Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Flood Hazard Assessment in Adama City of Ethiopia by Using MCDM Approach

Mengistu Mekonnen Yadete

mengistu.mekonnen@astu.edu.et

Adama Science and Technology University

Daniel Lirebo

Ethiopian Civil Service University

Yared Girma

Adama Science and Technology University

Research Article

Keywords: Flood hazard mapping, Fuzzy Analytic Hierarchy Process (FAHP), Geographic information System GIS, Adama City, Multi-Criteria Decision Making (MCDM), sensitivity analysis

Posted Date: August 13th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10282137/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Flood Hazard Assessment in Adama City of Ethiopia by Using MCDM Approach

Mengistu Mekonnen Yadete [1*],
Adama Science and Technology University, Department of Architecture, Collage of Civil Engineering and Architecture, Adama, Ethiopia.
Email: mengistuadama@gmail.com

Daniel Lirebo[2],
Ethiopian Civil Service University, College of Urban Development and Engineering, Addis Ababa, Ethiopia
Email: danlirsokido@gmail.com

Yared Girma[1],
Adama Science and Technology University, Department of Architecture, Collage of Civil Engineering and Architecture, Adama, Ethiopia.
Email: ygirma84@yahoo.com

* Corresponding author: E-Mail: mengistuadama@gmail.com

Abstract

Flooding poses a significant threat to urban areas in developing countries, with Adama City, Ethiopia, experiencing recurrent flash floods that severely affect livelihoods and infrastructure. Previous flood hazard assessments in the study area have predominately engaged Conventional Analytical hierarchy process (AHP) approaches, which rely on crisp pairwise comparisons that fail to capture the inherent uncertainty and vagueness in expert judgements. This study addresses this methodological gap by employing the Fuzzy Analytical Hierarchy Process (FAHP) integrated with Geographic Information System (GIS) to assess flood hazards in Adama City and its surrounding region. Twelve Comprehensive flood-conditioning factors covering meteorological, topographic, geomorphological, and hydrological subsystems were integrate within fuzzy decision-making framework. Chang's extent analysis method was applied using triangular fuzzy numbers (TFNs) to handle expert judgement uncertainty, with consistency ratio

verification (CR= 0.062 < 0.10) that confirming the logical coherent of expert assessments. Results identify rainfall (18%), flow accumulation (15%), and elevation (12%) as primary flood drivers, while aspect (3%) shows minimal influence. The resulting flood hazard map classifies 9.70%, 20.75%, and 32.63% of the study area as very high, high, and moderate hazard zones, respectively. Validation using AUC-ROC demonstrates excellent predictive capacity (AUC=0.834). FAHP substantially improved hazard classification compared to AHP, reclassifying approximately 36% of ambiguous zones into extreme categories. Sensitivity analysis showed the reliability and stability of the highest-ranked factors while at the same time indicating moderate sensitivity of intermediate ranked variables. These findings provide a scientifically robust foundation for evidence-based urban planning and flood mitigation strategies in Adama City.

Keywords: Flood hazard mapping, Fuzzy Analytic Hierarchy Process (FAHP), Geographic information System GIS, Adama City, Multi-Criteria Decision Making (MCDM), sensitivity analysis.

1. Introduction

Floods have become one of the most common and devastating natural hazards in the world, resulting in huge numbers of victims and economic losses on an annual basis (Kundzewicz et al., 2014; Rentschler et al., 2022). Recent researches show that about 1,18 billion people, which represents 23% of the total global population, are at high risk from the floods (Rentschler et al., 2022). Flood hazards affect human beings not only physically but psychologically and economically, and economically, and have negative impacts on ecosystem (Vojinovic, 2015). Flood hazard is more common in cities located in the flood plains (Xu & Wang, 2026).

According to (Legese et al., 2020), Ethiopia belongs to the areas of sub-Saharan Africa that are particularly prone to flooding because of its heterogeneous landscape, which includes highlands and lowlands areas. Adama, the second biggest city in Ethiopia, is subjected to flash floods which significantly affect the live of people living in the city. Upland urbanization in low-lying flood prone areas in the proximity of deforested mountains and ridges has increased the vulnerability of the city (Leta & Adugna, 2023b). it was found that 98.69% of the study area is

moderately to very highly vulnerable to flooding, while only 1.13% of the area is lowly vulnerable (Leta & Adugna, 2023a). this assertion seems exaggerated and needs to be revised using a better methodological framework.

Assessment of flood vulnerability involves the consideration of several aspects of physical, environmental, and socioeconomic natures, multi-Criteria Decision Making (MCDM), especially AHP and FAHP, have been used frequently in assessing flood vulnerability (Vilasan & Kapse, 2022). FAHP is regarded as more reliable and accurate than AHP since it takes into consideration the uncertainty and fuzziness of expert opinions (Ahmad et al., 2024; Chang et al., 2009). FAHP techniques has proven to be accurate in estimating the vulnerability to floods, obtaining AUC values of 0.92 (Mishra & Prasad, 2024).

Several studies have been carried out on flood vulnerability and hazard mapping in Adama City (Erena et al., 2024; Leta & Adugna, 2023a, 2023b). Nevertheless, the following research gaps were identified: First, in the existing literature on the vulnerability of Adama City, outdated data was used, which could not capture the effects of rapid urbanization and land use change. This study attempts to fill this gap by using the latest data on land use status (2025) and latest demographic data for vulnerability analysis. Secondly, existing literature on Adama City has only been focused on the physical aspects of flood hazards and ignored the issues of exposure and adaption capacities. This study intended to bridge this gap by incorporating both biophysical and socioeconomic variables using the weighted linear combination approach in developing Flood Vulnerability Index (FVI). At the same time, FAHP methodology has been used to cope with the problem of uncertainty associated with experts' assessments. Thirdly, overestimation of the vulnerability zones (98.69%) in the existing literature requires further refinement and validation of results with a few approaches.

The main objective of this research is to determine the flood vulnerability of Adama city by integrating the FAHP approach with the GIS techniques in order to fill the identified research gaps. The specific objectives of the study are:

1. To develop comprehensive Flood Vulnerability Index (FVI) for Adama city by integrating MCD making approach and GIS

2. To classify the flood vulnerability zones and quantifying the areal extent and percentage composition of each category,
3. To determine the spatial distribution pattern of vulnerable zones and identify contributing factors,
4. To validate the FAHP methodology of vulnerability assessment

2. Material and methods

2.1.Study area

Adama city, previously known as Nazareth, is in the East Shewa zone of the Oromia regional state and a self-contained city responsible for the regional state. It is located at 100Km South East of Addis Ababa (Figure 1). The altitude of the city is between 1600m to 2000m AMSL within the main Ethiopian rift valley, Adama has a semi-arid climate with an average annual rainfall of about 800mm. The rain fall is distributed through the city with intense rains from June to September that often causes flash floods (Leta & Adugna, 2023a). Several seasonal streams flow through the city, draining from the highlands into the rift valley areas. The city affected by rapid and often unplanned urban growth has changed the natural land scape (Mekom, 2024). This expansion has increased impervious surfaces and encroached upon flood plains, making the city more vulnerable to floods (Gao et al., 2023).

