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GIS-based mapping of flood hazard areas and soil erosion using analytic hierarchy process (AHP) and the universal soil loss equation (USLE) in the Awash River Basin, Ethiopia

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Abstract

Floods are the second most significant hazard in Ethiopia, primarily due to the country's diverse topography, including highland mountains and lowland plains. The Awash River Basin faces numerous environmental challenges, such as land degradation, topsoil erosion, high population density, water deterioration, wetland destruction, desertification, and salinity issues. Floods exacerbate these challenges, making effective flood hazard mapping vital for land use planning and mitigation strategies. This study aimed to create a GIS-based flood hazard map and estimate annual soil loss using the Universal Soil Loss Equation (USLE) while identifying the primary causes and impacts of flooding and soil erosion in the basin. Key parameters for the flood mapping included elevation, slope, drainage density, mean annual rainfall, proximity to rivers, land use, land cover change, and soil type. The results indicated that ~ 51.4% (5,855,130.12 ha) of the basin is highly susceptible to flooding, while 40.6% (4,625,378.51 ha) is moderately prone, and 7.6% (866,358.09 ha) is at low risk. The study identified drainage density, elevation, and slope as crucial factors influencing flood vulnerability. Additionally, the total estimated soil loss in the Awash River Basin was found to be 31,049,739 tons per year, with a mean annual loss of 28.6 tons per hectare. This research pioneers the combined study of flood hazards and soil erosion in the study area, where such an integrated analysis has not been previously conducted. It contributes to enhanced flood management and environmental planning while aligning with the Sustainable Development Goals (SDG 13) regarding climate change mitigation and adaptation.

Keywords Flood hazard, GIS, AHP, USLE, Drainage density, Elevation, Soil loss

Background Information

Flooding is among the most common and spatially scattered natural hazards in the world, and causes substantial destruction in different parts of the world. This has led to significant annual losses in terms of human and financial aspects (Shu and Finlayson 1993). A flood is described as a body of water that is not submerged or as occurring when silt and/or water are present in regions that are not commonly known as water bodies (Martini and Loat 2007; Ward 1978).

Flood is the second major hazard in Ethiopia next to drought (ERCS 2012). The reason behind this is the topography of highland mountains and lowland plains

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with natural drainage networks, which are created by primary river lines.

Because of climate and land use changes the frequency and magnitude of floods in the country have promptly increased in recent years (Zewde 2004; Semu 2007). And affects the lives of more than 357,000 people (UNOCHA 2006). Currently, the Awash River Basin encounters several environmental challenges, such as land degradation, high population density growth, deterioration of natural water, wetland destruction, desertification and salinity (Hailemariam 1999). Flooding is also a major problem that can increase the degree of severe environmental degradation in the Awash River Basin (Girma 2010).

The Awash River basin is one of the major river basins, located in the Rift Valley and is among the most frequently flooded areas in Ethiopia (Wondim 2016; Kefyalew 2003; Awash River Basin Authority report, 2017; Ashenafi 2006; Abebe 2007; Dejene et al. 2017; Yonas et al. 2022).

According to Ibrahim (2018) and World Bank (2015), due to urban expansion, surface floods are inevitable because urban areas can be changed to impervious structures that can reduces infiltration of runoff. Subsequently, the capacity and flow rate of runoff increased in downstream of the urban areas.

The degree of flood damage to social, economic and ecological aspects has increased over time in the Awash River Basin. Many city administrations in the Awash River basin lack integrated early warning and risk management systems, eventually leading to severe flood hazard damage. To avoid such frequent problems, hazard analysis, mitigation and management need to be enhanced (Ebert et al. 2009). Therefore, the use of geospatial models to map hazard prone areas is crucial for identifying and mitigating expected flood hazards and their significant causes.

Furthermore, there is a need for routine flood regulation, timely forecasting, enhancing early warning ability and introducing nature-based flood mitigation strategies in the Awash River Basin. Flood hazard mapping is a critical component of flood-prone land use planning and mitigation strategies (Bhatt et al. 2014). Various studies have shown that GIS-based flood hazard mapping is important for preventing severe flood hazards (Kebede 2012; Getahun et al. 2015; Yonas et al. 2022). Moreover, for flood risk assessment research, Alkema (2004) contended that remote sensing and GIS approaches are essential, particularly in places where data are limited or outdated. AHP is mostly known model to map flood hazard area worldwide, we have also employ in Awash River basin integrating with soil erosion model.

Assuming complete aggregation of several criteria, the AHP creates a linear additive model.

According to Danumah et al. (2016), the AHP is thought to be the best technique for combining several factors for unique decision-making to produce maps for flood risk zones with a high degree of accuracy. In addition, determined using a pairwise comparison matrix (Pourghasemi et al. 2014). Even though AHP has received a lot of attention lately for flood risk assessment and management, it is based on the theoretical knowledge, experience, and opinions of experts (Pourghasemi et al. 2014; Papaioannou et al. 2015), which may result in bias and ambiguity in perception (Pourghasemi et al. 2014).

Conversely, it is imperative to determine the annual soil loss, the volume of soil removed due to water-induced erosion, the geographical distribution of soil erosion, and the degree of soil erosion caused by catchment runoff. The estimations provide a thorough grasp of the mechanisms and variables influencing soil erosion as well as possible soil losses due to changes in land use and landscape location. Many people utilize soil erosion models to estimate the amount of runoff-related soil erosion worldwide. The Wischmeier and Smith's (1978) Universal Soil Loss Equation (USLE) and its enhanced variant, Renard et al. (1997) Revised Universal Soil Loss Equation (RUSLE), are the soil erosion models that are most frequently used.

