (Rs 150 crores), Qila Mohammadadi drain (Rs 68 crores)—represent infrastructure that should have been developed years earlier (Times of India, 2024).

Sewage System Deficiency

A critical infrastructure gap is sewage treatment. Lucknow generates 730 million litres daily sewage but treats only 450 MLD—a deficit of 280 MLD (38%) (Hindustan Times, 2025). Untreated sewage flows directly into the Gomti River through seven major drains, contaminating the river and reducing drainage capacity. During heavy rainfall, combined sewer overflow causes sewage to flow into stormwater drains, reducing drainage capacity and creating health hazards (International Scholars Journals, 2023).

Gomti River Degradation

Despite Rs 2,500 crores invested in cleanup projects over 20 years, the Gomti remains severely polluted. Seven major sewage drains discharge untreated sewage; solid waste dumping further degrades the river (Hindustan Times, 2025). Ecosystem collapse is evident. River degradation reduces drainage conveyance capacity, causing upstream waterlogging.Figure 8 explains the flooding scenario of Lucknow.

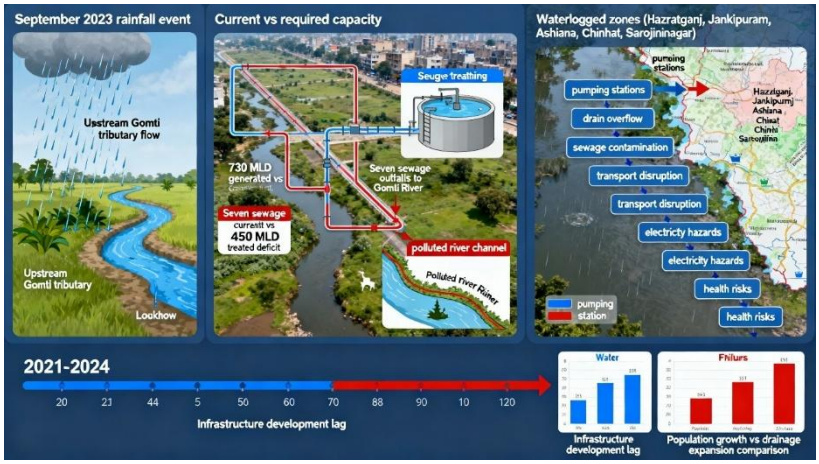


Figure 8 Analysis of Urban Flood of Lucknow *Source - Compiled by Author*

Institutional Response and Implementation Gaps

Lucknow Municipal Corporation has undertaken substantial infrastructure projects; however, these address minimum adequate capacity that should have existed years earlier. The infrastructure deficit across the city far exceeds current municipal resources and execution capacity (Times of India, 2024). While emergency response (pumping stations deployment) demonstrates institutional capacity, persistent waterlogging indicates symptom treatment rather than root cause resolution.

Framework Implications

The Lucknow case demonstrates that river-centric cities experiencing rapid urbanization require:

1. systematic drainage infrastructure scaling;
2. sewage system separation to prevent combined overflow;
3. river ecosystem restoration;
4. development density management; and
5. institutional coordination across fragmented departments.

Current reactive emergency responses must transition to proactive prevention through integrated planning.

Chapter 3:

STRATEGIC URBAN FLOOD MITIGATION FRAMEWORK

This chapter creates a complex structure of approaches that would serve as the basis for sustainable flood resilience and climate adaptation in the urban environment. Managing modern floods in urban settings calls for a change of the existing reactive approach to engineering fixes towards an approach that would involve balancing natural hydrology and the dynamics of the urban built environment. Through the assessment of the relationships between physical geography, municipal infrastructure, and policy making, this approach provides the means for sustainable urban development. The further parts of this paper discuss the main reasons why such strategic development is needed, the necessity of integration of different levels of governance, and the necessary structural approaches.

3.1 Frame Development Rationale

The causes of urban flooding in India are many, including natural causes (climate change), human causes (urbanisation, impervious surfaces, encroaching on water) and governance (different levels of planning, lack of coordination, lack of cooperation). To address this complex set of causes, an integrated approach must be developed, that includes structural approaches (grey) as well as non-structural approaches (planning and policy) and a Green Infrastructure/Nature Based Approaches (Nature Based Solutions) to Urban Design and Development.

3.2 Multiple Levels of Governance Integration

Co-ordinated efforts across multiple levels (national, state, municipal and community) and across different functional areas (urban planning, engineering, emergency management, environmental, and water management) are required for effective flood mitigation. The fragmented nature of current processes fundamentally undermines the effectiveness of flood mitigation.

Current Institutional Structure

1. National Level: NDMA (disaster policy), MoHUA (urban planning), CWC (water resources), MoEFCC (environment), IMD (meteorology) operate independently without formal coordination.
2. State Level: State Disaster Management Compiled by Authority, Water Resources Department, Urban Development Agency, and PWD manage state-level implementation with limited cross-sectoral coordination.

3. Municipal Level: Municipal Corporation (planning), Engineering Department (drainage), Disaster Management Cell, and Building Department operate in silos. Planning and engineering frequently pursue conflicting objectives.
4. District Level: District Disaster Management Compiled by Authority coordinates emergency response but lacks Compiled by Authority over prevention and planning.

Table 6 Current Institutional Structure

Source: Compiled by Author

Governance Level	**Primary Agencies**	**Key Responsibilities**	**Coordination Requirement**
National	NDMA, MoHUA, CWC, MoEFCC, IMD	Policy frameworks; technical guidelines; capacity building; financing; inter-state coordination	Coordination with state governments; policy alignment; financing mechanisms
State	State Disaster Management Compiled by Authority, Water Resources, Urban Development, Planning	State-level implementation; resource allocation to cities; capacity building; multi-city coordination	Coordination with municipalities; interstate water resource coordination; state development strategy
Municipal	ULB, Municipal Corporation, City Planning, Disaster Management, Engineering, Building, Utilities	City-level planning; infrastructure development; building control; emergency response; service delivery	Interdepartmental coordination; community engagement; inter-city learning from peer cities
Community	Resident associations, CBOs, Informal settlement groups, Civil society	Community awareness; local preparedness; planning participation; monitoring and feedback	Formal inclusion in planning processes; voice in decisions affecting communities

Critical Coordination Gaps

1. Vertical Gap - The National Policy is not properly transformed to the State and City level. NDMA Guidelines are available, but very few Cities have adopted them.
2. Planning/Engineering Gap - Planning Approved for Developments that Engineering acknowledges are not appropriate from a Drainage Perspective, with no process in place to coordinate solutions.
3. Water Resources/Urban Stormwater Gap - Dams & Rivers are Managed very differently from how Cities Manage Drainage Systems & create the potential for compounded Flooding.
4. Financing Gap - Existing Funding Sources (Disaster Management, Urban Development & Environmental) are not aligned to allow for Integrated Funding of Projects.
5. Compiled by Authority Gap - Multiple Agencies are involved in Flood Management, yet there is no one Single Agency that is Clearly Identified as the Responsible Body. The result is very little action takes place due to Fragmented Accountability.

Integration Mechanisms:

1. Policy Alignment - National Guidelines will be Translated into State Policy and Implemented at the Municipal Level, along with a process for providing Feedback.
2. Inter-Agency Coordination – Collaborative Planning, Shared Data Systems & Collaborative Infrastructure Design & Unified Decision-Making Enhance Coordination.
3. Resource Sharing - Collaboration will provide access to Funding from Multiple Sources, offer Incentives for Collaboration, and establish Cost-Sharing Mechanisms in Advance.
4. Information Sharing - Consistent Data Collection Methods, Real-Time Data Systems for Flooding Events, Learning from Past Events, and Information Platforms.

5. Capacity Building - National Training Programs to Establish Technical Support at the State Level, Create & Build upon the Community's Capacity through Peer-Supported Learning.

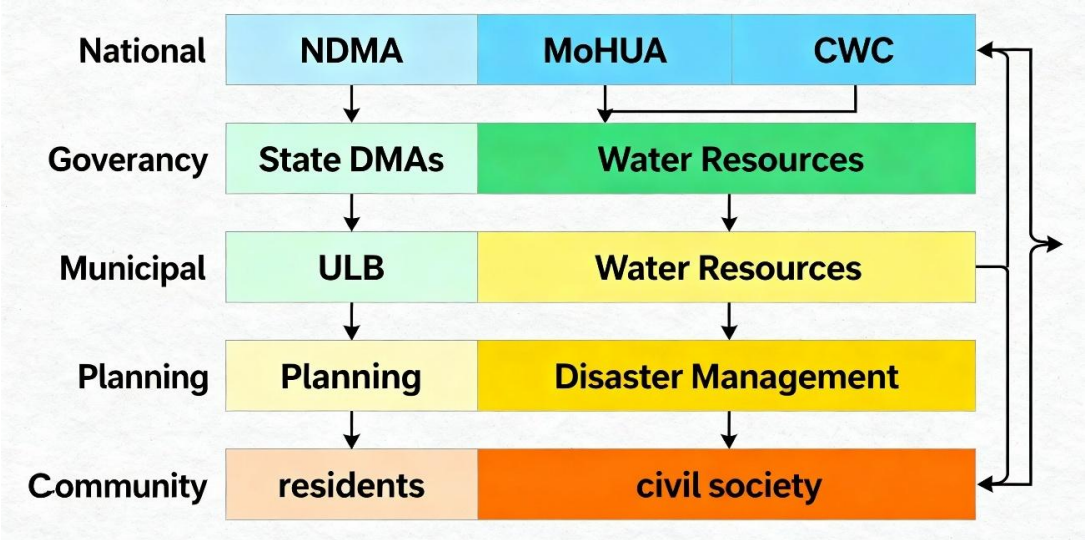


Figure 9 Multi-Level Governance Integration *Source: Compiled by Author*

3.3 Causes-Mitigation Strategy Matrix

The matrix systematically relates urban flood causes to applicable mitigation strategies, revealing which interventions effectively address specific causes:

Table 7 Causes-Mitigation Strategy Matrix *Source: Compiled by Author*

Cause	Strategy Type	Specific Strategy	Mechanism	Effectiveness	Integration Requirement
Extreme Rainfall Intensity	Structural	Drainage Expansion	Increase conveyance capacity for larger runoff volumes	Moderate—Limited to design event; overwhelmed by extreme rainfall	Combined with forecasting + planning
	Structural	Detention Basins	Store excess water reducing downstream peaks	Moderate to High—Effective but expensive	Combined with green infrastructure

	Non-Structural	Forecasting & Early Warning	Real-time monitoring enabling evacuation/preparedness	Moderate—Enables response but doesn't prevent flooding	Essential complement to structural measures
	Green Infrastructure	Green Roofs/Rain Gardens/Permeable Pavements	Intercept rainfall at source, promote infiltration	Moderate 20-50% runoff reduction	Must scale throughout urban area
	Governance	Climate-Adjusted Design Standards	Update design standards for intensified future rainfall	High—Addresses root design inadequacy	Foundational for all physical infrastructure
Impervious Surface Proliferation	Structural	(Insufficient by itself)	Gray infrastructure merely conveys excess runoff	Low—Addresses symptom not cause	Must combine with green infrastructure
	Non-Structural	Green Infrastructure Mandates in Development	Require green roofs, permeable pavements in new construction	High when scaled—Addresses root cause	Primary strategy for new development
	Non-Structural	Density Planning/Development Restrictions	Limit impervious surface coverage through density controls	High—Prevention more cost-effective than retrofitting	Integration with building codes and zoning
	Green Infrastructure	Extensive Green	Distributed green roofs, rain gardens,	High when comprehensively scaled—	Citywide program with

		Infrastructure Network	permeable surfaces	Restores infiltration	maintenance provisions
	Governance	Building Codes & Zoning Requirements	Mandate green infrastructure provision in development	High effectiveness—Prevents future vulnerability	Must include enforcement and monitoring
Water Body Encroachment	Non-Structural	Development Restrictions/Zoning Protection	Prohibit encroachment through legal/regulatory protection	Very High for prevention—Stops further loss	Prevention far preferable to restoration
	Non-Structural	Encroachment Enforcement & Removal	Remove existing encroachments, restore water body function	Moderate to High—Restores function but expensive	Time-consuming; should complement prevention
	Green Infrastructure	Wetland/Riparian Restoration	Deliberately restore natural water bodies and riparian zones	High for flood mitigation + ecosystem benefits	Most effective combined with protection
	Non-Structural	Community Monitoring	Community-based encroachment reporting/vigilance	Moderate to High as complement to government enforcement	Essential for persistent prevention
	Governance	Land Acquisition & Restoration Programs	Municipal programs acquiring encroached land for restoration	Moderate to High—Expensive but recovers natural function	Long-term commitment required

Inadequate Drainage Infrastructure	Structural	Drainage System Modernization	Upgrade drainage to contemporary design standards	High—Directly addresses capacity inadequacy	Must combine with green infrastructure
	Structural	Combined System Upgrades	Separate combined sewers; improve treatment capacity	High—Eliminates sewer backup issues	Complex infrastructure transition
	Green Infrastructure	Green Infrastructure (Reducing Demand)	Reduce drainage demand by source infiltration	Moderate to High—Reduces infrastructure burden	Complements but cannot replace drainage upgrades
	Non-Structural	System Maintenance Programs	Regular cleaning, repair, maintenance	Moderate—Maintains capacity at design level	Essential ongoing activity; often neglected
	Governance	Design Standards Updates	Ensure new systems designed for contemporary rainfall	High—Prevents future inadequacy	Foundation for all new infrastructure
Uncoordinated Urban Planning	Non-Structural	Integrated Urban Planning	Coordinate land use planning with drainage planning	Very High—Addresses root governance cause	Foundational for comprehensive mitigation
	Non-Structural	Flood Risk Zoning &	Incorporate flood risk	Very High—Prevents future	Integration into master plans essential

		Hazard Mapping	into land use planning	vulnerability creation	
	Non-Structural	Development Control & Enforcement	Enforce restrictions on development in flood-prone areas	High—Prevents inappropriate development	Often weak in practice; enforcement critical
	Governance	Inter-Agency Coordination Mechanisms	Establish coordinated planning across agencies	High—Enables integrated response	Essential institutional reform
	Governance	Master Plan Integration	Incorporate flood management into urban master plans	Very High—Provides comprehensive framework	Foundation for all city-level planning

Governance Fragmentation	Governance	Multi-Level Governance Structure	Establish clear responsibilities across governance levels	Very High—Enables coordinated response	Essential institutional foundation
	Governance	Inter-Agency Coordination Forums	Regular meetings and coordinated decision-making	High—Prevents gaps and duplication	Requires sustained commitment
	Governance	Shared Performance Indicators	Common metrics enabling	Moderate to High—	Requires agreement on indicators

			coordinated monitoring	Aligns incentives	
	Governance	Resource-Sharing Mechanisms	Joint funding for shared mitigation objectives	High—Enables scaled mitigation investment	Requires financial mechanisms
Limited Forecasting/ Emergency Preparedness	Non-Structural	Early Warning System Development	Real-time monitoring, forecasting, public notification	Moderate—Enables response; doesn't prevent flooding	Essential component of comprehensive approach
	Non-Structural	Community-Based Warning Systems	Community-level monitoring and local dissemination	Moderate to High—Reaches populations formal systems miss	Complements technical systems
	Non-Structural	Emergency Response Planning	Pre-event preparation of evacuation routes, shelters	High—Reduces mortality and improves recovery	Essential for life safety
					Sustained programs required

3.4 Implementation Roadmap: Four-Phase Timeline

Table 8 Implementation Roadmap: Four-Phase Timeline *Source: Author*

Phase	Duration	Key Activities	Primary Agencies	Deliverables
IMMEDIATE	Months 1-6	Establish coordination structure; conduct rapid flood risk assessment; engage communities; audit drainage infrastructure; update building bylaws	Municipal Corporation, City Planning, Disaster Management, Engineering, Building Department	Steering Committee operational; preliminary hazard map; community consultation mechanisms; drainage inventory; draft building bylaws
SHORT-TERM	6-24 months	Develop comprehensive city flood plan; implement priority land use restrictions; establish EOC and SOPs; implement pilot green infrastructure; launch preparedness programs; prioritize drainage repairs	All departments + Community representatives	Approved city flood plan; zoning restrictions in high-risk areas; functional EOC; pilot green infrastructure operational; community awareness program launched; priority drainage upgrades completed
MEDIUM-TERM	2-5 years	Scale green infrastructure citywide; complete drainage infrastructure	City Planning, Engineering,	Green infrastructure across neighbourhoods; modern drainage system; building code

Integrated Urban Flood Mitigation Framework- A Case of Lucknow, Kritika Pandey (24209011113)

		upgrades; enforce building bylaws; restore water bodies; establish flood forecasting system; strengthen informal settlement mitigation	Building, Disaster Management, Water Board	compliance in new construction; water body restoration; operational forecasting system; informal settlement mitigation implementation
LONG-TERM	5-10 years	Complete urban transformation to climate-resilient patterns; mainstream flood resilience in all planning; establish monitoring systems; achieve financial sustainability; conduct comprehensive evaluation	All agencies with Civil Society oversight	Climate-resilient development patterns; flood resilience as standard practice; monitoring systems operational; diversified financing mechanisms established; comprehensive evaluation with recommendations

Chapter 4:

SITE SELECTION AND SPATIAL ANALYSIS

The current chapter moves on from the strategic approach to the actual empirical spatial analysis of the chosen study area. In order to analyse the distribution of and the reasons for urban flooding, the geographical assessment needs to be carried out, which should include the integration of geographical and environmental features of the studied area as well as changes that occurred within the built environment. Using GIS techniques and digital elevation modelling, this chapter will conduct the macro-level analysis of the hazard dynamics in the metropolitan area. Below there is a thorough baseline analysis of the chosen study area, as well as the analysis of the factors causing localized drainage problems.

4.1 Introduction to Lucknow

The city of Lucknow, which serves as the capital of Uttar Pradesh, is one of the most rapidly growing tier-1 cities in India located within the middle Indo-Gangetic plain. Characterized by its flat alluvial topography and presence of the meandering stream of the river Gomti, the city acts as a significant administrative, commercial, and residential node in northern India. With increasing demographic influx over the past decades along with corresponding economic developments, large-scale development has occurred in the form of urban sprawl and structural change within the urban environment, thereby causing disruption of the natural environments of the region and increased vulnerability to urban pluvial flash floods.

As stated by the Lucknow Municipal Corporation [LMC] (2015), in the Revised City Development Plan for Lucknow City - 2040, the capacity of physical infrastructure of the city has been stressed to such an extent that conventional means of drainage become ineffective in dealing with rapid urbanization. Understanding these evolving spatial changes through GIS and terrain analyses is essential for going beyond mere emergency responses and developing an integrated flood management plan as recommended in the statutory guidelines.

4.2 Study Area Selection & Regional Justification

4.2.1 Selection Rationales (Why Lucknow?)

The choice of Lucknow Municipal Corporation (LMC) boundaries for the focus area of this study is justified by the fact that this urban municipality can be considered to be representative in nature for urban areas in India experiencing the problem of climate-related hydrological distress. The metropolitan urban centres such as Mumbai, Chennai and Kolkata etc. have been dominating the urban floods literature due to the reasons of storm surge, tidal effects and extreme monsoon fluctuations. Inland capital cities such as

Lucknow are suffering from similar but different kinds of problems arising from surface concretization and loss of natural catchment. Figure 10 shows the Locational Importance of Lucknow.

