WOLDIA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND WATER RESOURCE ENGINEERING

DEPARTMENT OF WATER RESOURCE AND IRRIGATION ENGINEERING

FLOOD HAZARD ASSESSMENT AND MAPPING USING GIS INTEGRATED WITH MULTI-CRITERIA DECISION ANALYSIS IN DEREK WONZE MEHAL AMBA TOWN

A thesis submitted in partial fulfilment of the requirement for the degree of master science in hydraulic engineering

By Desale Dagnaw

Advisor: Dr. Imran Ahmed Associate Professor

Co – advisor ____________________

June 2025

Woldia ethiopia

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By

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A thesis submitted to the School of Research and Graduate Studies of woldia school of civil and water resource engineering, Woldia University in Partial fulfillment of requirements for the degree of Master of Science in "Hydraulic Engineering"

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Approval letter

The undersigned, have examined the thesis entitled "**Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in Derek Wonze Mehal Amba Town**", presented by **Desale Dagnaw Afrasie** a candidate for the degree of master of science and hear by certify that it is worthy of acceptance.

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I hereby declare that this Master Thesis "**Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in Derek Wonze Mehal Amba Town** " is an original work. That is, it has not been submitted for the award of any academic degree, diploma, or certificate by any other university. All sources of materials that were used for this thesis have been duly acknowledged through citation.

Desale Dagnaw Afrasie ____ ______

Name of the Student Signature Date

This thesis has been submitted for examination with my approval as a university advisor.

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ADVISORS‟ APPROVAL SHEET (SUBMISSION SHEET)

This is to certify that the thesis entitled "**Flood hazard assessment and mapping using GIS integrated with multi-criteria decision analysis in Derek Wonze Mehal Amba Town**" submitted in partial fulfillment of the requirements for the degree of Master's with specialization in **Hydraulic**, the Graduate Program of the **School of Civil Engineering**, and has been carried out by

Desale Dagnaw Afrasie Id. No **__________**, under my supervision.

Therefore, I recommend that the student has fulfilled the requirements and hence hereby can submit the thesis to the department.

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ABSTRACT

Flooding remains a persistent challenge, driven by climate change and human-induced alterations that disrupt hydrological systems. The main goal of this study was flood hazard assessment and mapping using GIS integrated with multi criteria decision analysis in Derek Wonze Mehal Amba Town watershed which was a parts of upper awash river basin. To assess flood hazards, key environmental seven factors including slope, elevation, rain fall, drainage density, soil type, proximity to river and land use—were systematically analyzed. Expert judgments and institutional data were incorporated using the Analytic Hierarchy Process (AHP) to define criteria weights, which were then integrated into a Geographic Information System (GIS) framework. This methodology enabled precise spatial analysis, facilitating the development of detailed flood hazard maps categorizing vulnerable areas into the results of very low (11250 ha) of 10.5%, low (18990 ha) of 17.6%, moderate (34290 ha) of 31.9%, high (26550 ha) of 24.7% and very high (16560 ha) of 15.4% -risk zones. These maps provide actionable insights for policymakers, urban planners, and environmental agencies seeking to enhance regional flood preparedness. Beyond technical findings, this research emphasizes the necessity of collaborative flood risk management, advocating for proactive intervention strategies that align with ecological preservation and infrastructure planning. By harnessing GIS and AHP methodologies, the study offers a comprehensive model for evaluating flood vulnerability, ensuring informed decision-making that strengthens community resilience. The insights gained serve as a foundation for sustainable land and water management practices, equipping stakeholders with essential tools to mitigate future flood threats while safeguarding environmental stability. This study contributes to advancing adaptive strategies, reinforcing the importance of integrating science and policy to address evolving climatic and anthropogenic flood hazards.

Keywords: Multi-Criteria Decision Analysis; ArcGIS 10.4.1; Analytic Hierarchy Process; Flood hazard assessment; Derek Wonze Mehal Amba Town watershed

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LIST OF ABBREVIATIONS AND ACRONYMS

AHP	Analytic Hierarchy Process
CR	Consistency Ratio
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
LP	Lagged Persistence
FGDs	Focus Group Discussions
FHI	Flood Hazard Index
HBV	Hydrologika byrans vottenbalanavdelning Hydrology bureau's water balance division
GIS	Geographic Information System
LULC	Land Use and Land Cover
NMA	National metrology agency
MCDA	Multi-Criteria Decision Analysis
PERC	Maximum percolation rate from the upper ground water box to the lower
REACH	Registration Evaluation Authorization and Restriction of Chemical
SLMP	Sustainable Land Management Practice
SRTM	Shuttle Radar Topography Mission
USID	United States Agency for International Development
UTM	Universal Transverse Mercator
UZL	Upper Zone Limit
WGS84	World Geodetic System 1984

1. INTRODUCTION

Floods are among the most devastating natural disasters affecting societies worldwide, causing widespread damage to human life, infrastructure, agriculture, ecosystems, and economies (Roy et al., 2022). The impacts of flooding extend beyond immediate destruction, leading to long-term socio-economic challenges and environmental degradation. Flood events disrupt livelihoods, displace communities, and impose significant financial costs, making flood risk management a critical global concern. The frequency and intensity of floods have increased in recent decades, a trend largely attributed to climate change and anthropogenic land-use alterations that exacerbate hydrological instability (Ballut-Dajud et al., 2022).

Climate change plays a central role in shaping the dynamics of flood hazards. Rising global temperatures have significantly affected the hydrological cycle, leading to shifts in precipitation patterns, changes in snowmelt, and rising sea levels (Bosserelle et al., 2022). These factors collectively increase the likelihood of extreme weather events and intensify flood risks across various regions. For example, prolonged periods of heavy rainfall, often associated with climate change, result in soil saturation and excessive runoff, overwhelming drainage systems and causing flash floods in both urban and rural settings. Additionally, the increased rate of glacier melt due to global warming contributes to heightened river flows, further exacerbating flood hazards in low-lying areas.

Urbanization has also significantly contributed to the escalation of flood hazards. The transformation of natural landscapes into urban environments has led to the replacement of permeable surfaces with impermeable materials such as concrete and asphalt, reducing the natural infiltration of rainwater (Kurniawan et al., 2024). This change results in increased surface runoff during heavy rainfall events, overwhelming urban drainage infrastructure and leading to urban flooding. The encroachment upon floodplains, wetlands, and other natural retention areas further diminishes the ability of ecosystems to absorb excess water, heightening flood vulnerability. Consequently, the expansion of cities without adequate flood risk planning has left many urban centers exposed to recurrent flood hazards, necessitating robust mitigation strategies.

To effectively address flood hazards, Geographic Information Systems (GIS) have become indispensable tools for analyzing and managing flood risks. GIS technology enables the collection, processing, and visualization of spatial data, providing valuable insights into flood-prone areas. By integrating diverse datasets including hydrological, meteorological, and topographical information GIS facilitates the development of detailed flood hazard maps. These maps play a crucial role in identifying high-risk zones, allowing policymakers, urban planners, and disaster management authorities to implement targeted intervention strategies (Perosa et al., 2022). For instance, GIS-based flood modeling helps predict the extent and severity of flood events, enabling communities to prepare in advance and minimize potential losses.

Despite the robust capabilities of GIS in flood hazard assessment, it is often necessary to incorporate additional analytical methodologies to enhance the accuracy and reliability of risk evaluation. Multi-Criteria Decision Analysis (MCDA) is one such approach that complements GIS by systematically evaluating multiple flood risk factors and assigning priority weights to different criteria (Dung et al., 2022). MCDA allows researchers to consider environmental, infrastructural, and social variables in flood assessment, ensuring a comprehensive understanding of flood hazards. By integrating GIS with MCDA, flood risk assessments become more precise, enabling decision-makers to develop effective mitigation strategies tailored to specific geographic and socio-economic contexts

Ethiopia is one of many countries facing significant challenges related to flooding, particularly within the Awash River Basin. This basin serves as a vital socio-economic hub, supporting agricultural production, industrial activities, and urban development. However, the basin’s unique hydrological and climatic conditions characterized by erratic rainfall and complex drainage systems make it highly susceptible to flooding. The recurrent floods in the Awash River Basin disrupt livelihoods, damage infrastructure, and hinder economic growth, underscoring the need for advanced flood hazard assessments to strengthen regional flood preparedness and resilience (Ballut-Dajud et al., 2022).

Within the Awash River Basin, Derek Wonze Mehal Amba Town watershed exemplifies the vulnerabilities associated with recurrent flooding. The town's geographic location and climatic conditions, coupled with human-induced land-use changes, contribute to its heightened flood risks. Despite the persistent threat of flooding, the absence of comprehensive flood hazard assessments has left the community ill-equipped to manage flood events effectively. Local authorities struggle with limited resources, inadequate infrastructure, and insufficient land-use planning, further exacerbating the socio-economic and environmental consequences of flooding (Abebe et al., 2023). The lack of accurate flood hazard maps has hindered efforts to implement proactive flood risk mitigation measures, highlighting an urgent need for research that employs advanced methodologies such as ArcGIS and MCDA to assess and map flood hazards in Derek Wonze Mehal Amba Town (Der Sarkissian et al., 2022).

This study aims to fill the existing knowledge gap by applying GIS integrated with MCDA to evaluate and map flood hazards in Derek Wonze Mehal Amba Town watershed. By systematically analyzing key environmental factors including slope, elevation, rainfall patterns, drainage density, soil type, proximity to rivers, and land use the research seeks to identify high-risk flood zones (Dung et al., 2022). Expert judgment and institutional data will be incorporated using the Analytic Hierarchy Process (AHP) to define criteria weights, ensuring a data-driven approach to flood risk assessment (Perosa et al., 2022). Through this methodology, the study will produce a comprehensive flood hazard map that facilitates strategic decision-making, aiding local authorities in developing sustainable flood management practices.

Flooding remains one of the most pressing global challenges, with far-reaching implications for human and environmental systems. The integration of ArcGIS and MCDA offers a transformative approach to flood risk management by providing scientifically rigorous and practically applicable solutions. In the context of Derek Wonze Mehal Amba Town watershed, this research highlights the potential of advanced spatial analysis techniques to enhance flood preparedness and support sustainable development. By offering a blueprint for effective flood hazard assessment and mitigation, the study contributes to the broader goal of building resilient communities and ecosystems in the face of an increasingly uncertain climate future.

1.1. Statement of the problem

Flooding remains one of the most destructive natural disasters, causing far-reaching consequences for communities worldwide. The effects of flooding extend beyond immediate physical damage, claiming lives, displacing populations, and disrupting socioeconomic activities (Munzhedzi et al., 2024).

Property destruction, environmental degradation, and the loss of livelihoods are recurring themes in flood-affected regions. In vulnerable communities such as Derek Wonze Mehal Amba Town watershed, these challenges are exacerbated by inadequate flood hazard assessments and a lack of effective management strategies, leaving residents exposed to recurring disasters and their devastating impacts.

Derek Wonze Mehal Amba Town watershed, located in Ethiopia's Upper Awash River Basin, exemplifies the risks associated with flooding. Its geographic and climatic conditions characterized by erratic rainfall patterns, varied topography, and anthropogenic land-use changes make it highly susceptible to flood hazards (Rijal et al., 2024).

Despite the frequency of flooding, significant gaps remain in comprehensive research and data-driven approaches to identifying high-risk areas, prioritizing interventions, and designing effective mitigation strategies. The absence of critical flood hazard assessments has left local authorities with limited capacity for proactive planning, further compounding the town's vulnerability to flood events (Amankwaa et al., 2024).

Traditional methods of flood risk analysis often fail to capture the complexities of flooding. Factors such as drainage density, elevation, land cover, soil type, proximity to river, slope, and rainfall intensity, which collectively shape flood susceptibility, are rarely integrated into a cohesive analytical framework (Efraimidou & Spiliotis, 2024).

The omission of these essential components results in flood hazard assessments that lack accuracy and reliability, reducing the effectiveness of flood preparedness strategies. Without modern and integrative methodologies, communities like Derek Wonze Mehal Amba Town watershed continue to face challenges in understanding and addressing the multidimensional nature of flood risks.

Given these concerns, the need for advanced flood hazard assessment methodologies is urgent. Geographic Information Systems (GIS), when combined with Multi-Criteria Decision Analysis (MCDA), provide a robust framework for integrating spatial data and systematically evaluating complex risk factors (Ibrahim et al., 2025).

GIS enables the development of detailed flood hazard maps, while MCDA prioritizes risk factors through techniques such as the Analytic Hierarchy Process (AHP), improving the accuracy of flood risk evaluations. Together, these methodologies offer a powerful solution for flood hazard assessments, delivering actionable insights that guide planning, preparedness, and mitigation efforts.

This research seeks to bridge the gap in flood risk analysis for Derek Wonze Mehal Amba Town watershed by employing GIS and MCDA to identify flood-prone areas, analyze contributing factors, and develop comprehensive flood hazard maps. These outputs will empower policymakers, planners, and local authorities to allocate resources effectively, prioritize interventions, and enhance disaster management strategies (Efraimidou & Spiliotis, 2024). By reducing vulnerability and strengthening community resilience, this study aims to contribute to sustainable flood risk management practices in the region.

1.2. Objectives of study

1.2.1. General Objective

The general objective of this study is flood hazard assessment and mapping using GIS integrated with multi – criteria decision analysis in Derek Wonze Mehal Amba Town watershed which is apart upper awash river basin.

1.2.2. Specific Objectives

- To delineate flood-prone areas within Derek Wonze Mehal Amba Town watershed using Geographic Information Systems (GIS) to analyze spatial and environmental data.
- To apply Multi-Criteria Decision Analysis (MCDA) to evaluate and rank factors influencing flood hazards, including topographical and hydrological criteria.

- To create a comprehensive flood hazard map.

1.2.3. Research questions

- How can flood-prone areas within Derek Wonze Mehal Amba Town watershed be identified and analyzed using Geographic Information Systems (GIS)?
- What factors significantly influence flood hazards in the study area, and how can Multi-Criteria Decision Analysis (MCDA) be applied to rank these factors systematically?
- How can a comprehensive flood hazard map be developed?

1.3. Significance of the study

The significance of this study lies in its ability to address a critical need for improved flood hazard assessment and management in Derek Wonze Mehal Amba Town watershed, a region vulnerable to recurrent and devastating flooding events. Floods pose severe risks to lives, livelihoods, infrastructure, and the environment, and the increasing frequency of such events exacerbated by climate change and rapid land-use transformations underscores the urgency of implementing targeted mitigation strategies. By focusing on this area, the study provides a framework for sustainable flood risk management that can serve as a model for other vulnerable regions facing similar challenges.

This research stands out for its integration of Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), two innovative tools that offer a comprehensive approach to understanding and mitigating flood risks. The study leverages GIS to compile and analyze spatial data, including critical factors such as rainfall patterns, elevation, slope, land use, and drainage density.

GIS allows for the creation of detailed thematic maps that accurately identify flood-prone areas, which is a critical step in disaster preparedness. Meanwhile, MCDA adds depth to this analysis by enabling the systematic evaluation and prioritization of flood risk factors based on their relative importance. This integration ensures that all significant variables are accounted for and that the resulting flood hazard maps are both accurate and actionable.

One of the key contributions of this study is its potential to empower policymakers, urban planners, and disaster management agencies with reliable tools for decision-making. The comprehensive flood hazard map generated through this research will serve as a vital resource for identifying high-risk zones, guiding land-use planning, and developing focused mitigation strategies. These insights can help prioritize resource allocation, ensuring that interventions are directed toward areas and communities most at risk. Moreover, the study offers a foundation for long-term planning efforts that aim to build resilience against future flooding events.

The findings of this research have implications beyond the immediate study area. While the focus is on Derek Wonze Mehal Amba Town watershed, the methodologies employed integrating GIS with MCDA are highly adaptable and can be applied to other flood-prone regions. This adaptability ensures that the study contributes to the broader field of disaster risk reduction, paving the way for more efficient and effective flood management practices worldwide.

In addition to providing practical tools and insights, the study holds immense social importance. By identifying vulnerable populations and infrastructure, it ensures that mitigation measures are inclusive and equitable, addressing the needs of those who are most affected by flooding. This approach not only enhances community resilience but also fosters a sense of security and preparedness among residents, ultimately improving their quality of life.

In summary, this study bridges critical gaps in flood hazard assessment by employing cutting-edge technologies to deliver actionable insights. It is not merely an academic exercise but a strategic initiative with real-world applications, offering solutions that are sustainable, scalable, and transformative for disaster management and urban planning.

1.4. Scope of the research

Flood hazard assessment in the Upper Awash River Basin applies an integrative methodology combining Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) to evaluate varying levels of flood susceptibility. This study examines critical parameters such as slope, soil type, rainfall distribution, drainage density, and land use/land cover (LULC), providing a spatial and temporal perspective on flood risks (Zhou & Liu, 2024). The analysis seeks to capture dynamic interactions between hydrological and geomorphological processes that influence flood hazards.

The study area encompasses diverse terrain, with elevations ranging from 1,500 to 3,500 meters above sea level. Such variations in topography significantly impact runoff patterns, sediment transport, and erosion rates, all of which contribute to flood risk levels (Mir & Patel, 2024). Leveraging high-resolution Digital Elevation Models (DEMs) and remote sensing data, the research refines hydrological and geomorphological analyses to improve flood hazard mapping precision.

Temporally, the study incorporates both historical flood records and current meteorological data to assess seasonal variations in precipitation and their influence on flood events. Rainfall interpolation techniques are employed to enhance spatial resolution, improving the predictive accuracy of flood susceptibility modeling (Helmi et al., 2023). Additionally, the research examines long-term land use changes and their impacts on urban hydrology and flood susceptibility, offering a broader perspective on anthropogenic influences on flood dynamics (Alshammari et al., 2023).

This flood hazard assessment generates practical outputs, including thematic hazard maps and a composite flood risk model. These tools facilitate effective decision-making by policymakers, urban planners, and local communities in implementing flood mitigation strategies (Kader et al., 2024). By classifying flood-prone areas into varying hazard levels, the study provides actionable insights that enable targeted interventions, optimizing resource allocation for flood prevention and management.

The validation process ensures the reliability of the flood hazard assessment. Historical flood data comparisons and HBV light model analysis serve as key methodologies for evaluating model performance and validetion. The HBV light model quantifies predictive and observe accuracy, strengthening confidence in the flood hazard model's applicability to real-world scenarios (Gocoglu, Demirel, & Bozdogan, 2024). Accurate validation reinforces the utility of the study, ensuring that findings contribute to practical flood risk mitigation efforts.

