



Addis Ababa University College of Technology and Built Environment  
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Planning

Impact of Urbanization and Land Use Changes on urban Pluvial  
Flooding in Addis Ababa: A Spatial Analysis

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Date: Oct, 2025  
Addis Ababa, Ethiopia



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A THESIS IS SUBMITTED TO THE DEPARTMENT OF URBAN AND REGIONAL  
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ENVIRONMENTAL PLANNING AND LANDSCAPE DESIGN.

Advisor -Solomon Benti (Ph.D.)

Date: Oct, 2025

Addis Ababa, Ethiopia

**Approval sheet**

This is to certify that the thesis prepared by Nebil Muhidin Hussen titled: *Impact of Urbanization and Land Use Changes on urban Pluvial Flooding in Addis Ababa: A Spatial Analysis*, submitted in fulfillment of the requirements for the degree of Master of Science in Environmental Planning and Landscape Design complies with the regulations of the University and meets the accepted standards concerning originality and quality.

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## **Declaration**

I, the undersigned, declare that this thesis is my own and original work and has not been presented for a degree in any other university and that all sources of material used for the thesis have been duly acknowledged, following the scientific guidelines of the University.

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## **Abstract**

*Rapid urbanization in Addis Ababa has intensified urban pluvial flood risks by altering the land use and increasing the imperviousness hence overwhelming the existing stormwater drainage systems. This study seeks to address these challenges by mapping areas of the city susceptible to pluvial flooding, examining how land use changes increase surface impermeability and flood risk, and evaluating the effectiveness of current stormwater management practices. To achieve this, the study employs Analytic Hierarchy Process (AHP) with pairwise comparisons to determine the relative weights of eight flood-influencing factors: rainfall, slope, drainage density, elevation, land use/land cover, Normalized Difference Vegetation Index (NDVI), Topographic Wetness Index (TWI), and road proximity integrated with GIS mapping. Remote sensing and aerial photography are utilized to assess land use and land cover transformation between the years 2005-2025, whereas Hydrologic Engineering Center-River Analysis System (HEC-RAS) was utilized to simulate water accumulation and flow pattern. The findings reveal that over 55% of the city (237.28 km<sup>2</sup>) is very highly to highly vulnerable to pluvial flooding, predominantly in central flat areas that are characterized by dense infrastructure and urbanization. Built-up areas expanded from 42.5% in 2005 to 62.6% in 2025, leading to an increase in runoff from 0.54M to 1.03M m<sup>3</sup>/day as estimated using the SCS-CN method. The study further identified significant constraints within the current stormwater management system including clogged drains, poor maintenance, and lack of institutional coordination. Based on these findings, the study recommends upgrading and maintaining drainage infrastructure, correcting low-lying sag points, reconfiguring drainage networks, promoting green infrastructure, enforcing land-use regulations, and applying advanced modeling and technology. Overall, this research provides a spatial basis for prioritizing infrastructure improvements and incorporating nature-based solutions, offering a mechanism of enabling Addis Ababa to minimize the danger of pluvial flooding in the context of population growth and climate change.*

**Keywords:** Impervious surface, LULC, Pluvial flooding, Spatial analysis, susceptibility mapping

# Table of Contents

Declaration.....	ii
Acknowledgment.....	iii
Abstract.....	iv
List of Figures.....	vii
List of Tables.....	viii
List of Annex.....	viii
List of Acronyms & Abbreviations .....	ix
CHAPTER ONE: INTRODUCTION .....	1
1.1 Background of the Study .....	1
1.2 Statement of the Problem .....	2
1.3 Objectives of the study.....	4
1.3.1. General Objective .....	4
1.3.2. Specific Objectives .....	4
1.4 Research Questions .....	4
1.5 Scope of the Study .....	4
1.6 Significance of the Study .....	5
1.7 Research Limitations .....	5
1.8 Organization of the Paper .....	6
CHAPTER TWO: LITERATURE REVIEW .....	7
2.1 Definitions and Key Concepts.....	7
2.2 Theoretical Review.....	9
2.2.1. Runoff Generation and Concentration .....	9
2.2.2. Models of Flood Frequency .....	11
2.2.3. Flood Measurement Models.....	13
2.2.4. Sustainable Drainage Systems (SuDS) Theory.....	16
2.3 Conceptual Review.....	18
2.3.1. Pluvial Flooding in Urban Areas: Causes and Impacts .....	18
2.3.2. Urban Flood Risk Assessment.....	20
2.3.3. Urbanization and Land Use Change .....	22
2.3.4. Urbanization and imperviousness .....	23
2.3.5. Identifying the level of imperviousness .....	25
2.3.6. Stormwater Runoff .....	26
2.3.7. Factors affecting stormwater runoff and its management practices.....	28

2.3.8. Criteria for Flood Hazard mapping .....	30
2.3.9. Best Management Practice for stormwater management sustainability.....	33
<b>CHAPTER THREE: METHODS AND MATERIALS .....</b>	<b>36</b>
3.1 Description of the Study area.....	36
3.2 Research Design .....	37
3.3 Data types.....	38
3.4 Sources of Data.....	38
3.5 Method of data collection .....	39
3.6 Method of data analysis .....	40
3.7 Method of data presentation .....	46
3.8 Validation and Reliability.....	46
3.9 Ethical consideration .....	48
3.10 Methodological framework of the study .....	49
<b>CHAPTER FOUR: RESULTS AND DISCUSSION.....</b>	<b>50</b>
4.1 Results .....	50
4.1.1. Identifying flood-prone areas.....	50
4.1.2. Urbanization and Surface Impermeability .....	62
4.1.3. current stormwater management practices .....	70
4.2 Discussion.....	78
<b>CHAPTER FIVE: CONCLUSION AND RECOMMENDATION .....</b>	<b>84</b>
5.1 Conclusion.....	84
5.2 Recommendations .....	85
<b>References.....</b>	<b>87</b>
<b>Annex .....</b>	<b>102</b>

## List of Figures

<b>Figure 2.1:</b> Fluvial (left) versus pluvial (right) flooding. ....	18
<b>Figure 2.2:</b> Flood risk components .....	21
<b>Figure 2.3:</b> Impact of urbanization on surface infiltration, evapotranspiration, and runoff .....	24
<b>Figure 2.4:</b> Impact of Urbanization on runoff quantity.....	24
<b>Figure 3.1:</b> Location of study area .....	37
<b>Figure 3.2:</b> Methodological frame work of the study .....	49
<b>Figure 4.1:</b> Slope percentage and area coverage.....	50
<b>Figure 4.2:</b> A) Slope map B) Land use Land cover map .....	51
<b>Figure 4.3:</b> A) Normalized difference vegetation index (NDVI) map B) Distance to Road map	53
<b>Figure 4.4:</b> Distance to road - Area coverage .....	53
<b>Figure 4.5:</b> A) Elevation map B) Precipitation map .....	54
<b>Figure 4.6:</b> A) Drainage Density map B) TWI (topographic wetness index) map .....	56
<b>Figure 4.7:</b> Pluvial Flood susceptibility and registered flood map .....	60
<b>Figure 4.8:</b> Registered Flood and Flood Susceptibility Relation map .....	61
<b>Figure 4.9:</b> Land use Landcover map for the years 2005,2015&2025 .....	62
<b>Figure 4.10:</b> Landcover shifts between 2005-2015.....	64
<b>Figure 4.11:</b> Landcover shifts between 2015-2025.....	66
<b>Figure 4.12:</b> Impervious surface map .....	67
<b>Figure 4.13:</b> Area shift to impervious surface map .....	68
<b>Figure 4.14:</b> Pluvial Flood-prone area of the case study site (9.01930, 38.81987).....	74
<b>Figure 4.15:</b> Stormwater Drainage conditions (9.0119552, 38.819920) .....	75
<b>Figure 4.16:</b> Terrain Condition; Lamberet to Gurd Shola road(A), CMC to Megenagna road (B).....	76
<b>Figure 4.17:</b> Runoff simulation A) stormwater flow direction B) runoff accumulation prior to LRT ....	76
<b>Figure 4.18:</b> Runoff simulation A) stormwater flow direction B) runoff accumulation after the LRT...	77

## List of Tables

<b>Table 2-1</b> Components of impervious surfaces .....	25
<b>Table 3-1</b> Summary of data types & sources.....	39
<b>Table 3-2</b> List of Key informants selected.....	40
<b>Table 3-3</b> LULC classification .....	42
<b>Table 3-4</b> AHP scale of pairwise comparison matrix .....	43
<b>Table 3-5</b> Classes and ratings of the flood-conditioning factors .....	43
<b>Table 3-6</b> Normalized pairwise comparison matrix. ....	44
<b>Table 3-7</b> Random index (RI) table .....	47
<b>Table 3-8</b> Classification accuracy of 2005 .....	47
<b>Table 3-9</b> Classification accuracy of 2015 .....	47
<b>Table 3-10</b> Classification accuracy of 2025 .....	48
<b>Table 4-1</b> LULC area coverage .....	52
<b>Table 4-2</b> NDVI area coverage.....	52
<b>Table 4-3</b> Flood susceptibility criteria, sub-criteria ranges, and influence weight.....	58
<b>Table 4-4</b> Flood susceptibility area and percentage.....	59
<b>Table 4-5</b> Landcover area coverage.....	63
<b>Table 4-6</b> Runoff generation estimation .....	69
<b>Table 4-7</b> Demographic profile of respondents .....	70
<b>Table 4-8</b> Summary of the key informant interview.....	72

## List of Annex

<b>Annex 1</b> Daily precipitation of rainy season 2005,2015&2024 .....	102
<b>Annex 2</b> Reported flooding in 2015 EC .....	103
<b>Annex 3</b> Reported flooding in 2016 EC .....	104
<b>Annex 4</b> Case study area images .....	105
<b>Annex 5</b> Key informant questions .....	106
<b>Annex 6</b> Publishable manuscript.....	107

## **List of Acronyms & Abbreviations**

<b>AACRA</b>	Addis Ababa City Road Authority
<b>AAWSA</b>	Addis Ababa Water and Sewerage Authority
<b>AHP</b>	Analytic Hierarchy Process
<b>BGI</b>	Blue-Green Infrastructure
<b>DEM</b>	Digital Elevation Model
<b>EPA</b>	Environmental Protection Agency
<b>EU</b>	European Union
<b>FAO</b>	Food and Agriculture Organization
<b>GIS</b>	Geographic Information System
<b>HEC RAS</b>	Hydrologic Engineering Center's River Analysis System
<b>LRT</b>	Light Rail Transit
<b>LULC</b>	Land Use/Land Cover
<b>NDVI</b>	Normalized difference vegetation index
<b>RS</b>	Remote Sensing
<b>SRTM</b>	Shuttle Radar Topography Mission
<b>SuDS</b>	Sustainable Drainage Systems
<b>TWI</b>	Topographic Wetness Index
<b>USGS</b>	United States Geological Survey

# CHAPTER ONE: INTRODUCTION

## 1.1 Background of the Study

Urbanization is a global phenomenon that is unfolding worldwide. Currently, approximately 50% of the global population resides in urban areas, and this figure is predicted to rise mostly in developing nations (Farrell,2017). The United Nations Department of Economic and Social Affairs (UNDESA, 2019) pointed out that by 2050, 90% of the growth in urban populations will happen in Asian and African cities, this will add 2.5 billion people to urban areas around the world.

The rapid urban growth has already given rise to numerous environmental challenges, including extreme weather events, elevated energy consumption, pollution, habitat destruction, and the depletion of cultivated land (Wang et al., 2019). In light of the current and future urbanization trends, these challenges are expected to worsen, mostly in the developing world (UNDP and UN-Habitat, 2013).

Flooding is a predominant natural disaster that is common internationally, causing considerable economic, environmental, physical, and social impacts in both the short and long term (National Research Council, 2009). In the 21st century, floods have accounted for nearly half of all disaster incidents and fatalities related to natural disasters worldwide (Zhang et al., 2023). It arises when the volume of water surpasses the capacity of the natural or man-made systems designed to contain or convey it under current conditions (Getahun & Gebre, 2015).

Addis Ababa City is currently one of the cities vulnerable to flooding due to rapid urban growth, absence or improper implementation of urban flood management plans, and world common impacts of climate change (Jemberie & Melesse, 2021). The rate of population changes and urbanization is more than 30% in the city, indicating large urbanization, land use transition, and pervious green space loss (World Bank Group, 2015). Pervious green space losses and the installation of impervious surfaces as a result of urban sprawl generate more surface runoff, even for typical storms, and thereby enhance flood risk (Douglas et al., 2008). Hence, as a result of rapid urbanization and land use changes, the city is affected by a projected annual peak overflow increase at a growth rate above 2.5% (Birhanu et al., 2016).

In the city of Addis Ababa, the frequent occurrence of severe flooding during the rainy seasons is aggravated by a noteworthy increase in stormwater run-off accumulating in the city's low-lying areas (Muschalla & Ostrowski, 2002). As per Kebede & Adugna (2015), stormwater drainage service inadequacy in urban areas is widespread and rising concern voiced by citizens across various Ethiopian towns, mainly in Addis Ababa.

The existing stormwater management infrastructure in Addis Ababa is dependent on conventional drainage systems designed to divert excess runoff away from urban areas. However, the efficiency of these systems is diminishing in the face of changing climatic conditions and the escalating urban footprint (Muschalla & Ostrowski, 2002). In recent years, there has been a noticeable shift in public policy priorities and a growing interest among experts, decision-makers, and the general public in comprehending and clarifying destructive extreme events, such as urban flooding, from a climatic perspective (Tabari et al., 2020).

Traditionally, studies of urban flooding have mostly centered around fluvial (stream/river) or coastal flooding (Guerreiro et al., 2017). Despite the evident challenges of urban flooding there is limited research on how urbanization and land use changes specifically contribute to pluvial flooding in Addis Ababa. This study pursues to bridge that gap by providing insights into flood-prone areas, assessing the effectiveness of stormwater management practices, and suggesting ways to reduce pluvial flood risks in rapidly urbanizing areas. The takeaways from this study will be essential for urban planners, policymakers, and environmental experts working toward sustainable urban development in Addis Ababa.

## **1.2 Statement of the Problem**

The expansion of urban land worldwide is associated with rising impervious surfaces, largely due to the use of materials such as asphalt, concrete, glass, and metal in city construction (Scalenghe & Marsan, 2009). With expanding cities, impervious surfaces limit the natural seepage of rainwater into the ground and lead to increased runoff and drainage problems (Mohapatra et al. 2014).

The city of Addis Ababa is currently experiencing rapid population growth. A (UN-HABITAT) study conducted in 2013 stated that the city's population increased by 1.19 million between 1994 and 2010. Currently the city's population is 6 million, with an annual growth rate of 3.8%,

estimations suggest the population will exceed 7.4 million by 2030 (Addis Ababa Population 2025, n.d.). The conversion of natural and agricultural land to residential and commercial areas has taken place to accommodate the expanding urban development (Pierrat et al., 2018).

The most pressing issue caused by urbanization is pluvial flooding, due to inefficient management of stormwaters. Furthermore, drainage infrastructures are typically strained since more areas are occupied by impervious surfaces, further generating stormwater runoff. Beshir & Song (2021) indicated that the built-up area of Addis Ababa expanded from 80.1 km<sup>2</sup> in 1984 to 287.9 km<sup>2</sup> in 2020 and potentially around 367.1 km<sup>2</sup> if the trends continue through 2030.

The most critical matter within Addis Ababa is the lack of a comprehensive and up-to-date vulnerability map of pluvial flooding. without a thorough assessment of flood-prone areas, planners find it difficult to implement effective flood mitigation strategies and allocate resources efficiently (Birhanu et al., 2016). To add to this predicament, the existing stormwater management system often suffers from design flaws and poor maintenance making them inadequate to handle increased runoff. As emphasized by Muschalla and Ostrowski (2002), the repeated clogging of the drainage system by solid wastes and garbage further reduces the effectiveness of the system to handle stormwaters.

Moreover, there is gap in understanding how urbanization directly influences pluvial flooding pattern. while it is obvious that rapid city development increase flood vulnerability, very few studies have actually measured or defined the connection between urbanization and flooding of surface water within Addis Ababa. Assessing how changes in land use impacts runoff generation and evaluating the current stormwater system is necessary to develop sustainable flood prevention measures.

To mitigate future pluvial flood risks addressing the challenges through better infrastructure planning and conducting a study is important. Addressing these challenges is crucial to the sustainability of the city. Conducting a thorough characterization to determine regions prone to flooding and assess existing drainage infrastructure will provide a foundation from which sustainable strategies to prevent flooding can be developed, guided urban infrastructure growth can occur, and prospective risk can be managed.

### **1.3 Objectives of the study**

#### **1.3.1. General Objective**

This study seeks to evaluate the relationship between urbanization and pluvial flooding in Addis Ababa, Through the identification of flood-prone locations and an evaluation of the efficacy of the current stormwater management systems.

#### **1.3.2. Specific Objectives**

- To develop a map of Addis Ababa that are susceptible to pluvial flooding.
- To analyze the impact of land use changes and urbanization on surface impermeability and flooding.
- To explore the effectiveness of the current stormwater management practices.

### **1.4 Research Questions**

- Which areas in Addis Ababa are vulnerable to pluvial flooding?
- What is the implication of urbanization and land use change on surface permeability and runoff generation?
- How effective are the current stormwater management practices in mitigating pluvial flooding?

### **1.5 Scope of the Study**

The geographical extent of the study revolves around the city of Addis Ababa and it aims to detect flood vulnerable areas within the city. The study involves a comprehensive analysis of the relation between land use change and surface permeability in the city, diving into specific flood hotspot to assess the drainage systems and simulate and simulate stormwater runoff.

Thematically, the scope of this study focuses on spatial analysis for identifying pluvial flood-prone areas by applying flood-influencing factors and analyze the extent of impermeable surfaces through the changes from land use shifts. This analysis also provides information about the effectiveness of the current stormwater management practices associated with pluvial flooding.

## **1.6 Significance of the Study**

This study has major importance for a rapidly urbanizing metropolis facing increased pluvial flood risks due to upregulated urban expansion. By mapping flood-prone areas, the research tackles the necessity for spatial data to identify vulnerable infrastructures and communities. This spatial analysis is key for Addis Ababa city administration for targeted disaster preparation, sustainable urban design and mitigating infrastructure damage.

Assessing the land use changes and surface impermeability offers essential data linking urban sprawl to increased runoff, contributing to policymakers with a scientific basis to foster sustainable practices and regulated construction, that aids with the balance between environmental resilience and urban growth.

Additionally, this study would point out the gaps and strengths in the city's pluvial flood mitigation strategies by assessing the efficiency of the current stormwater management practices. This information is vital for improvement to existing systems and developing more efficient runoff management. Moreover, the results of this study are helpful to the scientific community by offering replicable insights into other developing regions that have flood-prone areas, underscoring the necessity for proactive flood risk management. This finding will also help integrate flood resilience in urban planning adhering to the country's climate-resilient green economy strategy and global sustainable development goals mainly, SDG 13(climate action) and SDG (sustainable cities).

## **1.7 Research Limitations**

The main limitations of this study are timeframe and resource constraints restricting the depth of analysis in certain facets, for instance, long-term assessment for stormwater management systems. Moreover, the lack of ample professionals related to the issue being studied was also another challenge and the availability of local data impacted the precision of the flood risk map and urbanization analysis.

Furthermore, limitations should be taken into consideration when interpreting the findings since the study relies on present data and simulations, thus hindering its association with real-world conditions and their applicability to different urban regions or future scenarios.

## **1.8 Organization of the Paper**

The opening chapter starts by presenting the background, problem statement, objectives, research questions, scope, significance of the study, and research limitations. The subsequent literature review chapter delves into the cause of pluvial flooding, the effects of urbanization, and stormwater management systems. Chapter three outlines the methodology used to conduct the research objectives which includes the description of the study area, research design, data types and sources, data collection and analysis methods, presentation techniques, validation of the research, ethical considerations and at the end methodological framework of the study is shown.

The fourth chapter presents the results and discussion of the study by showing the findings from the data analysis and its interpretations of the results in conjunction with the objectives of the study and existing literature. Finally, the fifth chapter contains conclusions and recommendations, synthesizing key takeaways and offering insights into pluvial flooding and stormwater management practices.

# **CHAPTER TWO: LITERATURE REVIEW**

## **2.1 Definitions and Key Concepts**

### **Urbanization**

The term "urbanization" describes how cities are growing economically, demographically, and physically. The phrase also refers to the concentration of social activities and people in patterns of settlement that are marked by high-density land development. Population expansion from immigration and natural causes, as well as economic, social, and technical advancements is are the reason that encourage people to relocate to places with more employment opportunities, that are some of the factors contributing to urbanization (Gotham & King, 2019).

### **Land use changes**

A delineable area of Earth's earthly surface, encompassing all attributes of the biosphere immediately either above or below this surface, which includes those of the near-surface climate, the soil and terrain forms, the surface hydrology (including shallow lakes, rivers, marshes, and swamps), the surface sedimentary layers and associated ground water reserve, the plant and animal populations, the human settlement pattern, and the physical results of past and present human activities like terracing, water storage or drainage structures, roads, buildings, etc. (FAO, 1995).

Land cover is "the biophysical state of Earth's surface and immediate subsurface," according to Turner et al (1990). In addition to man-made structures like pavement or buildings, the term is also used to refer the type of vegetation that covers the land surface and other elements of the physical environment such as soils, biodiversity, surfaces, and groundwater. According to these authors, land use encompasses both the intention behind the manipulation of the land's biophysical characteristics the reason for using the land, and the method of doing so (Turner et al., 1990).

### **Pluvial flooding (urban flooding)**

Pluvial flooding occurs when intense, localized rainfall leads to overland flow and ponding before water enters drainage systems or watercourses, or when such systems are already at capacity. This issue is more severe in cities with insufficient or absent sewer networks (Acosta-Coll et al., 2018). Pluvial flooding should not be conflated with "surface water flooding," which describes combined urban flooding during heavy rainfall events, including sewer overflow, groundwater emergence,

and small-channel inundation (Falconer et al., 2009). Unlike flash flooding, a rapid watercourse surge often linked to high-intensity rainfall pluvial flooding originates directly from rainfall-driven runoff. In this paper, terms such as “urban pluvial flooding,” “surface water flooding,” “urban drainage flooding,” and others will be treated interchangeably.

### **Flood-prone**

Flood vulnerability is a condition that describes whether an area is easily or not, affected by flooding based on natural factors that influence flooding, including meteorological factors (rainfall intensity, distribution of rainfall, frequency, and duration of rain) and characteristics of the watershed (slope land/marbles, land height, soil test, and land use) (Suherlan, 2001).

### **Stormwater management**

Stormwater management is defined as the application of knowledge to comprehend the behavior of water at various stages of the hydrologic cycle. In order to design the best system that can be used at a specific time, the majority of management work is based on rainfall events. Supplementary fields like water supply, agricultural drainage, lake management, and flood control are related to the application of this concept, design method, and maintenance work (Hung et al., 2012).

### **Stormwater runoff**

Stormwater runoff is rain or snowmelt that runs across the land surface and discharges to rivers or lakes. The majority of stormwater in natural areas either evaporates, percolates into the ground, or is transpired by plants; the sum of these processes is what causes evapotranspiration. More stormwater runoff is produced and released into our waterways in urbanized areas with more impervious surfaces (Rasmussen & Schmidt.,2009).

### **Spatial analysis**

In the literature on Geographic Information Systems (GIS) and Geographic Information Science (GISc), the term "spatial analysis" is frequently used. A definition of spatial analysis is that it describes a collection of techniques and models that explicitly use spatial referencing corresponding to each data value or object that is specified within the system under study. Methods

of spatial analysis must either assume or use data that describes the spatial relationships or interactions between cases (Haining,2003).

## **2.2 Theoretical Review**

### **2.2.1. Runoff Generation and Concentration**

Surface runoff arises when rainfall exceeds the soil's infiltration capacity leading to saturation excess overland flow or Hortonian overland flow, these mechanisms are dependent upon climate and geography within a watershed (Smith & Goodrich, 2005). In semi-arid zones, water-dependent runoff processes are seasonal because of water balance limitations (Lange & Leibundgut, 2003).

The complexity of runoff generation increases due to factors such as rainfall intensity patterns, storm extent, and antecedent wetness (Beven, 2002). Runoff usually occurs beyond a threshold and exhibits fast response times to precipitation (Pilgrim et al., 1988). Surface properties and vegetation shape Spatial infiltration patterns, nevertheless in arid climatic conditions abiotic factors play a larger role (Lavee et al., 1998). Moreover, in humid zones topography plays a key role in overland flow, semi-arid and arid regions are dependent on soil properties and land use types (Kirkby, 2001).

#### **Depression Storage**

Runoff occurs after surface depressions fill when the precipitation surpasses infiltration rates (Subramanya, 1994). These depressions interrupt downslope flow, with stored water lost to infiltration and evaporation. Surface characteristics, soil properties, and moisture levels influence Depression storage (Subramanya, 1994) and affect runoff generation in the short-term rather than in the long-term hydrological balances (Musy et al., 2014).

#### **Hortonian Overland Flow (Infiltration Excess Overland Flow)**

On Hortonian overland flow runoff occurs when precipitation intensity exceeds soil infiltration capacity (Horton, 1933). This mechanism is significantly influenced by surface conditions like bare soil, rock outcrops, or sealed surfaces (Bronstert & Katzenmaier, 2001). This process is more common in semi-arid and arid areas, where rainfall intensity is high, and infiltration capacity is low (Beven, 2002). It's also promoted by intense short-duration storms which frequently happen in Drylands (Smith & Goodrich, 2005).

### **Saturation Excess Overland Flow**

In humid regions where rainfall volumes are high and vegetation enhances infiltration, Saturation excess overland flow is prevalent (Smith & Goodrich, 2005). Unlike Hortonian flow, it is dependent on existing soil moisture rather than rainfall intensity. Studies in Mediterranean catchments reveal its significance even though it is usually considered irrelevant in arid conditions with runoff linked to soil storage capacity and rainfall volume (Cerdà, 1997).

In semi-arid zones, saturated areas expand during storms and contract afterward relying more on soil types than topography (Beven, 2002). Interaction with groundwater is usually limited to floodplains in arid regions different from humid areas in which shallow groundwater tables contribute to saturation (Grayson et al., 2006). When both infiltration excess and saturation excess occur at the same location, Runoff processes can shift dynamically during a storm (Lange et al., 2003). Seasonal changes, such as more frequent but lower-intensity storms, can also encourage saturation excess flow (Beven, 2002). Runoff generation mechanism changes along climatic gradients, from infiltration excess in arid areas to saturation excess dominance in humid environments (Lavee et al., 1998).

### **Subsurface Stormflow**

Interflow or Subsurface stormflow happens when water passes laterally through soil-permeable bedrock downslope (Weiler et al., 2005). The contribution to storm runoff in humid regions is substantial, mostly in steep topographies with thick soil and dense vegetation (Dunne, 1978; McDonnell, 2013). On the contrary, the vertical moisture movement dominates in semi-arid and arid regions, naturally occurring under extreme conditions of high precipitation and soil moisture otherwise making subsurface stormflow rare (Weiler et al., 2005). Field observations even show decreasing soil moisture levels downstream suggesting minimal lateral flow (Yair & Danin, 1980).

### **Runoff Concentration**

Overland flow is determined by geology, vegetation, and the basin's soil influencing runoff paths and hydrograph characteristics (Pilgrim et al., 1992). In dry environments, spatial and temporal variability in rainfall and infiltration rates create irregular runoff patterns (Lavee et al., 1998). Runoff movement is complicated because of Run-on effects, where upslope runoff infiltrates downslope instead of directly contributing to streamflow (Smith & Goodrich, 2005).

Run-on raises soil moisture in downslope topography, possibly leading to localized saturation excess runoff (Eilers et al., 2007). Moreover, run-on favors areas with higher infiltration capacities, such as vegetated patches or cracked soils (Beven, 2002). In semi-arid regions, landscapes consist of water-contributing and water-accepting areas, where continuous vegetation cover is absent (Lavee et al., 1998).

## **2.2.2. Models of Flood Frequency**

### **Extreme Value model**

Extreme Value model is a branch of statistics dealing with extreme deviations from the median of probability distributions." Leonard Tippett, in collaboration with Sir Ronald Fisher, made pioneering discoveries which culminated in the formulation of the Extreme Value Theory in the 1920s (Fisher & Tippet, 1928). Their Extreme Value model concepts have given rise to a growing interest in data coming from regions that have continually witnessed extreme occurrences, forcing them to learn about the process underlying extreme events (Gnedenko,1943).

A second study by Smith & Bate (2020) utilized flood frequency analysis to identify homogeneous flood areas and choose a proper frequency distribution for the areas in a homogeneous area. Data from similar locations need to be utilized.

Rare and extreme flooding events are increasingly being modeled and predicted using the Extreme Value Model. Extreme Value Model offers a strong framework for calculating the odds of extreme events that conventional statistical techniques might miss by concentrating on the tail behavior of flood data (Mosavi et al., 2018).

### **Stochastic Hydrological Models**

From the Greek word "Stochastikos" (Στοχαστικός), which is from "Stochazesthai" (Στοχάζεσθαι), which is from Stochos (Στόχος), is taken the word "stochastics." Stochos is the goal, and Stochazesthai is to conceive, think deeply, bethink, think about, cogitate, meditate, as also to shoot (an arrow) at a goal or to make an educated guess or conjecture (the goal) (Koutsoyiannis, 2010). The term "stochastic" for stochastic methods now reflects the random component which is part of such methods. Thus, the purpose of stochastic methods is to forecast a variable value at unseen points in time or space and also give us the extent of uncertainty present in our forecasts. Why are

we particularly concerned with uncertainty in our forecasts? There may be discrepancies between data and model outcomes, caused by:

**Observation errors:** A hydrological parameter can rarely be measured with some degree of error. External variables frequently affect measurements, for example, changes in air pressure and temperature while measuring water levels.

**Errors in boundary conditions, initial conditions, and input:** Groundwater flow within a small area is only one of the signs that hydrological models only approximate a part of reality. Boundary conditions are to be specified while, at times, they could remain unobservable, and that might result in errors. Predictions of the future are influenced by the uncertainty of initial conditions. Other errors arise due to the fact that it is difficult to estimate inputs like rainfall and evaporation across large areas (Bierkens et al., 2000).

**Unknown heterogeneity and parameters:** Land surface and subsoil characteristics differ significantly in space and time. The errors arise when the hydrological characteristics such as hydraulic conductivity and roughness of the surface are interpolated at high frequency from sparse data or assumed to be homogeneous. Accuracy is influenced by the non-ideal parameter estimates despite models accounting for heterogeneity (Bierkens et al., 2000).

**Scale discrepancy:** Hydrological model outputs, such as numerical approximations, are averages over model elements or blocks. The measurements, however, often correspond to much smaller volumes. Predictive accuracy is compromised by this scale difference, giving rise to differences between measured and modelled hydrological variables (Bierkens et al., 2000).

**Model or system errors:** Models are abstractions from reality that cannot replicate the complexity of natural systems. For example, Darcy's Law is used to describe groundwater flow but breaks down in non-laminar flow or variable velocities. Similarly, surface water models can include simplifying flow approximations that do not accurately describe the physics of the real world, thus leading to erroneous conclusions (Bierkens et al., 2000).

Finally, apart from observation errors, discrepancies between model outputs and observations are caused by a number of error sources in the modeling process. Two approaches exist to dealing with errors in the outputs of hydrological models:

**Deterministic Hydrology:** In deterministic hydrology, internal flaws are typically identified and accounted for in the model calibration, although often in a simplified manner. At this stage, the aim is to tune parameters of the model such as hydraulic conductivity or surface roughness so that residual errors are kept to a minimum. However, once the model has been calibrated, these errors are not specifically addressed in subsequent computations. Therefore, potential inaccuracies in model predictions are overlooked (Bierkens et al., 2006).

**Stochastic Hydrology:** Stochastic hydrology is not only predicting hydrological quantities; it attempts to estimate the errors in the model results as well. In practice, the actual errors in the model estimates are unknown if known, these could be corrected for to achieve perfect accuracy. What is often available, based on scanty measurements, is a distribution of errors with probabilities. This distribution will provide an estimate of the likelihood of different magnitudes of errors, to be further explicitly defined in later chapters (Bierkens et al., 2006).

### **2.2.3. Flood Measurement Models**

Flood modeling is one of the most important tools for both prediction and comprehension of flood processes and impacts (Nikoo et al., 2016). It is necessary to formulate mathematical models that simulate the hydrologic and hydraulic processes responsible for flooding in order to predict the spatial pattern and temporal evolution of floodwaters and the corresponding risks and damages. These models find application in a number of areas, including flood forecasting, risk analysis, mitigation strategies (Su & Tung, 2013), and emergency planning and management.

#### ***Hydrologic and Hydraulic Modeling***

Hydrologic and hydraulic modeling are essential techniques of assessing and managing flood hazard. Hydrologic modeling is conducted through the examination of the flow of water within a stream or river system through the use of computational and mathematical techniques (Herrera et al., 2021). For this purpose, information regarding topographic features like elevation and land use and variables like rainfall, evaporation, and soil water must be collected. These data sets are then employed to make estimates of water flow parameters, including rate, volume, and timing, between different points of the system (Acharya et al., 2021). The outcome of hydrologic modeling serves

as a foundation for hydraulic modeling, where predictions of what the water would be doing during floods are made.

The main goals of urban hydrological models are to: (1) assess how urbanization affects the natural water system and to increase our understanding of this intricate system; (2) make up for the lack of accurate data because measurements in the diverse urban environment are even more difficult than in the natural environment; and (3) forecast future events, such as floods, the impact of land use and climate change scenarios, and ecosystem protection (Salvadore et al., 2015).

The provision of fresh, clean water and the removal of waste (water) are the two main needs of the urban population. The early creation of models to aid in the design of water supply and sewer networks was directed by these requirements. Later on, researchers tackled the issues of safety, i.e., evaluating the risk of flooding and pollution through the creation of hydraulic and transport models (Price and Vojinovic, 2011). Hydrologic models generally consist of two parts: a surface scheme and a hydrological flow model (described as a natural, anthropogenic, or a combination drainage system frequently represented by a combination of a surface and groundwater module) that moves water through the study catchment.