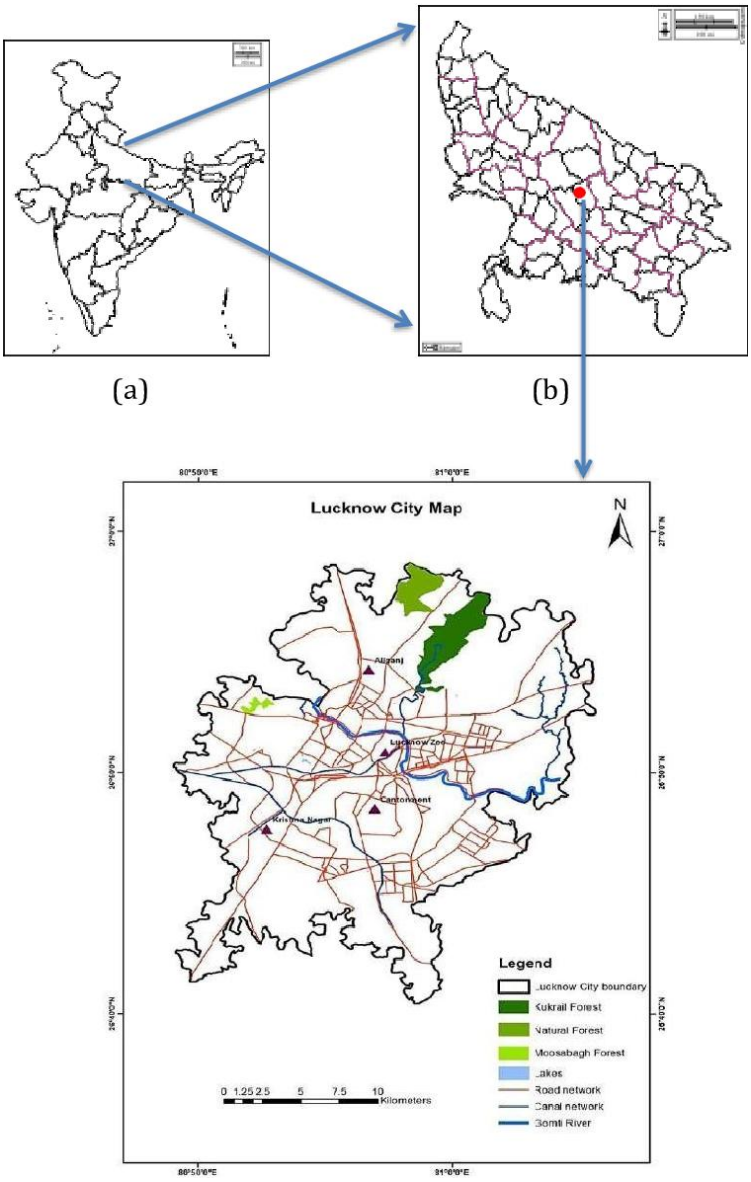


Figure 10 Location Map of Lucknow *Source: Compiled by Author*

According to the provisions laid down by the U.P. Urban Planning and Development Act of 1973, the boundaries of the Lucknow city have undergone a considerable expansion in terms of inclusion of fringe areas within the development zone (Lucknow Development Compiled by Authority [LDA], 2016). Lucknow is one such area that faces challenges in urban planning due to the constant intrusion of real estate projects, master plan alterations, and low-income housing into flood-prone and low-lying zones, nalas, and talabs. Analysing Lucknow will help understand how the mid-elevation plains cities deal with micro-hydrological processes without coastal outlets or gravity drains.

4.2.2 Comparing with Other Inland Indian Cities

In order to clearly identify the planning logic, it will be essential to understand how the structural flood mechanisms in Lucknow are different from those seen in other notable inland cities of India. For example, while flooding in Bengaluru is directly associated with structural collapse and segmentation of historical cascaded lake systems of interconnected waterbodies where unapproved building works obstruct the channels (rajakaluves) joining the waterbodies (National Disaster Management Compiled by Authority [NDMA], 2023), cities such as Hyderabad are flooded due to their rough, undulating granitic terrain.

Lucknow is faced with a unique set of problems due to its uniquely flat alluvial plain landscape where terrain gradients are extremely low, which automatically leads to slower velocities in the surface water runoff process. Such flat terrain implies that the presence of even minor structural barriers such as a raised road system, railroad embankments, or even an irregular building structure will automatically form an artificial basin and retain the surface water after heavy rainfall events. Moreover, while older cities can simply be burdened with obsolete infrastructure systems, Lucknow faces a double trouble, according to its official plans – an obsolescent and collapsing drainage infrastructure in its densely populated old part (zones 1 and 2), as well as a total absence of storm water drainage system in the rapidly developing outer zones (zones 5 and 6) of the city (LMC, 2015).

4.3 Baseline Profile of the Study Area

1. *Geographic Location and Spatial Limits:* In terms of geography, the study area is located in the central plains of the state of Uttar Pradesh and occupies both sides of the Gomti River. The elevations in the urban area range from the average height of 123 meters above mean sea level. As per the Master Plan for Lucknow Mahayojana-2031, the master plan development area covers the total limit of the municipality, further extending up to 8 kilometres from the limits of the LMC (LDA, 2016).

2. *Urban Administration and Planning Mechanisms:* The management and administration of the urban areas in terms of municipal services and functions is taken care of by the Lucknow Municipal Corporation [LMC] that divides the city into six primary administrative zones (Zone 1 to Zone 6), subdivided in wards (LMC, 2015). Spatial planning of the area, land-use zoning and infrastructure layout designs are done by the Lucknow Development Compiled by Authority [LDA]. Such a division calls for effective coordination among institutions to implement sustainable land zoning rules and preserve flood retention zones.

3. *Population Dynamics:* Based on demographic dynamics identified in the development plans of the city, there have been significant rates of population growth, where the municipality houses more than 3 million inhabitants. As mentioned in the Revised City

Development Plan, the demographic boom has led to a distortion of density patterns, resulting in concentrated growth in peripheral areas in low-lying areas as well as natural drainage courses. This has left vulnerable groups exposed to extensive waterlogging (LMC, 2015).

4. *Climate and Rainfall Patterns:* The climate type associated with Lucknow includes humid subtropical weather characterized by cold winters, hot summers, and strong southwest monsoons, resulting from moisture-loaded winds blowing from the Arabian Sea and the Bay of Bengal. The four months of monsoon between June and September produce the lion's share of annual rainfall in the city. In relation to the rainfall patterns included in the city's environmental profiles, July has been identified as the wettest month producing close to 40% of the annual rainfall (~311 mm), whereas November is the driest month, receiving an average of 2.7 mm per annum (LMC, 2015).
5. *Hydrology and Basin Formation:* In terms of hydrology, the city forms two parts on the basis of Gomti River that flows through the city and acts as a natural drainage system for the region. The two portions thus formed are called trans-Gomti and cis-Gomti basins. There exists an intricate network of natural channels like Kukrail nala and Haider canal to supplement the natural drainage system of the area. These channels were initially developed to drain out seasonal runoff water, but now they serve as conveyors of sewage water.

4.4 Chronology of Historical Floods – Pluvial and Fluvial

Hailed historically as a "non-flood" city because of its inland location and well-developed embankments, Lucknow has undergone tremendous changes in flood types within 25 years. Historically categorized under the category of cities experiencing fluvial flooding, or occasional overflowing of rivers due to riverine overtopping, Lucknow now regularly experiences short-duration pluvial flooding characterized by high-intensity rainfall inundation.

1. August 30, 2000: In the span of one day, Lucknow received an unprecedentedly high rainfall measure of 240 mm, causing floods that overwhelmed the entire drainage network and led to extensive damages in institutional areas and informal settlement sites across the city.
2. September 16, 2022: A brief rainfall in 24 hours resulted in record-breaking rainfall measures of 190 mm within 24 hours, the highest in any single day of September in the past 17 years, submerging commercial areas, disrupting power supply, and stranding commuters.
3. Monsoon 2024: Within less than two hours, a highly intensive convective storm dumped excessive rainfall volumes, instantly leading to heavy urban flooding, specifically the administrative area (Vidhan Sabha area), Hazratganj, and other important areas.
4. August 3-4, 2025: An extended period of precipitation amounting to 61.5 mm during a 24-hour interval led to massive flooding of all the older core sections and even the recently constructed peripheral zones. It adversely affected transportation networks,

damaged many vehicles, led to massive blackouts, and highlighted the crucial inadequacies of Lucknow's stormwater infrastructure.

4.5 Primary Terrain and Hydrological Study

4.5.1 Digital Elevation Model (DEM) and Relief Mapping

, Primary terrain and relief features were examined through the Digital Elevation Model (DEM) in Lucknow in order to comprehend the physical constraints imposed on the area. From the DEM study, it is evident that the highest elevations in the city occur in the northern and northwest fringes in the areas close to Kasmandi Road, Pajampur Road and Mall Road where elevations up to 154.29 meters above mean sea level prevail. Figure 11 shows the DEM analysis map, which shows the upland and low-lying area.

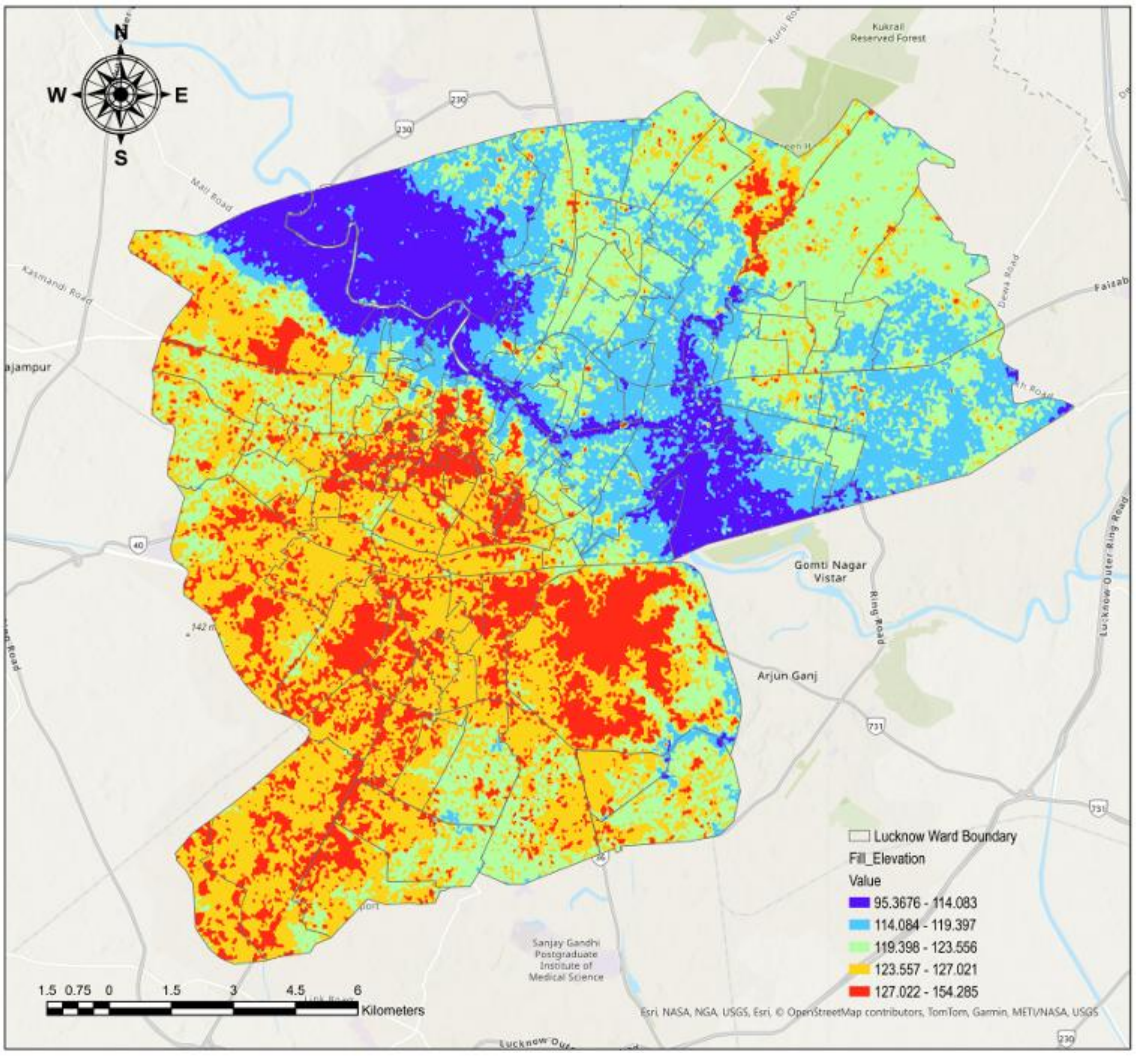


Figure 11 DEM Map of Lucknow *Source: Author (ArcGIS Pro)*

It is clear from these northern upland areas that the terrain falls consistently towards the central river valley at elevations from 95.37 to 114.08 meters above mean sea level close to the river banks and flood plains of Gomti River. In the south and southeast parts of the city such as Outer Ring Road, Dewa Road and Sanjay Gandhi Postgraduate Institute of

Medical Sciences (SGPGI) lie an intermediate transition zone of 114.08 to 123.56 meters above mean sea level. Clearly, the central river forms a natural depression implying that any haphazard growth perpendicular to this natural fall would lead to blocking of surface runoff and thereby form an artificial depression area within the city for collecting stormwater.

4.5.2 Surface Slope and Gradient Analysis

Surface slope map generated directly from the processed DEM provides the measurement of the rate of terrain elevation change over the municipal landscape (as shown in figure 12). From the findings of the gradient analysis, it is clear that most of the Lucknow city has a remarkably flat plain surface with slopes between 0.00° and 2.10°. This characteristic naturally results in a reduction of speed of surface water runoff leading to accumulation of stormwater in certain localities.

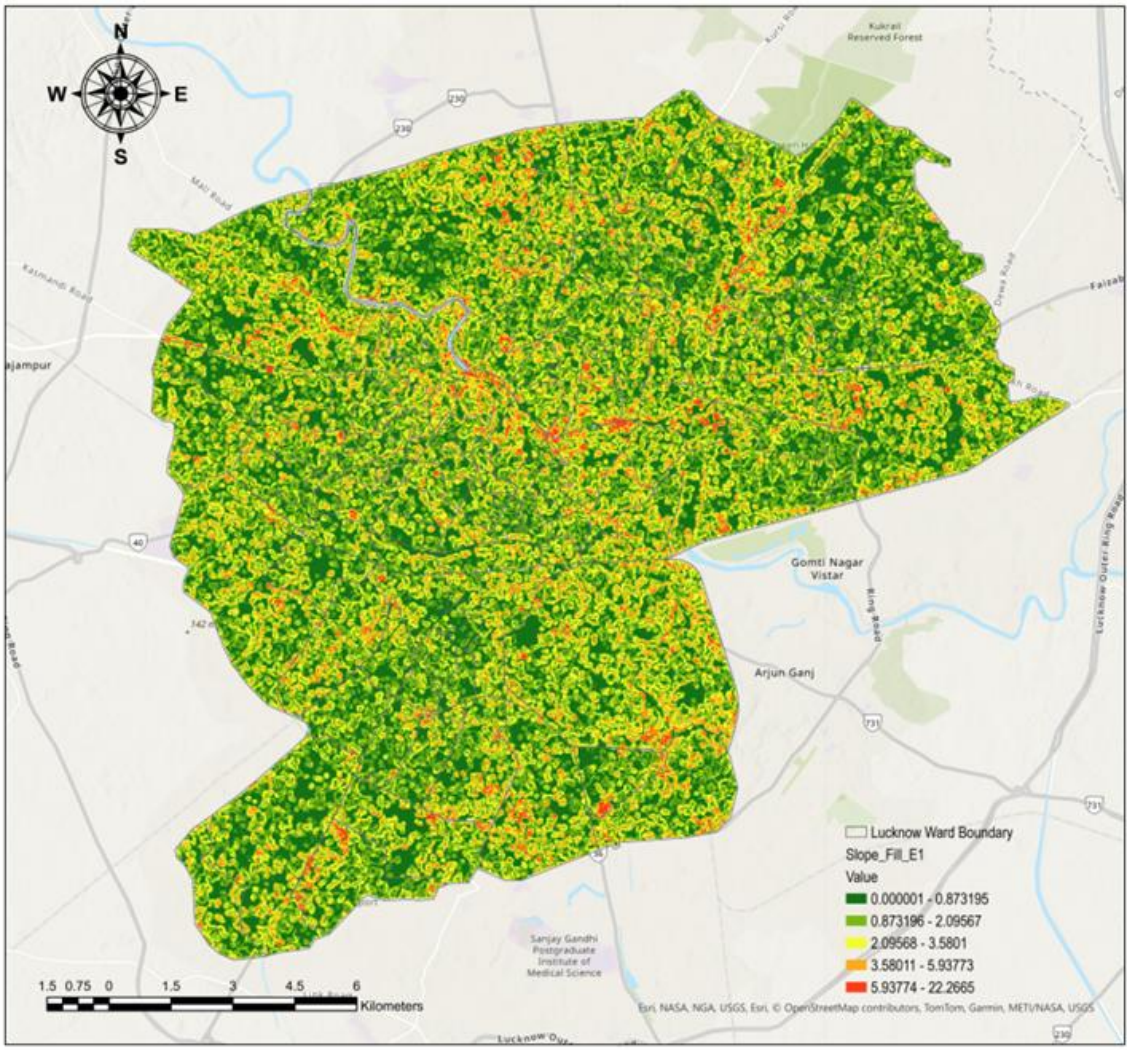


Figure 12 Surface Slope and Gradient Analysis *Source: Author (ArcGIS Pro)*

Areas with higher gradient values ranging from 3.58° to 22.27° are limited only to the cut and fill embankments of Gomti River, peripheries of Kukrail Reserved Forest and some linear features including railways and regional highways built above the natural terrain.

Such a flatness of natural topography poses another challenge of urban planning. Due to absence of the required gradient in the natural terrain, the structural obstructions, presence of silt in the drains, slight alterations in the ground levels due to paving of roads, etc., could obstruct stormwater flow causing heavy pluvial floods.

4.5.3 Flow Accumulation Pathways

Flow accumulation analysis follows the accurate pathways taken by surface water across the landscape according to topographical changes, highlighting where upstream cells funnel down to become channels downstream. In Lucknow, high flow accumulation pathway locations, denoted by cell values ranging from 1,000 to more than 15,668, highlight natural drainages and storm channels in the city are shown in figure 13.

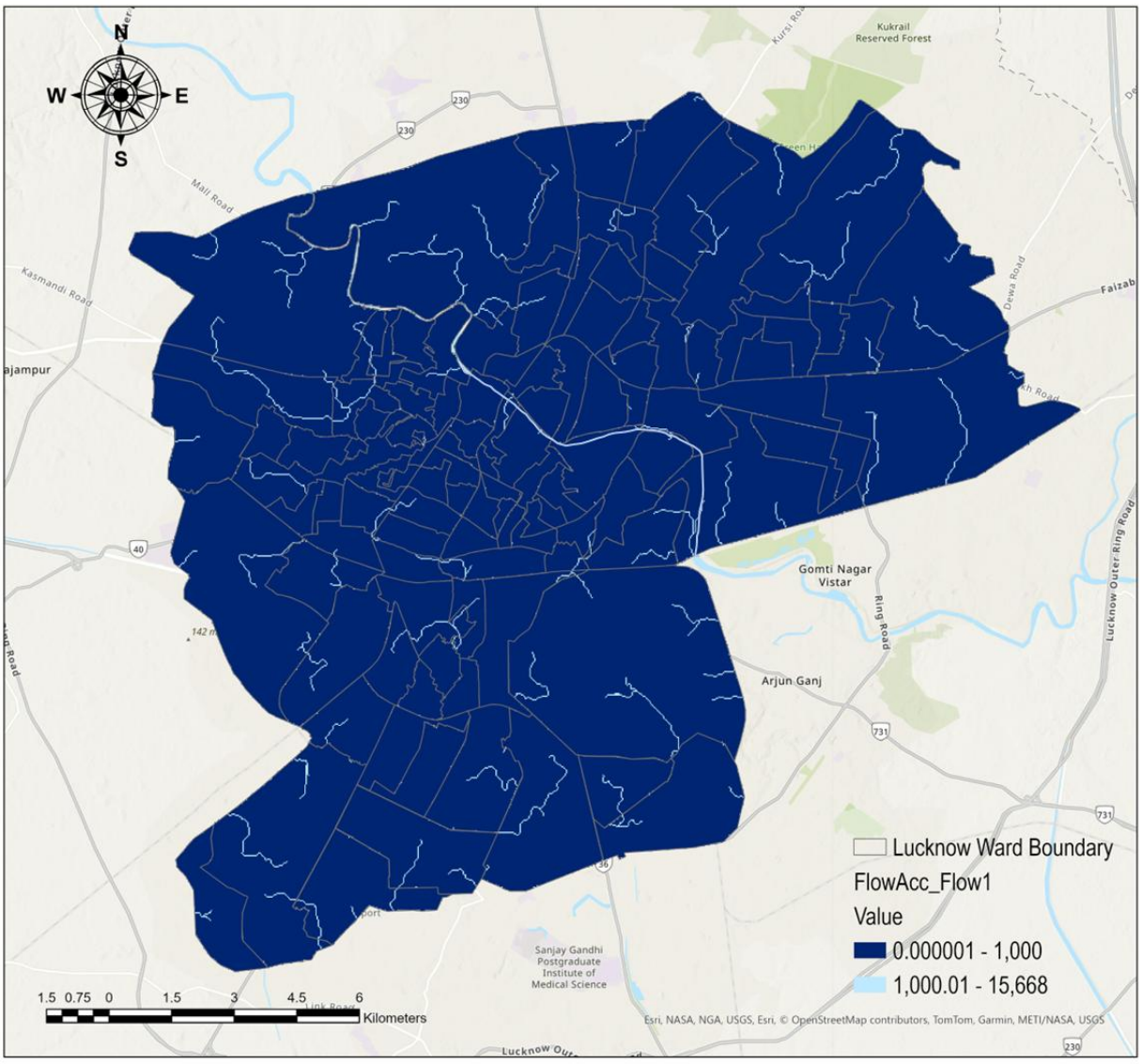


Figure 13 Flow Accumulation Pathways *Source: Author (ArcGIS Pro)*

Once overlaying these high accumulation locations with modern land use maps, however, it becomes apparent that several of these natural channels for surface water in the city have been deliberately built over by roads and constructions. Surface water flows through

these natural drainages despite any built structures. Consequently, when runoff water meets structures such as buildings and raised roads that do not allow water flow, it is blocked and creates pooling of water around these structures, thus causing immediate flooding in streets such as Kasmandi and Dewa Roads.

