

Flood Hazard Area Mapping Using GIS and Remote Sensing Techniques: A Case Study of
Baro River Basin, Gambella Zuria Wereda, Ethiopia



Helen Atlabachew

A Thesis Submitted to the Department of Architecture
College of Civil Engineering and Architecture (CoCEA)

Presented in Partial Fulfilment of the Requirements for the Degree of Masters of science in
Geoinformatics Engineering

Office of Graduate Studies
Adama Science and Technology University

June, 2025
Adama, Ethiopia

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DECLARATION

I declare that this thesis, titled “**Flood Hazard Area Mapping Using GIS and Remote Sensing Techniques: A Case Study of Baro River Basin, Gambella Zuria Wereda, Ethiopia**” is my original work and has not been submitted to any university for a similar purpose. The sources cited in this thesis are appropriately acknowledged through proper citations.

Helen Atlabachew

Name of student

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I, the major advisor/supervisor of this research thesis, hereby certify that I have closely advised/supervised the student while developing this thesis and read the draft thesis entitled “**Flood Hazard Area Mapping Using GIS and Remote Sensing Techniques: A Case Study of Baro River Basin, Gambella Zuria Wereda, Ethiopia**” prepared under my guidance by Helen Atlabachew. Therefore, I recommend the submission of the thesis to the department for further review and evaluation.

Dr. Getachew Brhanemeskel (Ph.D.)

Major Advisor/Supervisor

Signature

Date

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I, the advisor of the thesis entitled “**Flood Hazard Area Mapping Using GIS and Remote Sensing Techniques: A Case Study of Baro River Basin, Gambella Zuria Wereda, Ethiopia**” and developed by Solomon Tolosa hereby certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

Getachew Berhanemeskel (Ph.D.) _____

Major Advisor

Signature

Date

We, the undersigned, members of the Board of Reviewers of the thesis by Solomon Tolosa have read and evaluated the thesis entitled “**Flood Hazard Area Mapping Using GIS and Remote Sensing Techniques: A Case Study of Baro River Basin, Gambella Zuria Wereda, Ethiopia**” and reviewed the candidate during open defense. This is, therefore, to certify that the thesis is accepted.

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LIST OF ACRONYMS

Acronym	Full Form
AHP	Analytical Hierarchy Process
ALOS	Advanced Land Observing Satellite
CI	Consistency Index
CNN	Convolutional Neural Network
CR	Consistency Ratio
DEM	Digital Elevation Model
DEMs	Digital Elevation Models
DNN	Deep Neural Networks
DRR	Disaster Risk Reduction
EMA	Ethiopian Meteorological Agency
ESRI	Environmental Systems Research Institute
ESSGI	Ethiopian Space Science and Geospatial Institute
FC	Functional Runoff Connectivity
FHAM	Flood Hazard Area Mapping
FRM	Flood Risk Management
GIS	Geographic Information Systems
GRASS	Geographic Resources Analysis Support System
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HEC-RAS	Hydrologic Engineering Center River Analysis System
HDX	Humanitarian Data Exchange
IDF	Intensity Duration Frequency
IUSS	International Union of Soil Sciences
LULC	Land Use / Land Cover
MCDA	Multi-Criteria Decision Analysis

OCHA	Office for the Coordination of Humanitarian Affairs
OPGS	Office of Postgraduate Studies
PALSAR	Phased Array type L band Synthetic Aperture Radar
PFR	Property Flood Resilience
QGIS	Quantum Geographic Information System
SAGA	System for Automated Geoscientific Analyses
SCS-CN	Soil Conservation Service Curve Number
SGC	School Graduate Committee
TWI	Topographic Wetness Index
UK	United Kingdom
WOA	Weighted Overlay Analysis

ABSTRACT

Flooding, the overflow of water onto land that is normally dry, is an increasingly severe hazard in Ethiopia, particularly in flood-prone regions such as the Baro River Basin in Gambella Zuria Wereda. This area frequently experiences flooding due to the Baro River overflowing its banks, primarily caused by flat terrain and heavy seasonal rainfall. This study employs an integrated approach using Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytical Hierarchy Process (AHP) to assess flood risk and map flood-prone zones. Key flood causative factors slope, rainfall, land use/land cover (LULC), soil type, drainage density, and proximity to rivers were analyzed and weighted to generate a flood susceptibility map. The resulting classification identified five flood hazard zones: Very High (18%), High (27%), Moderate (23%), Low (23%), and Very Low (9%) risk areas, with the central and southern parts of the study area found to be the most vulnerable.

Keywords: *Flood hazard mapping, Flood Factor, Flood susceptibility*

CHAPTER 1. INTRODUCTION

1.1 . Background of the Study

Flooding is the overflow of water onto land that is normally dry. It can result from various factors such as heavy rainfall, river overflow, storm surges, or rapid snowmelt. Floods can cause significant damage to communities, ecosystems, and infrastructure. There are several types of floods, including river floods, coastal floods, flash floods, and urban floods, each with its own causes and consequences (Keith Smith and David N. Petley, 2013).

From 1990 to 2022, a total of 4,713 floods were recorded across 168 countries and territories, affecting more than 3.2 billion people, resulting in 218,353 deaths, and causing economic damages exceeding US\$ 1.3 trillion (Liu J. , 2024); the distribution of floods varied across WHO regions, with the African Region accounting for 19.73% of the floods, the Regions of the Americas for 21.83%, the South-East Asia Region for 16.49%, the European Region for 15.02%, the Eastern Mediterranean Region for 10.29%, and the Western Pacific Region for 16.63%.

According to the World Bank (2020) Flooding could affect over 250 million people annually worldwide if proper mitigation and adaptation measures are not adopted, with low- and middle-income countries being especially vulnerable due to inadequate infrastructure, poor disaster preparedness, and weak early warning

Flooding in Africa is mainly driven by unusually high rainfall, but it is also significantly affected by various human-induced factors. These factors include land degradation, deforestation in catchment areas, increasing population density along riverbanks, poor land-use planning, a lack of proper zoning for floodplain development, and insufficient drainage systems. Furthermore, poor management of water discharge from river reservoirs intensifies the flooding problem. (Abayneh et al., 2024).

Ethiopia is at significant risk of flooding because of various climatic, geographic, and socio-economic factors. These include heavy seasonal rainfall, diverse terrain that includes areas prone to flooding in both highlands and lowlands, and insufficient infrastructure. The Gambella Region in western Ethiopia faces significant risks due to its location near major rivers such as the Baro. These rivers often overflow during the heavy rains from June to September, leading to extensive flooding. This flooding negatively affects agriculture, displaces residents, damages infrastructure, and

impedes sustainable development in areas such as food security, public health, and economic stability (Amsalu, 2021).

Flood hazard mapping has become an essential tool for risk reduction and planning, with the integration of Geographic Information Systems (GIS), remote sensing, and multi-criteria decision-making approaches like the Analytical Hierarchy Process (AHP) proving particularly effective. Globally, these technologies have enhanced the assessment and monitoring of flood risks by incorporating key spatial variables such as land use, topography, and rainfall (Aslam et al., 2024) (Mohammed et al., 2024). In Africa, studies have demonstrated similar success; for example, (Blakime et al., 2024) found that over 53% of Greater Lomé in Togo is highly susceptible to flooding, and (Adzandeh et al., 2024) reported that 16.85% of Nigeria's Benue River Basin is at extremely high risk. In Ethiopia, GIS and AHP applications have identified significant vulnerabilities, with (Abayneh et al., 2024) revealing that 51.4% of the Awash River Basin is highly flood-prone, and (Yonas et al., 2024) showing that 41.6% of the Gidabo Watershed faces similar threats. These findings collectively underscore the value of spatial technologies in generating reliable flood hazard maps that inform evidence-based planning, disaster preparedness, and climate adaptation strategies across diverse geographic contexts.

Study by (Tesfay et al.) in Gambella Zuria Wereda, highlights the severe flood challenges Ethiopia faces, particularly in regions vulnerable to climate variability and poor infrastructure. The study emphasizes that traditional flood coping mechanisms are no longer sufficient and advocates for the integration of advanced tools such as GIS and remote sensing for effective flood risk management. Similarly, (Assefa, 2018) underscores the increasing vulnerability of lowland areas due to inadequate preparedness.

In contrast, the lack of similar comprehensive assessments in Gambella Zuria Wereda hinders local authorities' ability to implement necessary flood mitigation measures, leaving the region vulnerable to the impacts of flooding (Assefa, 2018). This gap in research underscores the critical need for targeted studies to equip stakeholders with the tools and knowledge required for effective flood risk management in Gambella Zuria (Diriba et al., 2024) (Lawal et al., 2014).

In conclusion, this study aims to address the critical gaps in flood hazard mapping for Gambella Zuria Wereda, situated within the Baro River Basin. By integrating GIS, remote sensing, and AHP,

the research provides a novel approach to flood risk assessment in Ethiopia, where such comprehensive mapping has not been extensively explored. The study not only contributes to the theoretical expansion of flood hazard mapping techniques in Ethiopia but also offers practical solutions for local flood management. The findings will help to improve flood preparedness, guide land use planning, and inform decision-makers in formulating effective strategies to mitigate flood-related challenges in the region, ultimately supporting sustainable development in the face of climate variability.

1.2 . Statement of the Problem

The Gambella Zuria Wereda area in Ethiopia is prone to frequent flooding, mainly due to the Baro River overflowing. The river flows mainly through flat and low areas, and combined with heavy seasonal rainfall, this often leads to the river overflowing its banks and causing floods (Gebremichael et al., 2018).

Flooding in Gambella Zuria Wereda, part of the Baro River Basin in Ethiopia, is a persistent and serious issue. It increases social and economic vulnerabilities and poses risks to the area's infrastructure, agriculture, and livelihoods. The Wereda often faces major flooding, resulting in extensive damage. Important infrastructure, including roads, bridges, and public buildings, is frequently damaged, which hinders transportation and access to necessary services. Agriculture, the main source of income for many residents, is particularly susceptible to damage, as floods frequently ruin crops, reduce soil quality, and carry away farming tools. These events lead to decreased agricultural output, food shortages, and prolonged economic difficulties for local communities (Tadesse et al., 2020).

A flood event in 2022 in Gambella Zuria Wereda highlighted the seriousness of flood disasters in the area, displacing an estimated 4,001 to 10,000 people and directly impacting around 9,000 individuals. This event highlights the increased susceptibility of the area to water-related hazards and the pressing requirement for effective flood risk management strategies (OCHA, 2022).

Flood hazard mapping is essential for effective flood risk management, particularly in vulnerable regions like Gambella Zuria Wereda, where its application remains underutilized despite the proven efficacy of GIS, remote sensing, and the Analytical Hierarchy Process (AHP) in other Ethiopian contexts. Studies indicate that these technologies facilitate the integration of critical spatial data, such as elevation, land use, and rainfall patterns, to produce detailed flood hazard maps.

In Ethiopia, Various studies have employed Geographic Information Systems (GIS), remote sensing, and the Analytical Hierarchy Process (AHP) to assess flood risks and create hazard maps. For Instance, (Abayneh et al., 2024) identified that 51.4% of the Awash River Basin falls within the high flood hazard zone. Likewise, (Yonas et al., 2024) identified that 41.6% of the Gidabo Watershed is at high flood risk, emphasizing the need for effective flood management strategies. In a similar, (Diriba et al., 2024) Flood risk zones in the Modjo catchment have been identified, showing that a large part of the area is at high risk of severe flooding. Moreover, (Girma, 2023) highlighted that southern Oromia is highly vulnerable to flooding, with 75.5% of the area classified as being at moderate to high risk.

Another study conducted in the Gidabo Watershed and the Upper Awash River Basin employed the Analytical Hierarchy Process (AHP) to evaluate flood hazards by incorporating factors such as drainage density, soil type, elevation, and rainfall. The findings from these studies indicate that substantial portions of these areas are at high risk of flooding (Yonas et al., 2024) (Woldemichael, 2023).

Despite these successes, the application of GIS, remote sensing, and AHP in flood hazard mapping within Gambella Zuria Wereda has not been fully explored. This research aims to bridge this gap by utilizing GIS, remote sensing, and AHP to develop accurate and detailed flood hazard maps for the Wereda. Flood risk factors such as LULC, soil type, rainfall, proximity to rivers, drainage density, and slope are essential in flood hazard mapping.

The integration of Geographic Information Systems (GIS), remote sensing, and the Analytical Hierarchy Process (AHP) for flood hazard mapping in Gambella Zuria Wereda is crucial for enhancing flood risk management, as evidenced by various studies across Ethiopia. Key factors influencing flood dynamics include land use/land cover, soil type, rainfall, proximity to rivers, drainage density, and slope, which have been effectively utilised in similar contexts, such as the Awash River Basin and Gidabo Watershed, where AHP was employed to weight these variables and produce detailed flood risk maps (Abayneh et al., 2024) (Diriba et al., 2024). These maps categorize areas into varying risk levels, facilitating targeted mitigation strategies and community resilience planning (Girma., 2023). This comprehensive approach underscores the necessity for local authorities to adopt advanced methodologies for effective flood risk management in Gambella Zuria Wereda.

Therefore, the purpose of this study is to develop a comprehensive flood hazard map for Gambella Zuria Wereda, using advanced GIS, remote sensing, and AHP methodologies. This will not only contribute to a better understanding of flood risks but also provide local authorities with the tools necessary for effective flood management, disaster preparedness, and long-term resilience planning.

1.3 . Objectives of the Study

1.3.1 . General Objective

The general objective of this study is to develop a comprehensive flood hazard map for the Baro River Basin in Gambella Zuria Wereda, Ethiopia, using GIS, Remote Sensing, and the Analytical Hierarchy Process (AHP).

1.3.2 . Specific Objectives

1. To analyze flood-causing factors using GIS and Remote Sensing
2. To apply the Analytical Hierarchy Process (AHP) for prioritizing and weighting flood contributing factors.
3. To Develop Comprehensive Flood Hazard Zone Map
4. To provide actionable recommendations for effective flood risk management and preparedness

1.4. Research Questions

The research seeks to answer the following questions:

1. What are the main flood-causing factors, and how can GIS and Remote Sensing help analyze them?
2. How can the Analytical Hierarchy Process (AHP) prioritize flood-contributing factors?
3. How can a comprehensive Flood Hazard Zone map be developed for Gambella Zuria Wereda
4. What recommendations can be made for flood risk management and preparedness in the region?

1.5 Scope of the Study

The scope of this study is defined by four key aspects: Geographic, temporal, thematic, and methodological. These parameters establish the boundaries within which the research is conducted, ensuring a focused approach to flood hazard mapping and risk assessment in the Baro River Basin, located in Gambella Zuria Wereda, Ethiopia.

Geographic Scope: The study focuses on the Baro River Basin in Gambella Zuria Wereda, Ethiopia, selected due to its vulnerability to flooding. The results are tailored to address flood risks and inform preparedness strategies for local authorities and communities in this region.

Temporal Scope: The study utilizes a multi-temporal framework that incorporates datasets from various time periods. Rainfall records extend from January 2015 to December 2024, documenting a decade of precipitation trends. The characteristics of the soil are derived from data collected in 2013. The spatial datasets, which include land use and land cover classifications, river network configurations, and the digital elevation model (DEM), are sourced from 2024.

Thematic Scope: The research identifies and classifies flood-prone areas into Very High, high, Moderate, Very Low and Low-risk zones. It examines contributing factors such as rainfall patterns, land use, topography, soil type, drainage density, and proximity to water bodies. GIS, Remote Sensing, and the Analytical Hierarchy Process (AHP) are used to assess and prioritise these factors.

Methodological Scope: This study employs GIS, Remote Sensing, and AHP for data collection, analysis, and integration. These tools are used to process satellite imagery and spatial data to create a comprehensive flood hazard map, providing a foundation for effective flood risk management strategies.

Therefore, the study is relevant, comprehensive, and directly addresses the specific flood risk management challenges in the region.

1.6. Significance of the Study

Flooding constitutes a recurrent and critical environmental hazard in the Baro River Basin, particularly within Gambella Zuria Wereda, where seasonal inundations persistently threaten human populations, livelihoods, infrastructure, and ecosystems. This study is significant as it applies an integrated methodological framework that combines Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytic Hierarchy Process (AHP) to generate a scientifically grounded and spatially explicit flood hazard map. The synergy of these tools enables a comprehensive assessment of flood-inducing factors, thereby supporting evidence-based decision-making for both immediate disaster response and long-term planning.

Practically, the findings of this research provide valuable insights for urban and regional planners by delineating areas of varying flood susceptibility. Such spatial risk stratification is instrumental in guiding land use decisions, infrastructure development, zoning regulations, and the identification of potential resettlement zones. Moreover, the outputs serve as critical inputs for enhancing early warning systems, optimizing resource allocation, and strengthening local disaster preparedness and mitigation strategies. The classification of flood-prone zones into very low, low, moderate, high, and very high risk enhances the capacity of relevant stakeholders to prioritize interventions in a targeted and efficient manner.

Theoretically, this study contributes to the scholarly discourse on spatial multi-criteria decision analysis (MCDA) in flood risk assessment. By integrating AHP within a GIS-RS framework, the research offers a robust and replicable methodology that can be adapted to other flood-vulnerable regions in Ethiopia and globally. This approach addresses existing gaps in localized flood risk modeling and reinforces the value of interdisciplinary geospatial techniques in hazard mapping and environmental risk analysis.

Additionally, the study has wider societal effects by encouraging community involvement, increasing awareness of risks, and creating strategies for flood preparedness that involve participation. This research combines scientific methods with the perspectives of stakeholders, making it a valuable addition to improving flood risk management practices that are resilient and adaptable in relation to climate change and social-environmental challenges.

Flooding is a frequent risk in the Baro River Basin, especially in Gambella Zuria Wereda, where seasonal floods consistently pose a threat to people, their livelihoods, infrastructure, and the environment. This research is important because it uses a combined method that includes Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytic Hierarchy Process (AHP) to create a scientifically based flood hazard map. This integration allows for a thorough and detailed evaluation of flood risk, aiding both long-term planning and everyday decision-making.

The results of this research provide important information for urban and regional planning by pinpointing areas at high risk and informing decisions about land use, infrastructure development, and resettlement plans. Local authorities, planners, and disaster management organizations can use the results to priorities actions, improve early warning systems, and manage resources more effectively.

This study enhances the use of geospatial multi-criteria analysis in evaluating flood risk. The AHP-based framework presented here can be used as a consistent model for other flood-prone areas in Ethiopia and elsewhere. This research contributes to the understanding of localized flood hazards in the Gambella region, filling a gap in the current knowledge on the topic.

The study encourages stakeholders to be aware of risks and aids in creating flood preparedness strategies within the community, which will lead to more effective and knowledgeable flood management practices.

CHAPTER 2. REVIEW OF RELATED LITERATURE

2.1 . Theoretical Review of Literature

2.1.1. Basic Concept

In the context of flood hazard mapping using GIS, remote sensing, and AHP, several foundational concepts form the theoretical basis for understanding flood risks and developing mitigation strategies. These concepts provide the necessary framework for the study and are essential for the integration of various tools and methodologies used in the analysis. The following are the core concepts:

2.1.1.1.Flood Hazard Mapping

Flood hazard mapping is a critical tool for identifying flood-prone areas and developing effective mitigation strategies, as it integrates various geographical and environmental factors to assess flood risks. Utilizing Geographic Information Systems (GIS) and remote sensing data, these maps incorporate key parameters such as Slope, Rainfall, Drainage Density, soil, river distance, and land use, which are essential for accurate flood risk assessment (Kamuju, 2024) (Aslam et al., 2024). The Weighted Overlay Analysis (WOA) and Analytical Hierarchy Process (AHP) are commonly employed methodologies that assign weights to these factors, allowing for a comprehensive evaluation of flood hazards (Kamuju, 2024) (Antony et al., 2022).

The integration of GIS and remote sensing techniques facilitates continuous monitoring and updating of flood hazard maps, accommodating changes in land use, climate, and hydrological conditions, thereby ensuring the safety and sustainability of communities (Aslam et al., 2024). Overall, flood hazard mapping serves as a vital component of flood risk management, enabling proactive strategies to mitigate the adverse effects of flooding (Stoyanova et al., 2022).

2.1.1.2.Geographic Information Systems (GIS)

GIS Geographic Information Systems (GIS) play a crucial role in flood risk management by enabling the integration and analysis of diverse spatial data, such as Slope, Rainfall, Drainage Density, soil, river distance, to create detailed flood hazard maps. These maps are essential for predicting flood events and assessing risks, as demonstrated in various studies. For instance, highlight the effectiveness of GIS in producing accurate flood maps and damage estimation, which are vital for early warning systems (Kiba et al., 2023). By utilized GIS combined with multi-criteria decision analysis to identify high-risk flood zones in Ethiopia, revealing that approximately 43.28% of the area was vulnerable to significant flooding (Hagos et al., 2022). Similarly, Kamuzu's research

employed a Weighted Overlay Analysis in GIS to delineate flood-prone areas in India, identifying 60% of the region at high to very high risk (Kamuju, 2024). These findings underscore GIS's capacity to support informed decision-making in flood risk management through comprehensive spatial analysis and visualization (Mohammed et al., 2024).

2.1.1.3.Remote Sensing

Remote sensing plays a pivotal role in flood hazard mapping by providing essential data on land use, vegetation, water bodies, and topography, which are critical for assessing flood risks. The integration of remote sensing with Geographic Information Systems (GIS) allows for the comprehensive analysis of geographical factors such as terrain slope and proximity to water streams, which are vital in identifying flood-prone areas (Aslam et al., 2024)(Al-Omari et al., 2024). Satellite technologies, particularly those utilizing radar, enhance flood monitoring capabilities by penetrating cloud cover and offering frequent observations, thus facilitating timely flood warnings and assessments (Stancalie et al., 2005). Moreover, remote sensing enables continuous monitoring of environmental changes, such as urbanization and deforestation, which significantly influence flood dynamics (Sharma& Sharma, 2019). For instance, studies have demonstrated the effectiveness of remote sensing in evaluating flood impacts in arid regions, showcasing its ability to map land cover changes and assess damage post-flood events with high accuracy (Nafia et al., 2023). This comprehensive approach underscores the importance of remote sensing in developing proactive flood management strategies.

2.1.1.4. Analytical Hierarchy Process (AHP)

The Analytical Hierarchy Process (AHP) is a pivotal decision-making tool in flood hazard mapping, enabling the systematic evaluation and prioritization of various flood risk factors such as rainfall, soil type, slope, proximity to rivers, and land use. This method enhances the objectivity and reliability of flood risk assessments by structuring complex problems into a multi-level hierarchy, allowing for the integration of diverse criteria. For instance, studies have demonstrated AHP's effectiveness in mapping flood-prone areas across different regions, including Paduka city in Kerala, the Rawa Pening Sub-Watershed in Indonesia, and the Cheliff-Ghrib watershed in Algeria, where it facilitated the identification of high-risk zones based on weighted parameters derived from GIS data (Antony et al., 2022). Additionally, AHP has been employed to create flood susceptibility maps in regions like Krishna District, Andhra Pradesh, showcasing its versatility in disaster management and

planning (Ramu et al., 2022). Overall, AHP serves as a crucial framework for enhancing flood risk analysis and informing mitigation strategies.

2.1.1.5. Flood Risk Factors

Flood risk factors are the underlying conditions or variables that contribute to the likelihood and severity of flooding. These factors include:

- **Land Use/Land Cover (LULC):** Flood risk factors, particularly Land Use/Land Cover (LULC) changes, significantly influence the likelihood and severity of flooding. Studies indicate that urbanization and deforestation lead to increased impervious surfaces, which heighten surface runoff and reduce groundwater recharge, thereby exacerbating flood risks. For instance, in the Kalu River Basin, a notable reduction of natural vegetation by 14.2% from 2001 to 2020 correlated with increased flood events, particularly in lower elevation areas like Kalutara (V et al., 2024). Similarly, in North Bhubaneswar, urban expansion by 71.8% and a decrease in cropland and forest areas have resulted in higher flood vulnerability across 90 villages (Mishra et al.). The Kelantan Basin study also highlights that urban development significantly contributes to increased runoff during flood events (Asmat et al., 2016). Furthermore, the Chiplun Flood analysis revealed that the transition from agricultural to built-up land was a primary factor in the flood's severity (Diwate et al., 2023). Collectively, these findings underscore the critical need for sustainable land use planning to mitigate flood risks effectively (Banjara et al., 2024).
- **Soil Type:** Soil characteristics, particularly permeability and water retention capacity, significantly influence water absorption and runoff during heavy rainfall events. High permeability soils, such as sandy types, allow rapid infiltration and have low water storage capacity, leading to increased runoff and necessitating frequent irrigation practices (Hura & Gulo, 2024). The interplay between soil moisture content and suction pressure further affects infiltration rates, with saturated soils promoting runoff formation during intense rainfall (Koutný et al., 2018). Thus, understanding these soil properties is essential for effective water management and flood risk mitigation (Wank & Atkinson, 2022).
- **Rainfall Patterns:** Rainfall is a key factor in flood hazards, as its intensity, duration, and spatial variability greatly affect the risk of flooding. Recent studies indicate that intensified rainfall and extended precipitation events can overwhelm both natural and artificial drainage

systems. This situation has increased flooding, especially in urban areas where the infrastructure is insufficient (Torelló-Sentelles et al., 2024). Additionally, the spatial distribution of rainfall is vital; localized heavy downpours can lead to flash floods in certain areas, even when the overall rainfall in the surrounding region is moderate (Akter et al., 2023). Climate change is increasing these risks by altering rainfall patterns. Research predicts an increase in both the occurrence and strength of extreme rainfall events, suggesting that brief storms are expected to become more intense (Li et al., 2023).