Despite many different erosion models available worldwide, the USLE (Wischmeier and Smith 1978) is the most popular model for predicting erosion because of its straightforward application and ability to predict only soil losses from sheet and rill erosion under specific cropping and management system conditions (Smit 1999). Since the RUSLE model (Renard et al. 1997) requires continuous, precise data for its calculation (Kim et al. 2005), including maximum 30-min rainfall intensity, rainfall kinetic energy, and soil erodibility, most of its enhancements and adjustments are challenging to adapt to new sites. Owing to several technical problems, such crucial data are typically not available at multiple study sites. Various study in different parts of Ethiopia utilize and confirmed that the applicability of USLE model to Ethiopian agro ecology (Ali and Hagos 2016; Bekele et al. 2019; Brhane and Mekonen 2009; Hailu et al. 2015; Tsegaye et al. 2019; Tesfaye et al. 2018).

In the Awash River basin, no combined study recorded, to predict the soil loss and to map the flood hazard areas at the same time. Combining study of soil erosion and flood hazard area mapping is significantly contributing a new paradigm for future studies and scholars. Even though flood hazard and soil erosion research has gotten a lot of attention discretely, the connection between soil erosion and flood disasters has not been thoroughly examined. This integrative approach, using AHP and USLE explicitly for this region, contributes new

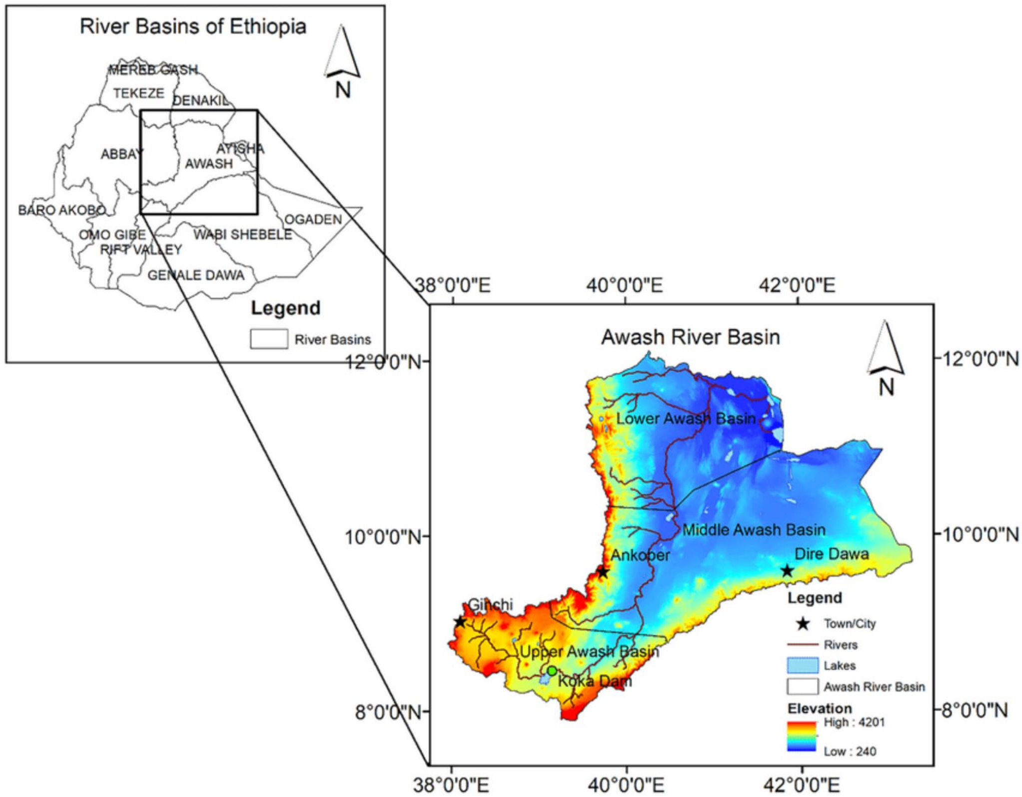

Fig. 1 Location map Awash River Basin (*Image source:* Karimi et al. 2013; Tola and Shetty 2021)

distinctive insights that have not been discovered in previous studies.

Our study clearly aligned with unique contributions for regional and global significances, such as sustainable development goals (SDGs), distinctively Goal 13 climate action, and Goal 15 life on land. Sustainable land use and disaster risk reduction can be achieved thoroughly when flood and soil erosion management is combined with this goal.

Indeed, mapping flood susceptible areas, understanding the potential of flood triggering factors and determining sustainable solutions for flooding and other related problems are vital (Dejene et al. 2017). Hence, this work will attempt to produce a GIS-based flood hazard area map using both AHP model and estimate Soil erosion using USLE model, and discuss the major causes and impacts of flooding and soil erosion in the Awash River Basin. Furthermore, it will strive to comprehend nature-based solutions (NBSs) to lessen the severe risk of flooding and soil erosion in the Awash River Basin. Moreover, this research paper meets the objectives of sustainable development goals (SDG 13) of 2030, which states that, climate change mitigation and adaptation: Investigating strategies to combat global warming and adapt to its effects.