Ultimately, this research bridges theoretical geospatial analysis with practical applications, offering a framework for sustainable flood management in vulnerable regions. By integrating GIS-based spatial analysis, remote sensing, and multi-criteria decision-making techniques, the study enhances our understanding of flood hazards while supporting resilience-building initiatives. These validated outputs serve as essential resources for land use planning, policy formulation, and disaster preparedness, promoting a comprehensive approach to flood risk mitigation.

1.5. Challenges in GIS-MCDA Integration

Integrating Geographic Information Systems (GIS) with Multi-Criteria Decision Analysis (MCDA) presents several nuanced challenges. One of the primary difficulties lies in the subjectivity associated with assigning weights to different criteria within the MCDA framework. This reliance on expert judgment can introduce inconsistencies and biases, potentially influencing the final outcomes of the analysis. According to Liao et al. (2023), advanced machine learning techniques can mitigate this issue by introducing data-driven approaches to weight assignment, thereby improving the objectivity of decision-making processes.

Another significant challenge is the limited availability of high-resolution and accurate datasets, particularly in regions with underdeveloped data infrastructure. Habib et al. (2024) emphasize that this scarcity hinders the precision of GIS-based analyses, often necessitating reliance on open-access sources such as Shuttle Radar Topography Mission (SRTM) Digital Elevation Models (DEMs). While these datasets provide valuable insights, they sometimes lack the resolution required for localized flood risk assessments. Furthermore, harmonizing diverse datasets each varying in format, resolution, and temporal consistency presents a major obstacle, potentially undermining the uniformity and reliability of GIS-MCDA models. Kayal et al. (2025) highlight this issue, noting that data inconsistencies can lead to challenges in agricultural land suitability modeling, a field closely related to environmental hazard assessments.

The computational demands of overlaying multiple weighted factors in GIS-MCDA are also substantial, requiring sophisticated hardware capabilities or cloud-based solutions to process datasets effectively. Additionally, inherent uncertainties in MCDA outputs such as variability in criteria weights and spatial inconsistencies necessitate robust validation techniques. Hossain and Mumu (2024) stress the importance of incorporating uncertainty and sensitivity analyses to enhance the reliability of flood susceptibility modeling derived from GIS-MCDA frameworks. Without such rigorous validation, the accuracy of risk assessments may be compromised, limiting their applicability in real-world disaster mitigation efforts.

Despite these challenges, GIS-MCDA integration remains a powerful tool for spatial decision-making. Its ability to synthesize multiple variables into comprehensive hazard assessments provides invaluable insights for policymakers and researchers working in flood risk management and environmental planning. Addressing the existing methodological and technological barriers through data-driven approaches, enhanced computational infrastructure, and improved validation techniques will be crucial in refining GIS-MCDA models and expanding their applicability across diverse geographical contexts.

1.6. Research Limitations

While this study provides significant insights into flood hazard assessment using Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA), several limitations must be acknowledged. First, the accuracy of the findings relies heavily on the quality and resolution of the data used. Inconsistencies or gaps in meteorological, topographical, or land-use datasets could impact the precision of the flood hazard maps. Un gauged river flows and interpolated rainfall data s and other criteria incurs poor performance of HBV light model simulation results. Similarly, limited access to updated and detailed spatial data might constrain the scope of analysis.

The current political situation is limited to move freely from place to place to gather GPS evidences to incorporate and identify other vulnerability factors of flooding for example population density, infrastructure and others. Second, the application of the Analytic Hierarchy Process (AHP) within MCDA depends on expert judgments to assign weights to various flood risk factors. These judgments, while informed, are inherently subjective and could introduce bias into the results.

Additionally, the study focuses exclusively on Derek Wonze Mehal Amba Town watershed, which limits the generalizability of the results to other regions with distinct geographic, climatic, or socio-economic conditions. Finally, resource constraints, such as computational capacity and software availability, posed challenges during data processing and analysis. Despite these limitations, the study offers a robust framework for flood risk assessment, paving the way for future research with improved data, methodologies, and broader applicability.

2. LITERATURE REVIEW

2.1. An Overview s of assessing flood hazard

Flood hazard assessments and risk management techniques have been the focus of extensive research due to the increasing frequency and severity of flood events worldwide (Jain, 2024). The growing impacts of floods on infrastructure, human lives, and ecosystems necessitate innovative approaches to identifying vulnerable areas and implementing mitigation strategies. Geographic Information Systems (GIS) have emerged as a cornerstone technology in spatial data analysis, providing researchers with powerful tools to map flood-prone regions and enhance disaster management strategies. GIS enables the visualization of complex flood dynamics, particularly in diverse topographical settings, facilitating more precise and effective flood risk evaluations.

One of the most crucial components of flood hazard mapping is the application of Digital Elevation Models (DEMs). High-resolution DEMs allow for precise analysis of slopes, drainage patterns, and elevation gradients key factors in assessing flood vulnerability (Xafoulis et al., 2023). DEMs enhance flood risk modeling by improving accuracy in detecting low-lying areas susceptible to inundation during extreme rainfall events. Additionally, advanced geospatial technologies have enabled researchers to utilize DEM-based hydrological models to simulate flood propagation and identify high-risk zones with greater precision. However, data availability and resolution inconsistencies remain significant challenges, particularly in developing regions where access to high-quality elevation datasets is limited.

The integration of GIS with Multi-Criteria Decision Analysis (MCDA) has gained traction as a robust framework for evaluating multiple flood-contributing factors simultaneously. MCDA systematically assigns weights to key flood hazard variables, such as rainfall intensity, land use, soil type, and slope gradient, enabling the creation of detailed flood hazard maps (Ibrahim et al., 2025). This integration enhances the accuracy of risk assessments and provides policymakers with actionable insights into flood-prone areas. By employing the Analytical Hierarchy Process (AHP), MCDA strengthens flood modeling methodologies by incorporating expert judgment to refine criteria weights for spatial analysis. As a result, GIS-MCDA models have become instrumental in prioritizing mitigation strategies and improving flood resilience.

Despite its advantages, GIS-MCDA-based approaches face several challenges. The subjectivity associated with criteria weighting introduces biases that can affect the reliability of flood hazard maps (Makadi et al., 2024). Furthermore, open-source data sources such as Shuttle Radar Topography Mission (SRTM) DEMs have been widely utilized in flood risk assessments due to their accessibility, but their resolution limitations often lead to inaccuracies in localized studies. Addressing these issues requires a combination of high-resolution datasets and robust validation techniques to enhance the precision of GIS-MCDA-based flood assessments.

2.2. Assessing Flood hazard in Ethiopia

Ethiopia, with its topographically diverse landscapes, presents a unique challenge in flood risk assessment. Studies have emphasized the importance of tailored methodologies that account for steep slopes, seasonal rainfall variations, and land-use practices in the Ethiopian Highlands (Muhammed, 2024). In particular, soil erosion and sediment transport have been identified as critical factors influencing flood hazards in mountainous regions (Liu et al., 2023). Research into hydrological processes has underscored the necessity of integrating geomorphological assessments into flood hazard mapping, ensuring comprehensive risk evaluations in regions prone to flash floods and landslides.

The Awash River Basin in Ethiopia is one of the most flood-prone areas, necessitating advanced GIS-MCDA methodologies to assess and manage flood risks (Abebe et al., 2023). The basin supports extensive agricultural and industrial activities, making flood preparedness essential for sustaining economic stability. However, recurrent flood events in the Upper Awash Basin have led to infrastructural damage, displacement, and economic losses, highlighting the urgent need for integrated flood hazard assessments. Despite these challenges, few detailed flood risk mapping studies have been conducted in the region, leaving gaps in disaster response planning.

2.3. Flood vulnerability in Derek Wonze Mehal Amba Town watershed

Within the Awash River Basin, with in Derek Wonze Mehal Amba Town watershed exemplifies the vulnerability associated with recurrent flooding due to anthropogenic land-use changes and hydrological complexities (Der Sarkissian et al., 2022). The absence of detailed flood hazard assessments has hindered sustainable land-use planning and infrastructure development, increasing flood susceptibility within the town. Local authorities often struggle to allocate resources effectively due to the lack of accurate flood risk data, resulting in inadequate disaster preparedness and response strategies. Addressing these gaps requires advanced GIS-MCDA methodologies that incorporate high-resolution spatial analysis to enhance flood hazard mapping and inform strategic decision-making.

This study aims to refine existing flood risk assessment models by applying ArcGIS integrated with MCDA to evaluate and map flood hazards in Derek Wonze Mehal Amba Town watershed. By systematically analyzing environmental factors including elevation, slope, rainfall patterns, drainage density, soil type, proximity to rivers, and land use the research seeks to develop precise flood hazard maps for improved disaster mitigation strategies (Dung et al., 2022). Through expert judgment and AHP-based criteria weighting, the study will ensure a scientifically rigorous approach to flood risk evaluation, supporting policymakers in implementing data-driven flood resilience initiatives (Perosa et al., 2022).

Flooding remains one of the most pressing environmental and socio-economic challenges, requiring advanced technological solutions for effective disaster management. The integration of GIS and MCDA provides a transformative approach to flood hazard assessment, enabling scientifically sound and practically applicable mitigation strategies. This study highlights the potential of ArcGIS-based spatial analysis to improve flood preparedness, sustainable land management, and urban planning (Ballut-Dajud et al., 2022). By developing comprehensive flood hazard maps, the research contributes to strengthening community resilience and informing proactive disaster risk reduction efforts, ensuring a sustainable future for flood-prone regions like Derek Wonze Mehal Amba Town watershed.

2.4. Overview of GIS Applications

Geographic Information Systems (GIS) are powerful tools that integrate spatial and attribute data to analyze, visualize, and interpret geographic phenomena. GIS applications span multiple disciplines, offering solutions for environmental management, urban planning, disaster response, and more.

1. Environmental Monitoring, GIS aids in tracking deforestation, climate change impacts, and biodiversity conservation (Goodchild, 2020).

2. Urban Planning & Infrastructure, Supports site selection, zoning regulations, and transportation network optimization (Batty, 2018).

3. Disaster Management Facilitates flood hazard mapping, earthquake risk assessment, and emergency response planning (Smith et al., 2019).

4.Agriculture & Land Use Enhances precision farming, soil analysis, and irrigation management (Zhang & Wang, 2021).

5.Public Health & Epidemiology Assists in disease mapping, healthcare accessibility analysis, and epidemiological studies (Mayer, 2017).

Beyond technical applications, GIS serves as a narrative tool, transforming raw data into compelling spatial stories. By layering historical maps, demographic shifts, and environmental changes, GIS enables policymakers and researchers to craft data-driven narratives that resonate with communities. This approach fosters engagement, making complex spatial analyses more accessible and actionable (Harvey, 2022).

2.5. MCDA application in Derek Wonze Mehal Amba Town watershed for flood hazard assessment

Multi-Criteria Decision Analysis (MCDA) has been effectively applied in flood hazard assessment within the Derek Wonze Mehal Amba Town watershed, integrating expert judgments and institutional data to define criteria weights. The Analytic Hierarchy Process (AHP) was used to systematically evaluate seven key environmental factors: slope, elevation, rainfall, drainage density, soil type, proximity to river, and land use.

These weighted criteria were then incorporated into a Geographic Information System (GIS) framework, enabling precise spatial analysis and the development of flood hazard maps. The study categorized vulnerable areas into very low (10.5%), low (17.6%), moderate (31.9%), high (24.7%), and very high (15.4%) risk zones. Spatial analysis facilitated the identification of flood-prone areas, supporting targeted mitigation strategies. The results provide actionable insights for urban planners, policymakers, and environmental agencies to enhance flood preparedness.

3. METHODOLOGY

3.1. Study Area Delineation and description

The focus of this study is a dynamic portion of the Upper Awash Basin, specifically the study area watershed located in Ethiopia's Amhara region. Positioned approximately 475 kilometers northeast of Addis Ababa, the watershed emerges as a complex landscape defined by its rugged topography and diverse hydrological features. Its geographic coordinates 11°35'32" N and 39°39'29" E anchor it within a region of steep slopes, mountainous terrain, and a wide range of elevations, spanning from 1,500 to 3,500 meters above sea level.

The watershed forms a pivotal part of the Awash River system, showcasing an intricate network of tributaries, drainage channels, and elevated landforms. These physical characteristics not only influence water flow but also shape the area's susceptibility to floods. Its semi-arid to sub-humid climate, coupled with pronounced seasonal rainfall patterns, adds another layer of complexity, requiring precise boundary delineation.

Using advanced geospatial techniques, the boundaries of Derek Wonze Mehal Amba Town watershed is meticulously defined. High-resolution topographic data, such as Digital Elevation Models (DEMs) from the Shuttle Radar Topography Mission (SRTM), are processed through GIS software. Hydrological modeling tools analyze elevation gradients, water flow pathways, and drainage densities to demarcate the watershed’s extent. This delineation captures its ecological diversity and ensures that flood hazard assessments are rooted in an accurate understanding of the region’s natural dynamics.

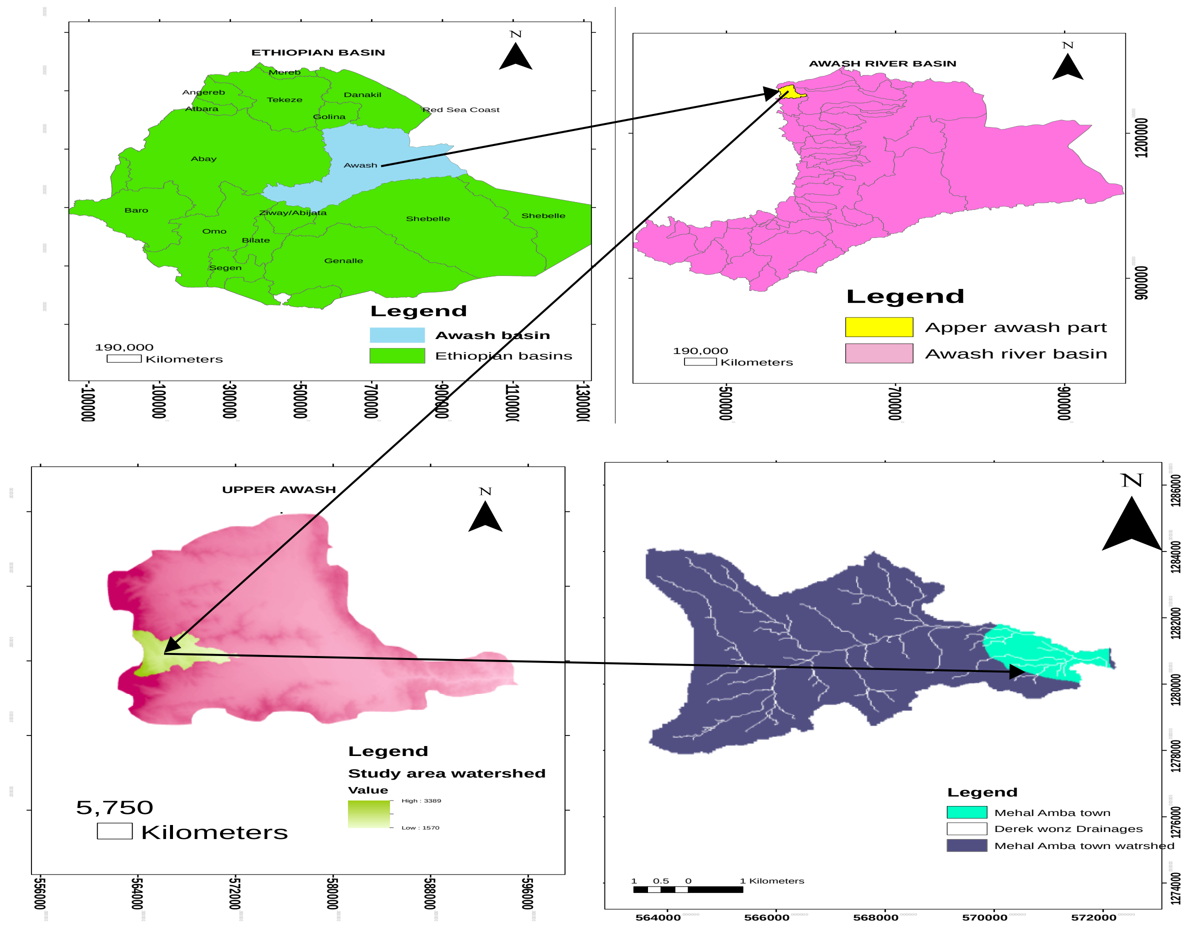

Figure 2 Study area map

Study area description

The climate in the study area is semi-arid to sub-humid, influenced by seasonal rainfall patterns typical of the Ethiopian highlands. The area experiences two primary rainy seasons: the *kiremt* (June to September) brings the main rains, while the *belg* (February to May) brings secondary rains. The mean annual rainfall can vary significantly, often ranging from 700 to 1,200 mm, depending on the location within the watershed. Temperatures can vary widely with elevation, with lower areas being warmer and higher altitudes experiencing cooler temperatures.

Land use within Derek Wonze Mehal Amba Town watershed is predominantly agricultural, with subsistence farming as the primary livelihood for the local communities. Crops like teff, maize, barley, and wheat are commonly grown in this area, often on terraced fields to counteract soil erosion due to the steep slopes. The region is prone to land degradation, including soil erosion and deforestation, largely due to overgrazing, unsustainable farming practices, and limited vegetation cover.

Derek Wonze Mehal Amba Town watershed is an essential area for water resources as it feeds into larger river systems downstream, making its conservation critical for both local agricultural productivity and broader environmental sustainability in the region.

3.2. Input Components

Flood hazard assessment relies on a comprehensive range of input components, each contributing to an in-depth understanding of the region's vulnerability. Digital Elevation Models (DEMs) provide critical data on elevation and slope, enabling the identification of runoff patterns and erosion hotspots. DEMs, such as SRTM or ASTER, are particularly valuable for precise spatial analysis (Saberi et al., 2023). These datasets facilitate accurate modeling of terrain features, allowing researchers to assess flood-prone areas based on topographical characteristics.

Land use and land cover (LULC) data offer insights into anthropogenic changes in the landscape, which significantly impact water flow and soil stability. Satellite imagery from Sentinel or Landsat enables the classification and monitoring of LULC trends over time, helping to identify areas where vegetation loss or urban expansion increases flood vulnerability (Acar & Zengin, 2023). These datasets are essential for tracking changes in hydrological response due to human activities, allowing for the incorporation of dynamic land-use patterns into flood hazard models.

Rainfall data, obtained from National Meteorological Agency (NMA) of Ethiopia adds a temporal dimension to flood susceptibility assessments. Helmi et al. (2023) emphasize the role of rainfall distribution in influencing surface water dynamics, particularly in regions with pronounced seasonal variations such as the Ethiopian highlands. Understanding rainfall intensity and duration is crucial for predicting peak runoff periods and assessing flood risks associated with extreme weather events.