- **Proximity to Rivers:** Areas close to rivers are indeed more prone to flooding due to the risk of river overflow during peak flow periods, as evidenced by multiple studies. The proximity to rivers is a significant factor contributing to flood risk, as highlighted in the flood hazard mapping of the Auranga watershed in India, where regions near rivers were identified as high to very high flood risk zones using a GIS-driven Weighted Overlay Analysis model (Kamuju, 2024). Similarly, a study on riverine flood susceptibility in India identified proximity to rivers as a key factor influencing flood occurrence, with high susceptibility zones concentrated in major river basins like the Brahmaputra, Ganga, and Indus, which are critical for agriculture and urban areas (Kumar et al., 2023). The risk of overtopping failure of river levees, a common flood control structure, further underscores the vulnerability of areas near rivers, as these structures can fail during peak discharge events, leading to significant flood disasters (Isola, 2022).
- **Drainage Density:** Drainage density, defined as the ratio of channel length to area, significantly influences water flow and the landscape's capacity to manage excess water, particularly in urban and varied topographical settings. Research indicates that higher drainage density enhances functional runoff connectivity (F_c), facilitating efficient water movement through landscapes, which is crucial for mitigating runoff during intense precipitation events (Smets et al., 2019); In urban environments, a dense drainage grid correlates with increased F_c , suggesting that fine-grained landscapes with numerous small impervious clusters are more effective in managing runoff than coarse-grained ones. Additionally, drainage density is affected by environmental factors such as topography, precipitation, and vegetation, with varying impacts across different climatic regions (Gao et al., 2022).

- **Slope:** Steeper slopes indeed contribute to higher flood risks due to the increased speed of water flow, which enhances erosion and runoff potential. Research indicates that on steeper slopes, such as those studied in the loess hilly and gully areas, the runoff generation time, confluence time, and equilibrium time decrease significantly, leading to more rapid and intense runoff processes compared to gentler slopes (Li et al., 2020). This is corroborated by findings from experiments on water-repellent soils, where steeper slopes (9°) resulted in greater runoff and erosion than gentler slopes (3°), although the difference between 6° and 9° slopes was not significant (Lowe et al., 2021). The complexity of runoff movement on steep slopes is further highlighted by the need for modified hydrodynamic models to accurately predict runoff behavior, as traditional models often fail to account for the rapid changes in flow dynamics on steep gradients (Li et al., 2020). Moreover, the decomposition of runoff gravity and pressure in steep river channels shows that traditional assumptions about gentle slopes do not hold, necessitating specialized equations to simulate flood evolution accurately in these areas (Xia, 2024). Overall, the evidence underscores the critical role of slope gradient in influencing flood risk through its impact on runoff speed and erosion potential.

2.1.2 . Review of Theories

In flood hazard mapping that utilizes GIS, remote sensing, and AHP, various important theoretical frameworks and models support the understanding of flood risk assessment, flood management, and decision-making processes. Theories from different fields, such as hydrology, geography, and decision science, are important in guiding the methods used and how results are understood. The following is a summary of the key theories related to this study:

2.1.2.1 . *Hydrological Model Theory*

The Hydrological Model Theory elucidates the movement of water through landscapes, significantly impacting flood hazard mapping by simulating flood events under varying conditions. Key models, such as the Soil Conservation Service Curve Number (SCS-CN) method, are instrumental in predicting runoff and flood characteristics, as demonstrated in studies that utilized HEC-HMS and HEC-RAS software to assess flood risks in regions like southeastern Cairo, where significant runoff volumes were calculated for different storm return periods (El-Bagoury et al., 2024). Additionally, advancements in deep learning techniques, such as Deep Neural Networks (DNN), have enhanced flood prediction accuracy by integrating historical meteorological data with hydraulic modeling

(Hawamdeh et al., 2024). The comprehensive review of rainfall-runoff models highlights the evolution of both traditional and data-driven approaches, emphasizing the need for hybrid models to improve flood prediction and management strategies (Sheth, 2018). Furthermore, remote-sensing-based models have shown promising results in simulating flood events, providing critical insights for basin management and disaster mitigation (Xu et al., 2022).

2.1.2.2 . Hydraulic Model Theory

The Hydraulic Model Theory, particularly through the application of the HEC-RAS model, plays a crucial role in understanding flood dynamics and predicting flood hazards across various landscapes, including the Baro River Basin. HEC-RAS facilitates the simulation of river flow and flood inundation by integrating topographical data, which is essential for accurate floodplain mapping and risk assessment (Saini et al., 2024). Studies have demonstrated its effectiveness in diverse regions, such as the Amik Plain in Turkey and the Godavari River in India, where it has been used to analyse flood behavior, depth, and velocity, thereby aiding in flood mitigation strategies (Rao et al., 2019). Additionally, the model's integration with GIS technology enhances the precision of flood inundation maps, allowing for better planning and response to flood events (Patel et al., 2023). This comprehensive approach underscores the importance of hydraulic modeling in flood risk management and urban planning, particularly in flood-prone areas.

2.1.2.3 . GIS and Remote Sensing Theory

The integration of Geographic Information Systems (GIS) and remote sensing technologies is crucial for effective flood risk assessment and management, as it enables the creation of detailed environmental models that account for various risk factors. Studies have demonstrated that GIS facilitates spatial analysis of critical elements such as land use, slope, and proximity to water bodies, while remote sensing provides essential real-time data, including satellite imagery and Digital Elevation Models (DEMs) (Aslam et al., 2024). For instance, the application of Weighted Overlay Analysis in these studies has successfully identified high-risk flood zones by combining multiple parameters, such as elevation and rainfall data, to produce comprehensive flood hazard maps (Kamuju, 2024). Furthermore, continuous monitoring through remote sensing allows for the timely updating of these maps, accommodating changes in land use and hydrological conditions, which is vital for urban planning and disaster mitigation strategies (Aslam et al., 2024).

2.1.2.3 . The Analytical Hierarchy Process (AHP) Theory

The Analytical Hierarchy Process (AHP) is a pivotal decision-making tool in flood risk assessment, enabling the systematic evaluation of various flood risk factors by structuring them into a multi-level hierarchy. This method facilitates the prioritization of critical contributors to flood hazards, such as land use/land cover (LULC), rainfall patterns, soil type, and slope, which are essential for effective flood hazard mapping. For instance, studies have demonstrated that AHP, when integrated with Geographic Information Systems (GIS), allows for the comprehensive analysis of flood-prone areas by assigning weights to factors based on their relative importance, as seen in the assessments conducted in regions like Pudukad, the Rapti River watershed, and the Krishna District (Antony et al., 2022) (Penki et al., 2022). The results indicate that significant portions of these areas fall within moderate to high flood hazard categories, underscoring AHP's effectiveness in guiding disaster management and mitigation strategies (Khumaeroh & Sari, 2024).

2.1.2.4 . The Flood Risk Theory

The Flood Risk Theory underscores the interplay between hazard, exposure, and vulnerability in assessing flood risk, which is crucial for effective flood mitigation strategies, particularly in regions like Gambella Zuria Wereda. Hazard refers to the occurrence of flooding, while exposure encompasses the population and assets at risk; vulnerability denotes the susceptibility of these elements to damage (Takara, 2013). Research indicates that socio-economic factors significantly heighten vulnerability, as seen in Afghanistan, where a high percentage of the population is exposed to flood risks due to inadequate infrastructure and climate change impacts (Ikram et al., 2023). Furthermore, a comprehensive assessment framework that integrates both physical and social vulnerability is essential for understanding community resilience and developing targeted interventions (Karagiorgos et al., 2016). Effective countermeasures, such as early warning systems and land use management, can mitigate exposure and enhance community preparedness, thereby reducing overall flood risk (Guddo D. , 2023).

2.1.2.5 . Sustainability Flood Management Theory

The Sustainability Theory in flood management emphasizes the integration of long-term environmental, social, and economic considerations into flood risk management, advocating for strategies that balance immediate responses with resilience-building measures. This approach is particularly relevant in regions like Gambella Zuria Wereda, where sustainable, ecosystem-based methods such as floodplain restoration and sustainable land use planning are essential for enhancing

flood resilience. Research indicates that effective flood management frameworks must prioritize risk assessment, considering the multifaceted impacts of floods on society and the environment (Ko et al., 2013). Furthermore, the shift from traditional flood management to resilience-focused strategies reflects a growing recognition of the need to adapt to climate change and urbanization, which exacerbate flood risks (Pandit, 2024). Ultimately, sustainable flood management aims to minimize future flood risks while promoting ecological health and community well-being (Alcoforado, 2022).

2.1.2.5 . The Disaster Risk Reduction (DRR) Theory

The Disaster Risk Reduction (DRR) Theory serves as a vital framework for managing flood risks by emphasizing proactive measures such as early warning systems, community engagement, and comprehensive policy development. It highlights the necessity of integrating hazard mapping and risk assessments to enhance community resilience against floods, thereby reducing vulnerabilities and improving coping capacities (Guddo, 2023) (Alexander, 2020). Effective flood risk management strategies, as outlined in the literature, include the establishment of social agreements on flood management goals and the implementation of sustainable practices that consider future environmental impacts (Agrawal, 2018). By fostering community involvement and utilizing risk assessment methods, DRR facilitates anticipatory actions that can significantly mitigate the adverse effects of flooding, aligning with the objective to provide actionable recommendations for effective flood risk management in Gambella Zuria Wereda (Sari, 2023).

These theories provide the conceptual foundation for understanding the dynamics of flood hazards, the tools used in flood risk assessment, and the approaches to flood management. They guide the use of GIS, remote sensing, and AHP in mapping flood risks and developing effective strategies for reducing the impact of floods on communities in Gambella Zuria Wereda, Ethiopia.

2.2 . Empirical Review of Literature

This section examines empirical studies that have investigated flood hazard mapping, flood risk assessment, and the use of GIS, remote sensing, and the Analytical Hierarchy Process (AHP) across various contexts. It offers a comprehensive overview of global, African, and Ethiopian experiences, emphasizing the methodologies, findings, and gaps that inform this current study.

2.2.1. Global Context

Globally, flood hazard mapping has become an essential tool for managing flood risks, particularly in areas that are highly vulnerable to extreme weather events. Studies by (Aslam et al., 2024) (Mohammed et al., 2024) highlight the effectiveness of integrating Geographic Information Systems (GIS) and remote sensing technologies in producing accurate and reliable flood hazard maps. For instance, research conducted in Indonesia and Sri Lanka illustrates how GIS enables the spatial analysis of critical variables such as land use, topography, and rainfall patterns, while remote sensing provides real-time data that enhances the accuracy of flood monitoring and prediction. Additionally, decision-support techniques such as the Analytic Hierarchy Process (AHP) and Weighted Overlay Analysis have been employed to assess and priorities flood-inducing factors. As emphasized by (Kamuju, 2024)and the report (Ke.Zhang. et al., 2022), these methods offer a comprehensive framework for evaluating flood risks in diverse geographic and data-scarce environments. Furthermore, according to (Kiba et al., 2023)and (Mohammed et al., 2024), the integration of these tools supports the identification of high-risk areas and the formulation of effective mitigation strategies, reinforcing the importance of adaptive and proactive flood risk management on a global scale.

Similarly, in Mumbai, AHP was employed to assess flood risks by evaluating factors such as land use, rainfall, and proximity to rivers, which helped in creating a detailed flood risk map that informs emergency preparedness measures (Yash et al., 2024). In Nashik, the integration of GIS and AHP facilitated a comprehensive flood susceptibility analysis, highlighting the influence of drainage density, elevation, and proximity to rivers on flood vulnerability (Madhusudhan et al., 2024). A broader study across India also utilised AHP to assess flood risks, emphasizing the roles of rainfall, elevation, and slope, and categorizing areas into various risk levels (Kumar et al., 2023).In the Thamirabarani river basin, the Srivaikundam region of Southern India, AHP combined with GIS was utilized to map flood susceptibility by analyzing factors such as land cover and land use (LCLU), drainage density, topographic wetness index (TWI), proximity to rivers, river length, slope, digital elevation model (DEM), and rainfall (Richard & Ravindran A, 2020) .Similarly,, in the Adayar River Basin, Tamilnadu, AHP and GIS were used to delineate flood hazard zones, with thematic layers such as rainfall and drainage density contributing to a detailed flood susceptibility map, aiding district planners in flood management (Sivaranjani, 2017). These studies collectively demonstrate

the efficacy of AHP in flood risk assessment across diverse Indian geographies, providing critical insights for policymakers and planners to mitigate flood impacts.

Another Research across various regions, including Indonesia, Sri Lanka, and Iran, highlights the effectiveness of integrating Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) for flood hazard mapping. Studies by (Mohammed et al., 2024) and (Ariyani et al., 2024) demonstrate that spatial data analysis significantly enhances the accuracy of flood hazard maps, which is crucial for disaster preparedness and urban planning. In Iran, research Conducted by (Chen, 2022) (Samuael et al., 2019) emphasizes that effective flood hazard maps are instrumental in guiding flood mitigation strategies, thereby equipping policymakers with essential tools to minimize flood impacts. Collectively, these findings underscore the importance of employing advanced geospatial technologies in flood risk assessment and management.

2.2.2 Africa Context

Flood hazard mapping in Africa has become increasingly critical due to the continent's susceptibility to flooding exacerbated by urbanization and climate change. Studies across various regions, including Togo, Nigeria, and Ethiopia, have employed Geographic Information Systems (GIS) and remote sensing to assess flood risks effectively. For instance, (Blakime et al., 2024) demonstrated that in Greater Lomé, 53.4% of the suburbs are highly susceptible to flooding, utilizing remote sensing data integrated with GIS and the Analytical Hierarchy Process (AHP).

Similarly, (Adzandeh et al., 2024) identified significant flood vulnerability in the Benue River Basin, with 16.85% of areas classified as extremely high risk. (Hagos et al., 2022) Reported that 43.28% of the Teji watershed in Ethiopia faced high flood risks, emphasizing the need for regular flood management practices. Furthermore, (Ndidi et al., 2022) highlighted that 48.2% of the Ona River Basin is at moderate to very high flood risk, linking urban infrastructure density to vulnerability. These findings underscore the importance of spatially explicit data in enhancing flood risk predictions and informing disaster management strategies across Africa (Ighile, 2022).

Another study by (Uwandu et al., 2023) in the Otamiri River Basin, Nigeria, demonstrated the effectiveness of the Analytic Hierarchy Process (AHP) in prioritizing flood risk factors by integrating variables such as drainage density, soil type, land use, and slope. The study produced a comprehensive flood vulnerability map that classified areas from very low to very high risk.

Similarly, research by (Hirwa et al., 2023) in Musanze, Rwanda, applied AHP to identify flood-prone zones, revealing that approximately 33% of the region was categorized as high to very high risk, thereby emphasizing the need for targeted infrastructure planning. In Algeria, (Mokhtari et al., 2023) utilized AHP in the Cheliff-Ghrib watershed and found that 22.5% of the area is extremely vulnerable to flooding, highlighting the method's applicability in semi-arid regions. A comparable study by (Ramson et al., 2024) in Ghana's Upper East Region also employed AHP to map flood risk, identifying water discharge as a critical factor influencing flood severity. Collectively, these studies underscore the utility of AHP in urban flood risk assessment across diverse African contexts, as further supported by (Nugraha et al., 2025), who emphasized its adaptability and accuracy in multi-criteria decision-making for flood hazard mapping.

Similar studies by (Santos et al., 2023) and (Douglas, 2017) have shown that flooding in African cities presents significant socio-economic challenges, particularly for low-income and vulnerable communities. These challenges are often worsened by rapid urbanization, inadequate infrastructure, and poor urban planning. Informal settlements, which are common in many African cities, tend to lack proper drainage systems and are frequently located in high-risk flood zones. In West African megacities, for example, weak infrastructure and ineffective flood management strategies have contributed to repeated flood disasters (D et al., 2022). In the Nile Basin, (Baldassarre et al., 2010) noted a critical lack of flood mitigation measures, calling for the development of hazard mapping and coordinated risk management plans. Similarly, (Namrata, 2011) found that urban flooding in Ethiopia is largely driven by poorly maintained infrastructure, a concern echoed across other African cities. Additionally, social and environmental factors such as poor waste management and substandard housing have increased flood vulnerability.

Therefore, addressing urban flooding in African cities requires a comprehensive, multi-level approach that includes infrastructure improvement, better urban planning, and coordinated efforts at the local, regional, and national levels.

2.2.3. Ethiopia Context

In Ethiopia, particularly in the Baro River Basin of Gambella Zuria Wereda, flood hazards have escalated due to changing rainfall patterns, urbanization, and land use changes. Various studies have employed Geographic Information Systems (GIS), Remote sensing, and the Analytical Hierarchy Process (AHP) to assess flood risks and create hazard maps. For instance, (Abayneh et al., 2024)

determined that a large area of the Awash River Basin (ARB) is at high risk of flooding, based on a flood hazard assessment carried out using GIS and the Analytical Hierarchy Process (AHP). 51.4% of the area is classified as having a high flood hazard. In a related study, (Yonas et al., 2024) identified that 41.6% of the Gidabo Watershed is at high flood risk, emphasizing the need for effective flood management strategies. Similarly, (Diriba et al., 2024) mapped flood risk zones in the Modjo catchment, revealing that a significant portion of the area is susceptible to severe flooding. Furthermore, (Burayu et al., 2023) (Girma, 2023) highlighted the impact of human activities, such as deforestation, on flood vulnerability in southern Oromia, indicating that 75.5% of the area is at moderate to high risk. These findings underscore the critical need for integrated flood risk management approaches in Ethiopia (Assefa, 2018).

Similarly, studies conducted in the Gidabo Watershed and the Upper Awash River Basin have employed the Analytical Hierarchy Process (AHP) to evaluate flood hazards by incorporating factors such as drainage density, soil type, elevation, and rainfall. The findings from these studies indicate that substantial portions of these areas are at high risk of flooding (Yonas et al., 2024) (Woldemichael, 2023). In southern Oromia, the integration of AHP with Geographic Information Systems (GIS) and remote sensing has been utilised to map flood vulnerability, revealing that a large percentage of the region falls within moderate to high flood risk zones, underscoring the need for development policies informed by such assessments (Girma., 2023). Additionally, the study in the Modjo catchment area supports the application of AHP combined with geo-informatics to identify and classify flood risk zones, demonstrating the method's effectiveness in delineating areas of varying flood susceptibility (Diriba et al., 2024). Therefore, these studies collectively highlight the significant role of AHP in flood risk assessment across Ethiopia, offering essential insights for the implementation of sustainable flood management strategies and the development of effective early warning systems.

Another study by (Tesfay et al., 2022) in Gambella Zuria Wereda, highlights the severe flood challenges Ethiopia faces, particularly in regions vulnerable to climate variability and poor infrastructure. The study emphasizes that traditional flood coping mechanisms are no longer sufficient and advocates for the integration of advanced tools such as GIS and remote sensing for effective flood risk management. Similarly, (Assefa, 2018) underscores the increasing vulnerability of lowland areas due to inadequate preparedness. In the Baro River Basin, a study by (Beshir & Song, 2021) found that climate change manifested through altered rainfall patterns has significantly

intensified flood risks, particularly in low-lying regions. (Teku & Eshetu, 2024) further support this, identifying climate change as a major factor in the growing frequency and intensity of flooding events.

Generally, the empirical literature highlights the growing importance of GIS, remote sensing, and AHP in flood hazard mapping across different contexts. Global studies have demonstrated the effectiveness of these technologies in improving flood risk assessments, while African and Ethiopian studies emphasize the need for tailored approaches due to the unique challenges posed by urbanization, land use changes, and climate variability. The gaps identified in previous studies underscore the need for further research on integrating flood risk factors, improving data availability, and developing effective flood risk management strategies in flood-prone areas like the Baro River Basin in Gambella Zuria Wereda, Ethiopia.

2.3 . Research Gap

In Ethiopia, particularly in the Baro River Basin of Gambella Zuria Wereda, flood hazards have escalated due to changing rainfall patterns, urbanization, and land use changes. Various studies have employed Geographic Information Systems (GIS), remote sensing, and the Analytical Hierarchy Process (AHP) to assess flood risks and create hazard maps. For instance, (Abayneh et al., 2024) identified that 51.4% of the Awash River Basin falls within the high flood hazard zone. Likewise, (Yonas et al., 2024) identified that 41.6% of the Gidabo Watershed is at high flood risk, emphasizing the need for effective flood management strategies. Moreover, (Girma, 2023) highlighted that southern Oromia is highly vulnerable to flooding, with 75.5% of the area classified as being at moderate to high risk.

Study by (Tesfay et al., 2022) in Gambella Zuria Wereda, highlights the severe flood challenges Ethiopia faces, particularly in regions vulnerable to climate variability and poor infrastructure. The study emphasizes that traditional flood coping mechanisms are no longer sufficient and advocates for the integration of advanced tools such as GIS and remote sensing for effective flood risk management. Similarly, (Assefa, 2018) underscores the increasing vulnerability of lowland areas due to inadequate preparedness.

Although previous studies have established general methodologies for assessing flood risk, the comprehensive application of GIS, remote sensing (RS), and the Analytical Hierarchy Process (AHP) to prioritize factors contributing to flooding has not been thoroughly investigated in the

specific context of Gambella Zuria Wereda. This research aims to address that gap by presenting an integrated approach to flood hazard assessment that is tailored to specific locations. This research aims to address that gap by offering a comprehensive and location-specific method for assessing flood hazards. It considers various factors, including slope, soil, land use and land cover (LULC), soil type, drainage density, and proximity to rivers.

This study aims to make a significant contribution to the development of more effective, evidence-based, and context-sensitive flood risk management strategies for Gambella Zuria Wereda. In doing so, it will ultimately support both local communities and policymakers in mitigating the impacts of flooding.

2.4 . Conceptual Framework

The conceptual framework for this study integrates the identification and analysis of key flood risk factors with advanced geospatial technologies to produce a comprehensive flood hazard map for Gambella Zuria Wereda. The framework is structured as follows:

1. Flood Risk Factors: The study begins by identifying and analyzing the primary flood risk factors in the Baro River Basin, which include:

- **Land Use/Land Cover (LULC):** Urbanization and deforestation influence runoff patterns and flood risks. LULC data from ESRI Sentinel-1 10m will be used to assess how land cover changes affect flood susceptibility.
- **Soil Type:** Soil characteristics, such as permeability, affect water retention and flood severity.
- **Rainfall Patterns:** Rainfall intensity and distribution are major flood contributors, influencing the frequency and magnitude of flood events.
- **Proximity to Rivers:** Areas near rivers are more vulnerable to flooding due to overflow from the Baro River.
- **Drainage Density:** High drainage density areas tend to accumulate runoff, increasing flood risks.
- **Slope:** Steeper terrains enhance runoff speed, contributing to higher flood risks.

2. **GIS and Remote Sensing:** The framework employs GIS and remote sensing tools to gather and analyze spatial data related to the identified flood risk factors. The data will be processed and analyzed using ArcGIS, QGIS, and Google Earth Pro to develop flood hazard maps.

3. **Analytical Hierarchy Process (AHP):** AHP will be applied to prioritize and assign weights to the various flood risk factors. This allows for a more accurate and objective flood risk assessment by quantifying the relative importance of each factor in contributing to flood hazards.

4. **Flood Hazard Map Development:** The integration of the identified risk factors and the results from AHP will lead to the creation of a flood hazard map for Gambella Zuria Wereda. This map will visually represent flood-prone areas, aiding in effective flood risk management and preparedness planning.

5. **Actionable Recommendations for Flood Risk Management:** Based on the flood hazard map, the framework concludes with the formulation of actionable recommendations. These will guide local authorities and stakeholders in implementing flood mitigation strategies, including land-use planning, infrastructure improvements, and emergency response measures. Figure 1. Shows the conceptual frame work of the study.

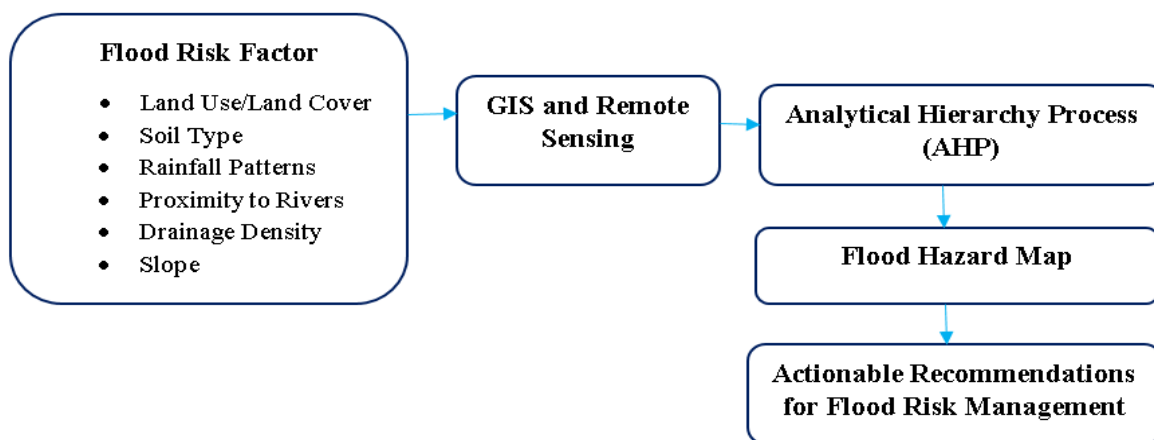


Figure 1. Conceptual frame work of the study

By applying this conceptual framework, the study aims to provide a comprehensive approach for flood risk management in Gambella Zuria Wereda, enhancing resilience to future flood events and informing long-term flood mitigation strategies.

CHAPTER 3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1 Location

This study focuses on Gambella Zuria Wereda, located in the Anuak Zone of the Gambella Regional State in western Ethiopia. It includes Gambella City, the regional capital, central to the region's administrative and economic activities. The Wereda is bordered by Abobo Wereda to the south, Itang Special Wereda to the west, and the Oromia Region to the north and east. Gambella Zuria lies within the **Baro River Basin**, with coordinates marking its boundaries at 8.475545° N (north), 7.765308° N (south), 35.157659° E (east), and 34.353961° E (west). The Wereda covers a total area of approximately 326832.03 hectares. These geographic and spatial data were sourced from (OCHA HDX. , 2024) .The Baro River, a major tributary of the White Nile, significantly influences the region's hydrology, and seasonal flooding poses challenges to infrastructure and livelihoods. Figure 2. Shows the Study Area map.