This type of model includes, for example, the Urban Forest Effects-Hydrology (UFORE-Hydro) model (Wang et al. 2008), the Semi-Urbanized Runoff Flow (SURF) model (Rodriguez et al. 2000), the Water and Energy transfer Processes (WEP) model (Jia et al. 2001), the Urban-Runoff Branching Structure Model (URBS-MO) (Rodriguez et al. 2008), the SIMGRO-model (van Walsum & Veldhuizen 2011), and the Semi-Urbanized Runoff Flow (SURF) model (Rodriguez et al. 2008). These models are commonly employed to analyze the performance of sewers and drains during rainfall (Rodriguez et al. 2008), evaluate the effects of runoff pollution (Rodriguez et al. 2000), simulate how urban areas influence natural catchment flows and flooding (Jia et al. 2001), and assess the role of urban trees and canopy interception in runoff and evapotranspiration (Wang et al. 2008).

### ***Numerical Flood Modeling***

Numerical flood models are computer code based on computational and mathematical methods to simulate water flow in flooding (Anees et al., 2016). Numerical models compute equations of flow

numerically depending on numerical algorithms, taking into account factors like rain, runoff, channel geometries, and river roughness. They are widely applied to model a variety of flood events and test the effectiveness of proposed alleviation measures (Saleh et al., 2012). In addition, numerical models may predict how the patterns of flooding vary with varying conditions of climate, land use, and other drivers.

Depending on their construction, these models may be of various types: one-dimensional models that model flow in river channels, two-dimensional models that model water movement over floodplains, and three-dimensional models that provide advanced details of the vertical distribution of water over floodplains (Marsooli et al., 2016). For numerical flood modeling, a number of software packages are available, including: HEC-RAS, MIKE FLOOD, TUFLOW, Flood Estimation Handbook and Environmental Protection Agency's Environmental Fluid Dynamics Code.

### ***Rainfall–Runoff Modeling***

Rainfall–runoff models are a type of hydrological model applied to simulate the process of rainfall conversion into runoff in a catchment. They play a key role in the forecasting of runoff volume and time, which is very essential in water resource planning and flood prediction. The models are generally divided into three categories: empirical, conceptual, and physically based models (Peel & McMahon, 2020). Conceptual models describe the hydrological cycle by oversimplified rules like water and soil balance equations and hence are suitable for sparse data catchments. Some of these are the Nash cascade model, Bayesian networks, and the HBV model (Hlavcova et al., 2005).

Physical process-based models are founded on a detailed knowledge of processes such as infiltration, evapotranspiration, and runoff routing. Although they consume enormous volumes of data and computer power, they are capable of accurately modeling catchment behavior under different conditions, SWAT, MIKE SHE and WATFLOOD (Kouwen, 1988) are examples. Empirical models, on the other hand, state statistical relationships between rainfall and runoff without having to model physical processes explicitly. Empirical models are easy to apply with small data requirements and have widespread usage in flood forecasting, drainage planning, and

water resource development. The most widely used examples are regression models, neural networks, machine learning techniques, and the SCS-CN model (Mishra & Singh, 2004).

### ***Remote Sensing and GIS-Based Flood Models***

Flood models make use of remote sensing and Geographic Information Systems (GIS) to assist in storm prediction and flood management. Remote sensing collects information about the Earth's surface through sensors onboard satellites or airplanes, while GIS provides tools for processing, analyzing, and visualizing spatial information (Kabenge et al., 2017). Through the integration of remotely sensed data and GIS, flood behavior can be modeled and water behavior can be predicted during floods (Sharma et al., 2020).

Flood models employ a variety of data sources which include satellite imagery, aerial photography, and ground measurements to determine the topography, hydrology, meteorology, and land use of the study site. Examples of flood models based on remote sensing and GIS include: SRTM Flood, Inundation Mapping System and ArcGIS Flood Analysis Tool.

### ***Multiple-Criteria Decision Analysis-Based Flood Management***

Multi-criteria decision analysis (MCDA) is a decision support method that helps stakeholders address complicated and frequently conflicting decisions, such as in flood management. MCDA considers quantitative and qualitative criteria in the decision-making process (Ganji et al., 2022). MCDA in flood management serves to assess and compare different strategies e.g., structural measures, non-structural measures, and land use planning based on objectives like minimization of flood risk and minimization of potential impacts (De Brito et al., 2019). Some examples of MCDM methods are Value/utility function, pairwise comparison, Outranking techniques, Distance-based and Fuzzy decision-making.

#### **2.2.4. Sustainable Drainage Systems (SuDS) Theory**

SUDS are a collection of management practices and control structures designed to drain surface water in a more environmentally friendly manner than some conventional methods (CIRIA, 2000). This was adopted worldwide in large quantities during the 1960s. This is when developed nations

started recognizing the contradictions between the then available rainwater drainage methods and conservation of the environment. This led to the development of a new drainage system, an evolution of the previous one, where public health was given precedence while also taking environmental concerns into consideration (Poletto & Tassi, 2012).

Later decades have seen focus on sustainable approaches with other names: Low Impact Development (LID) in the USA and Canada, Sustainable Urban Drainage Systems (SUDS) in the United Kingdom, Water Sensitive Urban Design (WSUD) in Australia, and Low Impact Urban Design and Development (LIUDD) in New Zealand (Poletto & Tassi, 2012). Despite the differences in terminologies, the basic principles and paradigms of these sustainable systems mostly agree in that they emphasize the need for balancing the elements of the hydrological cycle and their impacts on watersheds.

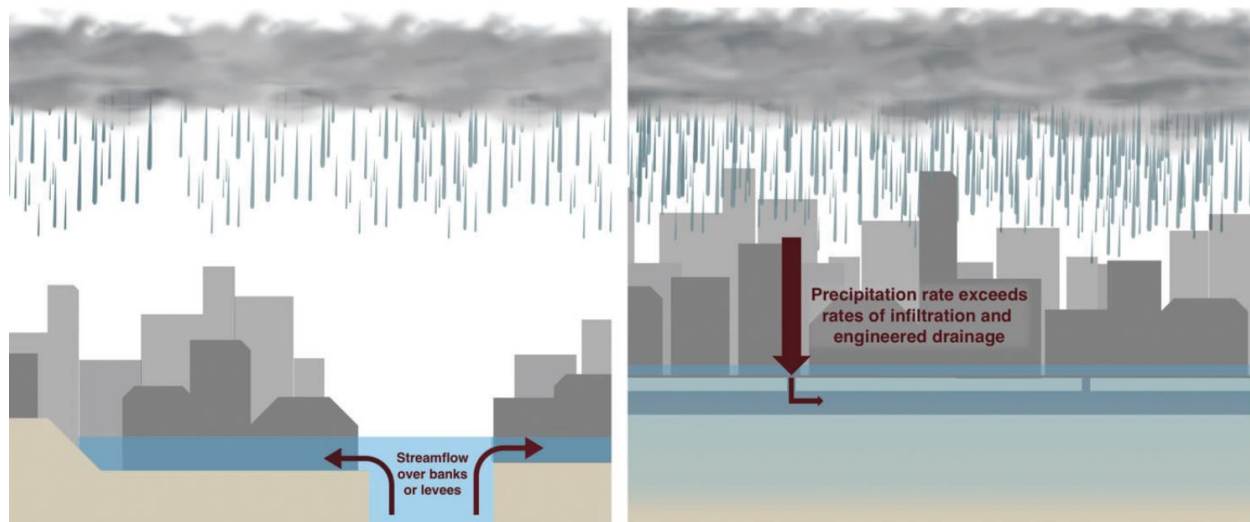
Three new approaches to stormwater management have been proposed: Source Control, Best Management Practices (BMPs), and Sustainable Urban Drainage Systems (SUDS) (Walker et al., 2000). Among these, SUDS is the newest and most integrated one, embracing the philosophies of the other two. The effectiveness of SUDS in flood prevention and mitigation of urban runoff pollution has been extensively studied, highlighting their contributions to sustainable urban water management (Macdonald, 2003).

- **Source Control:** This technique involves rain control at or near the source by slowing it down or allowing it to seep in. Porous paving and infiltration trenches are examples.
- **BMPs (Best Management Practices):** BMPs are an American product and seek to control diffuse pollution. BMPs consist of source control measures, as well as site or regional controls, such as detention ponds and basins, which are generally referred to as "end-of-pipe structures" (Roesner, 1999).
- **SUDS:** Expanding on the BMP concept, SUDS extends beyond both quality and quantity of runoff to amenity value of surface water in the urban environment. This holistic approach is then illustrated using the urban drainage triangle, emphasizing that systems must be designed to provide maximum benefits, either for flood prevention or pollution reduction, or for enhancing urban amenities. The capability of SUDS to tackle multiple objectives has been confirmed by a plethora of research studies (Macdonald, 2003).

## 2.3 Conceptual Review

### 2.3.1. Pluvial Flooding in Urban Areas: Causes and Impacts

Floods are typically classified based on their governing mechanisms, with the most prevalent types being coastal floods resulting from storm surges, often in conjunction with high tides, riverine or fluvial floods stemming from an overflow of rivers, and pluvial floods induced by rainfall. Other forms of flooding may manifest as groundwater flooding, dam breaks, or damage to water supply and drainage systems. Flash floods, occurring in mountainous terrains, are characterized by their abrupt onset.



*Figure 2.1: Fluvial (left) versus pluvial (right) flooding.*

*Source : (Bernice R et al, 2018)*

Urban hydrology is different from the surrounding environment, featuring decreased infiltration and evapotranspiration and corresponding increased total discharge and peak flow (Lull and Sopper, 1969). Urbanization typically corresponds with a short time of concentration, leading to a swift flow and elevated flood risk (Anderson, 1970). The primary hydrological process regulating city flooding is runoff, which is mainly from impervious cover (Boyd et al., 1993), and pervious cover (Berggren et al. 2013). The volume of precipitation on impervious surfaces is equivalent to runoff with minimal initial loss and lag.

Although the runoff from impervious surfaces remains continuous across various storms, pervious surface runoff is a function of rainfall depth. Pre-storm soil saturation becomes significant when

storms exceed 50 mm (Boyd et al., 1993), and antecedent precipitation prior to severe rain events makes a significant contribution to impacting flooding outcomes (Torgersen et al., 2015). Green/pervious surfaces do produce runoff during heavy rain (Berggren et al., 2013).

The urban surface hydrology is multifaceted and is based upon parameters such as age, slope, and maintenance (Redfern et al. 2016). Runoff is soil-type dependent, and thus the impact of urbanization differs for clayey soil regions and sandy soil regions (Sjöman & Gill, 2014). Frozen ground during winter elevates runoff, and a high-water table restricts infiltration. Field observations assessed by Redfern et al. (2016) revealed that impermeable surfaces such as roads can permeate more than earlier estimated in hydrological models, ranging from 50–60% of rainfall when degraded and as little as 2–3% when they are new.

Urbanization alters urban soils through topsoil removal and replacement, loss of vegetation, and compaction of soil. This shift, combined with local climatic changes and other indirect impacts, causes recently planted city green areas to generate 60–70% of runoff, declining to 5–30% after a few years. Root development and tree planting can support the restoration of the natural hydrological characteristics of the soil.

In general, the peak discharge of a catchment will increase with a decreasing time of concentration, with the significance of slowing down the runoff to mitigate flood risk (Villarreal et al. 2004) The operation of centralized sewers typically results in a complete quantity of water from upstream to downstream areas, which can result in flooding downstream due to the rapid transmission. Besides this, it can be inappropriately located along trunk pipelines, since systems such as these are typically designed for events no more than every 10 years. Distribution in time of rain also adds to flood depth at its peak, with such high-intensity storms resulting from extended lower-intensity storms producing deeper floods compared to the reverse situation (Hettiarachchi et al. 2018). This difference is most likely a result of the saturation of the soil and the application of detention ponds before the worst rain.

The response of the urban drainage system to rain events is characterized by two significant components, according to Bengtsson et al. (1993). The first is the surface run-off on natural slopes, or the major system. The second is the artificial drainage system, or the minor system. In all but a few cities, the artificial drainage system is managed either under a combined sewer system, which

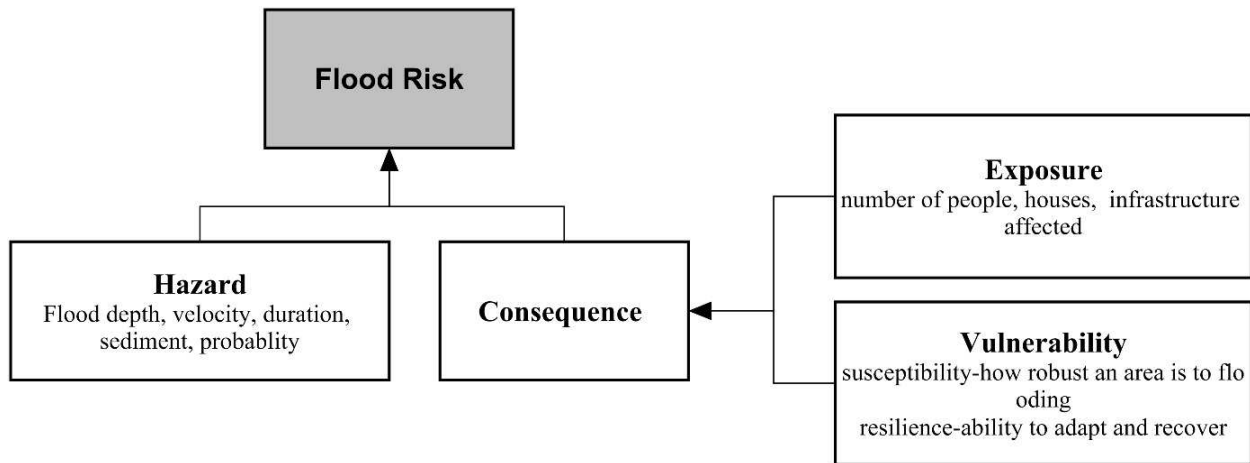
collects both stormwater and wastewater and delivers it to a treatment works, or individual surface water sewers.

While the primary system is typically overlooked in urban planning and therefore tends to be built in lowlands and weak locations, the minor system is usually built based on certain locally or nationally defined standards. Piped drainage systems efficiently channel stormwater from urban areas into a wastewater treatment plant or receiver in most rainfall situations. But it would be intolerably expensive in both build and run to plan for the most extreme storms (Fratini et al. 2012). Therefore, in establishing acceptable flood frequencies, it is crucial to find a balance between providing safety to residents protecting their properties and conformity with technical and economic constraints.

Urban flooding is usually blamed on sewer system failure even where they are highly designed. Misconnections (Ellis & Butler, 2015), poor maintenance (Arthur et al., 2009), pump failure (UK Environment Agency, 2007), and blockage of gully pots are some of the frequent causes leading to failures in urban drainage systems, which lead to flooding from even low-intensity rainfall events. Readiness for urban pluvial flooding is important, and sizing conduit systems effectively with blue-green infrastructure is needed. Effective flood risk management requires stormwater control, landscaping, and social preparedness.

### **2.3.2. Urban Flood Risk Assessment**

Flood risk is determined on the basis of the interaction of hazard and consequence, as explained by Kron (2005). The flood hazard factor can be characterized by variables such as depth of flood, duration, velocity, load of sediment, and probability. Conversely, consequences are based on exposure (number of people and structures exposed), as well as vulnerability and resiliency of the region. Holling in 1973 coined the term resilience, and it was employed to denote it as the capability of a system to endure extreme alterations but continue to operate. Vulnerability, on the other hand, is susceptibility or inclination of a system to suffering from harmful impacts (Lavell et al., 2012). Thus, urban flood risk depends on the resiliency and vulnerability of the system elements to flooding, combined with the intensity and probability of the flood hazard in the area.



**Figure 2.2:** Flood risk components

Source: (Abebe Y et. al, 2017)

Flood vulnerability assessment methods vary with regard to the degree, theoretical underpinnings, variables, and scale of analysis. Nasiri et al. (2016) categorize methods into the vulnerability indicators methods, curve methods, disaster loss data methods, and modeling methods. Balica et al. (2012) distinguish between physically based models and parametric models. While the majority of the suggested methods primarily address the physical component of vulnerability (Pradhan, 2010), others adopt a multidisciplinary strategy incorporating economic and social facets (Balica et al., 2012). What is notable is that the majority of studies focus on fluvial and coastal flooding with comparatively little attention to pluvial flood vulnerability. There is also considerable variation in analysis scale and detail level. Generally, the current methods of vulnerability analysis can be classified into three broad categories: physically based models, data-driven models, and expert knowledge-based models.

Physically based pluvial flood modeling approaches are advancing, particularly toward coupled 1D-2D simulation models (Van Dijk et al., 2014). Data-driven models encompass statistical methods, machine learning, and ensemble learning techniques that use empirical models with parameters having a direct or indirect influence on flood occurrence to estimate the flood susceptibility of an area (Pradhan, 2010). Vulnerability curve methods, such as empirical damage or fragility curves, establish the link between the exposed asset and flood hazard. Approaches to flood vulnerability assessment vary in scope, theoretical underpinnings, variables considered, and analytical scale.

According to Nasiri et al. (2016) categorizes methods into vulnerability indicators approaches, curve approaches, disaster loss data approaches, and modeling approaches. Balica et al. (2012) distinguish between physically based models and parametric models. Orencio and Fujii (2013) employed an analytic hierarchy process and weighted linear average in the construction of a disaster resilience index. Stefanidis and Stathis (2013) and Zou et al. (2013) employed the same methods to develop flood hazard and flood vulnerability indexes. More recently, Sun et al. (2016) proposed a flood resilience evaluation method based on analytic network process, contributing to the new direction of flood risk research.

### **2.3.3. Urbanization and Land Use Change**

Humans have been modifying land not only for farming but also for habitation and community use since the early days. That said, the physical extent of the settlements remained compact until industrialization took hold and hastened urbanization. As cities teemed with people and manufacturing activity, large swaths of land typically agricultural or nature were reclaimed for urban use. The transformation reshaped landscapes, covering open spaces with vast built-up areas and altering the very shape of cities (Henning & Stefan, 2020).

The massive growth of industrial cities in the 1800s was condemned with stark criticisms. Critics linked urbanization not just with social ills like overcrowding and poverty, but with the defacement of rural scenery (Whyte, 1958). By the 1930s, terms like "sprawl" entered the discussion, with critics like Earl Draper condemning unplanned urban development as inefficient, socially costly, and aesthetically unpleasing (Wassmer, 2002). Urban growth debates evolved over time, associating sprawl with concerns like inefficient infrastructure consumption, environmental deterioration, and loss of natural habitats (Nechyba & Walsh, 2004).

Today, words like "land consumption" reflect growing environmental awareness (Meadows et al., 1972), though land itself is not really "consumed" (Nuissl et al., 2009). Instead, these terms highlight the way that urbanization disrupts nature and depletes resources. But quantifying only the amount of land converted overlooks the greater picture. For example, the loss of wetlands for manufacturing has far worse environmental effects than constructing homes on previously agricultural land (McGranahan & Marcotullio, 2005). In the same way, compacted development

disturbs less ecosystems than dispersed, fragmented metropolitan fragments. The most significant determinants of the impact of urbanization are:

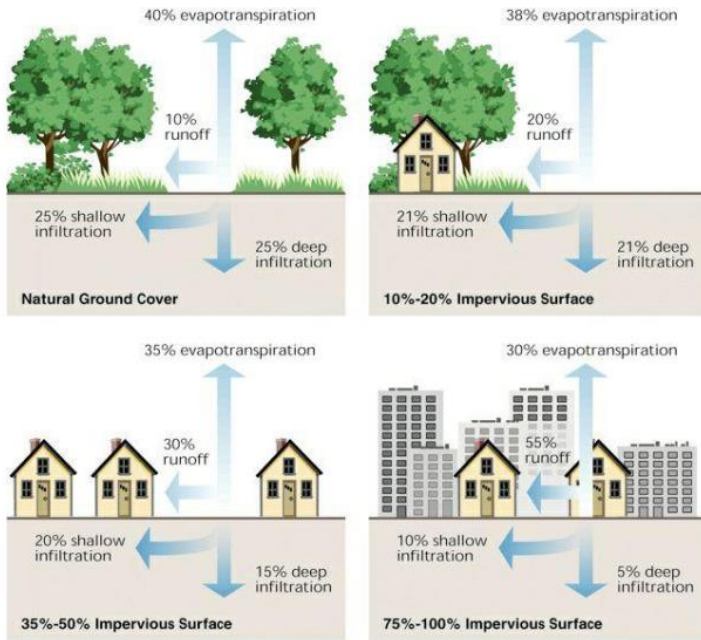
- The previous land use and land cover (agricultural, forest and natural);
- The dominant purpose of the new urban use (residential, commercial, industrial, recreational, or other) and the corresponding land cover features (such as the imperviousness of surfaces and the emission of pollutants);
- The location and pattern of new urban land; and
- The efficiency of land use.

These subtleties are crucial to sustainable planning. Luckily, mapping technology has developed to a level where it now facilitates the close observation of urban growth patterns, land use heterogeneity, and environmental impacts (Schneider & Woodcock, 2008). These information's can guide smarter policy to allow cities to grow without undermining ecological integrity or livability.

#### **2.3.4. Urbanization and imperviousness**

Urbanization has greatly affected stormwater runoff and generation (Butler & Davies, 2000). Consequently, stormwater travels downstream faster, taking into account the greater speed of water flow over impermeable surfaces compared to natural surfaces. The result is that the urban areas experience a more rapid runoff flow with an enhanced peak flow, which is received by the urban drainage system at a faster rate.

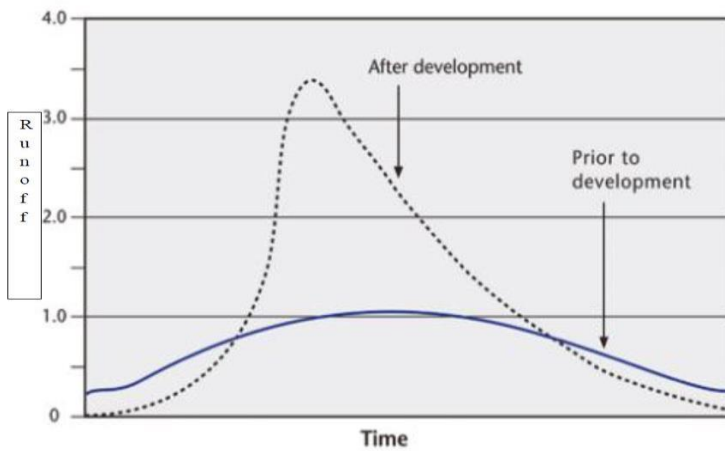
However, the urban runoff also recedes more quickly than natural green surfaces, thus resulting in a higher peak flow (Butler & Davies, 2000). This is because the natural green infiltration surfaces, i.e., natural soil cover, are substituted by impermeable surfaces such as concrete roads, buildings, and roofs in the urban areas (US EPA, 2003)



**Figure 2.3:** Impact of urbanization on surface infiltration, evapotranspiration, and runoff

Source : ( Burian & Pomeroy, 2010)

As per the findings of the US Environmental Protection Agency (EPA) in 2003, the significant implications of urbanization on the hydrologic cycle are a result of alteration of impervious cover with corresponding alteration of processes such as evapotranspiration, runoff, and shallow and deep infiltration. The pre-urban and post-urban difference in peak flows can be seen from the (Fig. 4) below.



**Figure 2.4:** Impact of Urbanization on runoff quantity

Source: (US EPA, 2003)

In terms of urbanization, the key concern is persistent urban build-out and destruction of natural habitat for man-made structures. These structures, made from asphalt and concrete, destroy the natural soil into non-permeable surfaces that will not let surface water flow into the groundwater (Choi, 2016). Urbanization increases the volume of runoff and has a bearing on stormwater quality, which contributes to enormous hydrological changes that may have adverse effects on streams, not to mention other water bodies and their associated ecosystems (Khaniya et al., 2016).

The impervious surfaces within the landscape manifest as building footprints, parking, and infrastructure and play an important role in issues with stormwater runoff. The impermeable surfaces disrupt the natural hydrologic cycle by failing to permit the water to seep through into the subsurface layer (Choi, 2016).

### 2.3.5. Identifying the level of imperviousness

Impervious surfaces are solid surfaces that do not allow water to percolate into the soil or result in increased runoff, as described by Powell et al. (2008). They include roofs, sidewalks, patios, driveways, parking lots, storage facilities, concrete or asphalt pavement, and gravel roads, as quoted by the US EPA in 2003. USGS (2006) emphasizes the need to map impervious surfaces for all watersheds at a very fine scale. The process involves utilizing existing detailed GIS data from municipal governments and digitizing spatially explicit classes of impervious surfaces from high-resolution ortho-imagery. The assembly results in highly detailed GIS data of various classes of impervious surface cover, enabling the determination of the relative contribution of each class of impervious cover.

*Table 2-1 Components of impervious surfaces*

<b>Impervious Surface Components</b>	<b>Component/Feature Descriptions</b>
<b>Buildings</b>	All roofed structures including storage sheds and trailers
<b>Roads</b>	Gravel, paved, or other hard surfaces that are mainly utilized
<b>Parking Lots</b>	Paved or hard-surfaced areas that exist primarily for the temporary storage for Automobiles and other vehicles, equipment, and materials.

<b>Driveways</b>	Hard surface or gravel areas that connect a house, garage, or other structure to a road surface for the purpose of automobile access and storage.
<b>Sidewalks</b>	Narrow hard surface areas that are generally found parallel to roadways and exist primarily for pedestrian traffic. Recreational trails, home and business entryways, park, and golf course cart paths are included in this category.
<b>Other</b>	Hard surface recreation areas, such as basketball or tennis courts, patios, and swimming pools - to include surrounding patios, and any other impervious surface that does not fit in any of the above categories.

*(Source: USGS, Reston, Virginia: 2006)*

Object-based on-screen digitization of elements of impervious surface is relatively more accurate than other methods utilized to generate built-up area in GIS. It is a method of precise on-screen digitizing of components to supply vector data (Alkan et al., 2010). But the final output is constrained by the character, quality, and scope of the data source, and in a majority of scenarios, these datasets are nonspecific regarding impervious information. In certain urban settings, certain land cover information may be available in the form of CAD drawings or surveys.

If data is digital and compatible with existing programs, then it can be identified and selected for land cover and for impervious features. Issues arise when it is being transferred from one file type to another, and errors can be made while processing missing data, such as unclosed polygons (Bauer et al., 2007).

**2.3.6. Stormwater Runoff**

Stormwater refers to rain or precipitation falling on impervious surfaces like roofs and impervious paved surfaces like driveways, roads, or sidewalks that is directed to the drainage systems (US EPA, 2003). At times, part of the rainwater infiltrates into the soil or gets absorbed by plants. The remaining runs over various surfaces and ultimately into the nearest outlet, either a drainage system or a river/water body. More precipitation volume gets converted into stormwater runoff in urban areas as a consequence of urbanization. This is predominantly due to the greater prevalence of impervious surfaces, which do not allow water to infiltrate into the ground but instead cause it to

flow rapidly towards the outfalls and drainage systems. Consequently, erosion and flooding result due to limitations in the capacity of the drainage system, clogging, underdevelopment, or other related problems (Rasmussen & Schmidt, 2009).

In urban settings, stormwater flooding occurs when runoff flow rates, predominantly from impervious surfaces, surpass the capacity of sewer and storm drainage systems. This is a common problem worldwide, attributable to various drainage system issues (Burns et al., 2015).

The runoff, enriched with atmospheric pollutants and particles from impervious urban surfaces, contributes to the contamination of surface water bodies and groundwater or rivers that receive it downstream (Yannopoulos et al., 2013). When stormwater runs directly over land surfaces, it becomes polluted with harmful chemicals such as sediment, fertilizer nutrients, bacteria, pesticides, metals, and petroleum products. This polluted runoff of stormwater can pose risks to plants, animals, and human health (Walsh et al., 2012).

Furthermore, stormwater runoff is not only documented to affect human health, vegetation, and wildlife but also to reduce the water quality of bodies (US EPA, 2003). Consequently, decreasing the sources of stormwater runoff is a socially, ecologically, as well as economically effective and preferable approach to limit its impact on surface and ground water bodies, ecosystems, and human health (Yannopoulos et al., 2013).

### ***Stormwater and Drainage Systems***

A storm drainage system is an assortment of facilities that are designed to gather and direct stormwater runoff from land surfaces to a point of discharge, effectively managing water flow on the highway and lessening the chance of flooding and the ensuing issues for nearby properties (Arizona Department of Transportation, 2007). The main components of storm drainage facilities include curbs, gutters, storm drains, and channels.

The structure design, the site, and the hydraulic capacity must consider potential damage to adjacent properties and attempt to reduce the risk of flooding-induced traffic disruption (Ethiopian Roads Authority, 2013). Stormwater resulting from various forms of precipitation like snowmelt and rainfall contains water in the surface flow (Butler & Davies, 2000). Therefore, both catchment properties and rainfall both have basic roles to play in governing stormwater characteristics. Part of the rainfall is absorbed by first-order loss processes like interception, depression storage,

infiltration, and evapotranspiration, with the remaining portion of water becoming runoff (Durrans, 2003).

Ensuring public health and safety continues to be a societal imperative, opting for the maintenance of stormwater and wastewater drainage to prevent the adverse impact of flooding on life and property. Environmental awareness identifies the need to protect receiving waters from the impurities carried by surface water under heavy rain conditions (Viessman Jr. et al., 2014). A split system, composed of individual waste and stormwater pipes, avoids basement and floor flooding from heavy rainfall and avoids contaminants from being released into the environment (EPA, 1999).

Stormwater, being generally less contaminated than sewage water, may be diverted to detention basins or bodies of water without extensive treatment, thereby saving energy and resources. In other places, like in our country, sewerage and stormwater lines are separate, leading to flood-like situations in the drainage system due to saturation of canals. Stormwater runs in open channels and gets merged into the river without treatment in close vicinity to the aforementioned area.

### **2.3.7. Factors affecting stormwater runoff and its management practices**

In addition to intensity, coverage, and duration of precipitation (rainfall), other factors have also been seen to influence stormwater runoff and the implementation of proper techniques to mitigate it. These include:

#### **Vegetation**

The vegetation type and quantity are the variables that play very important roles in managing stormwater runoff. Lands with a sufficient vegetation cover receive lower stormwater runoff compared to the cleared impervious areas. A high, evenly distributed vegetation cover on a slope lowers the surface flow of stormwater by enhancing the infiltration capacity of the soil, encouraging evaporation and infiltration. Secondly, the type of vegetation cover may also result in a greater retention effect on stormwater, best evident in the disparity between crops that possess sound water storage attributes and vegetation that lacks such characteristics (Demu, 2018).

## **Soil type**

In residential or neighborhood environments, soil plays a significant role in controlling stormwater flow. Porosity in the soil is at the core of an area's capacity to store and in the ability of stormwater flow to travel through deeper soils, which determines infiltration capacity. Soils vary in infiltration capacity, as can be demonstrated by the disparity between sandy and clay soils (Demu, 2018).

## **Slope**

Steeper slopes tend to have greater stormwater flow velocities from higher catchment areas to lower catchment areas, leading to various issues associated with runoff. In contrast, gentler slopes lead to low volume of runoff, where the water remains for longer. With the increased period, water has sufficient time to infiltrate the soil and undergo evaporation before flowing to lower catchment areas (Akhter et al., 2020).

## **Land (Plot) size and use**

Urban areas consist of various plots with distinct sizes and purposes, including residential, industrial, and commercial spaces. The prevalence of impervious surfaces is notably high in these areas. While the development of such plots often takes into account hydrological factors such as the timing, depths, and volumes of stormwater runoff, the trend of expanding urbanization and enlarging plots, without sufficient attention to enhancing pervious surfaces, results in a notable rise in the volume of stormwater runoff. This increase, in turn, gives rise to adverse consequences (Endreny, 2005).

## **Drainage**

Features like waste sewers, groundwater and/or surface waste reservoirs, and other drainage systems are used to eliminate waste from the collection area and convey stormwater to particular collection areas such as lakes, rivers, or wetlands. Drainage channels and networks, placed along roadsides and alongside individual plots, are employed for the proper collection and leading of stormwater to its collection storage area, thereby eliminating the adverse effects associated with it. Because roads and impervious surfaces that are close to drainage systems hinder infiltration, thereby leading to an increase in runoff volume and velocity, the incorporation of drainage mechanisms is a key element in road and residential area design and construction (Parkinson, 2003).

### **2.3.8. Criteria for Flood Hazard mapping**

The flood susceptibility mapping is based on the integration of numerous biophysical and anthropogenic parameters that contribute to forming, transporting, and depositing the surface runoff. Another parameter such as rainfall, slope, relief, land utilization, or distance to infrastructures, respectively, influences differentially the processes of floods, and their characterization to levels of susceptibility is derived on the basis of hydrology principles, geomorphologic process, and outcomes of knowledge that exist. Such parameters can correspondently be reclassified to Very Low to Very High ranges of susceptibility, and subsequently, the areas of risk of pluvial flooding can be objectively evaluated and mapped (Taoukidou et al., 2023).

Statistical procedures, including natural breaks (Jenks) or expert weighting procedures (e.g., AHP), are then typically applied to set threshold classes in the susceptibility analysis of floods to separate and define threshold classes. This is to make the classes not only represent actual data distribution but also to represent physically identifiable processes that have been determined to control flooding (Latif & He, 2024).

#### ***Rainfall***

Precipitation is broadly accepted as being the single largest control of pluvial flooding, with the strength, persistence, and frequency of rainfall controlling the amount of runoff and flooding. Brief-duration, short-duration storms often have a higher intensity than the capacity of urban drainage systems and thus cause rapid flooding of the surface. Rainfall data measured to a sub-kilometer resolution, as exemplified by Latif and He (2024), significantly improves the effectiveness of flood models, particularly with convective events. Rainfall datasets, therefore, generated either by design storms or by operational radar-gauge systems in real-time, provide the basis of pluvial flood hazard maps.

#### ***Slope***

Slope is an important topographic parameter influencing runoff dynamics. Greater inclines allow for higher velocity flows and reduce ponding, whereas flat surfaces prefer to allow stagnating and water pooling. Rayamajhi et al. (2025) showed that the slope of an area is a statistically significant driver of their Flood Susceptibility Models, with regions of low slopes always having higher flood

potential. Thus, the slope not only controls the velocity of flow but also determines the geographic extent and persistence of flooding occurrences.

### ***Elevation***

The relationship between elevation and slope is significant; their functions, however, differ considerably to that of hazard mapping of floods. Areas of low elevation function naturally as catchment areas of runoff of the surface and hence remain susceptible to episodes of flooding. From Latif and He (2024) study, elevation ranks among the best predictors of pluvial flood hazard within studies of research across Europe and therefore validates its significant role within the definition of hazard-prone areas. By comparison with datasets of slope, elevation facilitates identification of depressions and directions of runoff where water will collect.