Research methodology and materials

Study area description

Locations

The Awash River Basin is located between 7° 53′ N–12° N latitude and 37° 57′ E–43° 25′ E longitude (Fig. 1). And covered an area of 112,000 km^2, serves as home to 10.5 million inhabitants, and the annual surface water area accounts for approximately 4.9 BM^3 (MEFCC 2018). The elevation fluctuates between 210 and 4195 m above sea level. The total length of the Awash River is 1250 km and cover parts of the Oromia, Somali, Amhara, and Afar regions (Tiruneh et al. 2013). The river rises on the high plateau near Ginchi town, on the west side of the capital city of Addis Ababa, Ethiopia, flows along the Rift Valley into the Afar Triangle, and terminates in the salty Lake Abbe on the border with Djibouti (Sonder and Peden 2008).

The Awash River Basin is divided into three sections on the basis of physical and socio-economic factors: the Upper Awash covers the upstream parts from Koka Dam (areas above 1500 m); the Middle Awash, includes areas between Koka Dam and Awash station (areas between 1000 and 1500 m); and the Lower Awash coveres areas between 500 and 1000 m and the Eastern catchment (MEFCC 2018; Edossa et al. 2010; Hailemariam 1999).

The rainfall pattern is bimodal in upper and middle Awash, with a short rainy season (March–May) and the main rainy season occurs from July to September. The climate of the Awash River Basin varies from humid to arid over the upper parts to the lower parts of the basin.

The soil of ARB is characterized as high clay soils suitable for cotton growing, clay loam and sandy loam for cereals and sugarcane growing, and sandy soil for pasture with range grasses (MEFCC 2018).

Data collection for flood hazard mapping using AHP model

The following scientific instruments were heavily employed in this study to retrieve the required data: the United States Geological Survey (USGS) via (http://glovis.usgs.gov) provides a digital elevation model (DEM) with a resolution of five meters. Other important parameters included land surface elevation (Land Surface Elevation Model) data, annual rainfall data, and soil maps collected from the Ministry of Agriculture, Ethiopian Metrological Agency (EMA) and the FAO soil map website. Layer stacking of every band was performed with ERDAS IMAGINE. Satellite images of Landsat 8/9, captured by Operational Land Imager (OLI) sensor with pixel resolution of 30 m for the time period of 2020, were geo-referenced using the GCSWGS-1984 geographic coordinate system. Zone 37 N of the Universal Transverse Mercator (UTM) projection system was the projected coordinate system utilized for this study area (WGS, 37 N) obtained from USGS.

In addition, field work involves the collection of ground control points (GCPs), a review of various literatures, and other pertinent field data for the assessment of resources as well as land use and cover, identification of flood-prone areas, soil types, and other factors were employed. The satellite image data were analyzed by using different GIS models, via ArcGIS 10.8.

Flood hazard factors used for AHP model

The models are developed using the DEM, and the DEM is reclassified into very high flood hazard areas, high flood hazard areas, moderate flood hazard areas, low flood hazard areas and very low flood hazard areas using equal intervals of separation on the basis of the degree of severity of flooding. Flood causative factors such as slope, rainfall, elevation, LULC, drainage density, proximity to rivers and soil type were developed, reclassified and weighted using ArcGIS 10.8 to generate flood hazard map (Getahun and Gebre 2015). Finally, following weighted overlay, a flood hazard area map of the Awash River Basin (ARB) was produced.

The major flood generating factors used for flood hazard assessment are Elevation, Slope, drainage -density, Rainfall, Proximity to river, Land use and Soil type. Based on their capacity to flood the region, flood producing raster layers have been categorized according to earlier studies (Abebe 2007; Bapalu 2013; Yalcina et al. 2011; Juan 2006; Bishaw 2012; Knoop 2013). Flood hazard factors are assessed using a scale from 1 to 9, where a score of 1 signifies that both elements hold equal importance, whereas a score of 9 indicates a greater significance of one component over the other. Conversely, the reciprocals 1/1 and 1/9 reflect a situation where one element is considered less critical than the other (Table 1) (Saaty 1980; Saaty and Vargas 1991). To perform a multi-criteria evaluation of the influence on flood generation in the study area, the weights of these factors were analyzed.

Elevation

The ArcGIS environment and the DEM are used to build the elevation raster layers. Using the ArcGIS environment's categorization tool, the elevation raster layers were reclassified into five groups. According to many scholars likelihood of flooding can be severe when the elevation decreases, and contrariwise (Wondim 2016; Argaz et al. 2019; Choubin et al. 2019; (Al-Rawas et al. 2001; Nyarko 2002; Islam 2000; Bapalu 2005; Peduzzi et al. 2005; Sanyal 2003; Shrestha 2004; Todini et al. 2004; UNDP 2004; Gazi et al. 2019; Ogato et al. 2020). The research region was classified into five categories on the basis of how the flood threat was impacted by elevation:

Table 1 Satty's scale of relative importance (Saaty 1980; Saaty and Vargas 1991)

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type
Elevation	1	2	3	5	7	7	9
Slope	1/2	1	2	3	5	7	9
Drainage density	1/3	1/2	1	3	5	5	7
Rainfall	1/5	1/3	1/3	1	3	5	7
Proximity to river	1/7	1/5	1/5	1/3	1	3	5
Land use	1/7	1/7	1/5	1/5	1/3	1	3
Soil type	1/9	1/9	1/7	1/7	1/5	1/3	1