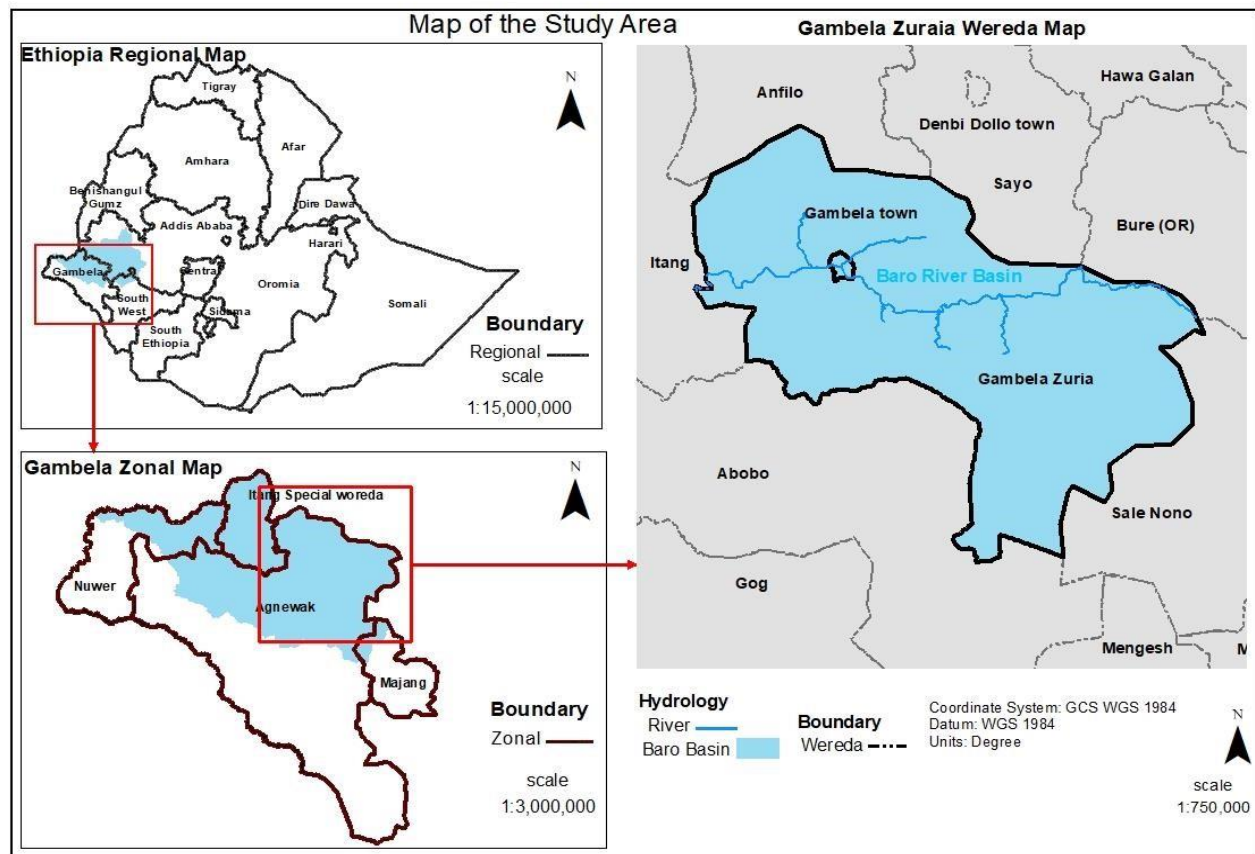


Figure 2. Study Area map

3.1.2. Topography

The study area, Gambella Zuria Wereda, is predominantly defined by flat to gently sloping terrain, characteristic of Ethiopia's western lowlands. Elevation data derived from the ALOS PALSAR Digital Elevation Model (DEM) with a 12.5-meter resolution indicate that the Wereda's altitude varies from **401 to 2079** meters above sea level. The variation in elevation showcases the impact of natural elements like river systems, wetlands, and distinct upland areas. The area's flood susceptibility is significantly influenced by these topographic features, with lower elevations being more prone to seasonal flooding, whereas higher elevations provide greater protection. Figure 3. Shows an Elevation map.

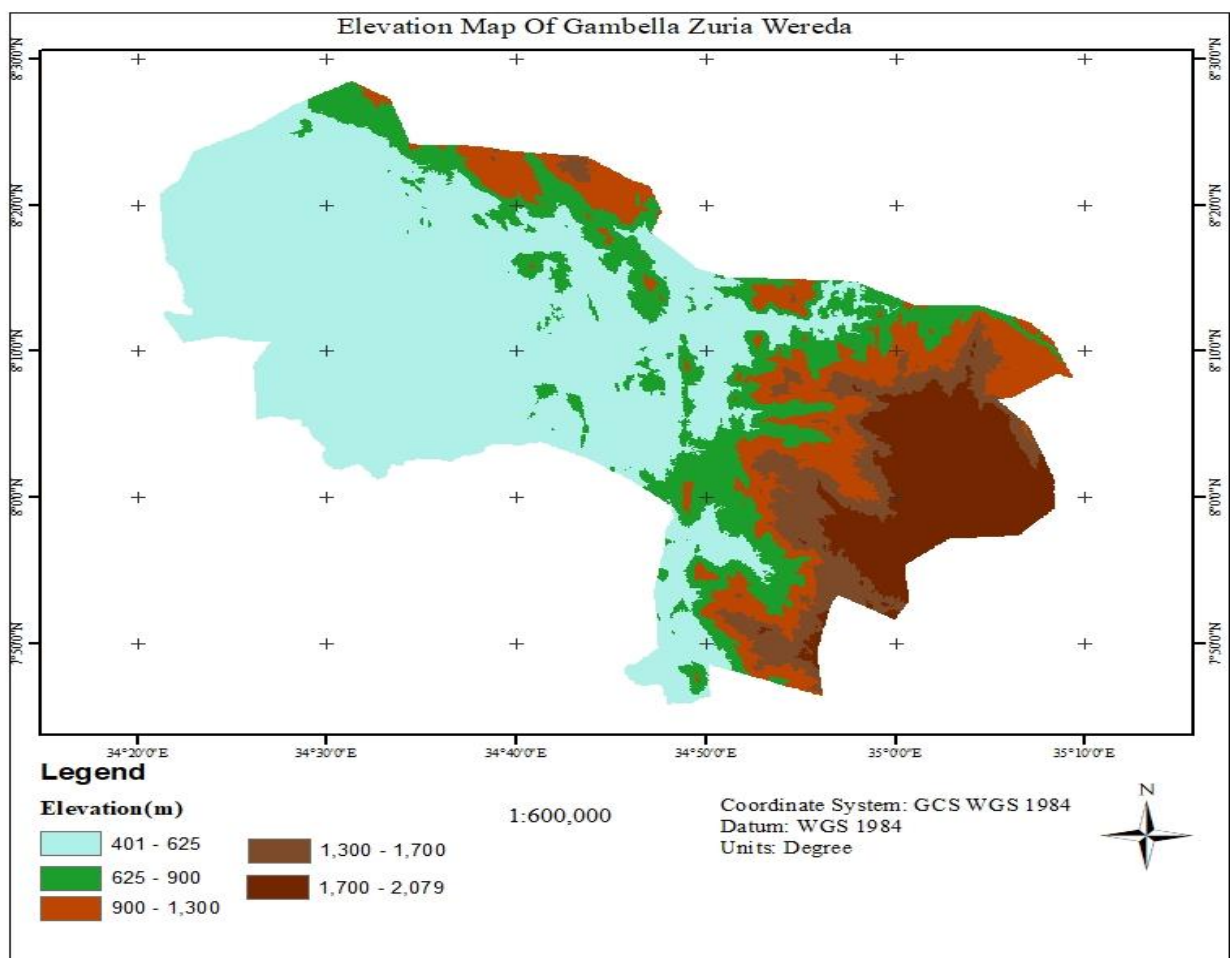


Figure 3. Elevation of Study Area map

3.1.3 . Land use Land cover

The 2024 Esri Sentinel-2 10m Land Use/Land Cover dataset (ESRI, 2024), produced through a collaboration between Esri, Impact Observatory, and Microsoft AI for Earth, offers globally consistent and high-resolution land cover classification using Sentinel-2 imagery and a deep learning convolutional neural network (CNN) trained on over 5.4 million accurately labeled samples. It classifies the Earth's surface into ten LULC types: tree cover, scrublands, grassland, cropland, urban areas, barren land, snow/ice, water, flooded vegetation, and mangroves, with an overall classification accuracy of approximately 90%, subject to variation by geographic context and category. In this study, the 2024 dataset was utilized to assess land use and land cover in Gambella Zuria Wereda, where the dominant LULC categories included tree cover, cropland, rangeland (grassland and scrubland), water bodies, flooded vegetation, built-up areas, and barren land. The detailed spatial information provided by the dataset supports environmental monitoring and flood risk assessment in the Wereda.

3.1.4 . Soil

The study area, Gambella Zuria Wereda characterized by a variety of soil types that influence its hydrological behaviors and flood potential. The soil types in the area include **Vertisols**, **Fluvisols**, **Nitisols**, **Luvisols**, **Acrisols**, **Leptosols**, and **Gleysols**. These soils were identified based on data obtained from the Ethiopian Space Science and Geospatial Institute (ESSGI, 2013). Each soil type plays a distinct role in flood dynamics, making them important parameters for the flood hazard assessment conducted in this study. Figure 4. Show Soil map of the study Area.

- **Vertisols** is a type of soil that contains a high amount of clay and is characterized by inadequate drainage and very low permeability. It expands when it is wet and develops deep cracks when it dries out. Its dense texture and ability to retain water cause water to gather on the surface during heavy rainfall, which increases the risk of flooding. It's generally flat terrain restricts water movement, leading to an increase in surface runoff. (IUSS, 2022)
- **Fluvisols** develops from new alluvial deposits, usually located near riverbanks and floodplains. It typically has silty or loamy textures, which enable moderate to high permeability. Although the area has decent soil fertility and is fairly well-drained, its low elevation makes it susceptible to occasional flooding, particularly during river overflows. (IUSS, 2022)

- **Nitisol** is a type of soil that is heavily weathered and contains a lot of clay. It is typically found in tropical highland areas. It has a solid structure and drainage system, but during heavy rainfall, it can still lead to surface runoff (IUSS, 2022).
- **Luvisols** is defined by the buildup of clay in the layer beneath the surface, featuring moderate drainage and the ability to retain water. Its potential for flooding is moderate and is influenced by the slope and the intensity of rainfall (IUSS, 2022).
- **Acrisols** is found in humid tropical areas and is characterized by low fertility and high acidity. It has low ability to retain water, which can result in quick surface runoff and raise the risk of flash floods in steep regions (IUSS, 2022).
- **Leptosols** is found in shallow, rocky areas where water retention is low. While it has a minor role in flooding, it can lead to rapid runoff in steep areas (IUSS, 2022).
- **Gleysols** develops in areas that are frequently waterlogged, indicating extended periods of saturation and reduced oxygen levels. It is located in low-lying areas and wetlands, where there is a significant risk of flooding because of inadequate drainage and continuous water saturation (IUSS, 2022).

3.1.5 . Hydrology

The Gambella National Region is rich in water resources. The major rivers are the Baro, Akobo, Alwero, and Gilo. The general direction of the rivers is from east to west. The rivers originate in the Ethiopian highlands (2,000–3,500 m) situated in the east of the area and flow to the Gambella plain (450 m) in the west (Gambella Vision, 2025). The Baro River and its tributaries in the Gambella Zuria Wereda are the primary causes of flooding, especially during the rainy season from June to September (Dame, 2017).

3.1.6 . Population

According to the 2023 report by OCHA Ethiopia, Gambella Zuria Wereda, which constitutes the study area for this research, has a total population of 15,841 individuals. Of this total, 7,660 are male (48.4%) and 8,181 are female (51.6%), indicating a slightly higher proportion of females. Although demographic data is not a direct input in the flood hazard mapping conducted in this study, it provides essential context about the human geography of the area. The population distribution within the Wereda can indirectly influence flood vulnerability, particularly in areas with higher settlement

density or limited infrastructure. Presenting this demographic overview supports a comprehensive understanding of the study area in the context of flood hazard assessment using GIS, remote sensing, and the Analytic Hierarchy Process (AHP).

3.1.7 . Climate

Gambella Zuria has a tropical climate with distinct wet and dry seasons. The wet season, from June to September, brings substantial annual rainfall, ranging from **1,400 to 1,800 mm**, with the heaviest rainfall occurring in July and August. In contrast, the dry season, from October to May, experiences significantly lower rainfall. Climate change is influencing these patterns, shortening the wet season and extending the dry season, with some areas even shifting to a biannual rainfall cycle. (Guo Hu & Guan, 2022). Temperatures in the region typically range from **22°C to 35°C**, with the hottest months, between February and May, reaching temperatures as high as 40°C (EMA, 2024) .

3.2.Data Sources

To effectively achieve the General and specific objectives of the study, both primary and secondary data sources were utilized. Key data were obtained from various publicly accessible websites offering free downloads, as well as from governmental and non-governmental organizations responsible for managing relevant geospatial information within the country.

3.2.1 Primary Data

3.2.1.1. DEM

A Digital Elevation Model (DEM) represents the landscape in a grid format, where each grid cell corresponds to an x, y coordinate in the datum plane, with an associated elevation value. The elevation, slope and orientation data, which can be extremely useful in engineering and hydrological applications of remote sensing and other application areas, can be derived from DEM (Dame, 2017). With this study, DEM data (ALOS PALSAR, 2024) with its **12.5 m** resolution is used for extracting the drainage density and for mapping the slope of the area.

3.2.2. Secondary Data

3.2.2.1 . Rainfall

This research used annual rainfall data sourced from the Ethiopian Meteorological Agency (EMA) from 2015 to 2024 (EMA, 2024). The dataset was compiled from seven meteorological stations located in and around Gambella Zuria Wereda, including Bechi, Dippa, Gubete, Yeki, Ermichi, Yina, and Gambella. The Gambella station is located within the study area, while the other stations are in nearby areas outside the main study boundary.

3.2.2.2 . Soil

The soil type data used in this study were obtained from the Ethiopian Space Science and Geospatial Institute (ESSGI 2013). The dataset corresponds to the year 2013 and has a spatial resolution of **300 meters**. It provided essential information on the spatial distribution of soil types within the study area, supporting the analysis of flood susceptibility in the Baro River Basin, Gambella Zuria Wereda.

3.2.2.3 . LULC

The Land Use/Land Cover (LULC) data used in this study were obtained from the ArcGIS Living Atlas of the World, specifically the **ESRI Sentinel-2 Land Use/Land Cover (Sentinel-10)** (ESRI, 2024) dataset for the year 2024. This dataset provides up-to-date and high-resolution land cover classifications derived from Sentinel-2 satellite imagery, offering valuable insights into the spatial distribution of land cover types within the study area. The LULC data played a critical role in identifying surface characteristics that influence flood hazard susceptibility in Gambella Zuria Wereda.

3.2.2.4 . Administrative Boundary

The administrative boundary data used in this study were obtained from the Humanitarian Data Exchange (HDX), which is maintained by the United Nations Office for the Coordination of Humanitarian Affairs (OCHA) (OCHA HDX. , 2024). Although hosted on HDX, the source of the data is the Central Statistical Agency (CSA) of Ethiopia, which is the official governmental body responsible for producing national statistics. The dataset includes the national boundary of Ethiopia, as well as the boundaries of its regions, zones, and Weredas. These boundaries were used to accurately delineate the study area within Gambella Zuria Wereda. However, it should be noted that while the data is widely used, it may not be formally authorized for legal or administrative purposes.

3.2.2.5 River and Basin

The river and basin data used in this study were obtained from the HydroSHED database, which is developed and maintained by the World Wildlife Fund (WWF). HydroSHED (HydroSHEDS, 2024) provides high-resolution hydrological data derived from NASA's Shuttle Radar Topography Mission (SRTM). It includes detailed information on river networks and basin boundaries, which was essential for mapping and analyzing the Baro River and its catchment area within Gambella Zuria Wereda.

3.3. Software Used

This study used various geospatial software tools to perform the analysis and create a map of the study area. ArcGIS 10.8 and its extensions were used for spatial analysis, visualizing data, and creating maps. QGIS 3.34, along with several plugins, provided improved features for advanced geospatial processing and data management. Google Earth Pro was used to visualize the study area and confirm spatial data. The use of these software tools allowed for a thorough and effective analysis of flood risks and the spatial characteristics of the Baro River Basin in Gambella Zuria Wereda.

3.4. Methods

This Study used a combined geospatial and multi-criteria decision-making method to identify flood hazard zones in the Baro River Basin in Gambella Zuria Wereda, Ethiopia. GIS, Remote Sensing, and the Analytical Hierarchy Process were used together to systematically analyze both Primary and Secondary data. Figure 7 shows the entire methodological workflow, detailing the sequential processes from data collection to flood hazard classification. To build a robust geospatial database, various datasets were collected from reliable sources. Elevation data were obtained from the ALOS PALSAR Digital Elevation Model (DEM) at a spatial resolution of 12.5 meters, which served as the foundation for generating slope and drainage density layers. Land use and land cover (LULC) Data was obtained from the 2024 ESRI Sentinel-2-based 10-meter Land Use and Land Cover (LULC) dataset, which offers a detailed classification of surface features. Annual rainfall data from 2015 to 2024 was obtained from the Ethiopian Meteorological Agency in CSV format, allowing for the analysis of precipitation trends over time. The Ethiopian Space Science and Geospatial Institute supplied information on soil types, and data on river networks and watershed boundaries was obtained from HydroSHEDS. Administrative boundaries were sourced from OCHA Ethiopia.

Preprocessing tasks including clipping Projection, Clip, and Subset were carried out using ArcMap 10.8 and QGIS. From the DEM, slope and drainage density maps were derived using spatial analyst tools. A proximity-to-river map was created through Euclidean distance analysis to assess flood risk based on nearness to water bodies. Rainfall data, originally in point format, were interpolated using the Inverse Distance Weighted (**IDW**) method to generate a continuous rainfall surface across the study area.

Each thematic layer, including slope, drainage density, land use and land cover, proximity to rivers, rainfall, and soil type, was reclassified into standardized categories representing varying degrees of flood susceptibility based on established criteria. Weights for these factors were systematically derived using the Analytical Hierarchy Process (AHP), and the consistency of the pairwise comparisons was confirmed by a Consistency Ratio (CR) below the acceptable threshold of 0.1. Subsequently, the weighted layers were integrated through a weighted overlay analysis in ArcGIS, following the formula $\text{Flood Hazard} = \sum (W_i \times X_i)$, where W_i denotes the weight assigned to factor i from AHP, and X_i represents the corresponding factor score. This methodology facilitated the creation of a flood hazard map that categorizes the study area into five distinct hazard levels: very high, high, moderate, low, and very low. Figure 7. Show Workflow Diagram of the study

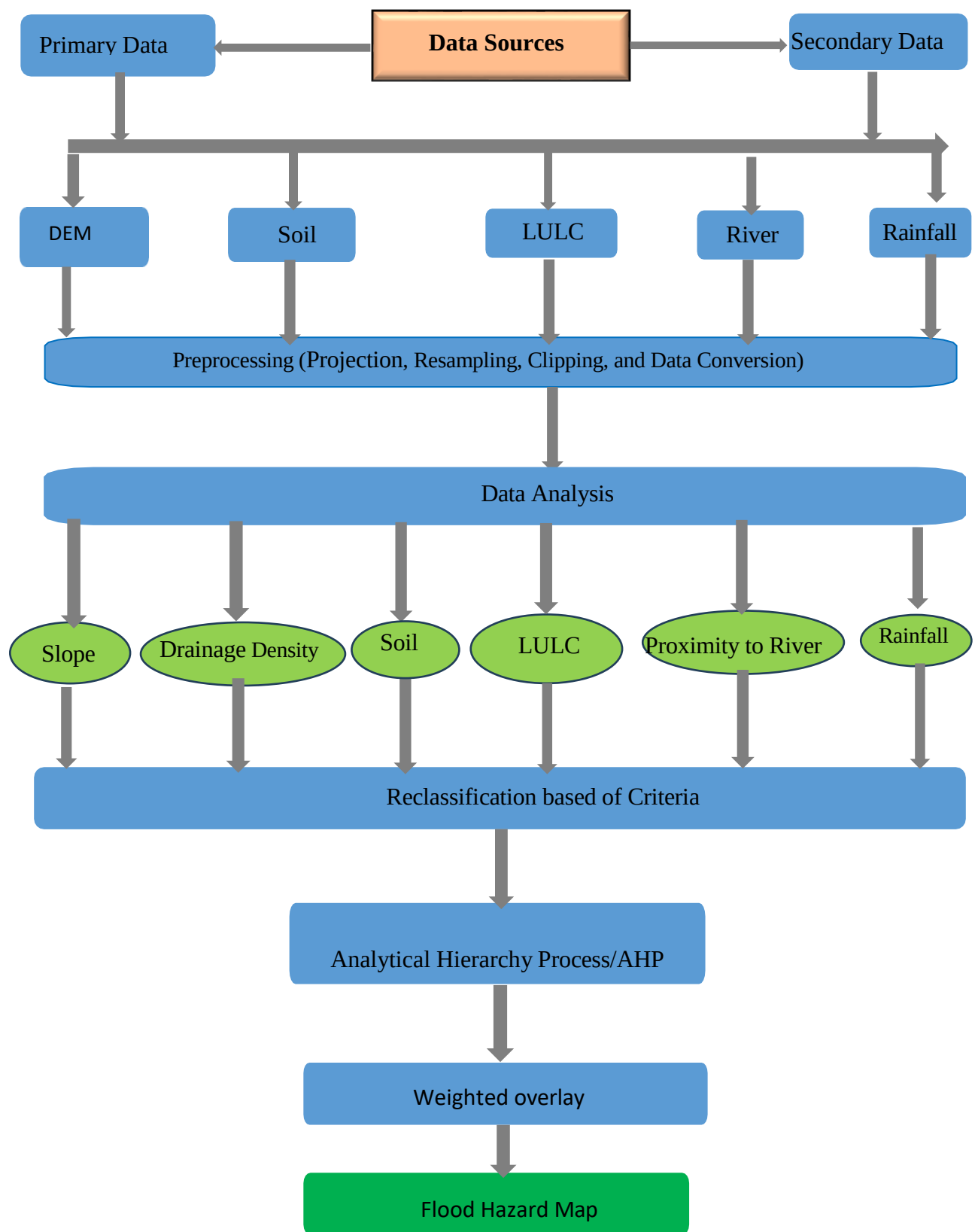


Figure 4. Work Flow Diaaram

3.4.1 Preprocessing Of Data

Preprocessing is an important step in spatial data analysis, as it establishes the basis for maintaining data consistency, accuracy, and alignment prior to integration and modeling. This study gathered various spatial and non-spatial datasets from reliable sources to identify flood hazard areas in the Baro River Basin, which is situated in Gambella Zuria Wereda. The preprocessing tasks were carried out using ArcMap 10.8 and QGIS to ensure that all datasets were converted to a standard spatial reference system and properly formatted for analysis.

3.4.1.1 . Coordinate System and Projection

To ensure consistent spatial alignment across all layers, each dataset, whether raster or vector, was converted to the Universal Transverse Mercator (UTM) Zone 36N, using the WGS 1984 geodetic datum. This projection system was selected because it is appropriate for regional studies in Ethiopia and facilitates distance-based spatial operations needed for the analysis.

3.4.1.2 Resampling

In this research, spatial resampling techniques were applied to a range of geospatial datasets, including maximum annual rainfall records from 2015 to 2024, soil data, a Digital Elevation Model (DEM), and Land Use/Land Cover (LULC) data, all of which were initially acquired at a spatial resolution of 10 meters. The primary objective of resampling was to standardize the spatial resolution and ensure alignment across all datasets to facilitate accurate spatial analysis. Appropriate interpolation methods were selected based on the data characteristics, with bilinear and cubic interpolation employed to preserve the continuity of values in continuous datasets such as rainfall and elevation.

3.4.1.1 Area of Interest Clipping

In this study, all geospatial datasets were clipped to the boundary of Gambella Zuria Wereda, which served as the defined area of interest (AOI). The administrative boundary, obtained in shapefile format from the Office for the Coordination of Humanitarian Affairs (OCHA) Ethiopia, was used as the spatial reference for this operation. Clipping was carried out using geoprocessing tools available in ArcMap 10.8 and QGIS, ensuring that all raster and vector datasets—including the Digital Elevation Model (DEM), Land Use/Land Cover (LULC), soil data, river networks, and interpolated rainfall surfaces were restricted to the Wereda's extent. This spatial refinement was critical for

maintaining analytical consistency, optimizing processing performance, and eliminating irrelevant data outside the study area.

3.4. Method of Data Analysis

3.5.1 . Slope

The slope dataset for Gambella Zuria Wereda was derived by clipping the slope raster generated from the Baro River Basin using a 12.5-meter resolution Digital Elevation Model (DEM). The slope analysis was conducted in ArcMap employing the Spatial Analyst extension to ensure accurate terrain characterization. Utilizing the entire Baro River Basin as the analysis extent was crucial for maintaining hydrological accuracy, as it incorporates upstream topographic influences that significantly impact surface runoff and flow dynamics. The slope values obtained ranged from 0 to 80 degrees across both the basin and the Wereda. By performing slope calculation at the basin scale prior to clipping, the resultant slope data for Gambella Zuria Wereda effectively captures the regional hydrological context, thereby supporting more reliable flood hazard assessment and land use planning.