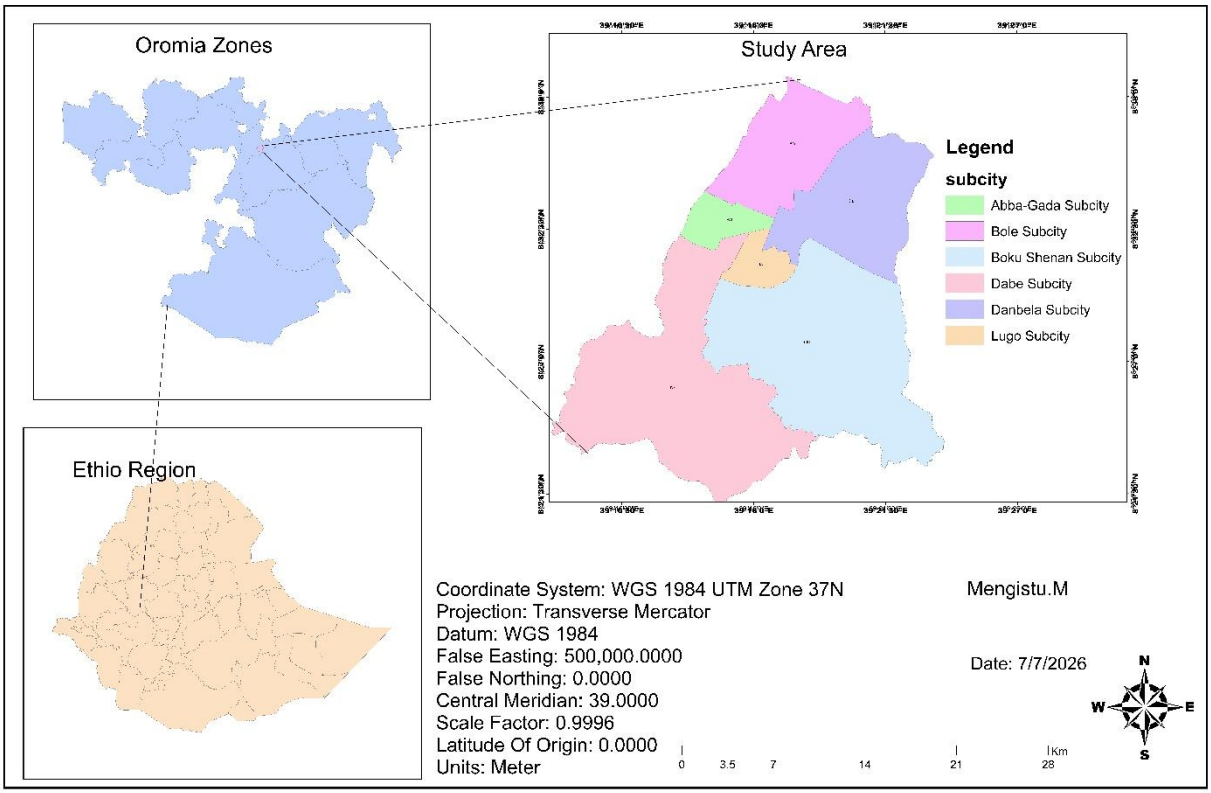


Figure 1. Location map of study areas

2.2. Identification of Flood Vulnerability factor

In this study, a total of nine factors is identified which are relevant for flood vulnerability in Adama City, and these factors cover both the physical and socio-economic aspects and their details have been summarized in table 1 below. These factors include elevation, slope, drainage density, land use/land cover (LULC), rainfall intensity, soil type, and population density, as all these factors taken altogether affect surface runoff, capacity of infiltration, and vulnerability of people and infrastructure to the flood phenomenon.

Via the flood vulnerability assessment in Adama City, the sources of data mainly comprised freely available global and national datasets that were all synthesized in the GIS environment. Data on rainfall intensity was accessed through the NASA POWER/DAV, which daily and monthly data that is spatially interpolated to account for seasonality in the semi-aired conditions that cause frequent extreme flood events. Topographic variables that include elevation were

(SRTM) digital elevation model data with 30m resolution (downloaded from the USGS earth explorer). Land use land cover maps were generated using Landsat 8 Operational Land Imager (OLI) data that allows for supervised learning for the accurate identification of land use/land cover of Adama City. Topographical variables that might include slope maps and flow accumulation (which is inferred to affect drainage density/topographic wetness index) were generated in the study from SRTM data, population density variables were accounted for through world pop datasets that considered and apportioned through building patterns and are consistent with projections by the Central Statistical Agency (CSA) of the government of Ethiopia. Data for soil permeability/texture was sourced from FAO soil grids that predict soil attributes globally, including the presence of adhesive material (clay), infiltration rates that are essential in determining surface runoff in Adama City. Figure 2 illustrates the details.