### ***Topographic Wetness Index (TWI)***

The topographic wetness index (TWI) represents an improvement over elevation and slope measures because it combines the upslope contributing area to provide an index of potential soil saturation. High TWI values indicate regions of convergence where runoff will have a tendency to pool during heavy rainfall. The study by Rayamajhi et al. (2025) showed that TWI represents a good predictor of flood susceptibility of Malay catchments, particularly with regards to identifying ponding regions and regions of prolonged saturation. As such, this index represents a more accurate terrain-based indicator of the pluvial flooding event mapping.

### ***Drainage Density***

Drainage density, which is the length of channels (natural and artificial) within units of area, is a proxy of conveyance runoff effectiveness. For natural conditions, higher drainage density tends to reduce the risk of flooding through effective runoff elimination. However, Latif and He (2024) argue that within urban conditions, poor maintenance or lacking drainage facilities can invert this relationship to cause a higher risk of flooding despite high-density drainage. The dual role of the indicator reflects a need to balance the measurement of drainage density with qualitative judgments of conveyance capacity and maintenance.

### ***Land Use / Land Cover (LULC)***

The land use and land cover (LULC) also influence flood dynamics due to their roles in defining infiltration capacity and surface roughness. Urban centers with hard surfaces significantly increase runoff compared to agricultural or vegetated surfaces. (Wang et al., 2023), documented that urbanization significantly increased the pluvial flooding hazard due to infiltration loss and increased water buildup on the ground. LULC classification, therefore, typically derived with satellite data, is inevitable during spatially allocating hydrological parameters within floods models.

### ***NDVI (Vegetation Index)***

Normalized difference vegetation index (NDVI), a common parameter applied in remote sensing, offers a quantitative measure of both vegetative cover and density. Positions with high-density NDVI vegetative cover greatly minimize flooding through enhancement of infiltration, interception, and evapotranspiration processes, while areas with bare or hard surfaces and low NDVI increase runoff. Islam et al. (2025) showed a significant negative correlation between the Flood hazard and NDVI and thus confirmed its potential to act as an indicator of land cover controls on vulnerability to flooding.

### ***Distance to Roads***

The distance to roadways is an anthropogenic variable that accounts for the influence of infrastructure on the dynamics of floods. The roadways provide usually provide channels for water, directing it to lower elevation positions such as underpasses, while concurrently altering natural channels of flow. Latif and He (2024) determined that damages during floods accumulate within roadways and nearby infrastructure, mirroring their dual function of channels and assets of vulnerability. The inclusion of distance to road within pluvial floods maps therefore takes into account both hydrological adjustments and elements of exposure by increase in urban development.

### 2.3.9. Best Management Practice for stormwater management sustainability

#### Reduce urban Run-off

Effective runoff reduction begins with the acknowledgement that land development or redevelopment within a watershed must necessarily enhance the impermeability of the land, and thus correspondingly enhance the volume, rate of runoff, and its associated pollutant load. A number of design and planning techniques are then described to minimize or eliminate this effect.

The extent of impermeable land covering the surface is an important indicator of the urban watershed's health, as well as the quantity and quality of the stormwater. Impermeable land cover is the foundation of urban and suburban landscapes, such as rooftops, pavement, parking lots, and other surfaces preventing rainwater from passing through the ground like it would have done before land development (Tafete, 2013). Techniques for reducing urban runoff are impervious area management in watersheds, reducing direct connections of impervious surfaces to storm drainage systems, and incorporating runoff reduction areas as part of planning and design development.

#### Protect the existing best management practices.

The functions that are provided by BMPs may include: volume reduction, treatment and slow release of the water quality capture volume (WQCV), and combined water quality and flood detention. If possible, site designs will include a "treatment train" that controls and treats pollutants at their sources, reduces runoff, and includes a combined variety of source control and treatment BMPs. According to (Urban Drainage Flood Control District, 2010), a few of the BMPs for stormwater management in an urban setting are:

- **Wet Retention Pond:** are stormwater control structures that provide contaminated stormwater retention and treatment. Through capturing and retaining stormwater runoff, wet retention ponds control its quantity and quality, while then removing pollutants by the works of the pond's natural processes. In order to improve bank stability and aesthetic benefits, Retention ponds are expected to be surrounded by natural vegetation.
- **Extended Detention Basin (EDB):** are stormwater BMPs that provide general flood protection while also controlling extreme and rare occurrence floods and storm events. These basins are ideally built during the construction of new land development projects.

They help manage the excess urban runoff generated by the impervious surfaces such as roads, and parking lots that are newly constructed.

- **Permeable Pavement Systems (PPS):** Permeable Pavement Systems are pavements that allow the movement of water into the layers below the pavement's outer surface. Permeable pavements can be used to promote volume reduction, provide treatment, slow release of the water quality capture volume (WQCV), and reduce imperviousness, depending on their design.
- **Sand Filter:** is used as a step in the water treatment process of water purification. A sand filter is filtering or infiltrating BMP that consists of a “surcharge zone underlain by a sand bed with an underdrain system (when necessary)”. During a storm event, accumulated runoff collects in the surcharge zone and it gradually infiltrates into the underlying sand bed, which fills the void spaces in the sand. The sand bed is then gradually dewatered by the under-drain and discharges the runoff to a nearby stormwater management mechanism such as a channel, swale, or storm sewer.

### **Pluvial flooding resilience practices**

Targeted approaches to enhance the resilience of cities to pluvial flooding have only been investigated in the past decade. Sørensen et al. (2016) suggested that a “regime shift” in urban water management is necessary, where integrated water management is favored over large-scale, single-purpose sewerage projects to mitigate flooding in sensitive areas, areas where controlled flooding can be tolerated are designated, and plans are made for reorganization in case damage occurs.

To an extent, this regime shift is already in progress many cities have begun adopting a “blue-green” infrastructure (BGI) approach to stormwater management, using multifunctional green infrastructure to try to restore predevelopment hydrologic function (Novotny et al., 2010). Examples of commonly employed BGI include rain gardens, bioretention basins, bioswales, green roofs, and porous pavement.

However, the extension of this approach to mitigate the impacts of pluvial flooding particularly during extreme rain events is in the earliest stages of development (Lawson et al., 2014). Although flood regulation is often listed as an important service provided by BGI, quantitative information on its actual effectiveness and optimal utilization remains limited. While numerous studies have

considered the general runoff retention provided by BGI (Eckart et al., 2022), few published studies have actually quantified the catchment-scale effectiveness of BGI in mitigating pluvial flooding, and of these, only two consider extreme (>20 years recurrence) precipitation events.

In practice, many types of BGI rely primarily on the infiltration of stormwater to mitigate flooding and would be limited in their effectiveness when rainfall rates greatly exceed the maximum infiltration rates of their soils. Some types of BGI are designed to detain water, temporarily storing stormwater runoff during rain events and releasing it slowly to prevent exceeding the conveyance capacity of water infrastructure. However, as with other types of urban water infrastructure, BGI is designed for the management of a design storm and may provide limited detention capacity during events that exceed the design storm intensity.

In addition to building resilience through land management and infrastructure planning, there are also opportunities to enhance resilience to pluvial flooding through nonstructural policies and practices. Providing advanced warning that pluvial flooding is likely to occur can be an important means to prevent loss of life or property damage by providing the time necessary to evacuate vulnerable areas, clear drainage infrastructure of debris to optimize conveyance capacity, relocate parked vehicles to higher ground and move furniture to higher floors (Rözer et al., 2016). However, providing early warning for pluvial flooding remains challenging, since it is often driven by highly localized and fast-moving cloudburst events that are difficult to forecast (Falconer et al., 2009). At present, the ability to provide warning of intense rainfall is often limited to the use of radar-based observations of approaching storms, however, numerical modeling packages to support near-term forecasting and warning are currently being tested (Gallo et al., 2017). Along with near-term forecasting of the occurrence of intense rainfall rates, the identification of rainfall thresholds that indicate that pluvial flooding will likely occur is critical to support flood warning systems. Rainfall threshold approaches used to support fluvial flood warning systems, such as the US NWS's Flash Flood Guidance, are based on the use of antecedent soil moisture conditions and less relevant to highly urbanized settings or extreme rainfall intensities (Ntelekos et al., 2006).

## CHAPTER THREE: METHODS AND MATERIALS

This chapter outlines the methodology for developing a pluvial flood-risk map, and quantifying the land use changes. It details the study's design, data sources, analytical tools, and ethical considerations, concluding with a framework integrating these components.

### 3.1 Description of the Study area

Ethiopia's capital and its largest city Addis Ababa was established in 1987 and is located at coordinates 9°01'48 N and 38°44'24" E. The city is divided into 11 sub-cities and 116 districts, locally known as "Weredas" As of 2022. the Central Statistical Agency approximated 3.95 million residents in 2023, while alternative approximations exceed 4.5 million and are growing at ~2.5% yearly (CSA, 2023). The city is very densely populated, with ~7,000–9,000 people/km<sup>2</sup>, and demographically young, with over 70% in the working-age population (UN-Habitat, 2020). The city receives about 1,200 mm of rainfall on average annually, with half of that falling between June and August which is the main rainy season (kiremt) a smaller Belg season in March–April (World Bank, 2020). Due to the city's rapidly expanding impermeable surface, floods are common during this time period (McFarland et al. 2019).

Addis Ababa's settlement pattern is a mixture of densely-occupied inner-city suburbs and fast-expanding peripheral zones. More than 70% of the city's population live in informal or slum conditions, both in older inner-city kebele housing and in uncontrolled peri-urban neighborhoods (Taye et al., 2025). Urbanization has been peripheral: satellite imagery studies show that more than 95% of 1990–2020 growth occurred at the edges, often at the expense of agricultural land (Woldemichael & Teshome, 2021). The city has high levels of urbanization therefore it was chosen for this study. The first two objectives examine the entire city while the third objective mostly focuses on an area that is vulnerable to pluvial flooding (next to Gurd Shola Light Rail Transit station).

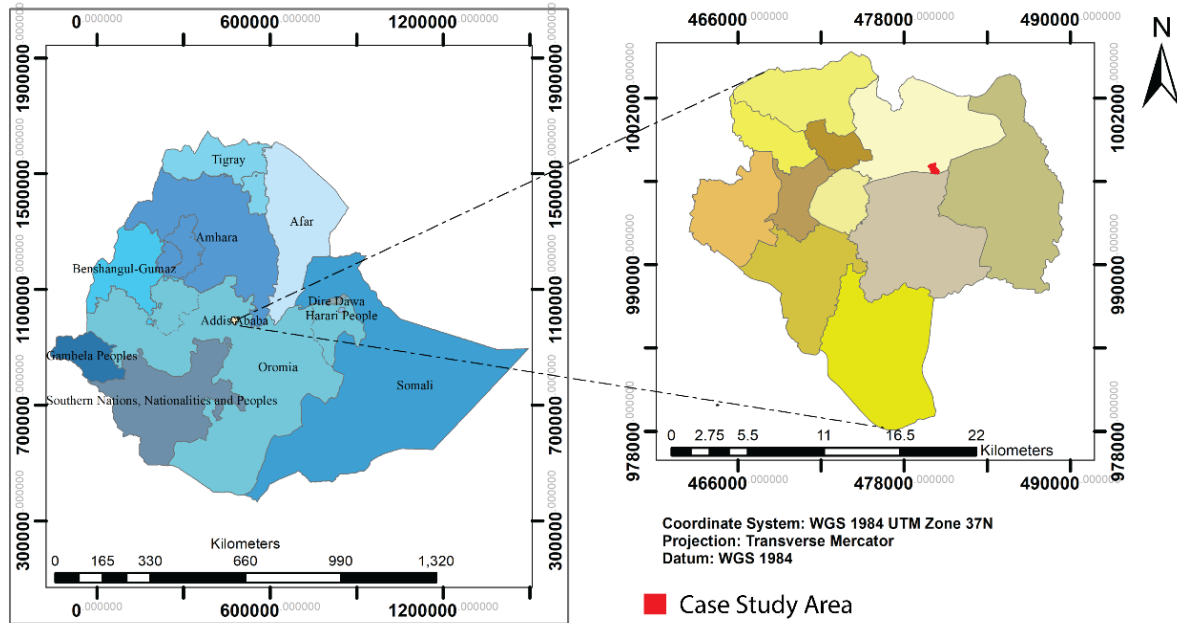


Figure 3.1: Map of study area

### 3.2 Research Design

This study utilized a mixed-method study comprising of both the qualitative and quantitative research methods to assess the effect of land cover change and urbanization on pluvial flooding in Addis Ababa.

**Quantitative Approach:** this method utilized a Numerical analysis to determine the connection between land use transformation and flood generation. The study has also applied remote sensing techniques on Geographic Information System (GIS) to map out flood-prone areas, measure land use changes over time, and simulate runoff in flood susceptible areas. Using these tools helps to visualize the spatial patterns and quantify how urbanization has influenced flood risks.

**Qualitative Approach:** Semi structured interviews were conducted with municipal authorities for better understanding about stormwater management practices and policy implications in Addis Ababa. Their perspective helps to assess the effectiveness of current strategies and recognize areas for improvement. Moreover, a review of government reports, urban planning policies, and historical flood records were used to support the study and help to understand how past interventions have shaped flood management efforts.

Direct site visit to the flood-prone area was key in assessing the functionality of stormwater drainage systems in minimizing floods and to identify the cause for flooding.

### **3.3 Data types**

The study used a combination of both primary and secondary data to investigate the research objectives.

#### **Primary data**

The main source of data for the study was field observations in flood-prone areas these observations include drainage locations, conditions, and types. Furthermore, data were also gathered from interviews of key informants such as municipal authorities and other relevant stakeholders, to gather insights and firsthand information on stormwater management and infrastructure challenges.

#### **Secondary data**

The type of secondary data includes satellite imagery and remote sensing data from archives such as Landsat for land use/cover analysis and Digital Elevation Models (DEMs). Hydrological data such as records of rainfall were also employed to study patterns of precipitation. Published literature and archives on pluvial flooding, as well as case studies of sustainable drainage design interventions, were analyzed.

### **3.4 Sources of Data**

The study compiled data from multiple reliable sources. A 30-meter resolution SRTM Digital Elevation Model (DEM) alongside Landsat 5, 7, and 8 satellite imagery with minimal cloud cover for land use landcover was extracted and downloaded from the United States Geological Survey (USGS) Earth Explorer. Road network data of the city was sourced from the Addis Ababa City Roads Authority and BBBike (berlin bike). Rainfall records were acquired from two sources one being the National Meteorological Agency of Ethiopia and the other is the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS). Additionally, information on drainage systems in identified flood-prone areas was provided by the Addis Ababa City Roads Authority.

*Table 3-1 Summary of data types & sources*

<b>Data Type</b>	<b>Description</b>	<b>Sources</b>	<b>Relevance</b>	<b>Date acquired</b>
Precipitation	Annual rainfall /daily rainfall	The national meteorological agency/ CHIRPS	Generation of rainfall layer, runoff estimation/simulation	2025
SRTM (DEM)	topography	USGS	Generation of slope, elevation, DD, TWI	2025
Landsat 5,7 &8 OLI	Arial imagery	USGS	Land use land cover classification, generation NDVI	2025
Road networks	Road network	Addis Ababa city roads authority / BBBike.	Distance to road	2025
Drainage Layout information	On flood-prone areas	Addis Ababa city roads authority	Efficiency assessment /flood simulation	2025

### **3.5 Method of data collection**

#### **Site Observation**

The site observation involved direct visits to the flood-prone area to collect data related to spatial and functional characteristics. Even though the site visit was not during the rainy season to experience the flood first hand, observing the distribution and conditions of stormwater drainage systems helps to assess the performance and efficiency in managing runoff and preventing water accumulation.

#### **Document Review**

The document review involved analysis of Addis Ababa city planning policies, government flood reports, stormwater drainage regulations, and flood-prone area documents. The method gives a clue on possible loopholes and the existing strategies.

#### **Key Informant Interviews**

Key informant face-to-face interviews were conducted to gain a deeper understanding of stormwater management practices and policy implications; these informants possess valuable insights into the current conditions of drainage systems and the cause of pluvial flooding. Key

informants selected from responsible institutions such as the Addis Ababa Water and Sewage Authority (AAWSA), Addis Ababa City Roads Authority (AARCA), Yeka sub-city Dry Waste Management Office, and Addis Ababa City Administration Fire and Disaster Risk Management Commission as seen on (Table 3).

*Table 3-2 List of Key informants selected*

No.	Code	Key Informants	Responsibility	No
1	KI1	Addis Ababa City Roads Authority (AARCA) Eastern AA Road Asset Main Directory	General Manager/ Hydraulic Engineer	1
2	KI2	Addis Ababa City Roads Authority (AARCA) Head Office	Hydraulic Engineer	1
	KI3		Road Design Department (Senior Structural Engineer)	1
3	KI4	Addis Ababa City Administration Fire and Disaster Risk Management Commission	Disaster Information Technology and Machinery Eng. Directorate	1
	KI5, KI6		Disaster Risk Prevention Directorate	2
4	KI7	Addis Ababa Water and Sewage Authority (AAWSA) Gurd Shola Branch	Operations Manager	1
5	KI8	Yeka Sub-city Dry Waste Management Office	Deputy General Manager	1
			<b>Total</b>	<b>8</b>

### 3.6 Method of data analysis

#### Spatial Analysis

This study took an empirical approach by integrating Remote Sensing (RS) data within a GIS framework and applying the Analytical Hierarchy Process (AHP) for weight assignment to develop a flood hazard map tailored to the specific characteristics of the study area. The combination of RS data, GIS, and AHP proves to be a powerful methodology for assessing flood risk.

#### Topographic Wetness Index (TWI)

The TWI represents spatial moisture within an area, it's a key factor in mapping flood-susceptibility models. The potential of water permeability in each region is calculated by the topographic wetness index (Nguyen et al., 2022). The TWI is typically constructed based on



investigations, high-resolution images of the city were viewed on Google Earth Pro. Built-up areas, vegetation, wetlands and/or water bodies, green spaces, open land, and cropland are examples of common land use classes in urban environments (Gashu and Gebre-Egziabher, 2018). since there were no water bodies visible on the satellite images, the LULC class was omitted from this research. The selected LULC classes are shown in the (Table 4)

*Table 3-3 LULC classification*

<b>LULC Class</b>	<b>Definition</b>
<b>Urban/Built-up</b>	Areas of intensive use covered by structures residential (high- to low-density), commercial, industrial, institutional, transportation, utilities, and mixed uses.
<b>Forest</b>	Dense tree covers, providing canopy and vegetation cover; includes deciduous, evergreen, and mixed.
<b>cropland</b>	Land used primarily for cultivating seasonal crops like grains or vegetables e.g., Agricultural Land, pasture, orchards.
<b>Rangeland</b>	Land where potential natural vegetation is predominantly grasses, grass-like plants, forbs, or shrubs, shaped by natural herbivory; may include brushlands and seeded areas.
<b>Barren Land</b>	Land with limited ability to support life thin soils, sand, or rock exposures (e.g., beaches, salt flats, quarries, rock outcrops).

*(Source: Anderson et al., 1976)*

### **The AHP weight allocation process**

The Analytic Hierarchy Process (AHP) is a decision-making system that involves multiple criteria by assigning weights to each criterion. This method evaluates various parameters and ranks them according to a set of criteria (Saaty, 2008), The AHP allowed the evaluation of quantitative, qualitative, and complex criteria and factors on a similar scale (Hoang and Kato, 2023). In the original stage, as proposed by Saaty in 1980, criteria, sub-criteria, and decision alternatives were developed in alignment with the study’s objectives.

Within this, the pairwise comparison method is a powerful tool that helps decision-makers subjectively determine the significance weights of each criterion in a study, thus creating a common system for decision-making processes grounded on multiple attributes (Yadollahi and Rosli, 2011). For this study, eight parameters that influence flooding precipitation, drainage density, land use/land cover (LULC), elevation, slope, TWI, NDVI, and distance to road were considered as measures. The Saaty scale, which ranges from 1 to 9, was useful to gauge each factor and its subclasses in relation to the other factors and subcategories as shown in (Table 5).

The pairwise comparison matrix

$$M = \begin{pmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & 1 & a_{23} & \dots & a_{2n} \\ a_{31} & a_{32} & 1 & \dots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots & 1 \end{pmatrix} \dots \dots \dots \text{Equation 4}$$

Equation to determine the weighting of each attribute

$$a_{ij} = \frac{\text{weight of attribute } i}{\text{weight of attribute } j} \dots \dots \dots \text{Equation 5}$$

Table 3-4 AHP scale of pairwise comparison matrix

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance	Experience and judgment slightly favor one activity over another
5	Strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2, 4, 6, 8	Intermediate values	Used for compromise between the above values

(Source: Saaty, 2008)

Table 3-5 Classes and ratings of the flood-conditioning factors

Parameter	slope	LULC	Distance to road	drainage density	TWI	rainfall	NDVI	elevation
slope	1	1	2	3	3	4	4	4
LULC	1	1	1	3	2	4	4	4
Distance to road	1/2	1	1	2	2	4	3	4
drainage density	1/3	1/3	1/2	1	1	1	2	2
TWI	1/3	1/2	1/2	1	1	1	1	1
rainfall	1/4	1/4	1/4	1	1	1	1	1
NDVI	1/4	1/4	1/3	1	1	1	1	1
elevation	1/4	1/4	1/3	1	1	1	1	1

(Source: computed by the author)

*Table 3-6 Normalized pairwise comparison matrix.*

<b>Parameter</b>	<i>slope</i>	<i>LULC</i>	<i>Distance to road</i>	<i>drainage density</i>	<i>TWI</i>	<i>rainfall</i>	<i>NDVI</i>	<i>Elevation</i>	<i>Average</i>
<i>slope</i>	0.225	0.218	0.338	0.250	0.250	0.235	0.235	0.240	0.25
<i>LULC</i>	0.225	0.218	0.169	0.250	0.167	0.235	0.235	0.240	0.22
<i>Distance to road</i>	0.128	0.218	0.169	0.167	0.167	0.235	0.176	0.180	0.18
<i>drainage density</i>	0.085	0.073	0.085	0.083	0.083	0.059	0.118	0.120	0.09
<i>TWI</i>	0.085	0.109	0.085	0.083	0.083	0.059	0.059	0.060	0.08
<i>rainfall</i>	0.064	0.055	0.042	0.083	0.083	0.059	0.059	0.060	0.06
<i>NDVI</i>	0.064	0.055	0.056	0.042	0.083	0.059	0.059	0.060	0.06
<i>Elevation</i>	0.064	0.055	0.056	0.042	0.083	0.059	0.059	0.060	0.06
<i>sum</i>	1	1	1	1	1	1	1	1	1

*(Source: computed by the author)*

### **Temporal analysis**

Time series Land Use/Land Cover (LULC) maps for flood-prone areas will be generated for the years 2005, 2015, and 2025 using supervised maximum likelihood classification. For LULC classification, satellite image bands will be stacked to create a composite. To analyze the changes in LULC, the percentage of change between the three maps will be calculated, where  $C_{A}^{n-1}$  and  $C_{A}^n$  represent the initial and final LULC area coverage (in km<sup>2</sup>), helping to track the growth of urbanization over time.

*To calculate the rate of change*

$$\Delta = \frac{C_A^n - C_A^{n-1}}{C_A^{n-1}} \times 100 \dots\dots\dots \text{Equation 6}$$

Urbanization alters surface permeability, imperviousness can be assessed in hydrological studies using retention capacity, curve number, and runoff coefficient. In this study, built-up areas, such as buildings, parking lots, and roadways, were considered impervious surfaces. The curve number signifies the stormwater runoff capacity of a drainage basin. According to Cronsley et al. (1985), curve number is an empirical measurement that is used to predict infiltration from excess rainfall or direct runoff.

The curve number is used to determine the potential maximum retention which is a measurement of the watershed’s ability to extract and absorb storm precipitation and is calculated using Equation 8. For LULC of Each year runoff coefficient was given, which quantifies the percentage of rainwater flowing out of a certain surface during a storm event. The weighted runoff coefficient was generated using Equation 9 and Equation 10 was used to estimate the equivalent impervious area that helped to calculate runoff using the rational technique for each class.

$$CN_{composite} = \frac{\sum A_i \cdot CN_i}{\sum A_i} \dots\dots\dots \text{Equation 7}$$

$$S = \frac{25400}{CN} - 254 \dots\dots\dots \text{Equation 8}$$

$$C_w = \frac{\sum A_i \cdot C_i}{\sum A_i} \dots\dots\dots \text{Equation 9}$$

$$EIA = C_i \cdot A_i \dots\dots\dots \text{Equation 10}$$

In this context, CN composite is the composite curve number used for runoff volume computations; Ci is runoff coefficient value for each subdivision; i is an index for the catchment subdivisions of uniform land use and soil type; CNi is the curve number for subdivision i; Cw is the weighted runoff coefficient; EIA is the equivalent impervious area (km<sup>2</sup>), and Ai is the drainage area of subdivision i (km<sup>2</sup>).

**HEC-RAS**

The Hydrologic Engineering Center's River Analysis System (HEC-RAS), developed by the U.S. Army Corps of Engineers was utilized to simulate urban runoff and flow dynamics. This robust tool supports two-dimensional (2D) hydrodynamic modeling with integration with Geographic Information Systems (GIS).

The Simulation was done using 2D unsteady flows with the rain-on-grid model which helped to map out precipitation effects on terrain. An in-depth terrain analysis was also done with HEC-RAS to identify terrain discrepancies. This mockup was done to identify the water flow direction and runoff accumulation without accounting for soil infiltration and other “losses”.

## Qualitative Analysis

A qualitative analysis was conducted to gather data from key informant interviews. Text format is used to interpret the interview data, with emphasis on key themes and insights shared by the informants.

### 3.7 Method of data presentation

The analyzed data is presented by applying both tabular formats and visual aids. Spatial patterns such as flood-prone areas, and temporal changes in land use and land cover are shown using Geographic Information System (GIS) maps. Moreover, combinations of text, Tabular formats, and graphical representations, such as bar graphs and pie charts, are employed to effectively illustrate quantitative data. Additionally, high-quality images were also included to visually showcase the conditions of stormwater drainage systems in flood-prone areas. Lastly, an overlay of flood simulation results to Google Earth image is presented.

### 3.8 Validation and Reliability

#### Accuracy assessment of AHP weighted criteria

A consistency check was required to validate the accuracy of weight values after assigning weight values to the parameters used in this study. Saaty's method is one of the most common ways in which to do this. The consistency ratio (CR) was calculated using the ratio of the consistency index (CI) and the random inconsistency index value (RI). The AHP validation mathematical technique was used to assess the consistency of the paired comparisons, resulting in the calculation of a consistency ratio (CR) and consistency index (CI) using Equations (11) and (12):

$$CI = \frac{\lambda_{max} - n}{n - 1} \dots\dots\dots Equation 11$$

$$CR = \frac{CI}{RI} \dots\dots\dots Equation 12$$

The average coherence index of the randomly generated comparison, denoted as RI (Table 8), was used alongside  $\lambda_{max}$  which is the highest eigenvalue of the pairwise comparison matrix, and  $n$  represents the number of factors being compared in the matrix. For the consistency ratio (CR) to

be considered accurate, it must be 0.10 or lower. If the CR exceeds this threshold, the pairwise comparison matrix requires recalibration.

*Table 3-7 Random index (RI) table*

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

(Source: Saaty ,2008)

### Accuracy of LULC classification

The overall accuracy and kappa coefficient were done using a confusion matrix, 200 random points were used in conjunction with Google Earth Pro to assess the accuracy of each LULC map. Consistently showing strong agreement with the aerial imagery, with values exceeding 0.79 for all three periods (Tables 9, 10 ,11). When the kappa values range between 0.80 and 0.90 it signifies strong classification accuracy (McHugh,2012).

*Table 3-8 Classification accuracy of 2005*

No	Class Value	Forest	Cropland	Built up	Rangeland	Barren land	Total	User Accuracy	Kappa
1	Forest	17	0	1	1	0	19	0.89	0
2	Cropland	0	79	6	5	0	90	0.88	0
3	Built up	0	1	31	4	0	36	0.86	0
4	Rangeland	1	0	8	46	0	55	0.84	0
5	Barren land	0	0	2	3	5	10	0.5	0
6	Total	18	80	48	59	5	210	0	0
7	Producer Accuracy	0.94	0.99	0.65	0.78	1	0	0.85	0
8	Kappa	0	0	0	0	0	0	0	<b>0.79</b>

*Table 3-9 Classification accuracy of 2015*

No	Class Value	Forest	Built up	Cropland	Rangeland	Barren land	Total	User Accuracy	Kappa
1	Forest	13	1	0	1	0	15	0.87	0
2	Built up	0	102	1	2	4	109	0.94	0
3	Cropland	2	1	26	6	0	35	0.74	0
4	Rangeland	1	2	3	30	0	36	0.83	0
5	Barren land	0	0	0	1	4	5	0.8	0
6	Total	16	106	30	40	8	200	0	0
7	Producer Accuracy	0.81	0.96	0.87	0.75	0.5	0	0.88	0
8	Kappa	0	0	0	0	0	0	0	<b>0.81</b>

*Table 3-10 Classification accuracy of 2025*

N0	Class Value	Forest	Cropland	Built up	Rangeland	Barren land	Total	User Accuracy	Kappa
1	Forest	5	0	0	0	0	5	1	0
2	Cropland	0	40	3	9	0	52	0.77	0
3	Built up	1	0	105	2	3	111	0.95	0
4	Rangeland	0	0	0	32	0	32	1	0
5	Barren land	0	0	0	0	0	0	0	0
6	Total	6	40	108	43	3	200	0	0
7	Producer Accuracy	0.83	1	0.97	0.74	0	0	0.91	0
8	Kappa	0	0	0	0	0	0	0	<b>0.85</b>

### 3.9 Ethical consideration

The primary data collection involved interviews, key informants were informed, and consent was obtained while clearly explaining the purpose of the study and their right to withdraw. Interview summaries avoided pessimistic language instead focusing on evidence-based mitigation strategies. The Spatial data used in this study were sourced from publicly available datasets. To avoid misinterpretation of results methodologies and limitations were transparently documented.

### 3.10 Methodological framework of the study

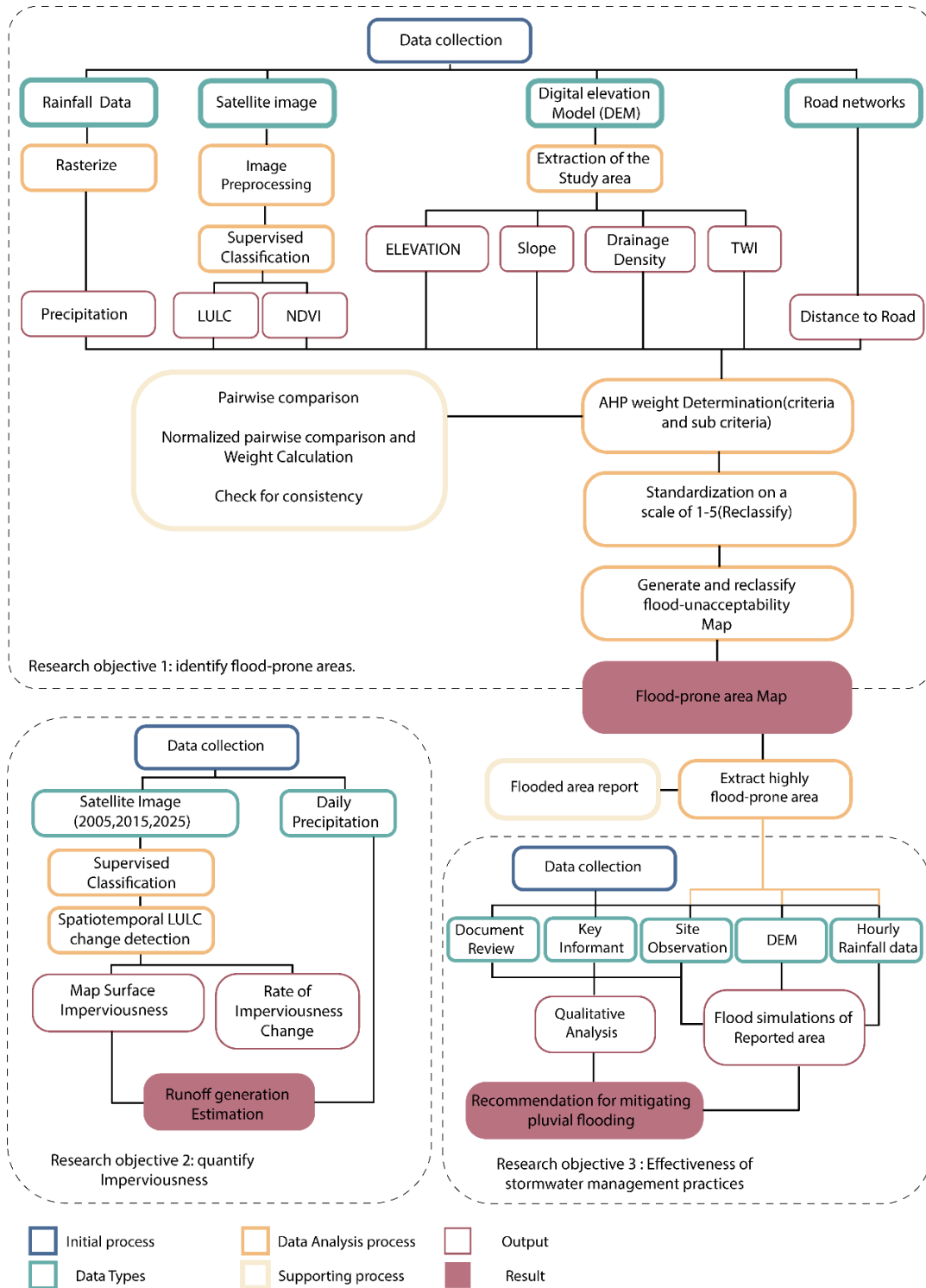


Figure 3.2: methodological frame work of the study

Source: Own computation (2025)

# CHAPTER FOUR: RESULTS AND DISCUSSION

## 4.1 Results

### 4.1.1. Identifying flood-prone areas

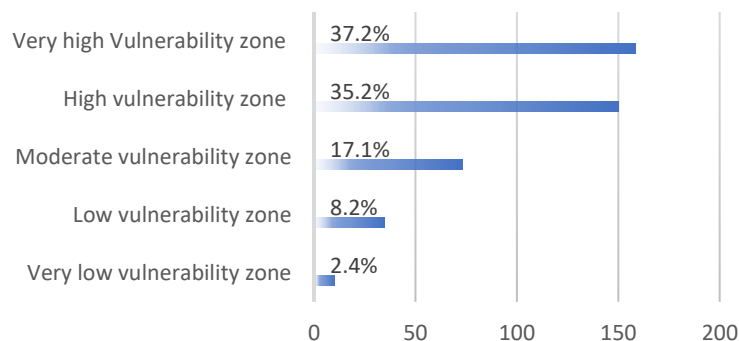
Identifying flood-prone areas has criteria that vary across regions, this research applies a composite pluvial flood vulnerability index integrating eight key factors: slope gradient, elevation, proximity to roads, rainfall intensity, Land use /Land cover (LULC), topography wetness index (TWI) and Normalized Difference Vegetation Index (NDVI). These flood influencing factors are assessed systematically and combined to evaluate their implication on flooding with the AHP model by weighting and prioritizing each factor based on their contribution to pluvial flooding.