4.6 Spatial characterization of Catchment and Infrastructure

4.6.1 Micro-watershed (MWS) identification

For decentralizing storm water management, the Lucknow Municipal Corporation has been hydrologically divided into eight different micro-watersheds termed as MWS1 to MWS8(refer figure 14). These micro-watersheds consist of individual hydrological units that discharge storm water into certain catchment zones in the Gomti river basin.

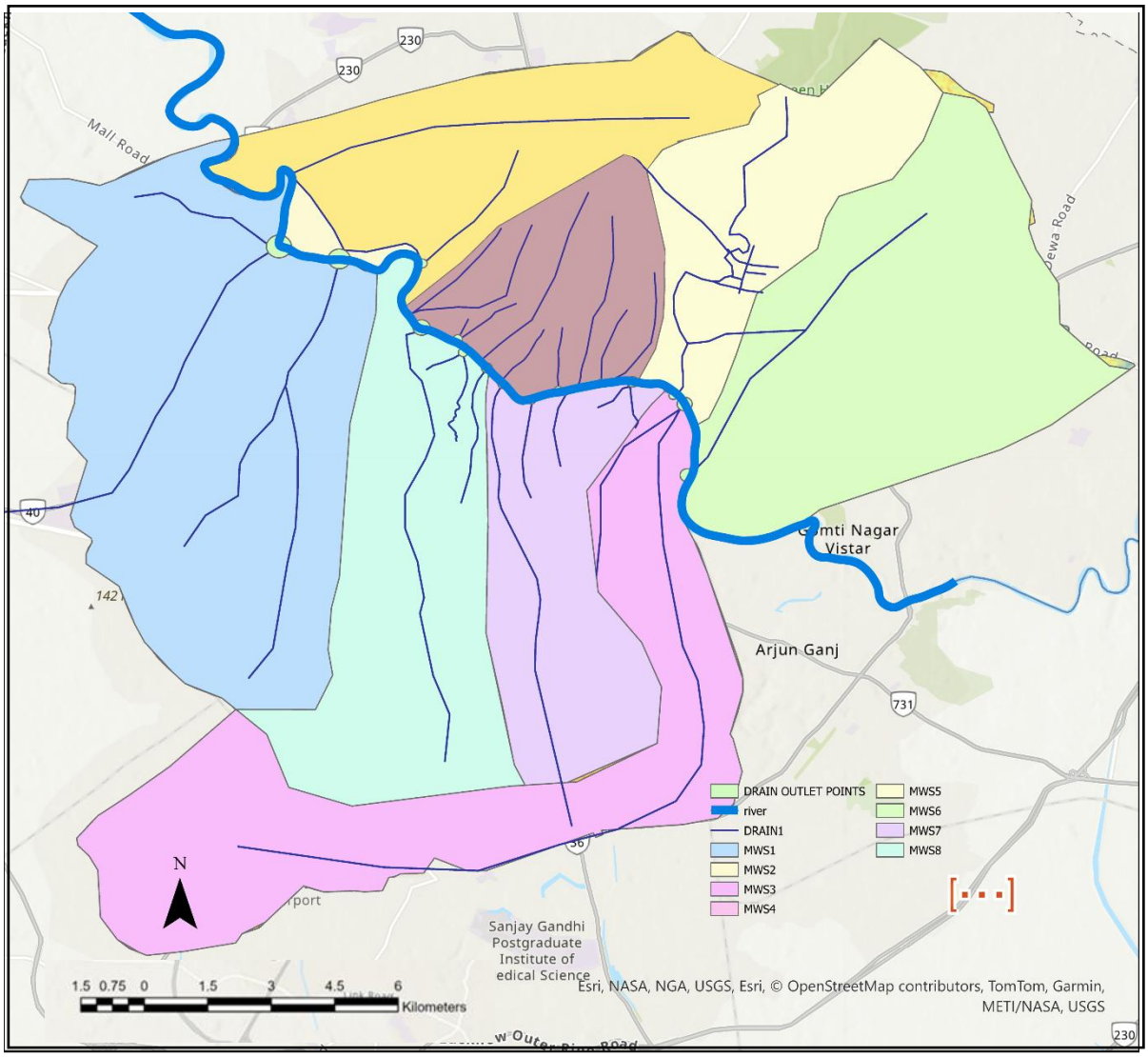


Figure 14 Major Drains and micro watershed

Source: Author (ArcGIS Pro)

The micro-watersheds cover extensive infrastructure boundaries like the Lucknow Outer Ring Road, Dewa Road, and the network of Kheri branch canals. Identification of micro-

watersheds illustrates that urban development has taken place irrespective of natural hydrological boundaries. Rather than treating storm water in independent catchments, drainage is presently considered by the city administration as a unified network throughout the city, leading to infrastructure overload in certain catchments when excess storm water of one micro-watershed overflows into another catchment downstream.

4.6.2 Naturally Occurring Drainage Channels and Names of Nala Systems

Drainage of the eight micro-watersheds in Lucknow occurs through a system of historical naturally occurring channels (nalas) which run through the heart of the city and then discharge into the Gomti River. According to the spatial identification done for the hydrological map (MWSS.pdf), the infrastructural map shows channels such as:

Western Sector (High Density Core): Which uses channels such as the Gaughat Nalah, Sarkata Nalah, Pata Nalah, and Nehru Nalah. These channels cut through high density urban profiles, with highly consolidated buildings.

Central Commercial Core: Which has channels such as the Ghasyari Mandi Nalah, Nala China, and Ezar (Wazirganj) Nalah, draining the densely populated institutional and market areas.

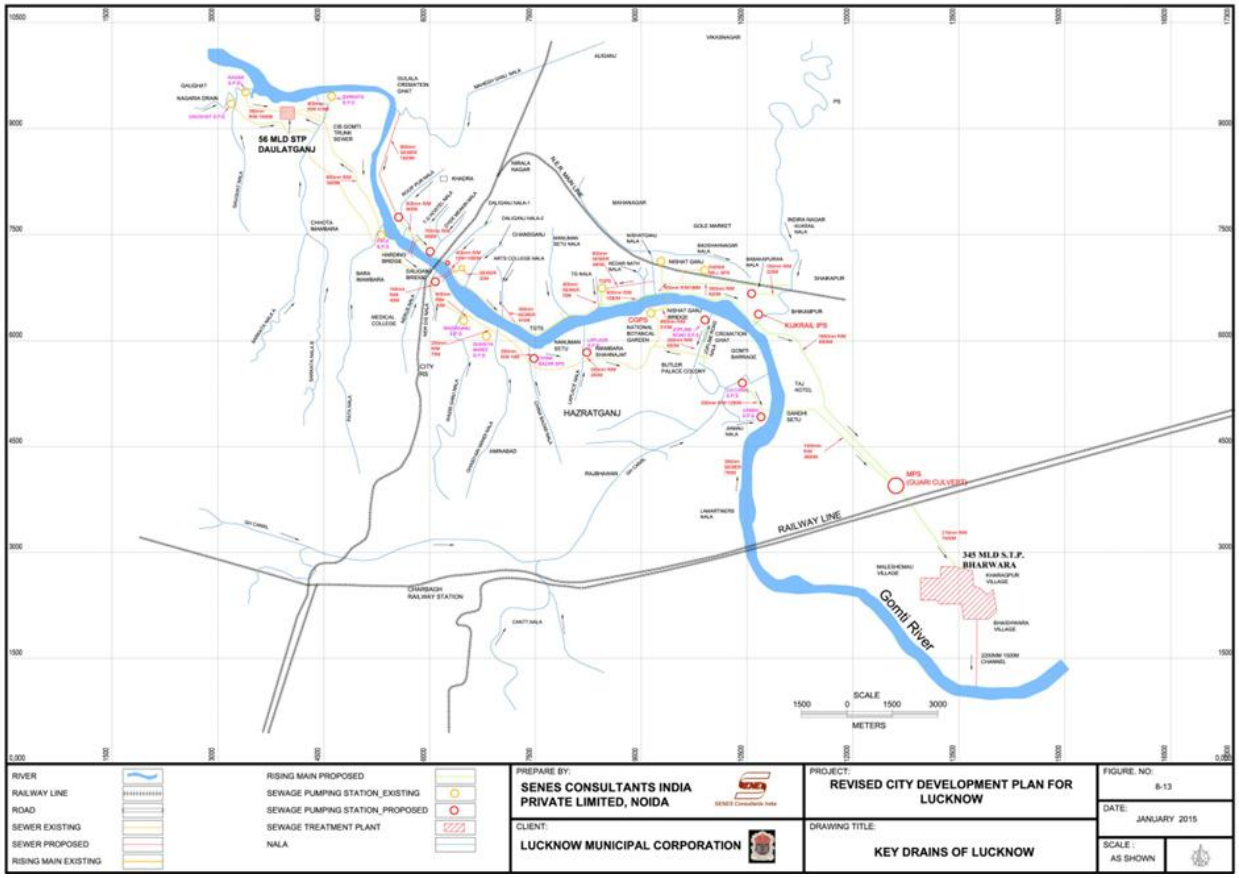
Eastern & Southern Growth Sectors: With bigger structural systems such as the Jopling Road Nalah, huge GH Canal Nalah, and the La Martiniere Nalah.

Spatial analysis shows that the channels have been severely encroached. The channels' natural floodplain has been constricted due to urban development and they are always blocked up with solid waste disposal and silt. For that reason, during monsoon periods when storm runoff is extremely high, there is overflow into the neighbourhood networks.

4.6.3 City's Storm Drainage Inlets and Outfalls

The engineered storm drainage network of the city is very fragmental and links several inlets of stormwater to outfalls located along the Gomti River. A closer look at the location of the outfalls indicates that the entire network depends on gravity outflows from inlets to the main river body.

At peak periods during monsoons, with high elevation of water level in the river body, these outfalls have to endure huge difficulties due to back flow effects. Given the fact that no automated gates, check valves, or retention basins exist within the drainage network, any rise in river level would impede discharge from storm channels. Consequently, the river water flows in reverse direction and floods the urban drainage network. Figure 15 shows the drainage map of Lucknow for the current situation as per LMC.



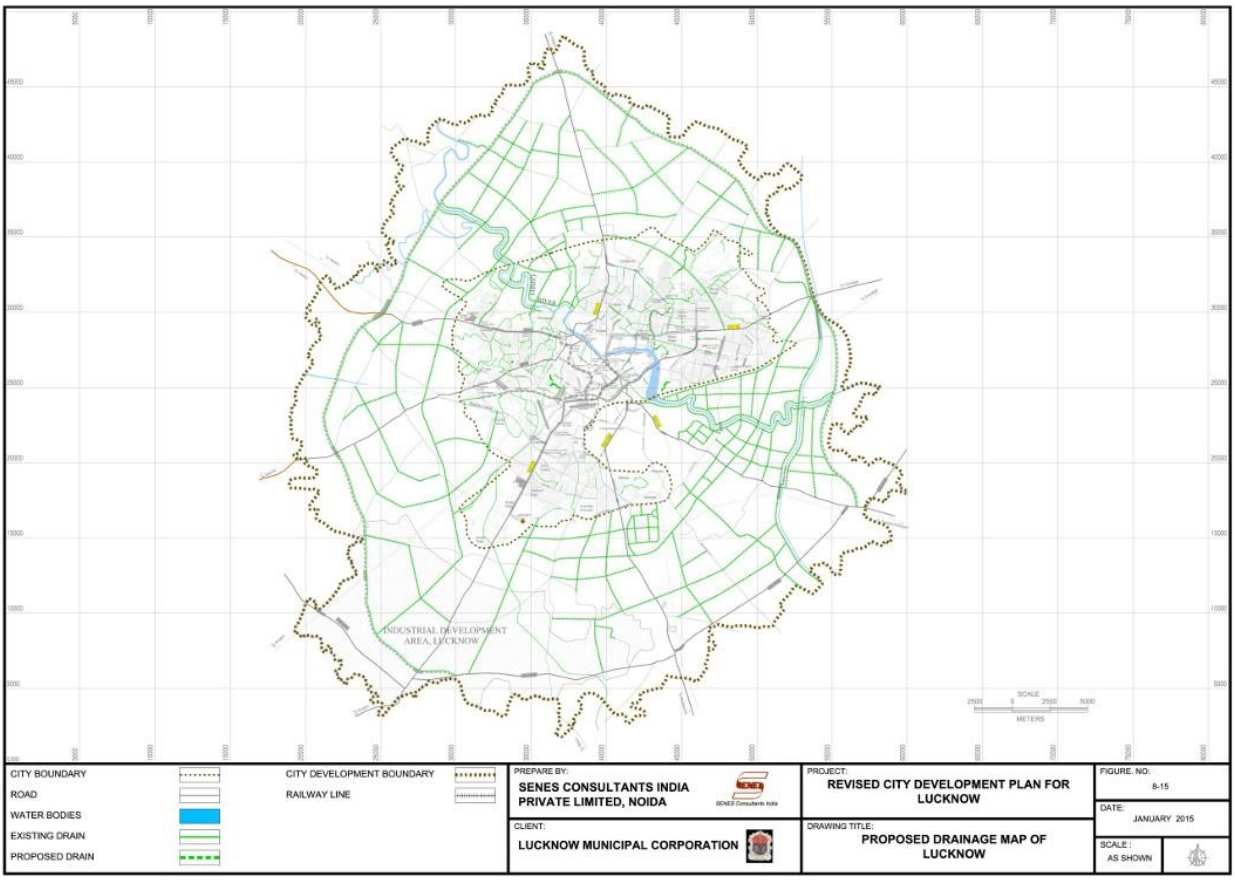


Figure 15 Drainage System of Lucknow *Source: Lucknow Municipal Corporation*

4.7 Anthropogenic and Infrastructure Conflict Analysis

4.7.1 Sprawl of Built-Ups & Surface Concretization (LULC & Impervious Cover Synthesis)

The sprawling of Lucknow's built-ups in the last two decades has completely altered the surface hydrology of the city. The built-ups have expanded outward rapidly towards Outer Ring Road, Dewa Road, Faizabad Road, and Sultanpur Road converting thousands of hectares of permeable agricultural lands, open vegetation, and wetlands into impervious urban built-ups.

Such an expansion has been formalized by statutory urban planning guidelines. According to Lucknow Mahayojana-2031, vast areas around the radial highways have been zoned for high density residential and commercial uses (LDA, 2016). In addition, the implementation of Transit Oriented Development (TOD) has been envisaged in form of 500 m to 600 m buffer zone development along Lucknow Metro rail line corridor from Chaudhary Charan Singh Airport to Alambagh, Charbagh, Indira Nagar, Munshipulia (LDA, 2016).

While such an approach ensures optimized transit ridership and maximizes FAR, it has increased the speed of surface concretization. Such an impervious profile leads to immediate generation of high volumes of stormwater runoffs overwhelming the historic low-capacity drainage pipes installed below the transit line corridors.

The hydrological impact assessments done within the framework of regional development planning suggest that this extensive paving process has raised the levels of stormwater runoff from about 10% in nature to over 55% in urbanized regions, where 75-100% of the surfaces have been paved (Bastia et al., 2021). The loss of surface permeability results in decreased natural rainwater filtration into the ground, thus leading to a decrease of groundwater level by 0.56 meters per year in the area (LMC, 2015).

Also, this phenomenon contributed to the rise in LST of 4.5 degrees Celsius since 2001 in the region (Tripathi & Gupta, 2023). This local temperature increase works together with atmospheric factors to raise the number of convective rainfalls in the area, increasing the probability of pluvial floods in densely populated areas within the city.

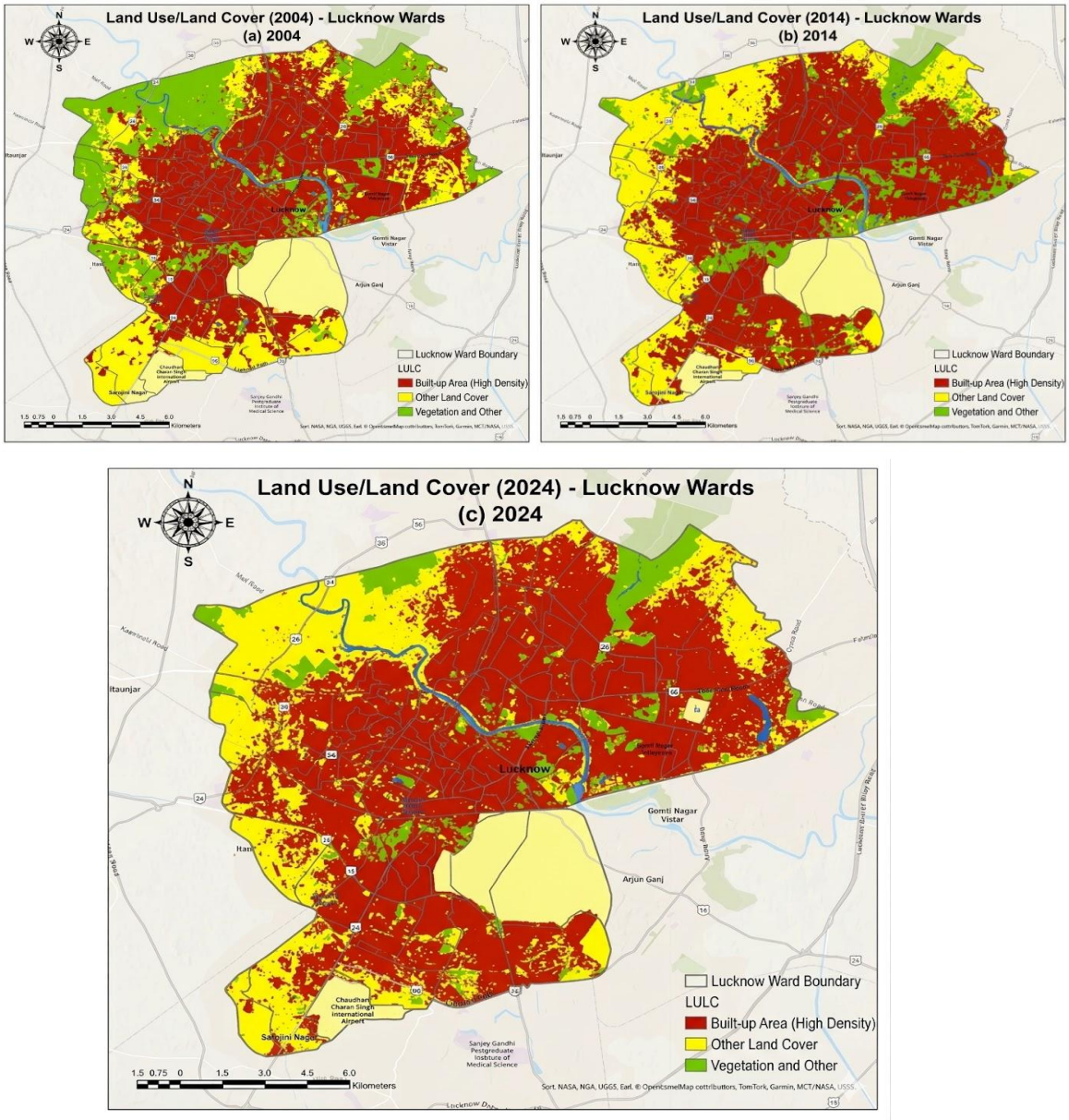


Figure 16 LULC Change of Lucknow Over years *Source: Author (ArcGIS Pro)*

4.7.2 Infrastructure-Hydrology Intersect (Conflict Between Road Network and Flow Accumulation)

A significant outcome of the spatial analysis is the evident structure conflict arising from the infrastructure-hydrology intersect between Lucknow's main transportation infrastructure and its natural hydrology. Superimposing the road network in Lucknow City on the flow accumulation models makes it clear that several major highways – such as the Kasmandi Road, the Hardoi Road, the Malihabad Road, and several ring roads – run across the main flow lines in the area (as per figure 17).

Since the roads have been built using raised and impermeable earthen embankments without proper cross drainage culverts, these roads can be considered effective dams for the area. In case of heavy rains, the sheet flow following natural topographic flows will hit these raised infrastructure elements and cannot pass through.