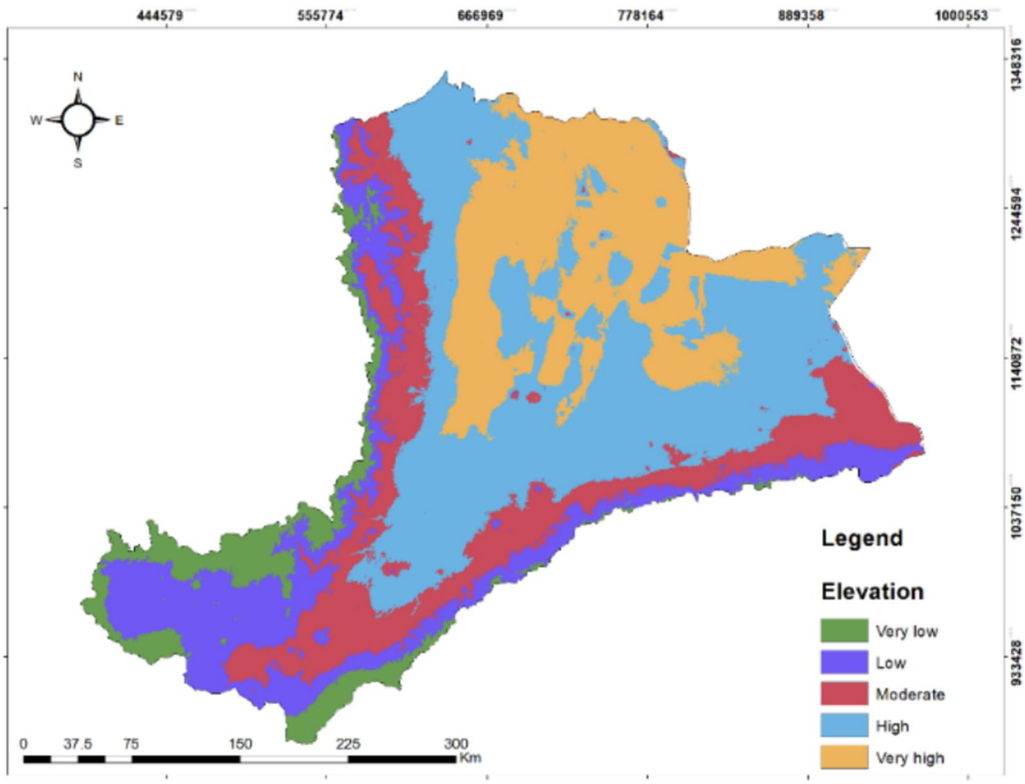

Fig. 2 Elevation map of Awash River basin

Very high (210–680 m), high (680–1104 m), moderate (1104–1659 m), low (1659–2287 m) and very low (2287–4171 m) (Fig. 2).

Slope

The slope is the ratio of a feature's steepness or degree of inclination to the horizontal plane. Slope is an important indicator of flood-prone surface zones (Alemayehu 2007; Wondim 2016). Moreover, inversely, the more inclined the terrain is, the greater the slope value. The lower the slope value is, the gentler the terrain. In the ArcGIS conversion tool environment, DEMs were converted into slopes and reclassified into five classes. When classifying, keep in consideration that higher flood vulnerability corresponds with a lower slope value and vice versa. Hence, based on this, class very high is less than 8% and given rank was 5, class high (8–21%) and ranked 4, class moderate (21–40%) ranked 3, class low (40–67%) ranked 2 and class very low which is (>67%) ranked 1 (Fig. 3).

Rainfall

Rainfall is a significant factor in creating a flood danger map. The rainfall map was created using the inverse distance weight method from historical rainfall data collected from meteorological stations located in and around the research area (Ogato et al. 2020; Desalegn and Mulu 2020). The Awash River basin's mean annual rainfall ranges from 940 to 1158 mm.

Rainfall intensity is important in causing flooding, so weight was assigned to rainfall classes. The runoff that causes flooding increases with increasing rainfall, and vice versa (Adiat et al. 2012; Blistanova et al. 2016; Gazi et al. 2019). Hence, the average rainfall of the raster layer was classified into five classes. An area with higher rainfall, classified as class very high which is greater than 1100 mm/year and ranked as 5, class high (1100–800 mm/year) ranked as 4, moderate (800–600 mm/year) ranked as 3, low (600–400 mm/year) ranked as 2 and very low ranked as 1 (<400 mm/year) (Fig. 4).