3.5.2. Rainfall

Rainfall data spanning 2015 to 2024 were gathered from various meteorological stations throughout the basin, including **Mukelemi, Enango, Figakobra, Kebe, Chanka, Rob Gebeya, Yembo, Menko, Dippa, Gecha, Didu ,Gordamo, Siba, Semodo, Billambilo, and Meligewa**. The Inverse Distance Weighting (IDW) interpolation method was employed in ArcMap 10.8 to create a continuous rainfall surface across the basin, estimating precipitation at locations without direct measurements based on the influence of nearby stations. The resulting rainfall map was then clipped to the Wereda administrative boundary to concentrate the analysis on the specific area of interest. Within this clipped region, **maximum** annual rainfall ranged between 1,791.2 mm and 2,083.2 mm, whereas the full basin showed rainfall values ranging from 1791.2 mm up to 2083.16 mm. This method improves accuracy by utilizing data from all stations within the basin while focusing on the Wereda area for detailed analysis.

3.5.3. Drainage Density

A drainage density assessment of the Baro Basin was conducted using spatial analysis tools in ArcMap 10.8, utilizing a Digital Elevation Model (DEM) with a spatial resolution of 12.5 meters. The drainage density across the basin was found to range between 1.6 to 15 km/km², reflecting varying degrees of stream network concentration. To refine the analysis to the local scale, the drainage density output was clipped to the administrative boundary of Gambella Zuria Wereda. Within this delineated area, drainage density values ranged from 1.18 to 13.1 km/km². This spatially focused evaluation facilitates a more precise understanding of hydrological characteristics at the Wereda level and enhances the reliability of flood risk assessments and watershed management planning.

3.5.4. Proximity to river

A river proximity analysis was performed within the Baro Basin using ArcMap 10.8 to quantify the spatial distribution of areas relative to major river channels. The analysis delineated zones located between **1,000 and 15,000 meters** from primary rivers, capturing regions likely influenced by fluvial processes such as flooding, sediment transport, and groundwater interaction. By clipping this proximity layer to the administrative boundary of Gambella Zuria Wereda, the study provides a refined spatial framework to support hydrological assessments and flood risk management at a localized scale. This approach enhances the understanding of riverine influences on the landscape, which is essential for effective water resource planning and disaster mitigation strategies.

3.5.5. Land-use land cover

The Land Use/Land Cover (LULC) dataset for Gambella Zuria Wereda was derived by spatially clipping the LULC classification of the broader Baro River Basin, thereby ensuring alignment with regional land cover patterns. This approach facilitates consistent analysis at both the watershed and local administrative levels. The classified land cover types within the Wereda include: Water bodies such as rivers and lakes; Crops, indicating cultivated agricultural lands; Flooded Vegetation, representing areas subject to periodic inundation; Tree cover, encompassing forested and wooded landscapes; Built-up areas, referring to regions of human settlement and infrastructure; Bare Ground, comprising sparsely vegetated or exposed surfaces; and Rangelands, which are primarily used for livestock grazing. These classifications were generated using Sentinel-2 satellite imagery from the

year 2024, at a 10-meter spatial resolution, providing crucial spatial data for flood risk assessment, land management, and environmental planning within the Wereda.

3.5.6. Soil

The soil data for Gambella Zuria Wereda was extracted by clipping the soil type dataset of the entire Baro River Basin using ArcMap, specifically by applying the Gambella Zuria Wereda boundary. The original soil data was sourced from the Ethiopian Space Science and Geospatial Institute (ESSGI). The soil types identified within the Wereda include Cambisols, Acrisols, Vertisols, Gleysols, Nitisols, Luvisols, Fluvisols, and Leptosols. These soils reflect the diverse geological and climatic conditions of the region. Understanding this soil distribution is essential for flood risk assessment, land use planning, and agricultural development in Gambella Zuria Wereda.

3.6 Reclassification of Criteria

3.6.1 Slope

Slope measures the steepness of the land, which in turn influences how water flows. Gentle slopes elevate the risk of flooding by slowing down runoff, whereas steep slopes accelerate it, which decreases water accumulation but increases erosion (Yalcin & Bulut, 2023). Research conducted by (Abayneh et al., 2024) and (Diriba et al., 2024) indicates that areas with flatter terrain, characterized by lower slope values, are generally more susceptible to flooding. In contrast, steeper slopes lead to quicker runoff and a decreased risk of flooding. The was calculated using a Digital Elevation Model (DEM) that has a spatial resolution of 12.5 meters, and this was done with the Spatial Analyst tool in ArcMap 10.8. The slope raster was later divided into five categories to indicate areas at risk of flooding. The classification criteria were adopted from Abayneh et al. (2024), which defined slope-based flood susceptibility as follows: Very High for slopes less than 8% (ranked 5), High for slopes between 8% and 21% (ranked 4), Moderate for slopes between 21% and 40% (ranked 3), Low for slopes between 40% and 67% (ranked 2), and Very Low for slopes greater than 67% (ranked 1).

3.6.2. Rainfall

Rainfall occurs when water droplets fall from the atmosphere to the Earth's surface. It plays a vital role in flooding, as heavy or prolonged rainfall can surpass the soil's ability to absorb water. This leads to excess water flowing over land, which contributes to flooding (Smith K. , 2020). Research

conducted by (Abayneh et al., 2024) and (Diriba et al., 2024) indicates that areas with flatter terrain that receive higher rainfall are generally more susceptible to flooding. The Annual rainfall data was gathered from **sixteenth** meteorological stations for each year from 2015 to 2024. Using ArcMap 10.8, we applied the Inverse Distance Weighted (IDW) interpolation method to create spatial rainfall distribution maps for each year. The maximum annual rainfall was calculated from these from 1,417.8 mm up to 2,565.5 mm. over the 10-year period. The classification criteria were derived from the work of (Abayneh et al., 2024)the rainfall classes were defined as follows: Very Low (1417.8-1700 mm), ranked 1; Low (1700-1900 mm), ranked 2; Moderate (1900-2000 mm), ranked 3; High (2000–2200 mm), ranked 4; and Very High (2200-2656.5 mm), ranked 5.

3.6.2. Drainage Density

Drainage density is calculated by dividing the total length of streams and rivers within a drainage basin by the area of that basin. It influences flooding by showing the speed at which water is drained; a higher drainage density typically results in quicker runoff and a greater risk of flooding (Wang et al., 20021). This study generated the drainage density using a 12.5-meter resolution Digital Elevation Model (DEM) in ArcGIS 10.8, specifically utilizing the Spatial Analyst toolset. The Drainage density 1.0 and 13.1 km/km². Following classification schemes from (Abayneh et al., 2024)and (Paul et al., 2019)these values were reclassified into Very Low (1.6–3.0 km/km², ranked 1), Low (3.1–5.0 km/km², ranked 2), Moderate (5.–8.5 km/km², ranked 3), High (8.5–10.0 km/km², ranked 4), and Very High (10 –15 km/km²), ranked 5

3.6.3. Proximity to river

Proximity to rivers is an important factor that affects the risk of flooding. Areas close to river channels are more likely to experience regular flooding and overflow during times of high-water flow (Demirtaş & & Aydın, 2022). This study created concentric buffer zones around the Baro River network in basin using ArcMap 10.8 to measure the distance of each location from the closest river channel. Recent studies on flood vulnerability using GIS methods (Abayneh et al., 2024) (Rahmati et al., Flood susceptibility mapping using GIS and remote sensing with AHP approach: A case study. Environmental Monitoring and Assessment, 2021) . these distances were reclassified into five flood risk categories: Very High risk (0–1,000 m, rank 5), High risk (1,000–2,000 m, rank 4), Moderate

risk (2,000–5,000 m, rank 3), Low risk (5,000–8,000 m, rank 2), and Very Low risk (8,000–15,000 m, rank 1).

3.6.4. Land-use land cover

Land-use land cover (LULC) refers to both natural and human-made features on the Earth's surface. Changes in land use and land cover, such as urban expansion, heighten the risk of flooding by diminishing water absorption and increasing runoff (Zhang et al., 2022). For this this Study the ESRI Sentinel-2 Land Use/Land Cover 2024 dataset, with a spatial resolution of 10 meters, was used as the primary data source and processed using ArcMap 10.8. The land use and land cover were classified into seven categories: water bodies, built-up areas, floodplain vegetation, bare ground, cropland, rangeland, and tree cover. The Lulc categorized seven categories such as water bodies, built-up areas, floodplain vegetation, bare ground, cropland, rangeland, and tree cover (ESRI, 2024). Based on the studies of (Tigist et al., 2017) and (Abayneh et al., 2024) Water bodies and built-up areas were assigned Very High vulnerability (rank 5), floodplain vegetation and bare ground as High vulnerability (rank 4), cropland as Moderate (rank 3), rangeland as Low (rank 2), and tree cover as Very Low (rank 1).

3.6.5. Soil

Soil characteristics play a crucial role in water infiltration and retention, ultimately impacting the potential for flooding. Soils with high permeability help reduce flooding by allowing water to be absorbed, whereas clayey or compacted soils tend to increase runoff and the risk of flooding (Famiglietti, 2014). The soils found in study area Gleysols, **Cambisols**, **Acrisols**, **Nitisols**, **Fluvisols**, **Vertisols**, **Xerosols**, **Luvisols**, **Solonchaks**, **Leptosols**, **Yermosols**, and **Phaeozems**, according to data from the Ethiopian Space Science and Geospatial Institute. According to (Liu et al., 2020) and (Abayneh et al., 2024) .these soils were grouped into five vulnerability ranks according to their permeability and water-holding capacity. Gleysols and Fluvisols were classified as Very High vulnerability (rank 5) due to their poor drainage and high-water retention, which increase flood risk. Vertisols and Cambisols were ranked High vulnerability (rank 4) because of their swelling behavior and weak structure that promote runoff. Acrisols and Leptosols fall under Moderate vulnerability (rank 3), while Luvisols and Phaeozems were rated Low vulnerability (rank 2) due to their relatively better drainage characteristics. Finally, Nitisols, Xerosols, Solonchaks, and Yermosols were

considered Very Low vulnerability (rank 1) because of their good drainage or saline and dry conditions. This classification provides valuable insight for flood risk analysis and effective land management strategies within the study area.

3.7. Analytical Hierarchy Process (AHP)

The Analytic Hierarchy Process (AHP) is a methodical approach to multi-criteria decision-making (MCDM) created by Thomas L. Saaty. It helps solve complex decision-making issues by organizing them into a hierarchical framework that includes a goal, criteria, sub-criteria, and options. The Analytic Hierarchy Process (AHP) uses pairwise comparisons to create priority scales that measure the relative importance of each element according to expert opinions. Combining qualitative and quantitative evaluations provides a thorough approach for logical decision-making, which is particularly beneficial in areas like environmental and spatial planning, including flood hazard area mapping. (Saaty, 1980).

3.7.1 Pairwise Comparison

Pairwise Comparisons play a crucial role in the Analytical Hierarchy Process (AHP), which helps evaluate how important various criteria are compared to each other. In this step, we compare the criteria in pairs to figure out how much more important one criterion is compared to another. These comparisons use Saaty's nine-point scale, which goes from 1 (showing equal importance) to 9 (showing extreme importance). Values like 3, 5, or 7 show different levels of importance.

The outcomes of these pairwise comparisons are arranged in a matrix format. The diagonal parts of the matrix always get a value of 1, showing how each criterion compares to itself. The upper **triangular** matrix displays numbers that indicate how much more important one criterion is compared to another. Meanwhile, the **lower triangular matrix** has the opposite values, which helps keep the comparisons consistent.

Once the pairwise comparisons are completed, normalization is performed by dividing each element in a column by the sum of the elements in that column. This results in normalized values that reflect the relative significance of each criterion. The normalized values are subsequently averaged across each row to calculate the final weights of each criterion. These weights are crucial for subsequent analyses, such as weighted overlay analysis, to generate meaningful outputs, like maps or reports,

based on the relative importance of each criterion. The following table illustrates Saaty's Importance Scale for conducting pairwise comparisons:

Table 1. Saaty's scale format

Importance Score	Definition
1	Equal importance of criterion i and criterion j
3	Weak importance of criterion i over criterion j
5	Strong importance of criterion i over criterion j
7	Very strong importance of criterion i over criterion j
9	Intermediate values between i and j
2, 4, 6, 8	If criterion i has one of the above non-zero numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i
Reciprocal values	If criterion i has one of the above non-zero numbers assigned to it when compared with criterion j, then j has the reciprocal value when compared with i

This research focused on mapping flood hazard areas in the Baro River Basin; six important Criteria chosen because they affect the likelihood of flooding. These factors include rainfall, slope, distance to the river, drainage density, land use/land cover (LULC), and soil type. Each of these elements measures a unique part of the water cycle or the land's shape, and looking at them together using AHP helps us make a strong and clear assessment of flood risk in different areas. Table 2. Pairwise table of Criteria

Table 2. Pairwise Table of Criteria

Criteria	Slope	Drainage Density	Rainfall	Proximity to the River	LULC	Soil
Slope	1	2	5	4	7	8
Drainage Density	1/2	1	3	2	5	6
Rainfall	1/5	1/3	1	0.5	2	3
Proximity to the River	1/4	1/2	2	1	3	4
LULC	1/7	1/5	1/2	1/3	1	2
Soil	1/8	1/6	1/3	1/4	1/2	1
Sum						
Criteria	Slope	Drainage Density	Rainfall	Proximity to River	LULC	Soil
Slope	1	2	5	4	7	8
Drainage Density	0.50	1	3	2	5	6
Rainfall	0.20	0.330	1	0.5	2	3
Proximity to the River	0.25	0.500	2	1	3	4
LULC	0.14	0.200	0.50	0.33	1	2
Soil	0.12	0.170	0.33	0.25	0.50	1
Sum	2.21	4.2	11.83	8.08	18.5	24

3.7.2 Normalization of the Pairwise Comparison Matrix

Normalization plays an essential role in the Analytic Hierarchy Process (AHP) because it makes sure that the impact of each criterion is assessed on a fair and uniform scale. This process changes the initial pairwise comparison values into comparable proportions, which makes it possible to calculate meaningful and trustworthy weights (priority vectors) for each criterion in multi-criteria decision-making (Saaty, 1980).

In AHP, normalization is performed by dividing each element in the pairwise comparison matrix by the sum of the elements in its respective column. This ensures that each column of the matrix totals to one, allowing the data to reflect the relative influence of each criterion accurately. This scaling method helps to standardize the criteria, making their comparative importance uniform and interpretable across the matrix.

This is especially important in applications such as flood hazard mapping, where criteria such as rainfall, slope, proximity to rivers, drainage density, land use/land cover (LULC), and soil type have varying degrees of influence. The normalization process ensures that stronger influences are proportionally highlighted while maintaining consistency in the decision model.

The normalization formula is expressed as:

$$N_{ij} = \frac{a_{ij}}{\sum_{i=1}^n a_{ij}}$$

Where:

- N_{ij} is the normalized value of the i-th criterion relative to the j-th criterion,
- a_{ij} is the original value in the pairwise comparison matrix,
- $\sum_{i=1}^n a_{ij}$ is the total of the j-th column in the matrix,
- n is the number of criteria.

Table 3. Normalization Table of Criteria

Criteria	Slope	Drainage Density	Rainfall	Proximity to River	LULC	Soil
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Slope	1	2	5	4	7	8
Drainage Density	0.5	1	3	2	5	6
Rainfall	0.2	0.33	1	0.5	2	3
Proximity to the River	0.25	0.5	2	1	3	4
LULC	0.14	0.2	0.5	0.33	1	2
Soil	0.12	0.17	0.33	0.25	0.5	1
Sum	2.21	4.2	11.83	8.08	18.5	24
Criteria	Slope	Drainage Density	Rainfall	Proximity to River	LULC	Soil
Slope	0.45	0.48	0.42	0.50	0.38	0.33
Drainage Density	0.23	0.24	0.25	0.25	0.27	0.25
Rainfall	0.09	0.08	0.08	0.06	0.11	0.13
Proximity to River	0.11	0.12	0.17	0.12	0.16	0.17
LULC	0.06	0.05	0.04	0.04	0.05	0.08
Soil	0.05	0.04	0.03	0.03	0.03	0.04

3.7.3 Criterion weight

In this study, researchers used the Analytic Hierarchy Process (AHP) to rank the factors related to flood hazards. Once the pairwise comparison matrix was normalized, we found the weight of each criterion by averaging the normalized values from each row. To find the importance of each criterion in flood hazard mapping, we added up the normalized values for all the criteria and then divided that total by six, the total number of criteria (Saaty, 1980).

$$\text{Criterion Weight} = \frac{\text{Sum of Normalized Row}}{n}$$

Table 4.Criteria

Criteria	Rainfall	Slope	Proximity to the River	Drainage Density	LULC	Soil	Criterion weight
Slope	0.426	0.496	0.455	0.544	0.385	0.296	0.426
Drainage Density	0.213	0.248	0.273	0.272	0.275	0.222	0.248
Rainfall	0.085	0.082	0.091	0.068	0.11	0.111	0.091
Proximity to River	0.107	0.124	0.182	0.136	0.165	0.148	0.136
LULC	0.06	0.05	0.046	0.045	0.055	0.074	0.055
Soil	0.051	0.042	0.03	0.034	0.028	0.037	0.037

In AHP, the criteria weights show how important they are compared to each other. Turning these weights into percentages, known as percentage influence, helps us better understand how much each factor adds to flood hazard mapping. This helps to prioritize the important factors in the study of the Baro River Basin.

Table 5.Criteria percentage

Criteria	Criterion weight	% Influence
Slope	0.426	42.64%
Drainage Density	0.248	24.76%
Rainfall	0.098	9.80%
Proximity to River	0.136	13.57%
LULC	0.055	5.52%
Soil	0.037	3.71%
total	1.0	100.00%

3.7.4 . Consistency Index (CI) Calculation

In this study, the Analytic Hierarchy Process (AHP) was utilized to determine the relative importance of various flood hazard criteria through pairwise comparisons. To ensure the reliability and logical coherence of these judgments, it is essential to assess their consistency by calculating the Consistency Index (CI) and Consistency Ratio (CR).

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

Where:

- $\lambda_{\max}$ is the maximum eigenvalue of the pairwise comparison matrix,
- n is the number of criteria compared, which in this case is 6.

The maximum eigenvalue $\lambda_{\max}$ is obtained through the weighted sum method, defined as:

$$\lambda_{\max} = \sum_{i=1}^n \frac{(PW)_i}{w_i}$$

Here:

- $(PW)_i$ represents the weighted sum of the i^{th} criterion,
- w_i is the normalized weight corresponding to the i^{th} criterion,
- n is the total number of criteria.

Table 6.Derived Consistency ratio (CR)

Criteria	Slope	Drainage Density	Rainfall	Proximity to the River	LULC	Soil			
Slope	1*0.426	2*0.248	5*0.091	4*0.136	7*0.055	8*0.037			
Drainage Density	0.5*0.426	1*0.248	3*0.091	2*0.136	5*0.055	6*0.037			

Rainfall	0.2*0.426	0.33*0.248	1*0.091	0.5*0.136	2*0.055	3*0.037			
Proximity to River	0.25*0.426	0.5*0.248	2*0.091	1*0.136	3*0.055	4*0.037			
LULC	0.14*0.426	0.2*0.248	0.5*0.091	0.33*0.136	1*0.055	2*0.037			
Soil	0.12*0.426	0.17*0.248	0.33*0.091	0.25*0.136	0.5*0.055	1*0.037			
Criterion weight	0.426	0.248	0.091	0.136	0.055	0.037			
Criteria	Rainfall	Slope	Proximity to the River	Drainage Density	LULC	Soil	Weighted sum value	Criterion weight	Ratio
Slope	0.426	0.496	0.455	0.544	0.385	0.296	2.602	0.426	6.11
Drainage Density	0.213	0.248	0.273	0.272	0.275	0.222	1.503	0.248	6.06
Rainfall	0.085	0.082	0.091	0.068	0.11	0.111	0.547	0.091	6.01
Proximity to River	0.107	0.124	0.182	0.136	0.165	0.148	0.862	0.136	6.34
LULC	0.06	0.05	0.046	0.045	0.055	0.074	0.33	0.055	6
Soil	0.051	0.042	0.03	0.034	0.028	0.037	0.222	0.037	6

$$\lambda_{\max} = \frac{6.11 + 6.06 + 6.01 + 6.34 + 6 + 6}{6}$$

$$= 6.027$$

Consistency Index

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

$$= \frac{6.027 - 6}{6 - 1} = 0.0174$$

The Consistency Index (CI) value of **0.0174** shows that there is a **high level of consistency** in the pairwise comparison matrix. Typically, CI values start at zero, indicating perfect consistency, and go up to just below one for levels of consistency that are still considered acceptable. A low CI indicates that the comparisons were reasonable, which boosts the reliability of how the criteria are weighted (Saaty, 1980).

3.7.5 Consistency Ratio (CR) Calculation

The Consistency Ratio (CR) measures how consistent the judgments are in the pairwise comparison matrix of the Analytic Hierarchy Process (AHP). It checks if the amount of inconsistency in the pairwise comparisons is acceptable, which helps create a trustworthy set of criteria weights (priority vector). The CR looks at the Consistency Index (CI) and compares it to the Random Consistency Index (RI). The RI shows the CI from a pairwise comparison matrix that is created randomly and is the same size.

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

$$CR = \frac{CI}{RI} =$$

Where;

- CR is Consistency Ratio
- CI is Consistency Index
- RI is Random index

$$CR = \frac{0.0174}{1.24} = 0.014$$

$$CR = 1.4\%$$

With a Consistency Ratio (CR) of 0.014, the matrix falls well within the acceptable limit of 0.10 (10%). As per (Saaty, 1980). CR below 0.10 shows that the inconsistency present is minimal and does not undermine the validity of the priority weights derived from the comparisons.

3.7.6 Flood Hazard Area Mapping

The final flood hazard map for the study area is made by combining important factors that together evaluate the flood risk across the region. The main factors looked at in this analysis are **Rainfall, Slope, Proximity to the River, Drainage Density, Land Use/Land Cover (LULC), and Soil**. Each of these factors is given a weight that shows how important it is in causing flood hazards. The flood hazard score for every location is determined by using this formula:

$$\text{Flood hazard} = \sum (W_i \times X_i)$$

Where

- W_i = weight of factor i
- X_i = criterion score of factors i

Therefore, using the calculated results of the weighted factors, we can create the flood hazard map for the study area as shown below on Fig

$$\text{Flood hazard} = [\text{Slope}] * 0.427 + [\text{Drainage Density}] * 0.248 + [\text{Rainfall}] * 0.098 + [\text{Proximity to River}] * 0.138 + [\text{LULC}] * 0.055 + [\text{Soil}] * 0.037$$

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Data Analysis Result

4.1.1 . Slope

The slope map for Gambella Zuria Wereda was derived by clipping a slope raster calculated for the Baro River Basin using a 12.5-meter resolution Digital Elevation Model (DEM) in ArcMap with the Spatial Analyst extension. Analyzing the entire basin ensured that upstream topographic influences critical for modeling surface runoff and flood behavior were preserved. The resulting slope values ranged from 0° to 80°, with lower slope areas (0°–5°) identified as more vulnerable to flooding due to slower water drainage, making the slope map a key input for flood hazard assessment. Figure 6. shows the slope map of study Area.

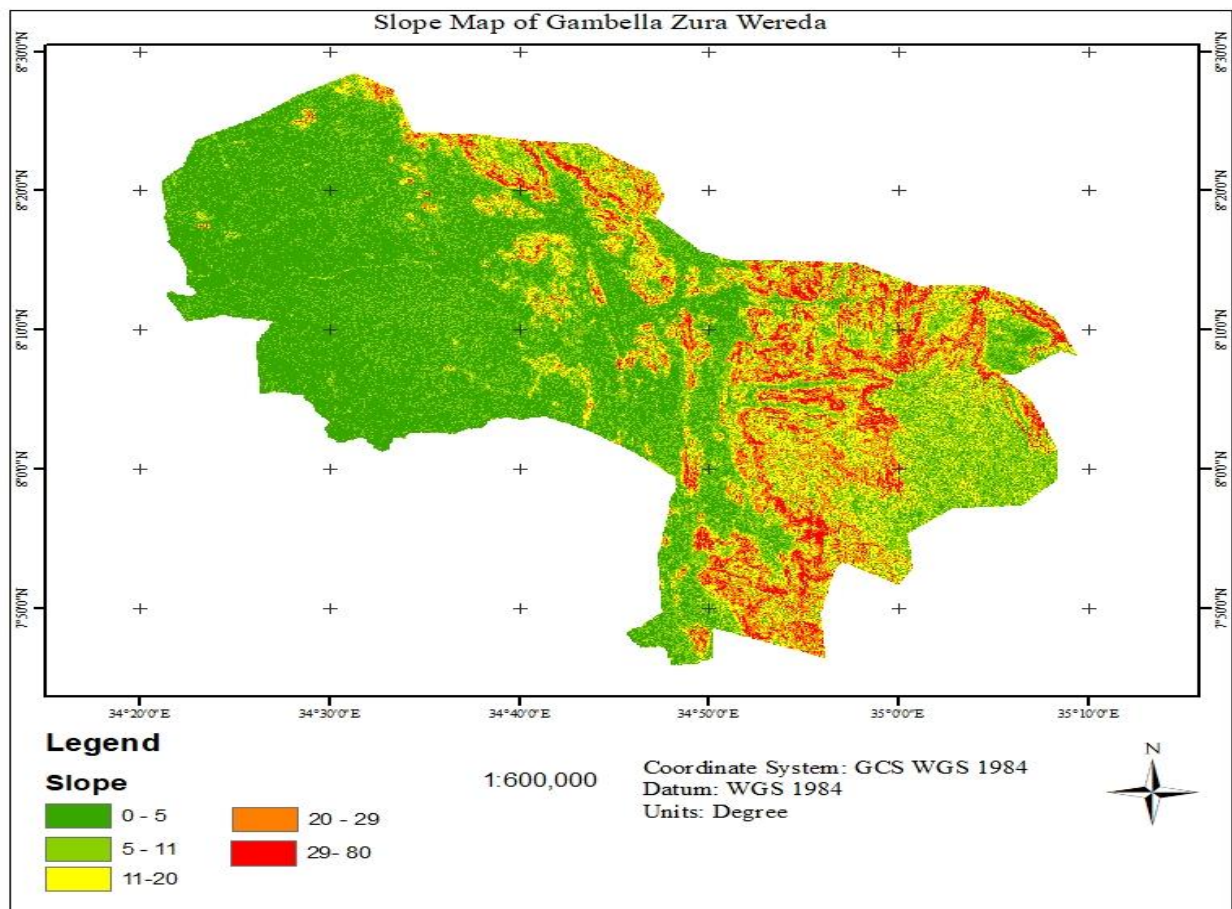


Figure 6.slope map of study Area

4.1.2 . Rainfall

The maximum rainfall map for Gambella Zuria Wereda was derived by clipping a rainfall surface interpolated for the entire Baro River Basin using the Inverse Distance Weighting (IDW) method in ArcMap 10.8. Rainfall data from 2015 to 2024 were obtained from multiple meteorological stations across the basin, ensuring spatial consistency and capturing regional precipitation patterns. Clipping the interpolated surface to the Wereda boundary allowed for localized analysis while preserving the hydrological context of the broader basin. Within Gambella Zuria Wereda, maximum annual rainfall values ranged from **1,791.2 mm to 2,083.2 mm**, highlighting spatial variation and supporting flood risk assessment and water resource planning in the area. Figure 7. Shows the maximum rainfall map of study Area.