Table 9 Conflict Between Road Network And Flow Accumulation

Infrastructure Name	**Location / Proximity**	**Hydrological Impact**
Lucknow Outer Ring Road	Near Chinhat / Dewa Road	Intersects a major "Blue" flow line entering from the agricultural periphery. High risk of upstream ponding in new residential layouts.
Faizabad Road (NH-27)	Near Gomti Nagar Vistar	The highway embankment cuts across natural drainage paths leading to the Gomti River basin, creating a "sink" effect in the Vistar area.
Raebareli Road	Near SGPGI / Amausi	Road infrastructure bisects low-velocity flow paths. Without adequate culverts, this leads to the paralyzed hospital access observed in previous monsoons.
Kursi Road / Sitapur Road	Near Kukrail Boundary	Intersects the flow entering from the North Zone (Faizulla Ganj), exacerbating the drainage congestion in the city's lowest elevation point.

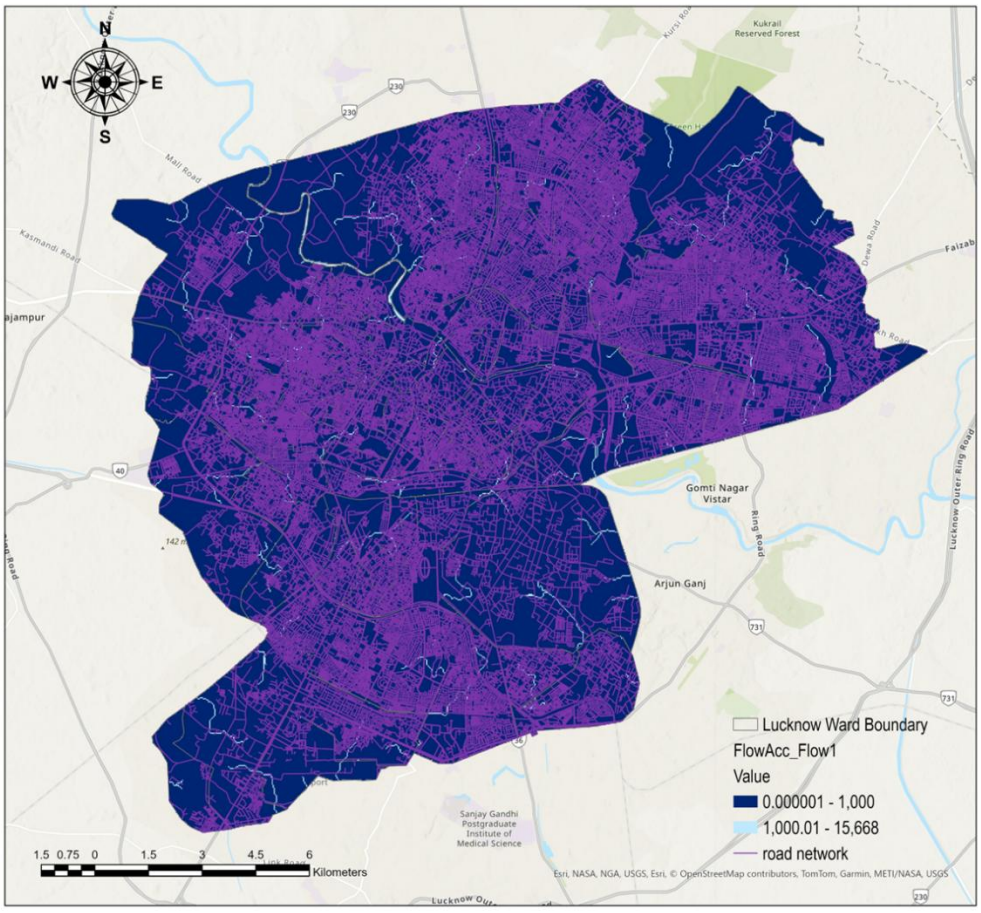


Figure 17 Conflict Between Road Network and Flow Accumulation *Source: Author (ArcGIS Pro)*

Thus, rain water gets trapped behind the raised roads leading to intense waterlogging in nearby residential areas.

4.8 Integrated Flood Hazard Maps & Identification of Hotspots

This chapter will highlight the scientific basis behind identifying and mapping out the areas prone to floods within the urban landscape of Lucknow. To effectively manage flood risks in rapidly expanding urban regions, there is a need to shift gears from ad-hoc measures towards adopting a holistic approach of considering the city's spatial dimension, where the relationship between the natural environment and the built environment is evident (Gupta et al., 2020). This can be achieved by synthesizing several layers of physical, environmental, and infrastructural data into one cohesive framework, which will serve as a foundation for a risk assessment study. The next sections will describe how GIS methodology was applied to develop the urban flood risk map, analyse the hazard zones within the urban municipal territory, and justify objectively the selection of three micro-scale hotspots for designing solutions.

4.8.1 GIS Approach and Weighted Overlay Analysis

In order to come up with an effective plan for managing flooding within Lucknow, it is important to have a clear understanding of all the geographical and anthropogenic factors which interact and lead to the flooding of the city. The map was constructed with the help of Geographic Information System (GIS) approach known as Weighted Overlay Analysis (Malczewski, 2010). As opposed to considering such factors individually as topography, the approach allows overlaying different layers of information to create one integrated indicator – the Flood Risk Index.

The preparation of the map required the collection of several key datasets and bringing them to a standardized format to allow direct comparison of factors. In particular, we collected the information about topography and terrain slopes, which indicates where water flows or pools. In addition, we utilized satellite images to conduct analysis of land use and identify areas of intensive construction covered by concrete (Suroor et al., 2022). Moreover, we identified the proximity zones in relation to roads, Gomti River, and municipal stormwater drains.

All of these had weights allocated to them, depending on their contribution towards flooding. For example, natural flow accumulation and low elevation were ranked with the most significance, followed by land use imperviousness; the other two were terrain slope and proximity to drainage. By adding together, the weights of all of these in a cell-by-cell

fashion within the GIS platform, the entire landscape of the city was automatically categorized into five distinct risk levels.

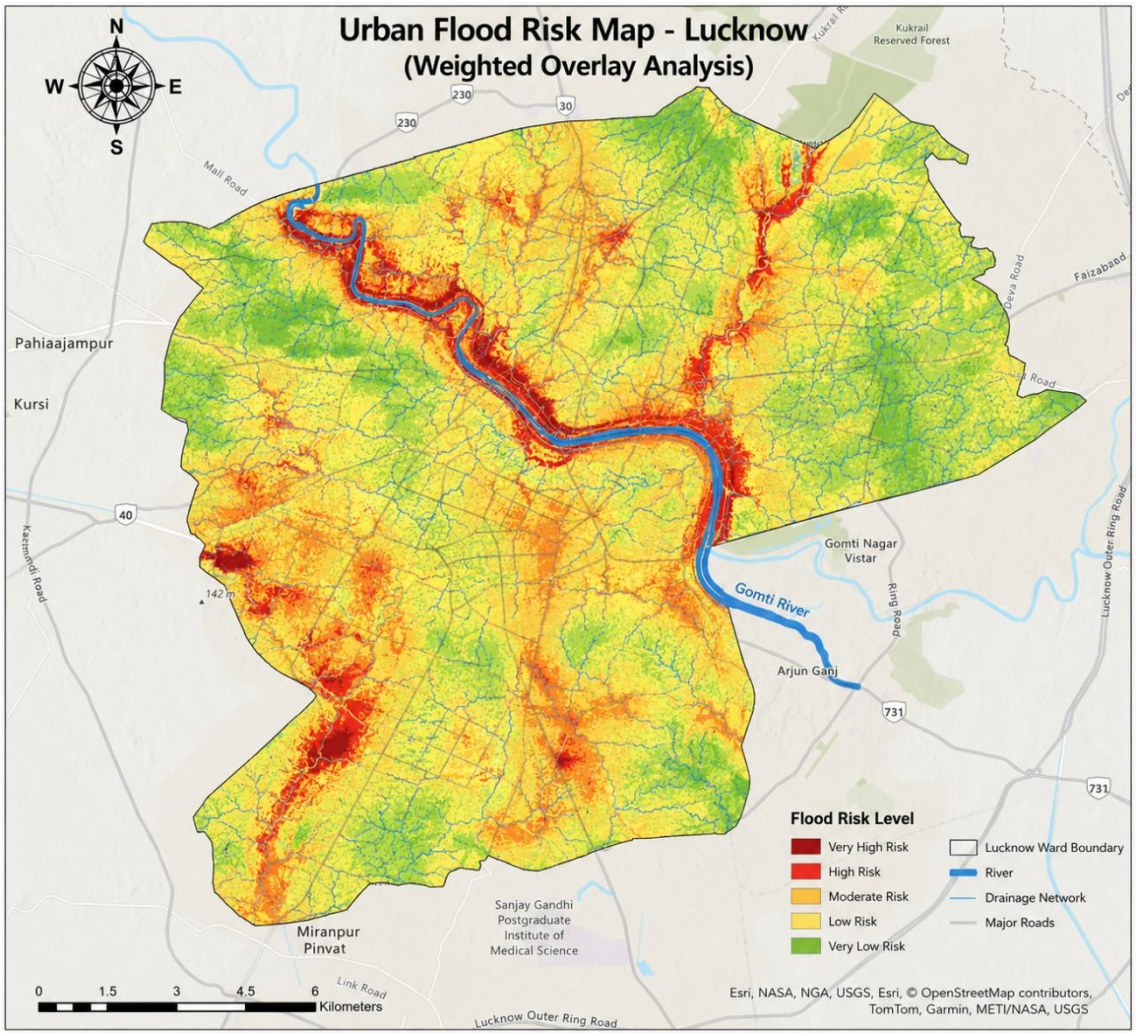


Figure 18 Urban Flood Risk Map

Source: Author (ArcGIS Pro)

4.8.2 Understanding of Flood Risk Levels in the Urban Areas

As shown in the Urban Flood Risk Map of Lucknow (figure 18), flood risk severity varies greatly throughout the metropolitan area according to the geographical topography and infrastructure development of the city (Ranger et al., 2011). The "Very High" and "High" categories of risk (depicted in dark red and bright red) can be seen in the active low terraces and floodplains along the Gomti River. Nevertheless, some high-risk areas also exist in the periphery of the city to the west and south. These include low-lying outer zones of rapid and unregulated housing construction that has turned the natural drainage depressions into bottlenecks during monsoon (Pathak et al., 2023).

The "Moderate" risk zones (depicted in orange colour) consist of the developed and mature urban areas of Lucknow. In general, these areas contain already existing roadside drainage systems, which become highly susceptible to sudden flooding due to high-intensity precipitation that exceeds the drainage capacity of the pipes (Ministry of Housing and Urban Affairs [MoHUA], 2019). At the opposite extreme, the "Low" and "Very Low" risk zones (depicted in yellow and green) are in full harmony with the high-altitude ridges and green spaces of the city. These zones maintain their original soil and vegetation coverage that absorbs precipitation naturally.

4.8.3 Hotspot Selection Approach and Multicriteria Screening Process

In order to go from the broad-scale overview of risk in Lucknow as an entire city down to concrete engineering solutions, a well-designed screening process was established in order to determine the actual study sites. In contrast to an arbitrary selection of case studies based on convenience sampling, the three hotspots were methodically chosen from the master risk map by means of a multistage spatial screening approach. This was done in order to make sure that the selected sites would be high-priority hazard areas and would represent different urban fabrics.

1. Stage 1: Spatial Hazard Intensity Filter: The initial stage in the selection procedure entailed the implementation of an extraction query based on the final weighted overlay raster. This particular filter excluded all regions that were identified as either low, medium or low risk, selecting only the clusters falling into the highest category of the Flood Risk Index. This allowed us to assume that any hot spot was caused only by extremely high physical and infrastructural vulnerability.
2. Stage 2: Morphological Diversity Filters: All the high-risk areas selected at the previous step were classified according to their urban development typology using city development plans as a reference point. The selection criteria for this step were the following: three different structural types had to be chosen – peripheral un-engineered sprawl, mature planned residential area and mixed commercial/industrial economic zones.
3. Stage 3: Structural Failure Filter: The last filter assessed the type of drainage failure in each morphological group. The selection criteria were regions suffering from three totally different hydraulic failures: absolute lack of drainage network, river outfall back flow and transport infrastructure damming.

Using this selection system on the master map yielded isolation of the three micro-scale hotspots as follows:

The first hotspot, named Faizullahganj, was selected due to its emergence as the largest contiguous area in dark red (Very High Risk) along the northern loop of the Gomti River. Based on the selection criteria, it was designated as the highest priority for low lying river terrace hazards, due to rapid informal expansion without any public drainage grid.

The second hotspot, known as Indira Nagar (Sector 25), was selected from among the mature, planned urban areas. It was identified through the screening due to its adjacency with high-risk orange and red linear stripes adjacent to the Kukrail Nala canal. This particular site has been chosen for understanding the reasons behind failure of high density planned residential sector due to canal backwater effect.

The third site, Alamnagar, was isolated using the infrastructural intersection filter within the western urban fringe. Here, the map pointed out clusters of very high risks that were evident outside of the river. Upon superimposition of transport information, it was found that there was an absolute plain surface cut off by a rail route running at high elevations, thus, becoming the ultimate choice to symbolize transport obstacles and industry

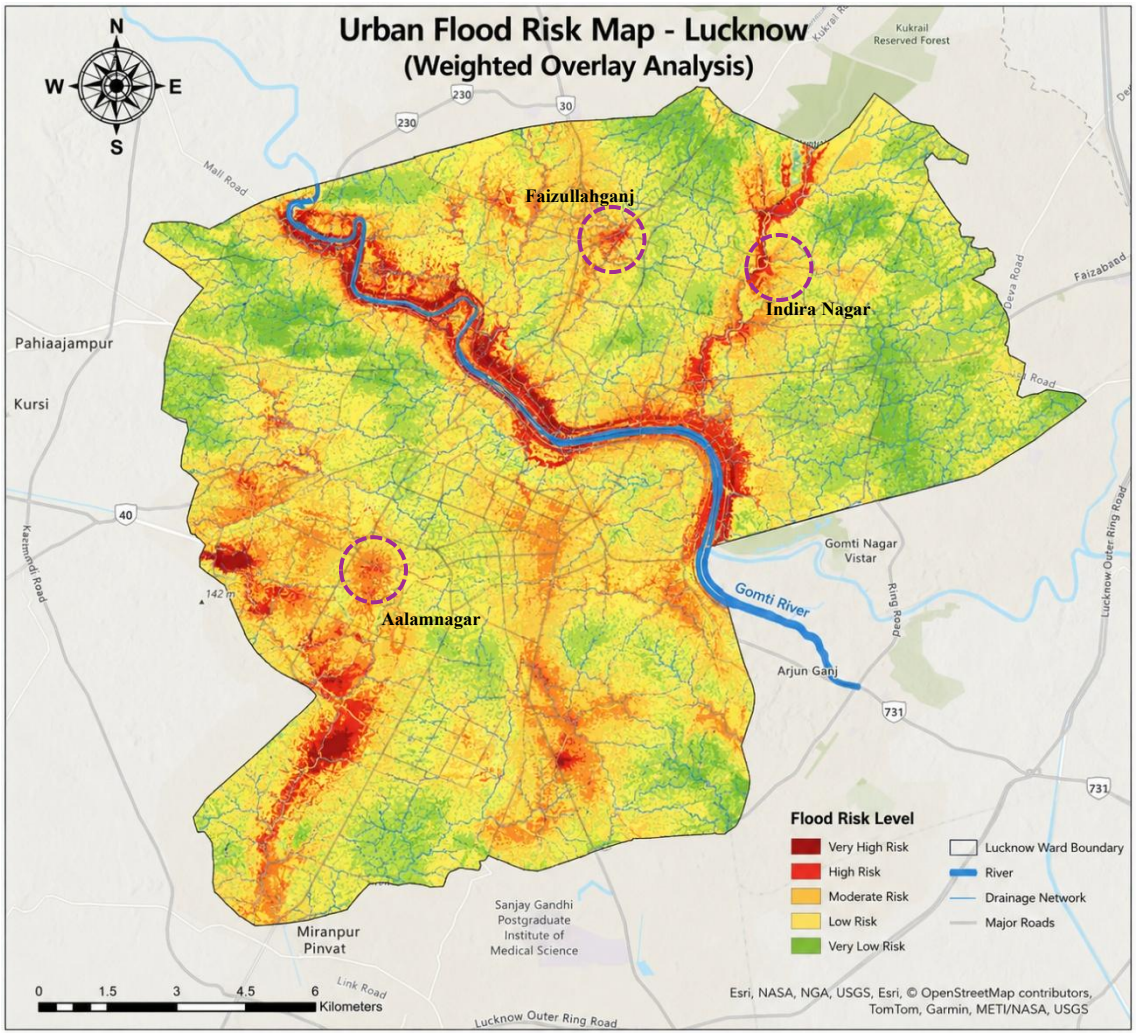


Figure 19 Hotspot Identification *Source: Author (ArcGIS Pro)*

4.8.4 Planning Implications and Future Directions

The above-mentioned screening and site selection method adopted in this chapter confirms that flooding in urban areas of Lucknow is caused by structural conflicts against natural geographical features (National Institute of Disaster Management [NIDM], 2022). As evident in image_211ae6.jpg, the evidence of risk accumulation clearly points out that the urban administration can no longer adopt a generic strategy to combat drainage

problems. It has become imperative to adopt a more scientific method of selecting hotspots, which will justify the move towards detailed and site-specific nature-based and structural engineering solutions in the following chapters.

4.9 Spatial Analysis Key Points and Planning Considerations

A few key observations resulting from the spatial and hydrological analysis of Lucknow are critical in forming the basis for the suggested holistic flood management strategy:

Runoff Reduction: The changes that have occurred in the geography of Lucknow have resulted in shifting the hydrologic characteristics of the city with stormwater runoff going up from 10% to greater than 55% in very concretized wards (Bastia et al., 2021). It is clear that the solution for addressing the city's flooding problem is not to increase concrete pipe sizes but to restore the hydrological cycle through increased surface porosity.

Infrastructure Obstruction: It is evident from the spatial analysis of Lucknow that transport infrastructure crosses high flow accumulation routes without providing sufficient cross-drainage capacity.

Environmental Interconnection: The correlation between an annual groundwater depletion rate of 0.56 meters (LMC, 2015) and a 4.5°C rise in Land Surface Temperature (Tripathi & Gupta, 2023) highlights the environmental cost of widespread surface concretization. This demonstrates the necessity of integrating Nature-Based Solutions (NBS)—such as bioswales, urban wetlands, and permeable pavements—to simultaneously lower urban temperatures, recharge aquifers, and manage peak stormwater volumes.

Context-Specific Strategy: The identification of the four distinct hotspots shows that urban flooding in Lucknow is driven by varying localized factors, rather than a single uniform cause. Addressing these risks requires a combination of targeted structural upgrades, non-structural zoning changes, and nature-based solutions tailored to the unique terrain and development patterns of each site.

Chapter 5

HOTSPOT ANALYSIS AND MICRO-LEVEL VULNERABILITY ASSESSMENT

Beyond the geospatial modelling of regions to determine the high-risk areas, this chapter takes the study to the neighbourhood scale and performs an assessment of the diagnosed areas. As vital as the models that are used to map hazards at the city scale, local conditions of flooding are largely affected by the geometry of streets and secondary infrastructures, as well as social vulnerability of the neighbourhoods. Shifting the analysis from the city to the micro scale, this chapter uses a combination of terrain and field studies to explore the experience and response of various urban fabrics to waterlogging.

5.1 Introduction to Micro-Level Vulnerability Analysis

Whereas macro-level hydrological models help create an overall topographic and regional drainage basin layout for the Lucknow Municipal Corporation (LMC) area, urban flooding is a phenomenon which is felt, navigated, and endured at the level of individual neighbourhoods and streets. While macro-level models offer useful baseline information about regional drainage basins and major river outlets, they often fail to capture the highly localized physical, structural, and institutional deficiencies responsible for local pluvial flooding.

With this in mind, Chapter 5 makes a transition from macro-hydrology to micro-urbanism by performing a fine-grain vulnerability assessment of three different urban hotspots located in Lucknow. These particular urban hotspots have been identified based on the following criteria: high flow accumulation values, high population density, high waterlogging frequency, and unique urban morphological typologies:

1. Unplanned Periphery Sprawl: Faizullahganj (Zone 5)
2. Linear Infrastructure & Industrial Barrier: Alamnagar (Zone 5/6 Axis)
3. Channel-Aided Urban Basin: Indira Nagar Sector 25 next to Kukrail Nala (Zone 4)

Through the use of high-resolution digital terrain modelling together with empirical information collected through a primary field study conducted locally at each site ($N = 150$ households total per site), this chapter is able to identify localized failure modes that may range from small-scale problems such as street grading all the way up to larger issues like cross drainage bottlenecks.