#### 4.1.1.1. Multi-influencing factors of flood-susceptible zone

##### *Slope*

The slope plays a key role in determining surface or subsurface drainage in a specific area or outlet. Higher slopes tend to experience surface runoff issues, while flatter surfaces are prone to water accumulation. In contrast, local depressions, which are cells in a digital elevation model with lower elevation than their surroundings, are more susceptible to pluvial floods.

The slope map (Fig. 4.2 A) was derived through analysis of DEM data; it reveals substantial deference between types of topography. The slopes are classified in to five categories:0-3.4° (very gentle), 3.4-6.9°(gentle) ,6.9-11.3°(moderate),11.3-17.9°(steep), and 17.9-42° (very steep). the spatial distribution of the very gentle slopes mainly lies in the central, southern, and eastern parts of Addis Ababa.



*Figure 4.1: Slope percentage and area coverage*

On the other hand, the steeper slopes are situated near the northern part of the city near Entoto and alongside rivers that run through all over Addis Ababa. The city's vulnerability zone is categorized into five levels, covering a total area of 430.1 km<sup>2</sup>. The smallest area is the very low vulnerability zone which accounts for 10.3 km<sup>2</sup> (2.4%). While the low vulnerability zone covers 35.9 km<sup>2</sup> (8.2%). The moderate vulnerability zone spans around 73.9 km<sup>2</sup> (17.1%), followed by the high vulnerability zone at 150.2 km<sup>2</sup> (35.2%) and finally, the very high vulnerability zone has the largest portion at 159.7 km<sup>2</sup> (37.2% of the total area). This distribution shows that 70% of the region falls within high to very high vulnerability classes.

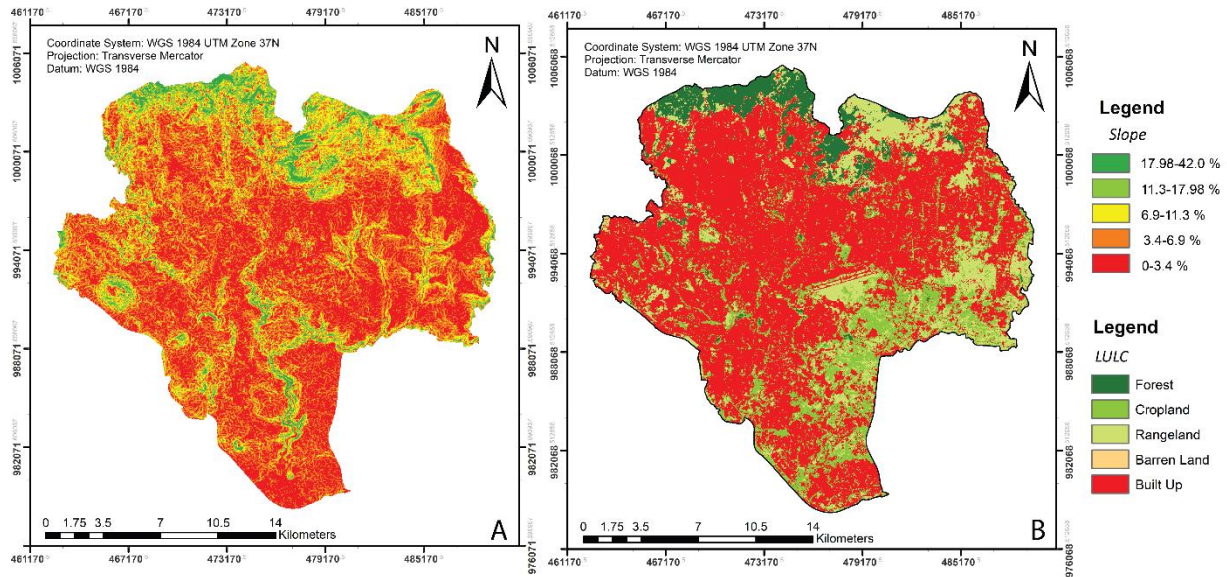


Figure 4.2: A) Slope map B) Land use Land cover map

### *LULC (land use and land cover)*

The land use and land cover (LULC) map delineated five main categories: agricultural land, forest, rangeland, barren land, and built-up areas. The map highlighted the spatial arrangement of these land types, underlining their environmental significance to pluvial flooding, the city center and the eastern part are predominantly covered with the built-up area which is highly susceptible to pluvial flooding, and the southeastern and northern parts of the city is covered by cropland, rangeland and forests which is less susceptible to flooding.

The city's land use distribution reveals the smallest portion is barren land spanning only 0.2 km<sup>2</sup> which is 0.05% of the total area, forests also account for a smaller share with 23.17 km<sup>2</sup> (5.47%). Cropland and rangeland occupy larger areas compared to barren land and forests, they account for

69.93 km<sup>2</sup> (16.37%) and 67.22 km<sup>2</sup> (15.50%) respectively. The dominance of built-up areas is clearly seen in (Fig. 4.2 B) with a cover of 268.36 km<sup>2</sup> (62.62% of the total 430.1 km<sup>2</sup>).

*Table 4-1 LULC area coverage*

<b>LULC Classification</b>	<b>Area</b>	<b>percentage</b>
<i>Forest</i>	23.17 km <sup>2</sup>	5.47%
<i>Cropland</i>	69.93 km <sup>2</sup>	16.37%
<i>Rangeland</i>	67.22 km <sup>2</sup>	15.50%
<i>Barren land</i>	0.2 km <sup>2</sup>	0.05%
<i>Built up</i>	268.36 km <sup>2</sup>	62.62%
<i>Total area</i>	430.01 km <sup>2</sup>	100.00%

### ***Normalized Difference Vegetation Index (NDVI)***

The presence of vegetation significantly reduces flood risk by reducing water movement and extending the duration of runoff. On the other hand, no vegetated zones increase the speed and power of water runoff leading to flood vulnerability. The normalized difference index (NDVI) helps to measure vegetation vitality and density, NDVI scores span from -1 to +1, with values closer to +1 showing thicker, healthier vegetation.

*Table 4-2 NDVI area coverage*

<b>NDVI value</b>	<b>Area (km<sup>2</sup>)</b>	<b>Percentage (%)</b>
<i>-0.19-0.07</i>	31.50	7.32%
<i>0.07-0.11</i>	68.80	16.00%
<i>0.11-0.17</i>	93.61	21.76%
<i>0.17-0.24</i>	121.22	28.18%
<i>0.24-0.54</i>	114.96	26.78%
<b>Total</b>	<b>430.1</b>	<b>100.00%</b>

The NDVI map of Addis Ababa (Fig. 4.3 A) shows five categories of vegetation density measured by NDVI (Normalized Difference Vegetation Index). The total area of the study area is 430.1 km<sup>2</sup> with varying vegetation density in these NDVI categories. The lowest range (-0.19 to 0.07) which is non-vegetated covers 31.50 km<sup>2</sup> or 7.32% of the total area. Slightly higher vegetation density (0.07–0.11) covers 68.80 km<sup>2</sup> (16.00%), moderate vegetation (0.11–0.17) covers 93.61 km<sup>2</sup> (21.76%), relatively healthy vegetation (0.17–0.24) covers 28.18% (121.22 km<sup>2</sup>) and dense vegetation (0.24–0.54) covers 114.96 km<sup>2</sup> (26.78%).

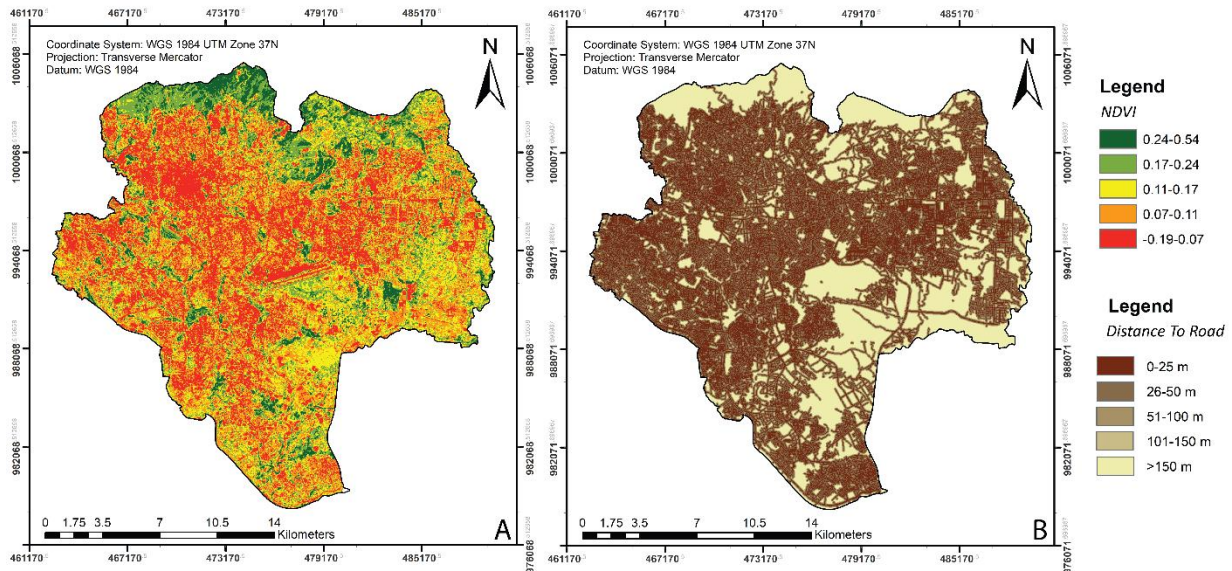


Figure 4.3: A) Normalized difference vegetation index (NDVI) map B) Distance to Road

map

### Distance to Road

Distance to road is an important aspect of pluvial flooding because road construction increases impermeable surfaces and alters natural topography affecting hydrological processes thus areas closer to roadways experience higher runoff during heavy rainfall. In addition, roads can channel water along their path obstructing its natural movement. Moreover, flood vulnerability can increase due to inadequate drainage systems that disrupt surface water flow and accumulate stormwater runoff.

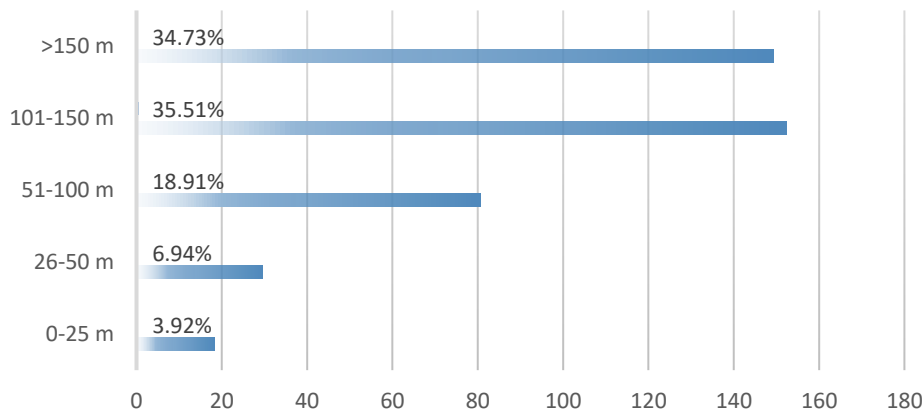


Figure 4.4: Distance to road - Area coverage

The farthest areas from the road cover 149.32 km<sup>2</sup>, and the second area that is relatively farther to the road falls within the 101-150 m range, covering 152.39 km<sup>2</sup> (35.51%), which is the largest of all the different values. Mid-range distances of 51-100 m from the road constitute 80.57 km<sup>2</sup> (18.91%); the second closest range is 26-50 m, which accounts for 29.56 km<sup>2</sup> (6.94%). The road-adjacent zones that lie between 0 and 25 cover 18.26 km<sup>2</sup>, representing 3.92% of the total area, which is the smallest of all the categories. The map clearly shows a concentration of areas with distances above 100m from the road, signifying their lesser susceptibility to flooding.

### Elevation

Elevation is an important factor for flood vulnerability, lower-lying areas are typically having a greater chance of risk due to their tendency to accumulate water. In contrast, places with higher elevations are generally less susceptible since they are less likely to experience water inundation. Although Addis Ababa's terrains gradually decrease from the mountainous areas at the north to the southern part of the city pluvial flooding can occur in the central part of the city due to flatter areas that are depressed from the surrounding terrain.

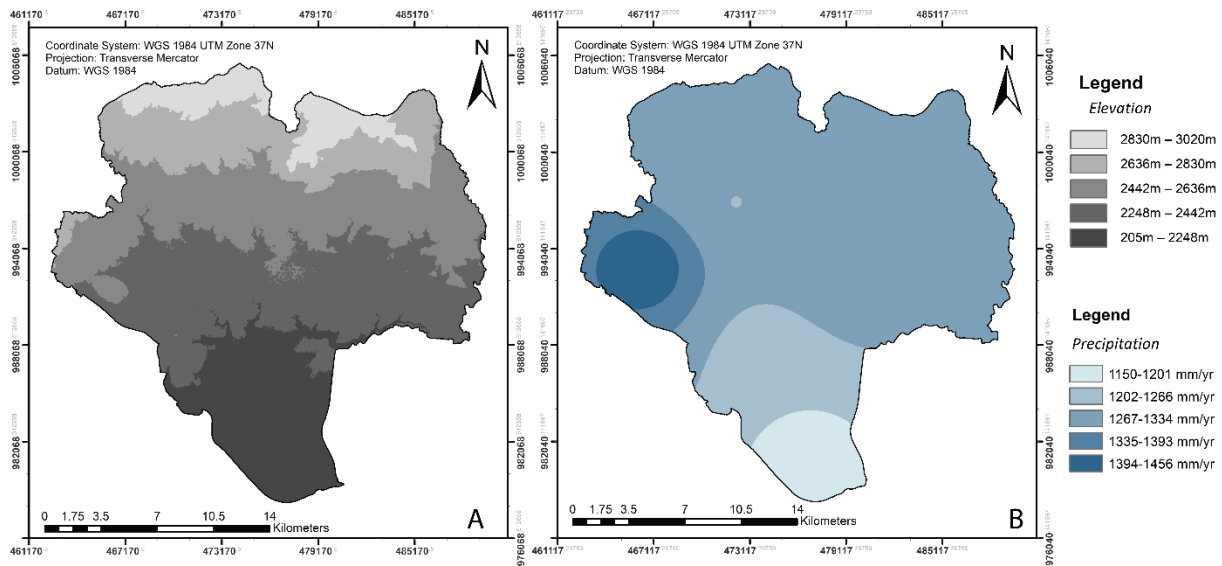


Figure 4.5: A) Elevation map B) Precipitation map

The elevation of Addis Ababa is classified into five major categories, the highest elevation near Mount Entoto has a range that spans from 2830 to 3020 meters covering an area of 32.06 km<sup>2</sup>. The second category with a slightly lower elevation encompasses the 2,636–2,830-meter range, which occupies a larger area of 69.24 km<sup>2</sup>, followed by the 2,442–2,636-meter zone with 119.59 km<sup>2</sup>. The

mid-elevation bracket 2,248–2,442 meters, covering 133.54 km<sup>2</sup> has the largest area which includes most of the central areas of the city (Fig. 4.5 A). Lastly, the lowest elevation category, 2,050–2,248 meters, comprises 75.83 km<sup>2</sup> and is located in the southern part of the city near Kaliti.

### ***Precipitation***

This study utilizes annual rainfall data to analyze long-term patterns and their influence on flood vulnerability in the city. Even though studying short-term extreme rainfall events is vital to assessing pluvial flooding risks, annual data shows an in-depth insight into how collective precipitation trends impact flooding. Moreover, the rainy season alone contributes to 60-65% of the city's total yearly rainfall. Areas with higher annual precipitation exhibit more flood susceptibility due to increased runoff, whereas regions with lower rainfall face less vulnerability.

There are five categories span across a total area of 430.10 km<sup>2</sup> based on annual rainfall ranges. The higher the rainfall brackets the more it is susceptible to flooding, higher ranges of 1394-1456 mm/yr and 1335-1393 mm/yr account for smaller portions: 22.70 km<sup>2</sup> (5.28%) and 19.24 km<sup>2</sup> (4.47%), respectively. Areas with rainfall of 1150-1201 mm/yr cover 28.17 km<sup>2</sup> (6.55%) and the second-largest segment, 58.27 km<sup>2</sup> (13.55%), falls within the 1202-1266 mm/yr range. The majority of the area, 301.72 km<sup>2</sup> (70.15%), experiences rainfall between 1267-1334 mm/yr, making it the dominant category as seen in (Fig. 4.5 B). Together, these classifications comprehensively represent the distribution of rainfall across the city.

### ***Drainage Density***

Drainage density is another important factor for pluvial flooding its derived from the total length of streams within a watershed divided by the watershed area. Areas with higher drainage density are more prone to flooding because of larger surface water flows while a lower density indicates less susceptibility.

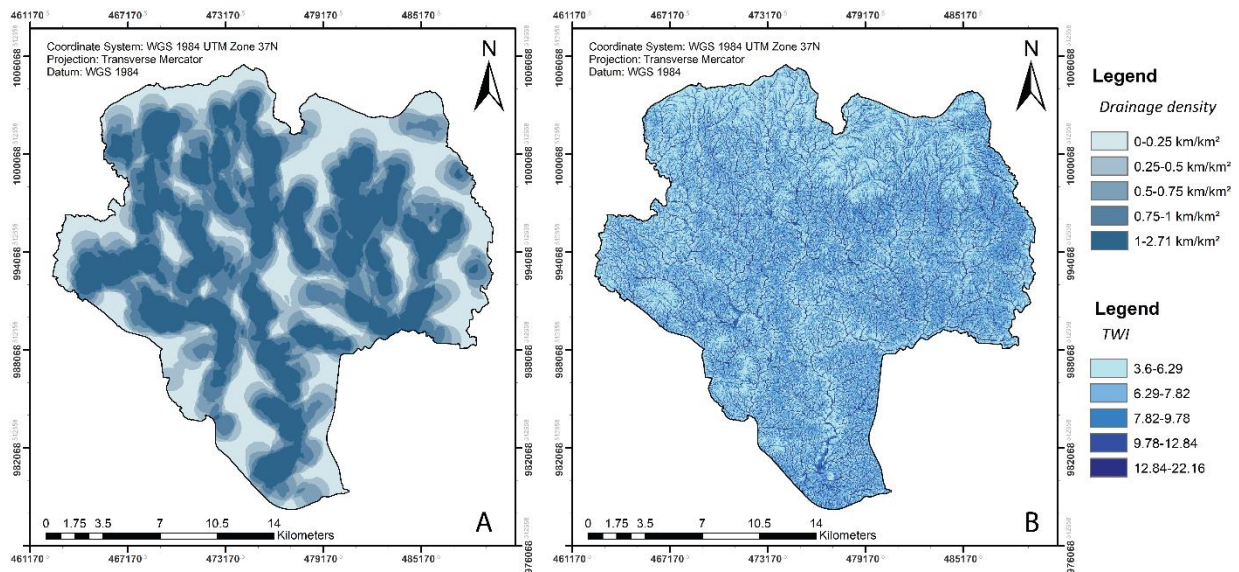
The drainage density distribution shows significant variation across the area, the lowest density range (0–0.25 km/km<sup>2</sup>) covers the largest area at 137.42 km<sup>2</sup> following that is the 0.25–0.5 km/km<sup>2</sup> range, which spans 171.02 km<sup>2</sup>. The lower-density categories take up the majority of Addis Ababa. Progressively smaller areas are associated with higher density ranges: 0.5–0.75 km/km<sup>2</sup> and 0.75–1 km/km<sup>2</sup> covering an area of 71.02 km<sup>2</sup> & 36.86 km<sup>2</sup> respectively, the highest density category (1–2.71 km/km<sup>2</sup>) only covers 10.83km<sup>2</sup>. This map (Fig. 4.6 A) highlights the inverse relationship

between drainage density and spatial coverage, with high drainage density occupying a smaller area of the total landscape.

***TWI (topographic wetness index)***

The topographic wetness index is a necessary tool for determining susceptibility by analyzing the distribution within a catchment. It is developed from the slope of the study area and flow accumulation data; it delineates areas with low elevation and higher water retention thus making it more flood-prone. Higher TWI values are flat areas that are naturally wetter, and lower values are relatively drier.

The topographic wetness index is divided into five different categories (Fig. 4.6 B), with varying levels of hydrological influence. The lowest range (3.6–6.29) covers 137.42 km<sup>2</sup> which is the second largest in area signifying more areas that are relatively drier. The next category (6.29–7.82) shows moderately wet conditions and takes up the largest area at 171.02 km<sup>2</sup>. Areas with higher wetness potential (7.82–9.78) occupy 71.02 km<sup>2</sup>, followed by significantly wetter zones (9.78–12.84) encompassing 36.86 km<sup>2</sup>. The most water accumulation-prone landscape with a value of (12.84–22.16) only covers an area of 10.83 km<sup>2</sup> which is the smallest of all the categories. The distribution shows a gradual decrease in coverage as the value increases and moderate wetness dominates the study area.



**Figure 4.6:** A) Drainage Density map B) TWI (topographic wetness index) map

#### **4.1.1.2. Interrelationship and pairwise comparisons**

From the eight flood-influencing factors, slope, and land use /landcover (LULC) emerge as the most critical factors, rated more influential than rainfall, NDVI, or elevation. Distance to road holds more weight than drainage density and TWI but has a lower influence than slope and LULC. Drainage density and TWI are more significant than rainfall, NDVI, and elevation usually elevation and rainfall hold more influence in pluvial flooding but in the case of Addis Ababa city the precipitation per year has lower variation between different zones signifying equal importance between the lower value and the highest value, it is also applicable for elevation since the elevation of the city gradually decrease from mountainous region on the north side to southern part of Addis Ababa overlooking the smaller pockets of recessed landforms .

After assigning different values for flood influencing factors the pairwise comparison matrix is done using the Analytic Hierarchy Process (AHP), the validation of the process shows a Consistency Index (CI) of 0.023958 and a Random Consistency Index (RCI) of 1.14 was used for the eight factors and the calculated Consistency Ratio (CR) is 0.021016, which is well below the acceptable threshold of 0.1 confirming that the pairwise comparison is logically consistent and free from contradictions. For further validation, the lambda ( $\lambda$ ) value 8.16 represents the mathematical coherence of weight assignments.

#### ***Weights of factors***

The AHP process provided different weights for the eight parameters, given that the class of susceptibility ranges (1–5: Very low to Very high) is assigned to the influencing factors, and the lowermost weights are given to Elevation (2050–3020 m), Rainfall (1150–1456 mm/yr), NDVI (-0.19–0.54) accounting for 6% each. The Topographic Wetness Index (TWI: 3.6–22.16) contributes 8% while the Drainage density (0–2.71 km/km<sup>2</sup>) is given a slightly higher weight of 9%. Distance to road (0–>150 m) is weighted 16%, prioritizing proximity as being more flood-prone, giving more emphasis to human activity Land Use/Land Cover (LULC: Forest to Built-up) holds 22% which is the second most influential and the first one being Slope (0–42°) with the weight of (26%), with gentler slopes rated riskier.

**Table 4-3** Flood susceptibility criteria, sub-criteria ranges, and influence weight

<i>Parameters</i>	<i>class</i>	<i>Susceptibility class ranges</i>	<i>Susceptibility ratings</i>	<i>Percentage weight</i>
<b>Rainfall (mm/yr)</b>	1150-1201	Very low	1	7%
	1202-1266	low	2	
	1267-1334	moderate	3	
	1335-1393	high	4	
	1394-1456	Very high	5	
<b>Slope</b>	0-3.4	Very high	5	26%
	3.4-6.9	high	4	
	6.9-11.3	moderate	3	
	11.3-17.98	Low	2	
	17.98-42.0	Very low	1	
<b>Drainage density</b>	0-0.25 km/km <sup>2</sup>	Very low	1	8%
	0.25-0.5 km/km <sup>2</sup>	low	2	
	0.5-0.75 km/km <sup>2</sup>	moderate	3	
	0.75-1 km/km <sup>2</sup>	high	4	
	1-2.71 km/km <sup>2</sup>	Very high	5	
<b>Topographic wetness index (TWI)</b>	3.6-6.29	Very low	1	7%
	6.29-7.82	low	2	
	7.82-9.78	moderate	3	
	9.78-12.84	high	4	
	12.84-22.16	Very high	5	
<b>LULC</b>	Forest	Very low	1	22%
	Rangeland	low	2	
	Cropland	moderate	3	
	Barren land	high	4	
	Built up	Very high	5	
<b>Distance to road</b>	0-25	Very high	5	16%
	26-50	high	4	
	51-100	moderate	3	
	101-150	low	2	
	>150	Very low	1	

<b>Elevation</b>	2830 – 3020	Very low	1	6%
	2636 – 2830	low	2	
	2442 – 2636	moderate	3	
	2248 – 2442	high	4	
	2050 – 2248	Very high	5	
<b>NDVI</b>	-0.19-0.07	Very high	5	8%
	0.07-0.11	high	4	
	0.11-0.17	moderate	3	
	0.17-0.24	low	2	
	0.24-0.54	Very low	1	

#### 4.1.1.3. Flood Prone zones

The pluvial flood susceptibility map shows areas at risk of surface water flooding caused by intense rainfall. By applying the AHP method and using the eight flood influencing factors, the map generated has five susceptibility classes, ranging from very low to very high based on their likelihood of flooding.

The very low susceptibility class accounts for 6.27 km<sup>2</sup> which is located north of Addis Ababa it is mostly covered with forest and has a higher slope making it less flood-prone, the low category represents a portion of 33.90 km<sup>2</sup> (7.95%) it has a hilly terrain covered by shrubs and trees. The moderate susceptibility class, spanning 119.46 km<sup>2</sup> (28.02%), represents the second largest area.

*Table 4-4 Flood susceptibility area and percentage*

<b>Susceptibility Class</b>	<b>Area (km<sup>2</sup>)</b>	<b>Percentage (%)</b>
<b>Very low</b>	6.27	1.47%
<b>Low</b>	33.90	7.95%
<b>Moderate</b>	119.46	28.02%
<b>High</b>	237.28	55.65%
<b>Very high</b>	29.63	6.95%

The High susceptibility class encompasses the main portion of the city, covering 237.28 km<sup>2</sup> (55.65%), stating that more than half of the area has a higher risk of flooding. Lastly, the Very High susceptibility category spanning 29.63 km<sup>2</sup> (6.95%) has a gentle and flat surface in a built-up area with an impervious surface contributing to the vulnerability, although it has a smaller

coverage it is mostly situated in the central part scattering to the eastern and western regions of the city affecting infrastructure and hindering day to day commute in the rainy season. Kirkos sub-city exhibits high flood susceptibility, largely attributed to its dense urban settlement, while Gullele demonstrates low susceptibility owing to its extensive forest cover and steep topography.

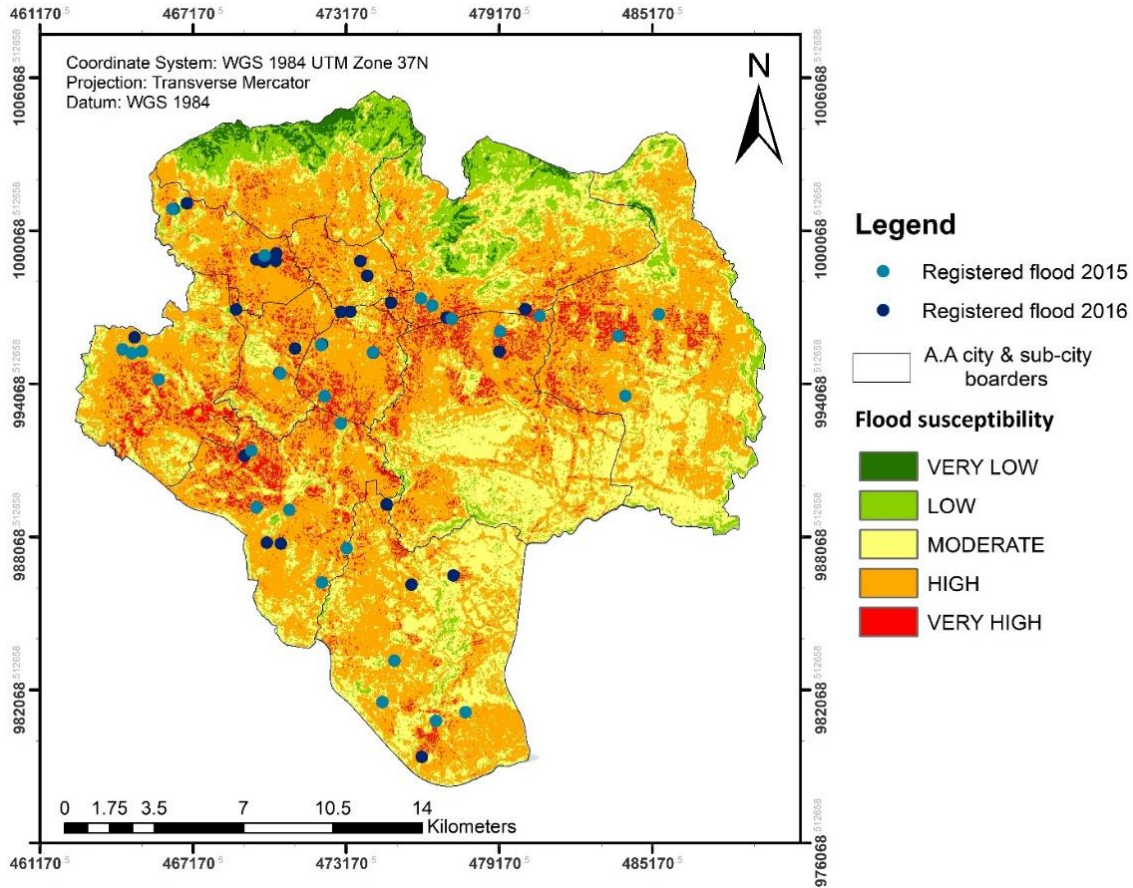


Figure 4.7: Pluvial Flood susceptibility and registered flood map

### Reported flood areas

From the 55 floods reported in the past two years, only 2 locations (3%) fall into the moderate flood susceptibility zone underscoring the possibility of flooding in this region is minimal compared to the other. In the high susceptibility zone, 31 food points (58%) were recorded, highlighting widespread exposure to flood hazards. Notably, some of the reported flood points are affected yearly signifying the need for conclusive resolution. On the other hand, some areas face repeated inundation within a single rainy season for example the region near Gurd Shola in front of the Ethio-telecom building and other regions like ‘wereda 9’ in Addis Ketema sub city are

affected by clustered points that amplify regional hazards. From the previously flooded areas, 22 sites (39%) have aligned with the Very High susceptibility zones, indicating extreme vulnerability to future flooding.