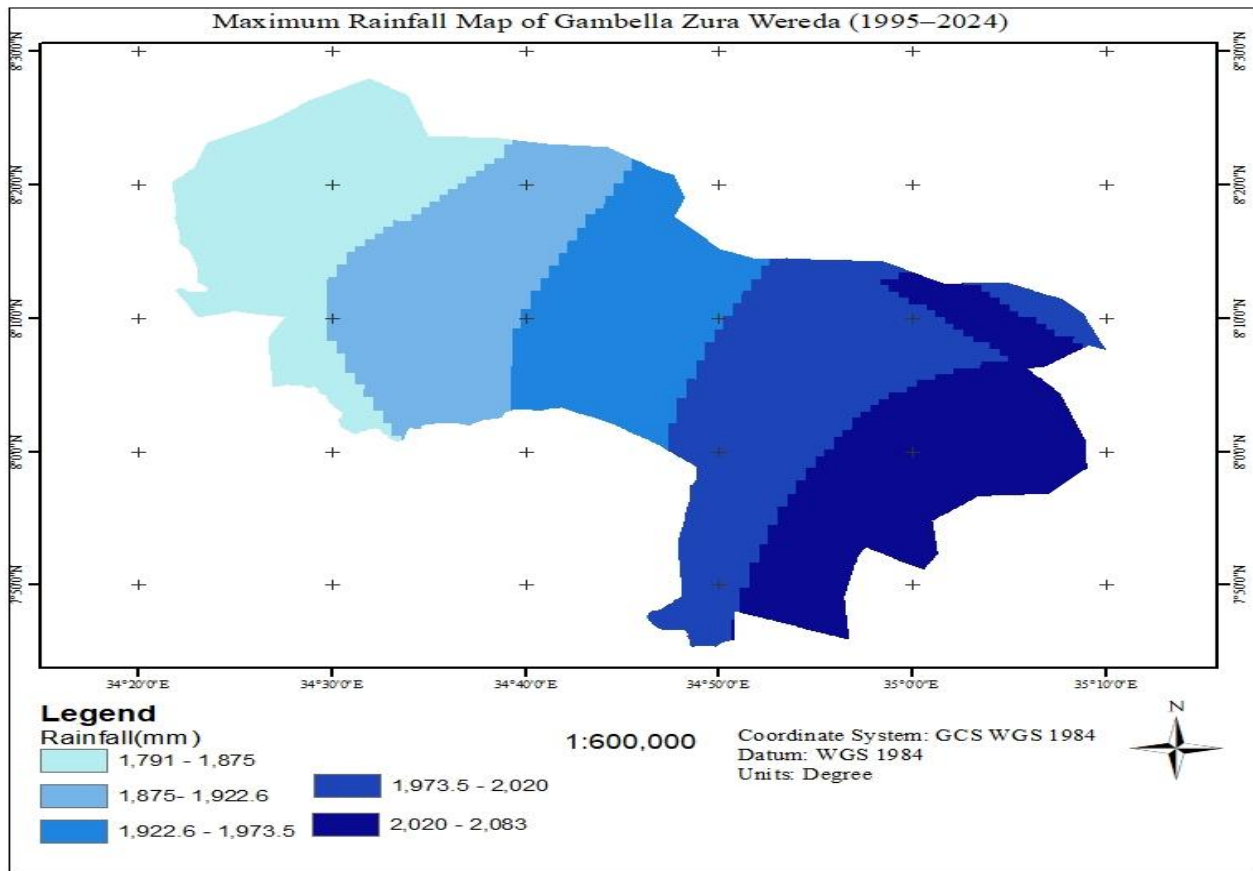


Figure 7. Maximum rainfall map of study Area.

4.1.3 . Drainage Density

The drainage density map for Gambella Zuria Wereda was derived by clipping a basin-wide drainage density raster calculated for the Baro River Basin using a 12.5-meter resolution Digital Elevation Model (DEM) in ArcMap 10.8. The initial analysis across the entire basin provided comprehensive insights into the spatial variation of stream network concentration, with drainage density values ranging from 1.6 to 15 km/km². To localize the results and support site-specific hydrological analysis, the drainage density output was clipped to the administrative boundary of Gambella Zuria Wereda. Within the Wereda, drainage density values ranged from **1.18 to 13.1 km/km²**, capturing both sparse and concentrated stream networks. This refined assessment enhances the accuracy of flood risk analysis. Figure 8. Shows the Drainage Density map of Study Area

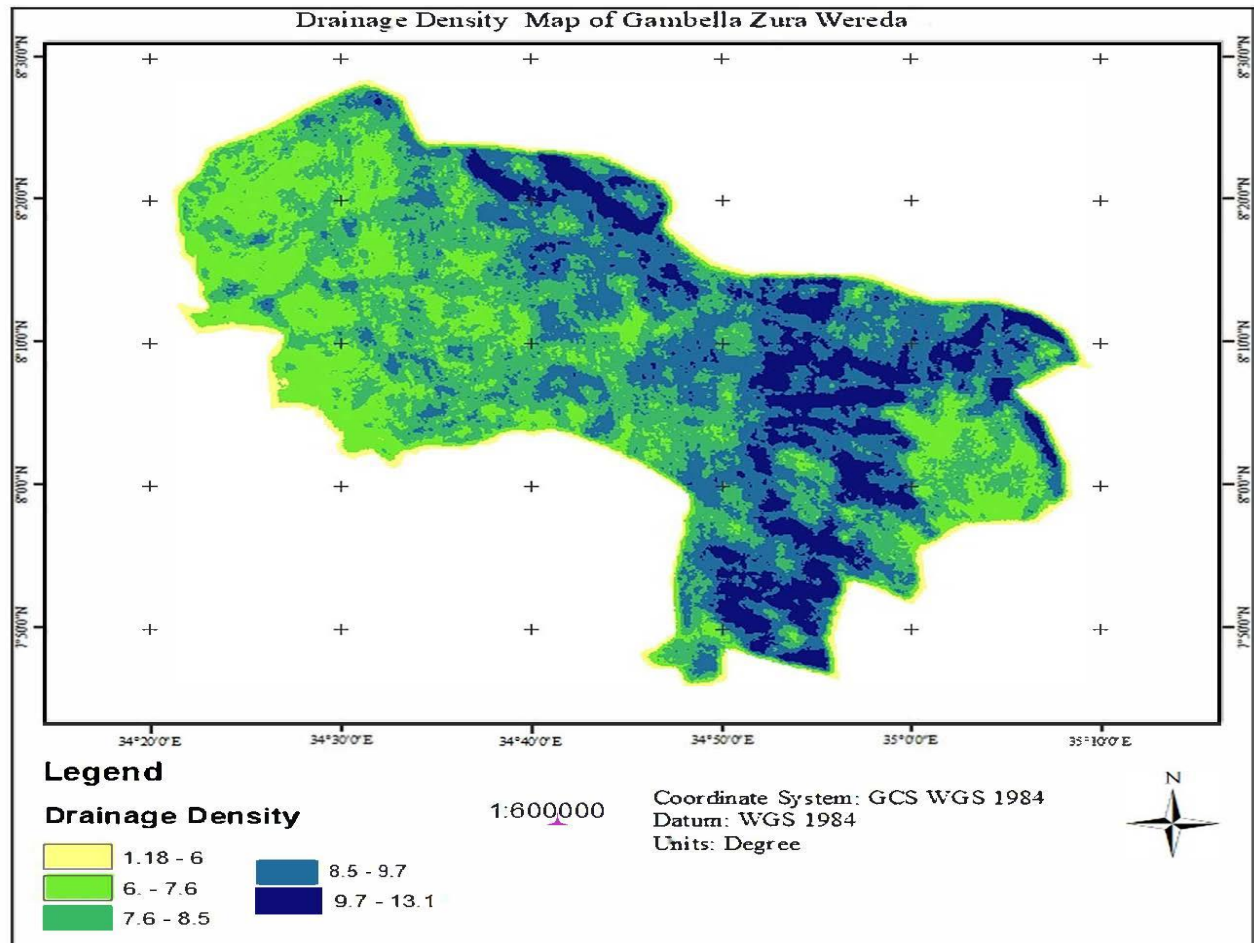


Figure 8. Drainage Density map of Study Area

4.1.4 Land use Land cover

The Land Use/Land Cover (LULC) map for Gambella Zuria Wereda was produced by extracting the LULC data of the Baro River Basin according to the Wereda's boundary using ArcMap. This ensures the land cover classification matches regional patterns. Using Sentinel-2 satellite images from 2024 at a 10-meter resolution, the map categorizes the area into several land cover types such as rivers and lakes (water bodies), agricultural fields (crops), areas prone to flooding (flooded vegetation), forests and wooded areas (tree cover), urban and built-up zones, exposed or sparsely vegetated surfaces (bare ground), and grazing lands (rangelands). Figure 9. Shows the. LULC map of the Study Area.

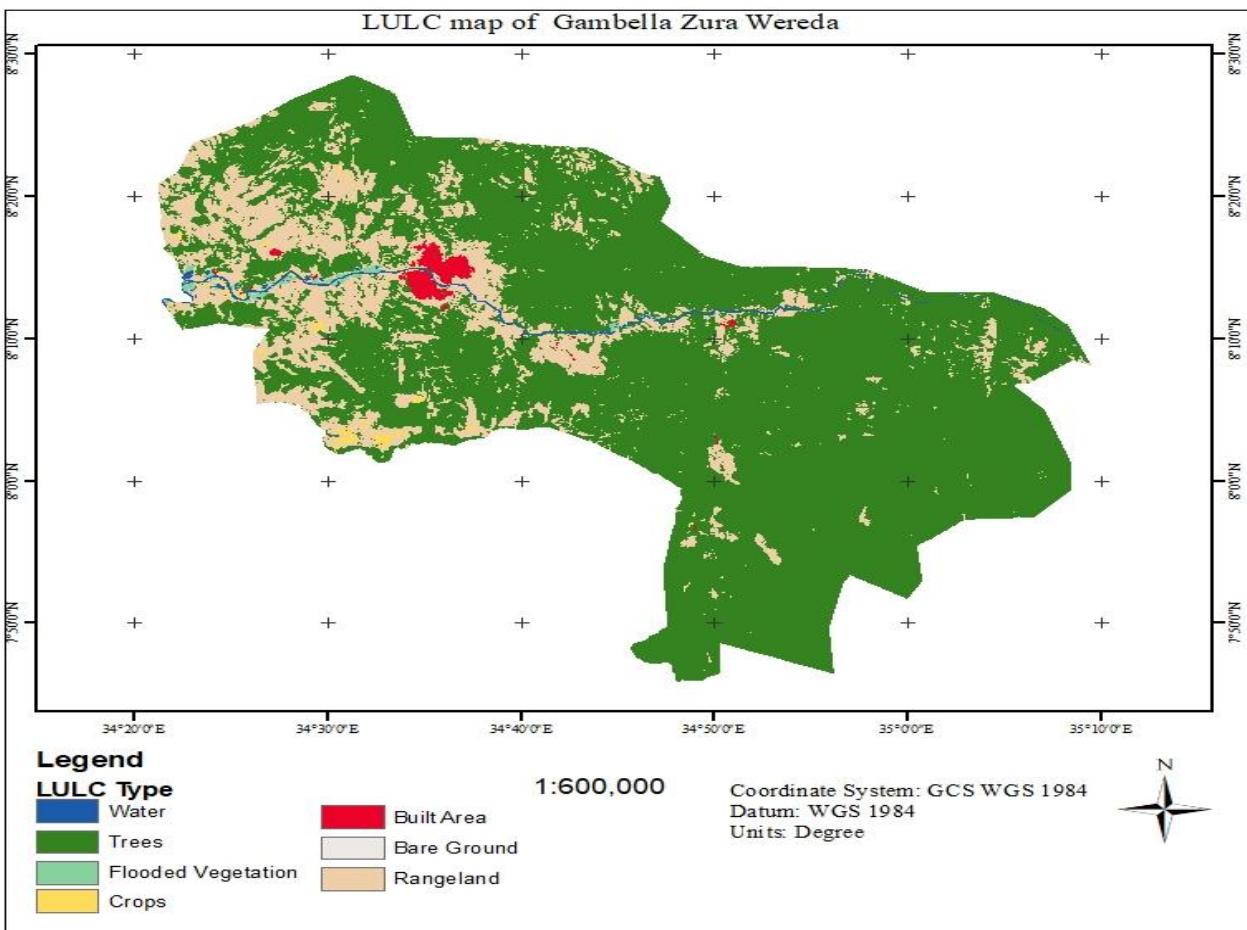


Figure 9.LULC map of the Study Area.

4.1.5 Proximity to river

A river proximity analysis was conducted across the Baro Basin using ArcMap 10.8 to map spatial zones based on distance from major river channels. The study identified areas situated between 1,000 and 15,000 meters from primary rivers, highlighting regions impacted by fluvial dynamics such as flooding, sediment deposition, and groundwater interaction. This proximity layer was then clipped to the Gambella Zuria Wereda boundary to focus the analysis locally, providing a detailed spatial framework for hydrological evaluation and flood risk management. The refined mapping improves insight into river influences on the landscape, aiding water resource planning and disaster preparedness within the Wereda. Figure 10. Shows Proximity to river map of the Study Area

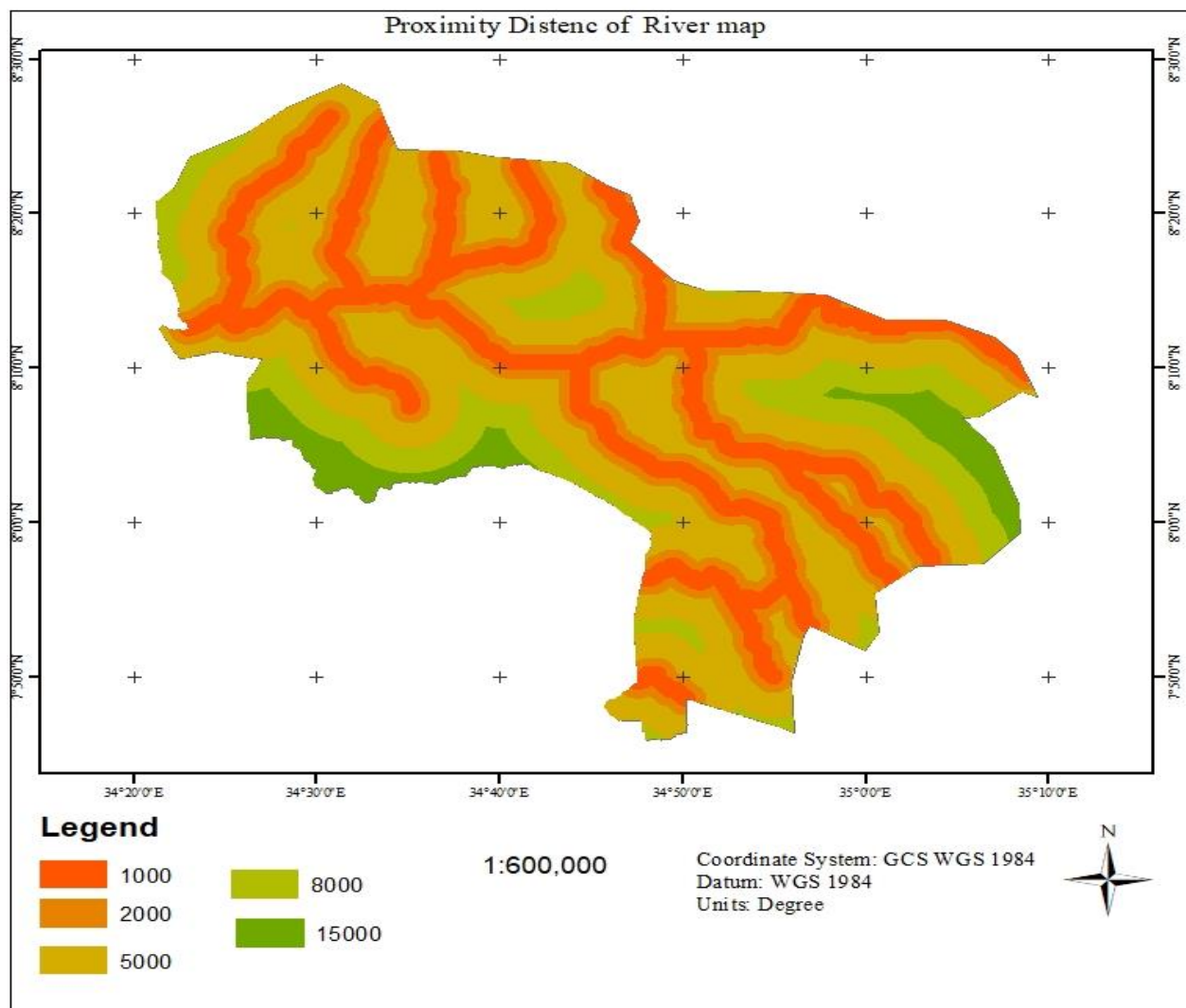


Figure 10. Proximity to river map of the Study Area

4.1.6. Soil

The soil data for Gambella Zuria Wereda was obtained by clipping the broader Baro River Basin soil dataset using the Wereda boundary in ArcMap. This dataset, originally sourced from the Ethiopian Space Science and Geospatial Institute (ESSGI), identifies key soil types present within the Wereda, including Cambisols, Acrisols, Vertisols, Gleysols, Nitisols, Luvisols, Fluvisols, and Leptosols. These soil types reflect the region's varied geological and climatic conditions. Accurate knowledge of soil distribution is vital for flood risk assessment, land use planning, and guiding agricultural development efforts in Gambella Zuria Wereda. Figure 11. Shows soil map of the Study Area

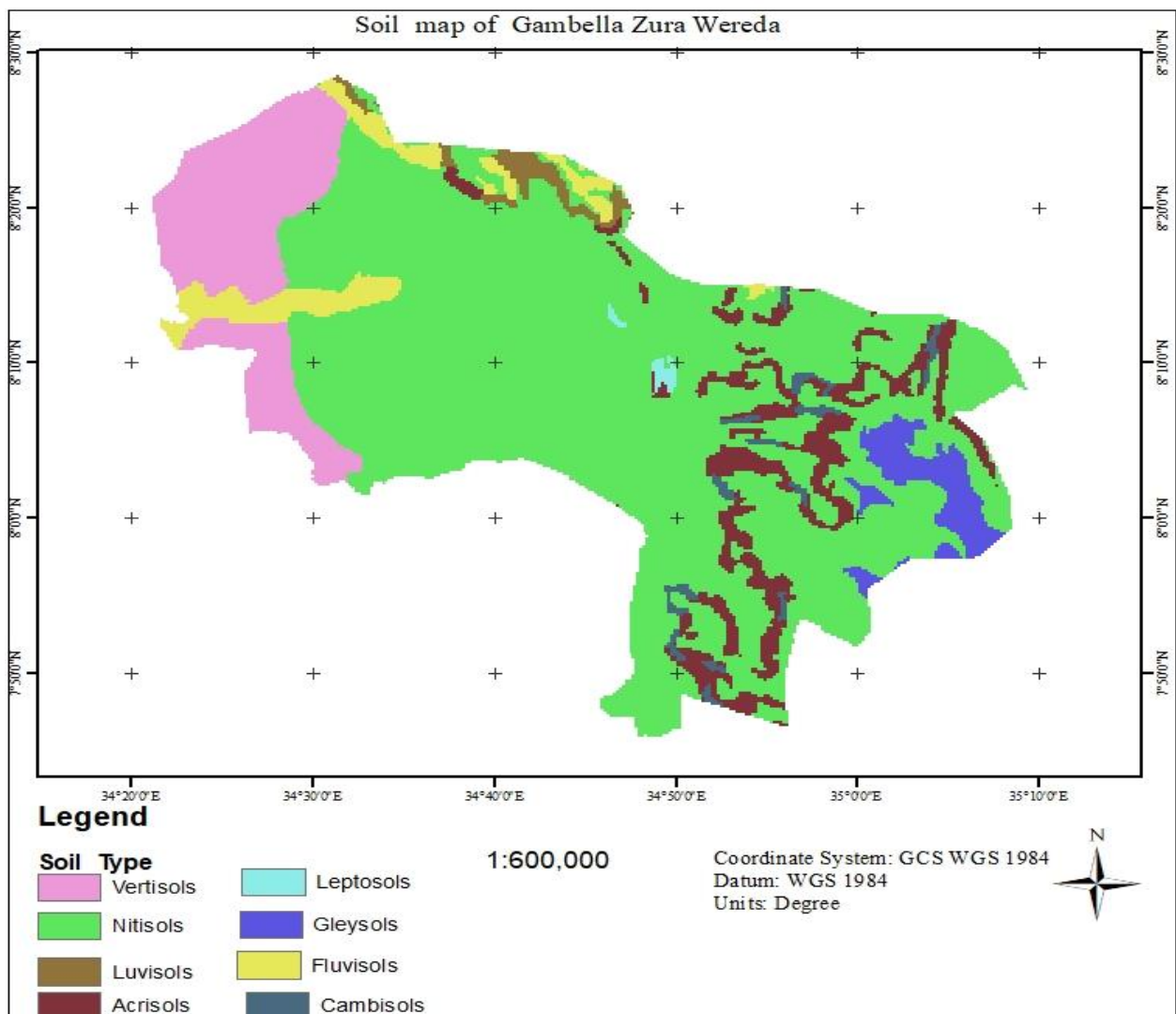


Figure 11. Soil map of the Study Area

4.2 . Reclassification Flood Factor Result

4.2.1. Slope

The slope raster for the Baro River basin was first reclassified into five flood risk categories. These categories are: Very High risk for slopes under 8% (rank 5), High risk for slopes between 8% and 21% (rank 4), Moderate risk for slopes between 21% and 40% (rank 3), Low risk for slopes between 40% and 67% (rank 2), and Very Low risk for slopes above 67% (rank 1). After this reclassification, the slope data for the entire basin was clipped to isolate the Gambella Zuria Wereda area. The resulting reclassified slope map identifies different flood susceptibility zones within Gambella Zuria Wereda, reflecting the influence of slope steepness on flood risk. Figure 12. Shows Reclassified Slope map of study Area