Soil type and drainage density are fundamental factors shaping water absorption, retention, and flow across the watershed. Soil properties influence runoff potential and erosion rates, as highlighted by Odoh et al. (2024). Similarly, drainage density provides insights into the watershed's hydrological connectivity, aiding in the identification of areas prone to rapid water accumulation during rainfall events (Odoh & Nwokeabia, 2024). The integration of these factors helps refine flood susceptibility models, ensuring a more accurate representation of flood dynamics.

GIS software, such as ArcGIS 10.4, serves as the primary platform for processing and integrating these diverse datasets. Through spatial analysis tools, thematic maps are generated for each criterion slope, rainfall, LULC, soil type, and drainage density offering a layered perspective on flood risks. These thematic layers support comprehensive flood hazard mapping, enabling data-driven decision-making for disaster preparedness and mitigation efforts.

Together, these input components form the backbone of the analytical framework, ensuring an accurate and holistic assessment of flood hazards across the study area. This integrative approach allows for the identification of vulnerable zones, supporting proactive flood management strategies.

Flood hazard map using Geographic Information Systems (GIS), specifically ArcGIS 10.4 captures the entire process from input data preparation to the final analysis, highlighting the systematic integration of various datasets to produce a precise and informative hazard map.

At the beginning we see the Input Data section, which outlines the essential datasets required to conduct a thorough flood hazard analysis. These datasets include information about slope, elevation, drainage density, proximity to rivers, rainfall, soil texture, and land use. Each of these factors plays a significant role in influencing the likelihood and severity of flooding in a given area. For example, slope determines how quickly water flows across the surface, while elevation indicates the potential accumulation of water in low-lying regions. Drainage density reflects the capacity of the natural terrain to channel water effectively, while proximity to rivers highlights areas that are at risk due to their closeness to water sources. Rainfall data provides insight into precipitation patterns and intensity, which are critical factors in determining flood risks. Soil texture reveals the permeability of the soil, influencing how much water is absorbed versus how much becomes surface runoff. Finally, land use data captures the human impact on the landscape, indicating areas that are built-up, agricultural, or vegetated, each of which has varying levels of susceptibility to flooding.

The second section is the Processing Phase using the ArcGIS 10.4 software. This part illustrates how the input data is standardized and prepared for analysis. The first step in this process involves projecting all datasets into a unified coordinate system, specifically the WGS_1984_UTM_Zone_37N. This ensures spatial alignment and accuracy across all data layers, enabling seamless integration. Spatial resolution is then set to a uniform cell size of 20×20 meters. This resolution is chosen to balance detail and computational efficiency, allowing for precise analysis without overwhelming processing resources. Through this phase, the input data undergoes transformation to ensure compatibility and consistency, setting the stage for the subsequent analysis.

The final section emphasizes the Raster Weighted Overlay Analysis, which is a key step in the methodology. In this part of the figure, the processed datasets are combined and analyzed using a raster-based overlay approach. Each dataset is assigned a weight based on its relative importance in contributing to flood hazards. For example, rainfall and proximity to rivers might be given higher weights due to their direct impact on flooding, while factors such as soil texture and land use could be assigned slightly lower weights depending on the specific context of the analysis. These weighted datasets are then aggregated to create a comprehensive flood hazard map. The overlay analysis involves advanced spatial modeling techniques to ensure that the final map accurately reflects the combined influence of all contributing factors.

The flood hazard map, which is the ultimate output of this process, is a valuable tool for decision-makers and planners. It provides a spatial representation of flood risk levels across the study area, highlighting regions that are highly susceptible to flooding as well as those with lower risk. This information is critical for disaster management, land-use planning, and infrastructure development. By identifying flood-prone areas, authorities can prioritize resources and interventions, such as constructing flood defenses, implementing zoning regulations, and designing early warning systems. The map also serves as a foundation for further studies and policy-making, enabling a proactive approach to flood risk mitigation.

Underscores the importance of integrating diverse datasets and leveraging GIS technology for environmental and hydrological analysis. The step-by-step approach ensures transparency and replicability, making it accessible for researchers and practitioners in the field. Moreover, the use of standardized methodologies and tools, such as ArcGIS 10.4, highlights the reliability and robustness of the analysis. The figure conveys a strong emphasis on spatial precision and data-driven decision-making, showcasing the potential of GIS in addressing complex challenges related to natural hazards and climate change.

By representing the process visually and effectively communicates the methodology to a wide audience, including those who may not have technical expertise in GIS or flood modeling. Its logical structure and clear labeling facilitate understanding, making it a valuable educational and reference tool. The process not only documents the steps involved in creating a flood hazard map but also serves as an inspiration for similar analyses in other contexts, such as landslide risk assessment, drought monitoring, and urban planning.

In summary, the process is a comprehensive depiction of the workflow for developing a flood hazard map, integrating multiple datasets and GIS technology in a systematic and transparent manner. It highlights the critical role of spatial analysis in disaster risk management, providing a blueprint for effective planning and decision-making. By combining scientific rigor with practical application, the flowchart exemplifies the transformative power of ArcGIS in addressing pressing global challenge.

3.3. Processing and Integration Components

Flood hazard analysis integrates diverse datasets through advanced geospatial techniques, transforming raw data into actionable insights. Digital Elevation Models (DEMs) provide essential elevation, slope, and hydrological flow patterns, refined through GIS software or GIS to identify vulnerable zones based on slope gradients and drainage networks (Nkonu, Antwi, Amo-Boateng, & Dekongmen, 2023).

Satellite imagery from sources like Sentinel and Landsat undergoes preprocessing for land use and vegetation classification, ensuring that temporal changes such as deforestation or urban expansion are accurately incorporated into flood risk models. The integration of machine learning and remote sensing data enhances urban sustainability by monitoring patterns affecting runoff and soil stability (Li, Yigitcanlar, Nepal, Nguyen, & Dur, 2023).

Rainfall data sourced from meteorological stations adds a dynamic component to hazard assessment. The use of interpolation methods enhances the spatial resolution of precipitation data, refining flood susceptibility mapping (Xu et al., 2023). ArcGIS tools facilitate the integration of thematic layers, including slope, elevation, proximity to river, soil type, land use, rainfall, and drainage density. Weighted overlay analysis assigns importance to each criterion using Analytical Hierarchy Process (AHP) modeling (Thakur & Mohanty, 2023).

Validation processes further refine flood hazard assessments by incorporating historical flood data comparisons and precipitation and evapotranspiration to ensure reliability. This structured approach supports informed decision-making for flood risk mitigation (Alves et al., 2024).

This workflow effectively transforms raw geospatial data into a comprehensive flood hazard framework, reinforcing spatial analysis and practical applications in flood risk management.

3.4. Conceptual framework

The conceptual framework for this study integrates Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) to assess flood hazards, grounded in an understanding of spatial and environmental dynamics within the watershed. At its core, the framework identifies critical factors such as topography, land use, soil type, drainage density, and rainfall that influence flood risks. These factors are structured into weighted criteria using the Analytical Hierarchy Process (AHP), ensuring a systematic approach to flood hazard mapping (Wijesinghe et al., 2023).

The study area's characteristics, including steep slopes, rugged terrain, and seasonal rainfall patterns, form the basis for defining the environmental inputs. Slope and elevation, obtained from high-resolution Digital Elevation Models (DEMs), play a crucial role in modeling runoff and erosion potentials, as these features are primary drivers of flood dynamics (Zandsalimi et al., 2024). Rainfall data, processed through geospatial interpolation techniques, provide a temporal dimension to flood susceptibility, reflecting the seasonal variability of precipitation in the region (Pan et al., 2024). Additionally, land use and land cover changes, analyzed through satellite imagery, highlight human-environment interactions that either exacerbate or mitigate flood risks (Mashood, 2024).

ArcGIS is employed to compile, process, and visualize these diverse datasets, generating thematic layers for each flood risk criterion. The MCDA process evaluates the relative importance of each factor, producing a weighted overlay that identifies hazard-prone zones across the watershed. This integrative approach not only pinpoints vulnerable areas but also supports decision-making by providing a robust foundation for resource allocation and risk mitigation efforts (Rezvani et al., 2023).

Validation of the framework involves comparing the generated flood hazard maps with historical flood data and field observations. Accuracy assessments, including HBV light model, ensure the reliability and applicability of the results. By bridging theoretical understanding with practical application, the conceptual framework offers a comprehensive pathway for flood risk assessment and management.

Diagram Representation

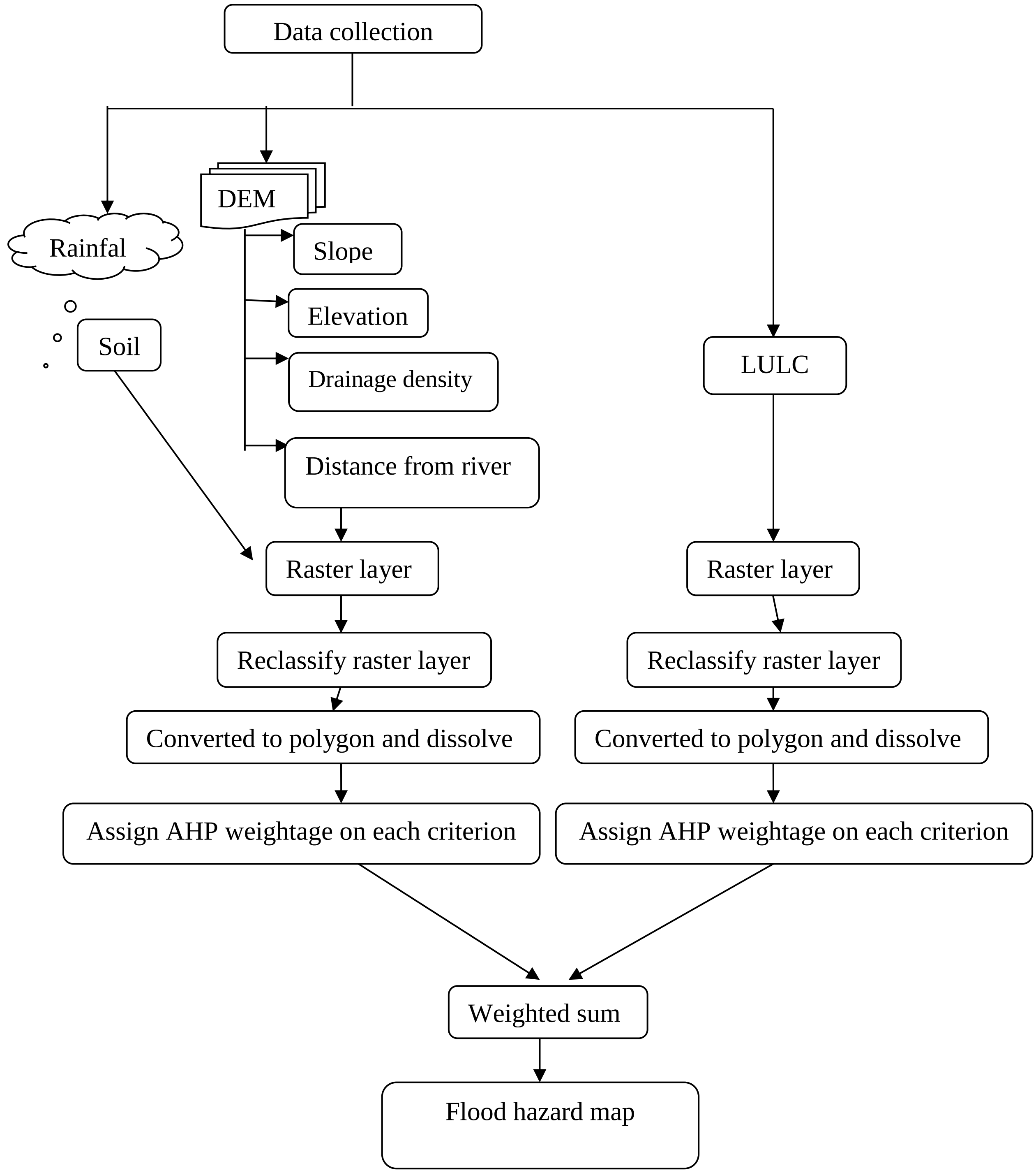

Figure 1 Diagram Representation of flood hazard assessment

3.5. Validation and Hazard assessment Mapping

Flood hazard mapping plays a critical role in assessing and visualizing spatial flood risks across a watershed. To ensure precision and practical applicability, the study area is classified into distinct hazard categories: very low, low, moderate, high, and very high-risk zones. These classifications are derived from overlay analyses of weighted flood hazard factors and are visualized using GIS-based raster and vector maps. The resulting outputs serve as actionable tools for identifying vulnerable areas and guiding strategic interventions (Al-Omari et al., 2024).

An essential step in flood hazard mapping is validation, which ensures the reliability and accuracy of risk assessments. Historical flood records, including documented inundation events and observed field impacts, are compared against predicted hazard zones to assess consistency. Additionally, field observations provide direct insights into flood-prone areas, validating model outputs through real-world evidence. These verification methods enhance confidence in hazard classifications, making them more useful for disaster preparedness and mitigation efforts.

Further refinement of hazard map accuracy relies on statistical validation techniques such as HBV light model. HBV light model analysis quantifies the predictive strength of flood hazard classifications, ensuring that high-risk zones align with observed and predicted flooding patterns. This modeling approach reinforces the credibility of hazard mapping and improves its utility for decision-makers involved in flood risk management (Efraimidou & Spiliotis, 2024).

By integrating robust spatial analysis with rigorous validation techniques, flood hazard mapping provides a comprehensive framework for proactive flood risk management. These tools support sustainable development planning by enabling authorities to prioritize high-risk areas, optimize mitigation strategies, and enhance community resilience. As climate variability continues to impact hydrological systems, accurate and well-validated flood hazard maps will remain essential for effective disaster response and long-term adaptation measures.

These weights reflect the relative influence of each factor on flood susceptibility, prioritizing topography and elevation as primary drivers.

3.6. HBV light Model inputs

That study by Oudin, Michel, and Anctil (2005) explores the role of potential evapotranspiration (PE) in rainfall-runoff models, questioning whether detailed PE inputs improve model performance. Their research suggests that simpler temperature-based PE models can be just as effective, if not more so, than complex approaches.

Evapotranspiration

It plays a crucial role in hydrological and agricultural studies, particularly in assessing water availability and climate change impacts. Trabucco et al. (2008) explored the hydrologic effects of afforestation and reforestation, analysing how changes in land cover influence water cycles. Their study highlights the importance of PET estimation in understanding these impacts, especially in the context of climate change mitigation.

Rainfall

Rainfall is a crucial input for the HBV model, as it directly influences runoff generation and overall water balance. The study by Abebe, Ogden, and Pradhan (2010) examines the sensitivity and uncertainty of the HBV model, highlighting how parameter estimation can impact simulation accuracy. Their research emphasizes the importance of high-quality rainfall data to ensure reliable hydrological modeling.

Temperature

The HBV model relies on mean daily temperature data to determine precipitation type, snowmelt processes, and potential evapotranspiration. In Yılmaz's 2023 study, long-term average daily temperature data was used to assess the performance of a novel HBV model compared to the existing HBV light model and climate projections. This comparative analysis provides insights into how different temperature datasets influence hydrological modeling accuracy.

Input data

Catchment Data

Data on elevation and vegetation cover were used to create the model. Elevation zones were divided into different vegetation zones and were considered the primary hydrological units of the catchment. The HBV model version used in this study allows the catchment to be divided into up to 20 elevation zones with three vegetation zones per elevation zone Seibert, 2002). Based on agroecological zones, Derek Wonze Mehal Amba Town watershed has been divided into four elevation zones and three vegetation zones. The zonings were created entirely using ArcGIS and the area elevation and land cover data are shown in table below.

Table1 Semi-distributed representation of the Derek Wonze Mehal Amba Town watershed into four elevations and three vegetation zones

Catchment	Mean Elev.(m)	Elev. Zone	Vegetation Zone (%)		
Derek Wonze			Forest land	Agriculture land	Others
Mihal	2194.180045	Zone-1	0.0008	0.193	0.034
Amba	2635.233452	Zone-2	0.012	0.2039	0.047
Town	3047.821728	Zone-3	0.045	0.173	0.04
watershed	3486.24645	Zone-4	0.0224	0.217	0.03

Model Performance Evaluation the Nash-Sutcliffe efficiency (NSE) (Moriasi, Arnold et al. 2007), percent bias (PBIAS), and coefficient of determination (R2) are the objective functions that are used to evaluate the model's performance. An NSE is a normalized statistic that determines the magnitude of residual variance in comparison to observed flow variance. An NSE is a number between 0 and 1. NSE values of 0.6 - 0.8 are fair to good performance, while NSE values of more than 0.8 indicate good performance (Moriasi, Arnold et al. 2007). PBIAS is the relative difference between observed and simulated flows. PBIAS measures the tendency of the average simulated flow to be 10 times larger or smaller than the observed flow (Moriasi, Arnold et al. 2007). Positive values indicate model underestimation bias, while negative values indicate model overestimation bias. R2 is used to evaluate the goodness of fit of the relations. R2 examines the degree of linear association between the observed and simulated flows.

NSE =1− [∑ $(Oi{-}Pi)$2 /n i=1 ∑ $(Oi{-}\overline{Oi})$2 n i=1]

$BIAS$ = [∑ (Oi−Pi) x100 /n ∑ Oi

R2 = [∑ $(Oi{-}\overline{O})$ $(Pi{-}\overline{P})$ n /√∑ (Oi−O 2)]2√∑ (Pi−$\overline{P}$2) i=1 n i=1

Where Pi = simulated flow, oi = observed flow, Oi = the mean of observed data, P is predicted flow, the remaining variable is stated above and n is the total number of observations. The Nash Sutcliffe efficiency (NSE) (Moriasi, Arnold et al. 2007), indicates how well the model expresses the variance in the observations. It generally ranges from -∞ to 1. The optimum value is unity, and it shows a good explanation of the observed versus simulated data fits on a one-to-one line.

Table 2 General performance rating

Performance rating	NSE	PBIAS	R2
Very good	0.75 < NSE < 1	PBIAS < ±10%	0.75 < R2 < 1
Good	0.65 < NS < 0.75	±10% < PBIAS < ±15%	0.65 < R2 < 0.75
Satisfactory	0.5 < NS < 0.65	±15%< PBIAS < ±25%	0.5 < R2 < 0.65
Unsatisfactory	NS < 0.5	PBIAS > ±25%	R2 < 0.5

Source: (Moriasi, Arnold et al. 2007)

3.7. Secondary Data Sources

Key hydrological and meteorological data such as rainfall intensity, elevation, proximity to river, drainage patterns, and slope are obtained from reliable sources like ArcGIS 10.4 software and digital elevation models (DEMs). Remote sensing data is employed to analyze land-use changes, vegetation cover, and soil type data.