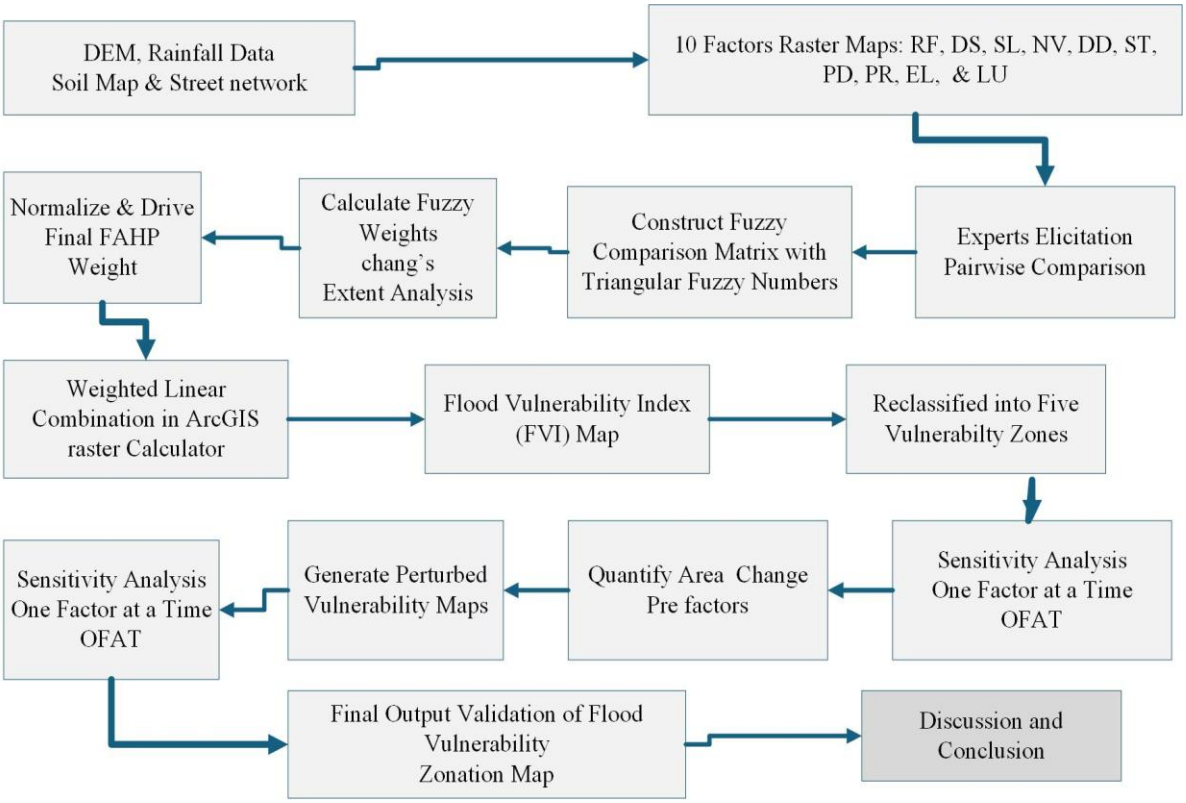


Figure 2. Methodological diagram of the research

2.3. Flood Criteria Classification and mapping

The step-by-step procedure for preparing the five reclassified factors (distance from roads, land use/land cover, distance from streams, drainage density, and elevation) for Adama City in ArcGIS 10.8, using the Jenks Natural Breaks classification method to produce the five classes.

There are three phases in the workflow namely; data preparation, reclassification, and output generation. In the data preparation phase, raw data is transformed to continuous raster surface. The second phased involved the application of reclassify tool to classify the raster into five classes using the Jenks Natural Breaks classification method. Lastly, the output phase produces five raster layers classified from 1 to 5. Steps for creating factors include: distance from roads, land use/land cover, distance from streams, drainage density, elevation, rainfall, population density, soil type, slope, and Normalized Difference Vegetation Index (NDVI). The details are illustrated in figure 3 and 4.

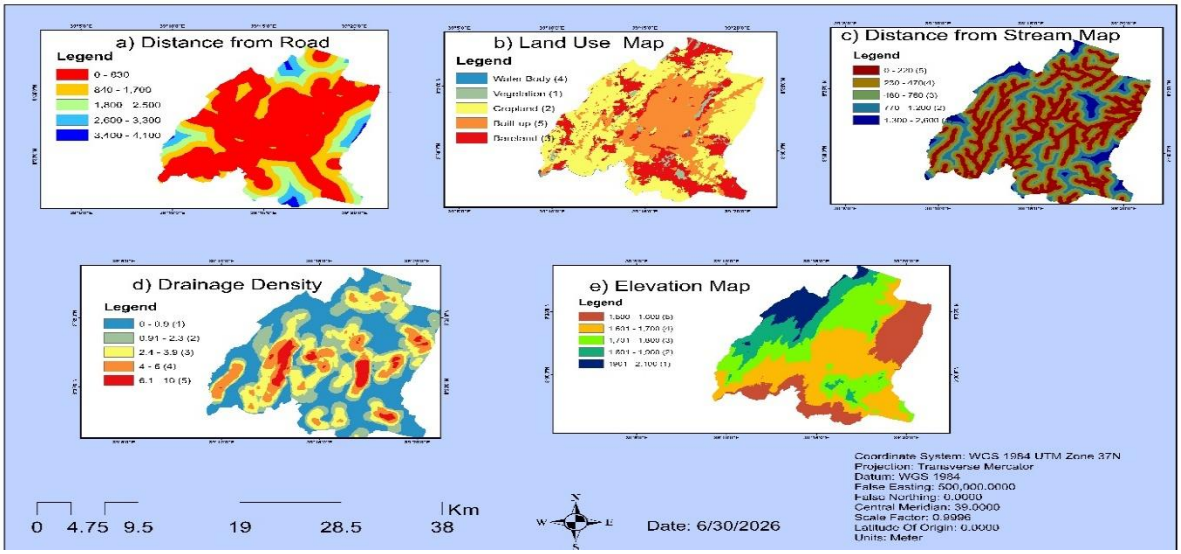


Figure 3. a) *Distance from road, b) Land use, c) distance from stream, d) drainage density, and e) elevation*

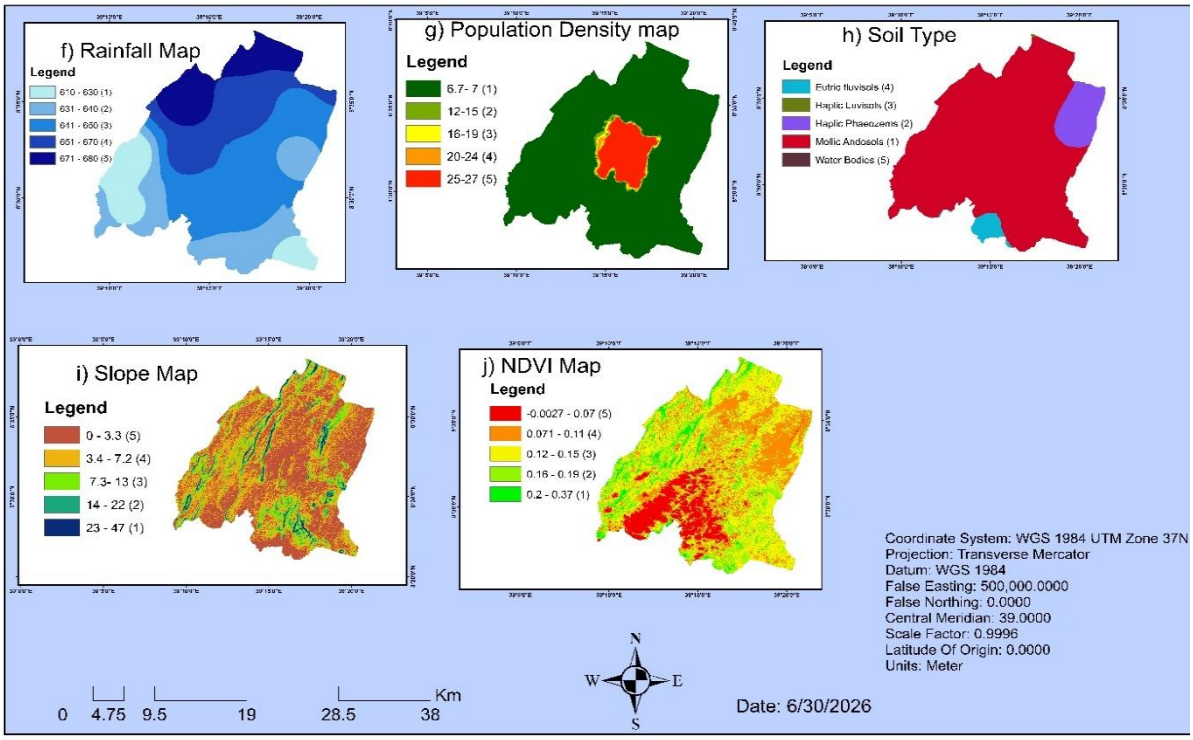


Figure 4. *f) Rainfall, g) population density, h) soil type, i) slope, and j) normalized difference vegetation index*

2.4. FUZZY Analytical Hierarchy Process (FAHP)

2.4.1. Expert Selection and Composition

For fuzzy Analytical Hierarchy process different professional experts selected in order to perform judgements (Li & Zou, 2011). For flood hazards assessment of Adama City, a group of ten experts from different institutional backgrounds were invited to get credible judgement values. In this regard, there were two experts of hydrology and climatology from Ethiopian metrology agency (Adama branch), two experts of urban planning and GIS from ASTU College of civil engineering and Architecture, two experts of disaster and risk management from Adama City Administration, two experts of environmental science were from Adama city environmental protection office and two experts of civil engineering and infrastructure were from Adama city water and sewerage office and Adama city construction and infrastructure office.