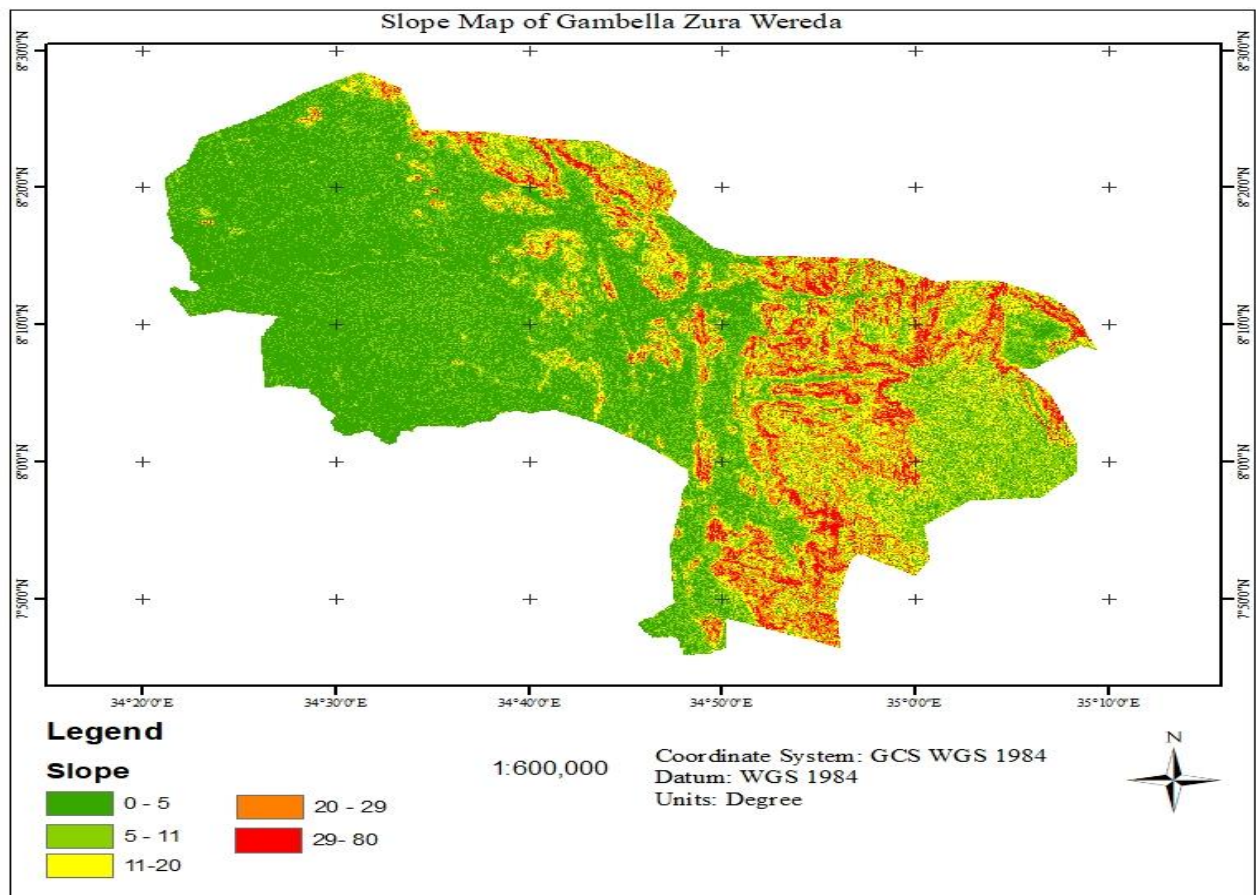


Figure 12. Reclassified Slope map of study Area

4.2.2. Rainfall

Annual rainfall data for the Baro River basin were interpolated using the Inverse Distance Weighted (IDW) method in ArcMap 10.8, based on records from sixteen meteorological stations collected between 2015 and 2024. The rainfall values ranged from a minimum of 1,417.8 mm to a maximum of 2,565.5 mm during this period. Using the classification scheme by Abayneh et al. (2024), the rainfall was divided into five categories: Very Low (1,417.8–1,700 mm, rank 1), Low (1,700–1,900 mm, rank 2), Moderate (1,900–2,000 mm, rank 3), High (2,000–2,200 mm, rank 4), and Very High (2,200–2,565.5 mm, rank 5). The reclassified rainfall map for the entire basin was then clipped to the Gambella Zuria Wereda boundary to provide localized insights into rainfall distribution and flood susceptibility. Figure 13. Shows Reclassified Rainfall map of study Area

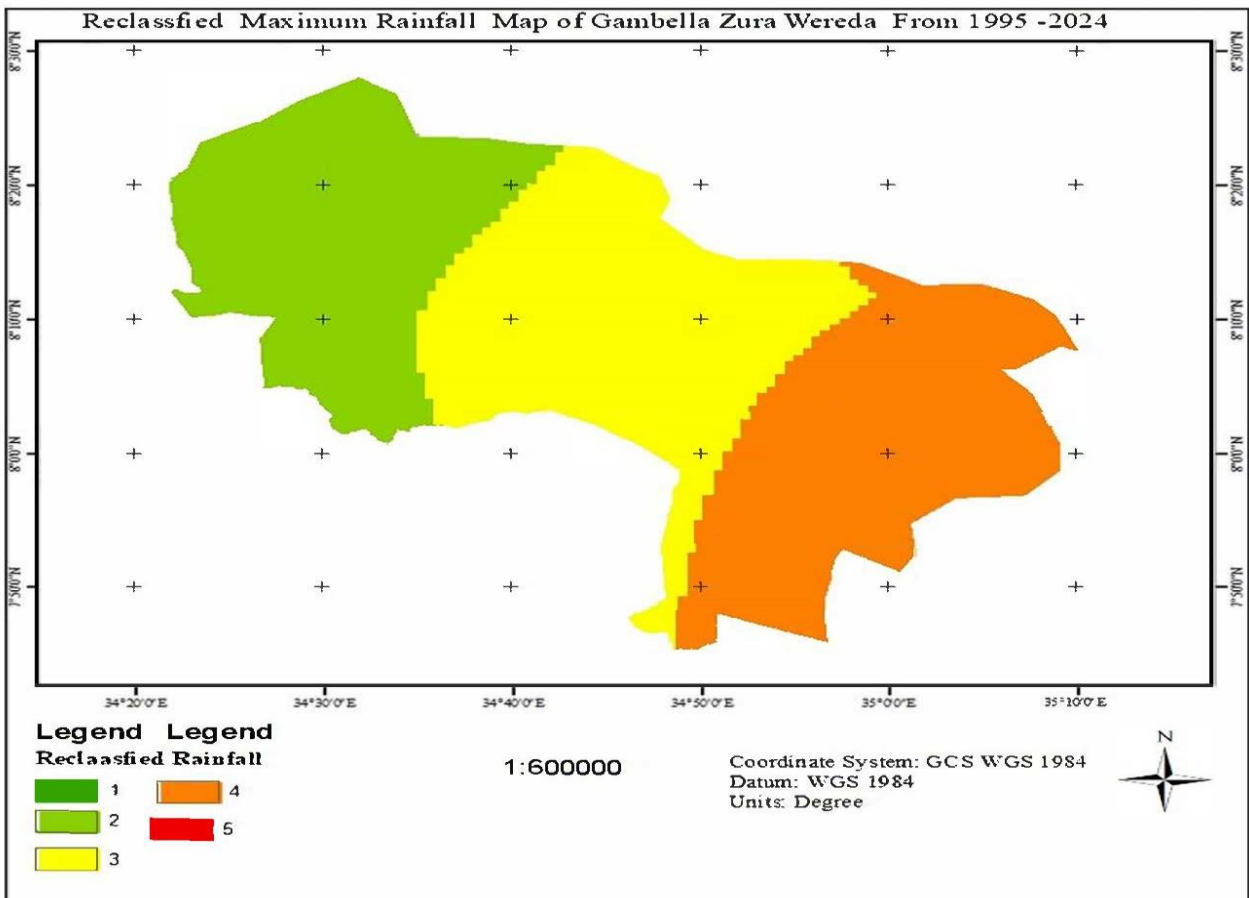


Figure 13. Reclassified Rainfall map of study Area

4.2.3 Drainage Density

The drainage density values of the Baro River basin ranged between 1.0 and 13.1 km/km². These values were categorized into five classes: Very Low (1.6–3.0 km/km², rank 1), Low (3.1–5.0 km/km², rank 2), Moderate (5.1–8.5 km/km², rank 3), High (8.6–10.0 km/km², rank 4), and Very High (10.1–15.0 km/km², rank 5). The reclassified drainage density map for the Baro basin was clipped to the boundary of Gambella Zura Wereda to analyze local drainage characteristics and flood susceptibility. Figure 14. Shows Reclassified map of Drainage Density map of Study Area

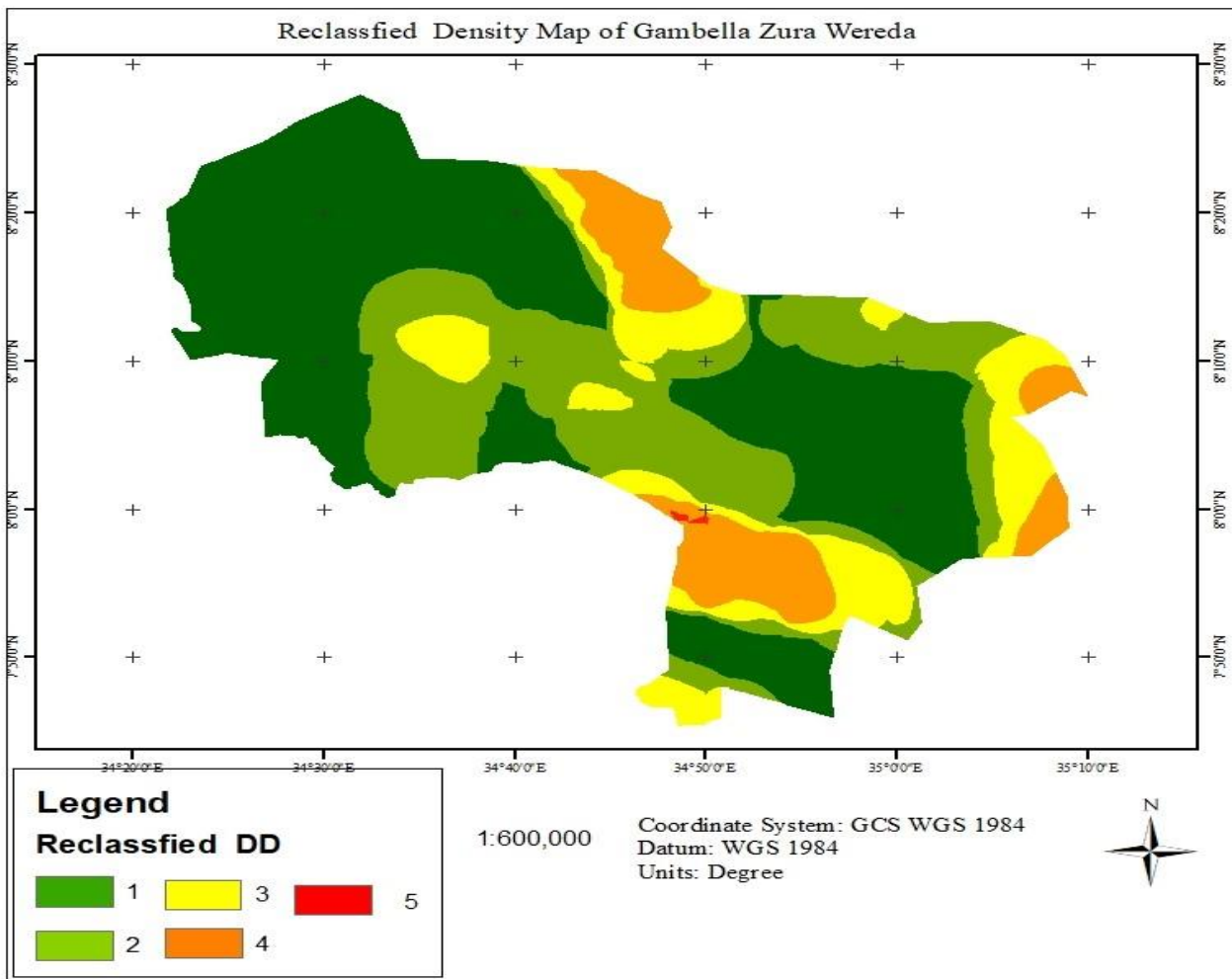


Figure 14. Drainage Density map of Study Area

4.2.4. Land use Land cover

The Land Use Land Cover (LULC) data of the Baro River basin was reclassified into five flood susceptibility classes and clipped to the Gambella Zuria Wereda boundary. The classification ranks and corresponding LULC types were: Very High flood risk (rank 5) wetlands and built-up areas; High (rank 4) agricultural land; Moderate (rank 3) scrublands; Low (rank 2) sparse vegetation; and Very Low (rank 1) forested areas. Figure 15. Shows Reclassified LULC map of study Area

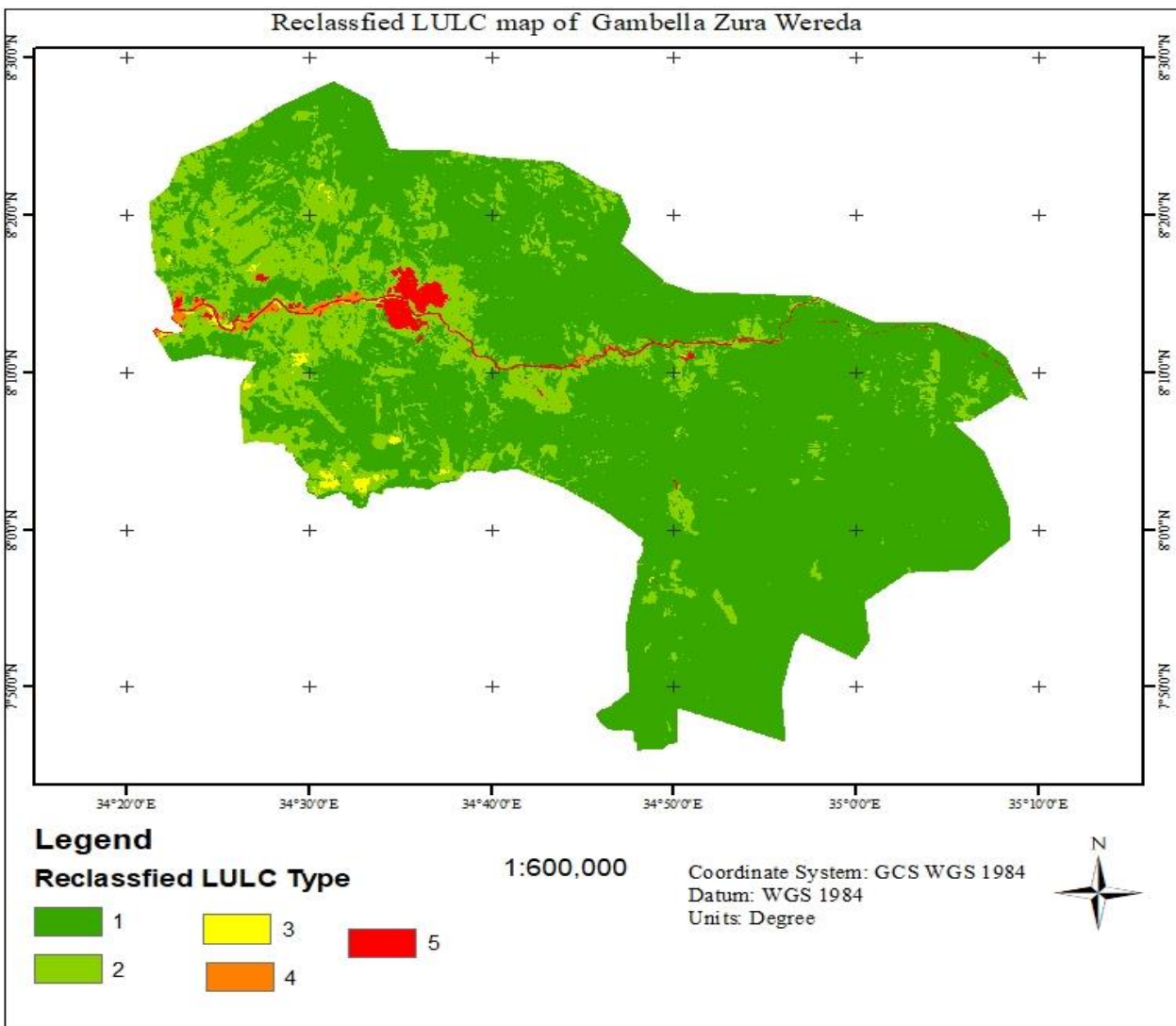
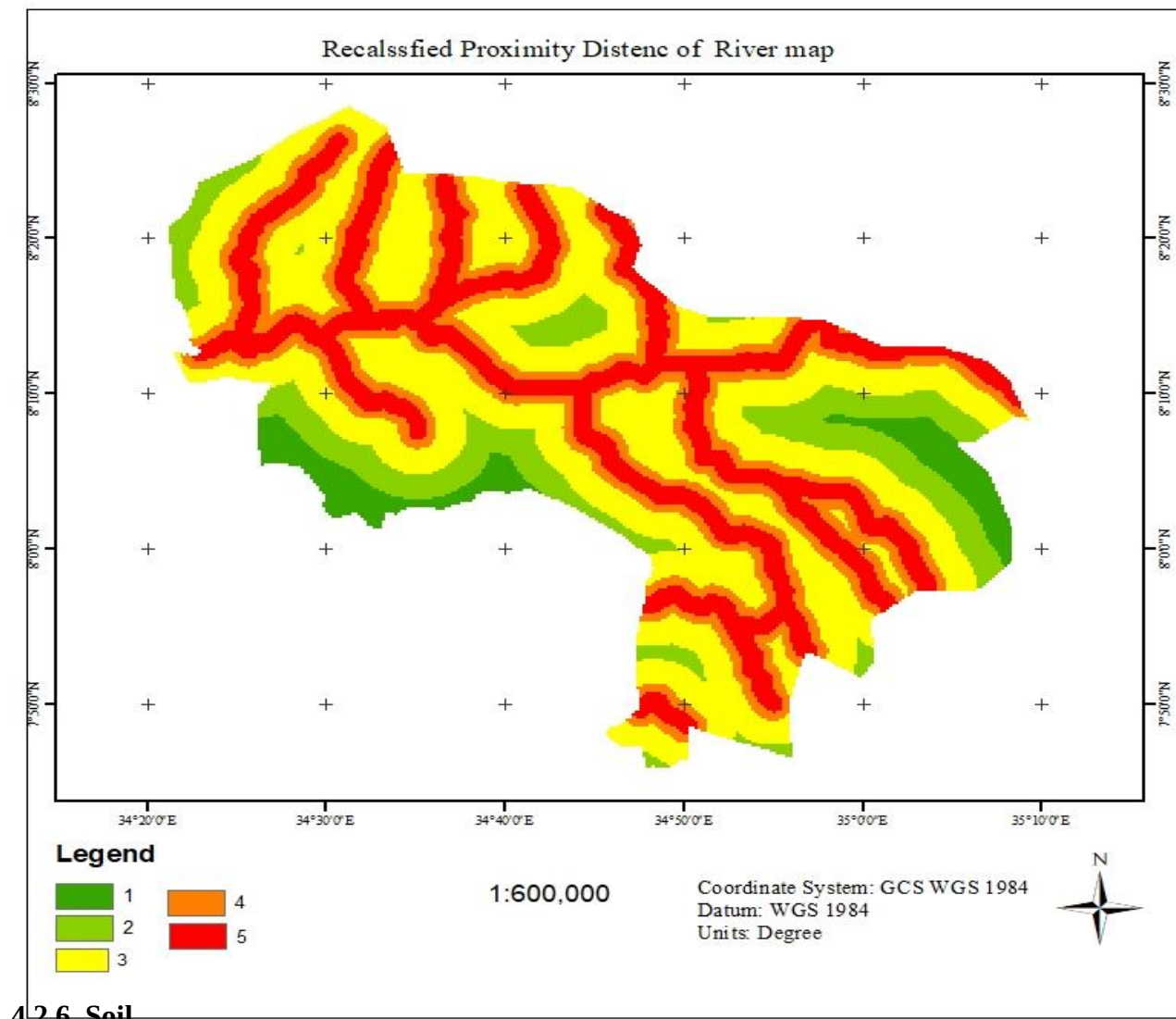


Figure 15. Reclassified LULC map of study Area

4.2.5. Proximity to River

Proximity to river channels, an essential parameter influencing flood susceptibility, was computed and reclassified at the scale of the entire Baro River basin using ArcMap 10.8. Distance values from river networks were categorized into five flood risk classes: Very High risk (0–1,000 m, rank 5), High risk (1,000–2,000 m, rank 4), Moderate risk (2,000–5,000 m, rank 3), Low risk (5,000–8,000 m, rank 2), and Very Low risk (8,000–15,000 m, rank 1). Subsequently, the reclassified proximity raster was spatially clipped to the boundaries of Gambella Zuria Wereda to facilitate site-specific flood risk analysis based on river proximity within the study area. Figure 16. Shows Reclassified Proximity to River map of study Area.



4.2.6. Soil

Figure 16. Reclassified Proximity to River map of study Area

Reclassified soil of Gambella Zuria Wereda was extracted by clipping soil data from the Baro River Basin and categorizing it based on permeability and water retention characteristics. The soils were grouped into five vulnerability ranks. Rank 5 (Very High vulnerability) includes Gleysols and Fluvisols, which have poor drainage and high-water retention. Rank 4 (High vulnerability) covers Vertisols and Cambisols due to their swelling properties and weak structure. Rank 3 (Moderate vulnerability) includes Acrisols and Leptosols. Rank 2 (Low vulnerability) consists of Luvisols and Phaeozems, which provide better drainage. Rank 1 (Very Low vulnerability) includes Nitisols, Xerosols, Solonchaks, and Yermosols, characterized by good drainage or arid conditions. This reclassification helps assess flood risk and inform land use decisions in the area. Figure 17. Shows Reclassified Soil map of study Area

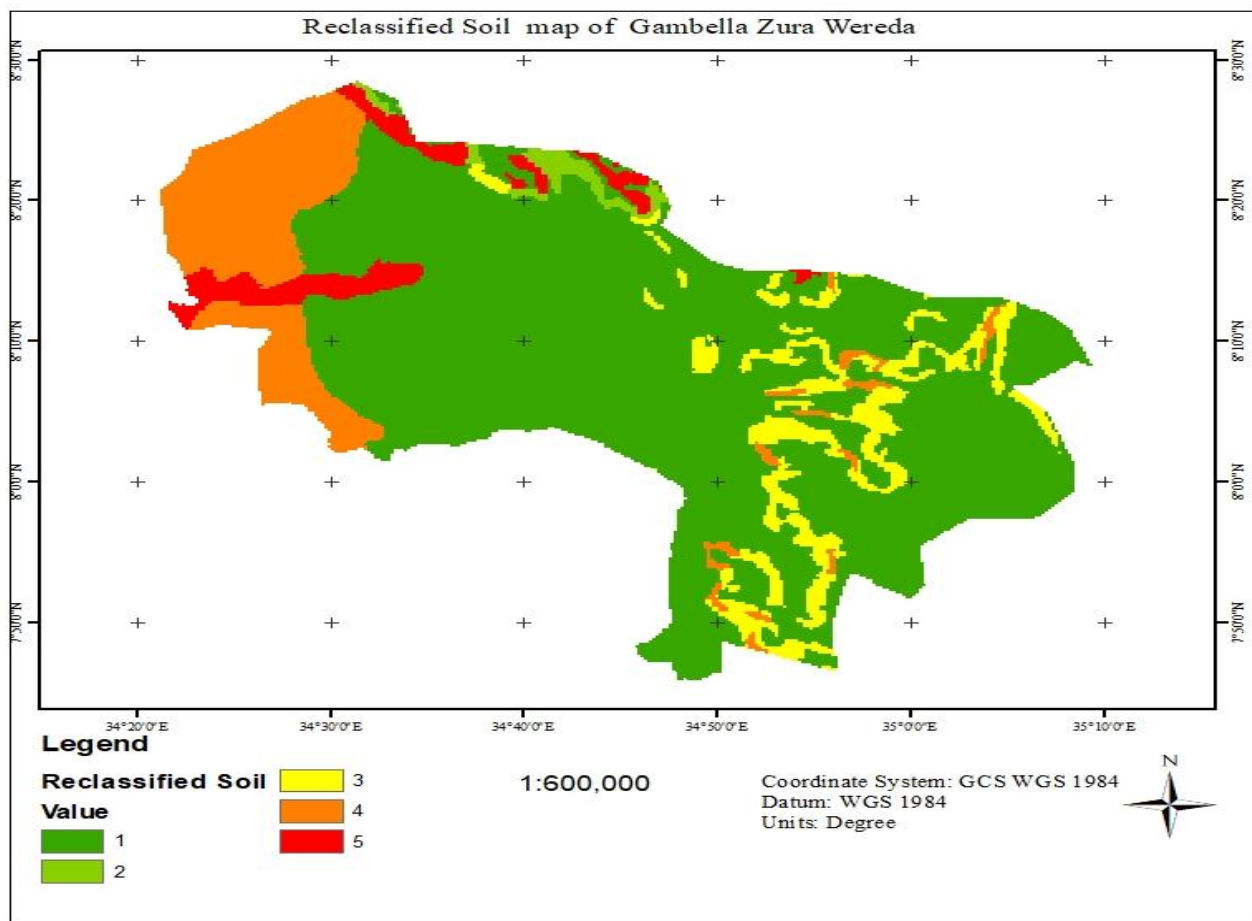


Figure 17. Reclassified Soil map of study Area

4.3 . Flood Hazard zone map

The flood hazard area mapping was conducted by integrating six key environmental factors that influence flooding within the Baro River basin. These factors—slope, drainage density, rainfall, proximity to rivers, land use/land cover (LULC), and soil characteristics—were assigned weights according to their relative importance. A weighted linear combination method was applied to compute the composite flood hazard index using the formula:

$$\text{Flood hazard} = [\text{Slope}] * 0.427 + [\text{Drainage Density}] * 0.248 + [\text{Rainfall}] * 0.098 + [\text{Proximity to River}] * 0.138 + [\text{LULC}] * 0.055 + [\text{Soil}] * 0.037$$

The analysis was first performed at the basin scale to ensure hydrological accuracy and spatial completeness. Subsequently, the resulting flood hazard map was clipped to the boundary of Gambella Zuria Wereda for a localized flood risk assessment. Within this area, the basin was classified into five flood hazard zones ranked from Very Low (rank 1) to Very High (rank 5), providing a comprehensive spatial overview to support flood management and mitigation planning. The flood hazard zones cover the following approximate areas and percentages of Gambella Zuria Wereda: Very High (18%, 57,943 ha), High (27%, 88,244 ha), Moderate (23%, ~75,300 ha), Low (23%, ~75,300 ha), and Very Low (9%, ~29,500 ha). The High Hazard Zone, characterized by low-lying terrain near river channels, is the most extensive and vulnerable to flooding. Moderate and Low zones, associated with higher elevations, better drainage, and denser vegetation, make up nearly half the area, indicating lower to moderate flood risk. The Very High zone highlights critical floodplains requiring prioritized intervention, while the Very Low zone comprises upland, well-drained areas with minimal flood susceptibility. This spatial distribution aligns with the physical and hydro-geomorphological characteristics of Gambella Zuria Wereda. Figure 18. shows the Flood Hazard Zone map of Gambella Zuria Wereda.