Drainage density

The DEM was used to compute the drainage density (Valleys) using the spatial analyst extension. However, all the valleys do not necessary carry water. The drainage density is the total length of all the streams and rivers in a drainage basin divided by the total area of the drainage basin (Rahmati et al. 2016). The drainage density is an inverse function of the soil permeability. A low permeable surface area is prone to high drainage density, and water from precipitation also leads to

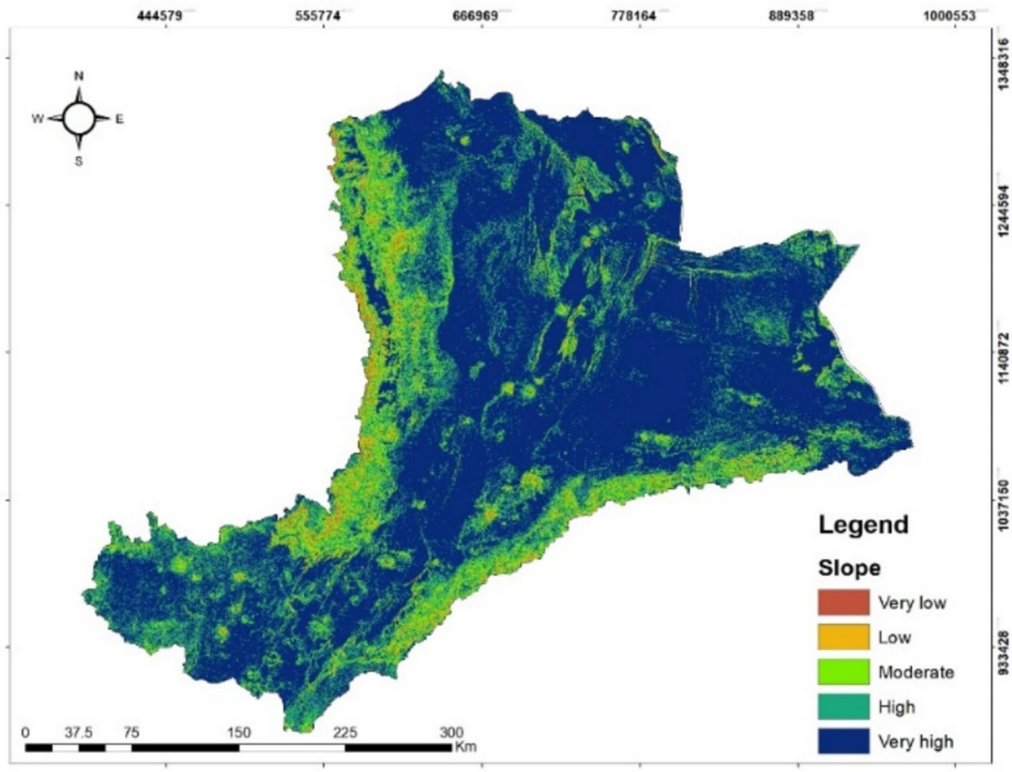

Fig. 3 Slope map of Awash River basin

high runoff and vice versa. As a result, greater drainage density means that the area is prone to flooding (Chibssa 2007; Wondim 2016; Paul et al. 2019). The drainage density layer was classified into five classes using a natural break. An area with a higher drainage density which is (11 km/km^2–17 km/km^2) is classified as very high and ranked as class 5, class high (6.7–11 km/km^2) ranked as 4, class moderate (3.7–6.7 km/km^2) ranked as 3, class low (2–3.7 km/km^2) ranked as 2 and class very low ranked as 1 (< 2 km/km^2) (Fig. 5).

Proximity to river

One of the primary criteria used to evaluate flood hazard map generation in the study basin was river proximity. River overtopping and flooding in river buffer zones are the most common cases in the study area (Bapalu and Sinha 2005; Rincón et al. 2018; Vojtek and Vojteková 2019). In this study, the class was divided into five categories based on its effect on flood menace, namely very high (0–1000 m), high (1000–2000 m), moderate (2000–5000 m), low (5000–8000 m) and very low (8000–15,000 m) which are derived from the basin river network (Fig. 6). The proximity map was reclassified and combined with other criterion maps for weighted overlay analysis.

Land-use land cover

The LULC of a basin influences infiltration rates, surface and groundwater interactions, and debris flows. Flooding is indirectly impacted by land cover as it directly affects several hydrological cycle characteristics, including as interception, infiltration, concentration, and runoff behavior. When combined, these features provide details regarding the hydrological response and level of flood risk (El Morjani 2011; Sarma 1999; Nyarko 2002; Islam 2000; Bapalu 2005; Peduzzi et al. 2005; UNDP 2004). The Awash River basin land use/land cover was reclassified into five classes and converted into a raster layer based on its ability to increase or decrease the flood rate.

Bare land was assigned as very high class and ranked as 5, urban/built up land was classified as high class and ranked as 4, agricultural land was classified as moderate and ranked as 3, wetland/shrub land was classified as low and ranked as 2, and forestland was classified as very low and ranked as 1, as shown in Fig. 7.