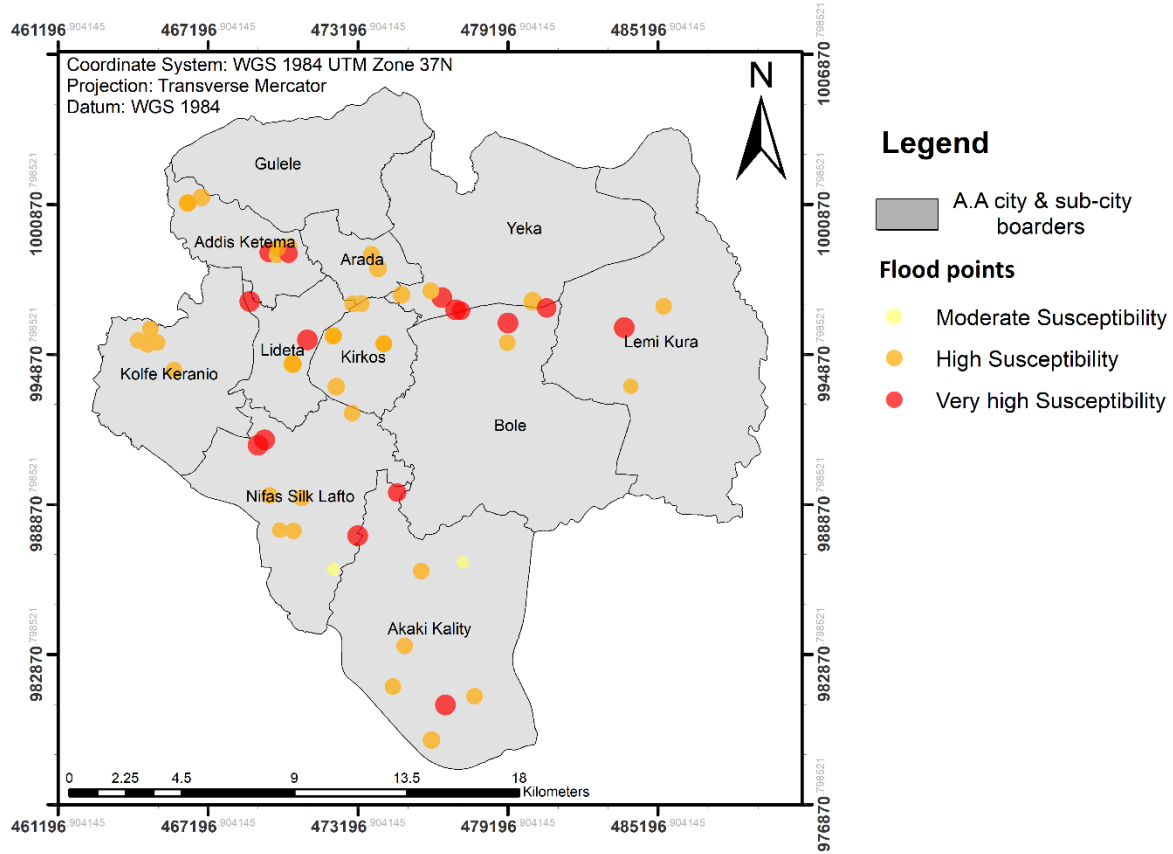
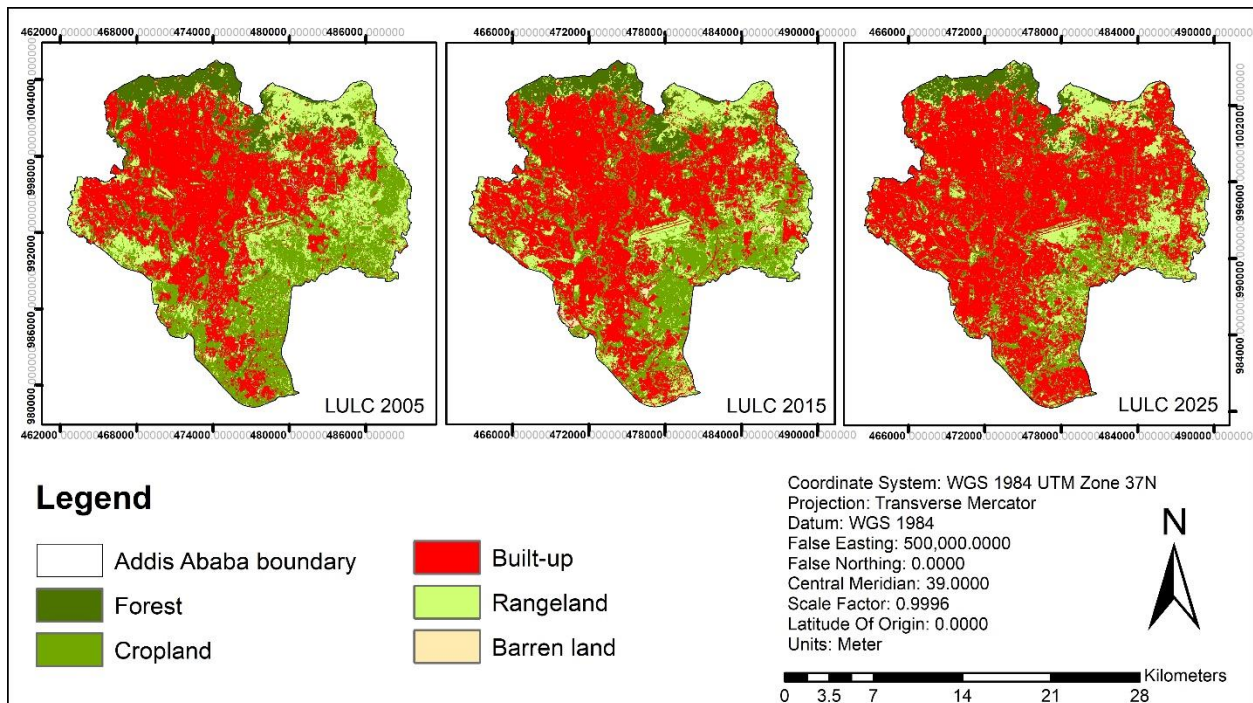


Figure 4.8: Registered Flood and Flood Susceptibility Relation map

## 4.1.2. Urbanization and Surface Impermeability

### 4.1.2.1. Spatiotemporal land use and land cover change

The Land use land cover change shows how human activities such as urbanization and infrastructure development alter landscapes such as agricultural land, forests, and rangeland. The time periods selected for this study are 2005, 2015 and 2025 which show significant amounts of changes to quantify and analyze.



*Figure 4.9: Land use Landcover map for the years 2005, 2015 & 2025*

The land cover of the year 2005 highlights diverse uses the smallest category at 6.83 km<sup>2</sup> (1.6%) is barren land indicating minimal unused terrain. Forest accounts for 32.71 km<sup>2</sup> (7.6%) underscoring limited woodland while the rangeland spans 80.05 km<sup>2</sup> (18.6%) showing more area for grazing. Following that is the cropland at 127.75 km<sup>2</sup> (29.7%), reflecting agricultural focus at that period, The most dominant land cover is built area at 182.96 km<sup>2</sup> (42.5%) highlighting urbanization.

In 2015 the land cover map revealed significant trends an increase of built-up area to 214.31 km<sup>2</sup> (49.8%), signifying accelerated urbanization. The cropland covers 112.51 km<sup>2</sup> (26.1%) revealing the importance of agriculture, while forests decreased to 26.94 km<sup>2</sup> (6.3%) signaling deforestation

activities. Rangeland accounted for 74.16 km<sup>2</sup> (17.2%) showing minimal change, lastly barren land shrank to 2.38 km<sup>2</sup> (0.6%) underscoring the occupation of unused terrain.

Lastly, the recent land cover shows that barren land has nearly vanished at 0.2 km<sup>2</sup>, marking the near-elimination of unused terrain. Another threatened land cover is the forest, which dwindled to 23.37 km<sup>2</sup> (5.4%). Rangeland spans 68.22 km<sup>2</sup> (15.9%) revealing small changes to native vegetation on the other hand Cropland declined steeply to 68.93 km<sup>2</sup> (16.0%) signifying reduced agricultural activity or land use change. An escalated change is seen in the built-up area which increased to 269.57 km<sup>2</sup> (62.6%), reflecting unprecedented urbanization.

*Table 4-5 Landcover area coverage*

<b>Land Cover</b>	<b>Area 2005 (km<sup>2</sup>)</b>	<b>Area 2015 (km<sup>2</sup>)</b>	<b>Area 2025 (km<sup>2</sup>)</b>
<b>Forest</b>	32.71	26.94	23.37
<b>Cropland</b>	127.75	112.51	68.93
<b>Built up</b>	182.96	214.31	269.57
<b>Rangeland</b>	80.05	74.16	68.22
<b>Barren Land</b>	6.83	2.38	0.2

#### **4.1.2.2. Land Use land cover change detection.**

To identify shifts in land use and land cover (LULC) across three time periods post-classification comparison was employed. This change detection focuses on categorical change analysis which involves evaluating differences between two thematic raster's quantifying pixels that have either transitioned between categories or remained stable.

#### ***Land Use Changes between 2005-2015***

Between 2005 and 2015, dynamic changes in land use and land cover are seen. Built-up areas dominating land use shifts, although 153.816 km<sup>2</sup> remained the same through the decade 37.461 km<sup>2</sup> of Cropland and 18.232 km<sup>2</sup> of Rangeland were converted to urban areas showing infrastructure development and population growth. Even barren land experienced urbanization with an alteration of (3.974 km<sup>2</sup>). Surprisingly built-up areas are also converted to Cropland (20.579 km<sup>2</sup>) and Rangeland (9.186 km<sup>2</sup>), suggesting temporary land repurposing for the use of urban farming.

Forest land cover remained stable with 21.621 km<sup>2</sup> unchanged, notable losses occurred through the years mostly to cropland and rangeland with alteration of 4.585 km<sup>2</sup> and 3.673 km<sup>2</sup> respectively, suggesting localized deforestation for agriculture and grazing encroachment. Forest covers also gained 3.44 km<sup>2</sup> from rangeland and 0.166 km<sup>2</sup> from Barren Land which is negligible compared to the city scale raising concerns about reforestation efforts.

Cropland and Rangeland experienced bidirectional land use shifts, signaling demands from other land cover types. Cropland losses were significant from 37.461 km<sup>2</sup> becoming urbanized to 20.957 km<sup>2</sup> changing to rangeland. On the other hand, Rangeland faced pressure from agriculture as well with 18.714 km<sup>2</sup> being converted to cropland. The two land losses change due to shifts in farming practices and food production requirements. Small amounts of area have changed from cropland to barren land possibly because of soil degradation. Lastly, Barren Land transitions were modest out of the landcover types, The most noteworthy change is from 3.974 km<sup>2</sup> being urbanized. These trends collectively stress the tension between urbanization and agricultural needs, with Rangeland and Cropland acting as essential parts of the transition.

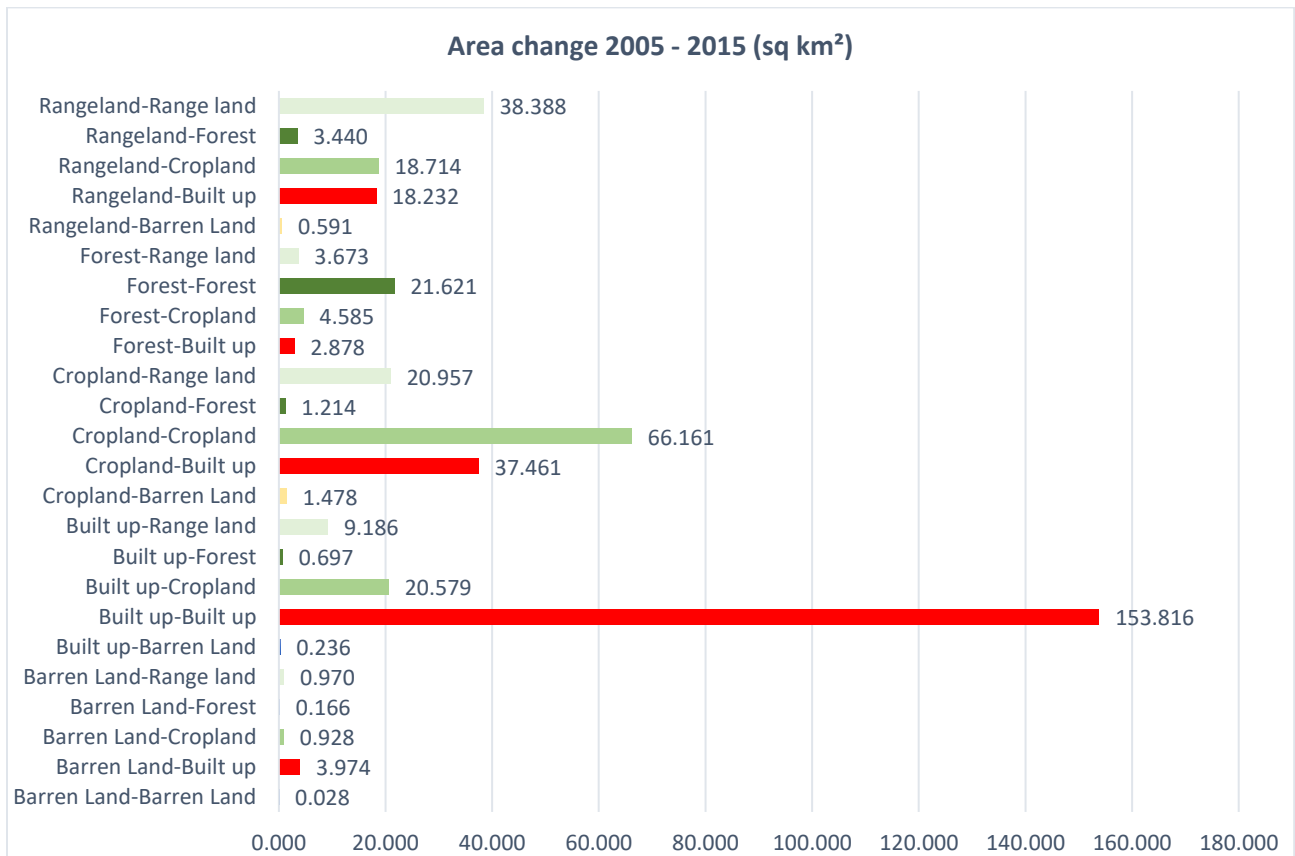


Figure 4.10: Landcover shifts between 2005-2015

### *Land Use Changes Between 2015-2025*

In the past ten years forest covers remained relatively intact with 19.12 km<sup>2</sup> unchanged but faced some pressure from urbanization with 2.59 km<sup>2</sup> of its coverage altered. Rangeland acquired 4.60 km<sup>2</sup> of forest cover due to grazing. Only a small area transitioned to cropland 0.82 km<sup>2</sup> suggesting small-scale deforestation for farming. Barren land cover is nearly eradicated, with only 0.07 km<sup>2</sup> remaining unchanged and urbanization claiming 1.10 km<sup>2</sup> signaling the encroachment of human activity into peripheral landscapes, driven by lack of viable land.

Built-up areas dominated the land use shift like the previous decade (2005-2015), with 196.64 km<sup>2</sup> remaining untouched. However, urbanization also encroached heavily on other land covers, 46.44 km<sup>2</sup> of Cropland was converted to Built-up areas and 26.19 km<sup>2</sup> of Rangeland shifted its land use signifying aggressive urban sprawl. Even the smaller land covers saw urbanization of 1.10 km<sup>2</sup> of surfaces changing through the years. Some notable shifts from built-up areas can be seen, 11.87 km<sup>2</sup> and 7.51 km<sup>2</sup> of area converted to Cropland and Rangeland respectively possibly due to land repurposing.

Cropland faced intense land use change in this period losing 46.44 km<sup>2</sup> to urbanization and 20.99 km<sup>2</sup> to Rangeland reducing its untouched area to 41.71 km<sup>2</sup>. Some expansion can be seen with 11.63 km<sup>2</sup> from Rangeland showing the demand for food production. Meanwhile, rangeland has become a challenged landscape amid urbanization and agricultural expansion with 26.19 km<sup>2</sup> urbanized and 11.63 km<sup>2</sup> converted to Cropland, the only remaining area being 33.09 km<sup>2</sup>. These shifts imply the demand for urban development and stress the necessity of sustainable land management and conservation of ecological areas.

The combination of these land use transformations emphasizes a critical intervention for regional sustainability. Over the past decade, net urban expansion has been approximately 58 km<sup>2</sup> which in turn reduces agricultural resilience and threatens biodiversity with some areas of forest being converted. Without an intervention, the city is at risk of irreparable degradation, while short-term developmental gains are admired the natural systems might take a longer time to recover.

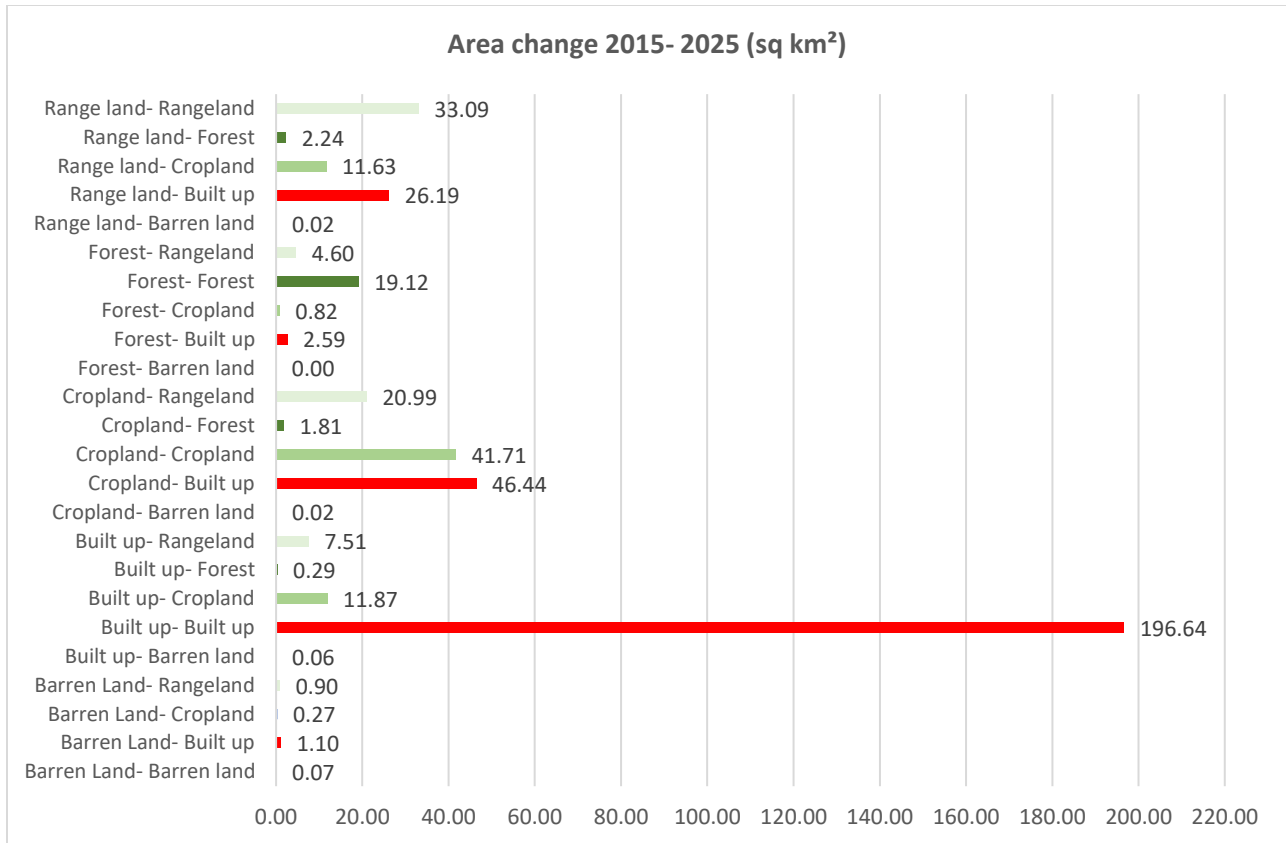


Figure 4.11: Landcover shifts between 2015-2025

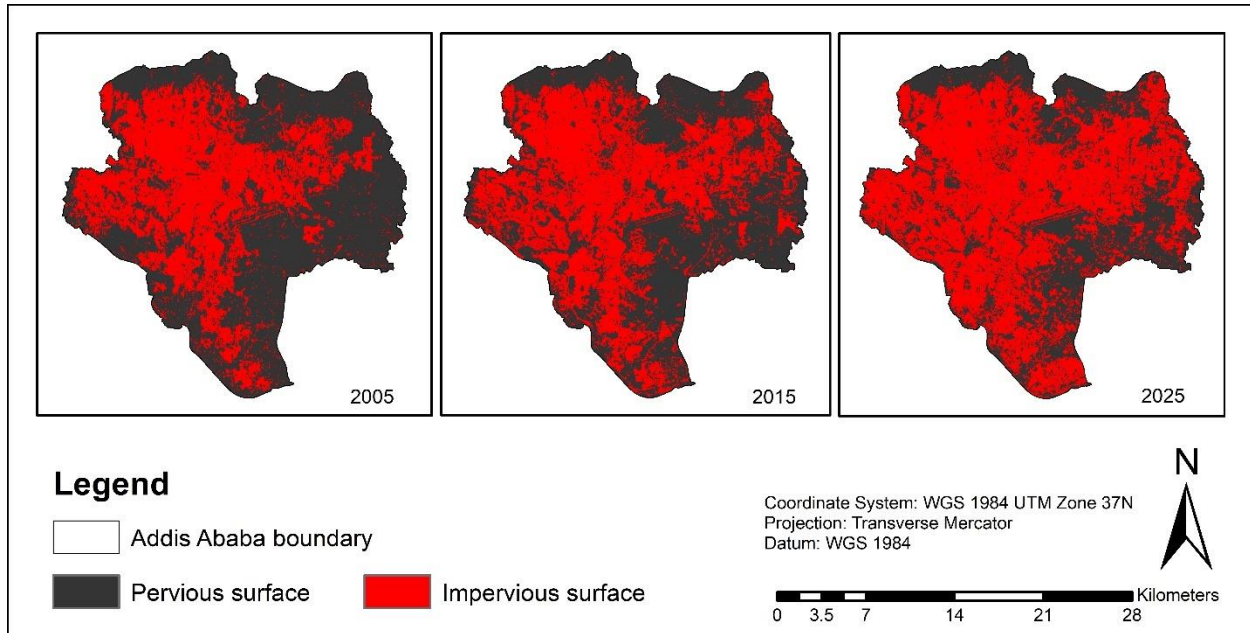
#### 4.1.2.3. Impervious surface change

The land use land cover (LULC) changes show an indication of transformations in urban and peri-urban landscapes. The human-made infrastructures increased making the surface impervious with the conversion of natural or vegetated surface (pervious) which is the main cause of pluvial flooding by limiting natural water infiltration.

Beginning in 2005, the number of pervious surfaces which include green spaces forests and cropland dominated covering 247.34 km<sup>2</sup> which is 57.50% of the total area. The impervious surfaces mainly consist of the built-up area which includes roads, buildings, and paved areas, it constituted about 42.50% (182.96 km<sup>2</sup>) signifying the slight supremacy of natural areas at that time period.

By 2015, the two categories seem to be balanced as urbanization intensifies. The pervious surface spans 215.99 km<sup>2</sup> which is 50.20% of the city, the shift in rangeland and cropland is the key influence for the increment of impervious surfaces which covers the remaining (214.31 km<sup>2</sup>)

49.80%. Presently the prevailing trend of impervious surface can be noted taking up an area of 269.57 km<sup>2</sup> that is 62.70% of Addis Ababa, dwarfing the previous area that constitutes (160.73 km<sup>2</sup>)37.30%. This shift is indicative of the need for sustainable city planning and land management.

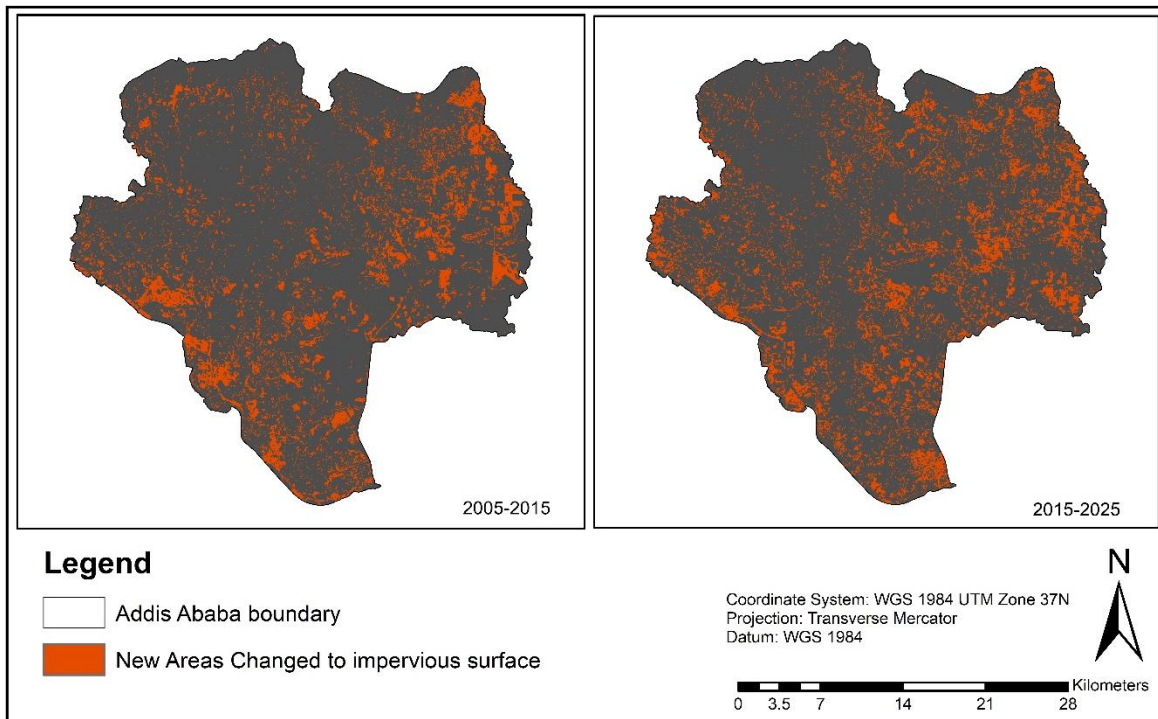


*Figure 4.12: Impervious surface map*

### ***Impervious surface change from 2005-2025***

The impervious surface expanded immensely over the two decades. From 2005-2015 the impervious surfaces grew by 31.35 km<sup>2</sup> which is approximately 3.14 km<sup>2</sup>/year, increasing the coverage from 42.5% to 49.8% of total land area. The growth rate seems to increase by 5.53 km<sup>2</sup>/year which makes the total area change 55.26 km<sup>2</sup>, soaring to 62.7% of the entire land area.

A near-doubling of the yearly impervious surface increment compared to 2005–2015. And by 2025 the pervious surfaces shrink to 37.3% which is down 20% since 2005. The implications of this are compounding flood risks as natural surface permeability declines and impermeable surface grows creating a higher runoff volume overwhelming the drainage systems.



*Figure 4.13: Area shift to impervious surface map*

#### 4.1.2.4. Impervious surface and runoff generation

The study area comprised 182.96 km<sup>2</sup> of impermeable surface in 2005 and the rainfall for the rainy season has a few days well above 40 mm/day but on average the precipitation per day is 11.25 mm (annex 1a). Since 2005, the urbanized cover of pervious surface has been larger than the impervious surface, the weighted runoff coefficient (C) is 0.56, and a weighted curve number (CN) of 91 to estimate the total runoff generation. Using the SCS-CN Method ~0.54 million (m<sup>3</sup>/day) of stormwater runoff is generated from the whole city, this method considers rainfall lost to infiltration, depression storage and interception before developing to a stormwater runoff.

By 2015, the urban expansion reached 214.31 km<sup>2</sup> of Impervious surface with the average rainfall declining to 9.01 mm/day even though there are days that are above 15mm/day and the highest being 43mm/day. By this time the runoff generated In Addis Ababa is ~0.49 million(m<sup>3</sup>/day), implying that even though there is an increase in impervious surfaces, the average daily rainfall has an important role in generating runoff.

Currently the impervious surface accounts for 269.57 km<sup>2</sup> raising the weighted average of runoff coefficient to 0.68 and the CN number to 94. The SCS-CN Method assumes there is ~1.03 million

(m<sup>3</sup>/day) runoff generated through an average rainfall (11.05 mm/day), signifying the overwhelming increase in an impervious surface has an impact even though the daily average perception is lower.

Lastly, there are notable changes in runoff generated between 2005, 2015, and 2025 influenced by the shifts in urban area, rainfall, runoff coefficients (C), and Curve Numbers (CN). the SCS-CN Method reflects a 9% runoff reduction (~0.54M to ~0.49M m<sup>3</sup>/day) between the 2005 and 2015. By 2025, however, the amount surges dramatically with a 110% spike in runoff to (~1.03M m<sup>3</sup>/day), This Method offers more conservative estimates by accounting for initial abstraction.

*Table 4-6 Runoff generation estimation*

<b>Year</b>	<b>Impervious Area (km<sup>2</sup>)</b>	<b>Rainfall (mm/day)</b>	<b>C</b>	<b>CN</b>	<b>SCS-CN Method (m<sup>3</sup>/day)</b>
<b>2005</b>	182.96	11.25	0.56	91	~0.54 million
<b>2015</b>	214.31	9.01	0.6	93	~0.49 million
<b>2025</b>	269.57	11.05	0.68	94	~1.03 million

### 4.1.3. current stormwater management practices

#### 4.1.3.1. stakeholder Perspectives on Stormwater Management

Interviews with the eight key informants revealed consistent themes in current stormwater management. All participants agreed that pluvial flooding is a critical issue in Addis Ababa. All those knowledgeable about drainage capacity noted the existing drainage system is inadequate for the current needs.

*Table 4-7 Demographic profile of respondents*

<b>KI Code</b>	<b>Age Range</b>	<b>Gender</b>	<b>Education Level</b>	<b>Years of Experience</b>
<b>KI1</b>	55-60	Female	MSc	20
<b>KI2</b>	41-50	Male	MSc	12
<b>KI3</b>	41-50	Male	MSc	10
<b>KI4</b>	31-40	Male	BSc	9
<b>KI5</b>	31-40	Male	BSc	11
<b>KI6</b>	31-40	Male	BSc	8
<b>KI7</b>	51- 60	Male	MSc	16
<b>KI8</b>	31-40	Female	BSc	7

#### *Drainage Infrastructure and Management Practices*

Respondents characterized management practices in the city as fragmented and infrastructure-focused. They explained most efforts go into clearing and rebuilding broken pipes rather than all rounded planning. one key informant stated that illegal connections between sewer lines and stormwater drains are widespread mixing wastewater with stormwater and hindering water quality, while reverse connections overload sewage treatment systems. Meanwhile, the mandate of mitigating all flood-related issues in the city is given to AARCA in collaboration with other governmental offices.

#### *Effectiveness and Current Measures*

Diving in to the effectiveness of existing measures, most key informants expressed doubts and felt recent infrastructure projects have only marginally reduced flooding. According to the interviews with stormwater drainage systems experts, the designs of the stormwater drainage systems were adequate during the time of implementation and discharged the rainwater runoff efficiently. They also pointed out some issues with inlet types not meeting the needs of the discharge intake,

asserting the necessity of appropriate designs for different types of sloped terrains. About 60% of the drainage system in Addis Ababa works efficiently, while the rest needs some modification and unity in discharging stormwater.

Another key informant noted that natural runoff retention is nearly non-existent in the city's stormwater plans, even though there is an increase in green initiatives. Nevertheless, a few positive notes emerge one of them being the current corridor development fixing some necessary drainage issues, yet two of the informants agreed that effective mitigation remains limited. Another high point is the ongoing drainage master plan expected to be finished soon and rectifying drainage-related matters.

### ***Challenges and Constraints***

The key informants identified several recurring obstacles. The leading challenge is solid waste and debris clogging the drains they repeatedly noted that plastic bottles, trash, and earth are frequently dumped or washed into stormwater lines. According to the key informant from the Dry Waste Management Office, the city's roads are cleaned three times a day and solid wastes near drainage areas are picked up. The remaining waste in the drainage inlet is cleaned once per year before the rainy season.

The AACRA is the one in charge of drainage systems, when discussing about pluvial flooding the informants acknowledge the existence of the issues. The identification of the flood-prone areas is done through reports from the own force assessment (collaboration with the five sub-branches) and information from the Addis Ababa City Administration Fire and Disaster Risk Management Commission. Even though the issues arise the monitoring and evaluation are lackluster especially on the hydraulic performance of drainage lines, some minor solutions are given based on complaints.

Other challenges include Institutional coordination. The key informants pointed out overlapping responsibilities among agencies creating redundancy of activities and resources. Another key issue is the lack of communication with the institutions, when maintenance of sewerage systems and telecommunication and electricity lines on the sidewalks is done most of the remanent from the excavation enters the drainage inlets. In Addis Ababa, there is no city-wide stormwater network

master plan. The drainage lines are done when the road network is being built which is normally done in segments one example being the corridor development. This approach lacks consideration of the overall runoff of the sub-watershed and doesn't account for future urbanization & increase in impervious surfaces.

According to the key informant, there is a technical manual to use for drainage design but it doesn't factor in the current status of the city. The pending drainage master plan is expected to cover some flood-related issues. Another issue pointed out by the informant is internal roads not being built properly, lack of proper design and follow-up from professionals creates roads with slope issues and poor drainage management. Finally, informants mentioned that the city has no integrated planning approaches in the context of stormwater management.

***Policy and Community Engagement***

Regarding policy implementation, key informants were open about weak enforcement. Two of them said that stormwater regulations (building setbacks, retention requirements, etc.) exist but are rarely enforced. They also pointed out the absence of a legal framework to manage stormwater at different levels and there is no adequate penalty for people who connect sewerage lines to drainage systems and almost no enforcement rule on dumping solid waste into drainage lines.

In terms of community engagement, a key informant working with Dry Waste Management said they are enforcing people to clean their drainage lines adjacent to their borders from solid waste and there is an emerging cleaning campaign that lessens the issue of poor solid waste management.

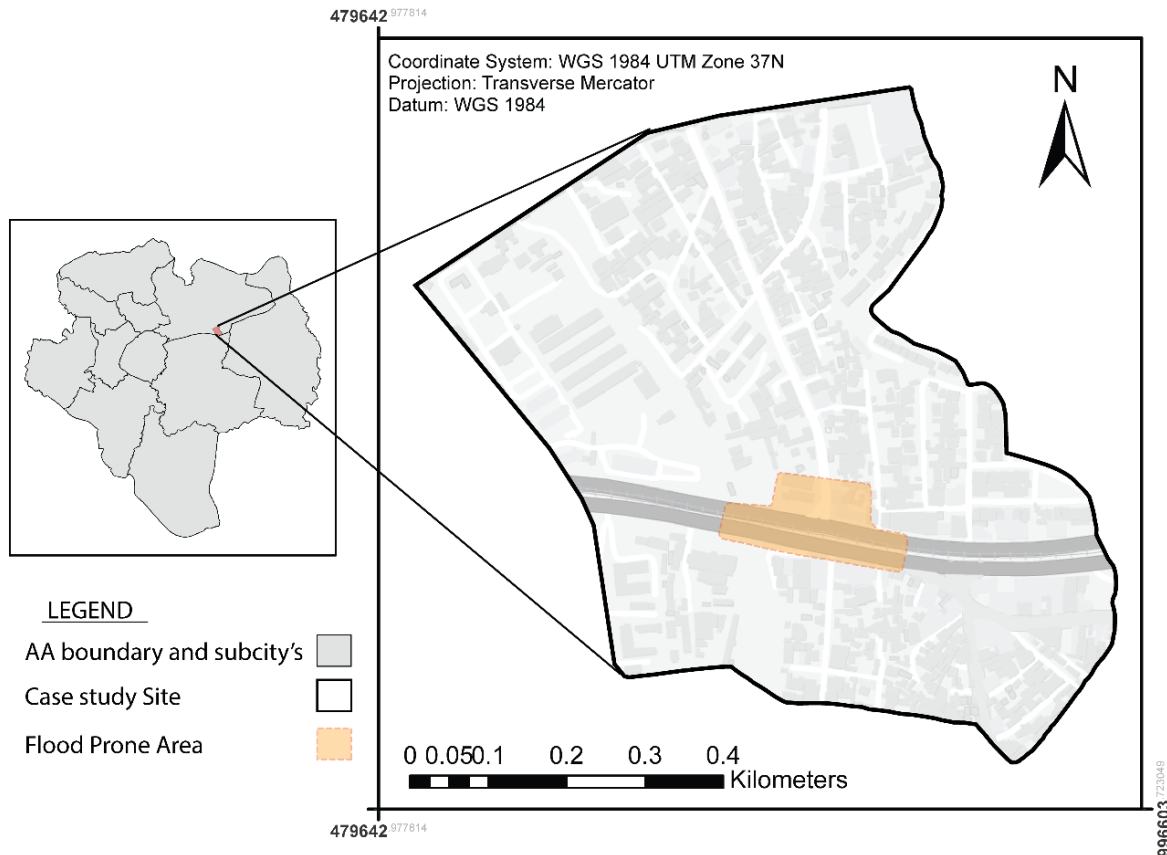
*Table 4-8 Summary of the key informant interview*

<b>Theme</b>	<b>Representatives Statement</b>	<b>Informant Codes</b>	<b>Interpretation</b>
<b>1. Inadequate Infrastructure</b>	“The drainage system is not sufficient for the current runoff”	KI1, KI2, KI3, KI4, KI5, KI6,	The system was designed for past conditions and is now overwhelmed by rapid urbanization and more intense storms.
<b>2. Poor Management Practices</b>	“Efforts mostly focus on fixing broken drainage pipes”	KI1, KI2, KI3, KI5	Municipality concentrates only on broken infrastructure, lack of long-term strategic planning.