5.2 Localized Hydrological Calculation Methodology

In order to develop a scientifically sound methodology for comparing these three very different typologies without relying on sophisticated hydrodynamic modelling tools, two basic urban hydrology formulas are employed at the micro catchment level:

1. The Weighted Runoff Coefficient ($C_{weighted}$)

The runoff coefficient (C) represents the fraction of total rainfall that is transformed into surface runoff. Because urban spaces feature highly varied surface materials, a composite or weighted coefficient must be calculated based on the spatial allocation of surfaces within a standardized sample catchment boundary (10 hectares or 100,000 m^2 for each

$$C_{weighted} = \frac{\sum_{i=1}^{n}(C_i \times A_i)}{A_{total}}$$

hotspot) using the formula:

Where C_i represents the standard engineering runoff value assigned to a specific land surface type, and A_i represents the area covered by that surface. Standard engineering reference coefficients utilized include:

1. *Roof Surfaces / Concrete Plazas:* 0.90 - 0.95
2. *Asphalt / Bituminous Roads:* 0.80 - 0.85
3. *Consolidated Built-up / Dense Residential:* 0.70 - 0.80
4. *Unpaved Roads / Vacant Earth Plots:* 0.20 - 0.30
5. *Parks / Open Green Spaces / Vegetated Soil:* 0.10 - 0.15

2. The Rational Method for Peak Discharge (Q)

To estimate the absolute volume of stormwater runoff generated during peak intensity monsoon occurrences, the classic Rational Method formula is applied:

$$Q = \frac{C \cdot I \cdot A}{360}$$

Where:

Q = Peak Surface Runoff Discharge (m^3/sec)

C = Calculated Composite Weighted Runoff Coefficient

I = Peak Rainfall Intensity (mm*/hr*). *Note: A uniform peak monsoonal storm intensity of 50 mm/hr is standard for Lucknow, reflecting its recent history of short-duration, high-intensity cloudburst events.*

A = Catchment Area (standardized to 10 hectares across all three hotspot sites to provide an even comparative baseline).

5.3 Faizullahganj Hotspot Analysis (The Unplanned Peripheral Sprawl Model)

5.3.1 Site Location and Socio-Spatial Profile

Located on the northern trans-Gomti periphery of Lucknow, Faizullahganj falls within the administrative purview of LMC Zone 5. Within the last two decades, the site has experienced intense volatility, changing drastically from a low density, agricultural fringe into a high density, low-income residential settlement. The development of the area has been unplanned and speculative, resulting in the expansion of the built-up area beyond the extents of trunk infrastructure.

The socio-economic profile of the area is very vulnerable, with a combination of masonry buildings and semi-permanent residential structures. Survey findings indicate that 64% of all properties are multi-generational houses developed incrementally. Boundaries of the property parcels are very tight with no scope for any municipal services to be provided. There has been excessive horizontal growth with absolutely no planning enforcement.



Figure 20 Layout Faizullahganj *Source: Author (ArcGIS Pro)*

5.3.2 Micro-Terrain and Local Hydrology

The topography of Faizullahganj indicates that it sits on an alluvial terrace which is close to the active floodplain of the Gomti River. The area is particularly flat, with local heights varying only slightly from 101 meters to 104 meters.

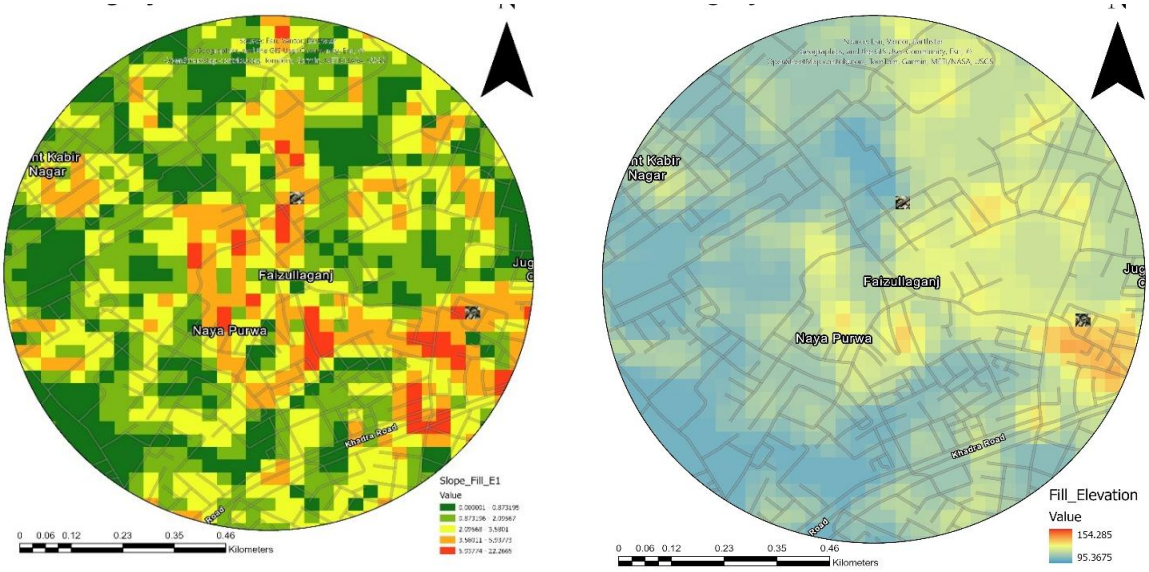


Figure 21 Slope and DEM of Hotspot *Source: Author (ArcGIS Pro)*

Natural soil profile comprises fine Indo-Gangetic alluvium with a significant proportion of clay, which inherently results in low hydraulic conductivity and low infiltration rate. In addition, because of its close proximity to the river corridor, the local water table is quite shallow, with the water table depth being less than 2 meters from the ground surface prior to the onset of monsoon rains. High water table makes for an inherent hydrological limitation, which is that during monsoon rainfall, the local soil profile gets saturated immediately, making infiltration impossible and resulting in surface runoff.

5.3.3 Built-Form Density and Deficiency of Drainage Infrastructure

The critical spatial problem faced by Faizullahganj lies in its absolute deficiency in drainage infrastructure. Through a quantitative study of the built form of the streets, one can conclude that 88 percent of the streets in Faizullahganj are either earthen roads or concrete lanes with no side drains along their sides. There is no stormwater infrastructure linking them to an outfall point.

Consequently, the actual physical structure becomes the main element that modifies the hydrology on the surface. As residential buildings were erected one by one without any master plan or benchmarks at ground level, the respective landowners have continuously elevated their building foundations for protection purposes. Such an approach has led to disturbance of the slope of the terrain, resulting in a disordered sequence of artificial land-locked basins, where water cannot drain away but is confined between two consecutive residential walls.

5.3.4 Primary Field Survey and Ground-Truth Results

The household survey conducted in the field (n=50 in this particular hotspot) has proven that there is a persistent problem of surface waterlogging. Almost all residents, 96%, suffer from waterlogging during the monsoon season.

Table 10 Empirical Flood Exposure Metrics - Faizullahganj Survey Data

Survey Observation Parameter	**Resident Response Metric (%)**	**Field Ground-Truth Context & Implications**
Maximum Water Inundation Depth	76% report depths exceeding 0.5 m- 1.0 m	High structural exposure; floodwaters regularly breach front doors, damaging interior property.
Water Stagnation Duration	72% report standing water lasting >3 days	Zero infrastructure outlet; water must slowly evaporate or undergo minimal subsurface seepage.
Plinth Level Configuration	62% of home plinths are lower than adjacent roads	Roads have been progressively elevated over time by ad-hoc municipal repaving, turning homes into catch basins.
Primary Perceived Cause	84% select "Total Absence / Blockage of Drains"	Confirms that flooding here is an infrastructure-driven governance failure, not just an act of nature.

Observations in the field have revealed the following instances of structural deterioration: high levels of moisture (seepage) seeping upwards through load-bearing masonry walls; structural subsidence of foundations; and continued degradation of the unpaved roads. This situation of stagnation of mixed stormwater and sewage poses a grave public health risk, as people are vulnerable to vector-borne diseases.

5.3.5 Local Hydrological Calculations

Through a spatial division of a **typical 10 Hectare** area within Faizullahganj using land use mapping, the following hydrological parameters can be determined:

Catchment Area (A): 10 Hectare

Surface Cover:

Built-Up Area with High Population Density = 6.0 Ha (C=0.75);

Unpaved Earth Roads/Plots = 3.5 Ha (C=0.25);

Open Greenery = 0.5 Ha (C=0.15).

$$C_{weighted} = \frac{(0.75 \times 6.0) + (0.25 \times 3.5) + (0.15 \times 0.5)}{10} = \frac{4.50 + 0.875 + 0.075}{10} = 0.545$$

Applying the Rational Method for a standard 50 mm/hr peak rainfall event:

$$Q = \frac{0.545 \times 50 \times 10}{360} = 0.757 \text{ m}^3/\text{sec}$$

Hydrological Interpretation: Although the use of dirt paths that can absorb some of the early rainfall is considered, the catchment area still produces an outflow rate of 757 Liters/second. Since there are no existing side drains or drainage channels in the catchment, the entire volume ends up being retained in the street right-of-way, hence the rapid rise of water to more than half a meter.

5.4 Alamnagar Hotspot Analysis (The Linear Infrastructure Barrier Model)

5.4.1 Site Location and Socio-Spatial Character

Alamnagar lies within the southwestern extension corridor of Lucknow and acts as an important intermediary zone between LMC Zones 5 and 6. This hotspot area has an urban character that has developed rapidly over the past two decades. Its spatial organization includes a combination of formal industrial warehouses, logistics freight yards, and new middle class residential colonies.

The land use development pattern has been characterized by speculation due to the area's strategic proximity to transport connections. Such rapid development has created a very complex urban landscape, where vast concrete footprints of industrial units are in direct juxtaposition with densely packed residential areas, creating a highly complicated system of drainage, where industrial runoff is discharged directly into the domestic catchments.

5.4.2 Micro-topography and Local Drainage Patterns

The natural micro-topography of the Alamnagar area consists of a very gentle, systematic south-westerly slope, which naturally directs surface water flow towards the periphery agricultural basins and local rivers. Nevertheless, the natural drainage pattern is entirely disturbed by a linear infrastructure asset – the main broad gauge rail line embankment of Indian Railways.

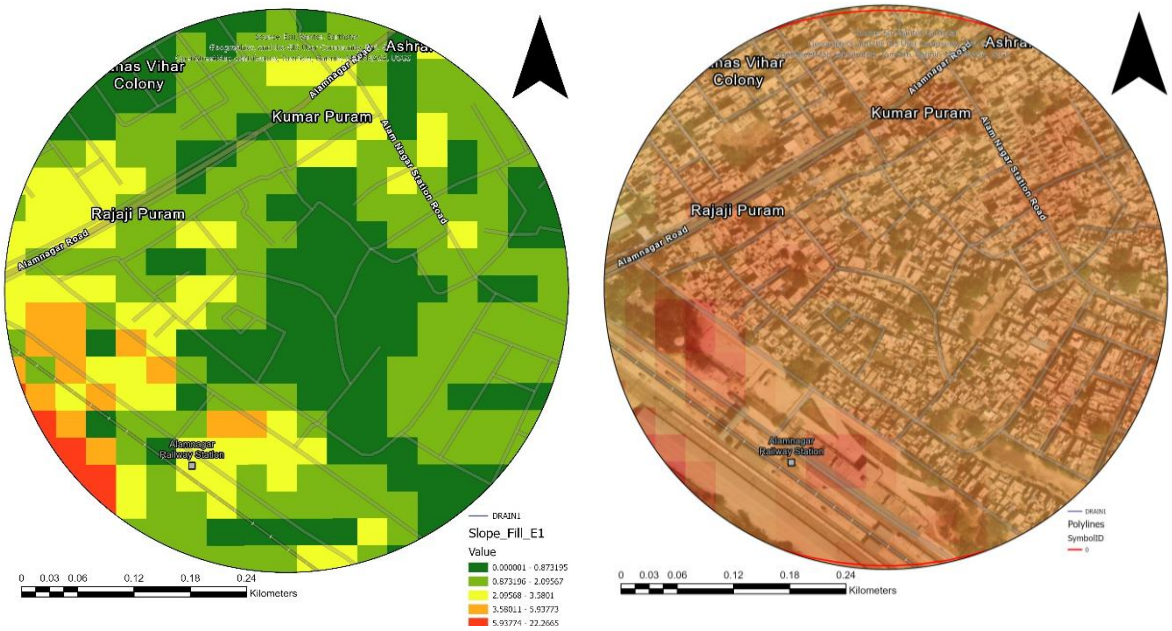


Figure 22 Slope and DEM for Aalamnagar *Source: Author (ArcGIS Pro)*

The rail track is constructed on an intensely compacted and raised earth embankment that stands between 3 m to 5 m higher than the natural ground level, cutting directly through the natural slope of the terrain. This artificial structure serves as a topographic dam in the area, creating upstream and downstream sections in the micro-watershed and significantly changing the natural pattern of surface runoff.

5.4.3 Built-Form Density and Drainage Infrastructure Deficit

With the growth of residential and industrial zones in Alamnagar, there has been a gradual invasion of the natural water absorbers in the area. Spatial analysis shows that the seasonal wetlands and talabs have been paved and covered with concrete structures such as industrial warehouses and housing units.

As a result, the total surface runoff has drastically increased, leaving the drainage infrastructure no option but to channel the stormwater to a few remaining cross-drainage points. Field investigations conducted on the existing drainage network reveal that the current Hume-pipe culverts are under-designed. The culverts, built many years ago for the highly porous and agricultural landscape, do not take into consideration the new peak runoff coefficients created by the current concrete cover.

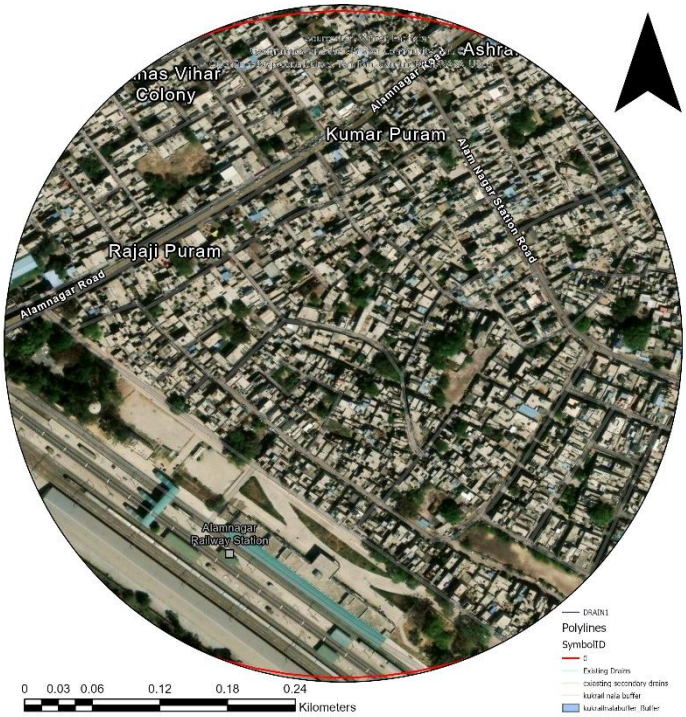


Figure 23 Layout of Hotspot (Aalamnagar) *Source: Author (ArcGIS Pro)*

5.4.4 Primary Field Survey and Ground Truth Data Collection

Primary data gathered from the households located at the residential development sites that border the north side upstream of the railway (n=50) suggests a high level of localized structural flood vulnerability. 84% of respondents point to the presence of the railway embankment structure, coupled with the quick blockage of its small under-track drainage structures, as the main cause of localized flooding.

During heavy rainfall, the runoff resulting from the new concrete surface on the industrial warehouses flows downhill until it reaches the raised railway embankment. Due to the inadequacy and constant blockages of the cross-drainage culverts, the water is unable to flow through the embankment, thereby creating a large “damming effect” at the upstream edge of the railway line.

This results in excessive waterlogging of the area, whereby the adjacent residential colonies remain submerged under water for 24-48 hours at depths greater 0.5 meter. This waterlogging affects the ground floor residences, ruins the vehicle infrastructure, and cuts off road communication.

5.4.5 Local Hydrological Calculations

The calculations of typical 10 Hectare catchment area for the area upstream of the railway embankment include the following metrics:

Catchment Area (A): 10 Hectares

Surface Composition:

Industrial Galvanized/Concrete Roof Sheets = 5.0 Ha (C=0.90);

Asphalt Internal Roads/Yards = 3.0 Ha (C=0.85);

Residential Built-up Units = 2.0 Ha (C=0.75).

$$C_{weighted} = \frac{(0.90 \times 5.0) + (0.85 \times 3.0) + (0.75 \times 2.0)}{10} = \frac{4.50 + 2.55 + 1.50}{10} = 0.855$$

Applying the Rational Method for a standard 50 mm/hr peak rainfall event:

$$Q = \frac{0.855 \times 50 \times 10}{360} = 1.187 \text{ m}^3/\text{sec}$$

Hydrological Analysis: Given the nature of the industrial warehouse's roof design, which entails vast areas of sheet metal and concrete roofs, the catchment is associated with a high weighted runoff coefficient (C = 0.855). This means that 85.5% of rainfall is instantly turned into surface runoff. The drainage system creates a huge peak discharge amount of 1,187 Liters per second. Channelling such high amounts of surface water through an obsolete 600 mm cross-drainage Hume pipe below the tracks leads to choking, hence causing water to back up and cause flooding in the neighbouring roads.

5.5 Indira Nagar Sector 25 Hotspot Analysis (The Channel-Adjacent Urbanized Basin Model)

5.5.1 Location of Site and Social-Spatial Context

Indira Nagar Sector 25 falls within the northeastern section of Lucknow in LMC Zone 4. In contrast to the unplanned peripheries of Faizullahganj or the industrial areas of Alamnagar, Indira Nagar comprises an organized development pattern consisting of dense housing and institutional buildings.

Indra Nagar Sector 25 can be classified socio-economically as predominantly occupied by middle-to-upper income classes. Moreover, the built environment consists largely of consolidated brick-and-mortar structures (92% of total sample area). Nevertheless, the

significant socio-spatial vulnerability of Sector 25 lies in its close proximity to the Kukrail Nala, which is a major natural drainage channel that acts as a tributary to the Gomti River.

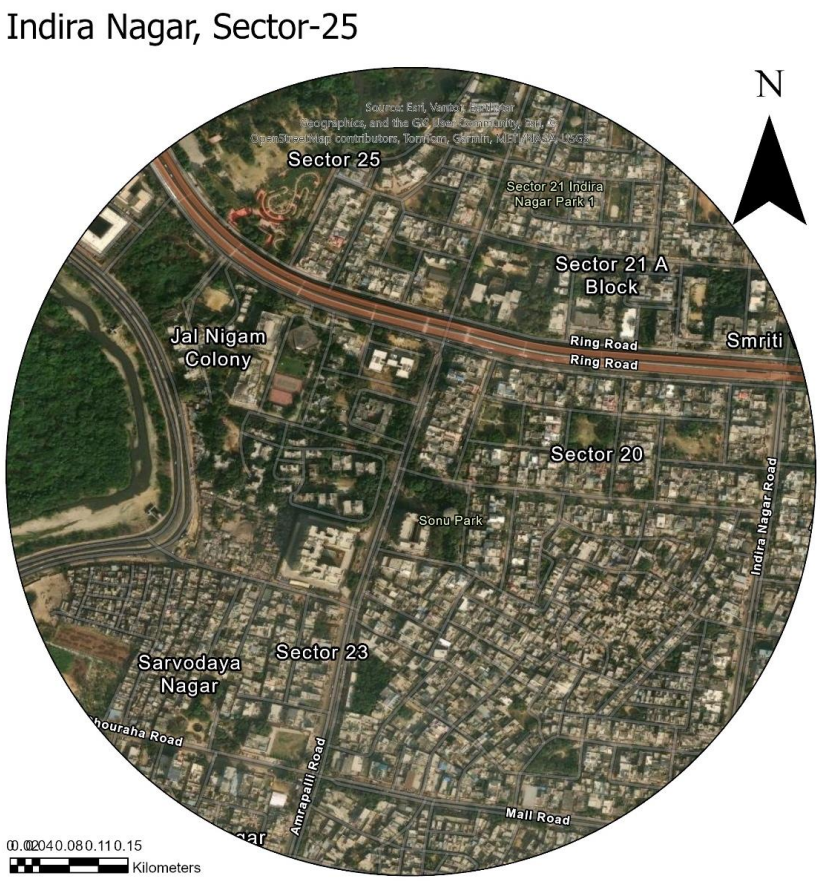


Figure 24 Layout Indira Nagar *Source: Author (ArcGIS Pro)*

5.5.2 Microtopography and Local Hydrology

Indira Nagar Sector 25 is situated on a highly sensitive terracing floodplain. The microtopography rises from 106 meters to 109 meters above mean sea level, with a consistent topographic slope leading down to the concrete banks of the Kukrail Nala.