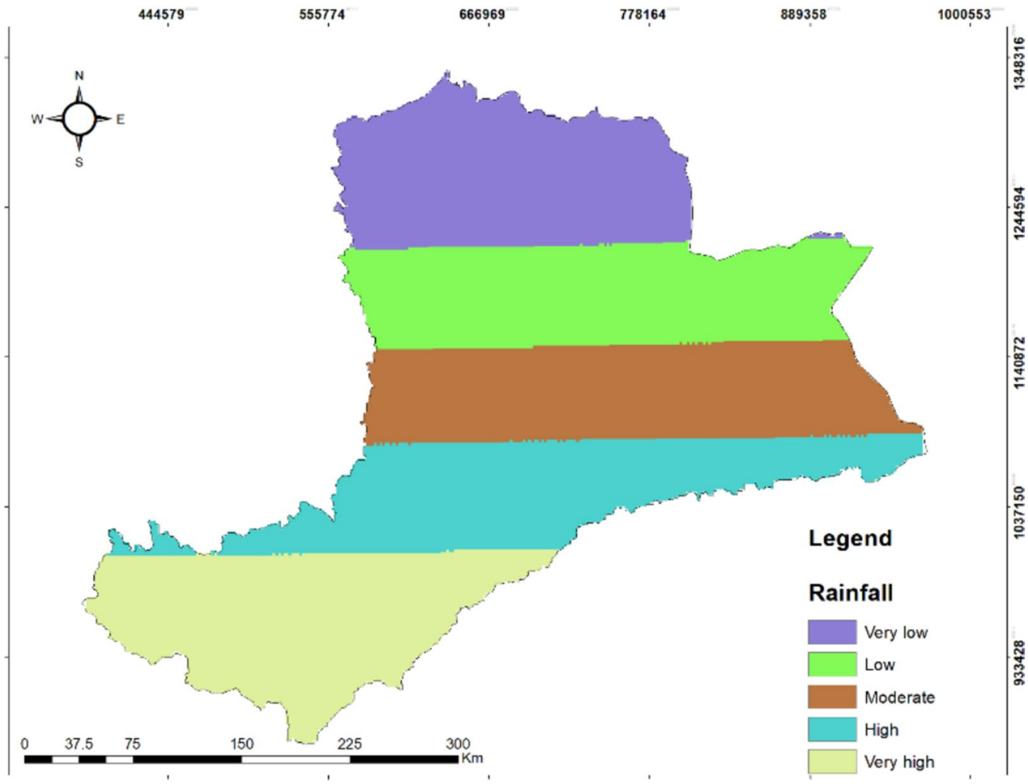

Fig. 4 Rainfall map of Awash River basin

Soil types

Despite the large variety of soil types, the hydrologic soil grouping method of the Ministry of Water and Energy in Ethiopia allows for the distinction of five primary soil classes. The classes are: Pellic Vertisols, Chromic Vertisols, Chromic Luvisols, Euthric Nitosols, and Lithosols (Abebe et al. 2007). These five categories of soil types underwent raster conversion and were reclassified according to their propensity to generate floods. Hence, very high ranked as Class 5, high ranked as Class 4, moderate as Class 3, low as Class 2, and very low as Class 1. Thus, it is assumed that Pellic Vertisols have a very high flooding capacity and reclassified as class 5, Chromic Vertisols have a high flooding capacity then reclassified as class 4, Chromic Luvisols/cambisols have a moderate class 3 flooding capacity, Euthric Nitosols have a low class 2 flooding capacity, and Lithosols have a very low flooding capacity then reclassified as class 1 (Fig. 8). Furthermore, according to Abebe et al. (2007), the predominant soil type in the Awash River Basin is vertisols.

Each weight was determined based on its contribution to flood hazard in the study area, topographical considerations and experimental judgments acquired from various experts (Tables 2, 3 and 4) (Wondim 2016; Argaz et al. 2019; Gazi et al. 2019; Vojtek and Vojteková 2019; Hussain et al. 2021).

Moreover, Jodhani et al. (2024) and Riaz and Mohiuddin (2025) reiterates that a multi criteria decision method (MCDM) employing the AHP technique was used to construct the relative weights for each raster layer, and the relative relevance of each indicator was established by assigning rankings based on information from published studies and expert perspectives.

Multi criteria (AHP) methodology and analysis of flood hazard map

The AHP, a multi-criteria decision-making technique, was used to rank and weight the flood causative factors depending on their potential impact on the outcome. The Analytic Hierarchy Process (AHP) is a multi-criteria decision making strategy that offers a methodical way to evaluate and integrate the effects of different elements. It involves many layers of dependent and independent, qualitative and quantitative information. It is a process for methodically comparing pairs of activities or criteria to ascertain their relative importance (Saaty 1980; Yalcina et al. 2011). Additionally, AHP has been widely used and