<b>3. Illegal sewer Connections</b>	“Wastewater and stormwater are mixing due to illegal sewer connection.”	KI7, KI2	Unauthorized sewer connection overload the drainage system, there is a law enforcement gap.
<b>4. Limited Effectiveness of New projects</b>	“Some new infrastructure helps, but overall flooding is still not fixed.”	KI1, KI2, KI3, KI5,	Recent corridor development project replaces some drainage structures which helps; root causes remain unaddressed.
<b>5. Inadequate Design for the city’s Terrain</b>	“Inlet types don’t suit sloped areas.”	KI1, KI2, KI3, KI4	One standard design that ignores slope variations reducing drainage intake efficiency.
<b>6. Solid Waste disposal</b>	“Plastic and debris clog the drains even after daily road cleaning.”	KI8, KI1, KI2	poor waste management practices, weakening drainage maintenance.
<b>7. Poor Institutional Coordination</b>	“Lack of communication between Organizations.”	KI1, KI2, KI3, KI5, KI6,	Organizations don’t communicate well when working on roads or utility lines
<b>8. No Citywide Stormwater Master Plan</b>	“Drainage is built per road project.”	KI1, KI2, KI3, KI7	Fragmented planning ignores the connection within the watershed and future urban growth.
<b>9. Weak Legal &amp; Policy Framework</b>	“Rules exist but are rarely imposed.”	KI1, KI2, KI7, KI8	Stormwater rules are weak and little to no enforcement authority

#### 4.1.3.2. Pluvial flooding of the case study area

From the findings of the first objective a pluvial flood-prone area was selected in Addis Ababa the site is situated near the telecommunications compound across from the Gurd Shola Light Rail Transit (LRT) station. In the past few years, this location has been repeatedly affected by flooding events, inadequate drainage systems, and unfavorable topographic conditions are the primary factors. The slope of this area exacerbates surface runoff buildup during strong storms, and drainage lines are either blocked or poorly built and are unable to reduce flooding. Studying this location provides critical insights into addressing terrain-related risks and upgrading drainage networks, essential for enhancing flood resilience and safeguarding communities and infrastructure in flood-prone urban areas.



**Figure 4.14:** Pluvial Flood-prone area of the case study site (9.01930,38.81987)

### ***Drainage Infrastructure Observations***

The images were taken from the roadside adjacent to the ethio-telecom compound, indicating various issues with the drainage inlets. In the images (Fig. 4.15 A, B), the inlets are visibly clogged with debris suggesting neglect in maintenance. Image (Fig. 4.15 B), reveals sand and bits of broken glass, which render even minor cleaning problematic. Images (Fig. 4.15 C, E), illustrate cases of tampering with the drainage facilities; in particular, image (Fig. 4.15 C) illustrates an inlet located beside a local café where wastewater is being illegally discharged. Image (Fig. 4.15 F) illustrates a drainage inlet clogged with stones, which also restricts water flow.



*Figure 4.15: Stormwater Drainage conditions (9.0119552, 38.819920)*

Most of the inlets that were not shown in the photos have the same problems, including debris accumulation, structural obstruction, and poor waste disposal practices, which compromise their efficiency in managing stormwater runoff.

### ***Terrain of the case study area***

The selected study area has a varying terrain, two cross-sections were selected for analysis. The first spans from Lamberet Roundabout to Gurd Shola Train Station, it is characterized by a steady elevation drop toward the station and a sudden change in elevation creating a terrain depression can be seen when reaching the LRT line as seen in (Fig. 4.16 A). The second cross-section runs along the main road from CMC to Megenagna.

This road has a fluctuation of elevations because of two streams crossing it, one stream lies adjacent to the Athletic Federation building, while the other is near Elfora Agro Industries. Between these streams there is a sag point where water tends to collect (Fig. 4.16 B). The two topographical factors contribute to the region's susceptibility to drainage challenges and surface water accumulation during intense rainfall events.

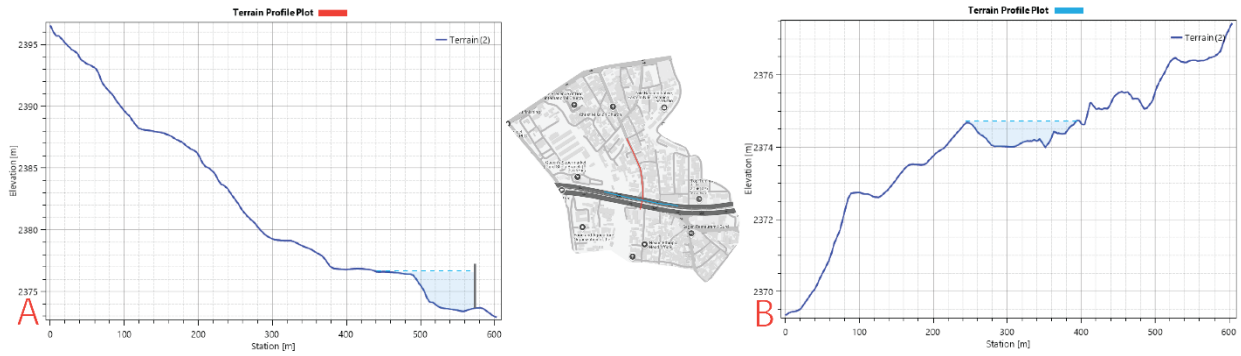


Figure 4.16: Terrain Condition; Lamberet to Gurd Shola road(A), CMC to Megenagna road (B)

### Flood simulations

Prior to the construction of the Light Rail Transit (LRT), surface runoff along the road flowed freely towards the lower-lying areas without any major obstructions. The existing drainage system in place was successfully linked to a culvert that released water into the nearby stream beside Elfora Agro Industries. As illustrated in (Fig. 4.17 A), the natural flow of runoff aligned with the topography, directing the flow of water toward the stream. Simulation results exhibit a minor accumulation of water in the middle of the road, which can be justified by minimal differences in terrain elevation.

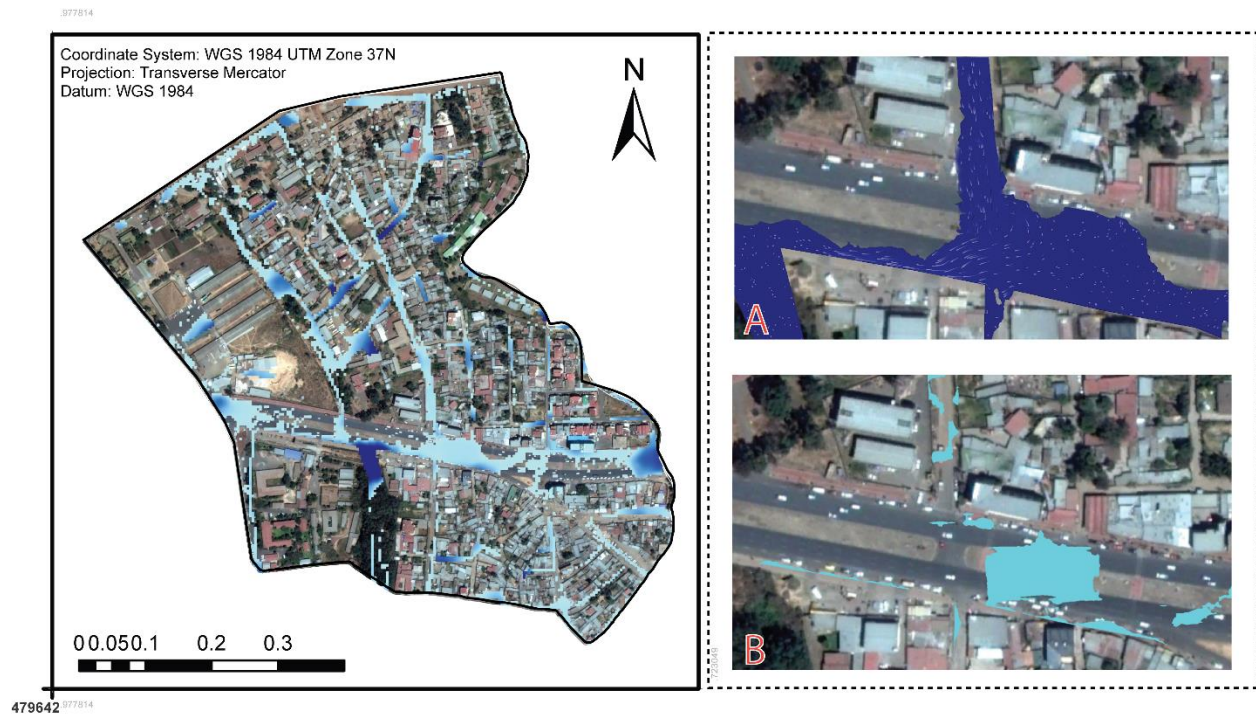
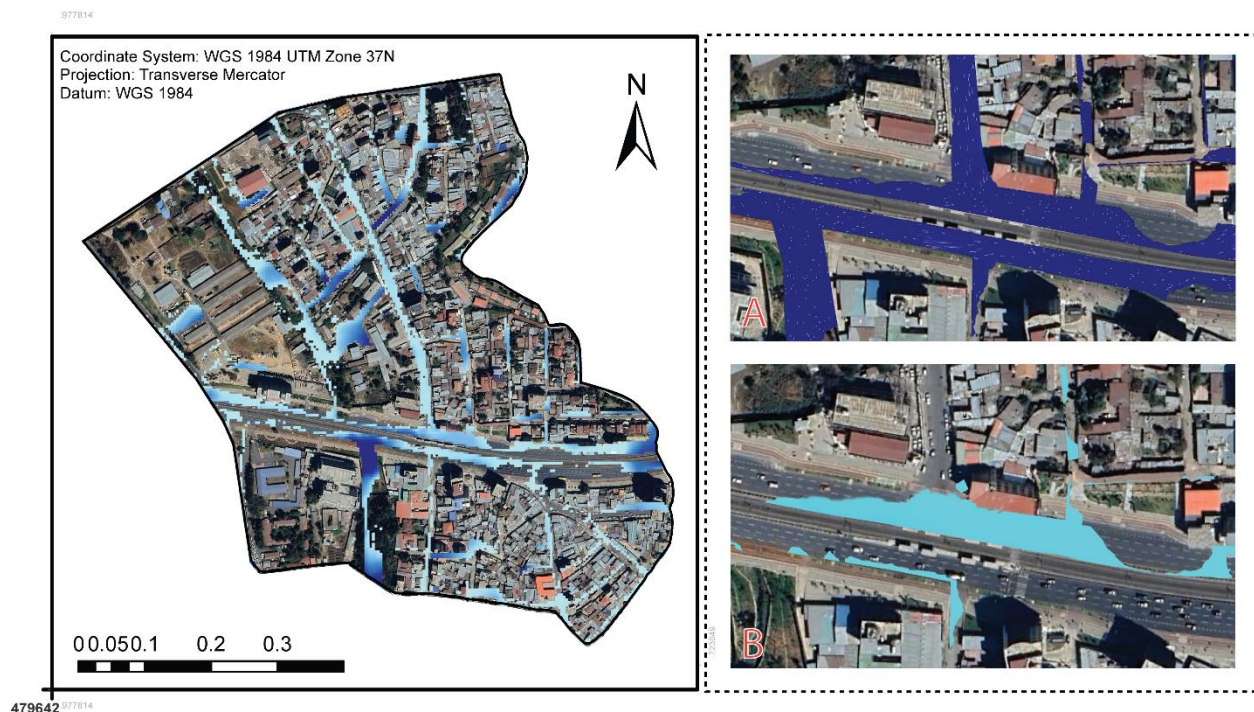


Figure 4.17: Runoff simulation A) stormwater flow direction B) runoff accumulation prior to LRT

Presently, the existence of the Light Rail Transit (LRT) line along the middle of the roadway greatly obstructs the natural course of surface run-off which previously used to flow from the Lamberet Roundabout to the adjacent lower-lying areas. The major issue noticed is the presence of a sag point along the LRT, where surface water tends to accumulate. Simulation results, as illustrated in (Fig. 4.18 B), clearly demonstrate the blockage of surface water and the resulting flooding in specific locations. During the site observation, some flood mitigation efforts were in place. A specific intervention is the inclusion of surface openings that are covered by concrete panels to allow water to pass through underneath and join the drainage system easily (Annex 4D). Another intervention was the widening of the adjacent stream to increase its capacity to handle greater volumes of water, it was done as part of the corridor development.

The causes of the observed pluvial flooding are grouped into four significant factors. First, drainage inlets are frequently blocked by silt and dry trash, which do not permit the free flow of water. Second, the LRT structure itself is a barrier to the natural flow path, and the use of an undersized 60 mm crossing pipe under the LRT is inadequate to convey stormwater. Third, the current ground surface creates sag points that naturally collect water. Last, there are grade mismatches between drainage and cross culvert lines, resulting in backflow from the stream.



*Figure 4.18: Runoff simulation A) stormwater flow direction B) runoff accumulation after the LRT*

## 4.2 Discussion

The pluvial flood-susceptibility map for Addis Ababa shows that the forested steep uplands (predominantly to the north of the city) are in the very low and low risk classes, while the densely urbanized low-lying areas are in the high and very high susceptibility classes. In fact, the majority of the urban territory (~62–63%) is classified under the high or very-high risk a sign that the majority of its population lives in flood risk locations (Wubneh & Beyene, 2022). The trend is similar to results showing that central Addis Ababa with impervious cover and low-slope southern communities are most vulnerable to intense rainfall it's also documented socio-economically that 67% of Addis's population currently live-in flood-prone zones (Nigatu et al., 2022).

In each case, areas labeled “high/very high” correspond to zones where flooding has been historically problematic or could impact many people (Cabrera and Lee ,2020), (Zhran et al., 2024). This study similarly identifies concentrated urban districts as highly susceptible. Thus, the pattern of a minority of areas holding a majority of risk is consistent globally. The pluvial flood susceptibility map shows that very high- and high-risk zones cluster in low-lying, urbanized areas especially along major drainage channels and valley areas, while the very low and low zones are situated on higher ground in vegetated highland districts. This pattern is consistent with runoff dynamics: flat or areas with gentle slope tend to accumulate water and “pond,” while impermeable built up landcover increases runoff volume (Islam et al., 2025).

Moreover, Low-elevation channels and convergent areas (high topographic wetness index) emerged as hotspots, while plateau and ridge-top regions (lower wetness index) were safer. For example, most of Arada and Lideta sub-cities situated on gentle gradients channels fell into high-susceptibility zones, Conversely, peripheral sub-cities on Addis's outskirts like Yeka and gullele sub-city showed lower susceptibility, reflecting both higher relief and more permeable land use. In 2017 alone, the Addis Ababa emergency services reported 76 separate flood events causing 20 million birrs in damage across the city (Jemberie & Melesse, 2021), notably in the same central sub-cities as this paper's analysis flags as very high risk.

Land cover and imperviousness strongly control risk in this study. Paved and constructed features are strongly associated with high vulnerability, since they prevent infiltration and transmit runoff rapidly (Islam et al., 2025). The analysis designated very high risk to city-center asphalt- and tile-covered, in agreement with the reality that those zones added hundreds of hectare-flooded lands in

past occurrences (Bekele et al., 2022). on the contrary areas with dense vegetation or rangelands act as water seeping surfaces, soil infiltration in these areas mitigates flooding thus mostly falling on lower susceptibility classes (Islam et al., 2025).

The findings broadly converge with prior flood mapping research in Addis Ababa and other urban catchments. Bekele et al. (2022) used radar to delineate flood in the Akaki catchment and determined that 544 ha of impervious urban land was inundated during 2017-2020 events. This corroborates the result that impervious urban areas are highly likely flood-prone. Similarly, Asfaw et al. (2024) applied machine learning to the same akaki sub-basin and pointed out rainfall and human-induced drivers, when they noted that the addition of infrastructure and high-resolution rainfall enhanced flood susceptibility prediction significantly.

Their Random Forest model showed that 0.54 million residents and tens of thousands of buildings were in the very high susceptible class. Which resonated with the current map output, classifying densely urbanized zones like Addis Ketema, Kolfe Keranio sub-cities as high risks. In both of the cases the studies note sprawl onto natural floodplains and weak drainage exacerbates flood risk, consistent with the theme of this study.

The flood susceptibility map is very valuable for providing direction to urban planners and emergency response personnel. Areas identified as having high or very high flood susceptibility should be the priority for implementation of mitigation measures. For example, the Addis Ababa City Roads Authority is preparing a master plan for drainage for the entire city to mitigate flooding-prone areas; this study can augment that work by identifying specific neighborhoods and sub-catchments for reinforcement.

LULC analysis indicates the rapid growth of the built-up area in Addis Ababa from 2005–2025. The built-up area grew from 182.96 to 269.57 km<sup>2</sup> (42.5 to 62.6% of the city), primarily encroaching on agricultural land and forestland. Cropland, in particular, decreased significantly (from 127.75 to 68.93 km<sup>2</sup>), and green cover has also decreased in combination. This corresponds with other studies: for example, Hirpa et al. (2023) reported that Addis's urban footprint expanded more than six-fold from 2000 to 2020, at the expense of cultivated land. Likewise, Hailu et al. (2024) found that nearly all natural land covers in Addis (cropland, forests, etc.) have declined as built area more than doubled (a 224.7% increase).

These results confirm that urbanization in Addis is being driven by the conversion of pervious, vegetated landscapes into impervious urban fabric, a trend common to many rapidly growing sub-Saharan cities. The shift toward impervious surfaces has clear hydrological consequences. In this study the impervious fraction rose from about 42.5% in 2005 to 62.7% in 2025, indicating extensive paving and construction. Hydrologically, this means far less rainfall can infiltrate into the soil. As Ramiarmanana and Teller (2021) note, urbanization “generally leads to an increase in impervious surfaces, which limits the possibility of water infiltration and increases the volume of water runoff”.

Consistent with this study’s runoff simulation that shows a roughly 1.8–1.9× increase in daily runoff volumes over 20 years (~0.54 to ~1.03 Mm<sup>3</sup>/d using the SCS-CN method). Such increases are expected: numerous studies demonstrate that as impervious cover grows, peak runoff and flood frequency rise sharply (Ramiarmanana & Teller, 2021). In practical terms, the loss of pervious areas (cropland, forests, and urban green space) underpins this effect, since these surfaces formerly absorbed and slowed rainfall. The hydrological modeling thus corroborates the known theory that increased sealing of the land surface leads to proportionally larger and faster runoff generation.

These hydrologic shifts have manifested as escalating flood risk in Addis Ababa. Studies of the city and similar urban centers document rising flood incidence linked to urban cover expansion. For example, one spatiotemporal study recently revealed that the expansion of impervious surfaces in Addis Ababa was linked to an increase of 36% in flash flood occurrences between 1984 and 2020 (Yasin et al., 2025). Flooding has become more extensive in recently developed areas, as revealed through empirical research.

Examinations of drainage infrastructure demonstrate that Addis's stormwater infrastructure is already at capacity: sidewalks and thoroughfares are more and more constructed over drainage channels, and the drains are often clogged or too narrow. Jemberie et al. (2023) note in particular that the "rapid growth of impervious surfaces intensifies flash flooding" and that it is "frequently observed that recurring surface urban flooding and waterlogging" occur during rainfall events because of the coupling of sealed surfaces and a lack of drainage infrastructure. These findings align with a broader African context in which informal or fast-growing settlements often encroach on floodplains and drainage capacity lags behind urban growth. In sum, as natural landscapes give way to impermeable cityscape, flood volumes and hazards in Addis Ababa have risen immensely.

Addressing these trends poses significant stormwater management challenges. Unlike natural catchments, urban areas must cope with rapid runoff and reduced infiltration. In Addis, this has strained the existing system, as highlighted above. Urban planning and engineering responses are therefore critical. Experts underscore the necessity to avoid unrestricted increases in surface impermeability: this can be done by concentrating growth within already-developed areas and preserving open land wherever possible.

Increasing the proportion of pervious or vegetated surfaces directly counters flood risk: urban green infrastructure (rain gardens, parks, swales) and low-impact development (LID) elements (green roofs, permeable pavements, rainwater harvesting) can restore infiltration pathways. Another emerging concept is the “sponge city”, Jemberie & Melesse (2021) advocate designing Addis Ababa in ways that maximize storage and delay runoff (green spaces, depressions, permeable materials). Such measures can greatly mitigate peak flows without requiring purely gray infrastructure solutions. Overall, the marked increase in impermeable cover identified in this study validates the heightened flood risk documented for Addis Ababa.

The current case of Addis Ababa echoes a pattern seen in many rapidly growing cities: more intense rainstorms and rampant urbanization are overwhelming antiquated drainage systems. As one local study notes, “frequent surface floods” have become “a common problem in most rapidly sprawling urban environments” when climate-driven runoff meets inadequate drainage (Jemberie et al., 2023). In Addis Ababa, pluvial flooding now ranks as a critical hazard, indicating both more extreme rainfall and a built environment that has become largely impervious.

Globally, analysts warn that as urban populations soar (70% by mid-century, mostly in developing nations (Jemberie et al., 2023), traditional drainage infrastructure designed for past conditions will be tested by extraordinary runoff increases. In fact, studies of stormwater management in developing contexts routinely find that aging networks, often “built several decades ago,” are undersized or obsolete relative to today’s demand (Francisco et al., 2022). In this study, interviews and field observations confirmed that existing stormwater pipes and channels have deteriorated or been outgrown by expansion.

This neglect of maintenance and capacity fits a broader trend: in Brazil, for example, researchers report that urban drainage systems often fail because they are “undersized” or in a state of “deterioration or obsolescence” (Francisco et al., 2022). In sum, Addis Ababa’s flooding problem

is hardly unique: it is symptomatic of a systemic mismatch between rapid urban growth and legacy stormwater infrastructure.

The city's roads and drainage suffer from potholes and erosion precisely because culverts and drainage systems are clogged or broken a common pattern when maintenance is neglected. Moreover, a systematic assessment in Addis identified "debris and various solid wastes" as the single largest cause of drainage failure (roughly one-third of incidents) (Jemberie et al., 2023). In practical terms, this means that even when storm drainages exist, their hydraulic capacity is undermined by sediment, refuse, and blockages.

In Addis Ababa, the informants described similar dynamics inlets clogged with trash and illegal connections discharging sewage into drains. These unsanctioned pipe connections and uncollected garbage are not mere nuisances; they "reduce the hydraulic efficiency" of the network and turn any storm into surface flooding. Just as significantly, the study revealed that several agencies have overlapping or unclear authority over stormwater. This institutional fragmentation of legal jurisdictions split across sectors and levels of government is well-documented and it is a barrier to effective urban drainage.

In the city, water, road, and environment bureau officials reported confusion as to what channels needed to be addressed and by whom, which created gaps and overlaps. According to Aduugna et al. (2019), The disorganized and unsystematic provision of drains by different actors without collaboration further worsens stormwater management. Such practices failed to update the current stormwater management systems that may be able to help in forecasting stormwater-associated problems due to rapid urbanization and increasing deification in Addis Ababa. Other studies on municipal water governance also underscore this problem: "Traditional forms of stormwater management lead to jurisdictional and institutional fragmentation," causing "institutional overlap and absence of clear roles" among agencies (Carriquiry et al., 2020).

These complications are compounded by technical inconsistencies as the informants observed that Addis's drainage infrastructure was largely not suited for the modern urban setting. For example, some of the drainage pipes were either improperly installed or had grading problems such that water would stagnate instead of flowing. The new Light-Rail tracks unintentionally created "sag" areas where drainage cannot flow through, and the drainage size is inadequate catching only a small proportion of the stormwater runoff.

Such issues reflect a short-sighted design philosophy: previously, engineers used to treat stormwater as waste to be removed rapidly, with no concern for local topography and hydrology (Francisco et al., 2022). Conversely, contemporary practices emphasize landscape-sensitive design accomplishing this through properly graded channels, detention ponds, and low-impact solutions that mimic natural flow paths.

Beyond technical issues, social and policy dimensions undermine resilience. Building and environmental code enforcement in Addis Ababa is very weak. Many informants cited rampant development in flood susceptible zones, blocked culverts due to improper dumping, and the absence of accountability among developers. In effect, stormwater policy is mostly on paper: awareness-raising and local bylaws are minimal. This reality is resonated in other studies, showing that where stormwater management is not a political priority, the focus continues to be on water supply and sanitation, leading to the marginalization of drainage (Francisco et al., 2022).

Overall, the interview and field data in Addis Ababa paint a dire but familiar picture. The floods and drainage breakdowns are not random; they are the product of a series of interconnected issues: overloaded networks, design issues, institutional fragmentation, and weak governance. These findings align with global studies showing that effective stormwater management in growing cities demands integrated solutions of both “hard” and “soft”. Without addressing these systemic and policy challenges, Addis Ababa’s path to a water-secure, resilient future will remain unattainable, despite the technical fixes under consideration.

## CHAPTER FIVE: CONCLUSION AND RECOMMENDATION

### 5.1 Conclusion

The analytic hierarchy process (AHP) was employed to model pluvial flood susceptibility in Addis Ababa, to identify the most significant factors and spatial patterns controlling the flooding risk. The findings showed that 55.65% of the city (237.28 km<sup>2</sup>) falls under High susceptibility, with an additional 6.95% (29.63 km<sup>2</sup>) classified as Very High risk. Moreover, the result identified central sub-cities such as arada, lideta and addis ketema as are particularly vulnerable due to their gentle topography, and impervious surfaces, following global patterns where urbanization heightens runoff and ponding. conversely, Peripheral sub-cities such as yeka and gullele are covered with rangeland and forests exhibiting lower susceptibility grading in comparison to their counterparts, indicating the role by permeable land cover in flood risk reduction.

The Historical flood records validate the model accuracy, which shows that 58% of the past flood occurrences were in High susceptibility zones and 39% in Very High-risk zones. The frequent flooding of key locations such as Gurd Shola and Addis Ketema, Wereda 9, demonstrates their inherent vulnerabilities. On the other hand, only 3% of historical floods occurred in Moderate-risk zones, highlighting the model's strength in prioritizing high-exposure regions.

Land-cover change has been significant: built up areas expanded from 182.96 km<sup>2</sup> (42.5%) in 2005 to 269.57 km<sup>2</sup> (62.6%) in 2025, showing a dynamic urbanization rate that has consumed nearly all areas that was previously bare lands (from 6.83 km<sup>2</sup> to 0.20 km<sup>2</sup>) and encroached on cropland, rangeland, and forest cover. The amount of land considered for agriculture decreased from 127.75 km<sup>2</sup> to 68.93 km<sup>2</sup>, rangeland from 80.05 km<sup>2</sup> to 68.22 km<sup>2</sup>, and forest cover decreased from 32.71 km<sup>2</sup> to 23.37 km<sup>2</sup>. All of these transformations not only indicate a loss of green cover and diversity but also directly raise the level of risk for flooding, as natural, permeable surfaces that once soaked up rainfall are now dominated by impermeable surfaces.

Impervious cover conversion has also had a quantifiable impact on the generation of runoff. In 2005, 57.5% of the study area remained pervious, producing 0.54 million m<sup>3</sup>/day of stormwater using the SCS-CN method. Imperviousness had risen to 62.7% in 2025, with runoff rising to 1.03 million m<sup>3</sup>/day giving a 110% increase. Although mean daily precipitation varied between 9.01 mm/day and 11.25 mm/day over the period, it is the increase in impermeable surface that is most

accountable for such noticeable runoff increases, overloading existing drainage capacity under heavy storm.

Moreover, infrastructural and organizational deficiency exacerbate such environmental problems. Currently 60% of the city's drainage work well but the remaining 40% is hindered by issues such as poor design, frequent blockage because of solid waste, and lack of proper maintenance .key informant interviews validate the lack of appropriate management system, poor coordination with different utility organization, lack of a watershed-based master plan and weak legal enforcement have led to fragmented and one-off solutions. In addition, even though it enhances transportation projects like the light rail transit (LRT) line have unintentionally developed low points and poor crossings that disrupt natural runoff flow, thus aggravating localized flooding issues.

Lastly, Addis Ababa's growth pattern demonstrates a fundamental principle: that increasing urbanization creates dire risks for water security. This study reiterates the imperative of balanced, sustainable planning that aligns city development with ecosystem management. The time to reimagine Addis Ababa as a flood-resilient city has arrived, before the intensification of runoff and climate variability convert today's problems into tomorrow's emergencies.

## **5.2 Recommendations**

- Replace undersized drainage pipes under the light rail transit line with a larger-diameter ducts or add more pipes by tunnelling through the LRT line to accommodate peak storm flows.
- Correct low-lying “sag point” on the road through solutions such as filling with the appropriate material, height and slope to eliminate water accumulation or creating a trench drain covered with grates at the lowest point of the sag.
- Reconfigure sections of stormwater network in appropriate places to divert runoff in the adjacent streams before it reaches low laying areas. This decreases the burden on the drainage lines located at the lower elevations.
- Establish a continuous schedule for cleaning solid waste and clearing clogged debris from drainage inlets and culverts particularly ahead of the rainy season to ensure unobstructed flow and prevent flooding in the case study area (next to gurd shola LRT station) and areas where pluvial flooding arise.

- Promote natural conveyance of stormwater to lower flood risk by designing new development with consideration of runoff and flow direction.
- Protect the remaining forests, agricultural and rangelands by focusing on high density development rather than outward encroachment. This retains the natural permeable areas and limits the increase in runoff generation.
- Upgrade drainage networks to match the city's current runoff demand while considering the future expansion. Moreover, improve regular maintenance on damaged drainage lines and inlets.
- Incorporate green infrastructure in urban planning by adding rain gardens & bioswales on road medians where flooding frequently disrupts traffic, green roofs on Government-owned buildings as demonstration projects and continue it by Providing incentives/subsidies for retrofitting existing buildings and permeable pavements to enhance on-site infiltration and delay runoff.
- Integrate pluvial flood vulnerability in to master plans to enhance infrastructural resilience and enforce Land-use regulations that help to promote avoiding large-scale increase in surface impermeability.
- For future study better data such as high-resolution LIDAR or updated aerial imagery could refine mapping of pluvial flooding. The inclusion of detailed drainage layouts and real-time measurements can help generate more specific flood prone areas. Extending the model to project future land-use or climate scenarios would help anticipate how flood susceptibility might change through time. Lastly using technological innovations to create more accurate map by using machine learning and training data-driven models on historical rainfall and landcover, it can also be enhanced by applying more accurate flood simulation models like random forest or logistic regression.