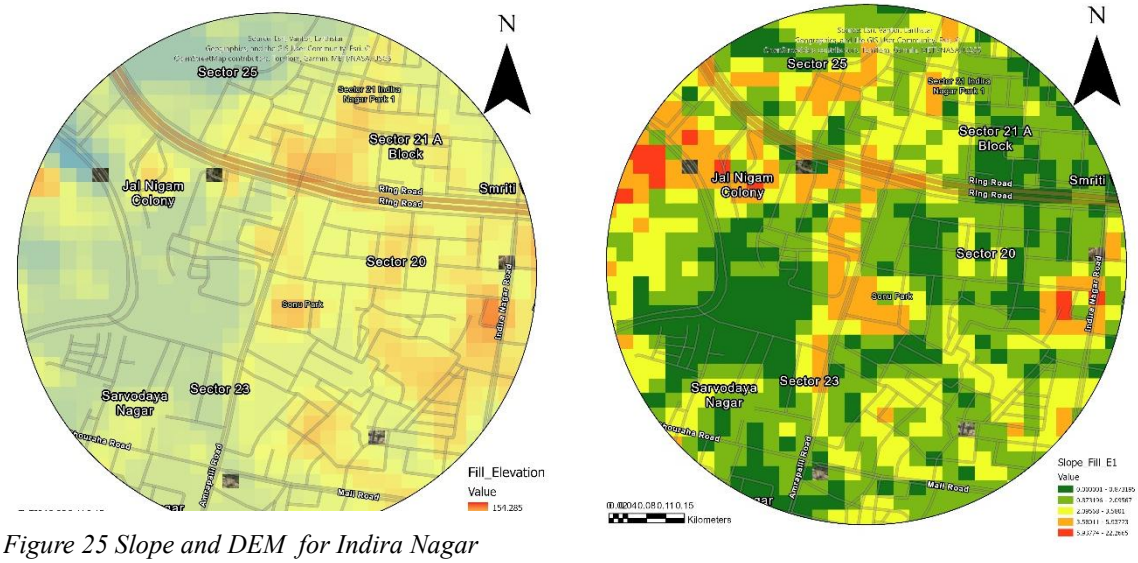


Figure 25 Slope and DEM for Indira Nagar

Source: Author (ArcGIS Pro)

From a hydrological point of view, the whole sector constitutes an urbanized micro-basin. Naturally, all water from the surface of the sector was drained off to neighbouring flood meadows. At present, however, the sector uses artificial concrete storm drainage outfalls for directing all surface runoffs to the Kukrail Nala through gravity.

5.5.3 Built-Up Density and Drainage Infrastructure Shortage

The analysis of the built structure shows that the area has an extremely high level of surface sealing. In the past 30 years, private plots have been maximally developed, leaving practically no areas with green grass, free land, or unsealed soil. The second problem of high built-up density is represented by a structural engineering deficiency: there is no protection against backflow in the internal storm drainage pipes of the sector, which are connected to the Kukrail Nala, and therefore there are no devices such as automatic flap gates or check valves.

5.5.4 Field Survey Findings

The results of primary household surveys, conducted in Sector 25 (n=50), show that the dominant type of flooding is rapid flash pluvial flooding. 88% of inhabitants reported that waterlogging at street level occurred within 30 minutes after rainfall commenced.

Table 11 Empirical Flood Exposure Metrics - Indira Nagar Sector 25 Survey Data *Source: Author*

Survey Observation Parameter	**Resident Response Metric (%)**	**Field Ground-Truth Context & Implications**
Maximum Water Inundation Depth	82% report water depths between 0.3 m - 0.6 m	Moderate depth but high velocity; floods street channels and stalls local traffic.
Water Stagnation Duration	64% report drainage within 3 – 6 hours post-storm	Drainage is relatively fast *unless* the Kukrail Nala is full, which extends stagnation.
Observed Secondary Flood Source	78% report water bubbling backwards out of manholes	Confirms the occurrence of drain reversal due to high water levels in the main channel.

The fast flooding is caused by the huge amount of runoff produced by the paved neighbourhood being too much for the intake capacity of the drain inlets. In addition, during peak monsoons, this problem is worsened by the fact that there is a lot of water in the Kukrail Nala. As the Kukrail Nala fills due to heavy rains in the area, the water level exceeds the drainage outfall levels of the neighbourhood.

Since the outfalls do not have any backflow valves, the rising water in the river forces water backwards into the drainage system. This prevents the drainage system from discharging and traps the runoff in the neighbourhood for hours after the rain stops.

5.5.5 Local Hydrological Calculations

When evaluating a standard sample block layout consisting of 10 hectares, the following spatial variables are identified:

Catchment Area (A): 10 Hectares

Composition of Surface: Planned Pucca Residential Roofs = 6.5 Ha (C=0.85); Lined Concrete/Asphalt Roads = 2.5 Ha (C=0.80); Institutional Paved Frontages = 0.8 Ha (C=0.85); Residual Green Parks = 0.2 Ha (C=0.15).

$$C_{weighted} = \frac{(0.85 \times 6.5) + (0.80 \times 2.5) + (0.85 \times 0.8) + (0.15 \times 0.2)}{10} = \frac{5.525 + 2.00}{}$$

Applying the Rational Method for a standard 50 mm/hr peak rainfall event:

$$Q = \frac{0.823 \times 50 \times 10}{360} = 1.143 \text{ m}^3/\text{sec}$$

Hydrological Implications: As a result of its planned but extremely compacted concrete nature, Sector 25 has a very high composite runoff coefficient C = 0.823, meaning that 82.3% of all rainfall is converted into instantaneous surface runoff. The catchment produces an amount of peak runoff of 1,143 Liters per second. Although the concrete storm sewers in the neighbourhood are designed to accommodate such a peak flow rate, they are unable to do so when backwater pressure from the overflowing Kukrail Nala prevents them from discharging and forces floodwater to spill out via local manholes.

5.6 Comparative Analysis of Hotspots

In order to go beyond mere site descriptions, Table 5.3 presents a comparative analysis matrix where all three hotspots are compared against each other with respect to their critical hydrological, physical, structural, and institutional characteristics. It clearly shows that urban flooding in Lucknow arises from distinct localized causes, not a uniform one.

Source: Author

Table 12 Comparative Analysis of Hotspots

Analytical Evaluation Parameter	Faizullahganj (Section 5.3)	Alamnagar (Section 5.4)	Indira Nagar Sec 25 (Section 5.5)
Dominant Hotspot Typology	Unplanned Peripheral Sprawl Model	Linear Infrastructure Barrier Model	Channel-Adjacent Urbanized Basin Model
Primary Localized Flood Driver	Complete absence of engineered trunk drains; informal housing on low flood terraces.	Earthen railway embankment acting as a physical dam; under-designed culverts.	High surface impermeability; backwater pressure and drain reversal from Kukrail Nala.
Composite Runoff Coeff. (C)	0.545	0.855	0.823
Peak Discharge (Q) per 10 Ha	0.757 m^3/sec (757 L/s)	**1.187 m3/sec** (1,187 L/s)	1.143 m^3/sec (1,143 L/s)
Max Inundation Depth (Survey)	76% report 0.5 m - 1.0m depths	**86% report extreme depths >1.0m**	82% report moderate flash depths (0.3 - 0.6m)
Water Stagnation Profile	**Prolonged chronic stagnation (>3 days to weeks)**	Moderate standing duration (24 - 48 hours)	Short-duration flash flooding (3 - 6 hours max)
Primary Institutional Agency	Lucknow Municipal Corporation (LMC)	Indian Railways & Lucknow Development Compiled by Authority	Lucknow Development Compiled by Authority (LDA) & LMC

Source: Compiled by Author

5.7 Key Findings from the Three Chosen Urban Hotspots and Their Spatial Implications

The detailed study of the three selected urban hotspots leads to some very significant conclusions on which the proposed integrated flood mitigation strategy is based:

1. The Myth of One-Sized-Fits-All Engineering Interventions: The spatial and mathematical analysis has proved that an engineered solution such as constructing bigger concrete pipe drainage systems throughout the city is neither feasible structurally nor financially. The problem at each chosen location lies in the failure mode, which requires site-specific structural and non-structural measures along with nature-based approaches, depending on their spatial characteristics.

2. The Hydrological Burden of Surface Concretization: The study of the two hotspots—Alamnagar and Indira Nagar Sector 25—clearly shows that there are serious hydrological consequences of extensive surface concretization. Increasing the runoff coefficients beyond 0.80 results in a very high volume of runoff, making it impossible to handle through conventional pipe drainage systems.

3. Institutional Coordination Shortfall: The infrastructure conflicts observed in Alamnagar and Indira Nagar demonstrate an acute deficiency in the coordination of operations among the various institutions responsible for managing the flood problem. Effective stormwater management necessitates an institutional structure that facilitates coordination of planning actions among the Lucknow Municipal Corporation, Lucknow Development Compiled by Authority, UP Jal Nigam, and the para-state institutions such as Indian Railways.

4. Social Inequalities in Flood Impacts: The consequences of pluvial floods are differentiated along socio-economic fault lines. Whereas the immediate effect of floods is on aesthetic spaces and disruption of vehicular movement in institutional and middle-class areas, Faizullahganj experiences long-term physical deterioration of low-value buildings and perpetual public health emergencies. This calls for a holistic approach that considers technical effectiveness as well as social justice in planning action. These findings provide empirical support for the structural, non-structural, and Nature-Based Solutions (NBS) described in Chapter 6.

Chapter 6

PROPOSALS AND MITIGATION FRAMEWORK

In this chapter, there is the presentation of the engineering designs, NBS, and planning policies put in place to counter recurring floods in Lucknow. Through dealing with the hydraulics of inundation from lack of infrastructure to linear transport barriers and outfall backflow, the mitigation strategy presented in this chapter becomes practical in terms of climate resilient urban development. The sections below will show the strategic vision underpinning this proposal, its objectives, and finally the matrix designs for each hotspot.

6.1 Vision for Mitigation Proposal

The vision behind the proposal of this mitigation framework lies in converting the flood-prone urban area of Lucknow into a resilient city based on water management by moving from a conventional concrete-based drainage system towards IUWM. The proposal recognizes that conventional approaches such as rapid drainage of stormwater through concrete drains have become inadequate due to rapid changes in land use and occurrence of storm bursts due to climatic changes.

This framework aims to achieve a balanced hydrology in the city by prioritizing the retention and release of stormwater within the city. The ultimate objective of this framework is the protection of human life and property, removal of standing water, and improvement of public health standards in the most vulnerable areas of Lucknow.

6.2 Planning Objectives

In order to realize this vision, the proposal framework presents the following five critical planning and engineering objectives:

1. Decrease Surface Imperviousness: Decrease composite surface runoff coefficients in developed catchments through the use of permeable surfaces and incorporation of NBSs in public spaces.
2. Remove Structural Hydraulic Obstacles: Increase the capacity of cross-drainage structures and improve the gravitational drainage capability of urban rivers in high stage states.
3. Design Neighbourhood-Level Drainage Patterns: Construct the missing neighbourhood-level drainage networks in informal peripheral areas to ensure correct alignment with terrain topography.
4. Integrate Water-Centric Land Use Planning: Incorporate flood hazard zoning, blue-green infrastructure requirement, and strict wetland protection measures in statutory master plans.

5. Create Multi-Institution Resilience: Create operational guidelines for coordination among infrastructure providers during disasters and regular maintenance of the assets.

6.3 Proposal Strategy Framework

The practical core of Chapter 6 is the transition from synthesis to application through use of the Strategic Urban Flood Management Matrix created in the previous chapters of this thesis. This unique matrix categorizes the typology of flood drivers in terms of proven structural, non-structural, and NBS measures that are best suited to the Indian urban condition.

Using the matrix in combination with the local physical, environmental, and socio-spatial weaknesses identified in the primary field survey conducted in Chapter 5, the general strategies are translated into specific proposal strategies.

6.4 Faizullahganj (Unplanned Peripheral Sprawl Model)

6.4.1 Structural Measures

To compensate for the total drainage deficit measured through the field survey in Section 5.3.3, a completely new drainage structure must be laid out. Following the identified micro-terrain sinks on the terrain geometry maps, a 4.2-km drainage network will be developed along the slope, leading to the lower terraces.

Aside from the irregularities and constraints of the site, these side drains will be constructed as covered masonry drains with precast concrete lintels. The structure will prevent waste disposal in the drain and shield it from light vehicle loads, but allow easy cleaning through removable inspection chambers placed every 25 meters. Moreover, a regrading exercise will be conducted. Elevated passages due to successive municipal repaving of streets should be dug and regraded to a lower level than the plinth levels of the old houses, creating a slope towards the drain.

6.4.2 Non-Structural Measures

Any future development in Faizullahganj has to be regulated carefully to prevent additional informal footprint expansion into the active floodplain terrace of the Gomti River. For this purpose, the LDA has to introduce the Low-Income Incremental Housing Regularization Policy on a local scale. In accordance with this regulation, pattas or modifications can be issued only if the building footprint area does not exceed 60%, leaving 40% of the site surface unplanted to allow natural soil infiltration.

On a practical level, an early warning system based on local initiatives should be introduced. Given the shallow water table in the area, a network of three groundwater and pluvial depth sensors will be placed in local public locations. All these sensors will be

directly connected to a centralized warning system run by ward neighbourhoods' committee members, providing residents with a 2-hour period to protect their ground-floor properties from flash flooding.

6.4.3 Nature-based solutions (NBS)

Due to the high clay content and poor infiltration of the local alluvial soils, hard engineering needs to be complimented by effective source control infiltration techniques. It is recommended that the existing concrete paths be converted into Permeable Shared Streets. The central portion of the streets will be renovated using 1.2 meters wide strips of interlocking porous concrete pavers placed over an aggregate filtration trench. This design will help collect surface water which will then be filtered directly into the shallow aquifer before it is able to pool at the surface. A 1.5-hectare piece of unutilized land located at the lowest elevation point in the ward (101 m elevation zone at the edge of the river terrace) will be purchased to construct a Decentralized Community Stormwater Wetland. By allowing the water to flow through gravity instead of pressurizing the water into costly pumping systems, all local surface runoff will be directed into this constructed basin. This wetland will utilize native aquatic plants (Typha latifolia and Phragmites australis) to uptake nutrients from the sewage water, while retaining 15,000 cubic meters of water during extreme monsoonal rains.

6.4.4 Concept Plan and Drainage Plan

The positioning, nodal location, and layout formation of all these structures and solutions are clearly identified in the concept plan prepared for this hotspot. This map shows the exact spatial location of the planned network, guaranteeing that each intervention will cross the flow-accumulation zones that were confirmed during micro-terrain analysis.

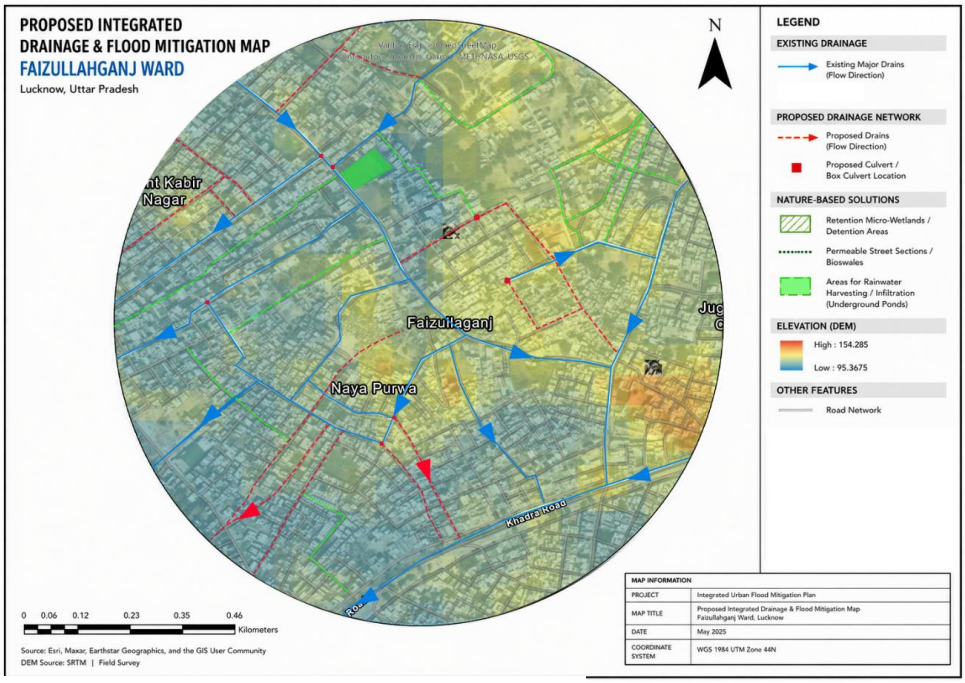
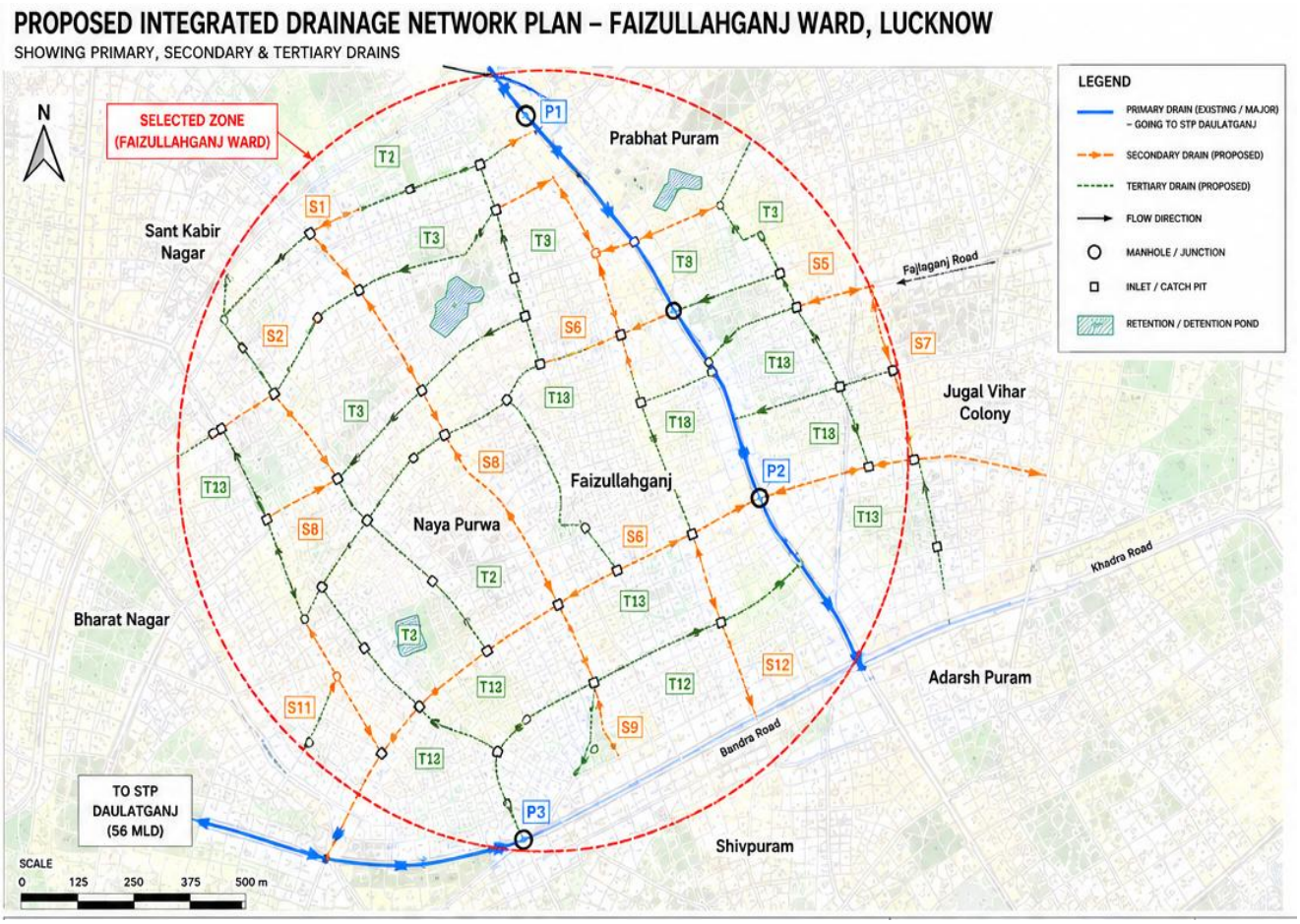