Table 3 Data types and sources used to map flood-prone areas

Data types	Data Sources	Use
STRM DEM Digital Elevation Model (20 m spatial resolution)	Obtained from https://search.asf.alaska.edu/	The DEM was input data for GIS to delineate watersheds, generate slope maps and elevation maps.
Digital Soil Map of the District (1:250,000 scale)	Ethiopian Ministry of Water, Irrigation, and Energy	Used to generate soil maps of Derek Wonze Mehal Amba Town watershed
Sentinel 2 10 m spatial resolution Land Use/Land Cover (LULC) Map (2021)	Downloaded from U.S Geologic Survey from https://earthexplorer.usgs.gov/	LULC data was used to determine the land use and land cover map of Derek Wonze Mehal Amba Town watershed.
Annually Rainfall Data (2006–2023)	National Meteorological Agency (NMA) of Ethiopia	By cokriging interpolating system Used to forecast Derek Wonze Mehal Amba Town watersheds rainfall patterns
River map of the study area with 15 arc-second resolution	Downloaded from the HydroSHEDS website https:// www. hydro sheds. org/	Used to generate river proximity maps of Derek Wonze Mehal Amba Town watershed

3.8. GIS and Remote Sensing Integration

Preprocessed datasets, including satellite imagery (Sentinel, Landsat) and DEMs (SRTM, ASTER), are integrated using GIS software like GIS. These tools facilitate the creation of thematic maps for criteria such as slope, rainfall, land-use, and drainage density, supporting spatial analysis and hazard zone classification. This multifaceted approach ensures the collection of both qualitative and quantitative data, enabling an accurate and holistic flood hazard assessment tailored to the study area. Factors that contribute flood hazard assessment

3.9. Factors that contribute MCDA

3.9.1. Slope factor

Flood hazard assessment relies on terrain slope as a key determinant of hydrological behavior and flood susceptibility. Slope defines the gradient or steepness of the land, affecting the velocity at which water moves across surfaces. In regions characterized by steep slopes, rainfall leads to rapid runoff, limiting infiltration time and amplifying flood risks and erosion potential (Tamer, Adego, & Abiyu, 2025). Conversely, gentle slopes facilitate water retention and infiltration, reducing surface runoff and mitigating flood hazards.

For example, studies of anti-dip rock slopes reveal that steeper gradients intensify surface and internal deformation, heightening flood hazards and destabilizing terrain structures (Zhao et al., 2025). In Ethiopia's highlands, the combination of steep slopes and intense rainfall frequently triggers flash floods and severe soil erosion, making slope analysis a critical component of flood risk assessments (Desta, Legesse, Ahmed, Muluneh, & Birhanu, 2024). Identifying high-risk zones based on slope characteristics enables the development of targeted mitigation strategies.

Geospatial tools such as Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) enhance the understanding and quantification of slope dynamics. These technologies support the creation of effective flood hazard maps, enabling researchers and policymakers to implement measures that safeguard vulnerable communities and ecosystems. By integrating slope analysis within broader flood risk assessments, decision-makers can strengthen resilience efforts and improve disaster preparedness strategies.

3.9.2. Elevation factor

Elevation gradients play a critical role in shaping the hydrological and geomorphological dynamics of the study area. Higher elevations, often marked by steep slopes, accelerate surface runoff during intense rainfall, reducing infiltration and increasing erosion and sediment transport. This rapid flow of water can overwhelm downstream floodplains, raising flood susceptibility. Additionally, elevation influences temperature variations and vegetation coverage, which affect soil stability and water absorption, further contributing to flood risks (Lv et al., 2024).

In Ethiopia, elevation differences are fundamental to the country's hydrological patterns. The rugged highlands serve as key sources of major river systems, with steep terrains channeling water rapidly to lower-lying areas. These regions generate substantial sediment loads that get transported downstream during storm events, reducing river channel capacity and worsening flood hazards. The interaction between elevation-driven processes and climatic factors underscores the need for effective flood mitigation strategies such as upstream sediment control and floodplain management (Tiwari et al., 2024).

Integrating elevation analysis into flood risk assessments allows for strategic planning and mitigation efforts. Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) provide detailed spatial analysis of elevation dynamics, enabling the identification of high-risk zones. These insights are vital for policymakers and researchers working to develop targeted interventions that enhance resilience in vulnerable areas. By applying geospatial techniques, communities can implement proactive flood management practices, minimizing risks and protecting infrastructure.

This comprehensive approach to elevation-driven flood hazard assessment supports sustainable water resource planning, helping mitigate extreme hydrological events.

3.9.3. Drainage Density factor

Drainage density, defined as the total length of streams and rivers per unit area within a drainage basin, plays a critical role in flood hazard assessment. A high drainage density indicates an extensive network of water channels that facilitates rapid runoff during heavy rainfall. This swift movement of water can overwhelm river systems, particularly in areas with steep slopes, leading to flash floods and increased flood risks. The efficiency of water conveyance in high drainage density areas often reduces infiltration, intensifying surface runoff and exacerbating flood impacts (Barrocu & Eslamian, 2022).

Conversely, regions with low drainage density tend to have lower surface runoff rates, allowing for greater water infiltration into the soil. This characteristic helps mitigate flood risks by reducing the volume and velocity of runoff. However, flood hazards are influenced by additional factors such as soil permeability, vegetation cover, and land use practices. Areas with impermeable surfaces, deforested landscapes, or extensive urbanization experience increased flood susceptibility, regardless of their drainage density levels (Odoh & Nwokeabia, 2024).

In mountainous regions, such as the Himalayas, the interaction between high drainage density and steep topography significantly elevates the risk of flash floods. The rapid movement of water combined with intense sediment transport can further compromise river channels, reducing their capacity to contain floodwaters. Research highlights the role of sediment deposition in amplifying flood hazards, particularly in regions where high drainage density accelerates erosion and sediment displacement (Hamidifar, Nones, & Rowinski, 2024).

A comprehensive flood management strategy must account for drainage density alongside other geomorphological and climatic factors. Utilizing Geographic Information Systems (GIS) and hydrological modeling techniques allows researchers to analyze drainage networks and their impact on flood hazards. By integrating drainage density data with slope gradients, soil permeability, and land use patterns, planners can develop accurate flood susceptibility maps that support targeted mitigation measures.

Understanding the implications of drainage density in flood hazard assessment is essential for proactive flood risk management. By incorporating this factor into broader hydrological studies, decision-makers can refine strategies for flood mitigation, erosion control, and sustainable watershed management. Adopting an integrated approach that considers drainage density within regional hydrological frameworks ensures a more effective response to flood hazards, reducing vulnerabilities and safeguarding communities from extreme weather events.

3.9.4. River Proximity factor

Proximity to rivers is a crucial factor in flood hazard assessment, as areas near watercourses are inherently more susceptible to inundation. The risk of flooding increases significantly in regions where riverbanks are prone to overflow, particularly during peak rainfall or seasonal flooding events. The severity of these floods is often intensified by sediment accumulation or narrowing of river channels, which reduces carrying capacity and leads to widespread inundation (Juan-Diego et al., 2025).

Beyond direct flooding, proximity to rivers also influences groundwater dynamics, which further affects flood risks. Communities located near rivers often experience elevated water tables, causing soil saturation that limits its ability to absorb additional rainfall. As a result, excess surface runoff contributes to flood hazards, particularly in areas subject to intense seasonal precipitation (Knighton et al., 2021). Moreover, floodwaters tend to remain in river-adjacent areas for extended periods, delaying drainage and prolonging recovery efforts.

To effectively manage flood risks associated with river proximity, it is essential to analyze how these hazards interact with topography, soil types, and land use practices. In urbanized areas, impervious surfaces limit infiltration, exacerbating flood susceptibility. Similarly, deforested regions lack vegetation that would otherwise slow water movement and improve absorption, increasing the likelihood of severe flooding. Understanding these factors enables planners to develop tailored flood mitigation strategies that address the distinct challenges of riverine environments (Su et al., 2024).

Integrated flood management approaches must incorporate both technical and social strategies. Geographic Information Systems (GIS) and hydrological modeling provide valuable insights into flood-prone areas, allowing researchers to refine hazard assessments. Additionally, implementing nature-based solutions such as wetland restoration and riparian buffer zones can improve water retention and reduce flood impacts.

By considering proximity to rivers alongside geomorphic and climatic variables, policymakers and urban planners can formulate targeted strategies to mitigate flood risks and enhance resilience in vulnerable communities. This approach ensures that flood hazard assessments are comprehensive, data-driven, and adaptable to evolving environmental conditions.

3.9.5. Rainfall factor

Rainfall is a key driver of flood hazards, influencing critical hydrological processes such as runoff generation, soil saturation, and water channel overflow. Intense rainfall events often exceed the soil's infiltration capacity, leading to excessive surface runoff that overwhelms natural drainage systems and causes flooding. The impact of rainfall on flood susceptibility is particularly pronounced in regions with steep terrain or compacted soils, where water absorption is limited, resulting in rapid runoff and increased flood risks (Qiu et al., 2024).

The watershed under study is shaped by its geographic and climatic conditions, which include seasonal patterns of heavy precipitation. During peak rainfall periods, rapid water flow contributes to sediment transport, gradually reducing river channel capacity and increasing flood vulnerability. The interaction between rainfall intensity, landscape features, and soil composition highlights the complex nature of flood hazards, emphasizing the need for advanced flood risk assessments (Rupngam & Messiga, 2024).

To enhance flood risk management, modern spatial analysis tools such as ArcGIS have been employed to map rainfall distribution and identify flood-prone areas. These analytical techniques rely on meteorological station data and remote sensing technology to offer precise insights into how variations in rainfall patterns influence hydrological vulnerabilities across different zones. By integrating GIS-based methodologies, planners can pinpoint high-risk areas and develop targeted flood mitigation strategies (Alshaikh et al., 2023).

The ability to predict flood-prone zones based on rainfall intensity plays a crucial role in developing effective disaster preparedness plans. Infrastructure improvements, such as enhanced drainage systems and flood-resistant construction, can mitigate the adverse effects of extreme precipitation events. Furthermore, land use planning strategies, including afforestation and soil conservation techniques, help to regulate water absorption and reduce runoff.

A data-driven approach to flood hazard assessment enables the implementation of proactive strategies that strengthen resilience in flood-prone areas. By combining meteorological insights with spatial analysis and hydrological modeling, researchers and policymakers can formulate informed flood risk management policies that address immediate threats while promoting long-term environmental sustainability. Understanding rainfall-induced flooding mechanisms ensures better preparedness and supports the development of adaptive solutions for vulnerable communities.

By leveraging technology and scientific analysis, flood-prone areas can transition toward sustainable water management practices that minimize risks associated with extreme rainfall.

3.9.6. Soil Type factor

Soil type is a fundamental factor in flood susceptibility, as its physical properties—such as permeability, water-holding capacity, and infiltration rate—directly influence runoff patterns during rainfall events. Highly permeable soils, such as sandy soils, facilitate drainage, reducing surface water accumulation and minimizing flood risks. In contrast, clay-rich soils exhibit low permeability, limiting infiltration and resulting in greater surface runoff, which increases vulnerability to flooding during heavy precipitation events (Shah & Ai, 2024).

Soil erosion effects are intensified by human activities such as agriculture, which compromise soil stability and heighten flood risks. Conversely, sandy soils offer better infiltration, mitigating immediate runoff but posing erosion challenges during prolonged rainfall. This erosion leads to sediment transport into rivers, diminishing channel capacity and exacerbating downstream flood hazards (Dey & Pan, 2025).

Spatial variability in soil composition across the watershed significantly influences localized flood risks. Erosion-prone soils, particularly those found on steep slopes, contribute sediment to waterways, reducing river capacity and impeding natural drainage. The accumulation of sediment increases flood severity in downstream areas, underscoring the necessity of integrating soil type analysis into flood risk mapping to identify high-risk zones and prioritize mitigation efforts (Agrawal et al., 2024).

Effective flood management strategies must account for soil-driven vulnerabilities by promoting sustainable practices such as erosion control, reforestation, and soil stabilization techniques. Employing advanced geospatial tools, including Geographic Information Systems (GIS) and remote sensing technology, allows researchers and planners to refine flood hazard assessments and develop targeted interventions. These approaches ensure long-term resilience by addressing the interplay between soil properties, land use practices, and hydrological dynamics.

By incorporating soil analysis into flood prevention frameworks, policymakers can design comprehensive strategies that enhance watershed management and reduce flood vulnerability. Understanding the complex interactions between soil type and hydrological processes strengthens the ability to mitigate flood hazards effectively.

3.9.7. Land Use Factors

The upper Awash River Basin exhibits a complex interplay between land use practices and hydrological dynamics, directly influencing flood risks. Agricultural expansion, urbanization, and deforestation have significantly altered the natural balance of water flow and soil stability, exacerbating runoff and erosion. Farming intensification has led to soil compaction and reduced infiltration rates, making the land less capable of absorbing rainfall. Similarly, urban expansion has introduced impervious surfaces, accelerating surface water flow into river channels during storms and increasing flood susceptibility in regions with minimal vegetation cover (Tang et al., 2024).

Deforestation further compounds these challenges by removing tree cover that would typically absorb rainfall and stabilize the soil. Without vegetation, water moves swiftly across the terrain, eroding topsoil and carrying sediment into nearby rivers. The accumulation of sediment reduces the carrying capacity of water channels, leading to downstream bottlenecks that intensify flooding during peak rainfall events (Hamidifar et al., 2024). These effects underscore the need for land management practices that promote soil retention and hydrological stability.

Urbanization has fundamentally reshaped the basin's hydrological dynamics. Concrete and asphalt surfaces prevent water absorption, increasing runoff rates and contributing to localized flooding. The expansion of urban settlements without sustainable planning intensifies these effects, leaving communities vulnerable to extreme rainfall events. To mitigate such risks, cities within the basin must integrate green infrastructure, such as permeable pavements, rain gardens, and urban forests, to enhance natural drainage systems.

Addressing flood vulnerability requires an integrated approach to land management. Implementing reforestation programs, erosion control measures, and sustainable agricultural practices can restore the watershed's natural ability to manage water flow. Reforestation enhances soil permeability, reducing runoff while stabilizing erosion-prone regions. Additionally, sustainable agricultural practices, including contour farming and mulching, improve soil retention and decrease surface runoff, helping to mitigate flood risks.

Understanding the interaction between land use, soil properties, and flood hazards is essential for developing effective management strategies. Future planning efforts should incorporate geospatial analysis tools like GIS to map high-risk zones, allowing targeted interventions that enhance resilience. By adopting a holistic land management approach, the upper Awash River Basin can improve flood mitigation, protect vulnerable communities, and promote long-term environmental sustainability.

4. RESULT AND DISCUSSION

4.1. Data Quality Check

4.1.1. Outlier Test

This is calculating the maximum and range of cumulative deviations from the mean and testing outliers of a time-series data at the stations for rainfall and streamflow listed in Outlier tests for the kombolcha station are shown in Figure 3 below.

1. Data consistency checking

Standard error of mean	$\delta_n = \frac{\delta_{n-1}}{\sqrt{N}}$	4.393	
Relative standard	$\delta_n = \frac{\delta_n}{X_n}$	9.708	< 10%, There for the data could be regarded as Reliable and Adequate.

2. Chexk for outliers

2.1 Test for higher outlier

$$Y_H = Y_{mean} + K_n * \sigma_y$$

YH =	2.120	
Depth = 10^{YH}	131.77	85.10 Ok!

2.2 Test for lower outlier

$$Y_L = Y_{mean} - K_n * \sigma_y$$

YL =	1.109	
Depth=10^{YH}	12.85	15.00 Ok!

Therefore, the data is within the higher and lower outliers.

Figure 3 Outlier test for kombolcha station

The lowest recorded rainfall at kombolcha rainfall station was 15 mm in 2017 (shown in Figure 3), which is higher than the boundary of lower outliers. Hence, the rainfall data recorded to lower outliers is within a reasonable range. There are no lower outliers in this sample data. The highest recorded rainfall data at kombolcha rainfall station was 85.1 mm in 2014, which is lower than the boundary value of higher outliers. Hence, there is no higher outlier data recorded.

4.1.2. Homogeneity Test

The homogeneity of a time series data was tested at the four stations and the streamflow listed, it is shown in figure 4 by evaluating the maximum and range of 48 cumulative deviations from the mean. For example, the homogeneity test of annual precipitation at mersa station was described next respectively. The homogeneity plot and statistics menu of mersa station annual rainfall is shown in Figure 4.