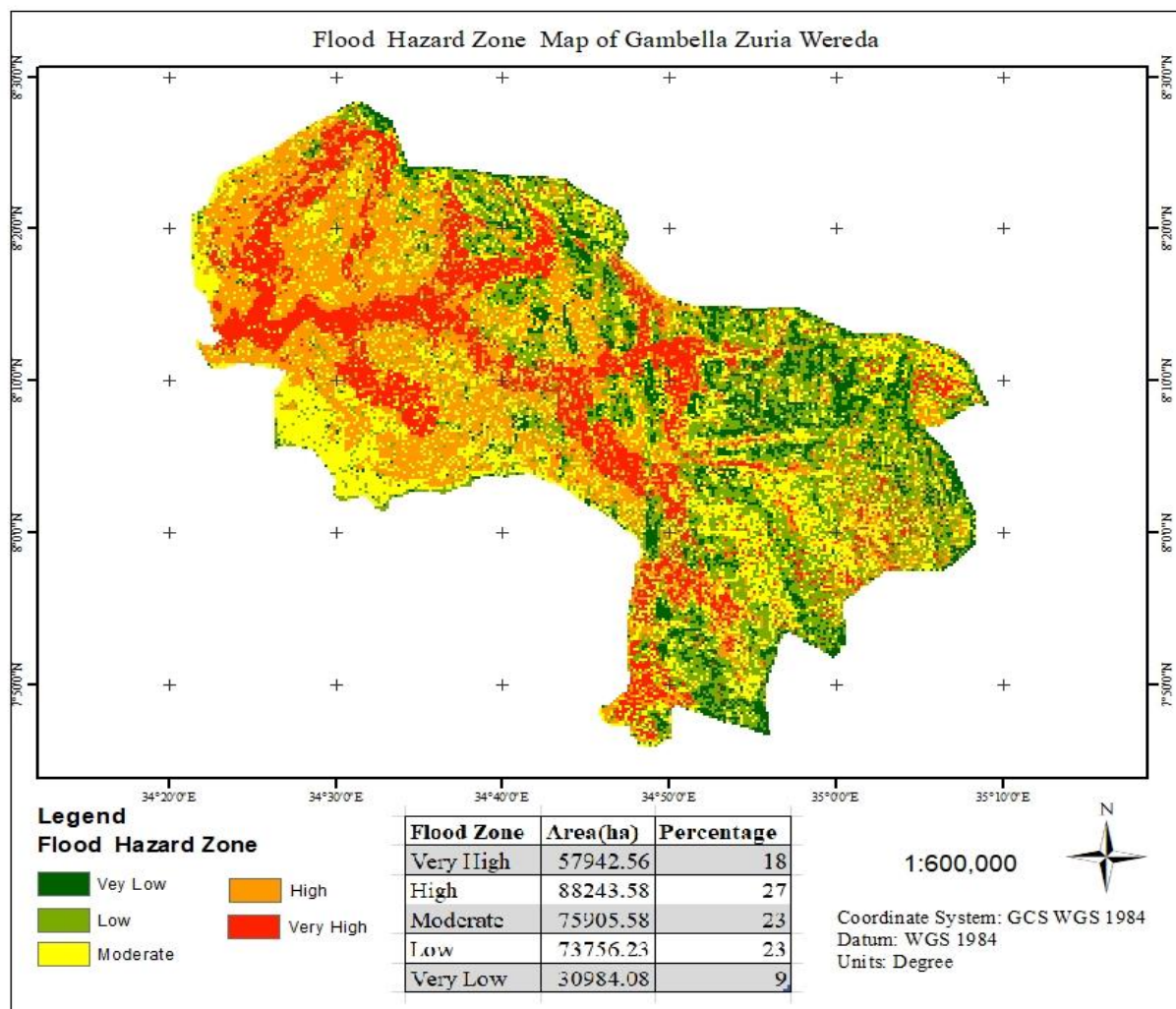


Figure 18. Hazard Zone map of Gambella Zuria Wereda.

4.3.1 . Validation

The Gambella region of Ethiopia, specifically the Baro River basin within Gambella Zuria wereda, is highly susceptible to recurrent flooding due to its unique geophysical and climatic conditions. The region's relatively low elevation and flat alluvial plains, coupled with intense seasonal rainfall during the May–October rainy season, create ideal conditions for frequent overbank flooding of the Baro River. This flooding has historically resulted in widespread inundation events, including significant floods in 2006, 2007, and a period of sustained flooding from 2010 to 2012. More recently, the overbank flows recorded in September 2023 and the extensive flooding in August 2024 have further highlighted the ongoing vulnerability of the area.

To rigorously validate the flood hazard mapping undertaken for this basin, a multi-temporal remote sensing analysis was performed using high-resolution satellite imagery available through Google Earth Pro. This approach involved analyzing satellite images captured before, during, and after flooding events over multiple years. The satellite imagery allowed for the precise identification of flooded extents, duration, and spatial patterns across the landscape. These observed flood extents were then spatially overlaid with the delineated flood hazard zones from the mapping exercise.

The analysis revealed a high degree of spatial congruence between the areas mapped as flood hazard zones and the actual inundation observed in the satellite imagery. Notably, the flood-prone areas along the Baro River floodplain in Gambella Zuria woreda consistently showed inundation during major flood events, confirming that the mapping accurately captures the geographic extent of flood risk. Furthermore, temporal analysis across multiple years demonstrated that these flood-prone zones experience recurrent inundation, reinforcing the reliability of the hazard delineation.

This validation process confirms that the flood hazard maps developed are effective tools for identifying high-risk zones in the Baro River basin. Such validated mapping is critical for informing flood risk management, disaster preparedness, land use planning, and community resilience-building initiatives within Gambella Zuria woreda. By integrating historical flood records with empirical remote sensing data, the mapping provides a robust foundation for targeted mitigation and adaptation strategies tailored to the specific flood dynamics of the Baro River basin.

4.4. Discussion

The findings of this study offer significant insights into the spatial distribution of flood hazard zones within the Baro River Basin and are in agreement with outcomes from similar research across Ethiopia. By employing GIS, Remote Sensing, and the Analytical Hierarchy Process (AHP), the study successfully delineated the basin into five distinct flood hazard classes: Very Low, Low, Moderate, High, and Very High. This classification enhances the understanding of flood exposure levels and supports informed planning and risk mitigation.

Approximately 45% of the study area was classified as being within High (27%) and Very High (18%) flood hazard zones. These results indicate that a substantial portion of the Baro River Basin is at significant risk of flooding. When compared to the study by in the Awash River Basin, where 51.4% and 40.6% of the area were classified as High and Moderate hazard zones respectively, the trend of flood susceptibility near low-lying regions and riverbanks is consistent. This similarity suggests common flood-generating mechanisms across major Ethiopian watersheds

The study conducted by (Yonas et al., 2024) in the Gidabo Watershed also supports this observation, reporting that 41.6% of the area was at High to Very High risk. Factors such as topography, slope, drainage density, and rainfall patterns were identified as critical determinants of flood vulnerability, all of which also influenced the hazard distribution in the Baro River Basin. Moreover, the Modjo Catchment study by (Diriba et al., 2024) in the Awash Basin, which reported 74.12% of the area under intermediate risk and 8.44% under high risk, further validates the use of integrated spatial techniques in flood assessment, though it used a slightly different classification scheme (negligible to severe).

The similarities among these studies underscore the strength and reliability of employing AHP alongside GIS and Remote Sensing for flood hazard mapping. Regardless of the differences in geographic and climatic conditions, the consistent pattern of hazard distribution indicates that these methodologies can be scaled and adapted for use in other river basins across Ethiopia. The prevalence of High and Very High-risk zones in the Baro River Basin highlights the urgent need for early warning systems, enhanced land use management, and sustainable watershed interventions. This is particularly crucial given the region's susceptibility to extreme weather events and the pressures of a growing population.

Furthermore, the significant correlation identified between flood hazard zones and environmental factors such as elevation, land use/cover, slope, and proximity to river networks highlights the necessity of incorporating multi-criteria datasets. The use of AHP facilitated a systematic weighting of these variables, ultimately producing a flood hazard map that is both scientifically robust and practically beneficial for disaster risk reduction planning.

In conclusion, the results of this study are consistent with both regional and national flood mapping initiatives. The consistent methodology and comparable results highlight the effectiveness of spatial and decision-support tools for flood risk management in Ethiopia. These tools also offer localized insights that are crucial for safeguarding lives, infrastructure, and ecosystems in flood-prone regions like the Baro River Basin.

CHAPTER 5. CONCLUSION AND RECOMMENDATION

5.1 . Conclusion

This study aimed to develop a comprehensive flood hazard map for the Baro River Basin in Gambella Zuria Wereda, Ethiopia, utilizing Geographic Information Systems (GIS), Remote Sensing (RS), and the Analytical Hierarchy Process (AHP). The primary objective was to pinpoint areas vulnerable to flooding, assess the environmental and geographical factors that contribute to this risk, and propose evidence-based strategies to enhance flood risk management and preparedness.

The six key factors influencing flood susceptibility slope, rainfall, drainage density, proximity to rivers, land use/land cover (LULC), and soil type were carefully evaluated and weighted using the Analytic Hierarchy Process (AHP). The analysis indicated that rainfall and slope are the primary factors influencing flood risk, while other elements such as drainage density, proximity to rivers, land use and land cover (LULC), and soil type have a moderate impact. To verify the reliability of the AHP results, a consistency check was conducted, yielding a Consistency Index (CI) of 0.0174 and a Consistency Ratio (CR) of **1.4%**. Given that the consistency ratio (CR) is significantly below the acceptable limit of 0.1, the consistency of the pairwise comparisons is deemed acceptable. This confirms the methodological reliability and logical validity of the weighting process (Saaty, 1980)

The methodological reliability and thematic significance of this study were further strengthened by comparative validation with earlier research conducted. The comparison with similar studies carried out in the Awash River Basin (Abayneh et al., 2024), the Gidabo Watershed (Yonas et al., 2024), and the Modjo Catchment in the Awash River Basin (Diriba et al., 2024) supported the reliability of the methods used and the importance of the themes addressed in this research. The similarities observed in the weighting systems derived from the AHP method and the arrangement of flood risk zones in different geographical and hydrological areas highlight the dependability and adaptability of the GIS-AHP method. These studies demonstrate the effectiveness and practicality of using GIS-AHP for flood hazard modeling by combining different multi-criteria spatial datasets, such as rainfall intensity, slope, land use and land cover, soil type, drainage density, and Proximity to River. This alignment emphasizes its broader importance as a tool for assisting in decision-making regarding flood risk management in at-risk regions of Ethiopia.

5.2 . Recommendation

Based on the detailed flood hazard zoning and spatial analysis conducted for Gambella Zuria Wereda within the Baro Basin, this chapter outlines a comprehensive set of recommendations. These recommendations are designed to guide effective flood risk management, mitigation strategies, and sustainable land use planning, fostering enhanced resilience within the wereda. The approach emphasizes a multi-faceted and multi-stakeholder framework, acknowledging the dynamic nature of flood risks influenced by climatic variability and anthropogenic land use changes.

1. Prioritize Interventions in High-Risk Flood Hazard Zones

This recommendation emphasizes a strategic allocation of resources and efforts towards areas identified as most susceptible to flooding, ensuring maximum impact on reducing vulnerability and potential damage.

- The Very High Hazard Zone (18% of the total area) represents critical floodplain regions experiencing the highest frequency and severity of flooding. Interventions here must be immediate and robust, focusing on advanced early warning systems and structural mitigation measures like protective embankments. These systems should leverage modern technology for real-time data and rapid dissemination, crucial for the safety of communities in Gambella.
- The High Hazard Zone (27% of the total area) comprises extensive low-lying terrains near river channels. Targeted interventions for these areas include riverbank stabilization using both bio-engineering and hard engineering solutions, improved drainage infrastructure to enhance water flow, and strict land use restrictions to prevent further exposure of critical assets. This is vital given the agricultural importance of these low-lying areas.

2. Promote Sustainable Land Use Planning in Lower Hazard Zones

This recommendation focuses on leveraging safer areas for development while safeguarding their natural flood-buffering capacities, promoting sustainable growth in Gambella.

- The Moderate and Low Hazard Zones, constituting nearly half of Gambella Zuria Wereda, offer significant opportunities for safer settlement and agricultural activities due to their higher elevation and better drainage. Land use policies should actively encourage

development in these zones through incentives and infrastructure investment, while simultaneously preserving natural vegetation to maintain their flood buffering capacity.

- Updated and rigorously enforced zoning regulations are crucial to direct future development away from high-risk areas and ensure that any activities in lower-risk zones do not inadvertently increase vulnerability elsewhere. This provides a clear framework for responsible expansion in the region.

3. Protect and Enhance Natural Flood Mitigation Features

This recommendation highlights the importance of leveraging and restoring ecological systems that naturally reduce flood risk, often more sustainably and cost-effectively than solely engineered solutions, which is particularly relevant in Ethiopia's diverse ecosystems.

- Natural features like existing vegetation cover and natural drainage networks in Moderate and Low Hazard Zones significantly reduce flood risk by enhancing infiltration and slowing runoff. Efforts should primarily focus on conserving and restoring wetlands, which act as natural sponges, preserving riparian buffers along riverbanks, and promoting forest conservation and reforestation within the Wereda. These ecosystem services are essential for effective flood regulation and maintaining biodiversity.

4. Implement Community-Based Flood Risk Awareness and Preparedness Programs

This recommendation underscores the critical role of community empowerment in building resilience and ensuring effective local responses to flood events, acknowledging the importance of local knowledge and participation in Ethiopia.

- Flood risk education and preparedness initiatives must be tailored to the specific hazard zones, equipping local communities with the knowledge and skills to respond effectively. This includes providing clear information on flood dynamics, safe evacuation routes, and emergency contacts.
- Special attention should be given to vulnerable populations in Very High and High Hazard Zones, providing practical training on flood-proofing homes, basic search and rescue techniques, first aid, and comprehensive emergency response planning. Establishing and

training local emergency response teams will further enhance community self-sufficiency during crises.

5. Integrate Flood Hazard Data into Local Development Planning

This recommendation emphasizes that the scientific findings from flood hazard mapping must be a foundational element in all planning and developmental decisions within the wereda, ensuring evidence-based governance.

- The spatial flood hazard maps should be fully integrated into the Wereda's land use master plan and its broader disaster risk reduction strategies. This ensures that urban and rural development decisions are made with a clear understanding of flood risks.
- Decision-makers and planners must leverage this spatial information to guide the optimal location and design of all new infrastructure development (e.g., roads, schools, health centers), optimize resource allocation for flood protection projects, and strategically deploy emergency services to minimize potential flood damage and ensure efficient resource use across the Wereda.

6. Conduct Regular Monitoring and Adaptive Flood Hazard Assessments

This recommendation addresses the dynamic nature of flood risks, advocating for continuous vigilance and adjustments to management strategies based on evolving environmental conditions and climate change impacts, which are increasingly critical for Ethiopia.

- Given that flood risks are influenced by factors like climate change (e.g., altered rainfall patterns, increased intensity of extreme weather events) and land use changes (e.g., urbanization, agricultural expansion), periodic reassessment of flood hazard zones is crucial. This ensures that flood risk maps remain accurate and reflective of current conditions.
- Integrating advanced methodologies like remote sensing (e.g., SAR for all-weather monitoring), hydrological and hydraulic modeling (using tools like HEC-RAS 2D with climate change projections), and comprehensive field surveys will provide up-to-date and accurate flood risk maps, supporting an adaptive management approach that can respond to new challenges.

7.Stakeholder Roles and Responsibilities for Implementation:

Effective implementation of these recommendations demands a coordinated, multi-stakeholder approach. Each entity has distinct, yet interconnected, responsibilities vital for success:

- **Local Planners & Governments:**
 - Role: Utilize flood maps for comprehensive zoning and land use planning.
 - Key Actions: Integrate flood hazard data into local development plans; enforce building codes and land use restrictions in flood-prone areas; guide sustainable urban and rural development away from high-risk zones.
- **Disaster Management Authorities:**
 - Role: Implement and manage critical early warning and emergency response systems.
 - Key Actions: Develop and operate robust flood early warning systems; coordinate emergency response, evacuation plans, and relief efforts; conduct regular flood preparedness drills for communities and first responders.
- **Community-Based Organizations (CBOs):**
 - Role: Act as a vital link between communities and authorities, fostering grassroots resilience and participatory preparedness.
 - Key Actions: Raise flood risk awareness within their communities through education; mobilize local resources for flood preparedness and immediate response; facilitate the implementation of community-led flood mitigation measures.
- **Urban Planners:**
 - Role: Design, improve, and maintain critical urban drainage infrastructure to manage stormwater runoff.
 - Key Actions: Develop and implement sustainable urban drainage systems (SUDS); ensure regular maintenance and improvement of existing drainage networks; integrate green infrastructure solutions.

- Environmental Agencies:
 - Role: Protect and restore natural ecosystems that provide crucial flood mitigation services.
 - Key Actions: Conserve and restore wetlands, riparian buffers, and forests; implement policies for sustainable land management; monitor environmental changes impacting flood risk.
- National & Regional Institutions:
 - Role: Provide overarching coordination, policy frameworks, and resource allocation for flood mitigation efforts.
 - Key Actions: Develop national and regional flood risk management strategies and policies; coordinate large-scale flood mitigation projects; facilitate data sharing and collaboration among various stakeholders.
- Academic & Research Institutions:
 - Role: Provide scientific expertise, conduct research, and develop innovative solutions for flood risk assessment and management.
 - Key Actions: Conduct ongoing research to update flood hazard maps and improve hydrological models; assess the impacts of climate change on flood patterns; expand study areas; develop new technologies for flood prediction and mitigation.

References

- Advances, Conceptualization of Flooding Disaster: A Theoretical Perspective of Management (2023). *Disaster Advances*. Retrieved from <https://doi.org/10.25303/172da040045>
- Application of Geographical Information System-Based Analytical Hierarchy Process Modeling for Flood Susceptibility Mapping of Krishna District in Andhra Pradesh . (2022). Retrieved from <https://doi.org/10.21203/rs.3.rs-1399020/v1>
- Conceptualization of Flooding Disaster: A Theoretical Perspective of Management. (2023). *Disaster Advances*. Retrieved from <https://doi.org/10.25303/172da040045>
- Impacts of Displacement: Flood displacement in Beledweyne, Somalia. (2021). Retrieved from <https://doi.org/10.55363/idmc.vcai4770>
- Remote Sensing Mapping and Modeling for Flood Hazards in Data-Scarce Areas . (2022). 69–85. Retrieved from <https://doi.org/10.1002/9781119159131.ch4>
- Remote Sensing Monitoring of Flood hazard in Arid Environments. A Case Study of Saquia El Hamra Watershed Morocco . (2023). Retrieved from <https://doi.org/10.5194/egusphere-egu23-12908>
- Review of Flood Disaster Risk Management in six West African Megacities . (2022). *Proceedings of the 17th International Conference on Environmental Science and Technology*. Retrieved from <https://doi.org/10.30955/gnc2021.00018>
- Abraha, T, Tibebe, A, & Ephrem. (2022). Rapid Urbanization and the Growing Water Risk Challenges in Ethiopia: The Need for Water Sensitive Thinking. *Frontiers in Water*, 4. Retrieved from <https://doi.org/10.3389/frwa.2022.890229>
- Adedeji, T, Proverbs, D, Proverbs, D, & Proverbs. (2024). The evolution of flood risk management strategies and the role of property flood resilience: current research trends and directions (pp. 132–142). *Edward Elgar Publishing*. Retrieved from <https://doi.org/10.4337/9781839102981.00017>
- Adesse, Suryabagavan, Nedaw, Hailu, & D., & Hailu, B. T. (2022). A model-based flood hazard mapping in Itang District of the Gambella region, Ethiopia. *Geology, Ecology, and Landscapes*, 1–18. Retrieved from <https://doi.org/10.1080/24749508.2021.2022833>
- Adzandeh, E, Hamid-Mosaku, I. A, G, E, & Olayinka-Dosunmu. (2024). Integrating GIS and AHP for a multi-criteria flood vulnerability assessment in the Benue River Basin, Nigeria. Retrieved from <https://doi.org/10.4314/dujopas.v10i3b.12>
- Agrawal. (2018). Disaster Risk Management (pp. 81–145). *Springer, Dordrecht*. Retrieved from https://doi.org/10.1007/978-94-024-1283-3_3
- Aldosari, Aldosari, D, Almedeij, & Alsumaiei. (2020). Update of intensity–duration–frequency curves for Kuwait due to extreme flash floods. *Environmental and Ecological Statistics*, 27(3), 491–507 . Retrieved from <https://doi.org/10.1007/S10651-020-00454-4>
- Alexander. (2020). Disaster Risk Reduction. Retrieved from <https://doi.org/10.1093/ACREFORE/9780190228637.013.1538>
- Allen, K, Dupuy, J. M, Gei, M. G, . . . Medv. (2017). Will seasonally dry tropical forests be sensitive or resistant to future changes in rainfall regimes. *Environmental Research Letters*, 12(2), 023001. Retrieved from <https://doi.org/10.1088/1748-9326/AA5968>

- Al-Omari, Shatnawi, Shbeeb, Istrati, & Laga. (2024). Utilizing Remote Sensing and GIS Techniques for Flood Hazard Mapping and Risk Assessment. *Civil Engineering Journal*, 10(5), 1423–1436. Retrieved from <https://doi.org/10.28991/cej-2024-010-05-05>
- Antony, Rahiman, & Vishnudas. (2022). Flood Hazard Mapping Using Geographical Information System (GIS) and Analytical Hierarchy Process (AHP). 105–116. Retrieved from https://doi.org/10.1007/978-981-16-5501-2_9
- Ariyani, D, Purwanto, M. Y. J, Sunarti, E, . . . P. (2024). Integrated flood hazard assessment using multi-criteria analysis and geospatial modeling. *Journal of Degraded and Mining Lands Management*, 11(4), 6121–6134. Retrieved from <https://doi.org/10.15243/jdmlm.2024.114.6121>
- Ariyani, Purwanto, Sunarti, & Perdinan. (2024). Integrated flood hazard assessment using multi-criteria analysis and geospatial modeling. *Journal of Degraded and Mining Lands Management*, 11(4), 6121–6134. Retrieved from <https://doi.org/10.15243/jdmlm.2024.114.6121>
- Asmat, A, Mansor, S, Saadatkhah, N, . . . Khuzaimah. (2016). Land Use Change Effects on Extreme Flood in the Kelantan Basin Using Hydrological Model (pp. 221–236). *Springer, Singapore*. Retrieved from https://doi.org/10.1007/978-981-10-0500-8_18
- Assefa. (2018). Flood Risk Assessment in Ethiopia. *Civil and Environmental Research*, 10(1), 35–40. Retrieved from <https://iiste.org/Journals/index.php/CER/article/download/40579/41730>
- Assefa. (2018). Flood Risk Assessment in Ethiopia. *Civil and Environmental Research*, 10(1), 35–40. Retrieved from <https://iiste.org/Journals/index.php/CER/article/download/40579/41730>
- Baldassarre, D., G, Montanari, A, Lins, H. F, & Koutsoyiannis. (2010). Flood fatalities in Africa: From diagnosis to mitigation. *Geophysical Research Letters*, 37(22). Retrieved from <https://doi.org/10.1029/2010GL045467>
- Banjara, M, Bhusal, A, Ghimire, A, & Kalra. (2024). Impact of Land Use and Land Cover Change on Hydrological Processes in Urban Watersheds: Analysis and Forecasting for Flood Risk Management. *Geosciences*. Retrieved from <https://doi.org/10.3390/geosciences14020040>
- Baudhanwala, D, Mehta, D, De Zoysa, S, & Rathnayake. (2024). Rainfall Intensity-Duration-Frequency Relationships: A Robust Foundation for Urban Decision-Making and Flood Management: A Case Study. *Journal of Environmental Informatics Letters*. Retrieved from <https://doi.org/10.3808/jeil.202400131>
- Bedada & Dibaba. (2024). Geoinformatics and AHP-MCDM integrated flood hazard zone mapping over Modjo catchment, Awash River basin, central Ethiopia. Retrieved from <https://doi.org/10.21203/rs.3.rs-5239078/v1>
- Beshir & Song. (2021). Urbanization and its impact on flood hazard: the case of Addis Ababa, Ethiopia. *Natural Hazards*, 109(1), 1167–1190. Retrieved from <https://doi.org/10.1007/S11069-021-04873-9>
- Blakime, T.-H, Komi, K, Adjou, K, . . . Gbafa. (2024). Derivation of a GIS-Based Flood Hazard Map in Peri-Urban Areas of Greater Lomé, Togo (West Africa). *Urban Science*, 8(3), 96. Retrieved from <https://doi.org/10.3390/urbansci8030096>
- Burayu, D. G, Karuppannan, S, & Shuniye. (2023). Identifying flood vulnerable and risk areas using the integration of analytical hierarchy process (AHP), GIS, and remote sensing: A case study of southern Oromia region. *Urban Climate*, 51, 101640. Retrieved from <https://doi.org/10.1016/j.uclim.2023.101640>