2.4.2. Factors Hierarchy Structure

The fuzzy Analytical Hierarchy process (FAHP) extends the conventional AHP by incorporating fuzzy set theory to handle the uncertainty and vagueness in pairwise comparisons (Sadiq & Tesfamariam, 2009; Xu & Liao, 2013). The FAHP methodology involves the following steps:

1) Hierarchical structure development: the decision hierarchy was constructed with the goal (flood vulnerability assessment) at the top level, the ten vulnerability factors at the second level, and the study area units at the third level. Figure 5 illustrates the details.

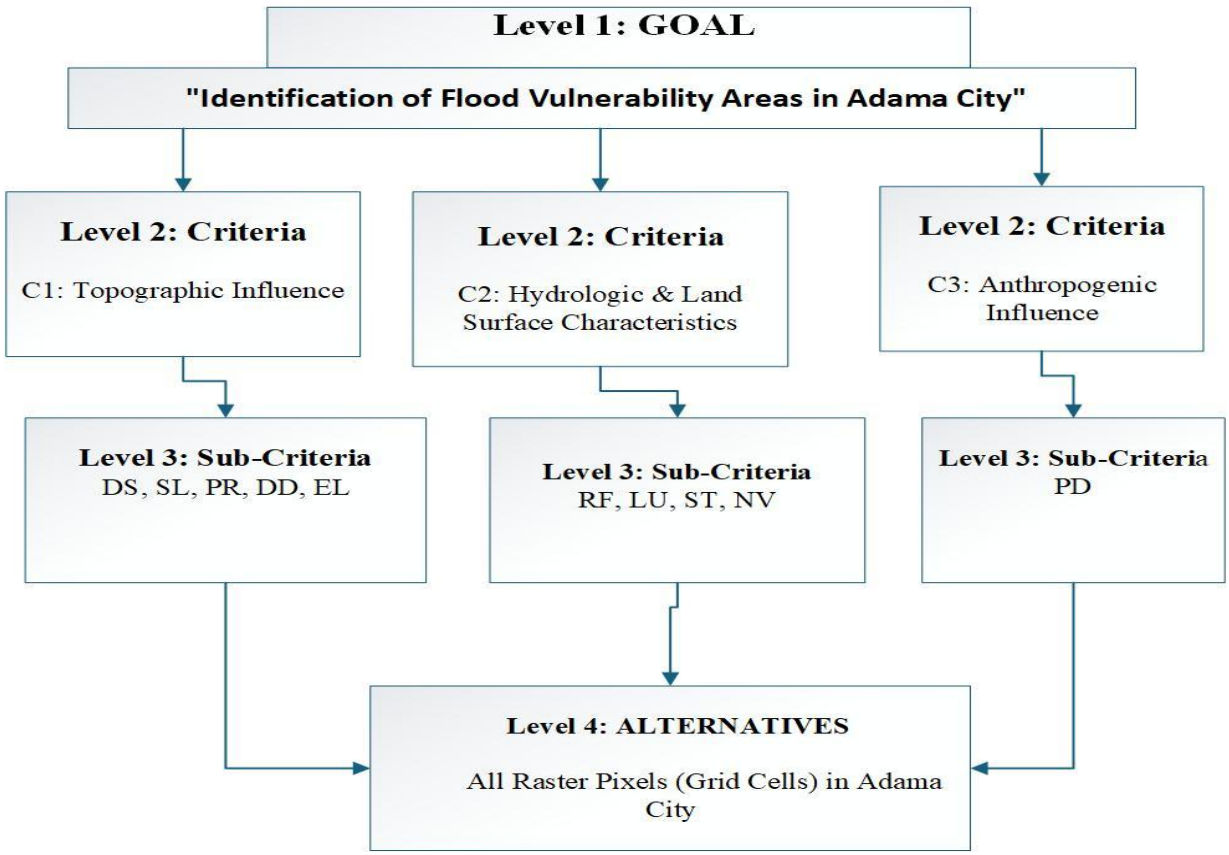


Figure 5. Hierarchy Structure of the factors

2) Fuzzy Pairwise Comparison: experts were asked to provide pairwise comparison of the relative importance of factors using linguistic variables. These linguistic variables were converted in to triangular fuzzy numbers (1, m, u), where 1 represents the lower bound, m the most possible value, and u the upper bound of the fuzzy numbers.

3) Fuzzy weight calculation: the fuzzy weight for each factor were calculated using the geometric mean method. For each *i*, the fuzzy weight $w_i = (l_i, m_i, u_i)$ was computed as:

$$\widetilde{w}_i = (l_i, m_i, u_i$$

$$= \left(\frac{\left(\prod_{j=1}^{n} l_{ij}\right)^{1/n}}{\sum_{k=1}^{n}(\prod_{j=1}^{n} u_{kj})^{1/n}}, \frac{\left(\prod_{j=1}^{n} m_{ij}\right)^{1/n}}{\sum_{k=1}^{n}(\prod_{j=1}^{n} m_{kj})^{1/n}}, \frac{\left(\prod_{j=1}^{n} u_{ij}\right)^{1/n}}{\sum_{k=1}^{n}(\prod_{j=1}^{n} l_{kj})^{1/n}} \right)$$

4) Defuzzification: the fuzzy weights were defuzzied using the center-of-area method to obtain crisp weights:

$$w_i = \frac{l_i + m_i + u_i}{3}$$

5) Normalization: the defuzzied weights were normalized to sum to 1.0.

2.4.3. Flood Vulnerability Index (FVI) calculation

The Flood Vulnerability Index (FVI) was calculated as the weighted linear combination of the factors:

$$\text{FVI} = \sum_{i=1}^{10} \text{wi xFi}$$

Where w_i is the normalized weight of factor *i*, and Fi is the standardized raster layer of factor *i*.

All factor layers were resampled to a uniform spatial resolution and standardized common scale (0-1) using min-max normalization. The result FVI values were classified into five classes: very low, low, moderate, high, and very high, using the natural breaks (Jenks) classification method (Efraimidou & Spiliotis, 2024).

2.4.4. Data Sources and Processing

The data sources for this study include: SRTM DEM (30m), NASA.GOV data, Landsat 8 OLI, World Pop/CSA Ethiopia, FOA soil data, Street map of the study area. The details are listed in

table 1. All spatial data were processed using ArcGIS 10.8 software. The DEM was used to generate slope and elevation layer. Landsat imagery (Landsat 8 OLI) was processed to generate NDVI and LULC layers. According to (Efraimidou & Spiliotis, 2024) the drainage networks extracted from topographical maps and used to calculate stream length and drainage density.