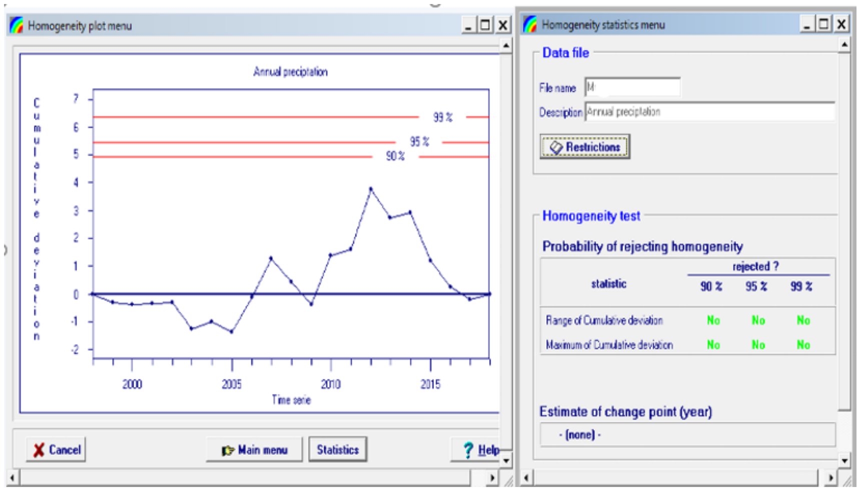

Figure 4 Homogeneity plot and statistics menu of annual rainfall (Mersa station)

4.2. HBV-light Model Sensitivity Analysis, Calibration, and Validation

4.2.1. Sensitivity Analysis

Manual sensitivity analysis was performed by changing the value of one model parameter at a time while keeping the others constant. That is, the value of each model parameter was increased and decreased by 10% increments up to 50%, with steep slopes considered the most sensitive and moderate-to-gentle slopes considered the less sensitive. Each of the model parameters helps to conceptualize runoff processes, which results in the hydrograph being simulated. As a result, if one of the model parameters is changed, the hydrograph will change. However, not every parameter contributes the same amount of change to the hydrograph. The sensitivity analysis for the Derek Wonze Mehal Amba Town watershed is shown in Figure 5

Table 4 Sensitivity analysis of HBV model parameters values (1999-2018)

percent	LP	BETA	PERC	UZL	MAXBASE
50%	0.685	0.676	0.6904	0.69	0.684
40%	0.6866	0.682	0.6904	0.69	0.686
30%	0.688	0.685	0.6904	0.69	0.6874
20%	0.6889	0.687	0.6904	0.69	0.6888
10%	0.69	0.689	0.6904	0.69	0.69
0%	0.6904	0.69	0.6904	0.69	0.6904
-10%	0.6897	0.69	0.6904	0.69	0.69
-20%	0.689	0.689	0.6903	0.69	0.6899
-30%	0.6875	0.688	0.6903	0.69	0.6889
-40%	0.6851	0.686	0.6902	0.69	0.687
-50%	0.6815	0.683	0.6901	0.69	0.685

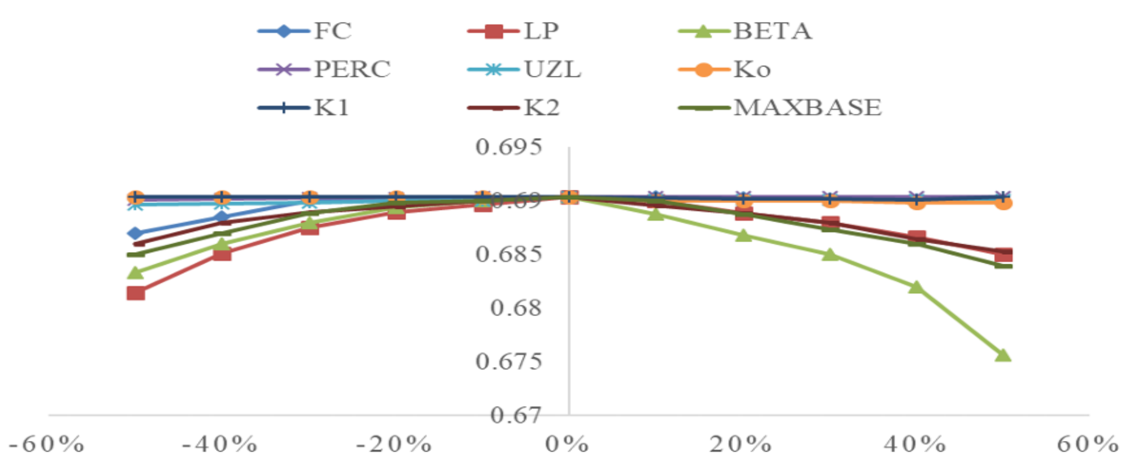

Figure 5 Graphically sensitivity analysis of HBV-light model parameters

In terms of the R2 value, BETA, and LP are the most sensitive parameters among the model parameters, demonstrating nonlinear model performance for these parameters. MAXBAS, PERC, and FC have relatively high sensitivity to model performance as well as nonlinear behavior. UZL, are more sensitive parameters that have a smaller effect on model performance. Appendix (6,7,8)

4.2.2. HBV-light Model Calibration

Based on existing watershed characteristics, manual calibration was achieved by optimizing the parameters of various HBV light hydrologic model routines. For both model calibration and validation, 20 years (1999–2018) were used. The first year of data (1999) was used to warm up the model before moving on to the 19 years of data, in which 2/3 (2000–2012) was used for model calibration and the remaining 1/3 (2013–2018) was used for model validation for the Derek Wonze Mehal Amba Town watershed. As a result, the model was run several times to obtain the corresponding observed and simulated discharge values. As a result, the model was run multiple times to obtain the observed and simulated discharge values. For the Monte Carlo runs of the model, parameter optimization was done by using the lower and upper ranges to get an optimum value excluding the snow routine, which was left out due to the absence of snow in the river catchments. Daily observed Vs simulated streamflow discharge for calibration is shown in Figure 6.

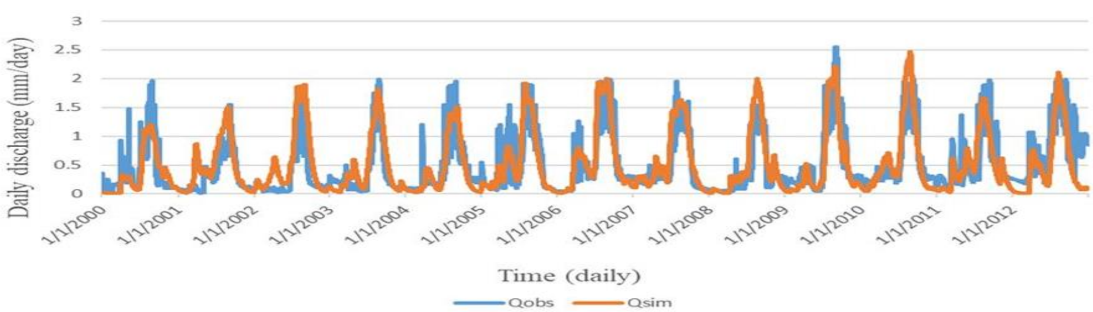

Figure 6 Daily observed Vs simulated discharge streamflow using HBV light model for calibration period.

After running 300,000 Monte Carlos, the calibrated parameter value as a constant, the results of Nash Sutcliff efficiency (NSE), coefficient of determination (R2) and percent of bias (PBIAS) were 0.644, 0.709, and 1.361% respectively.

4.2.3. HBV-light Model Validation

The streamflow was also successfully validated by the HBV light model for an independent period (2013-2018). The validation results are: R2 (0.76), percent bias (PBIAS) (5.275%), and NSE (0.6963). Generally, the model performance was better during the validation period than during the calibration period. The relationship between observed and simulated discharge for the validation period is shown in the Figure 7.

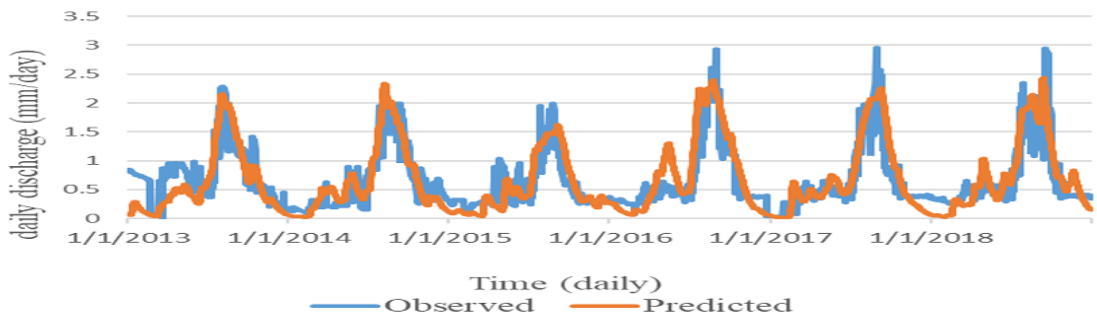

Figure 7 Daily observed and simulated streamflow using HBV light model for the validation period

Table 5 Model performance evaluation for calibration and validation on a daily time basis for the Derek Wonze Mehal Amba Town watershed.

Period	Model Performance Measures		
	R2	NSE	PBIAS (%)
Calibration	0.709	0.644	1.361
Validation	0.76	0.6963	5.275

4.3. Analyzing spatial and environmental data s

4.3.1. Slope as a Determinant of Flood Hazards

The slope of a landscape is a fundamental factor in determining its hydrological behavior and flood vulnerability. Steeper slopes promote rapid runoff, reducing water infiltration and increasing flood risks. This rapid runoff exacerbates flash flooding and accelerates soil erosion, leading to significant sediment deposition in downstream regions (Desta, Legesse, Ahmed, Muluneh, & Birhanu, 2024). Conversely, gentler slopes slow water movement, facilitating greater infiltration and reducing surface runoff, thereby minimizing flood hazards.

In Ethiopia’s highlands, the convergence of steep terrain and heavy rainfall creates conditions conducive to severe flood events. Water moves swiftly across steep gradients, funneling into rivers and streams at accelerated rates, frequently exceeding their capacities and resulting in destructive floods (Al-Kindi & Alabri, 2024). Additionally, land degradation driven by these hydrological dynamics further amplifies flood vulnerability, heightening the need for strategic mitigation measures.

Given the critical role of slope in flood susceptibility, analyzing its impact through advanced geospatial techniques is essential. Tools such as Geographic Information Systems (GIS) and Digital Elevation Models (DEMs) enable detailed slope assessments, facilitating the identification of high-risk zones. This geospatial analysis forms the foundation for effective flood hazard mapping, supporting informed decision-making for mitigation strategies and community protection.

By integrating slope analysis within flood risk assessments, planners and policymakers can develop targeted approaches to reducing flood-related damage and enhancing resilience in vulnerable regions

4.3.1.1. Slope Characteristics in the study area Watershed and Ethiopian Context

Slope is a fundamental factor influencing hydrological processes in the study area watershed, shaping water movement, runoff patterns, and erosion dynamics. Steeper slopes accelerate surface runoff, limiting infiltration capacity and increasing sediment transport, which amplifies flood risks, particularly in areas with sparse vegetation or compacted soils (Abdela, Shiferaw, Abdulsemed, & Seid, 2025).

By utilizing Geographic Information Systems (GIS) and Digital Elevation Models (DEMs), slope variations with precision, allowing for the identification of high-risk zones and informed flood hazard mapping. These geospatial tools enable planners to develop targeted interventions that enhance watershed management and strengthen community resilience against flooding.

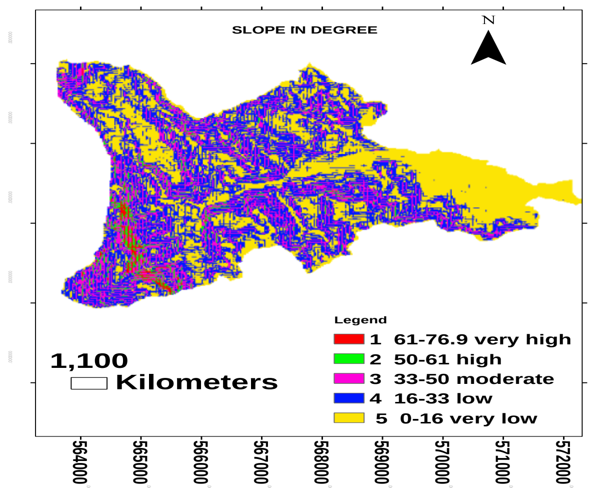

Figure 8 Slope map of the study area

Table 6 slope description table

Slope Ranges in degree	FHI
61° - 76.9°	very high
50° - 61°	high
33° - 50°	moderate
16° - 33°	low
0° - 16°	very low

The study by Ahmed et al. (2024) explores flood hazard zonation using a GIS-based multi-parametric Analytical Hierarchy Process (AHP).

4.3.2. Impact of Elevation on Soil Stability, Erosion, and Flood Risk

Elevation plays a fundamental role in influencing soil stability, erosion dynamics, and flood susceptibility within a watershed. Higher-altitude regions, typically marked by steep slopes, experience rapid surface runoff during intense rainfall, which reduces soil moisture retention and heightens vulnerability to erosion. This accelerated water movement strips away topsoil, leading to long-term land degradation. As soil stability diminishes in elevated zones, sediment is transported downstream, decreasing river capacity and exacerbating flood risks in lower-lying areas (Areu-Rangel, Hernández-Hernández, & Bonasia, 2024).

Additionally, elevation-driven variations create distinct microenvironments that impact vegetation cover and soil cohesion. Areas with dense vegetation help mitigate these effects by enhancing soil integrity and reducing runoff intensity. Conversely, regions with sparse vegetation struggle to retain soil structure, making them more susceptible to erosion and exacerbating the effects of extreme weather events (Hu et al., 2023).

Geospatial tools, including Geographic Information Systems (GIS) and Digital Elevation Models (DEMs), provide crucial insights for analyzing elevation patterns. By leveraging these technologies.

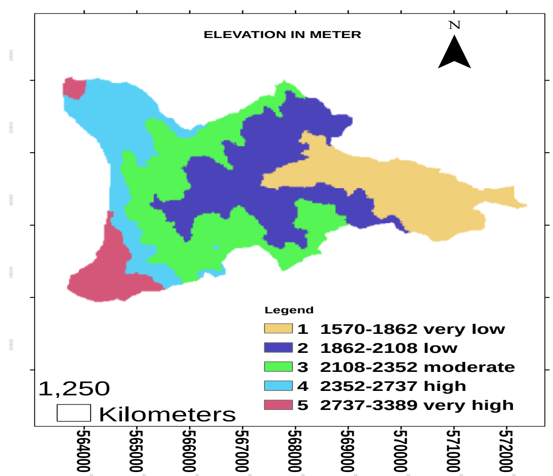

Figure 9 elevation map

Table 7 elevation table

Elevation in m	FHI
1570 - 1862	very low
1862 - 2108	low
2108 - 2352	moderate
2352 - 2737	high
2737 - 3389	very high

The study by Jamali et al. (2023) explores path selection using topographic analysis, comparing vector re-classification and raster fuzzification as spatial multi-criteria approaches within cost-path analysis.

4.3.3. The Interaction of Drainage Density with Other Factors

Drainage density interacts with various environmental factors, influencing flood risks and hydrological behavior. One of the most significant variables affecting drainage density is soil type. In regions with low-permeability soils, such as clay-rich areas, high drainage density intensifies surface runoff since water is unable to infiltrate effectively. This leads to excessive water flow and heightened flood hazards. Conversely, in high-permeability soils like sandy terrains, increased infiltration moderate's runoff, reducing flood risks (Chapman, 2023).

Topography further influences drainage density's role in flood dynamics. Steep slopes combined with high drainage density facilitate rapid water conveyance, increasing the probability of flash floods. In contrast, flatter terrains enable slower water movement, promoting absorption and reducing flood hazards (Xu et al., 2023).

Understanding these interactions is vital for effective flood risk management. By integrating drainage density analysis with soil properties, vegetation cover, and topographic data, researchers can create comprehensive flood hazard maps.

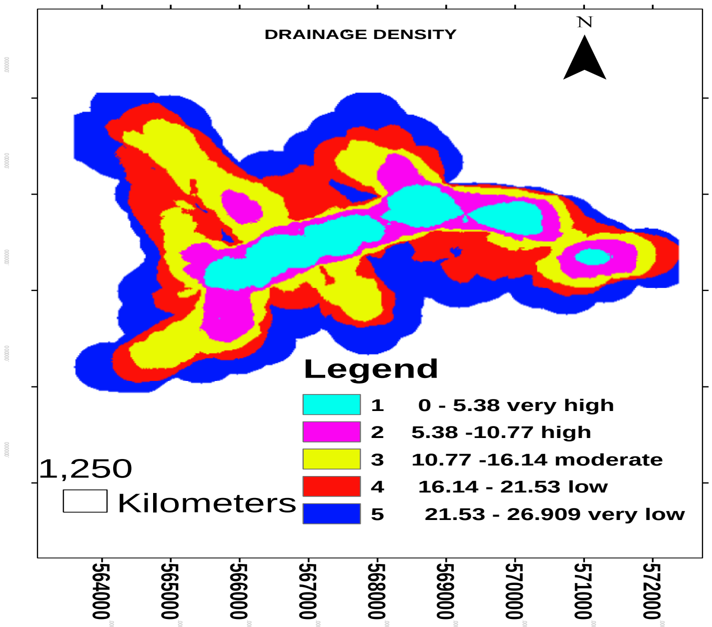

Figure 10 Drainage density map

Table 8 drainage density table

Ranges in m/sq.km	FHI
0 - 5.38	very high
5.38 - 10.77	high
10.77 - 16.14	moderate
16.14 - 21.53	low
21.53 - 26.909	very low

The study by Odoh and Nwokeabia (2024) examines the impact of drainage density and geological factors on flood risk in Abia State.

4.3.4. Impact of River Proximity on Flood Hazard

Proximity to river systems plays a fundamental role in determining flood vulnerability, as areas situated near watercourses are at a higher risk of inundation. The severity of flooding in riverine regions often intensifies during peak discharge events caused by heavy rainfall or rapid snowmelt. These risks are further amplified in areas where river channels are constricted due to sediment deposition or inadequate drainage capacity, making nearby communities more susceptible to flooding (Roy, 2023).

In addition to direct flooding, proximity to rivers influences groundwater dynamics, further exacerbating flood hazards. River-adjacent areas often experience elevated water tables, reducing the soil's ability to absorb excess rainfall. This saturated ground leads to increased surface runoff and accelerates water movement during storm events, heightening localized flood risks (Wang et al., 2025). The prolonged retention of floodwaters in river-adjacent zones also slows the natural drainage process, leading to extended recovery times and compounding the economic and environmental consequences of flooding.

Urbanization and land use changes further shape flood vulnerability in riverine regions. In cities near rivers, impervious surfaces such as roads and buildings limit infiltration, increasing runoff and worsening flood impacts. Similarly, deforestation along riverbanks removes natural barriers that would otherwise slow water movement and enhance absorption, leading to intensified flood severity in affected areas (Hossain, Sarker, & Sohel, 2025).

4.3.5. River Proximity, and Flood Vulnerability

Proximity to river systems plays a significant role in flood vulnerability, as areas situated near rivers are exposed to heightened risks of inundation, particularly during periods of intense rainfall or seasonal surges. Flood severity in these regions is often exacerbated by river overflow, which can result from excessive discharge, sediment accumulation, or narrowing of channels. Such conditions reduce the river's carrying capacity, leading to widespread inundation and prolonged flood events (Gao et al., 2023).

In addition to direct flooding, communities near rivers face hydrological challenges linked to elevated groundwater levels. These areas often experience saturated soils, which limit infiltration capacity and increase surface runoff. When soil permeability is low, as in clay-rich terrains, water movement accelerates, exacerbating localized flood hazards. The combined effects of river proximity and reduced infiltration make adjacent areas more susceptible to rapid and extreme flooding (Mandal et al., 2024).

Floodwaters in riverine zones tend to linger longer than in other regions due to slower drainage processes. Extended periods of inundation hinder recovery efforts, increasing economic and environmental impacts. The prolonged presence of floodwaters can lead to infrastructure damage, agricultural losses, and disruptions to local communities (Padhiary, 2025).