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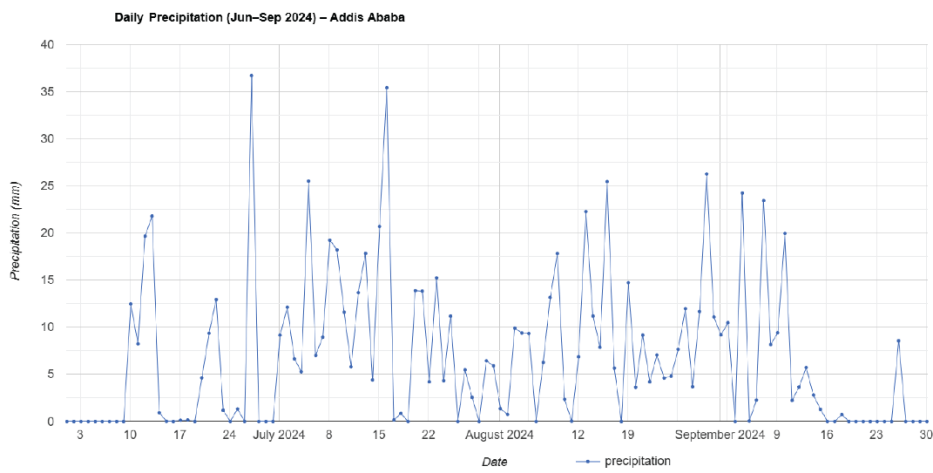
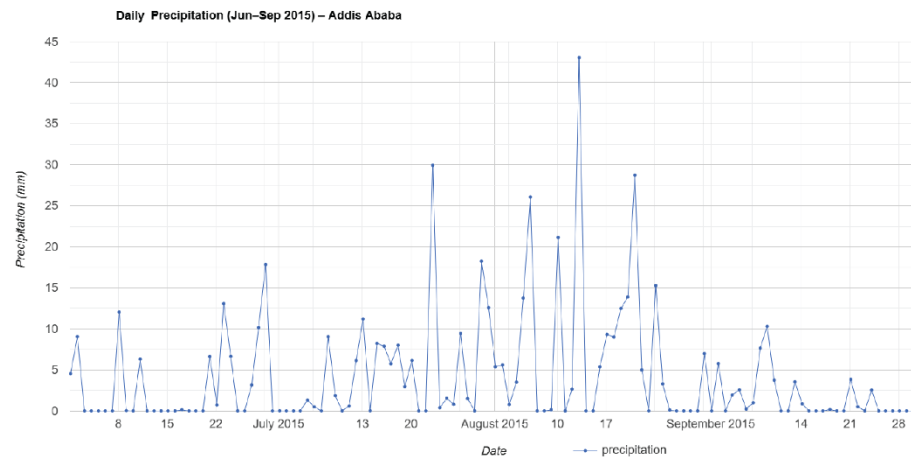
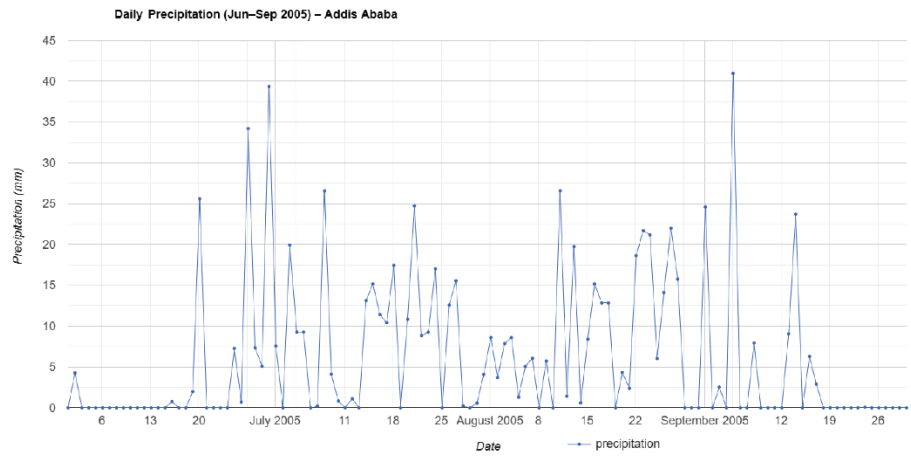
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# Annex



*Annex 1* Daily precipitation of rainy seasons 2005, 2015 & 2024

አደጋው የተከሰተበት ቀን	ከ/ከተማ	ወረዳ	ልዩ ቦታ	የአደጋው አይነት	ብዛት	የሞተሰው	የወደመ ንብረት
5/7/2015	ቦሌ	6	መገናኛ እግዚ. ቤ/ክ ጀርባ	የጎርፍ አደጋ	1	0	0
22/8/2015	ለሚኩራ	13	መሬ ሉኬ (ባድሜ ሰፈር)	የጎርፍ አደጋ	1	0	100,000
22/8/2015	ለሚኩራ	9	ፍየል ቤት	የጎርፍ አደጋ	1	0	100,000
23/8/2015	ለሚኩራ	5	አብሲኒያ ባንክ ሳሊተ ምህረት	የጎርፍ አደጋ	1	0	0
28/8/2015	አቃቂ	3	አቃቂ ብረታ ብረት ማቅለጫ	የጎርፍ አደጋ	1	0	20,000,000
29/8/2015	የካ	8	ድንበራ ምስራቅ አጠቃላይት/ቤት	የጎርፍ አደጋ	1	0	500
30/8/2015	አቃቂ	3	አቃቂ ብረታ ብረት ማቅለጫ	የጎርፍ አደጋ	1	0	5,000,000
30/8/2015	አቃቂ	1	ፊት አውራሪ ት/ቤት አካባቢ	የጎርፍ አደጋ	1	0	50,000
6/9/2015	ቂርቆስ	10	ፌደራል ወንጀል ምርመራ ግቢ ውስጥ	የጎርፍ አደጋ	1	0	0
7/9/2015	አቃቂ	3	አቃቂ ብረታ ብረት ማቅለጫ	የጎርፍ አደጋ	1	0	10,000,000
12/9/2015	ን/ስልክ	2	ሕብር ት/ቤት አካባቢ	የጎርፍ አደጋ	1	0	0
12/9/2015	የካ	8	ለም ሆኖ አብዮት ት/ቤት ጀርባ	የጎርፍ አደጋ	1	0	0
17/9/2015	ልደታ	6	ካርለ አደባባይ	የጎርፍ አደጋ	1	0	45,000
17/9/15	ን/ስልክ	2	ቴሌ ሰፈር	የጎርፍ አደጋ	1	0	200,000
3/10/2015	ኮልፌ	7	አስኮ ፊት አውራሪ ት/ቤት	የጎርፍ አደጋ	1	0	50,000
5/10/2015	አ/ከተማ	14	አስኮ ፊት አውራሪ ት/ቤት ለፊት	የጎርፍ አደጋ	1	0	0
7/11/2015	ለሚኩራ	7	ሰሜን ኮንደሚኒየም	የጎርፍ አደጋ	1	0	0
11/11/2015	አ/ከተማ	9	ኳስ ሜዳ ኮንደሚኒየም	የጎርፍ አደጋ	1	0	33,000
15/11/2015	ኮልፌ	4	ኪዳነ ምህረት ቤ/ክ ፊት ለፊት	የጎርፍ አደጋ	1	0	80,000
15/11/2015	ኮልፌ	7	ጥቁር አባይ	የጎርፍ አደጋ	1	0	10,000
21/11/15	ኮልፌ	7	ሜዳ መስኪድ	የጎርፍ አደጋ	1	0	300,000
10/12/2015	ን/ስልክ	1	አንድነት ህንጻአካባቢ	የጎርፍ አደጋ	1	0	0
10/12/2015	አቃቂ	4	ገላን ኮንደሚኒየም	የጎርፍ አደጋ	1	0	0
14/12/2015	ን/ስልክ	5	ጎፋ ገብርኤል	የጎርፍ አደጋ	1	0	0
17/12/2015	ቂርቆስ	6	ማንዴላ ካራ	የጎርፍ አደጋ	1	0	300,000
22/12/15	ን/ስልክ	12	ለቡሙብራት ሀይል	የጎርፍ አደጋ	1	0	0
22/12/15	ቂርቆስ	9	ደንበል ጀርባ	የጎርፍ አደጋ	1	0	25,000
5/13/2015	የካ	5	ሲግናል ጋር	የጎርፍ አደጋ	1	0	500,000
6/13/2015	ቂርቆስ	9	ደንበል ማርሻል ክሊሊክ	የጎርፍ አደጋ	1	0	20,000
<b>አጠቃላይ በ2015 የተከሰተ የጎርፍ አደጋ ብዛት</b>					<b>29</b>	<b>0</b>	<b>36,813,500</b>

Annex 2 Reported flooding in 2015 EC

አደጋው የተከሰተበት ቀን	ከ/ከተማ	ወረዳ	ልዩ ቦታ	የአደጋው አይነት	ብዛት	የሞተ ሰዎች	የወደመ ንብረት
4/1/2016	አቃቂ	10	መንደር 6	የጎርፍ አደጋ	1	0	0
4/1/2016	አቃቂ	5	ጥቁር አባይ ጎን	የጎርፍ	1	0	0
8/1/2016	አ/ከተማ	9	ኳስ ሜዳ	የጎርፍ አደጋ	1	0	50,000
21/6/2016	ኮልፌ	7	ቤቴል ደልያ ት/ቤት አካባቢ	የጎርፍ አደጋ	1	0	200,000
21/6/2016	ቦሌ	14	ገርጂ መብራት	ጎርፍ አደጋ	1	0	0
25/7/2016	ቦሌ	7	ጎለጎል ደንበል አካባቢ	የጎርፍ አደጋ	1	0	165,000
25/7/2016	አራዳ	9	ቤተክህናት ጊቢ ውስጥ	የጎርፍ አደጋ	1	0	0
12/8/2016	ን/ስልክ	11	አ/አ ኮንዶሚኒየም	የጎርፍ አደጋ	1	0	500000
15/10/16	አ/ከተማ	9	ኬቴ ተራ መሳለሚያ	የጎርፍ አደጋ	1	0	-
15/10/16	አ/ከተማ	14	ፊት አውራሪ ት/ቤት	የጎርፍ አደጋ	1	0	-
15/10/16	አ/ከተማ	14	ብርጭቆ አካባቢ	የጎርፍ አደጋ	1	0	-
8/11/2016	አቃቂ	6	ቀጠና ዘጠኝ/ቶራ ቦራ	የጎርፍ አደጋ	1	0	205,000
29/11/16	የካ	6	ካሳንቺስ መለስ ፋውንዴሽን አጠገብ	የጎርፍ አደጋ	1	0	100,000
29/11/16	የካ	9	ጉድር ሾላ ቴሌ ፊት ለፊት	የጎርፍ አደጋ	1	0	-
29/11/16	የካ	9	ጉድር ሾላ ቴሌ ፊት ለፊት	የጎርፍ አደጋ	1	0	-
29/11/16	ቂርቆስ	7	አምባሳደር አካባቢ	የጎርፍ አደጋ	1	0	50,000
29/11/16	ቂርቆስ	7	ፊንፊኔ ምግብ አዳራሽ	የጎርፍ አደጋ	1	0	500,000
29/11/16	አራዳ	9	አምባሳደር ሞል	የጎርፍ አደጋ	1	0	-
29/11/16	ቂርቆስ	9	ደምበል ጀርባ	የጎርፍ አደጋ	1	0	20,000
30/11/16	የካ	9	ጉድር ሾላ ቴሌ ፊት ለፊት	የጎርፍ አደጋ	1	0	-
1/12/2016	ን/ስልክ	1	ሀይሌ ጋርመንት አሮሚያ ኮንዶሚኒየም	የጎርፍ አደጋ	1	0	250,000
2/12/2016	ልደታ	10	አፍሪካ ት/ቤት	የጎርፍ አደጋ	1	0	50,000
2/12/2016	ልደታ	6	ካርል አደባባይ	የጎርፍ አደጋ	1	0	1,550,000
2/12/2016	ኮልፌ	9	ሆላንድ ኤምባሲ አካባቢ	የጎርፍ አደጋ	1	0	100,000
8/12/2016	አ/ከተማ	9	ኳስ ሜዳ እድት ጽ/ቤት አካባቢ	የጎርፍ አደጋ	1	0	-
9/12/2016	አቃቂ	3	ቦሎቄ ወፍሬቤ ቤት አጠገብ	የጎርፍ አደጋ	1	0	7,000,000
19/12/16	ቂርቆስ	9	ደንበል ጀርባ	የጎርፍ አደጋ	1	0	10,000
30/12/16	ቂርቆስ	10	ሜክሲኮ ወንጀል ምርመራ ጀርባ	ጎርፍ ቤት ውስጥ መግባት	1	0	20,000
5/13/2016	ን/ስልክ	1	ጀም አፍሪካ ህንፃ ጀርባ	የጎርፍ አደጋ	1	0	-
<b>አጠቃላይ በ2016 የተከሰተ የጎርፍ አደጋ ብዛት</b>					29	0	10,770,000.00

Annex 3 Reported flooding in 2016 EC



*Annex 4 Case study area supplementary images*

## **Key informant questions**

1. What are the main causes of pluvial flooding in Addis Ababa?
2. Which areas in the city are most frequently affected by pluvial flooding?
3. What drainage infrastructure is currently in place to manage stormwater and prevent pluvial flooding?
4. How effective is the city's drainage system in managing pluvial flooding?
5. How often does AARCA inspect and maintain the urban drainage system.
6. Are there any ongoing or planned projects to improve flood resilience in Addis Ababa?
7. Does AARCA/ Fire department maintain a database of flood events in the city? If yes, can this data be accessed for research?
8. How does AARCA / AAWSA / Fire department engage with the public in raising awareness about flood risks and safety?
9. What policies or regulations exist to control urban development in flood-prone areas?
10. How is climate change being considered in flood risk management strategies?
11. Is there any collaboration with other agencies or academic institutions on urban flood modeling or mitigation?
12. What infrastructure improvements can help reduce pluvial flooding?

*Annex 5 Key informant questions*

## **Geospatial approach to pluvial flood susceptibility modelling using AHP in Addis Ababa, Ethiopia**

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### **Abstract**

Urbanization heightens pluvial flooding in developing cities like Addis Ababa, where expansion increases impervious surfaces and stresses drainage infrastructure. pluvial flood susceptibility was mapped in this study using Remote Sensing (RS), Geographic Information Systems (GIS), and the Analytic Hierarchy Process (AHP). The weights were assigned to the flood influencing factors such as slope, elevation, rainfall, land use/land cover (LULC), drainage density, Topographic Wetness Index (TWI), NDVI, and road proximity. The finding indicates that 55.65% (237.28 km<sup>2</sup>) of Addis Ababa is situated under high susceptibility, and 6.95% (29.63 km<sup>2</sup>) under very high risk. vegetated highlands in the north had lower exposure while the central part of the city like arada, lideta and addis ketema sub-cities with high urbanization, low slopes and poor drainage were mostly exposed. The 55 documented floods aligned with susceptibility mapping with 97% of events taking place in high or very high-risk areas, respectively. The finding highlights the overwhelming influence of topography and impervious surfaces on flood characteristics emulating global trends of urban vulnerability. This study offers the spatial basis for prioritizing infrastructure improvement and helps to incorporate nature-based solutions into the Addis Ababa drainage master plan. The city can reduce the effects of pluvial flooding under population growth and climate change by applying a coordinated approach of urban development with hydrological resilience.

**Keywords:** Analytic Hierarchy Process (AHP), Flood susceptibility, GIS, Pluvial flooding, Remote Sensing

## **Introduction**

Urbanization is a global phenomenon that is unfolding worldwide. Presently, approximately 50% of the global population resides in urban regions, and this figure is predicted to rise mainly in developing nations (Farrell, 2017). According to the United Nations Department of Economic and Social Affairs (UNDESA, 2019), it is projected that by 2050, 90% of the growth in urban population will occur in Asian and African cities, resulting in a net addition of 2.5 billion people to urban areas worldwide.

The rapid urban growth has already given rise to numerous environmental challenges, including extreme weather events, elevated energy consumption, pollution, habitat destruction, and the depletion of cultivated land (Wang et al., 2019). In light of the current and future urbanization trends, these challenges are expected to worsen, mostly in the developing world (UNDP and UNHabitat, 2013).

Flooding is a predominant natural disaster that is common internationally, causing considerable economic, environmental, physical, and social impacts in both the short and long term (National Research Council, 2009). In the 21st century, floods have accounted for nearly half of all disaster incidents and fatalities related to natural disasters worldwide (Zhang et al., 2023). It arises when the volume of water surpasses the capacity of the natural or man-made systems designed to contain or convey it under current conditions (Getahun & Gebre, 2015).

In the city of Addis Ababa, the frequent occurrence of severe flooding during the rainy seasons is aggravated by a noteworthy increase in stormwater run-off accumulating in the city's low-lying areas (Muschalla & Ostrowski, 2002). The most pressing issue caused by urbanization is pluvial flooding, due to inefficient management of stormwaters. Furthermore, drainage infrastructures are typically strained since more spaces are occupied by impervious surfaces, further generating surface runoff.

Conventionally, the focus in urban flooding studies has predominantly centered on fluvial (stream/river) or coastal flooding (Guerreiro et al., 2017). One of the most critical matters is the lack of a recent pluvial flood risk map. Without detailed assessments of flood-prone areas, it becomes difficult for planners to implement effective mitigation strategies and allocate resources efficiently (Birhanu et al., 2016). This study aims to map the parts of Addis Ababa that are

susceptible to pluvial flooding. based on Remote Sensing (RS), Geographic Information Systems (GIS), and Analytical Hierarchy Process (AHP). The findings of the study will significantly enhance pluvial flood monitoring, risks, and potential hazards, and provide technical support for spatial planning decisions.

## 2. Materials and Methods

### 2.1. Description of the Study area

Ethiopia's capital and its largest city Addis Ababa was established in 1987 and is located at coordinates 9° 0' 19.4436" N and 38° 45' 48.9996" E. The city is divided into 11 sub-cities and 116 districts, locally known as "Weredas" As of 2022. Although there were 2.7 million people living there as of the 2007 population census, estimates from a number of sources, including UN-Habitat reports, indicate that the current population is over 4 million. The city receives about 1,200 mm of rainfall on average each year, with half of that falling between June and August during the rainy season. Due to the city's rapidly expanding impermeable surface, floods are common during this rainy season (McFarland et al. 2019).

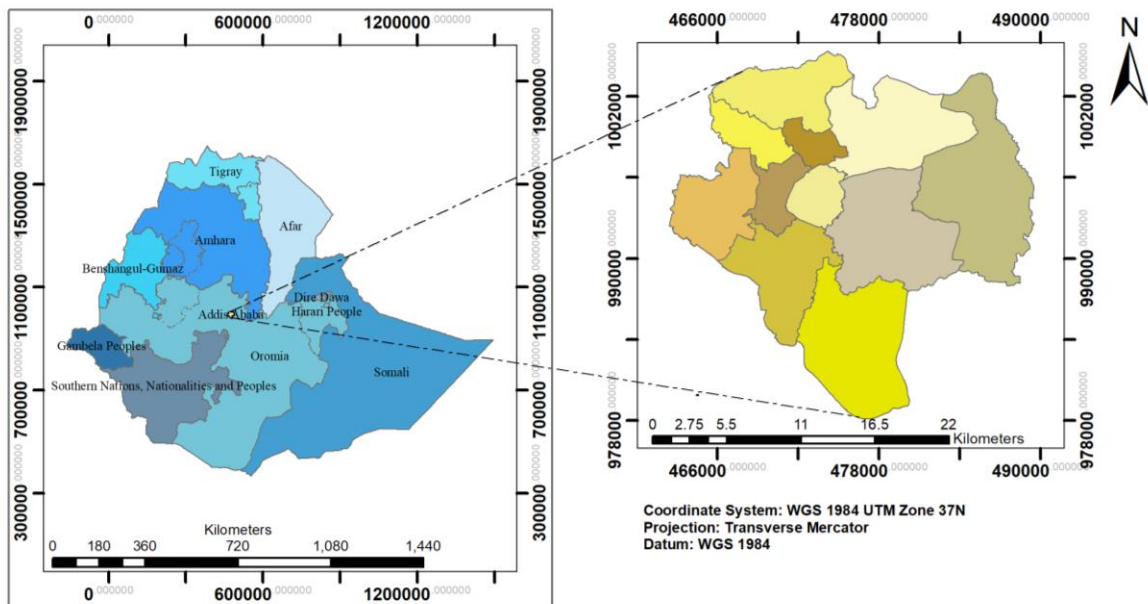


Figure 1 Location of study area

## 2.2. Type and source of data

The study compiled data from multiple reliable sources. A 30-meter resolution SRTM Digital Elevation Model (DEM) alongside Landsat 5, 7, and 8 satellite imagery with minimal cloud cover for land use landcover was extracted and downloaded from the United States Geological Survey (USGS) Earth Explorer. Road network data of the city was sourced from the Addis Ababa City Roads Authority and BBBike. Rainfall records were acquired from two sources one being the National Meteorological Agency of Ethiopia and the other being the Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS).

*Table 1 Summary of data types & sources*

Data Type	Description	Sources	Relevance	Date Acquired
Precipitation	Annual rainfall /daily rainfall	The national meteorological agency/ CHIRPS	Generation of rainfall layer	2025
SRTM (DEM)	topography	USGS	Generation of slope, elevation, DD, TWI	2025
Landsat 5,7 &8 OLI	Arial imagery	USGS	Land use land cover classification, generation of NDVI	2025
Road networks	Road network	Addis Ababa city roads authority / BBBike.	Distance to road	2025

## 2.3. Method of data analysis

### Spatial Analysis

This study takes an empirical approach by integrating Remote Sensing (RS) data within a GIS framework and applying the Analytical Hierarchy Process (AHP) for weight assignment to develop a flood hazard map tailored to the specific characteristics of the study area. The combination of RS data, GIS, and AHP proves to be a powerful methodology for assessing flood risk.

### *Topographic Wetness Index (TWI)*

The TWI represents spatial moisture within an area, it's a key factor in mapping flood-susceptibility models. The potential of water permeability in each region is calculated by the topographic wetness index (Nguyen et al., 2022). The TWI is typically constructed based on

information about the slope and flow accumulation of an area as shown in (Equation 1). Areas that are highly susceptible to flooding have higher TWI, capable of retaining more water (Costache et al., 2020).

$$TWI = \ln \left( \frac{\alpha}{\tan \beta} \right) \dots \dots \dots \text{Equation 13}$$

The  $\beta$  is the slope of each grid cell in the model which was calculated using elevation data and  $\alpha$  represents the flow accumulation, showing the capability to channel water from a point on the map to the main drainage point.

***Drainage density***

Flow Accumulation values as an Input raster were used to generate a Stream Network using the Con tool under the Conditional tool. It created a raster where cells with flow accumulation above the threshold were considered part of the stream network. To convert the binary stream raster to a polyline, feature The Stream to Feature tool under Hydrology was used. The DD was derived from the Line Density tool in Density under the Spatial Analyst Toolbox.

$$\text{Drainage density (Dd)} = \frac{\text{Total Length of Streams}}{\text{Area of the Watershed}} \dots \dots \dots \text{Equation 14}$$

***Normalized difference vegetation index (NDVI)***

The coefficient for assessing vegetation health and density is called NDVI, which is widely used to identify flood events (Ali et al., 2020). Vegetative cover plays a crucial role in mitigating flood susceptibility by interrupting water flow, increasing delay times, and reducing flood hazards, whereas deforested areas can intensify water force and soil erosion, consequently elevating flood susceptibility (Parvin et al., 2022). Areas with higher vegetation indices are less prone to flood compared to those with Lower vegetation indices. In the current study, the NDVI was computed using the Landsat 8 dataset where Bn5 and Bn4 are near-infrared bands and red bands, respectively.

$$NDVI = \frac{Bn5 - Bn4}{Bn5 + Bn4} \dots \dots \dots \text{Equation 15}$$

### ***Land use classification***

The study area's current state was assessed visually using imagery, its spectral and spatial resolution, and the availability of different land types to determine the number of LULC classes. The classification's fineness, and the output's intended use. In order to perform preliminary investigations, high-resolution images of the city were viewed on Google Earth Pro. Built-up areas, vegetation, wetlands and/or water bodies, green spaces, open land, and cropland are examples of common land use classes in urban environments (Gashu and Gebre-Egziabher, 2018). since there were no water bodies visible on the images the LULC class was omitted from this research. The selected LULC classes are shown in the (table 4)

**Table 2** LULC classification

<b>LULC Class</b>	<b>Definition</b>
<b>Urban/Built-up</b>	Areas of intensive use covered by structures residential (high- to low-density), commercial, industrial, institutional, transportation, utilities, and mixed uses.
<b>Forest</b>	Dense tree covers, providing canopy and vegetation cover; includes deciduous, evergreen, and mixed.
<b>cropland</b>	Land used primarily for cultivating seasonal crops like grains or vegetables e.g., Agricultural Land, pasture, orchards.
<b>Rangeland</b>	Land where potential natural vegetation is predominantly grasses, grass-like plants, forbs, or shrubs, shaped by natural herbivory; may include brushlands and seeded areas.
<b>Barren Land</b>	Land with limited ability to support life thin soils, sand, or rock exposures (e.g., beaches, salt flats, quarries, rock outcrops).

*(Source: Anderson et al., 1976)*

### ***The AHP weight allocation process***

The Analytic Hierarchy Process (AHP) is a decision-making system that involves multiple criteria by assigning weights to each criterion. This method evaluates various parameters and ranks them according to a set of criteria (Saaty, 2008), The AHP allows the evaluation of quantitative, qualitative, and complex criteria and factors on a similar scale (Hoang and Kato, 2023). In the original stage, as proposed by Saaty in 1980, criteria, sub-criteria, and decision alternatives were developed in alignment with the study's objectives.

Within this, the pairwise comparison method is a powerful tool that helps decision-makers subjectively determine the significance weights of each criterion in a study, thus creating a

common system for decision-making processes grounded on multiple attributes (Yadollahi and Rosli, 2011). For this study, eight parameters that influence flooding precipitation, drainage density, land use/land cover (LULC), elevation, slope, TWI, NDVI, and distance to road were considered as measures. The Saaty scale, which ranges from 1 to 9, was useful to gauge each factor and its subclasses in relation to the other factors and subcategories as shown in (table .3).

*The pairwise comparison matrix*

$$M = \begin{pmatrix} 1 & a_{12} & a_{13} & \dots & a_{1n} \\ a_{21} & 1 & a_{23} & \dots & a_{2n} \\ a_{31} & a_{32} & 1 & \dots & a_{3n} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & a_{n3} & \dots & 1 \end{pmatrix} \dots \dots \dots \text{Equation 16}$$

*Equation to determine the weighting of each attribute*

$$a_{ij} = \frac{\text{weight of attribute } i}{\text{weight of attribute } j} \dots \dots \dots \text{Equation 17}$$

**Table 3** AHP scale of pairwise comparison matrix

<b>Intensity of Importance</b>	<b>Definition</b>	<b>Explanation</b>
<b>1</b>	Equal importance	Two activities contribute equally to the objective
<b>3</b>	Moderate importance	Experience and judgment slightly favor one activity over another
<b>5</b>	Strong importance	Experience and judgment strongly favor one activity over another
<b>7</b>	Demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
<b>9</b>	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
<b>2, 4, 6, 8</b>	Intermediate values	Used for compromise between the above values

(Source: Saaty ,2008)

**Table 4** Classes and ratings of the flood-conditioning factors

<b>Parameter</b>	<b>slope</b>	<b>LULC</b>	<b>Distance to road</b>	<b>drainage density</b>	<b>TWI</b>	<b>rainfall</b>	<b>NDVI</b>	<b>elevation</b>
<b>slope</b>	1	1	2	3	3	4	4	4
<b>LULC</b>	1	1	1	3	2	4	4	4
<b>Distance to road</b>	1/2	1	1	2	2	4	3	4
<b>drainage density</b>	1/3	1/3	1/2	1	1	1	2	2
<b>TWI</b>	1/3	1/2	1/2	1	1	1	1	1
<b>rainfall</b>	1/4	1/4	1/4	1	1	1	1	1
<b>NDVI</b>	1/4	1/4	1/3	1	1	1	1	1
<b>elevation</b>	1/4	1/4	1/3	1	1	1	1	1

(Source: computed by the author)

**Table 5** Normalized pairwise comparison matrix.

<b>Parameter</b>	<b>slope</b>	<b>LULC</b>	<b>Distance to road</b>	<b>drainage density</b>	<b>TWI</b>	<b>rainfall</b>	<b>NDVI</b>	<b>Elevation</b>	<b>Average</b>
<b>slope</b>	0.225	0.218	0.338	0.250	0.250	0.235	0.235	0.240	0.25
<b>LULC</b>	0.225	0.218	0.169	0.250	0.167	0.235	0.235	0.240	0.22
<b>Distance to road</b>	0.128	0.218	0.169	0.167	0.167	0.235	0.176	0.180	0.18
<b>drainage density</b>	0.085	0.073	0.085	0.083	0.083	0.059	0.118	0.120	0.09
<b>TWI</b>	0.085	0.109	0.085	0.083	0.083	0.059	0.059	0.060	0.08
<b>rainfall</b>	0.064	0.055	0.042	0.083	0.083	0.059	0.059	0.060	0.06
<b>NDVI</b>	0.064	0.055	0.056	0.042	0.083	0.059	0.059	0.060	0.06
<b>Elevation</b>	0.064	0.055	0.056	0.042	0.083	0.059	0.059	0.060	0.06
<b>sum</b>	1	1	1	1	1	1	1	1	1

(Source: computed by the author)

## 2.4. methodological framework of the study

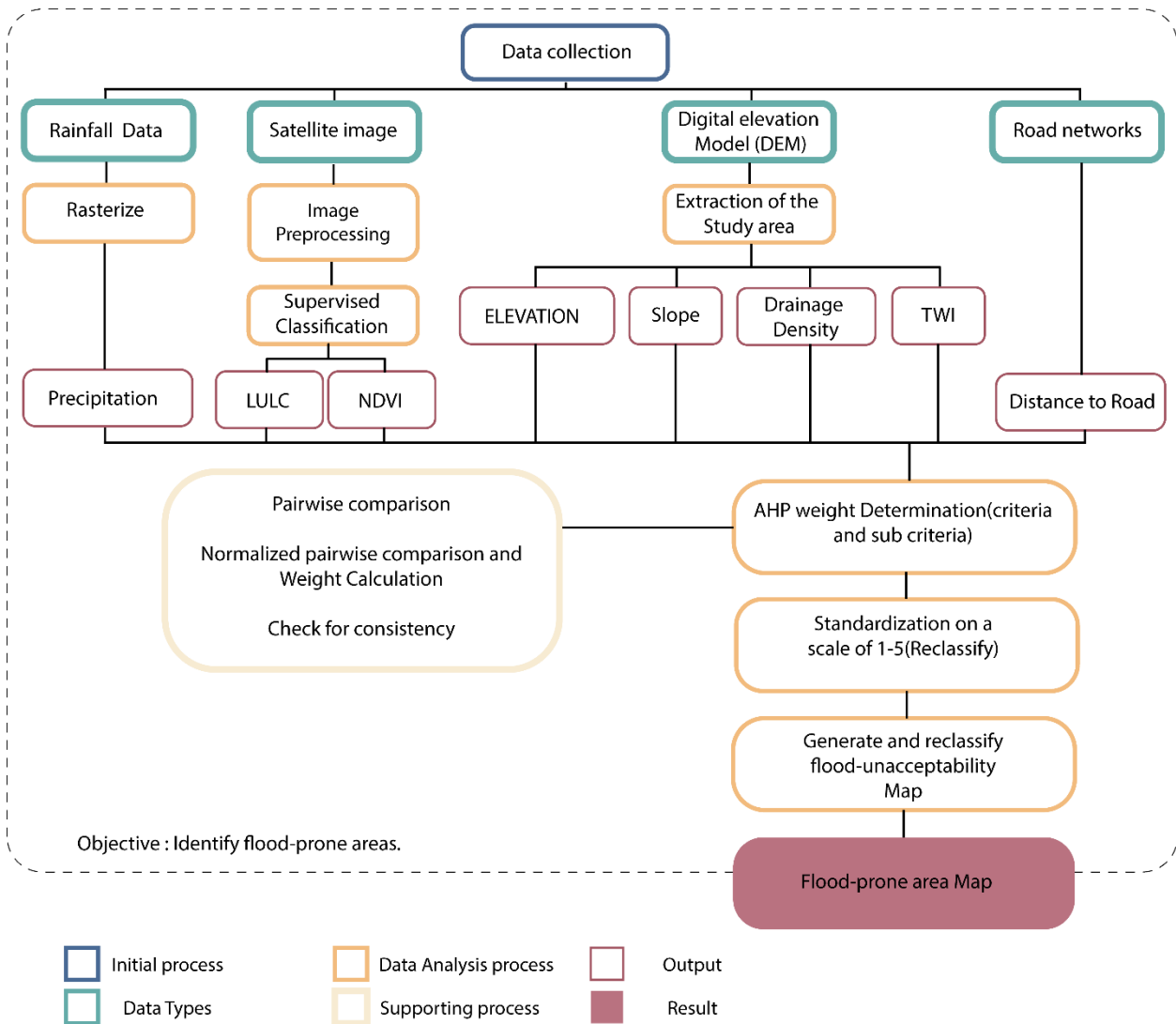


Figure 2 Methodological frame work of the study

### **3. Results and Discussion**

#### **3.1. Results**

##### **Identifying flood-prone areas**

Identifying flood-prone areas has criteria that vary across regions, this research applies a composite pluvial flood vulnerability index integrating eight key factors: slope gradient, elevation, proximity to roads, rainfall intensity, Land use /Land cover (LULC), topography wetness index (TWI) and Normalized Difference Vegetation Index (NDVI). These flood influencing factors are assessed systematically and combined to evaluate their implication on flooding with the AHP model by weighting and prioritizing each factor based on their contribution to pluvial flooding.

##### **3.1.1. Multi-influencing factors of flood-susceptible zone**

###### ***Slope***

The slope plays a key role in determining surface or subsurface drainage in a specific area or outlet. Higher slopes tend to experience surface runoff issues, while flatter surfaces are prone to water accumulation. In contrast, local depressions, which are cells in a digital elevation model with lower elevation than their surroundings, are more susceptible to pluvial floods.

The slope map (Fig. 4A) was derived through analysis of DEM data; it reveals substantial difference between types of topography. The slopes are classified into five categories: 0-3.4° (very gentle), 3.4-6.9° (gentle), 6.9-11.3° (moderate), 11.3-17.9° (steep), and 17.9-42° (very steep). The spatial distribution of the very gentle slopes mainly lies in the central, southern, and eastern parts of Addis Ababa. On the other hand, the steeper slopes are situated near the northern part of the city near Entoto and alongside rivers that run through all over Addis Ababa.

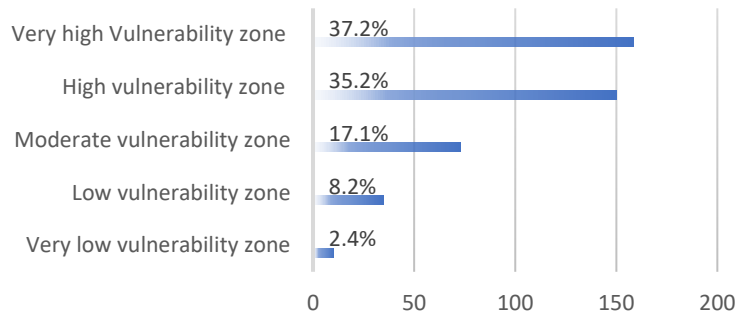


Figure 3 slope percentage and area coverage

The city's vulnerability zone is categorized into five levels, covering a total area of 430.1 km<sup>2</sup>. The smallest area is the very low vulnerability zone which accounts for 10.3 km<sup>2</sup> (2.4%). While the low vulnerability zone covers 35.9 km<sup>2</sup> (8.2%). The moderate vulnerability zone spans around 73.9 km<sup>2</sup> (17.1%), followed by the high vulnerability zone at 150.2 km<sup>2</sup> (35.2%) and finally, the very high vulnerability zone has the largest portion at 159.7 km<sup>2</sup> (37.2% of the total area). This distribution shows that 70% of the region falls within high to very high vulnerability classes.