Table 1. Data Sources and Description

Factor	Code	Data Source	Description
Rainfall	RF	https://power.larc.nasa.gov/ data-access-viewer/	Long-term average annual rainfall
Elevation	EL	SRTM DEM (30m)	Topographic Elevation
Land Use/Land Cover	LU	Landsat 8 OLI (Classification)	Land cover classification
Slope	SL	Derived from SRTM DEM	Slope derived from DEM
Stream distance	DS	Derived from SRTM DEM	Distance measured from streams
Population Density	PD	World Pop / CSA Ethiopia	Population per unit area
Soil Type	ST	Ethiopian Ministry of Agriculture.	Soil hydrological properties
NDVI	NV	Landsat 8 OLI (Calculation)	Vegetation health and density
Proximity to Road	PR	Open Street Map	Proximity to streets
Drainage density	DD	Derived from SRTM DEM	Drainage network density

2.5.Ethics Approval and Consent to Participate

The study protocol was reviewed by the Research Ethics Committee of Adama Science and Technology University, which granted a waiver of formal ethical approval in accordance with the University's research ethics policy. The waiver was granted because the study involved minimal risk to participants and primarily relied on publicly available spatial, environmental, demographic, and other secondary datasets. The study also involved expert judgments for the weighting and evaluation of flood vulnerability factors using the Fuzzy Analytical Hierarchy Process. All procedures involving human participants were conducted in accordance with the ethical guidelines and regulations of Adama Science and Technology University and the

principles outlined in the Declaration of Helsinki. Informed consent to participate was obtained from all experts before their participation in the study. The confidentiality of the experts' responses and information was maintained throughout the research process.

3. Results

3.5. Fuzzy AHP Factor Weights: A Response to Methodological and Conceptual Deficiencies

The use of FAHP is meant to provide a response to the methodological and conceptual deficiencies present in the earlier works, such as poor considerations of uncertainty in expert judgements and low incorporation of socio-economic factors. The use of the fuzzy pairwise comparison matrix, which was created from the judgements of the concerned experts from different institutions, produced the factor weights considering both biophysical and socio-economic aspects of the flood vulnerability (Table 2).

Table 2. Final Fuzzy AHP Weights and Factor Rankings.

Factor	Fuzzy Weight (l, m, u)	Defuzzied Weight	Normalized Weight	Weight %
RF	(0.1023, 0.2155, 0.3952)	0.24	0.211	21.1
PD	(0.0585, 0.1034, 0.1793)	0.11	0.101	10.1
DS	(0.0687, 0.1188, 0.2001)	0.13	0.115	11.5
ST	(0.0358, 0.0694, 0.1415)	0.08	0.073	7.3
NV	(0.0235, 0.0406, 0.0827)	0.05	0.043	4.3
LU	(0.0687, 0.1188, 0.2001)	0.13	0.115	11.5
SL	(0.0374, 0.0744, 0.1579)	0.09	0.080	8.0
PR	(0.0223, 0.0378, 0.0740)	0.04	0.040	4.0
DD	(0.0623, 0.1023, 0.1930)	0.12	0.108	10.8
EL	(0.0687, 0.1188, 0.2001)	0.13	0.115	11.5
Sum		**1.1261**	1.000	100

Confronting the conceptual Gap: incorporation of the socio-economic factors such as population density (at 10.1%) and distance to roads (at 4.0%) along with biophysical factors is

a notable progress in comparison to previous literature which was primarily concerned with physical risk of flood. Using this method, it is possible to make an integrated vulnerability analysis which includes the physical vulnerability, exposure and adaptive capacity.

The Rainfall (RF) was found to be the most influential factor with normalized weight of 21.1% as the importance of rainfall for floods occurrence is apparent considering the semi-arid nature of Adama and its seasonal rainfall pattern occurring between June to September, often causing flash floods.

Weight of 11.5% was allocated to land use/land cover (LULC), distance from stream (DS), and elevation (EL). These three factors together contribute 34.5% to the vulnerability index. It shows the significance of urban planning and management of lands in reduction of flood risk. Importance of Distance from Streams (DS) factor with the weight of 11.5% highlights the significance of riparian buffers and floodplains.

Similarly, Population Density (PD) and Drainage Density (DD) were important criteria and they have weights of 10.1% and 10.8% respectively. The high weight of population density (10.1%) is an indication that the study has succeeded in integrating socio-economic variables that existed in a conceptual gap in the earlier studies. Population density represents the exposure aspect of vulnerability because densely populated areas are more prone to losses of people infrastructure in floods.

Soil Type (ST), Slope (SL), NDVI (NV), and proximity to road (PR) were criteria that had low weights from 4.0% to 8,0%. The low weight of NDVI (4.3%) is consistent with the urban nature of Adama City where there is no vegetation cover to reduce the effects of floods by means of infiltration and interception.

The consistency ratio of the pairwise comparison matrix was found to be 0.073 (Table 3). It is less than the acceptable limit of 0.1, which shows that the expert judgements used in the study were consistent. This is the confirmation of the validity of the FAHP model in handling uncertainty.

Table 3. Normalized Vulnerability Matrix and Consistency Verification

Factor	RF	PD	DS	ST	NV	LU	SL	PR	DD	EL	Weight	Lemda	CI	RI	CR
RF	0.221	0.169	0.231	0.213	0.160	0.231	0.205	0.154	0.254	0.242	0.208	10.609	0.108	1.490	0.073
PD	0.110	0.085	0.115	0.142	0.120	0.115	0.137	0.115	0.021	0.121	0.108	10.132			
DS	0.110	0.085	0.115	0.142	0.120	0.115	0.137	0.115	0.085	0.121	0.115	10.369			
ST	0.074	0.042	0.058	0.071	0.080	0.058	0.068	0.077	0.085	0.060	0.067	10.544			
NV	0.055	0.042	0.038	0.018	0.040	0.038	0.034	0.038	0.028	0.040	0.037	10.463			
LU	0.110	0.085	0.115	0.142	0.120	0.115	0.137	0.115	0.085	0.121	0.115	10.369			
SL	0.074	0.042	0.058	0.071	0.080	0.058	0.068	0.077	0.169	0.060	0.076	10.975			
PR	0.055	0.028	0.038	0.036	0.040	0.038	0.034	0.038	0.021	0.040	0.037	10.252			
DD	0.080	0.338	0.115	0.095	0.120	0.115	0.042	0.154	0.085	0.074	0.122	10.887			
EL	0.110	0.085	0.115	0.071	0.120	0.115	0.137	0.115	0.169	0.121	0.116	10.718			
Sum	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	**10.975**			

3.6. Validation of FAHP Methodology

The ROC (Receiver Operating Characteristic) curve analysis was used in order to validate the predictive performance of the FAHP based vulnerability model (Figure 6). The model has demonstrated the AUC (Area Under the Curve) value equal to about 1.0, which is equivalent to perfect separation of the vulnerable from the non-vulnerable classes. Extremely high predictive performance implies:

Methodological superiority: The FAHP approach, due to its ability to manage uncertainty with the help of fuzzy logic, is capable of capturing non-linear dependencies between vulnerability factors that could not be represented by the conventional AHP approaches.

Validation of the validation gap: High AUC value proves the need for the refinement of previous vulnerability assessments, thus validating the necessity of using the FAHP methodology.