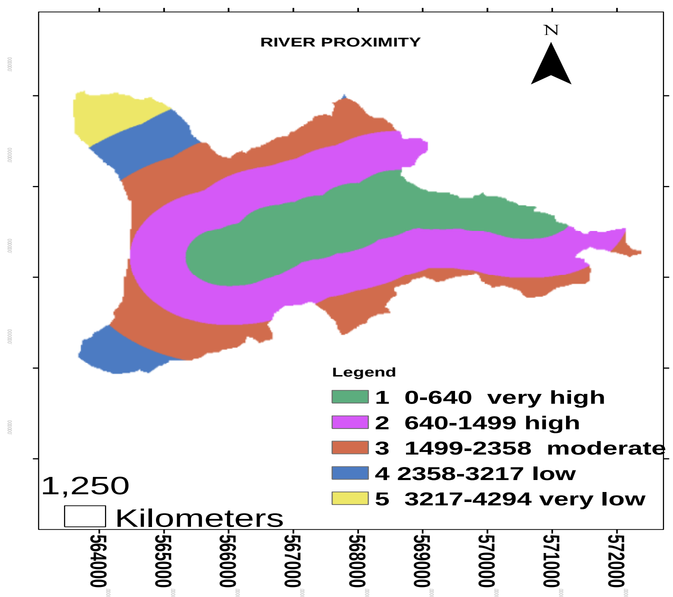

Figure 11 River proximity map

Table 9 River proximity table

River proximity in m	FHI
10 - 640	very high
2640 - 1499	high
31499 - 2358	moderate
42358 - 3217	low
53217 - 4294	very low

The study by Anees (2024) explores the role of remote sensing and GIS applications in river-related research, emphasizing their significance in watershed management and hydrogeological analysis.

4.3.6. Rainfall and Flooding

Rainfall is a fundamental driver of flood hazards, initiating processes such as surface runoff, soil saturation, and groundwater recharge. Intense rainfall events can overwhelm the soil's ability to absorb water, leading to excessive runoff and flash flooding. This phenomenon is particularly severe in urbanized areas or regions with low-permeability soils, where water infiltration is limited. The inability of the ground to absorb water exacerbates flood intensity and duration, increasing vulnerability in affected zones (Marino, 2024).

Beyond surface runoff, heavy precipitation also alters subsurface hydrology by raising groundwater levels and destabilizing soil structures. When combined with steep slopes or degraded soils, rainfall-induced erosion accelerates sediment transport, reducing the capacity of waterways to manage excess flows. This sedimentation further heightens downstream flood risks, illustrating the cascading effects of extreme rainfall on hydrological systems (Hamidifar, Nones, & Rowinski, 2024).

4.3.6.1. Rainfall Patterns and Flood Hazard Dynamics

Ethiopia's climatic patterns are shaped by two distinct rainy seasons Kiremt (long rainy season) and Belg (short rainy season)—which play a pivotal role in determining hydrological behavior and flood susceptibility. The Kiremt season, occurring between June and September, delivers the majority of the country's annual rainfall, often resulting in widespread flooding due to sustained precipitation. The Belg season, which spans from February to May, provides less intense rainfall but still contributes to localized flood risks, particularly in areas with poor drainage or vulnerable soil conditions (Tradowsky et al., 2023).

Regions with steep slopes and limited vegetation cover experience heightened flood vulnerability during these rainy seasons. Intense precipitation triggers rapid surface runoff, reducing infiltration capacity and accelerating erosion processes. In semi-arid and mountainous terrains, water absorption is often restricted by compacted soils, leading to flash floods and significant sediment transport. As sediment accumulates in river channels, their capacity to contain floodwaters diminishes, increasing downstream flood risks during peak rainfall periods (Hamidifar, Nones, & Rowinski, 2024).

In addition to seasonal rainfall patterns, broader climatic variability influences Ethiopia's flood risks. Large-scale atmospheric phenomena such as El Niño and the Indian Ocean Dipole disrupt expected precipitation levels, intensifying extreme weather events. These fluctuations contribute to periods of excessive rainfall or prolonged drought, complicating flood management efforts and exacerbating risks in regions with fragile infrastructure and inadequate land management strategies (Balgah et al., 2023).

To address these challenges, integrating climate and hydrological data into flood hazard assessments is essential. Geographic Information Systems (GIS) and advanced spatial modeling tools enable to analyze rainfall distributions and pinpoint high-risk flood zones. These technologies provide valuable insights into hydrological vulnerability, helping planners develop targeted interventions such as improved drainage systems, erosion control measures, and floodplain restoration projects.

4.3.6.2. Rainfall Characteristics in the study area

Derek Wonze Mehal Amba Town watershed experiences distinct rainfall patterns that significantly shape its hydrological behavior. Seasonal variability in precipitation plays a crucial role in influencing surface runoff, infiltration rates, and overall water flow dynamics within the Derek Wonze Mehal Amba Town watershed. Most of the annual rainfall occurs in concentrated rainy periods, leading to pronounced hydrological responses that affect flood risks. Extreme rainfall events, recorded sporadically in recent years, pose additional challenges by overwhelming natural drainage systems and triggering flash floods (Yin et al., 2023).

Rainfall intensity, combined with the region's topographic features, further amplifies its hydrological susceptibility. Steep slopes in the watershed accelerate runoff, reducing the soil's ability to absorb water. This interaction between intense rainfall and terrain structure leads to significant sediment transport, increasing channel sedimentation and heightening flood vulnerability in downstream areas. Erosion-driven sediment displacement can obstruct river channels, reducing their capacity to manage excess water flow effectively (Hamidifar, Nones, & Rowinski, 2024).

4.3.6.3. Rainfall-Related Soil Saturation and Runoff in Flood Formation

Rainfall intensity and duration significantly influence flood susceptibility by determining soil saturation levels and runoff dynamics. When precipitation exceeds the soil's infiltration capacity, saturation occurs, leading to excessive surface runoff. In regions with low-permeability soils or degraded land, water accumulates rapidly rather than being absorbed into the ground, increasing the likelihood of flooding. The inability of the soil to retain water exacerbates flood risks, especially in urbanized areas with impervious surfaces that further limit infiltration (Adão, Pádua, & Sousa, 2025).

Runoff behavior is closely linked to vegetation cover, soil composition, and topography. In steep-sloped landscapes with sparse vegetation, rainfall accelerates erosion, stripping away topsoil and increasing sediment transport. These displaced sediments settle in waterways, obstructing channels and reducing their capacity to manage excess water flow, thereby amplifying downstream flood risks. The interaction of sediment transport and intense precipitation highlights the cascading impact of erosion on hydrological systems (Zhang et al., 2023).

Prolonged or intense rainfall further compounds soil erosion, which weakens land stability and intensifies sediment deposition in rivers. These sediment loads diminish river carrying capacity, heightening flood risks for nearby communities. In degraded landscapes with limited ground cover, runoff accelerates erosion, worsening the effects of extreme precipitation events. The absence of adequate soil protection intensifies flood hazards by increasing water velocity and reducing absorption potential (Kumar et al., 2023).

4.3.6.4. Interpolating Rainfall Data by Cokriging method

Cokriging enhances kriging by incorporating secondary correlated variables (e.g., elevation, temperature, humidity) to improve predictions. It is useful when the primary variable (rainfall) is sparsely distributed, but secondary variables are more widely available.

Identifying Secondary Variables Select complementary variables that correlate with rainfall (e.g., altitude affects precipitation patterns). For practical applications, various GIS and geostatistical tools support kriging and cokriging: GIS (Geostatistical Analyst Tool) Establish the spatial relationships between the primary and secondary variables. For practical applications, various GIS and geostatistical tools support kriging and cokriging.

The cokriging equation is an extension of the kriging equation that incorporates secondary variables to improve spatial predictions. It is formulated as:

$$Z^{*}(u)=\sum_{i=1}^{n}\lambda_i Z(u_i) +\sum_{j=1}^{m}\mu_j Y(u_j)$$

Where:

- ($Z^*(u)$ is the estimated value at location (u).

- ($Z(u_i)$ represents the primary variable at known locations.

-($Y(u_j)$ represents the secondary variable at known locations.

- (lambda i) and (mu j) are the weights assigned to the primary and secondary variables, respectively.

- (n) and (m) are the number of known data points for the primary and secondary variables. See appendix (1)

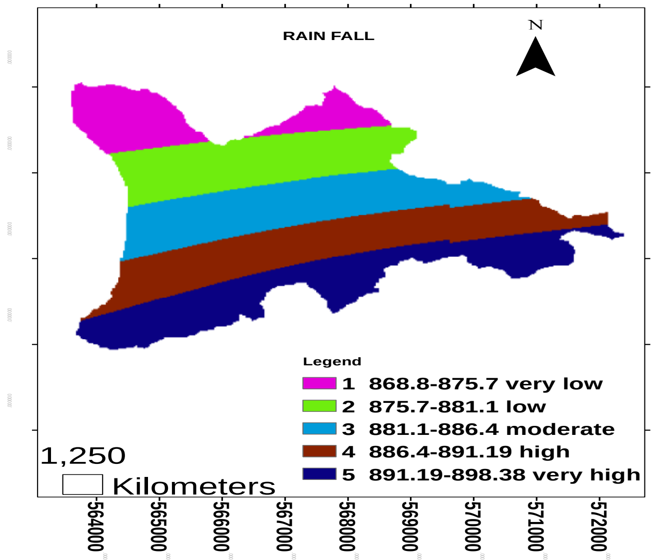

Figure 12 Rainfall distribution figure

Table 10 rain fall table

Annual average Rain fall in mm	FHI
868.8-875.7	very low
875.7-881.1	low
881.1-886.4	moderate
886.4-891.19	high
891.19-898.38	very high

The study by Anees (2024) explores the role of remote sensing and GIS applications in river-related research, emphasizing their significance in watershed management and hydrogeological analysis.

4.3.7. Soil Type and Flood Hazard Dynamics

Soil properties play a crucial role in flood hazard assessment, as they directly impact water absorption, retention, and runoff behavior. Key characteristics such as infiltration rate, porosity, permeability, and water-holding capacity determine how soil interacts with rainfall, influencing hydrological responses during intense precipitation events. Sandy soils, which have high permeability, facilitate rapid drainage and minimize surface runoff, reducing flood risks. In contrast, clay-rich soils exhibit low permeability, restricting infiltration and increasing runoff accumulation, making these areas more susceptible to flooding during heavy rainfall (Idoko, Ibuot, & Ekpa, 2025).

Runoff generation is strongly influenced by soil texture, structure, and land conditions. Compacted or eroded soils tend to have reduced infiltration capacities, causing water to accumulate and flow across the surface instead of being absorbed into the ground. In areas with sloped terrain, this rapid runoff intensifies erosion, leading to sediment displacement and deposition in river channels. As sediment accumulates in water systems, channel capacity declines, heightening downstream flood risks. These sedimentation processes create long-term hydrological challenges that exacerbate flood hazards in vulnerable regions (Hamidifar, Nones, & Rowinski, 2024).

Soil erosion also plays a significant role in flood severity, as displaced sediments obstruct waterways and limit natural drainage. In areas where soil stability is compromised due to deforestation or land degradation, erosion accelerates sediment transport, further restricting river capacity. Implementing erosion control techniques, such as reforestation, terracing, and soil conservation strategies, can help stabilize landscapes and mitigate flood vulnerability (Teku & Derbib, 2025).

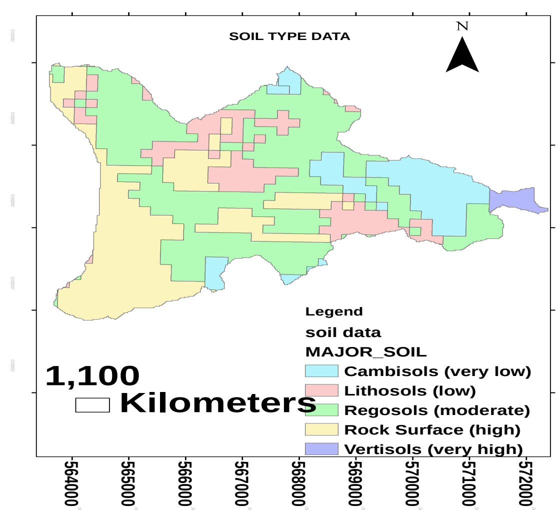

Figure 13 Soil textural class map

4.3.8. Land Use Changes and Their Impact on Flood Hazards

Land use transformations, driven by population growth, agricultural intensification, and urban expansion, significantly alter hydrological dynamics and magnify flood hazards within the study area. The conversion of natural landscapes into agricultural fields often leads to soil compaction and erosion, reducing water infiltration and increasing surface runoff. These effects are especially pronounced in clay-rich soil regions, where limited water retention exacerbates flood susceptibility (Sutormin et al., 2024).

Urbanization especially Derek Wonze Mehal Amba Town watershed further intensifies flood risks by introducing impervious surfaces such as roads, buildings, and parking lots, which prevent water absorption and accelerate runoff during rainfall events. The rapid movement of water overwhelms existing drainage systems, increasing the frequency and severity of urban flooding. Additionally, vegetation displacement due to expanding infrastructure diminishes the land's ability to regulate water movement, creating flash flood conditions in vulnerable communities (Othman et al., 2023).

Deforestation, another major driver of land use change, exacerbates flood vulnerability by removing tree cover essential for soil stabilization and water infiltration. The absence of vegetation accelerates erosion, increasing sediment transport into river systems and reducing the channel capacity needed to manage excess water during peak rainfall events. This sedimentation leads to downstream bottlenecks that further heighten flood risks.

Deforestation and Vegetation Cover Loss: Deforestation in the study area has significantly altered hydrological dynamics by diminishing vegetation cover, which serves as a vital buffer in regulating water movement and stabilizing soil. Trees and vegetation play a crucial role in intercepting rainfall, slowing its flow, and facilitating infiltration into the soil. Their removal disrupts these processes, increasing both the volume and velocity of surface runoff during heavy precipitation events, thereby intensifying flood risks (Wang et al., 2025).

The absence of tree cover further impacts soil moisture retention, making the ground more susceptible to erosion and compaction. In regions where deforestation has eliminated this protective layer, exposed soils degrade rapidly, accelerating runoff and increasing flood vulnerability. Additionally, heightened sediment transport into river systems reduces their capacity to accommodate excess water, creating downstream bottlenecks that amplify flood hazards (Hamidifar et al., 2024). This sedimentation process not only reduces water storage capacity but also exacerbates the risk of flash floods in adjacent communities.

Riparian zones, which depend on vegetation for soil stabilization, are particularly affected by deforestation. Vegetation along riverbanks acts as a natural buffer that slows water movement and limits erosion. However, its loss results in increased runoff entering watercourses unimpeded, elevating peak flows and extending flood durations. Studies have shown that reforestation and the restoration of vegetative buffers improve infiltration rates, moderate surface water flow, and reduce flooding intensity (van Meerveld & Seibert, 2025). As a result, implementing forest regeneration in degraded riparian areas plays a crucial role in mitigating flood risks.

Agricultural Practices: Agricultural activities in the study area exert a significant influence on hydrological processes and flood vulnerability. Traditional farming methods, such as monoculture and deep tillage, disrupt soil structure, reducing its ability to retain water. This disturbance leads to increased surface runoff during rainfall events, particularly in clay-rich soils that already exhibit low permeability. Over time, unsustainable practices degrade soil integrity, accelerate erosion, and heighten sediment transport into waterways, reducing channel capacity and exacerbating downstream flood risks (Mishra, 2025).

The intensive use of chemical fertilizers and irrigation in agricultural zones further impacts soil composition by increasing compaction and diminishing its water retention capacity. These conditions amplify runoff and soil loss, leading to the siltation of rivers and streams. The deposition of fine sediments not only reduces the ability of river systems to accommodate excess water but also disrupts aquatic ecosystems, creating additional challenges associated with agricultural intensification (Gupta et al., 2023).

Wetland Degradation: Wetlands, often described as natural "sponges," play a vital role in mitigating flood hazards by absorbing and gradually releasing excess rainfall. However, human-induced degradation driven by agricultural expansion, urban development, and land conversion has significantly reduced their capacity to regulate water flow. In the study area, these disruptions have heightened flood risks by accelerating surface runoff and diminishing natural water storage during peak rainfall events (Roberts et al., 2023).

Agricultural encroachment into wetland areas commonly involves drainage and land leveling, stripping wetlands of their natural water retention properties. Without their function as hydrological buffers, rainfall is rapidly converted into runoff, increasing the likelihood of flash floods in adjacent areas. Urban expansion further amplifies these risks by introducing impervious surfaces such as roads and buildings that channel water into wetlands more quickly, overwhelming their reduced storage capacities (Ghosh et al., 2024). The combination of these land-use changes significantly compromises flood resilience.

Degraded wetlands also lose their ability to stabilize soils, resulting in heightened erosion rates and increased sediment transport into rivers. This sedimentation diminishes the capacity of waterways to accommodate excess water, creating downstream bottlenecks that exacerbate flooding. Additionally, wetland destruction has far-reaching ecological consequences, including biodiversity loss and disruptions to essential ecosystem services (Onoh et al., 2024). The cascading effects of wetland degradation extend beyond flood vulnerability, impacting water quality, habitat stability, and regional climate adaptability.

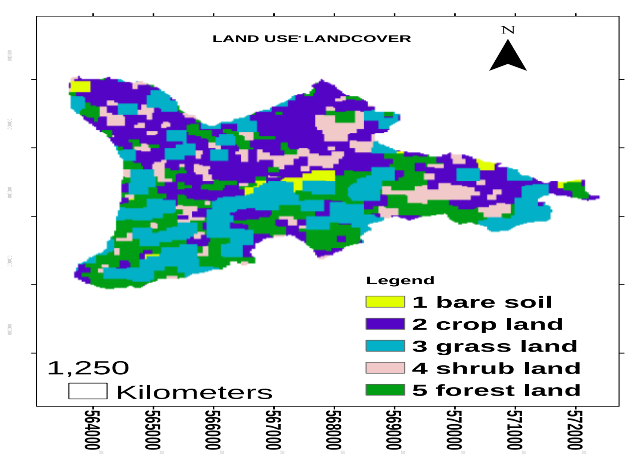

Figure 14 Land use land cover map

Table 11 land use table

Land use land cover	FHI
0-1 forest land	very low
1-3 shrubs	low
3-4 grass land	moderate
4-7 crop land	high
7-10 bare soil	very high

The study by Sadiq et al. (2025) examines soil classification and land suitability evaluation for tomato cultivation using the Analytic Hierarchy Process (AHP) under different land uses.

4.4. Output Components

Flood hazard assessment generates crucial outputs that serve as the foundation for spatial risk analysis and decision-making. These outputs primarily consist of thematic maps that visually represent significant flood risk factors, including slope, elevation, rainfall distribution, land use/land cover (LULC), soil type, proximity to river, and drainage density. These thematic layers, developed using GIS tools, enhance the understanding of hydrological and geomorphic dynamics within flood-prone regions (Anees, 2024).