- Che, L, Shu-yan, Y, & Guo. (2024). Flood risk assessment combining the historical disaster statistics method with the index system method. *Hydrological Sciences Journal-Journal Des Sciences Hydrologiques*. Retrieved from <https://doi.org/10.1080/02626667.2024.2441320>
- Chen. (2022). Flood hazard zone mapping incorporating geographic information system (GIS) and multi-criteria analysis (MCA) techniques. *Journal of Hydrology*, 612, 128268. Retrieved from <https://doi.org/10.1016/j.jhydrol.2022.128268>
- Collalti. (2024). Reply on RC2. Retrieved from <https://doi.org/10.5194/nhess-2023-162-ac2>
- Degife & Mauser. (2017). Socio-economic and Environmental Impacts of Large-Scale Agricultural Investment in Gambella Region, Ethiopia. *Journal of US-China Public Administration*, 14(4). Retrieved from <https://doi.org/10.17265/1548-6591/2017.04.001>
- Diriba, Takele, Karuppannan, & Husein. (2024). Flood hazard analysis and risk assessment using remote sensing, GIS, and AHP techniques: a case study of the Gidabo Watershed, main Ethiopian Rift, Ethiopia. *Geomatics, Natural Hazards and Risk*, 15(1). Retrieved from <https://doi.org/10.1080/19475705.2024.2361813>
- Diwate, P, Golekar, R, Ambadkar, A, . . . Mishr. (2023). Analysis of Land Use/Land Cover Change and Its Impact on 2021 Chiplun Flood, Maharashtra, India (pp. 65–75). *Springer Nature*. Retrieved from https://doi.org/10.1007/978-981-99-3660-1_4
- Douglas. (2017). Flooding in African cities, scales of causes, teleconnections, risks, vulnerability and impacts. *International Journal of Disaster Risk Reduction*, 26, 34–42. Retrieved from <https://doi.org/10.1016/J.IJDRR.2017.09.024>
- El-Bagoury, H, Gad, & A. K. (2024). Integrated Hydrological Modeling for Watershed Analysis, Flood Prediction, and Mitigation Using Meteorological and Morphometric Data, SCS-CN, HEC-HMS/RAS, and QGIS. *Water*. Retrieved from <https://doi.org/10.3390/w16020356>
- Fu, G, Meng, F, Rivas Casado, M, & Kalawsky. (2020). Towards integrated flood risk and resilience management. *Water*, 12(6), 1789. Retrieved from <https://doi.org/10.3390/W12061789>
- Gao, H, Liu, F, Yan, T, . . . L. (2022). Drainage Density and Its Controlling Factors on the Eastern Margin of the Qinghai–Tibet Plateau. *Frontiers in Earth Science*, 9. Retrieved from <https://doi.org/10.3389/feart.2021.755197>
- Girma. (2023). Flood vulnerability and Risk assessment using the Integration of Analytical Hierarchy Process (AHP), GIS, and Remote Sensing: A Case Study of southern Oromia Region. *American Journal of Open Research*, 2(2), 128–144. Retrieved from <https://doi.org/10.58811/opsearch.v2i2.30>
- Girma. (2023). Flood vulnerability and Risk assessment using the Integration of Analytical Hierarchy Process (AHP), GIS, and Remote Sensing: A Case Study of southern Oromia Region. *American Journal of Open Research*, 2(2), 128–144. Retrieved from <https://doi.org/10.58811/opsearch.v2i2.30>
- Guo Hu & Guan. (2022). Regime shifts of the wet and dry seasons in the tropics under global warming. *Environmental Research Letters*, 17(10), 104028. Retrieved from <https://doi.org/10.1088/1748-9326/ac9328>

- Hagos, Andualem, Yibeltal, & Mengie. (2022). Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in upper Awash River basin, Ethiopia. *Applied Water Science*, 12(7). Retrieved from <https://doi.org/10.1007/s13201-022-01674-8>
- Hagos, Andualem, Yibeltal, & Mengie. (2022). Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in upper Awash River basin, Ethiopia. *Applied Water Science*, 12(7). Retrieved from <https://doi.org/10.1007/s13201-022-01674-8>
- Hagos, Y, Andualem, T. G, Yibeltal, M, & Mengie. (2022). Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in upper Awash River basin, Ethiopi. *Applied Water Science*, 12(7). Retrieved from <https://doi.org/10.1007/s13201-022-01674-8>
- Haile, Kusters, K., & Wagesho, N. (2013). Loss and damage from flooding in the Gambella region, Ethiopia. *International Journal of Global Warming*, 5(4), 483–497. Retrieved from <https://doi.org/10.1504/IJGW.2013.057290>
- Haile, A. T, Kusters, K, & Wagesho. (2013). Loss and damage from flooding in the Gambella region, Ethiopia. *International Journal of Global Warming*, 5(4), 483–497. Retrieved from <https://doi.org/10.1504/IJGW.2013.057290>
- Hartmann, T, Jilkova, J, & Schanze. (2018). Land for flood risk management: A catchment-wide and cross-disciplinary perspective. *Journal of Flood Risk Management*, 11(1), 3–5. Retrieved from <https://doi.org/10.1111/JFR3.12344>
- Hawamdeh, A, Tarawneh, A, Sharrah, Y, & Al-Fraihat. (2024). Deep Neural Networks Hydrologic and Hydraulic Modeling in Flood Hazard Analysis. Retrieved from <https://doi.org/10.21203/rs.3.rs-4107156/v1>
- Hawamdeh, A, Tarawneh, A, Sharrah, Y, & Al-Fraihat. (2024). Deep Neural Networks Hydrologic and Hydraulic Modeling in Flood Hazard Analysis. Retrieved from <https://doi.org/10.21203/rs.3.rs-4107156/v1>
- Hirwa, H, Ngwijabagabo, H, Minani, & Habimana. (2023). Geospatial Assessment of Urban Flood Susceptibility Using AHP-Based Multi-Criteria Technique: Case Study of Musanze, Rwanda. *Rwanda Journal of Engineering, Science, Technology and Environment*, 5(1). Retrieved from <https://doi.org/10.4314/rjeste.v5i1.6>
- Hura & Gulo,. (2024). Analisis Permeabilitas Tanah Berpasir Dan Tanah Lempung Dalam Hubunganya Dengan Manajemen Irigasi. *Jurnal Ilmu Pertanian Dan Perikanan.*, 1(2), 60–67. Retrieved from <https://doi.org/10.70134/penarik.v1i1.63>
- Ibrahim, M, Huo, A, Ullah, W, . . . Xuanta. (2025). An integrated approach to flood risk assessment using multi-criteria decision analysis and geographic information system. A case study from a flood-prone region of Pakistan. *Frontiers in Environmental Science*, 12. Retrieved from <https://doi.org/10.3389/fenvs.2024.1476761>
- Ighile. (2022). Application of GIS and Machine Learning to Predict Flood Areas in Nigeria. *Sustainability*, 14(9), 5039. Retrieved from <https://doi.org/10.3390/su14095039>
- Ikram, Q, Jamalzi, hA, R, Hamidi, . . . S. (2023). Flood risk assessment of the population in Afghanistan: A spatial analysis of hazard, exposure, and vulnerability. *Natural Hazards Research*. Retrieved from <https://doi.org/10.1016/j.nhres.2023.09>

- Isola. (2022). A methodology for the bivariate hydrological characterization of flood waves for river-related flood risks assessments. Retrieved from <https://doi.org/10.20868/upm.thesis.70457>
- Kabenla, R, Ampofo, S, Owusu, G, . . . Boate. (2024). Application of Analytical Hierarchy Process (AHP) and Multi-Criteria Evaluation (MCE) for a Case Study and Scenario Assessment of Flood Risk in the White Volta Basin of the Upper East Region, Ghana. Retrieved from <https://doi.org/10.21203/rs.3.rs-4186633/v1>
- Kamuju. (2024). A Study on Flood Hazard Zonation Mapping Based on GIS-driven Approach using Remote Sensing Data and Weighted Overlay Analysis (Woa) Model. *International Journal For Multidisciplinary Research*, 6(5). Retrieved from <https://doi.org/10.36948/ijfmr.2024.v06i05.27842>
- Karagiorgos, K, Thaler, T, Maris, F, & Fuchs. (2016). Assessing flash flood vulnerability using a multi-vulnerability approach. 7, 08004. Retrieved from <https://doi.org/10.1051/E3SCONF/20160708004>
- Kassa. (2022). Current climate change impacts and risks reviewed in Africa by giving especial emphasis in Ethiopia: Short review. *International Journal of Multidisciplinary Research and Growth Evaluation*, 326–332. Retrieved from <https://doi.org/10.54660/anfo.2022.3.6.14>
- Kaya, B & Çelik, R. (2025). Dynamic and Scalable Flood Risk Assessment Using GIS, AHP, and Novel Fuzzy AHP: A Case Study of the Upper Tigris Basin. Retrieved from <https://doi.org/10.21203/rs.3.rs-5776107/v1>
- Khumaeroh& Sari. (2024). Application of Analytical Hierarchy Process (AHP) and Geographic Information System (GIS) in flood hazard analysis in the Rawa Pening Sub-Watershed, Indonesia. Retrieved from <https://doi.org/10.1088/1755-1315/1314/1/012114>
- Kiba, Nengzouzam, & Ranjan. (2023). Flood Hazard Mapping Using Hydraulic Models and GIS: A Review. *Disaster Resilience and Green Growth*, 65–72. Retrieved from https://doi.org/10.1007/978-981-99-4811-6_4
- Klimczuk. (2021). Introductory Chapter: Demographic Analysis (pp. 3–6). *IntechOpen*. Retrieved from <https://doi.org/10.5772/INTECHOPEN.100503>
- Ko, I. H, Kang, M. G, & Park. (2013). Flood risk management framework and strategies for sustainable flood management.
- Kolstad, E. W, Parker, D. J, MacLeod, D, & Wainwright. (2024). Beyond the regional average: Drivers of geographical rainfall variability during East Africa’s short rains. *Quarterly Journal of the Royal Meteorological Society*. Retrieved from <https://doi.org/10.1002/qj.4829>
- Koutný, L, Skoupil, J, & Veselý. (2018). Physical Characteristics Affecting the Infiltration of High Intensity Rainfall into a Soil Profile. *Soil and Water Research*, 9(3), 104–110. Retrieved from <https://doi.org/10.17221/93/2013-SWR>
- Kumar, R, Kumar, Tiwari, A, Majid, . . . Bhadwal. (2023). Assessment and Mapping of Riverine Flood Susceptibility (RFS) in India through Coupled Multicriteria Decision Making Models and Geospatial Techniques. *Water*. Retrieved from <https://doi.org/10.3390/w15223918>
- Laidlaw & Percival. (2024). Flood resilience: a review of evolving definitions. *Natural Hazards*. Retrieved from <https://doi.org/10.1007/s11069-024-06627-9>
- Lamond, B.-M. &. (2011). A review of the flood risk situation in African growing economies. Retrieved from <https://uwe-repository.worktribe.com/output/959048>

- Lawal, D. U, Matori, A. N, Yusof, K. W, & Hashim. (2014). Flood Susceptibility Modeling: A Geo-spatial Technology Multi-criteria Decision Analysis Approach. *Research Journal of Applied Sciences, Engineering and Technology*, 7(22), 4638–4644. Retrieved from <https://doi.org/10.19026/RJASET.7.845>
- Li, X, Gao, J, Guo, Z, . . . Sun. (2020). A Study of Rainfall-Runoff Movement Process on High and Steep Slopes Affected by Double Turbulence Sources. *Scientific Reports*, 10(1), 9001. Retrieved from <https://doi.org/10.1038/S41598-020-66060-3>
- Lowe, A, McGrath, G, & Leopold. (2021). he Impact of Soil Water Repellency and Slope upon Runoff and Erosion. *Soil & Tillage Research*, 205, 104756. Retrieved from <https://doi.org/10.1016/J.STILL.2020.104756>
- Madhusudhan, R. M, Bhavani, G, Avinash, G, . . . J. (2024). Integrative GIS-AHP Techniques for Flood Susceptibility Analysis in Nashik, Maharashtra. *Disaster Advances*, 18(2), 24–37. Retrieved from <https://doi.org/10.25303/182da024037>
- Malakeel, G. S, Abdu Rahiman, K. U, & Vishnudas. (2021). Flood Risk Assessment Methods—A Review (pp. 197–208). *Springer, Singapore*. Retrieved from https://doi.org/10.1007/978-981-15-8151-9_19
- Mishra, R, Jena, D, Thakur, R, . . . Javed. (n.d.). Peri-Urban Floodscapes: Identifying and Analyzing Flood Risk Areas in North Bhubaneswar in Eastern India. *Water*, 16(21), 3019. Retrieved from <https://doi.org/10.3390/w16213019>
- Mitiku & Woldemichael. (2023). Flood Hazard Zoning of Upper Awash River Basin, Ethiopia, Using the Analytical Hierarchy Process (AHP) as Compared to Sensitivity Analysis. *The Scientific World Journal*, 2023, 1675634. Retrieved from <https://doi.org/10.1155/2023/1675634>
- Mohammed, Hussein, & Abood. (2024). Potential Flood Hazard Mapping Based on GIS and Analytical Hierarchy Process. *Journal of Water Management Modeling*. Retrieved from <https://doi.org/10.14796/jwmm.c528>
- Mokhtari, E. H, Mezali, F, Abdelkebir, B, & Engel. (2023). Flood risk assessment using analytical hierarchy process: a case study from the Chelif-Ghrib watershed, Algeria. *Journal of Water and Climate Change*. Retrieved from <https://doi.org/10.2166/wcc.2023.316>
- Molnar. (2014). Rush for the blue gold . The governance of agricultural investments influencing the socio-ecological system of the Gambella region, Ethiopia. Retrieved from <https://lup.lub.lu.se/student-papers/record/4589244/file/4589250.pdf>
- Natarajan, S., & Radhakrishnan. (2020). Flood hazard delineation in an ungauged catchment by coupling hydrologic and hydraulic models with geospatial techniques—a case study of Koraiyar basin, Tiruchirappalli City, Tamil Nadu, India. *Environmental Monitoring and Assessment*, 192(11), 1–26. Retrieved from <https://doi.org/10.1007/S10661-020-08650-2>
- Ncube& Chipfakacha. (2021). On crossroads between the right to shelter and looming chances of displacement: Charting towards a resilient and sustainable framework for rural dwellers in flood-prone areas. *Development Southern Africa*, 1–14. Retrieved from <https://doi.org/10.1080/0376835X.2021.1980376>
- Ndidi, N. F, Innocent, B, & Ganiy. (2022). Flood risk mapping and urban infrastructural susceptibility assessment using a GIS and analytic hierarchical raster fusion approach in the Ona River Basin, Nigeria. *International Journal of Disaster Risk Reduction*, 77, 103097. Retrieved from <https://doi.org/10.1016/j.ijdr.2022.103097>

- Nugraha. (2018). Peningkatan Akurasi dan Presisi Analisa Spasial Pemodelan Banjir Kota Semarang Menggunakan Kombinasi Sistem Informasi Geografis Dan Metode Logika Fuzzy. 39(1), 16–24. Retrieved from <https://doi.org/10.14710/TEKNIK.V39I1.16524>
- Nugraha, N. B, Puspaningrum, A, & Santosa. (2025). Using AHP to prioritize flood mitigation measures in urban areas. *E3S Web of Conferences*, 605, 03001. Retrieved from <https://doi.org/10.1051/e3sconf/202560503001>
- Okafor. (2021). Flood, Livelihood Displacement, and Poverty in Nigeria: Plights of Flood Victims, 2012–2018 (pp. 2535–2545). *Springer, Cham*. Retrieved from https://doi.org/10.1007/978-3-030-45106-6_124
- Olesen, L, Löwe, R, Arnbjerg-Nielsen, & K. (2017). Flood damage assessment – Literature review and recommended procedure. Retrieved from https://orbit.dtu.dk/files/130797720/IN_PC956_B4_1_Flood_Damage_web.pdf
- Pandit. (2024). A Concentrated Analysis of the Situation of Flood Control Management: A Review. *International Journal For Science Technology And Engineering*, 12(10), 133–137. Retrieved from <https://doi.org/10.22214/ijraset.2024.64469>
- Patel, A, Keriwala, N, Yadav, & S. M. (2023). 2D Flood Simulation and Mapping Using Hydraulic Model and GIS Technology (pp. 71–85). Springer Nature. Retrieved from https://doi.org/10.1007/978-981-99-1890-4_6
- Penki, R, Basina, S. S, & Tanniru. (2022). Application of geographical information system-based analytical hierarchy process modeling for flood susceptibility mapping of Krishna District in Andhra Pradesh. *Environmental Science and Pollution Research*, 1–14. Retrieved from <https://doi.org/10.1007/s11356-022-22924-x>
- Poudel, K, Basnet, K, & Sherchan. (2021). Hydrological and Hydraulic Modeling for Flood Analysis: A Case Study for Modi Catchment. *International Journal of Engineering Research and Technology*, 10(8). Retrieved from <https://doi.org/10.17577/IJERTV10IS080220>
- Rao, G. S, Surwase, T, Begum, A, . . . P. J. (2019). 2D Flood Simulation and Development of Flood Hazard Map by using Hydraulic Model. *International Journal of Advanced Remote Sensing and GIS*, 8(1), 3096–3105. Retrieved from <https://doi.org/10.23953/CLOUD.IJARSG.424>
- Saini, D, Barik, & D. K. (2024). Simulation of the Hydraulic Model HEC-RAS Coupled with GIS and Remote Sensing to Study the Effect of River Cross-section Width in Detecting Flood-prone Areas. *Journal of Geological Society of India*, 100(3), 367–376. Retrieved from <https://doi.org/10.17491/jgsi/2024/173843>
- Samuael, S. J, Arul, J. S, & Padua. (2019). Geospatial Flood Risk Mapping and Analysis Tool (pp. 337–345). Springer, Cham. Retrieved from https://doi.org/10.1007/978-3-319-77276-9_30
- Santos, D., S, Karamoko, A. W, Attoumane, A, & Zahiri. (2023). Socio-Environmental and Physical Factors of Flood Risk in African Cities: An Analysis of Vulnerabilities in Two Contrasting Neighbourhoods in Abidjan, Côte d’Ivoire. *The Journal of Population and Sustainability*, 7(2), 31–58. Retrieved from <https://doi.org/10.3197/jps.63799953906871>
- Sari. (2023). Mitigasi bencana melalui pengurangan risiko bencana terhadap kemampuan tanggap darurat bencana banjir. *Nursing Up Date*, 14(3), 1–5. Retrieved from <https://doi.org/10.36089/nu.v14i3.1154>

- Sharma & Sharma. (2019). Remote sensing: A tool for sustainable environment. *Journal of Pharmacognosy and Phytochemistry*, 8(1), 1270–1276. Retrieved from <https://www.phytojournal.com/archives/?year=2019&vol=8&issue=1&ArticleId=6936&si=false>
- Sheth. (2018). Review: Rainfall Runoff Modelling. *International Journal of Engineering Research and Technology*, 7(4). Retrieved from <https://www.ijert.org/research/review-rainfall-runoff-modelling-IJERTV7IS040169.pdf>
- Shibru. (2017). Rural Livelihood Diversification Strategies of Sodo Zuria Wereda: Determinants and Constraints. *Journal of Economics and Sustainable Development*, 8(5), 53–61. Retrieved from <https://www.iiste.org/Journals/index.php/JEDS/article/download/36087/37080>
- Singh, A., & Singh, A. (2023). Identifying Crucial Aspects in Formulating Urban Flood Mitigation Strategies. *International Journal For Science Technology And Engineering*, 11(4), 3483–3486. Retrieved from <https://doi.org/10.22214/ijraset.2023.50997>
- Sivaranjani, S. &. (2017). Modelling of Flood Susceptibility Based on GIS and Analytical Hierarchy Process—A Case Study of Adayar River Basin, Tamilnadu, India (pp. 91–110. *Springer, Singapore*. Retrieved from https://doi.org/10.1007/978-981-32-9527-8_6
- Smets, V, Verbeiren, B, Hermy, M, & Somers. (2019). Urban Spatial Configuration and Functional Runoff Connectivity: Influence of Drainage Grid Density and Landscape Metrics. *Water*, 11(12), 2661. Retrieved from <https://doi.org/10.3390/W11122661>
- Solanki, P, Kumar, V, Sharma, V, . . . A. A. (2024). Flood hazard analysis in Mumbai using geospatial and multi-criteria decision-making techniques. *Journal of Water and Climate Change*. Retrieved from <https://doi.org/10.2166/wcc.2024.053>
- Stancalie, Craciunescu, Catana, & Irimescu. (2005). Contribution of satellite remotely sensed data to flood risk mapping. Retrieved from <https://meetings.copernicus.org/www.cosis.net/abstracts/EGU05/00315/EGU05-J-00315.pdf>
- Stoyanova, Balabanova, Koshinchanov, & Yordanova. (2022). Flood hazard mapping using two-dimensional hydraulic modeling results. Retrieved from <https://doi.org/10.5593/sgem2022/3.1/s12.12>
- Tadesse, Suryabhadgavan, Nedaw, & Hailu. (2022). A model-based flood hazard mapping in Itang District of the Gambella region, Ethiopia. *Geology, Ecology, and Landscapes*, 1–18. Retrieved from <https://doi.org/10.1080/24749508.2021.2022833>
- Takara. (2013). Consideration of Disaster Risk and Floods. *Journal of Flood Risk Management*, 6(4), 289. Retrieved from <https://doi.org/10.1111/JFR3.12078>
- Tamiru & Wagari. (2021). Machine learning and HEC-RAS integrated models for flood inundation mapping in Baro River Basin, Ethiopia. *Modeling Earth Systems and Environment*, 1–13. Retrieved from <https://doi.org/10.1007/S40808-021-01175-8>
- Teku & Eshetu. (2024). Impact of climatic variabilities and extreme incidences on the physical environment, public health, and people's livelihoods in Ethiopia. *Frontiers in Climate*, 6. Retrieved from <https://doi.org/10.3389/fclim.2024.1435138>
- Tilahun, Gebremariam, & Desta. (2024). Flood Hazard Area mapping Using GIS and AHP in Awash River Basin (ARB), Ethiopia. Retrieved from <https://doi.org/10.21203/rs.3.rs-4894497/v1>

- Tonni, Begum, M., & Parvin, R. (2024). The Causes and Consequences of Flood-induced Temporary Displacement in Southwest Coastal Bangladesh. *Indonesian Journal of Social and Environmental Issues*, 5(3), 335–346. Retrieved from <https://doi.org/10.47540/ijsei.v5i3.160>
- Uwandu, I. G, Ejikeme, & Chukwu. (2023). GIS-Based Analytical Hierarchy Process Modeling for Flood Vulnerability Assessment of Communities Along Otamiri River Basin Imo State, Nigeria. *Journal of Engineering Research and Reports*, 25(11), 123–134. Retrieved from <https://doi.org/10.9734/jerr/2023/v25i111027>
- V, A, D, W, R, P, . . . M. (2024). Floods and Land Use Land Cover Changes in the Kalu River Basin: A Call to Action. Proceedings of the International Forestry and Environment Symposium. Retrieved from <https://doi.org/10.31357/fesympo.v27.7051>
- Vestby, Schutte, Tollefsen, & Buhaug. (2024). Societal determinants of flood-induced displacement. Proceedings of the National Academy of Sciences of the United States of America, 121(3), e2206188120. Retrieved from <https://doi.org/10.1073/pnas.2206188120>
- Wank& Atkinson. (2022). Global water cycle from a soil perspective. Elsevier eBooks. Retrieved from <https://doi.org/10.1016/b978-0-12-822974-3.00121-x>
- Weldegebriel & Amphune. (2017). Livelihood resilience in the face of recurring floods: an empirical evidence from Northwest Ethiopia. *Geoenvironmental Disasters*, 4(1), 1–19. Retrieved from <https://doi.org/10.1186/S40677-017-0074-0>
- Wijesooriya, Chathuranga, Dinusha, & Vithanage, . (2024). An Assessment of Land Use and Land Cover Changes on Urban Flooding: A Case Study in Sri Jayawardenepura Kotte. *KDU Journal of Multidisciplinary Studies*, 6(2), 18–29. Retrieved from <https://doi.org/10.4038/kjms.v6i2.125>
- Woldemichael, M. &. (2023). Flood Hazard Zoning of Upper Awash River Basin, Ethiopia, Using the Analytical Hierarchy Process (AHP) as Compared to Sensitivity Analysis. *The Scientific World Journal*, 2023, 1675634. Retrieved from <https://doi.org/10.1155/2023/1675634>
- Wondim. (2016). Flood Hazard and Risk Assessment Using GIS and Remote Sensing in Lower Awash Sub-basin, Ethiopia. *Journal of Environment and Earth Science*, 6(9), 69–86. Retrieved from <https://iiste.org/Journals/index.php/JEES/article/download/32924/33820>
- Xia. (2024). River channel confluence routing based on steep slope. Retrieved from <https://doi.org/10.5194/egusphere-egu24-9970>
- Xu, C, Yang, J, & Wang. (2022). Application of Remote-Sensing-Based Hydraulic Model and Hydrological Model in Flood Simulation. *Sustainability*, 14(14), 8576. Retrieved from <https://doi.org/10.3390/su14148576>
- Yoo. (2022). Sustainability in Flood Management (pp. 41–52). CRC Press eBooks. Retrieved from <https://doi.org/10.1201/9780429463327-3>
- Yoo. (2022). Sustainability in Flood Management (pp. 41–52). CRC Press eBooks. Retrieved from <https://doi.org/10.1201/9780429463327-3>

APPENDIX

Appendix A: Data Sources

Data Type	Source/Provider	Website
Digital Elevation Model (DEM)	ALOS PALSAR, NASA/JAXA	https://globaljapan.jaxa.jp/press/2010/09/20100921_alos_en.html
Land Use and Land Cover (LULC)	ESRI Sentinel-2 (2024 Dataset)	https://www.arcgis.com/home/item.html?id=cfc7609de5f478eb7666240902d4d3d
Rainfall Data	Ethiopian Meteorological Agency (EMA)	https://ethiomet.gov.et/
Soil Data	Ethiopian Space Science and Geospatial Institute (ESSGI)	http://www.essgi.gov.et/
River Networks and Watershed Boundaries	HydroSHEDS	https://www.hydrosheds.org/
Administrative Boundaries	OCHA Ethiopia	https://data.humdata.org/

Appendix B: Software

Software	Purpose	Website
ArcMap 10.8	GIS data preprocessing, clipping, projection, analysis	https://www.esri.com/en-us/arcgis/products/arcmap/overview
QGIS	GIS mapping, spatial analysis, data visualization	https://qgis.org/
ArcGIS (Weighted Overlay Analysis)	Area measurement, spatial validation	https://www.google.com/earth/versions/#earth-pro

Getachew Brhanemeskel

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