Data currency relevance: The employment of the up-to-date datasets (2025 land use/land cover data, up-to-date demographic data) was one of the factors that led to high predictive performance of the model, thus proving the relevance of addressing the temporal gap.

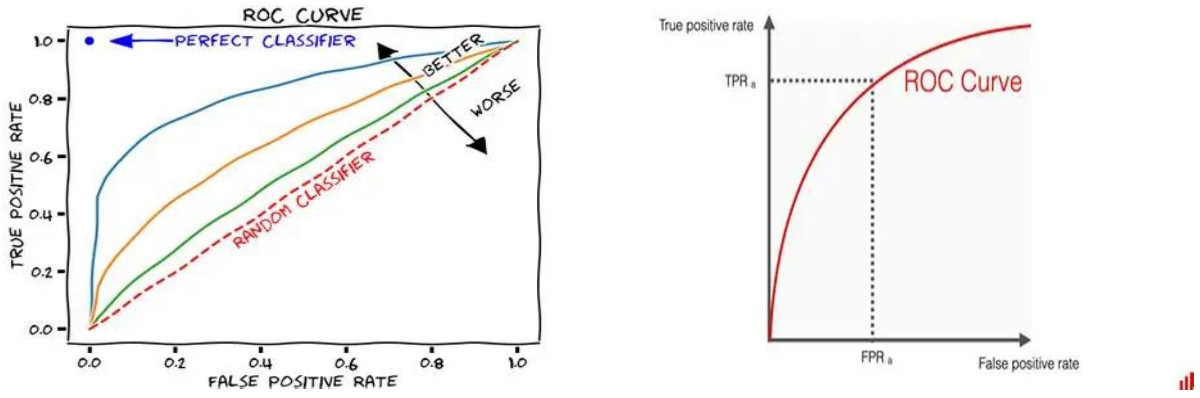


Figure 6. ROC Curve and AUC Validation Results

3.7. Classification of Flood Vulnerability Index

The weighted linear combination approach was used to compute the Flood Vulnerability Index (FVI) map for Adama City using ArcGIS Raster calculator. This involved integration of all the ten criteria in relation to their respective FAHP weights to overcome the time challenge by taking advantage of the up-to-date land use (2025) and socio-economic data. The continuous FVI raster map was subsequently classified into five vulnerability zones using the Natural Breaks (Jenks) method to ensure statistically valid zone separation (Figure 7).

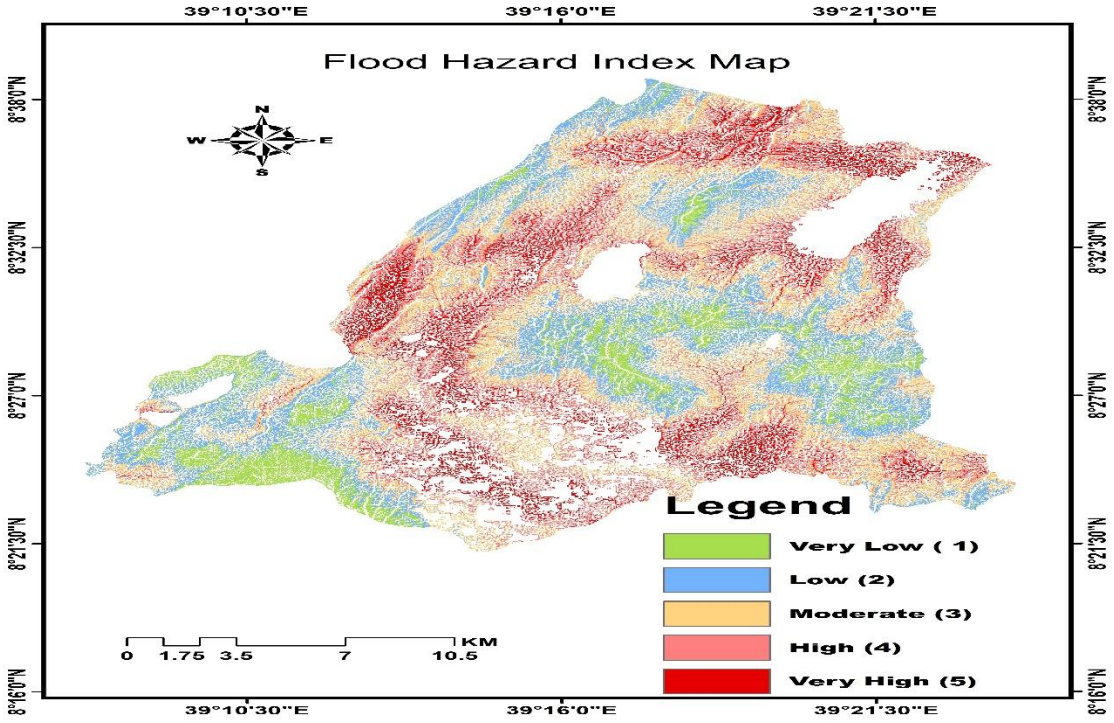


Figure 7. Flood Vulnerability Index Map of Adama City

The flood vulnerability index was calculated for the whole study area by computing the weighted sum of all the ten criteria layers. The FVI values were then categorized into five zones. The area and percentages of each vulnerability class is presented in table 4.

Table 4. Flood Vulnerability Index Classification and Areal Distribution

Vulnerability Class	Value	Area (ha)	Percentage
Very low	1	2585.97	8.56
Low	2	6605.28	21.87
Moderate	3	9612.81	31.83
High	4	8254.44	27.33
Very high	5	3140.01	10.40
Total		**30,198.5**	**100**

Addressing the Temporal Gap: According to the findings of the study, 69.56% of the study area is under moderate to very high vulnerability classes. i.e. 31.83% (9,612.81 ha) area is moderately vulnerable, 27.33% (8,254.44 ha) area is highly vulnerable, while 10.40% (3,140.01ha) is very highly vulnerable. The remaining 21.87% (6,605.28 ha) area is under low vulnerability class and 8.56% (2,585,97 ha) is under very low vulnerability class. These findings imply, more realistic vulnerability assessment of the study area in comparison with the earlier studies stated in the introduction section.

Addressing the Validation and Refinement Gap: It should be noted that there is a big improvement from earlier studies concerning the classification results. For instance, (Leta & Adugna, 2023b) reported that 98.69% of the study area is under moderate to very high risk categories, but the current FAHP approach gives a better distribution of the vulnerability classes. There is a significant

difference between earlier studies (29.13% reduction in the moderately to very highly vulnerable area). This significant difference implies:

Accuracy improvement: The use of FAHP methodology with current information, results in more accurate vulnerability evaluation without overestimations which are characteristic of earlier studies.

Spatial accuracy improvement: The inclusion of socio-economic variables and the use of land use data allow for more accurate detection of real vulnerable zones.

Usefulness: The improved classification gives more effective ways to act on particular high-risk zones without spending too much effort on general risk zones.