One of the most significant outputs is the composite flood hazard map, which integrates weighted criteria through overlay techniques. This classification system categorizes areas into different flood susceptibility zones, ranging from low to very high hazard levels. Such classifications provide valuable insights, enabling precise interventions and the effective allocation of resources for flood mitigation measures (Kader et al., 2024). By combining various environmental and meteorological parameters, decision-makers can formulate targeted responses to minimize flood risks.

Ensuring the accuracy of flood hazard models requires a rigorous validation process that compares predicted flood risk areas with historical flood data and field observations. HBV light model serves as a statistical tool for evaluating the predictive performance of these models (Gocoglu, Demirel, & Bozdogan, 2024). The validation process strengthens confidence in the hazard assessment methodology, ensuring its relevance for guiding proactive flood mitigation strategies.

Ultimately, these outputs transform raw geospatial data into actionable intelligence, supporting informed decision-making in flood risk management. By leveraging GIS-based spatial analysis and multi-criteria evaluation techniques, researchers and urban planners can generate reliable flood risk assessments that contribute to sustainable development and disaster preparedness efforts. These validated outputs facilitate long-term resilience-building initiatives in flood-prone areas, helping communities adapt to and mitigate the impacts of extreme weather events.

This integration of geospatial techniques ensures comprehensive flood hazard analysis, leading to well-informed planning strategies that promote both environmental sustainability and risk reduction.

Flood Hazard Map**,** A comprehensive flood hazard map was developed using weighted overlay techniques, delineating the study area into five hazard categories: very low, low, moderate, high, and very high susceptibility. This classification provides a clear visualization of flood-prone areas, facilitating targeted risk mitigation and optimized resource allocation. High and very high-risk zones, concentrated in critical regions of the watershed, require immediate attention for intervention planning to reduce potential flood impacts (Li et al., 2024).

By integrating hydrological, topographical, and environmental factors, the flood hazard map enhances decision-making processes for flood management strategies. The spatial distribution of flood susceptibility levels enables policymakers to prioritize infrastructure reinforcements, land use modifications, and ecological restoration efforts in the most vulnerable areas. Additionally, the identification of hazard-prone zones supports sustainable urban planning and disaster resilience frameworks, ensuring long-term adaptation to changing hydrological conditions.

Effective flood hazard mapping serves as a fundamental tool in disaster risk reduction, reinforcing proactive planning approaches that mitigate damage and protect communities. Leveraging geographic information systems (GIS) for hazard mapping provides valuable insights into flood dynamics, fostering data-driven policies that enhance regional preparedness and response strategies.

4.5. AHP for Flood hazard

Wetlands, often described as natural "sponges," are vital for flood mitigation, as they absorb and gradually release excess rainfall. However, human-induced degradation—driven by agricultural expansion, urban development, and land conversion—has significantly reduced their ability to regulate water flow. In the study area, these disruptions have heightened flood risks by accelerating surface runoff and diminishing natural water storage during peak rainfall events (Roberts et al., 2023).

Agricultural encroachment into wetland areas typically involves drainage and land leveling, stripping wetlands of their water-retention properties. Without their ability to function as hydrological buffers, rainfall quickly translates into runoff, increasing the likelihood of flash floods in adjacent areas. Urban expansion further exacerbates these risks by introducing impervious surfaces such as roads and buildings—that accelerate water movement into wetlands, overwhelming their reduced storage capacities (Ghosh et al., 2024). The combined effects of these land-use change severely compromise flood resilience.

Additionally, degraded wetlands lose their soil stabilization properties, leading to increased erosion and sediment transport into rivers. This sedimentation process reduces the capacity of waterways to accommodate excess water, creating downstream bottlenecks that intensify flooding. Moreover, wetland destruction has significant ecological consequences, including biodiversity loss and disruptions to essential ecosystem services that contribute to long-term environmental stability (Onoh et al., 2024). These cascading effects extend beyond flood vulnerability, affecting water quality, habitat integrity, and climate adaptability.

Table 12 Satty's scale of relative importance (Saaty 1980; Saaty and Vargas 1991)

Intensity of Importance	Degree of preference	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate Importance of one factor over another	Experience and judgment slightly favor one activity over another
5	Strong or essential importance	Experience and judgment strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is needed

Table 13 Pairwise comparison of seven criterion decimal matrix

Factor	Slope	Elevation	Drainage density	Proximity to river	Rainfall	texture	land use
Slope	1	2	3	3	5	7	

Elevation	1/2	1	2	3	5	7	
Drainage density	1/3	1/2	1	2	3	5	
Proximity to river	1/3	1/3	1/2	1	3	5	
Rainfall	1/5	1/5	1/3	1/3	1	3	
Soil texture	1/7	1/7	1/5	1/5	1/3	1	
land use	1/9	1/9	1/7	1/7	1/5	1/3	

Factor	Slope	Elevation	Drainage density	Proximity to river	Rainfall	Soil texture	Land use
Slope	1.00	2.00	3.00	3.00	5.00	7.00	9.00
Elevation	0.50	1.00	2.00	3.00	5.00	7.00	9.00
Drainage density	0.33	0.50	1.00	2.00	3.00	5.00	7.00
Proximity to river	0.33	0.33	0.50	1.00	3.00	5.00	7.00
Rainfall	0.20	0.20	0.33	0.33	1.00	3.00	5.00
Soil texture	0.14	0.14	0.20	0.20	0.20	1.00	3.00
Land use	0.11	0.11	0.14	0.14	0.14	0.20	1.00
Sum	2.61	4.28	7.17	9.67	17.34	28.20	41.00

4.6. Expert Judgments Documentation in AHP

Documenting expert judgments is a critical part of ensuring transparency, credibility, and reproducibility in multi-criteria decision analysis (MCDA), especially when using methods like the Analytic Hierarchy Process (AHP).

Five experts were selected based on their extensive experience in hydrology, GIS-based modelling, and flood hazard assessment. They included two university professors, one senior hydrologist from the Ministry of Water and Energy, and two GIS specialists from a regional disaster risk management bureau.All experts held at least a Master's degree in a relevant field, with three holding PhDs. Their qualifications were complemented by practical experience in flood modelling and spatial analysis.

Experts were provided with a standardized AHP questionnaire and a guidance document explaining the criteria and the Saaty scale. Judgments were collected through individual documentation to avoid groupthink. Individual pairwise matrices were aggregated using the geometric mean to form a group judgment matrix. In cases where the consistency ratio exceeded 0.1, experts were asked to review and revise their judgments. Disagreements were resolved through a follow-up workshop where experts discussed divergent views and reached consensus.

Table 14 expert judgment table

Component	Description
Number of Experts	5
Fields of Expertise	Hydrology, GIS, Environmental Science, Disaster Risk Management
Qualifications	MSc/PhD, 10+ years experience, relevant publications
Judgment Collection	Structured with Saaty scale, individualy their documentation
Disagreement Resolution	Geometric mean aggregation, consistency checks, consensus workshop

Table 15 Flood hazard parameters and weights

Parameters	Weight variables	Sub-class of parameters	Rating level
Slope in degree	5	61 - 76.9	1
		50 - 61	2
		33 - 50	3
		16 - 33	4
		0-16	5
Elevation in meter	5	2737 - 3389	1

		2352 - 2737	2
		2108 - 2352	3
		1862 - 2108	4
		1570 - 1862	5
Drainage density in m/sq.km	5	0 - 5.38	1
		5.38 - 10.77	2
		10.77 -16.14	3
		16.14 -21.53	4
		21. 53 - 26.909	5
River proximity in meter	5	10 - 640	1
		2640 - 1499	2
		31499 - 2358	3
		42358 - 3217	4
		53217 - 4294	5
Annual Rainfall in mm	5	891.19-898.38	1
		886.4-891.19	2
		881.1-886.4	3
		875.7-881.1	4
		868.8-875.7	5
soil type textural class	5	Cambisols	1
		Lithosols	2
		Regosols	3
		Rock surface	4
		Vertisols	5
Land use type	5	0-1 Bare soil	1
		1-3 Crop land	2
		3-4 Grass land	3
		4-7 shrubs	4
		7-10 Forest land	5

4.7. Flood Hazard Calculation Framework

The flood hazard map was generated using the equation below:

$$\text{Flood Hazard} = \Sigma\, W_i X_i$$

Where:

W_i = Weight of each factor

X_i = Criterion score for each factor

In this study, the hazard map incorporated the following weighted factors:

Step 1. Establishment of judgment matrices (P) by pair wise comparison. Table-----10

$$P = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \cdots & \ddots & \vdots \\ P_{n1} & P_{n2} & \cdots & P_{mn} \end{pmatrix}$$

Where, n denote the nth row and m denotes the m th column elements of the judgment matrix.

Step 2. Calculation of normalized weight This step is to normalize the matrix by totaling the numbers in each column. Each entry in the column is then divided by the column sum to yield its normalized score. The sum of each column is 1.

Step 3. Calculates a consistency ratio (CR) to verify the coherence of the judgements. Now, calculate the consistency ratio and check its value. The purpose for doing this is to make sure that the original preference ratings were consistent.

CR= CI /RI--------- table 16

Consistency index (CI) is denoted as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n_i}{n_i - 1}$$

Max is the eigenvalue of judgment matrix and it is calculated as:

$$\lambda_{\max} = \sum_{n=1}^{n_i} \frac{(\mathrm{PW})_n}{n_i w_n}$$

Where, W is the weight vector (column). Random index (RI) can be obtained from standard tables (Table 9, Saaty 1980.

4.8. Multi-Criteria Decision Analysis (MCDA)

Multi-Criteria Decision Analysis (MCDA) provides a structured approach to flood hazard assessment by integrating diverse risk factors. Key variables—including slope, elevation, rainfall, drainage density, soil texture, proximity to rivers, and land use—are assigned relative weights based on their impact on flood susceptibility. These weights reflect expert judgment, environmental conditions, and historical flood data, ensuring a balanced and data-driven risk assessment (Efraimidou & Spiliotis, 2024).

In practical applications, MCDA is implemented through overlay analysis within Geographic Information System (GIS) platforms, combining weighted spatial layers to generate a comprehensive flood hazard map. This process enables clear visualization of flood-prone zones, categorizing areas into different susceptibility levels, ranging from low to very high risk. By identifying high-risk zones, MCDA allows policymakers to prioritize mitigation measures, such as infrastructure improvements, flood defenses, and ecosystem restoration, in the most vulnerable locations (Rezvani et al., 2023).

The adaptability of MCDA makes it a valuable tool for analyzing flood risks in varied landscapes and climatic conditions. In the case of Derek Wonze Mehal Amba Town watershed, where hydrological dynamics are shaped by complex terrain and fluctuating rainfall patterns, MCDA facilitates tailored flood risk modeling that accurately captures localized vulnerabilities. This ensures that mitigation strategies are aligned with the region’s environmental and socioeconomic characteristics.

By integrating MCDA with GIS technology, flood risk assessment becomes more precise and actionable, enabling planners to develop sustainable resilience measures. The technique’s systematic approach improves decision-making, helping communities manage flood hazards effectively and reduce the long-term impacts of extreme weather events.

Table 16 Normalized pairwise matrix calculated

Factor	Slope	Elevation	Drainage density	Proximity to river	Rainfall	Soil texture	Land use
Slope	0.38	0.47	0.42	0.31	0.29	0.25	0.22
Elevation	0.19	0.23	0.28	0.31	0.29	0.25	0.22
Drainage density	0.13	0.12	0.14	0.21	0.17	0.18	0.17
Proximity to river	0.13	0.08	0.07	0.1	0.17	0.18	0.17
Rainfall	0.08	0.05	0.05	0.03	0.06	0.11	0.12
Soil texture	0.05	0.03	0.03	0.02	0.01	0.04	0.07
Land use	0.04	0.03	0.02	0.01	0.01	0.01	0.02

Table 17 Determined relative criterion weight

Factor	Slope	Elevation	Drainage density	Proximity to river	Rainfall	Soil texture	Land use	criteria weight
Slope	0.38	0.47	0.42	0.31	0.29	0.25	0.22	0.32
Elevation	0.19	0.23	0.28	0.31	0.29	0.25	0.22	0.25
Drainage density	0.13	0.12	0.14	0.21	0.17	0.18	0.17	0.16
Proximity to river	0.13	0.08	0.07	0.1	0.17	0.18	0.17	0.10
Rainfall	0.08	0.05	0.05	0.03	0.06	0.11	0.12	0.11
Soil texture	0.05	0.03	0.03	0.02	0.01	0.04	0.07	0.04
Land use	0.04	0.03	0.02	0.01	0.01	0.01	0.02	0.02

Table 18 Normalized weight factor

Factors	Normalized weight	Influence (%)
Slope	0.32	32
Elevation	0.25	25
Drainage density	0.16	16
Proximity to river	0.10	10
Rainfall	0.11	11
Soil texture	0.04	4
Land use	0.02	2
Sum	1	100

Table 19 Random inconsistency

n	1	2	3	4	5	6	7	8	9	10
CR	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.46	1.49

Table 20 Determined consistency ratios (CR)

Factor	Slope	Elevation	Drainage density	Proximity to river	Rainfall	Soil texture	Land use	Weighted sum value	criteria weight	weighted sum /weighted criteria
Slope	0.38	0.47	0.42	0.31	0.29	0.25	0.22	2.33	0.32	7.28
Elevation	0.19	0.23	0.28	0.31	0.29	0.25	0.22	1.77	0.25	7.08
Drainage density	0.13	0.12	0.14	0.21	0.17	0.18	0.17	1.11	0.16	6.94
Proximity to river	0.13	0.08	0.07	0.1	0.17	0.18	0.17	0.9	0.1	9.00
Rainfall	0.08	0.05	0.05	0.03	0.06	0.11	0.12	0.49	0.11	4.45

Soil texture	0.05	0.03	0.03	0.02	0.01	0.04	0.07	0.26	0.04	6.50
Land use	0.04	0.03	0.02	0.01	0.01	0.01	0.02	0.14	0.02	7.00
Total	1	1	1	1	1	1	1		CI	0.065
									RI	1.410
									CR	0.046
									CR	CR<0.1 Consistency is acceptable

4.9. Final flood hazard map

The flood hazard analysis revealed the following distribution of susceptibility across the study area watershed. The findings emphasize that out of a total of 107640 ha 1250 ha was very low flood susceptible which was cover 10.5% of a total area ,18990 ha was low flood susceptible covers 17.6%, 34290 ha was moderate flood susceptible covers 31.9%, 26550 ha was high flood susceptible covers 24.7%, 16560 ha was very high flood susceptible covers 15.4% of the total area predominantly high to very high in specific regions, requiring urgent interventions to minimize risks and safeguard the community.

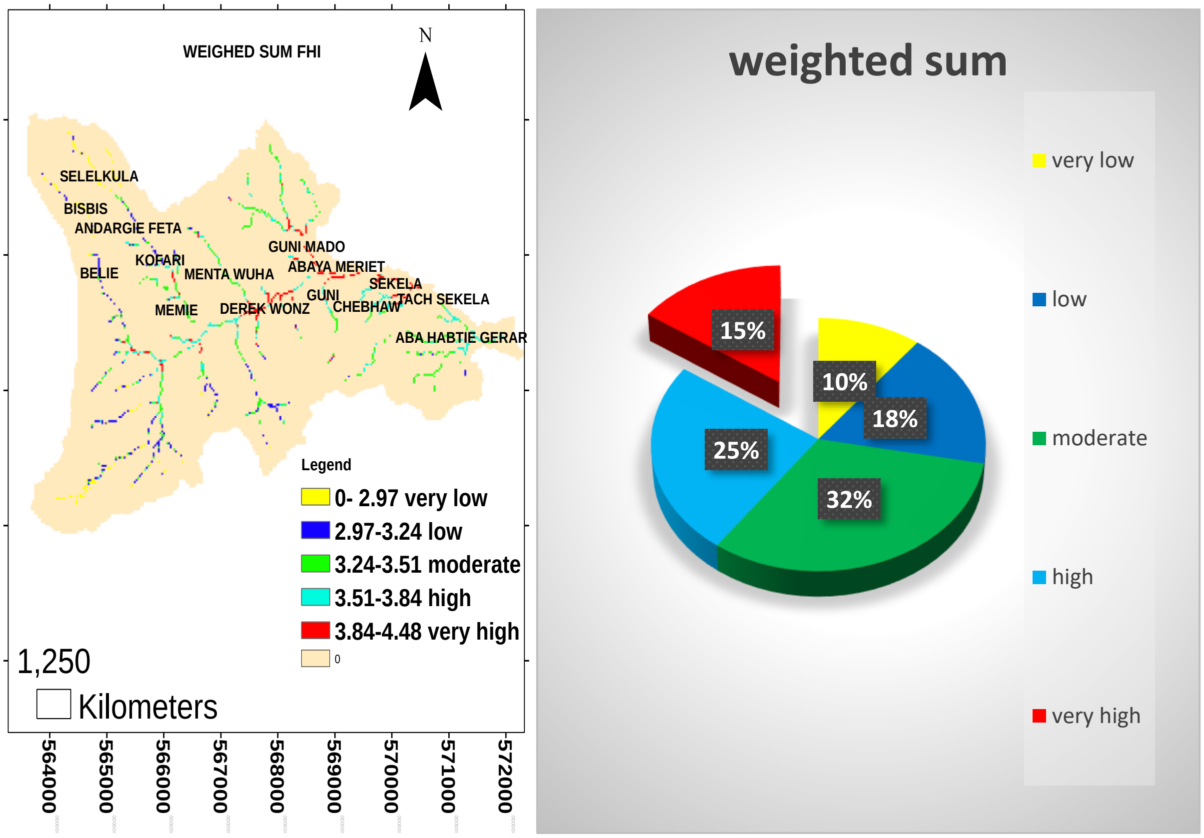

Fig 15 Flood hazard weighted sum

Table 21 flood hazard rang

flooding range	rating	area in ha	% of area covered	Representative area
0-2.97	very low	11250	10.5	Slelkula, Bisebise
2.97-3.24	low	18990	17.6	BLie, Anedargie feta, Qofari
3.24-3.51	moderate	4290	31.9	Mmie , Menta weha
3.51-3.84	high	26550	24.7	Chebehawe ,Aba habtie gerare ,Guni
3.84-4.48	very high	16560	15.4	Guni mado, Abeya meriet Seqela, Dereqe wonz
Total area ha		107640	100.0	

4.10. Comparison of Modeled Hazard Zones vs. Actual Flood Events in Mehal Amba town

In the above table 21 flood hazard zones in Mehal Amba town were classified into five categories by Using AHP-based GIS-MCDA, these zones were derived from weighted factors such as slope, elevation, proximity to rivers, drainage density, rainfall, land use, and soil texture.