Figure 26 Concept Proposal Plan *Source: Author (ArcGIS Pro)*

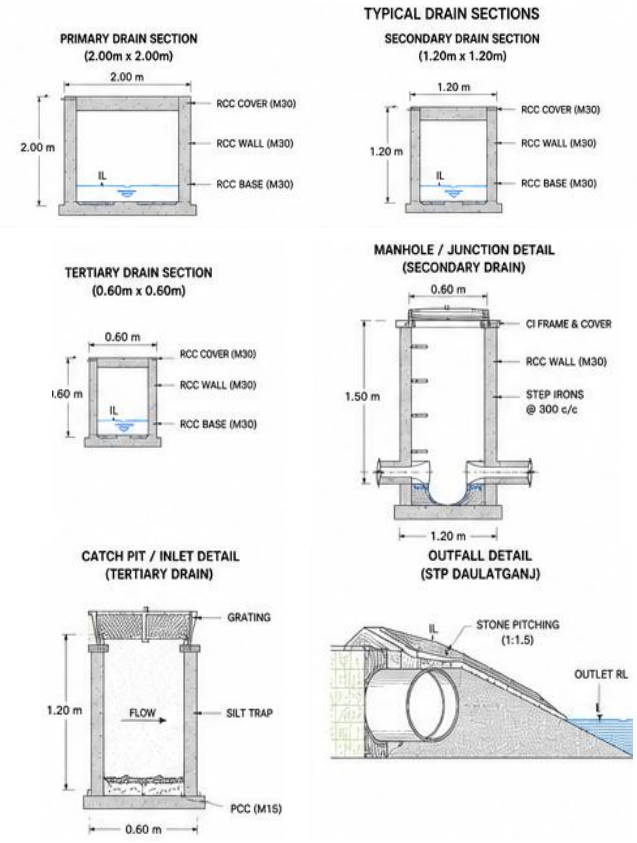


DRAIN HIERARCHY & TYPICAL DIMENSIONS				
TYPE	SIZE (W x D)	PIPE DIA (mm)	SLOPE (1 in)	MATERIAL
PRIMARY DRAIN	2.00 x 2.00 m	1200 – 1800	200	RCC (M30)
SECONDARY DRAIN	1.20 x 1.20 m	600 – 900	300	RCC (M25)
TERTIARY DRAIN	0.60 x 0.60 m	300 – 450	400	RCC (M20)

DRAIN SCHEDULE – PRIMARY DRAIN (EXISTING / MAJOR)					
ID	FROM	TO	PIPE DIA (mm)	LENGTH (m)	SLOPE
P1	Upstream Network	P2	1500	1,240	1 in 200
P2	P1	P3	1500	1,320	1 in 200
P3	P2	STP Daulatganj	1800	2,150	1 in 200

DRAIN SCHEDULE – SECONDARY DRAIN (PROPOSED)					
ID	FROM (MH)	TO (MH)	PIPE DIA (mm)	LENGTH (m)	SLOPE
S1	MH-S1-1	MH-S1-2	900	410	1 in 300
S2	MH-S2-1	MH-S2-2	750	380	1 in 300
S3	MH-S3-1	MH-S3-2	750	560	1 in 300
S4	MH-S4-1	MH-S4-2	600	300	1 in 300
S5...S12	-	-	600 – 900	300 – 700	1 in 300

DRAIN SCHEDULE – TERTIARY DRAIN (PROPOSED)					
ID	FROM (INLET)	TO (MH)	PIPE DIA (mm)	LENGTH (m)	SLOPE
T1	CP-T1-1	MH-T1	300	120	1 in 450
T2	CP-T2-1	MH-T2	300	110	1 in 450
T3...T20	-	-	300 – 450	80 – 250	1 in 450



Source: Author (ArcGIS Pro)

Figure 27 Faizullahganj proposal drawing

6.4.5 Expected Hydrological Impacts

The implementation of the above strategies will totally transform the hydrology of the area. The introduction of permeable pavement on streets and the protection of the micro-wetland basin will reduce the composite runoff coefficient (C) of the 10-hectare catchment as follows:

Proposed Built-up Area: 6.0 Ha (C decreases from 0.75 to 0.60, owing to micro-infiltration) Proposed Permeable Streets/Plots: 3.5 Ha (C decreases from 0.25 to 0.15) Proposed Wetland Basin: 0.5 (C=0.10)

$$C_{weighted} = \frac{(0.60 \times 6.0) + (0.15 \times 3.5) + (0.10 \times 0.5)}{10} = \frac{3.60 + 0.525 + 0.05}{10} = 0.417$$

Recalculating peak discharge via the Rational Method for a standard 50 mm/hr peak rainfall event:

$$Q_{proposed} = \frac{0.417 \times 50 \times 10}{360} = 0.579 \text{ m}^3/\text{sec}$$

Mitigation Strategy for Hydrology: The approach effectively reduces the peak discharge rate from 0.757 m3/sec to 0.579 m3/sec (23.5% decrease). The rest of the runoff water is then effectively discharged through the newly constructed 0.579 m3/sec masonry channel to the community wetland, thereby ensuring that the standing water on streets decreases from 3 days down to less than 2 hours.

6.5 Alamnagar Proposal (Linear Infrastructure & Industrial Barrier Model)

6.5.1 Structural Measures

The first critical structural need at Alamnagar involves removal of the severe hydraulic damming effects created by the elevated linear railway infrastructure acting as a levee to obstruct the natural south-westerly surface drainage flow. Following the principles outlined in the Strategic Urban Flood Management Matrix, the current 600 mm diameter circular Hume-pipe culvert beneath the railway track must be dismantled. In its place, the Lucknow Municipal Corporation (LMC), working in structural conjunction with the Northern Railway engineering division, must construct Twin Precast Concrete Box Culverts, with each unit having a cross-sectional dimension of 2.5 meters wide by 2.0 meters high. The new box culverts must be installed at a point along the natural downward slope of the terrain, as derived from the local digital elevation model.

For efficient flow into the new culverts, without any localized surge effects, a 1.8 km reinforced concrete collector drain (1.5 m base width) will be built parallel to the railway barrier along its northern edge. The new collector drain will effectively intercept and convey storm water from the secondary networks directly into the newly installed culverts, thereby preventing any backwater accumulation in the adjacent residential areas.

6.5.2 Non-structural Measures

In order to accommodate the fast growth of logistics facilities characterized by high impervious surfaces within its jurisdiction without compromising the financial state of the municipality, LDA needs to revise the current statutory building bye-laws for the Alamnagar Industrial and Warehouse Zone. All existing and future commercial warehousing sites with combined roof area greater than 2,000 m^2 will have to comply with an On-site Runoff Neutrality Requirement. The new by-law will mandate that all commercial warehouses submit proof of hydrological calculations which demonstrate that the post-development peak stormwater flow is no greater than pre-development conditions. The fulfilment of the requirement will be a condition of obtaining annual trade and operation license, otherwise heavy drainage utility fees will be imposed.

Property developers will also be restricted from encroaching on a mandatory 25-meter-wide structural buffer strip running adjacent to the entire railway embankment. This buffer strip should remain free of any informal material storage, boundary walls, or dumping of solid waste.

6.5.3 Nature-Based Solutions (NBS)

In order for the industrial and warehouse owners to be able to comply with the runoff neutrality regulations without sacrificing valuable indoor storage floor area by building concrete underground tanks, this plan calls for the installation of decentralized green infrastructure on a landscape scale. The properties will be mandated to replace the perimeter concrete setbacks with Vegetated Bioswales and Dry Detention Basins. The boundary drainage lanes, which are currently paved with plain asphalt, will be dug up again to form wide and shallow grassed swales that are lined with a native turf aggregate and stone check dams.

The bioswales will have two functions: they will serve to reduce the peak flow velocity of the sheet runoff coming off the roofs of huge warehouses, and secondly, they will employ phytoremediation to clean out the heavy metals and petroleum contamination that is common in heavy freight truck parking areas before entering the municipal infrastructure.

During heavy rainfall events, these bioswales will then discharge into interconnected shared dry detention basins—which during the dry season are designed as attractive shallow grass depressions—that can hold back peak flows for up to 45 minutes.

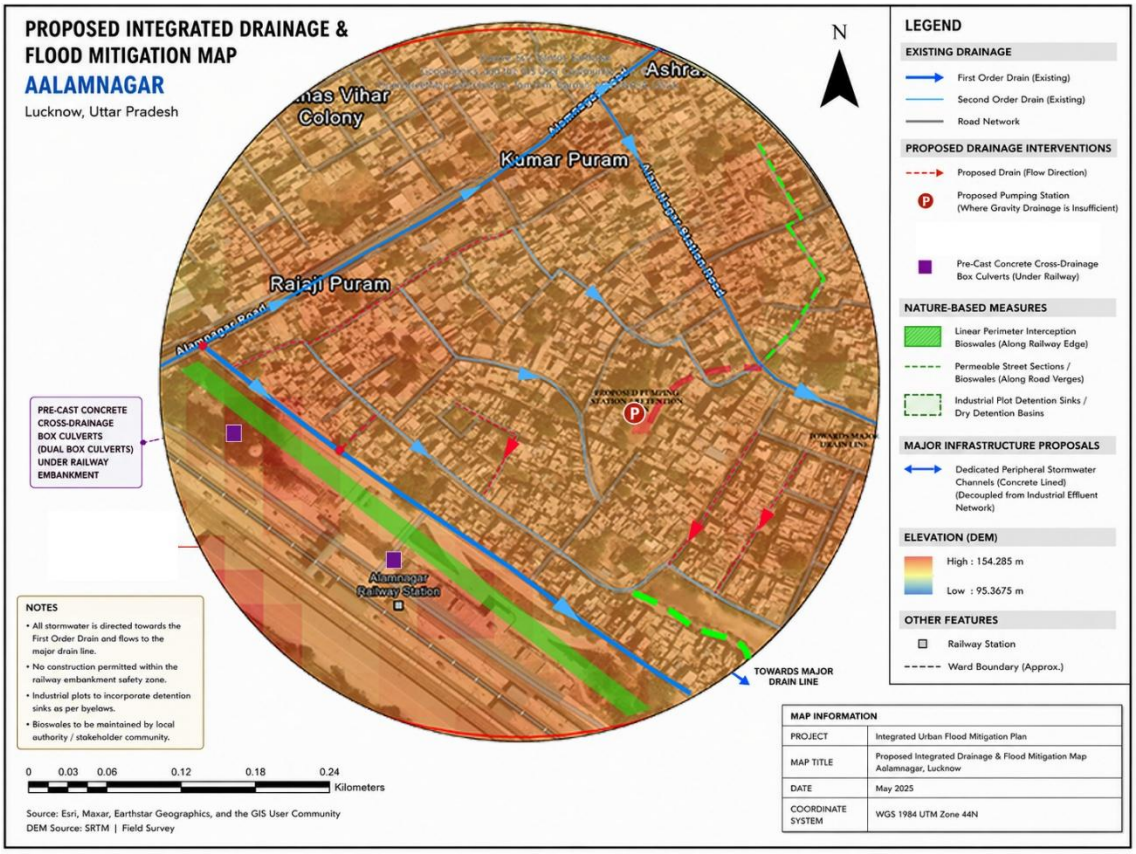


Figure 28 Concept Proposal Plan Aalamnagar *Source: Author (ArcGIS Pro)*

6.6 Indira Nagar Sector 25 Solution (The Adjacent Urbanized Basin Approach to the Drainage Problem)

6.6.1 Structural Solutions

The first and foremost structural solution required for Indira Nagar Sector 25 is the prevention of high stage backwater flooding from the Kukrail Nala during extreme storm events, as identified from the field study. By following the drainage management protocols of the Strategic Urban Flood Management Matrix, all municipal storm outfall pipes that discharge into the Kukrail Nala will have to be fitted with Mechanical Automated Flap Gates (Non-return check valves). The operation of these gates is automatic based on the hydraulic pressure difference; when the level of water in the Kukrail Nala exceeds the level of the neighbourhood drainage system, the external pressure closes the gates to prevent the reverse flow of water in the canal.

In order to handle the internal pluvial runoff that is retained in these closed gates due to simultaneous rainfall events, there needs to be construction of an Underground Sump Wet-Well Chamber right behind the main outfall protection wall. In the chamber, there should be an automatic, heavy-duty 25-HP axial stormwater pump. In the event of sealing of the flap gate and water being detected by the sensors inside the trunk lines, the pump

will turn on and lift the collected stormwater from the neighbourhood and discharge it over the embankment to enter the high-stage Kukrail Nala.

6.6.2 Non-Structural Measures

Due to Sector 25 being a mature and high-density planned neighbourhood with inflexible rights-of-way, any physical alterations to the street network are limited. Consequently, the non-structural measures that are implemented need to focus on source-volume control through a Mandatory Residential Rainwater Harvesting (RWH) Ordinance. The Lucknow Municipal Corporation (LMC) should rigorously implement requirements for all residential and institutional plots whose surface area exceeds 150 ^{m2} to prove the existence of a minimum 5,000 Liter rainwater storage tank.

From a process perspective, there is a need for a coordinated Integrated Sluice-Gate Protocol to be put in place between the LMC and the State Irrigation Department. This process will use telemetry from upstream gauges on the Kukrail Nala catchment to mechanically open up control gates to the river downstream ahead of a forecasted period of heavy rains. Through such a process, it is possible to ensure that the baseline water level in the channel is lowered prior to the arrival of any heavy rainfall, and thereby allow gravity to assist in draining water from the adjoining urban neighbourhoods while reducing the time that outfall flap gates remain closed.

6.6.3 Nature-Based Solutions (NBS)

It will be necessary to use decentralized nature-based solutions in order to store peak flows in Sector 25. In other words, decentralized parks should be used in order to store peak surface water. For this purpose, parks will be transformed into Sunken Bio-Retention Basins, where the inside of each park is due to a depth of 0.6 meters and then filled with a matrix of soil (60% sand, 20% organic compost, 20% topsoil), which will be covered with deep-rooted vegetation.

Also, the unlined areas left within the periphery of the Kukrail Nala will be classified as the Riparian Forest Buffer Zone which will have an extent of 30 meters. No structural developments will take place in this buffer zone according to the local zoning laws, and indigenous tree species will be planted to ensure stabilization of the banks of the canal from erosion due to high velocity.

6.6.4 Concept Plan and Drainage Scheme

The spatial location of the above-mentioned structural, regulatory, and naturalistic measures is provided in the map below:

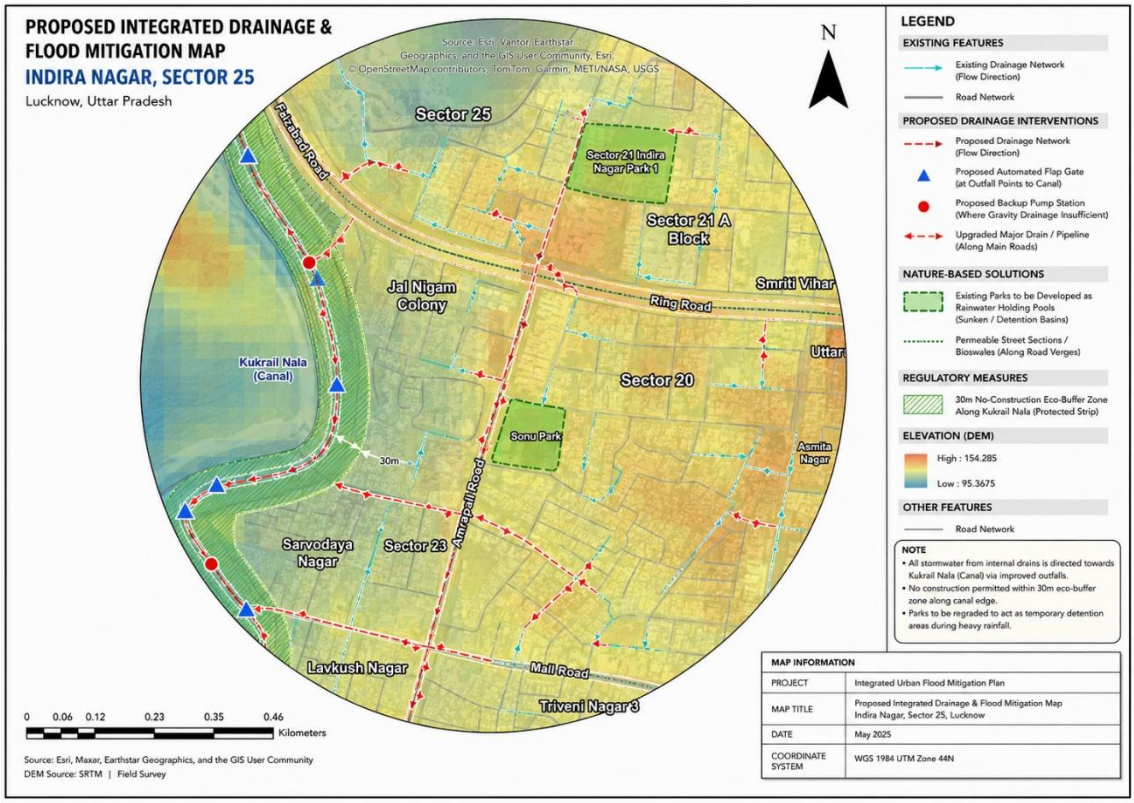


Figure 29 Concept Proposal Plan *Source: Author (ArcGIS Pro)*

This plan map clearly indicates how the proposed improvements directly target the high runoff corridors that pass through the residential zones, thereby blocking any threat of surface water pooling prior to entering the lower elevation roads.

6.6.5 Expected Hydrological Impacts

The combination of residential rainwater harvesting with bio-retention facilities in the park will enable the high values of runoff resulting from the impervious surfaces of Sector 25 to be greatly reduced. The reduction in the composite value of the runoff coefficient (C) for the 10-hectare area is as follows:

Planned Residential Development Area: 6.5 Ha (value of C decreases from 0.85 to 0.65 due to the use of RWH tanks) Lined Asphalt/Pavement: 2.5 Ha (value of C= 0.80) Institutional Frontage: 0.8 Ha (value of C = 0.85) Sunken Park Bio-Retention Cells: 0.2 Ha (value of C decreases from 0.15 to 0.05)

The new weighted runoff coefficient is calculated as:

$$C_{weighted} = \frac{(0.65 \times 6.5) + (0.80 \times 2.5) + (0.85 \times 0.8) + (0.05 \times 0.2)}{10} = \frac{4.225 + 2.00 + 0.68 + 0.01}{10} = 0.692$$

Recalculating the peak discharge using the Rational Method for a standard 50 mm/hr peak monsoon rainfall event (I = 50 mm/hr):

$$Q_{proposed} = \frac{0.692 \times 50 \times 10}{360} = 0.961 \text{ m}^3/\text{sec}$$

Hydrological Mitigation Analysis: This focused set of source control measures helps bring down the peak discharge in the neighbourhood from 1.143 m^3/sec to 0.961 m^3/sec (a 15.9% absolute decrease in the runoff volume). However, the critical improvement comes from the implementation of automated flap gates along with backup pumping stations, which prevents any chances of a backwater failure mode. In such a scenario, the Kukrail Nala being full of water does not pose a problem for the clearance of runoff in the neighbourhood.

6.7 Comparative Analysis of Mitigation Methods at Hotspots

6.7.1 Inter-Hotspot Strategy

The adoption of the integrated urban flood management concept within Lucknow city needs to be considered differently for all hot spots selected for the implementation process. As each hot spot has its own unique urban morphology, which may range from densely populated areas to fully developed commercial industrial sectors and mature planning sub-cities, the distribution and choice of engineering methods need to be changed accordingly (Gupta et al., 2020). Through the comparison of the structural measures, non-structural measures, and NBS methods, this comparative analysis reveals how different measures can address hydraulic failures.

Instead of depending solely on huge investments for grey infrastructures, the approach takes into consideration the balance between the intervention strategies by taking the spatial considerations and the terrain features into account (NIDM, 2022). The approach involves the use of decentralization of runoff through green infrastructure and permeable transition layers in crowded and unplanned settlements where there is no possibility of constructing major channels for drainage due to space constraints. On the other hand, when it comes to commercial warehousing hubs, the strategy entails the use of stringent zoning laws that make private property owners responsible for the hydrological consequences of their impervious properties. Finally, in case of planned sub-cities that face challenges of outfall failures, the strategy centres on boundary control measures and use of available institutional green spaces as holding areas (MoHUA, 2019).

6.7.2 Comparative Interventions Matrix

The matrix below(Table 13) highlights the comparative interventions across all the three hotspots considered in the study.

Table 13 Comparative Structural, Regulatory, and Nature-Based Flood Mitigation Matrix *Source: Author*

Evaluation Parameter	**Alamnagar Hotspot**	**Faizullahganj Hotspot**	**Indira Nagar (Sector 25) Hotspot**
Urban Fabric Typology	Mixed Industrial, Warehousing, and Logistics Zone.	Informal, High-Density Peripheral Residential Sprawl.	Mature, Planned Residential and Institutional Sub-City Grid.
Primary Hydraulic Failure Mode	Linear Damming Effect: Raised railway track embankment blocks natural southwest flow; large warehouse roofs generate immediate peak surges.	Absolute Network Deficit: Complete absence of formal public drains; organic street networks trap pooling water in terrain sinks.	Outfall Backwater Intrusion: High monsoonal water stages in the adjacent Kukrail Nala trigger reverse flow back into local street lines.
Applied Structural Measures	i. Twin Precast Concrete Box Culverts (2.5 m × 2.0 m) jacked under tracks. ii. 1.8 km concrete trunk collector drain along tracks. iii. Decoupled storm-effluent channels.	i. Construction of a brand-new primary and secondary masonry drainage grid. ii. High-capacity box culverts at un-engineered street crossings.	i. Automated mechanical non-return flap gates at outfalls. ii. 25-HP axial backup pumping stations at low sumps. iii. Deepening trunk lines along Amrapali Road.
Applied Nature-Based Solutions (NBS)	i. Retrofitting industrial plot setbacks with linear interception bioswales. ii. Open grassed channels lined with stone check dams.	i. Converting lowest terrain depressions into a 1.5-hectare community retention wetland. ii. Paving narrow roads with permeable interlocking blocks.	i. Landscape regrading of flat neighbourhood parks (Sonu Park) into sunken bio-retention basins. ii. Permeable green roadside verges.