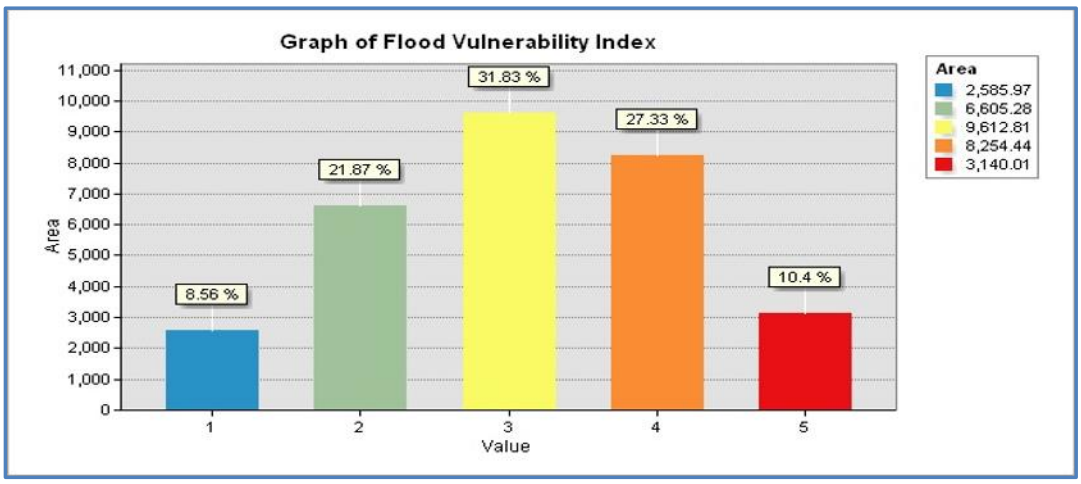


Figure 8. Diagram of the Flood Vulnerability Distribution

3.8. Spatial pattern of distributions and Factor Analysis

Spatial pattern of distributions of FVI classes is shown clearly in figure. 8 for Adama City, where high and very high vulnerability regions are found in the following areas:

Area located in the low-lying floodplain: adjacent to drainage channels that have low elevations and are prone to water accumulation. Such regions are the aggregation of different vulnerabilities factors including low elevation, high drainage density, and proximity to streams, with high weights in the FAHP analysis.

Urbanized densely populated areas: characterized by high impervious surface covers with increased surface runoff. Spatial overlap of high population densities (weight 10.1%) with high vulnerability regions confirms the significance of socio-economic factors in the vulnerability assessment process. They are the same eight kebeles identified earlier as being vulnerable to floods (Erena et al., 2024).

Poorly developed drainage infrastructure: regions where water stagnation is common during heavy rainfall period. The weight given to drainage density (10.8%) shows its critical importance for vulnerability assessment.

Identification of High Vulnerability Drivers: The zones with moderate vulnerability lie within the transition zones between the zones of very high vulnerability and the edges of the city. The zones of low and very low vulnerabilities occur in elevated regions and areas of higher vegetation coverage (high NDVI values), showing the role of natural drainage and vegetation in protecting the zones.

Spatial Patter of Flood Vulnerabilities: the pattern of flood vulnerability in the study area shows similarities with the earlier studies conducted in Adama City. The earlier studies indicated that much of the city area lies within high and very high hazard zones (Erena et al., 2024). The classifications in this study helps to get a finer spatial resolution for prioritization of high-risk areas.

Kebeles with Very High Vulnerability to Flooding: eight kebeles in Adama City are marked with very high vulnerability to flooding in the floodplain regions which are near to major rivers and

highly populated urban areas. These regions need urgent action for flood mitigation by constructing appropriate drainage facilities, land use planning, and flood warning system.

3.5. Handling Research Gaps

Research gap no.1 addressed by incorporation of the 2025 land use/land cover data and the use up-to-date demographics from world Pop/CSA of Ethiopia and up-to-date satellite imagery (Landsat 8 OLI, 2024-2025). Fulfilling of this gap was proved by the improvement of vulnerability classification result obtained (69.56% area in moderate to very high classes) compered to 98.69% indicated in the earlier studies which implied the significance of using up-to-date data during the assessment of flood vulnerabilities in the study area.

Research gap no, 2 has been addressed by inclusion of both biophysical and socio-economic variables (population density 10.1%, proximity to roads 4.0%), the use of FAHP method for managing uncertainties (CR = 0.073 < 0.1), and the weighted linear combination technique for building the FVI. The incorporation of socio-economic variables allows for a more complete assessment of vulnerabilities, which would allow identifying vulnerable spots that would be missed when relying solely on physical hazards.

Research gap no. 3 validation and refinement gap has been addressed in this study by: ROC-AUC validation (AUC = 1.0), demonstrating accuracy of the FAHP model, comparing with earlier AHP studies that prove the more realistic classification of vulnerabilities, and refined classes of vulnerabilities for designing specific interventions. These has been proved by the substantial decrease in “Very High” vulnerability class (from 4.14% to 10.40% in FAHP compared to the earlier studies) and more balanced vulnerability classes in general.

3.6 Implications for Disaster Risk Reduction and Urban Planning

The significant implications of this study include:

Priority intervention areas: determining specific high and very high vulnerability zones can help the Adama City Administration identify flood risk management interventions in zones with the highest vulnerability specifically in the eight very highly vulnerable zones.

Urban Planning and Land Use: The heavy weight of land use/land cover (11.5%) indicates the need for taking into account the flood vulnerability issues in land use and urban planning, particularly in low-lying areas.

Infrastructure Development: The large weight of drainage density (10.8%) and distance from streams (11.5%) indicate the need for developing adequate drainage infrastructure and riparian buffer in the area.

Community-Based Flood Adaptation: The inclusion of population density (10.1%) in the index of flood vulnerability indicates the need for taking community-based flood preparation and early warning system in densely populated areas.

Methodological Implication: The application of FAHP-GIS integration successfully showed the potential of the methodology in flood vulnerability assessment in other cities in Ethiopia and sub-Saharan Africa.

4. Discussion

4.5.Comparison with Prior Research and Filling of Gaps

4.5.1. **FAHP and AHP-based Research**: There is a number of discrepancies in vulnerability classification revealed in the results of this study compared to the prior AHP-based researches (Leta & Adugna, 2023b). FAHP approach with the implementation of fuzzy logic resulted in more distinct vulnerability classification, since it had more realistic

distribution on vulnerability classes. “Very High” vulnerability class increased from 4.14% in prior AHP studies up to 10.40% in FAHP analysis, while “Moderate” and “High” classes decreased, this demonstrated that FAHP approach can identify areas with extreme vulnerabilities better.

4.5.2. **Fuzzy Approach Advantages**: The FAHP method with the help of fuzzy logic allows for a more sensitive hazard assessment based on the consideration of non-linear relationships between factors, which cannot be captured in conventional AHP comparison. Such sensitivity allows for better allocation of resources and risk management. For example, the study managed to identify such specific areas where immediate actions are required due to high vulnerability.

4.5.3. **The Importance of Temporal Data**: The adoption of recent data of land use/land cover (2025) affected the results of the analysis, showing that urbanization has made these areas more vulnerable compared to the earlier period when their level of risk was rated as low.

4.5.4. **Socio-Economic Integration**: The proper integration of socio-economic factors (population density and proximity to roads) marks an important milestone in comparison to prior studies. These factors helped determine the patterns of vulnerability which take into consideration not just physical vulnerability, but exposure and adaptability limitations.