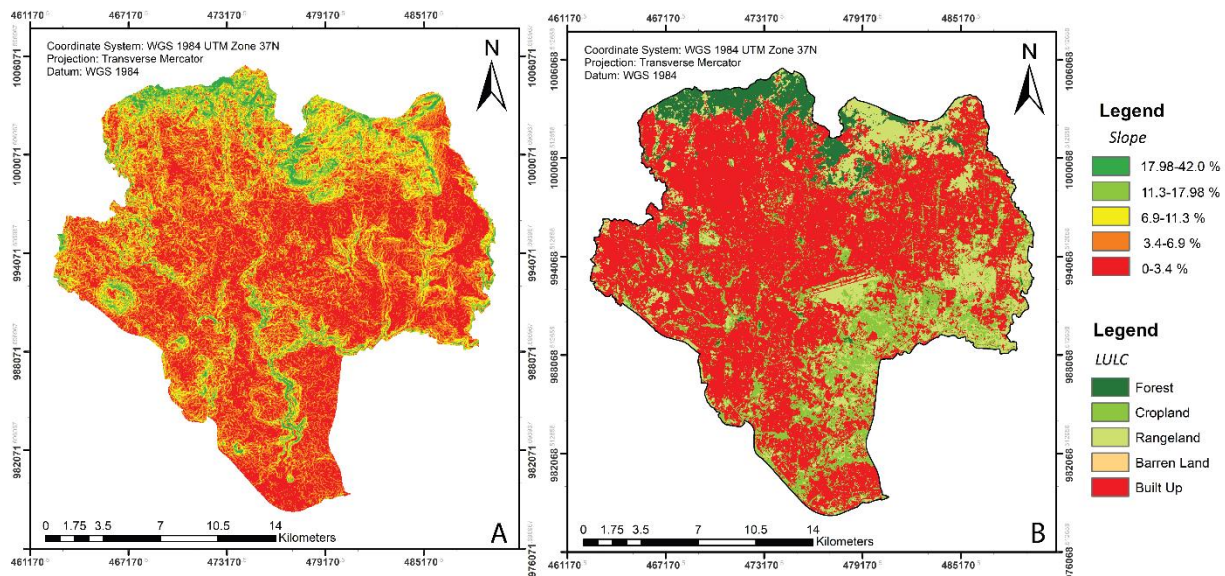


Figure 4 A) Slope map B) Land use Land cover map

**LULC (land use and land cover)**

The land use and land cover (LULC) map delineated five main categories: agricultural land, forest, rangeland, barren land, and built-up areas. The map highlighted the spatial arrangement of these land types, underlining their environmental significance to pluvial flooding, the city center and the

eastern part are predominantly covered with the built-up area which is highly susceptible to pluvial flooding, and the southeastern and northern parts of the city is covered by cropland, rangeland and forests which is less susceptible to flooding.

The city's land use distribution reveals the smallest portion is barren land spanning only 0.2 km<sup>2</sup> which is 0.05% of the total area, forests also account for a smaller share with 23.17 km<sup>2</sup> (5.47%). Cropland and rangeland occupy larger areas compared to barren land and forests, they account for 69.93 km<sup>2</sup> (16.37%) and 67.22 km<sup>2</sup> (15.50%) respectively. The dominance of built-up areas is clearly seen in (Fig. 4B) with a cover of 268.36 km<sup>2</sup> (62.62% of the total 430.1 km<sup>2</sup>).

**Table 6** LULC area coverage

LULC Classification	Area	percentage
Forest	23.17 km <sup>2</sup>	5.47%
Cropland	69.93 km <sup>2</sup>	16.37%
Rangeland	67.22 km <sup>2</sup>	15.50%
Barren land	0.2 km <sup>2</sup>	0.05%
Built up	268.36 km <sup>2</sup>	62.62%
Total area	430.08 km <sup>2</sup>	100.00%

### **Normalized Difference Vegetation Index (NDVI)**

The presence of vegetation significantly reduces flood risk by reducing water movement and extending the duration of runoff. On the other hand, no vegetated zones increase the speed and power of water runoff leading to flood vulnerability. The normalized difference index (NDVI) helps to measure vegetation vitality and density, NDVI scores span from -1 to +1, with values closer to +1 showing thicker, healthier vegetation.

**Table 7** NDVI area coverage

NDVI value	Area (km <sup>2</sup> )	Percentage (%)
-0.19-0.07	31.50	7.32%
0.07-0.11	68.80	16.00%
0.11-0.17	93.61	21.76%
0.17-0.24	121.22	28.18%
0.24-0.54	114.96	26.78%
Total	<b>430.1</b>	<b>100.00%</b>

The NDVI map of Addis Ababa (Fig. 5A) shows five categories of vegetation density measured by NDVI

(Normalized Difference Vegetation Index). The total area of the study area is 430.1 km<sup>2</sup> with varying vegetation density in these NDVI categories. The lowest range (-0.19 to 0.07) which is non-vegetated covers 31.50 km<sup>2</sup> or 7.32% of the total area. Slightly higher vegetation density (0.07–0.11) covers 68.80 km<sup>2</sup> (16.00%), moderate vegetation (0.11–0.17) covers 93.61 km<sup>2</sup> (21.76%), relatively healthy vegetation (0.17–0.24) covers 28.18% (121.22 km<sup>2</sup>) and dense vegetation (0.24–0.54) covers 114.96 km<sup>2</sup> (26.78%).

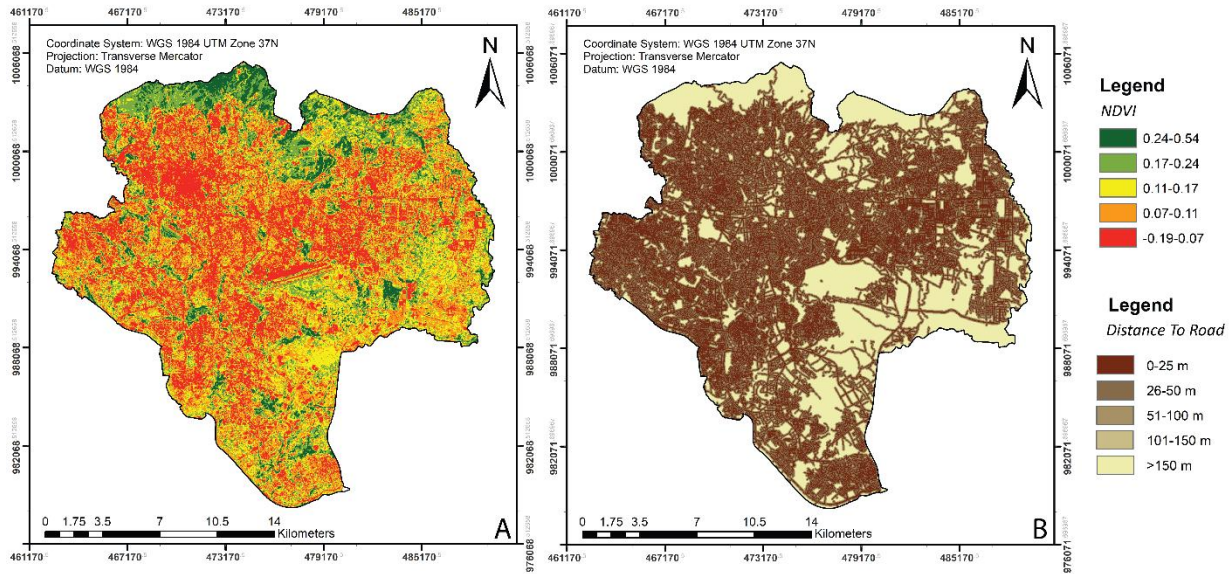


Figure 5 A) Normalized difference vegetation index (NDVI) map B) Distance to Road map

### ***Distance to Road***

Distance to road is an important aspect of pluvial flooding because road construction increases impermeable surfaces and alters natural topography affecting hydrological processes thus areas closer to roadways experience higher runoff during heavy rainfall. In addition, roads can channel water along their path obstructing its natural movement. Moreover, flood vulnerability can increase due to inadequate drainage systems that disrupt surface water flow and accumulate stormwater runoff.

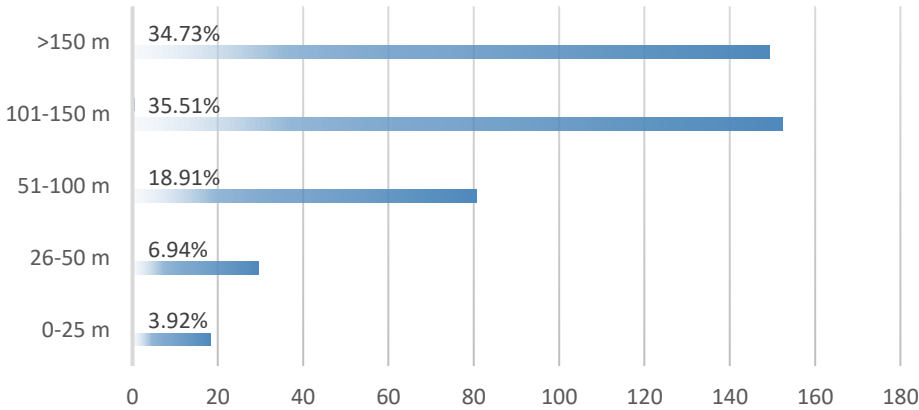


Figure 6 Distance to road - Area coverage

The farthest areas from the road cover 149.32 km<sup>2</sup>, and the second area that is relatively farther to the road falls within the 101-150 m range, covering 152.39 km<sup>2</sup> (35.51%), which is the largest of all the different values. Mid-range distances of 51-100 m from the road constitute 80.57 km<sup>2</sup> (18.91%); the second closest range is 26-50 m, which accounts for 29.56 km<sup>2</sup> (6.94%). The road-adjacent zones that lie between 0 and 25 cover 18.26 km<sup>2</sup>, representing 3.92% of the total area, which is the smallest of all the categories. The map (Fig. 5B) clearly shows a concentration of areas with distances above 100m from the road, signifying their lesser susceptibility to flooding.

### ***Elevation***

Elevation is an important factor for flood vulnerability, lower-lying areas are typically having a greater chance of risk due to their tendency to accumulate water. In contrast, places with higher elevations are generally less susceptible since they are less likely to experience water inundation. Although Addis Ababa's terrains gradually decrease from the mountainous areas at the north to the southern part of the city pluvial flooding can occur in the central part of the city due to flatter areas that are depressed from the surrounding terrain.

The elevation of Addis Ababa is classified into five major categories, the highest elevation near Mount Entoto has a range that spans from 2830 to 3020 meters covering an area of 32.06 km<sup>2</sup>. The second category with a slightly lower elevation encompasses the 2,636–2,830-meter range, which occupies a larger area of 69.24 km<sup>2</sup>, followed by the 2,442–2,636-meter zone with 119.59 km<sup>2</sup>. The mid-elevation bracket 2,248–2,442 meters, covering 133.54 km<sup>2</sup> has the largest area which

includes most of the central areas of the city (Fig. 7A). Lastly, the lowest elevation category, 2,050–2,248 meters, comprises 75.83 km<sup>2</sup> and is located in the southern part of the city near Kality.

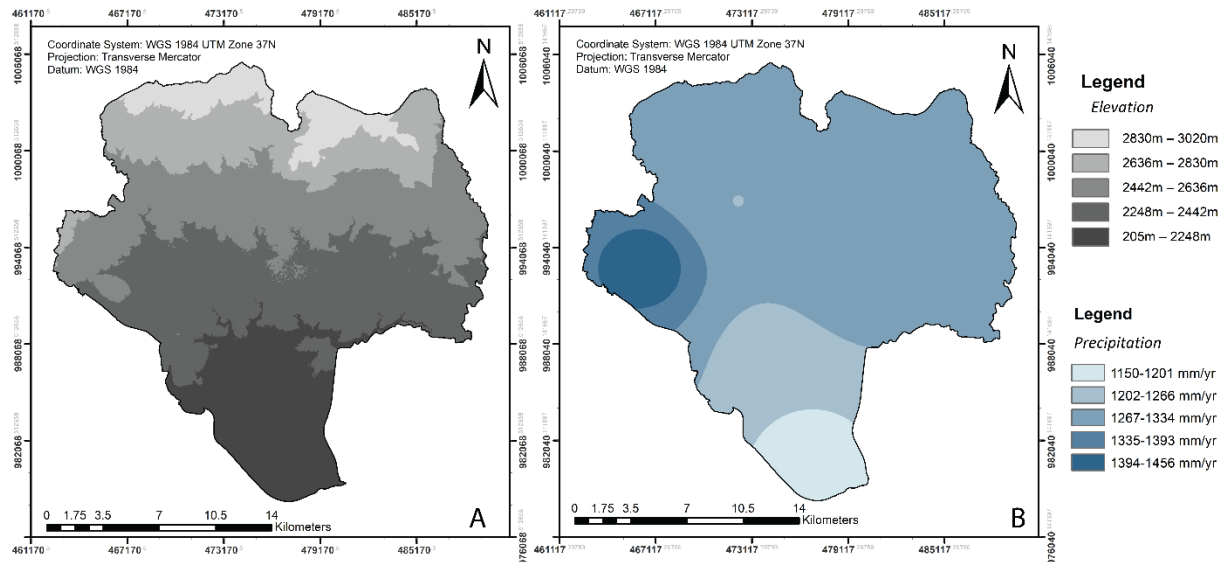


Figure 7 A) Elevation map B) Precipitation map

### ***Precipitation***

This study utilizes annual rainfall data to analyze long-term patterns and their influence on flood vulnerability in the city. Even though studying short-term extreme rainfall events is vital to assessing pluvial flooding risks, annual data shows an in-depth insight into how collective precipitation trends impact flooding. Moreover, the rainy season alone contributes to 60-65% of the city’s total yearly rainfall. Areas with higher annual precipitation exhibit more flood susceptibility due to increased runoff, whereas regions with lower rainfall face less vulnerability.

There are five categories span across a total area of 430.10 km<sup>2</sup> based on annual rainfall ranges. The higher the rainfall brackets the more it is susceptible to flooding, higher ranges of 1394-1456 mm/yr and 1335-1393 mm/yr account for smaller portions: 22.70 km<sup>2</sup> (5.28%) and 19.24 km<sup>2</sup> (4.47%), respectively. Areas with rainfall of 1150-1201 mm/yr cover 28.17 km<sup>2</sup> (6.55%) and the second-largest segment, 58.27 km<sup>2</sup> (13.55%), falls within the 1202-1266 mm/yr range. The majority of the area, 301.72 km<sup>2</sup> (70.15%), experiences rainfall between 1267-1334 mm/yr, making it the dominant category as seen in (Fig. 7B). Together, these classifications comprehensively represent the distribution of rainfall across the city.

### ***Drainage Density***

Drainage density is another important factor for pluvial flooding its derived from the total length of streams within a watershed divided by the watershed area. Areas with higher drainage density are more prone to flooding because of larger surface water flows while a lower density indicates less susceptibility.

The drainage density distribution shows significant variation across the area, the lowest density range (0–0.25 km/km<sup>2</sup>) covers the largest area at 137.42 km<sup>2</sup> following that is the 0.25–0.5 km/km<sup>2</sup> range, which spans 171.02 km<sup>2</sup>. The lower-density categories take up the majority of Addis Ababa. Progressively smaller areas are associated with higher density ranges: 0.5–0.75 km/km<sup>2</sup> and 0.75–1 km/km<sup>2</sup> covering an area of 71.02 km<sup>2</sup> & 36.86 km<sup>2</sup> respectively, the highest density category (1–2.71 km/km<sup>2</sup>) only covers 10.83km<sup>2</sup>. This map highlights the inverse relationship between drainage density and spatial coverage, with high drainage density occupying a smaller area of the total landscape.

#### ***TWI (topographic wetness index)***

The topographic wetness index is a necessary tool for determining susceptibility by analyzing the distribution within a catchment. It is developed from the slope of the study area and flow accumulation data; it delineates areas with low elevation and higher water retention thus making it more flood-prone. Higher TWI values are flat areas that are naturally wetter, and lower values are relatively drier.

The topographic wetness index is divided into five different categories, with varying levels of hydrological influence. The lowest range (3.6–6.29) covers 137.42 km<sup>2</sup> which is the second largest in area signifying more areas that are relatively drier. The next category (6.29–7.82) shows moderately wet conditions and takes up the largest area at 171.02 km<sup>2</sup>. Areas with higher wetness potential (7.82–9.78) occupy 71.02 km<sup>2</sup>, followed by significantly wetter zones (9.78–12.84) encompassing 36.86 km<sup>2</sup>. The most water accumulation-prone landscape with a value of (12.84–22.16) only covers an area of 10.83 km<sup>2</sup> which is the smallest of all the categories. The distribution shows a gradual decrease in coverage as the value increases and moderate wetness dominates the study area.

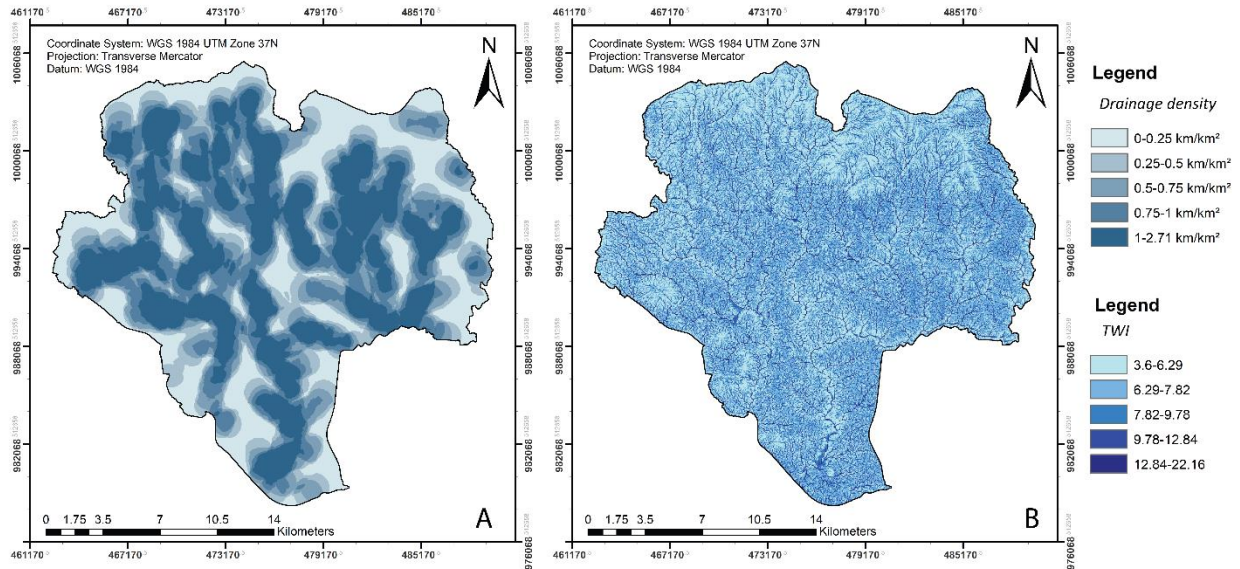


Figure 8 A) Drainage Density map B) TWI (topographic wetness index) map

### 3.1.2. Interrelationship and pairwise comparisons

From the eight flood-influencing factors, slope, and land use /landcover (LULC) emerge as the most critical factors, rated more influential than rainfall, NDVI, or elevation. Distance to road holds more weight than drainage density and TWI but has a lower influence than slope and LULC. Drainage density and TWI are more significant than rainfall, NDVI, and elevation usually elevation and rainfall hold more influence in pluvial flooding but in the case of Addis Ababa city the precipitation per year has lower variation between different zones signifying equal importance between the lower value and the highest value, it is also applicable for elevation since the elevation of the city gradually decrease from mountainous region on the north side to southern part of Addis Ababa overlooking the smaller pockets of recessed landforms.

After assigning different values for flood influencing factors the pairwise comparison matrix is done using the Analytic Hierarchy Process (AHP), the validation of the process shows a Consistency Index (CI) of 0.023958 and a Random Consistency Index (RCI) of 1.14 used for the eight factors and the calculated Consistency Ratio (CR) is 0.021016, which is well below the acceptable threshold of 0.1 confirming that the pairwise comparison is logically consistent and free from contradictions. For further validation, the lambda ( $\lambda$ ) value 8.16 represents the mathematical coherence of weight assignments.

### *Weights of factors*

The AHP process provided different weights for the eight parameters, given that the class of susceptibility ranges (1–5: Very low to Very high) is assigned to the influencing factors, and the lowermost weights are given to Elevation (2050–3020 m), Rainfall (1150–1456 mm/yr), NDVI (-0.19–0.54) accounting for 6% each. The Topographic Wetness Index (TWI: 3.6–22.16) contributes 8% while the Drainage density (0–2.71 km/km<sup>2</sup>) is given a slightly higher weight of 9%. Distance to road (0–>150 m) is weighted 16%, prioritizing proximity as being more flood-prone, giving more emphasis to human activity Land Use/Land Cover (LULC: Forest to Built-up) holds 22% which is the second most influential and the first one being Slope (0–42°) with the weight of (26%), with gentler slopes rated riskier.

**Table 8** Flood susceptibility criteria, sub-criteria ranges, and influence weight

<i>Parameters</i>	<i>class</i>	<i>Susceptibility class ranges</i>	<i>Susceptibility ratings</i>	<i>Percentage weight</i>
<b>Rainfall (mm/yr)</b>	1150-1201	Very low	1	7%
	1202-1266	low	2	
	1267-1334	moderate	3	
	1335-1393	high	4	
	1394-1456	Very high	5	
<b>Slope</b>	0-3.4	Very high	5	26%
	3.4-6.9	high	4	
	6.9-11.3	moderate	3	
	11.3-17.98	Low	2	
	17.98-42.0	Very low	1	
<b>Drainage density</b>	0-0.25 km/km <sup>2</sup>	Very low	1	8%
	0.25-0.5 km/km <sup>2</sup>	low	2	
	0.5-0.75 km/km <sup>2</sup>	moderate	3	
	0.75-1 km/km <sup>2</sup>	high	4	
	1-2.71 km/km <sup>2</sup>	Very high	5	
<b>Topographic wetness index (TWI)</b>	3.6-6.29	Very low	1	7%
	6.29-7.82	low	2	
	7.82-9.78	moderate	3	

	9.78-12.84	high	4	
	12.84-22.16	Very high	5	
<b>LULC</b>	Forest	Very low	1	22%
	Rangeland	low	2	
	Cropland	moderate	3	
	Barren land	high	4	
	Built up	Very high	5	
<b>Distance to road</b>	0-25	Very high	5	16%
	26-50	high	4	
	51-100	moderate	3	
	101-150	low	2	
	>150	Very low	1	
<b>Elevation</b>	2830 – 3020	Very low	1	6%
	2636 – 2830	low	2	
	2442 – 2636	moderate	3	
	2248 – 2442	high	4	
	2050 – 2248	Very high	5	
<b>NDVI</b>	-0.19-0.07	Very high	5	8%
	0.07-0.11	high	4	
	0.11-0.17	moderate	3	
	0.17-0.24	low	2	
	0.24-0.54	Very low	1	

### 3.1.3. Flood Prone zones

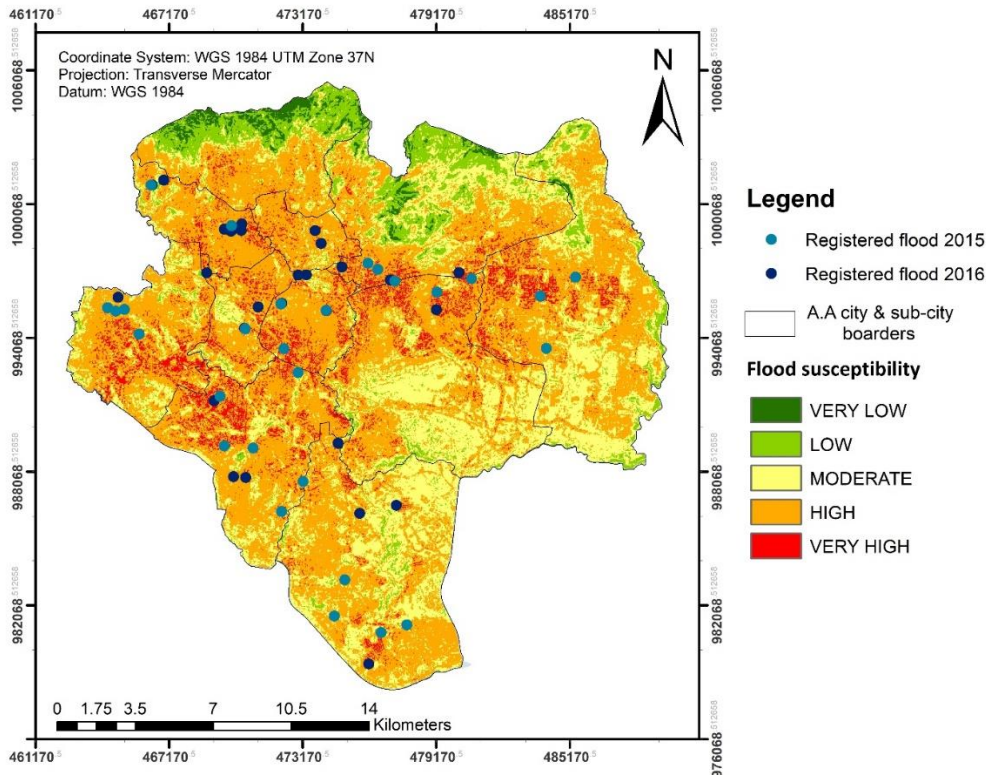
The pluvial flood susceptibility map shows areas at risk of surface water flooding caused by intense rainfall. By applying the AHP method and using the eight flood influencing factors, the map generated has five susceptibility classes, ranging from very low to very high based on their likelihood of flooding.

The very low susceptibility class accounts for 6.27 km<sup>2</sup> which is located north of Addis Ababa it is mostly covered with forest and has a higher slope making it less flood-prone, the low category represents a portion of 33.90 km<sup>2</sup> (7.95%) it has a hilly terrain covered by shrubs and trees. The moderate susceptibility class, spanning 119.46 km<sup>2</sup> (28.02%), represents the second largest area.

**Table 8** Flood susceptibility area and percentage

<b>Susceptibility Class</b>	<b>Area (km<sup>2</sup>)</b>	<b>Percentage (%)</b>
<b>Very low</b>	6.27	1.47%
<b>Low</b>	33.90	7.95%
<b>Moderate</b>	119.46	28.02%
<b>High</b>	237.28	55.65%
<b>Very high</b>	29.63	6.95%

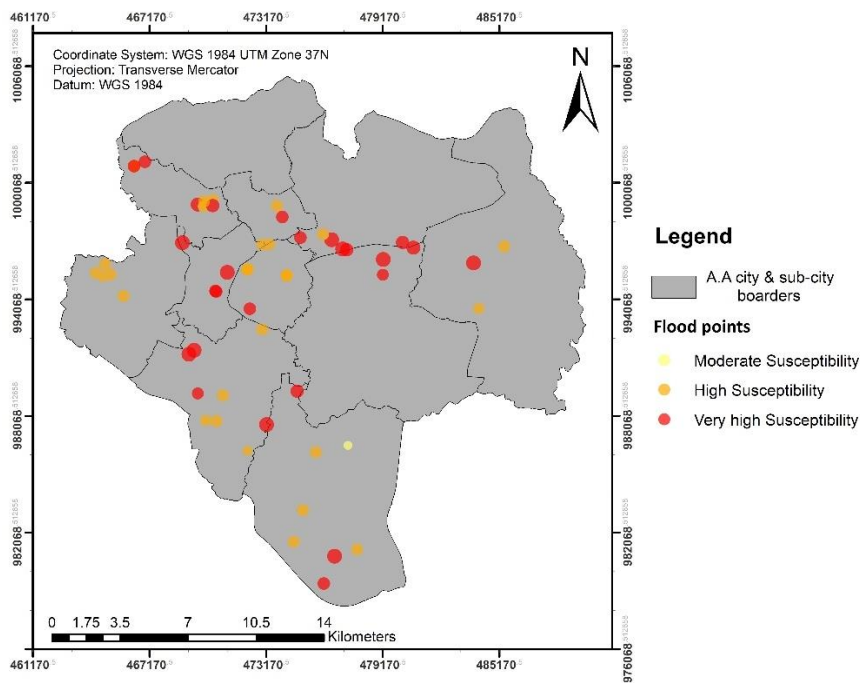
The High susceptibility class encompasses the main portion of the city, covering 237.28 km<sup>2</sup> (55.65%), stating that more than half of the area has a higher risk of flooding. Lastly, the Very High susceptibility category spanning 29.63 km<sup>2</sup> (6.95%) has a gentle and flat surface in a built-up area with an impervious surface contributing to the vulnerability, although it has a smaller coverage it is mostly situated in the central part scattering to the eastern and western regions of the city affecting infrastructure and hindering day to day commute in the rainy season.



*Figure 9* Pluvial Flood susceptibility and registered flood map

### ***Reported flood areas***

From the 55 floods reported in the past two years, only 2 locations (3%) fall into the moderate flood susceptibility zone underscoring the possibility of flooding in this region is minimal compared to the other. In the high susceptibility zone, 31 food points (58%) were recorded, highlighting widespread exposure to flood hazards. Notably, some of the reported flood points are affected yearly signifying the need for conclusive resolution. On the other hand, some areas face repeated inundation within a single rainy season for example the region near Gurd Shola in front of the Ethio-telecom building and other regions like ‘wereda 9’ in Addis Ketema sub city are affected by clustered points that amplify regional hazards. From the previously flooded areas, 22 sites (39%) have aligned with the Very High susceptibility zones, indicating extreme vulnerability to future flooding.



*Figure 9 Registered Flood and Flood Susceptibility Relation map*

### **3.2. Discussion**

The current study’s identification of such zones can be compared with other urban contexts. In many cases, a substantial fraction of the area falls into the top categories: for instance, the Teji watershed (Awash basin, Ethiopia) was mapped with 43.3% high and 13.1% very-high risk (Hagos et al., 2022). In Pakistan’s Swat Valley, 5.6% of the area was very high risk and 52% high risk,

meaning roughly 57.6% was in the two top classes. The previous examples were of fluvial flooding but Even in the Philippine pluvial study has ~22% of land and 30% of the population classified as high risk (Cabrera and Lee ,2020).

In each case, areas labeled “high/very high” correspond to zones where flooding has been historically problematic or could impact many people (Cabrera and Lee ,2020), (Zhran et al., 2024). This study similarly identifies concentrated urban districts as highly susceptible. Thus, the pattern of a minority of areas holding a majority of risk is consistent globally. The pluvial flood susceptibility map shows that very high- and high-risk zones cluster in low-lying, urbanized areas especially along major drainage channels and valley areas, while the very low and low zones are situated on higher ground in vegetated highland districts. This pattern is consistent with runoff dynamics: flat or areas with gentle slope tend to accumulate water and “pond,” while impermeable built up landcover increases runoff volume (Islam et al., 2025).

Moreover, Low-elevation channels and convergent areas (high topographic wetness index) emerged as hotspots, while plateau and ridge-top regions (lower wetness index) were safer. For example, most of Arada and Lideta sub-cities situated on gentle gradients channels fell into high-susceptibility zones, Conversely, peripheral sub-cities on Addis’s outskirts like Yeka and gullele sub-city showed lower susceptibility, reflecting both higher relief and more permeable land use. In 2017 alone, the Addis Ababa emergency services reported 76 separate flood events causing 20 million birrs in damage across the city (Jemberie & Melesse, 2021), notably in the same central sub-cities as this paper’s analysis flags as very high risk.

In this study, land cover and imperviousness strongly modulate risk. Built structures and paved areas are strongly associated with high susceptibility, because they prevent infiltration and rapidly convey runoff (Islam et al., 2025). The analysis assigned very high risk to city-center which is covered by asphalt and tile, matching with the data that these zones contributed with hundreds of flooded hectares in past events (Bekele et al., 2022). on the contrary areas with dense vegetation or rangelands act as water seeping surfaces, soil infiltration in these areas mitigates flooding thus mostly falling on lower susceptibility classes (Islam et al., 2025).

The findings broadly converge with prior flood mapping research in Addis Ababa and other urban catchments. Bekele et al. (2022) used radar to delineate flood in the Akaki catchment, finding that 544 ha of built-up urban area were flooded during 2017-2020 events. This aligns with the result

that urban impervious areas are highly likely flood-prone. Similarly, Asfaw et al. (2024) applied machine learning to the same akaki sub-basin and emphasized anthropogenic and rainfall factors, they reported that integrating infrastructure and high-resolution rainfall data significantly enhanced flood susceptibility prediction. Their Random Forest model showed that 0.54 million residents and tens of thousands of buildings in the highly susceptible category. Which resonated with the current map output, classifying densely urbanized zones like Addis Ketema, Kolfe Keranio sub-cities as high risks. In both of the cases the studies note sprawl onto natural floodplains and weak drainage exacerbates risk, consistent with the theme of this study.

The susceptibility map offers concrete guidance for planners and emergency service workers. zones classified as high or very high flood susceptibility should be prioritized for mitigation measures. For instance, the Addis Ababa City Roads Authority is currently developing a city-wide drainage master plan to address flood-prone areas, this analysis can help refine that effort by pointing out which neighborhoods and sub-catchments to reinforce.

#### **4. Conclusion**

The analytic hierarchy process (AHP) was employed to model pluvial flood susceptibility in Addis Ababa, to identify the most significant factors and spatial patterns controlling the flooding risk. The findings showed that 55.65% of the city (237.28 km<sup>2</sup>) falls under High susceptibility, with an additional 6.95% (29.63 km<sup>2</sup>) classified as Very High risk. Moreover, the result identified central sub-cities such as arada, lideta and addis ketema as are particularly vulnerable due to their gentle topography, and impervious surfaces, following global patterns where urbanization heightens runoff and ponding. conversely, Peripheral sub-cities such as yeka and gullele are covered with rangeland and forests exhibiting lower susceptibility grading in comparison to their counterparts, indicating the role by permeable land cover in flood risk reduction.

The Historical flood records validate the model accuracy, which shows that 58% of the past flood occurrences were in High susceptibility zones and 39% in Very High-risk zones. The frequent flooding of key locations such as Gurd Shola and Addis Ketema, Wereda 9, demonstrates their inherent vulnerabilities. On the other hand, only 3% of historical floods occurred in Moderate-risk zones, highlighting the model's strength in prioritizing high-exposure regions The findings have a big impact for urban planning and disaster management. The hazard concentration in inner sub-cities demands priority mitigation measures, such as upgrading drainage infrastructure, imposing

permeable surface mandates, and relocating essential assets from flood risk corridors. At the same time, reduced exposure of vegetated, steep edges (e.g., northern parts of the city) enhances the protective role of natural environments.

This research offers the basis for the integration of flood susceptibility maps into the drainage master plan of Addis Ababa in order to enable selective interventions to safeguard populations and infrastructure at risk. Future initiatives should concentrate on nature-based solutions like green roofs, permeable pavements and swales, adaptive land-use policies are also necessary to counteract sprawl onto floodplains. By integrating development with hydrological resilience, the city can reduce the impact of pluvial flooding in a changing climate.

For future study better data such as high-resolution LIDAR or updated aerial imagery could refine mapping of pluvial flooding. The inclusion of detailed drainage layouts and real-time measurements can help generate more specific flood prone areas. Finally, extending the model to project future land-use or climate scenarios would help anticipate how flood susceptibility might change.

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