4.10.1. Community Reported Flood Events

Field observations and informal interviews with residents (as referenced in local studies and participatory mapping efforts) revealed:

Dereqe Wonz and Guni Mado: Frequently cited as flood hotspots, especially during the kiremt season (June–September).

Chebehawe and Aba Habtie Gerare: Reported cases of crop damage and temporary displacement due to flash floods.

Menta Weha and Mmie: Moderate flooding reported, often linked to poor drainage and upstream runoff.

Slelkula and Bisebise: Rarely affected, consistent with their classification as very low hazard zones.

Table 22 Alignment Between Model and Reality

Zone Type	Model Prediction	Community Reports	Agreement
Very High	15.4%	Frequent flooding	Strong
High	24.7%	Seasonal flooding	Strong
Moderate	31.9%	Intermittent	Partial
Low	17.6%	Rare	Good
Very Low	10.5%	No reports	Strong

Notably, some moderate hazard zones (e.g., Menta Weha) experienced more frequent flooding than expected, suggesting possible underestimation due to: Unmapped micro-drainage channels, Recent land use changes, Localized rainfall variability.

5. CONCLUSION AND RECOMMENDETION

5.1. Conclusion

Flooding remains a persistent challenge in Derek Wonze Mehal Amba Town watershed, exacerbated by complex hydrological dynamics, seasonal rainfall patterns, and human-induced pressures. This study employed Geographic Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) to comprehensively assess flood hazards, offering a systematic and data-driven approach to identifying vulnerable areas. The integration of these methodologies has proven effective in evaluating flood susceptibility and providing actionable insights for targeted mitigation strategies.

The findings emphasize the critical role of spatial analysis in flood risk management. By incorporating diverse environmental variables are topography, land use, soil type, rainfall intensity, drainage density and proximity to water bodies the study developed a comprehensive flood hazard map that highlights the most vulnerable zones. This mapping framework enables policymakers and planners to allocate resources efficiently, ensuring that high-risk areas receive prioritized intervention. Improved drainage infrastructure, reforestation efforts, and sustainable land use planning emerge as key recommendations to strengthen flood resilience in the town.

Beyond its immediate application, this research underscores the broader potential of GIS and MCDA in disaster risk management. The methodologies employed in this study can be adapted to other flood-prone regions in Ethiopia, contributing to a cohesive national framework for flood hazard assessment. By standardizing these analytical approaches, local governments can enhance early warning systems, optimize land use regulations, and develop more effective long-term mitigation strategies.

The study also highlights the necessity of integrating scientific methodologies with community engagement. Raising awareness among local populations about flood risks, preparedness measures, and sustainable practices ensures that resilience-building efforts extend beyond technical solutions. Public involvement, supported by accurate hazard mapping and responsive policy frameworks, strengthens adaptive capacity and fosters proactive disaster management.

In conclusion, the research demonstrates that the intersection of advanced spatial analysis and decision-support tools offers a robust framework for flood risk mitigation. By leveraging GIS and MCDA, Derek Wonze Mehal Amba Town watershed can better anticipate and manage flood hazards, reducing the socio-economic and environmental impacts of extreme weather events. The study's insights serve as a foundation for future resilience planning, highlighting the importance of data-driven strategies in ensuring the safety and sustainability of vulnerable communities. As flood risks continue to evolve, adopting innovative approaches to hazard assessment and mitigation will be crucial in building a climate-adaptive and disaster-resilient future.

5.2. Recommendation

To mitigate flood risks and enhance resilience in Derek Wonze Mehal Amba Town watershed, several strategic approaches must be implemented. First, the town's drainage infrastructure should be improved and modernized to manage heavy rainfall effectively and prevent waterlogging. Regular maintenance and clearance of drainage channels are essential to ensure their functionality during flood events. Constructing protective structures such as levees, flood walls, and retention basins will further safeguard vulnerable areas.

Enforcing zoning regulations to prevent construction in high-risk areas is critical, alongside promoting reforestation and land rehabilitation efforts to enhance soil infiltration and reduce surface runoff. Controlled agricultural activities can be encouraged to curb erosion and preserve the health of the watershed.

Land use planning plays a crucial role in mitigating flood hazards in watersheds like Derek Wonze Mehal Amba Town watershed. Effective planning involves strategies such as zoning regulations, sustainable land management, and infrastructure development to minimize flood risks.

Integrated Flood Management Implementing policies that balance development with flood prevention. Sustainable Land Use policies with soil water conservation measure as well as Encouraging vegetation cover and proper drainage systems to reduce runoff.

Community awareness programs play a vital role in educating residents about flood risks, evacuation protocols, and preventive measures. Active involvement of local stakeholders in flood risk management initiatives fosters a collective sense of responsibility and resilience within the community.

Establishing a comprehensive early warning system that leverages real-time meteorological and hydrological data can significantly improve preparedness. Integrating GIS-based hazard maps into this system allows for targeted alerts and timely responses in vulnerable areas.

Policy frameworks should be strengthened to support flood mitigation strategies. Local governments must enhance their capacity to plan and execute effective risk reduction measures while integrating hazard data into urban planning and disaster management frameworks. Collaboration among governmental bodies, NGOs, and research institutions can facilitate coordinated efforts.

Periodic updates to flood hazard maps are crucial to ensure their accuracy and relevance, accounting for changes in land use, climate, and hydrological conditions. High-resolution satellite imagery and advanced modeling techniques should be employed to refine assessments further.

Nature-based solutions hold great potential for reducing flood risks. Restoring wetlands and natural floodplains enhances water retention capacities, while the adoption of green infrastructure reduces urban runoff and promotes sustainable water management. Additionally, securing funding for key mitigation projects, such as infrastructure upgrades and reforestation programs, is essential to the success of these strategies.

By implementing these comprehensive recommendations, Derek watershed can significantly reduce its flood vulnerability, protect lives and property, and foster sustainable development for its community and future generations

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APPENDIX

Appendix 1: Maximum rainfall of each station

Kombolcha		Mersa		Wurgesa	
Year	Max RF	Year	Max RF	Year	Max RF
1999	34.6	1999	36.2	1999	36.8
2000	52.9	2000	22.5	2000	64.8
2001	73.1	2001	36.8	2001	33
2002	34.3	2002	34.2	2002	44.5
2003	61.8	2003	36.2	2003	46
2004	29.2	2004	27	2004	50.4
2005	69.9	2005	47.8	2005	70.5
2006	74	2006	44.2	2006	44.4
2007	31.9	2007	26.1	2007	30.6
2008	20.2	2008	31.3	2008	30
2009	25.4	2009	20.4	2009	28.5
2010	38.6	2010	36.8	2010	71
2011	46.1	2011	41	2011	9.1
2012	59.6	2012	28.4	2012	49.3

2013	44.5	2013	31.8	2013	32.3
2014	85.1	2014	35.6	2014	27.9
2015	29.9	2015	47.8	2015	40
2016	43.9	2016	37	2016	28.2
2017	15	2017	20.7	2017	18.19
2018	34.9	2018	27.3	2018	28.7
Sum	764.98	Sum	765	Sum	765.0
Mean	45.24	Mean	31.8	Mean	41.2
St. Dev.	19.64	St. Dev.	10.5	St.Dev.	14.8
Cs		Cs		Cs	
Max	85.1	Max	47.8	Max	71
Min	15	Min	3.7	Min	18.19

1. Data consistency checking

Standard error of mean $\delta_n = \frac{\delta_{n-1}}{\sqrt{N}}$ 3.308

Relative standard $\delta_s = \frac{\delta_s}{X_n}$ 8.649 < 10%, There for the data could be regarded as Reliable and Adequate.

2. Chexk for outliers

2.1 Test for higher outlier

$$Y_H = Y_{mean} + K_n * \sigma_y$$

YH = 1.956

Depth = 10^{YH} 90.45 71.00 Ok!

2.2 Test for lower outlier

$$Y_L = Y_{mean} - K_n * \sigma_y$$

YL = 1.222

Depth=10^{YH} 16.67 18.19 Ok!

Therefore, the data is within the higher and lower outliers.

Appendix 2: wurgesa rainfall station for outlier test

1. Data consistency checking

Standard error of mean $\delta_n = \frac{\delta_{n-1}}{\sqrt{N}}$ 1.820

Relative standard $\delta_s = \frac{\delta_n}{X_m}$ 5.440 < 10%, There for the data could be regarded as Reliable and Adequate.

2. Chexk for outliers

2.1 Test for higher outlier

$$Y_H = Y_{mean} + K_n * \sigma_y$$

YH = 1.790

Depth = 10^{YH} 61.68 47.80 Ok!

2.2 Test for lower outlier

$$Y_L = Y_{mean} - K_n * \sigma_y$$

YL = 1.233

Depth=10^{YH} 17.11 20.40 Ok!

Therefore. the data is within the higher and lower outliers.

Appendix 3: mersa rainfall station for outlier test

Appendix 4: Maximum streamflow for derek wonze Nr. Mehal amba un gauged station

Mean X'	S.No.	Year	streamflow	Descending Order	Rank (m)
18.7444	1	1999	12.69	24.143	1
18.7444	2	2000	13.20	22.817	2

18.7444	3	2001	14.94	22.553	3
18.7444	4	2002	19.69	21.757	4
18.7444	5	2003	17.78	21.437	5
18.7444	6	2004	15.16	21.324	6
18.7444	7	2005	18.22	21.139	7
18.7444	8	2006	20.27	20.273	8
18.7444	9	2007	17.07	19.687	9
18.7444	10	2008	19.21	19.374	10
18.7444	11	2009	21.14	19.211	11
18.7444	12	2010	22.82	18.223	12
18.7444	13	2011	16.19	17.778	13
18.7444	14	2012	19.37	17.066	14
18.7444	15	2013	21.44	16.194	15
18.7444	16	2014	22.55	15.922	16
18.7444	17	2015	15.92	15.158	17
18.7444	18	2016	24.14	14.937	18
18.7444	19	2017	21.76	13.202	19
18.7444	20	2018	21.32	12.694	20

Sum	374.89
Mean	18.74
St. Dev.	3.29
Cs	
Max	24.14
Min	12.69

1. Data consistency checking

Standard error of mean	$\delta_n = \frac{\delta_{n-1}}{\sqrt{N}}$	0.736	
Relative standard	$\delta_x = \frac{\delta_n}{X_m}$	3.928	< 10%, There for the data could be regarded as Reliable and Adequate.

2. Chexk for outliers

2.1 Test for higher outlier

$$Y_H = Y_{mean} + K_n * \sigma_y$$

YH =	1.457	
Depth = 10^{YH}	28.64	24.14 Ok!

2.2 Test for lower outlier

$$Y_L = Y_{mean} - K_n * \sigma_y$$

YL =	1.075	
Depth=10^{YH}	11.89	12.69 Ok!

Therefore, the data is within the higher and lower outliers.

Appendix 5: derek wonze Nr. Mehal amba un gauged station for outlier test

Appendix 6: derek wonze Nr. Mehal amba un gauged station average monthly streamflow

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1999	2.772	2.849	3.136	4.439	2.406	2.511	9.060	12.694	11.395	6.423	3.405	3.032
2000	2.902	2.081	3.208	3.086	2.732	1.087	8.525	13.202	9.291	4.874	3.548	3.447
2001	2.550	2.545	4.236	4.778	4.604	3.927	10.414	14.937	11.311	3.902	2.702	2.557
2002	2.795	2.274	2.974	3.852	3.721	3.475	10.069	19.687	15.679	5.280	2.487	2.919
2003	2.812	2.650	3.200	4.511	3.563	1.991	9.875	17.778	13.113	4.656	1.327	3.540
2004	2.703	2.430	2.920	4.295	2.531	1.763	9.512	15.158	13.165	5.224	1.561	2.665
2005	2.773	2.520	3.065	4.227	4.002	3.880	10.778	18.223	12.306	4.581	1.510	3.618
2006	2.924	2.686	3.258	3.921	4.265	3.042	9.667	15.233	12.769	6.241	3.054	3.155
2007	2.899	2.037	3.003	4.434	4.607	3.961	9.720	17.066	14.089	5.646	2.063	3.589
2008	2.753	2.558	3.157	1.882	3.946	3.564	10.244	15.211	13.752	4.642	5.013	3.463
2009	2.973	2.668	3.322	4.281	3.692	1.643	11.215	17.139	12.878	5.655	2.864	3.037
2010	2.923	2.347	2.915	4.237	4.401	3.623	11.124	13.517	10.832	5.737	2.689	3.044
2011	2.872	2.739	3.117	3.622	4.716	5.753	9.614	16.144	10.648	4.250	4.255	3.471
2012	2.842	2.130	2.638	3.649	4.649	2.568	9.796	15.334	12.531	4.820	1.573	3.393
2013	2.935	2.564	2.824	3.745	5.332	4.382	10.662	13.437	12.802	6.622	3.959	3.592
2014	2.839	2.870	4.225	4.357	4.284	4.001	10.096	15.523	12.235	5.675	3.766	2.700
2015	2.834	2.839	2.812	2.479	5.251	3.752	9.844	13.922	11.511	6.234	3.636	3.284
2016	2.811	2.209	2.870	4.713	4.582	3.352	10.185	24.143	13.236	5.401	3.777	3.276
2017	2.741	2.722	4.093	4.433	3.729	3.505	9.781	12.757	11.336	7.330	3.763	3.554
2018	2.827	2.705	2.647	4.240	6.600	3.258	9.455	17.324	10.935	6.440	7.052	3.482
Mean	2.824	2.521	3.181	3.959	4.181	3.252	9.982	15.921	12.291	5.482	3.200	3.241

Appendix 7: mehal amba Average monthly precipitation

Year	Jan	Feb	Mar	April	May	June	July	Agu	Sep	Oct	Nov	Dec
1999	0.30	0.00	0.02	0.56	0.01	0.00	9.23	9.20	3.62	0.33	0.97	0.83
2000	0.00	0.00	0.75	2.01	0.42	0.00	7.91	6.19	1.25	0.31	0.70	0.12
2001	0.00	0.38	2.60	0.99	0.25	1.12	9.60	7.80	0.53	0.04	0.00	0.07
2002	0.89	0.32	0.75	1.85	0.31	0.78	7.26	7.87	1.69	0.05	0.00	0.80
2003	0.21	0.46	0.73	1.40	0.54	0.75	6.24	8.64	1.27	0.00	0.42	0.00
2004	0.12	0.32	1.01	0.61	0.15	1.50	5.77	6.95	0.30	0.32	0.03	0.00
2005	0.02	0.00	0.86	0.66	3.00	0.14	7.95	7.67	1.32	0.00	0.64	0.00
2006	0.05	0.00	2.46	1.44	0.17	1.23	9.68	9.77	0.94	0.44	0.64	0.05
2007	1.68	0.58	0.53	0.92	0.25	1.23	6.38	5.89	2.75	0.00	0.05	0.00
2008	0.00	0.00	0.00	0.37	0.30	0.60	7.07	8.47	1.34	0.19	1.98	0.14
2009	0.00	0.31	0.85	0.44	0.08	0.17	6.23	3.56	0.77	0.96	0.43	0.00
2010	0.13	0.00	0.35	1.62	1.05	0.18	8.76	13.33	1.61	0.09	0.32	0.00
2011	0.19	0.00	1.76	1.90	1.13	0.90	4.89	6.50	1.74	0.21	0.31	0.00
2012	0.00	0.00	1.85	2.41	0.64	2.74	7.13	7.90	1.04	0.00	0.07	0.00
2013	0.14	0.00	0.36	1.09	0.27	2.22	8.76	6.86	0.29	0.37	0.83	0.00
2014	0.10	0.53	0.84	0.30	0.00	0.44	8.87	5.79	1.78	0.00	0.16	0.00
2015	0.02	0.00	0.86	0.66	3.00	0.97	7.95	7.67	1.65	0.29	0.03	0.13
2016	0.05	0.21	0.96	1.06	1.49	1.22	8.60	7.19	1.22	0.28	0.42	0.12
2017	0.00	1.83	1.75	1.25	1.30	0.00	1.75	5.13	0.22	0.08	0.29	0.00
2018	0.00	0.38	0.06	0.43	0.11	24.05	7.01	3.13	0.32	0.29	0.46	0.13

Appendix 8: mehal amba Average Monthly Max Temperature

Year	Jan	Feb	Mar	April	May	June	July	Agu	Sep	Oct	Nov	Dec
1999	26.0	27.5	28.0	27.3	27.3	26.9	23.0	22.8	24.1	24.9	25.0	24.7
2000	26.0	27.5	28. 0	27.4	27.3	26.9	23.1	22.8	24.1	24.9	25.0	24.7
2001	26.0	27.5	28.0	27.4	27.4	26.9	23.1	22.8	24.1	25.0	25.0	24.6
2002	26.0	27.5	28.0	27.3	27.4	26.9	23.1	22.8	24.1	24.9	24.9	24.6
2003	26.0	27.5	28.0	27.4	27.4	26.9	23.1	22.8	24.1	24.9	25.0	24.6
2004	26.0	27.5	27.9	27.4	27.4	26.9	23.0	22.8	24.1	24.9	24.9	24.6
2005	26.0	27.5	28.0	27.4	27.4	26.9	23.0	22.7	24.1	24.9	25.0	24.6
2006	26.0	27.5	28.0	27.4	27.3	26.9	23.1	22.8	24.1	25.0	24.9	24.6
2007	24.9	26.5	28.2	27.2	27.8	25.4	21.4	21.8	23.4	25.3	25.4	24.9
2008	26.3	26.9	28.7	27.2	27.5	26.6	22.9	22.5	24.0	25.0	24.6	25.2
2009	26.0	27.3	28.6	28.3	28.6	29.1	22.8	22.9	25.1	25.7	26.3	25.3
2010	25.9	27.2	27.2	27.7	27.5	28.0	23.2	21.9	24.0	25.7	25.7	24.6
2011	25.5	27.7	25.9	27.7	26.1	26.4	23.4	22.0	23.6	25.7	25.2	25.8
2012	26.4	28.5	26.7	27.1	27.4	27.3	22.5	22.3	24.4	25.8	26.2	26.1
2013	26.8	28.4	28.4	28.9	28.3	26.4	22.8	21.8	24.7	25.4	25.9	25.4
2014	26.0	26.8	27.8	27.7	26.7	27.5	24.0	22.2	23.5	25.3	25.7	25.1

2015	25.9	28.0	28.4	29.2	26.9	26.6	25.8	26.2	24.1	27.2	26.7	24.6
2016	25.8	27.6	29.9	27.8	26.8	27.6	22.2	22.8	24.1	25.0	25.0	24.6
2017	26.7	27.5	28.0	27.4	27.4	27.0	23.0	22.8	24.1	24.9	25.0	24.6
2018	26.0	27.5	28.0	22.3	27.4	25.3	22.5	24.2	24.2	19.2	18.0	19.1