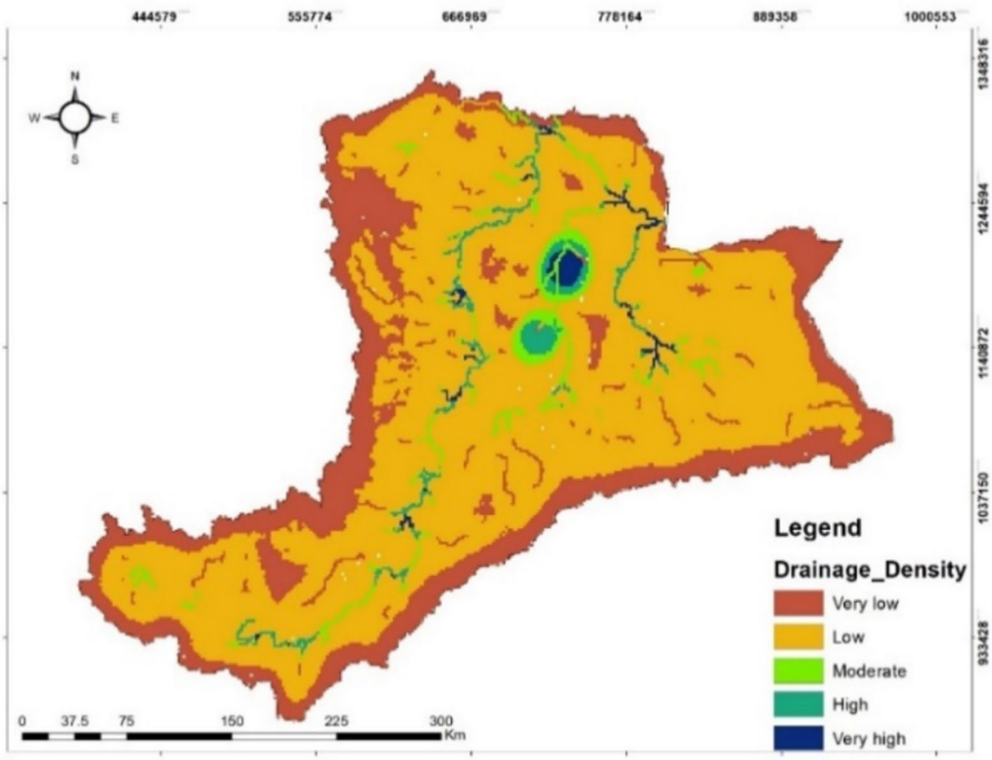

Fig. 5 Drainage density map of Awash River basin

preferred due to its simplicity, reliability, and effectiveness (Abdel karim et al. 2020; Kafle 2018).

Hence, the rasterized and reclassified potential flood generating factors are weighted, and pair-wise comparisons are made (Table 5). Following a weighted overlay analysis of these layers, a final map was produced and classified according to the impact of each layer on flood hazard.

The weighting technique is used to determine the relative importance of one factor in relation to another. The higher the weight, the more significant the component in weighted overlay compared to other factors. Relative comparisons of the seven raster layers were done. Therefore, Using a GIS and the Analytical Hierarchical Process (AHP), the elevation, slope, Drainage density, Rainfall, Proximity to river, land use and soil type are considered when generating flood hazard map (Bapalu 2013; Yalcina et al. 2011; Juan 2006; Bishaw 2012).

The calculated consistency ratio (CR) values are computed by using (Eqs. 1, 2 and 3) and should meet the scientific standard, which is less than (<0.1). Hence, the calculated Consistency ratio for pair-wise weights comparison was ***0.07*** which is pair-wise weights are at acceptable level (Table 6). In addition, the CR results verify that the consistency of judgments is coherent.

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}. \tag{1}$$

Consistency index (CI) value can be obtained by:

$$\mathrm{CI} = \frac{\lambda_{\max} - n_i}{n_i - 1}, \tag{2}$$

$\lambda_{\max}$ obtained from the following equation:

$$\lambda_{\max} = \sum_{n=1}^{n_i} \frac{(\mathrm{PW})_n}{n_i\, w_n}, \tag{3}$$

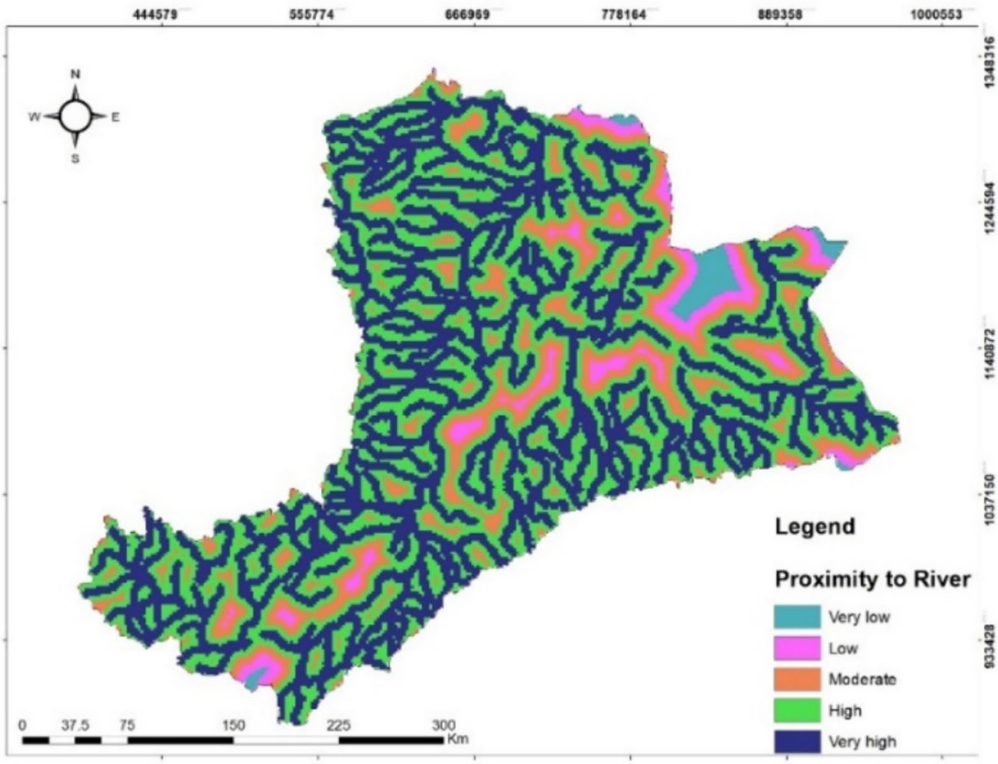

Fig. 6 Proximity to river

where, W is the weight vector (column).

$$\lambda_{\max} = \frac{7.7 + 6.6 + 8.1 + 10.2 + 7.5 + 6.25 + 6.5}{7} = 52.85/7 = \mathbf{7.55},$$

$$\mathrm{CI} = \frac{\lambda_{\max} - n_i}{n_i - 1} \quad \frac{7.55 - 7}{7 - 1} = 0.09166,$$

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} \quad \frac{0.09166}{1.32} = 0.069 = 0.07$$

The random index (RI) can be acquired from standard tables (Table 7) (Saaty 1980). RI value determined by the number of the parameters, hence, random inconsistency value for seven parameters is ***1.32*** as per clearly stated in the table.