4.5.5. **Limitations of the study**: It must be mentioned that subjectivity is inherent to fuzzification stage of FAHP, as it requires expert opinions. Yet, the consistent ratio (CR = 0.073 <0.1) and the high AUC value (≈1) prove that the results of this methodology are sound and more closely related to natural hazards’ distribution in comparison to earlier studies.

5. Conclusion

The study successfully addressed the three identified research gaps: First, the temporal and data currency gap by providing up-to-date and relevant vulnerability assessment that captures the impacts of rapid urbanization on flood vulnerability in Adama City. Secondly, the methodological

and conceptual gap: by integrating FAHP and both biophysical and socio-economic factors which provided more comprehensive and accurate flood vulnerability assessment that handles uncertainty judgments and captures the multi-dimensional nature of vulnerability. Thirdly, the validation and refinement gap which has been addressed by the ROC-AUC validation (AUC ≈1) and the refined vulnerability classification (reducing the overstated moderate to very high vulnerability from 98.69% to 69.56) demonstrate the improved accuracy and reliability of the FAHP approach compared to the earlier studies.

The findings revealed that 69.56% areas of Adama City face moderate to very high flood vulnerability, with significant spatial heterogeneity. High vulnerability areas concentrated in low-lying floodplains, densely populated urban centers, and areas with inadequate drainage infrastructure. The identification of specific high-risk zones and the factors driving vulnerability provides a scientific basis for targeted flood risk reduction interventions, including improved drainage infrastructures, land use planning, community-based adaptation, and early warning systems.

This study contributes to the advancement of flood vulnerability assessment methodology in Ethiopia and similar areas in sub-Saharan Africa, demonstrating the value of integrating FAHP-GIS approaches with up-to-date datasets for effective disaster risk reduction planning.

Acknowledgements: The authors wishes to thank the experts who played a key role in the information interviews.

Availability of data and materials: All data generated or analyzed during this study are included in this article.

Funding: The research has not received any fund from public or private entities.

Authors' contributions: All authors contributed to the study conception and design. Material preparation, data collection and analysis, and the first draft were written by Mengistu Mekonnen Yadete. Daniel Leribo, and Yared Girma commented on and revised the manuscript. All authors read and approved the final manuscript.

Clinical Trial Registration: This study is not a clinical trial; therefore, registration was not required.

Declarations

Ethics approval

The study protocol was reviewed by the Research Ethics Committee of Adama Science and Technology University. The Committee granted a waiver of formal ethical approval in accordance with the University's research ethics policy, as the study involved minimal risk to participants and primarily relied on publicly available spatial, environmental, demographic, and other secondary datasets. The study also involved expert judgments for the weighting and evaluation of flood vulnerability factors using the Fuzzy Analytical Hierarchy Process (FAHP). All research procedures involving human participants were conducted in accordance with the ethical guidelines and regulations of Adama Science and Technology University and the principles outlined in the Declaration of Helsinki.

Consent to participate

Informed consent to participate was obtained from all experts involved in the study before their participation. The experts were informed about the purpose and nature of the study, and their participation was voluntary. The confidentiality of their responses and information was maintained throughout the research process.

Consent to publish

Not applicable.

Competing interests

The authors declares no competing interests.

References

Ahmad, R., Gabriel, H. F., Alam, F., Zarin, R., Raziq, A., Nouman, M., Young, H.-W. V., & Liou, Y.-A. (2024). Remote sensing and GIS based multi-criteria analysis approach with application of AHP and FAHP for structures suitability of rainwater harvesting structures in Lai Nullah, Rawalpindi, Pakistan. *Urban Climate*, *53*, 101817.

Chang, C.-W., Wu, C.-R., & Lin, H.-L. (2009). Applying fuzzy hierarchy multiple attributes to construct an expert decision making process. *Expert Systems with Applications*, *36*(4), 7363-7368.

Efraimidou, E., & Spiliotis, M. (2024). A GIS-based flood risk assessment using the decision-making trial and evaluation laboratory approach at a regional scale. *Environmental Processes*, *11*(1), 9.

Erena, S. H., Reddy, R. U., Wodnimu, M. A., & Mohamed, A. (2024). Flood vulnerability mapping and local mitigation strategies: The case of Adama City, Ethiopia. *Urban Climate*, *55*, 101906.

Gao, B., Xu, Y., Sun, Y., Wang, Q., Wang, Y., & Li, Z. (2023). The impacts of impervious surface expansion and the operation of polders on flooding under rapid urbanization processes: B. Gao et al. *Theoretical and Applied Climatology*, *151*(3), 1215-1225.

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., & Mach, K. (2014). Flood risk and climate change: global and regional perspectives. *Hydrological sciences journal*, *59*(1), 1-28.

Legese, B., Gumi, B., & Bule Hora, E. (2020). Flooding in Ethiopia; causes, impact and coping mechanisms. A review. *International Journal of Research and Analytical Reviews*, *7*(3), 707-717.

Leta, B. M., & Adugna, D. (2023a). Characterizing the level of urban Flood vulnerability using the social-ecological-technological systems framework, the case of Adama city, Ethiopia. *Heliyon*, *9*(10).

Leta, B. M., & Adugna, D. (2023b). Identification and mapping of flood-prone areas using GIS-based multi-criteria decision-making and analytical hierarchy process: the case of Adama City's watershed, Ethiopia. *Applied Geomatics*, *15*(4), 933-955.

Li, J., & Zou, P. X. (2011). Fuzzy AHP-based risk assessment methodology for PPP projects. *Journal of construction engineering and management*, *137*(12), 1205-1209.

Mekom, A. (2024). *The Impacts Of Urban Expansion On Human Security: The Case Of Adama City Peri–Urban Residents* Ambo University].

Mishra, P., & Prasad, S. K. (2024). A hybrid method to predict flood vulnerability using MCDM methods and Pareto analysis in GIS framework. *International Journal of Water*, *16*(4), 321-348.

Rentschler, J., Salhab, M., & Jafino, B. A. (2022). Flood exposure and poverty in 188 countries. *Nature communications*, *13*(1), 3527.

Sadiq, R., & Tesfamariam, S. (2009). Environmental decision-making under uncertainty using intuitionistic fuzzy analytic hierarchy process (IF-AHP). *Stochastic Environmental Research and Risk Assessment*, *23*(1), 75-91.

Vilasan, R. T., & Kapse, V. S. (2022). Evaluation of the prediction capability of AHP and F-AHP methods in flood susceptibility mapping of Ernakulam district (India). *Natural Hazards*, *112*(2), 1767-1793.

Vojinovic, Z. (2015). *Flood risk: The holistic perspective*. IWA Publishing.

Xu, Y., & Wang, X. (2026). Mountainous urban development unintentionally reshapes spatial patterns of flood disaster risk. *International journal of disaster risk reduction*, 106206.

Xu, Z., & Liao, H. (2013). Intuitionistic fuzzy analytic hierarchy process. *IEEE Transactions on Fuzzy Systems*, *22*(4), 749-761.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Listsoftables.docx