Applied Regulatory / Non-Structural Policies	Mandatory On-site Runoff Neutrality for plots >2,000 sq. m. Strict 25-meter-wide unbuilt rail buffer strip.	Community-led micro-maintenance and de-siltation pacts. Zero-tolerance enforcement against waste dumping.	Mandatory 30-meter non-construction eco-buffer strip directly along the canal banks. Restricting further building footprint expansions.
Core Hydrological Target	35.8% absolute reduction in peak discharge, dropping storm volumes from 1.719 m^3/sec down to 1.104 m^3/sec.	23.5% reduction in peak monsoonal surge volume, maximizing localized unpaved surface infiltration.	15.9% reduction in pluvial storm volume loads and complete protection against backwater network failures.

6.7.3 Engineering Synergies and Typological Trade-offs

Trade-off analysis between these typologies shows the obvious connection between institutional planning level and types of flood mitigation measures that can be successfully implemented.

In Faizullahganj, the absence of legally delineated property lines and structured streets prevents implementation of traditional wide concrete drainage channels without demolishing existing buildings. For that reason, the model makes a trade-off between costly hard grey infrastructure and soft engineering network. The transformation of natural low-lying basins into functional wetland communities and reconstruction of narrow earthen streets into porous paving system allows handling flood volume without the need to invest in costly city-wide underground piping system.

Engineering design at Indira Nagar (Sector 25) changes from making internal networks to repairing external broken outfall links. Since this is a fully grown, planned neighbourhood, its internal network of drainage is established. Problems occur at the border of the local drains and the Kukrail Nala. The plan here uses the best structural features that would ensure border security from canal backflow, like automated flap gates and forced mechanical pump wells. These structures are supported by ecological resources available only in a planned neighbourhood, namely large and public parks. These flat parks can be regraded into sunken bio-retention areas, allowing the neighbourhood to collect excess precipitation during floods without using any residential lands.

Flood problem at Alamnagar happens due to a huge and high-elevation asset for transportation that cuts across a flat land. Solution to this problem would require capital-intensive engineering (trenchless box culvert jacking) together with a tough policy. In Alamnagar, all the lands belong to profit-making logistic companies and private warehouses. Thus, the municipal corporation has a chance to implement runoff neutrality law. This will shift the financial burden of storm water storage tanks and perimeter bioswales construction from public money onto the developers.

6.7.4 Section Conclusion

To conclude, this highlights the fact that resolving the urban flooding issue in Tier-II cities such as Lucknow cannot simply be achieved by following the existing conventional process of constructing bigger and larger storm water channels out of concrete. Rather, an effective approach in addressing the issue must combine structural measures, regulatory approaches, and nature-based solutions within one coherent framework based on the specificities of each locality (Suroor et al., 2022).

From overcoming the physical challenges posed by the peripheral sprawl area in Faizullahganj to fixing outfalls in the well-planned grid pattern of Indira Nagar, and overcoming the physical obstacles presented by important transport links in Alamnagar, this comparative analysis proves that source control and spatial zoning measures are just as important as the traditional civil engineering methods. All in all, this comparative analysis provides the missing link between high-level master planning and project implementation. This comparative analysis reveals the fact that it is possible to develop climate resilience of the city without compromising the needs of dense population growth (NIDM, 2022).

CHAPTER 7: Integrated urban flood mitigation framework (IUFMF)

The purpose of this chapter is to integrate the engineering designs and tactics devised in previous chapters to form an overarching plan of implementation. Even though micro-interventions are essential for addressing the urgent need of local flooding situations, any sustainable solution involves incorporation of the same into a broader administration and spatial context. The IUFMF is such a comprehensive structure that can be used to fill in the gaps between local civil engineering works and urban planning. The next paragraphs discuss the conceptual basis for the formation of this framework, its socio-ecological principles, and the regulatory measures required for the same.

7.1 Introduction

The site-specific plans discussed in Chapter 6 for Faizullahganj, Indira Nagar, and Alamnagar show that urban flooding in Lucknow is not a generalized engineering disaster, but rather a manifestation of larger systemic weaknesses. In order to avoid falling into the trap of piecemeal and reactive approaches, it is imperative that such plans be embedded within a city-wide conceptual framework.

Chapter 7 introduces the concept of the Integrated Urban Flood Mitigation Framework (IUFMF). The IUFMF shifts the paradigm of urban water management from a fragmented municipal works approach towards a socio-ecological and spatial planning approach. Through the synthesis of spatial, structural, institutional, and environmental factors, the IUFMF offers a proactive model for restoring hydrological resilience in rapidly growing urban settings.

7.2 Framework Development

The development of the IUFMF stems from a fundamental planning premise: urban flooding is a spatial design and governance problem, not just a hydraulic capacity problem. The framework was constructed by cross-referencing the empirical findings of the micro-terrain and drainage network analyses with the *Strategic Urban Flood Management Matrix* compiled in the early phases of this research.

The conceptual architecture of the framework is built on three progressive tiers:

1. The Core Diagnostic Tier: Utilizing spatial data analytics (DEM, slope, flow accumulation, and LULC tracking) to identify physical choke points and terrain vulnerabilities.
2. The Strategic Intervention Tier: Balancing hard infrastructure retrofits with nature-based surface controls and non-structural planning ordinances.
3. The Institutional Integration Tier: Aligning multi-agency workflows to ensure long-term regulatory enforcement, capital funding allocation, and operational maintenance.

7.3 Components of the Framework

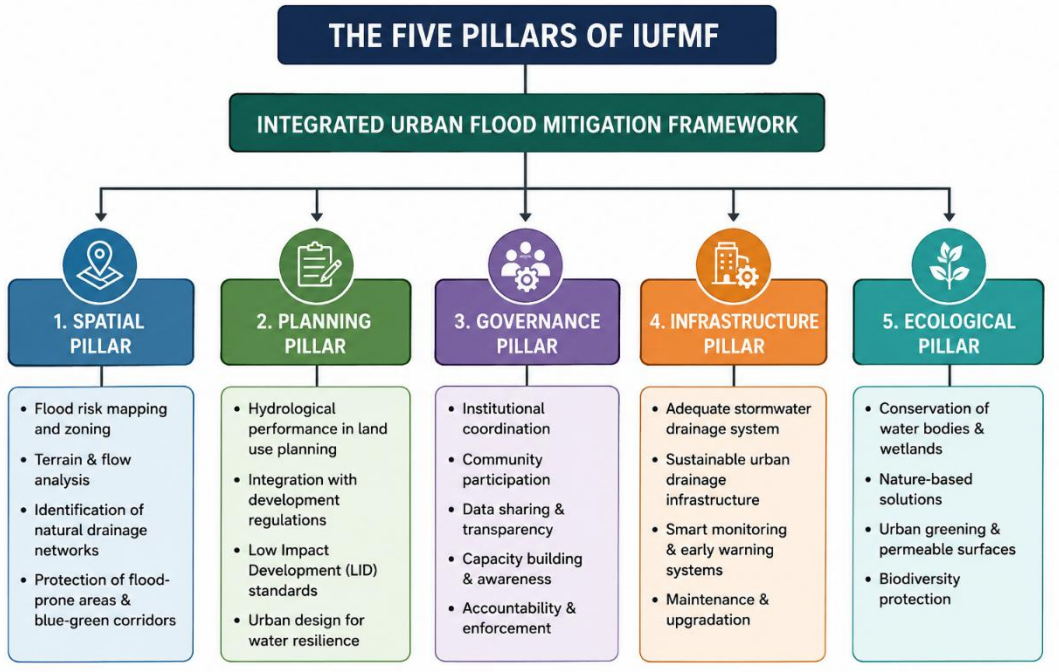


Figure 30 Components of the Framework *Source: Compiled by Author*

The IUFMF is operationalized through five interconnected pillars. Each component targets a specific layer of the urban environment, transforming high-level policy objectives into practical, enforceable planning tools.

7.3.1 Spatial Component

1. The spatial component is the foundation of data within the proposed framework. This involves the shift from two-dimensional static paper Master Plans to dynamic Spatial Decision Support Systems (SDSS) powered by GIS technology.
2. Dynamic Flood Hazard Zoning: The requirement for incorporation of high-resolution Digital Elevation Models (1 meter grid resolution or higher through LiDAR) into the statutory process of Master Plan preparation.
3. Flow-Path Preservation Maps: Preparation of statutory overlay maps that map out and preserve drainage paths, valley lines, and terrain sinkholes from future development.

7.3.2 Planning Component

1. The planning component uses the power of regulations and building bylaws to control the amount of runoff produced from the development itself. This will force the internalization of hydrological impacts through private land development.
2. Runn-off Neutral Building Bylaws: All future commercial, industrial, and large residential buildings must have maximum discharge rates equal to the pre-development baseline.

3. Infiltration Requirements: Inclusion of FAR bonuses based on the amount of permeable surface space. For example, developments with over 40% of soil coverage get additional buildable space on upper floors.

7.3.3 Governance Component

This governance component breaks down the institutional siloes by integrating overlapping administrative jurisdictions through a common mandate.

1. Unified Water Compiled by Authority: Working to improve communications between land-use planners (LDA), infrastructure asset developers (LMC, PWD), and regional water Compiled by Authorities (Irrigation Department).
2. Data-Sharing Standards: Setting up a common open access dashboard to share telemetry data, gauge readings, and drainage maintenance logs from all public utilities.

7.3.4 Infrastructure Component

This infrastructure component improves the physical infrastructure by moving away from the mere rapid evacuation of water to intelligent systems that can serve multiple functions.

1. Smart Asset Improvements: Using mechanical backflow prevention devices, automated outfall flap gates, and smart sensors at strategic drainage discharge points.
2. Right-of-Way Improvements: Re-engineering street cross sections to incorporate underground utility ducts together with covered, sloping side drains to eliminate unplanned utility cuts damaging the drains.

7.3.5 Ecological Component

This ecological component recognizes nature itself as an infrastructural asset, employing nature-based systems to retain, treat, and infiltrate stormwater flows.

Blue-Green Infrastructure Networks: Building blue-green infrastructure networks consisting of urban parks, wetlands, and riparian zones.

Phytoremediation & Storage Basins: Building community-scale storage basins and bioswales lined with native wetland vegetation to treat mixed urban runoffs while controlling peak flood flows.

7.4 Framework Using the DPSIR Approach

The IUFMF makes use of the DPSIR framework to ensure that the cause-and-effect relationships that lead to urban flooding in Lucknow are mapped out, providing strategic points of entry into addressing this problem.

Table 14 DPSIR framework

Source: Author

DPSIR Element	Contextual Realities in Lucknow	Targeted IUFMF Response Interventions
Drivers	Rapid population influx and peripheral sprawl. Climate change induced high-intensity, short-burst monsoon rainfall events.	Regional smart growth policies. Climate-resilient infrastructure design standards.
Pressures	Exponential increase in surface imperviousness (LULC conversion). Natural drainage path encroachment. Widespread informal solid waste dumping in urban channels.	Runoff neutrality mandates for large real estate holdings. 30-meter non-construction riparian buffer zones. Community-led decentralized solid waste recycling systems.
State	Loss of natural landscape infiltration capacity. Reduced hydraulic cross-sectional volume in primary trunk drains. Chronic water table shallowing matched with surface water accumulation.	Widespread conversion of concrete paths into Permeable Shared Streets. Desilting schedules backed by GIS asset mapping. Construction of deep groundwater recharge shafts.
Impact	Severe property damage and structural plinth inundation. Prolonged local traffic gridlock and economic disruption. Vector-borne public health crises due to multi-day standing water.	Delineation of high-risk structural adaptation zones. Emergency evacuation routing maps. Pre-monsoon public sanitation and drainage cleaning drives.

Response	Historical Approach: Ad-hoc concrete walling, channelization, and localized emergency pumping.	**Proposed Paradigm (IUFMF):** Integrated spatial zoning, multi-agency command systems, and nature-based retention networks.

7.5 Multi-Level Governance Framework

A successful spatial planning strategy necessitates an appropriate institutional structure. The implementation of the IUFMF framework is structured within a multi-level governance matrix, which clearly outlines both vertical and horizontal operational linkages.

State-Level Coordination: The Uttar Pradesh Urban Development Department provides overall policy guidance, amends state building codes, and allocates capital funds. It works directly with the State Disaster Management Compiled by Authority (SDMA) to make sure that the city's investment plans conform to climate change adaptation goals.

Metropolitan-Level Coordination: The Lucknow Development Compiled by Authority (LDA) integrates the spatial flood hazard zones directly into its statutory Master Plan. It possesses the power to veto any real estate development plans that encroach on the flow accumulation zones or riparian buffers.

Local-Level Implementation: The Lucknow Municipal Corporation (LMC) acts as the main implementation organization. It is responsible for regular maintenance activities, drain cleaning, auditing of tax incentives, and emergency management systems through localized Ward Committees.

CHAPTER 8: Conclusion and Recommendations

8.1 Overview of Study

This study was carried out in response to the growing problem of pluvial and flash floods in the fast-growing Indian Tier-II cities, with Lucknow as the main case study. The conventional paradigm of engineering, which views stormwater as a threat to be quickly collected and evacuated via concrete grey infrastructure, has become increasingly ineffective due to the dual challenges of climate-induced short-burst rains and fast land-use conversions. To tackle this challenge, this dissertation proposed an Integrated Urban Flood Mitigation Framework (IUFMF), wherein hydrological performance becomes an essential factor in spatial planning.

The study was conducted following a clear methodological framework. First, a comprehensive review of literature led to the construction of a proprietary Strategic Urban Flood Management Matrix, which categorized global structural, non-structural, and nature-based solutions (NBS) tailored to the Indian institutional and physical context. For the city-scale analysis, large-scale geospatial analysis involving DEM, slope analysis, and flow accumulation modelling was compared against past municipal waterlogging data to identify urban flooding hotspots.

Three typical hotspots were chosen for a more focused micro analysis as follows:

1. Faizullahganj: An example of informal, densely packed peripheral sprawl that lacks primary drainage networks and invades low-lying active river terraces.
2. Indira Nagar Sector 25: An example of mature planned residential area that faces problems of high surface concretization and structural failure of backwater systems due to the nearby Kukrail Nala.
3. Alamnagar: An example of industrial-warehousing area where significant linear transport infrastructure in the form of raised railway embankments creates a man-made barrier to natural drainage pathways in the region.

This study carried out primary field audit and household perception survey in these areas and documented physical, infrastructural, and regulatory gaps. This information was used to design the site specific spatial, structural, and nature-based proposals presented in Chapter 6, which were finally integrated in the multi-level governance framework presented in Chapter 7.

8.2 Key Findings

The empirical and spatial investigations conducted across this study yielded several critical insights regarding the changing dynamics of urban flooding in Lucknow:

Typology-Driven Flooding Modes: Urban flooding is not a uniform hydraulic failure. The root causes are deeply tied to local urban morphology. In peripheral zones like

Faizullahganj, flooding is driven by a total lack of neighbourhood-scale secondary networks combined with structural fills that disrupt natural terrain sinks. In planned areas like Indira Nagar, flooding is a function of high-stage river backflow coupled with excessive interior paving that prevents local infiltration. In industrial sectors like Alamnagar, flooding is a structural barrier issue caused by under-designed cross-drainage assets beneath linear infrastructure.

The Failure of Static Master Planning: Longitudinal analysis of Lucknow's spatial growth reveals that statutory master plans (such as the Lucknow Master Plan 2031) treat drainage as a post-facto utility layout rather than a baseline spatial constraint. Consequently, formal permissions and informal expansions have systematically encroached upon natural flow-accumulation corridors, critical wetlands, and active floodplains.

Quantifiable Mitigation Benefits of Source Control: Hydrological calculations executed via the Rational Method proved that hard engineering upgrades alone cannot safeguard urban catchments. By integrating nature-based solutions—such as converting neighbourhood streets into Permeable Shared Streets and transforming public parks into Sunken Bio-Retention Basins—the weighted runoff coefficient (C) of high-density sectors can be reduced substantially (e.g., from 0.545 to 0.417 in Faizullahganj). This alleviates peak discharge volumes by up to 23.5%, bringing stormwater volume within the safe carrying capacity of proposed masonry channels.

Institutional Fragmentation: Ground-level institutional mapping highlighted a profound horizontal disconnect between the planning Compiled by Authorities (LDA), asset creators (PWD), and maintenance agencies (LMC). The absence of a unified, real-time data-sharing protocol or synchronized operational manuals (such as outfall gate operations during high-stage river levels) significantly worsens the duration and severity of pluvial standing water.

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Annexure

Kritika Pandey

KRITIKA PANDEY THESIS

MPlan Thesis Report June 2026

Document Details

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Survey Questionnaire

Q.No	Question	Options	How It Will Be Used in Thesis
1	Ward / Locality Name	Open-ended	Spatial tagging of responses in GIS; linking survey to hotspot polygons
2	Type of House	Pucca / Semi-Pucca / Kutcha	Structural Vulnerability Score (Kutcha = higher weight in vulnerability index)
3	No. of Family Members	Numeric	Exposure Index (population at risk per household)
4	Years living in this area	<5 / 5–10 / 10–20 / >20	Flood history validation & reliability of responses
5	Have you experienced flooding?	Yes / No	Validation of Flood Susceptibility Map
6	Frequency of flooding	Every year / Once in 2–3 yrs / Rare	Flood Hazard Intensity classification
7	Maximum water depth during worst flood	<0.5m / 0.5–1m / >1m	Severity Layer for Risk Mapping
8	Duration of waterlogging	Few hours / 1 day / 2–3 days / >3 days	Water Stagnation Index
9	Main cause (as per perception)	Drain blockage / Heavy rainfall / River overflow / Encroachment / Low-lying area	Helps interpret hazard drivers (Drainage vs Rainfall vs Topography)
10	Type of drainage available	Covered drain / Open drain / No drain	Infrastructure Deficiency Layer
11	Condition of drains	Good / Moderate / Poor / Frequently blocked	Drainage Performance Index
12	Solid waste disposal method	Door-to-door / Community bin / Open dumping / Drain dumping	Drain clogging factor (Indirect flood amplifier)
13	Road level compared to house	Higher / Same / Lower	Micro-topography validation
14	Property damage during floods	Yes / No	Economic Vulnerability Indicator
15	Estimated loss	<₹10k / ₹10k–50k / >₹50k	Risk Severity Classification
16	Health problems after flood	Yes / No	Social Vulnerability Layer
17	Access disruption during flood	School / Work / Hospital / Market / None	Critical Infrastructure Risk Mapping
18	Do you receive flood warnings?	Yes / No	Adaptive Capacity Indicator
19	Source of warning	TV / Social media / Govt SMS / Neighbours	Institutional preparedness assessment

20	Household flood protection measures	Raised plinth / Sandbags / Pumping / None	Community Resilience Score
21	What should govt prioritize?	Drain improvement / Desilting / Encroachment control / Rainwater harvesting / Green spaces	Mitigation Preference Mapping
22	Willingness to relocate (if high risk)	Yes / No / Maybe	Feasibility of Managed Retreat Policy
23	Suggestions	Open-ended	Context-based Mitigation Framework development

S. No	Observation Parameter	Field Options	How It Will Be Used in Thesis
1	Drain Type	Covered / Open / No Drain	Identifies drainage infrastructure gaps for Mitigation Mapping
2	Drain Condition	Good / Moderate / Poor / Blocked	Used to create Drainage Deficiency Score
3	Solid Waste in Drain	None / Partial / Severe	Indicates clogging factor (Flood trigger in Lucknow)
4	Road Surface Type	Concrete / Bitumen / Earthen	Helps assess imperviousness (Runoff potential)
5	Surface Slope	Flat / Slight / Noticeable	Validates DEM-based susceptibility zones
6	Water Stagnation Evidence	None / Marks Visible / Severe	Ground-truthing of Flood Susceptibility Map
7	Encroachment on Drain	None / Partial / Severe	Identifies flow obstruction for mitigation priority
8	Plinth Height vs Road	Lower / Same / Higher	Measures household exposure level
9	Nearby Low-Lying Area	Yes / No	Micro-topographic flood risk indicator
10	Presence of Green/Open Space	Adequate / Limited / None	Assesses natural infiltration capacity