A weighted value obtained from pairwise comparison shows that, the highest weight is given to elevation, followed by slope factor, drainage density, rainfall, proximity to rivers, land use and soil type to be merged together in ArcGIS. The flood hazard map for the Awash River basin was produced based on the formula/equation (Eq. 4):

$$\text{Flood hazard} = \sum W_i X_i, \tag{4}$$

where

W_i = weight of factor i;

X_i = criterion score of factors i.

Hence, based on the calculated and finding results of weighted factor the flood hazard map for study area can be generated as follows.

$$\begin{aligned}\text{Flood hazard} = {} & 0.36 \times [\text{Elevation}] + 0.24 \times [\text{Slope}] \\ & + 0.17 \times [\text{Drainage density}] + 0.11 \\ & \times [\text{Rainfall}] + 0.06 \times [\text{Proximity to river}] \\ & + 0.04 \times [\text{Land use}] + 0.02 \times [\text{Soil type}]\end{aligned}$$

Soil erosion analysis using USLE model

The techniques for predicting soil loss have evolved over time. The most often used equation for estimating soil loss over an entire river basin is the Universal Soil Loss Equation (USLE), which consists of five elements whose values are determined using their formulas. The following empirical equation, which is the sum of five

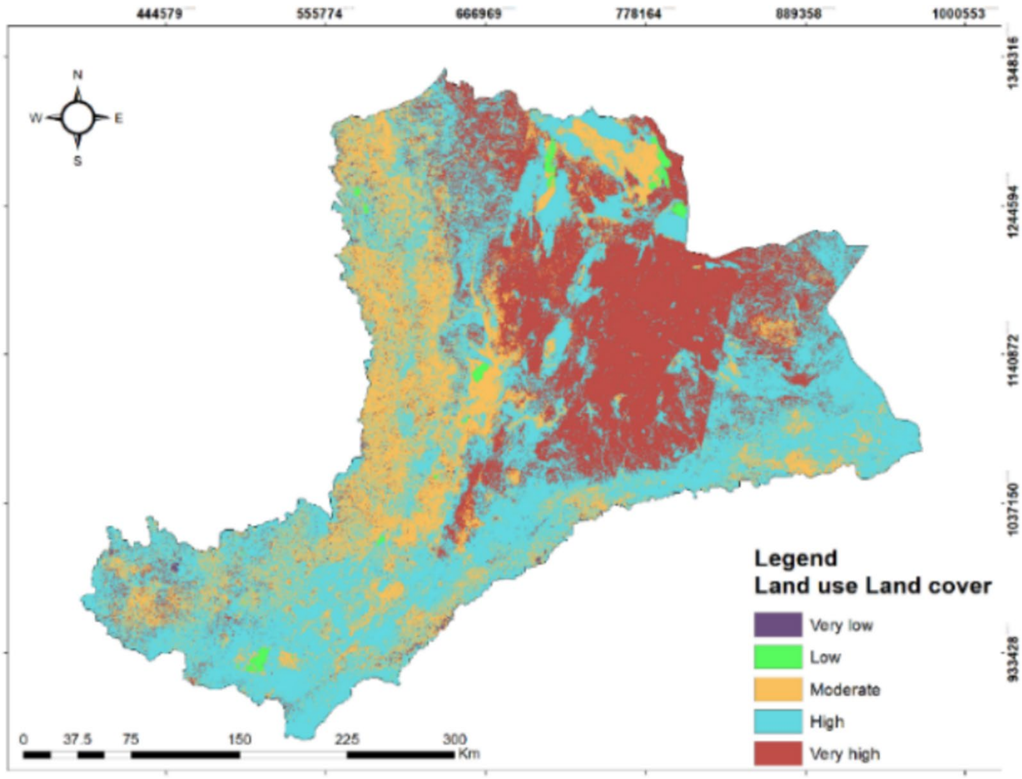

Fig. 7 Land use land cover map of Awash River basin

Table 2 Satty's scale format

Intensity of importance	Degree of preference	Explanation
1	Equal importance	Two activities contribute equally to the objective
3 (1/3)	Moderate importance of one factor over another	Experience and judgment slightly favor one activity over another
5 (1/5)	Strong or essential importance	Experience and judgment strongly favor one activity over another
7 (1/7)	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9 (1/9)	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 3 Satty's scales in decimal form

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type
Elevation	1	2	3	5	7	7	9
Slope	0.5	1	2	3	5	7	9
Drainage density	0.33	0.5	1	3	5	5	7
Rainfall	0.2	0.33	0.33	1	3	5	7
Proximity to river	0.14	0.2	0.2	0.33	1	3	5
Land use	0.14	0.14	0.2	0.2	0.33	1	3
Soil type	0.11	0.11	0.14	0.14	0.2	0.33	1
Sum	2.42	4.28	6.87	12.67	21.53	28.33	41

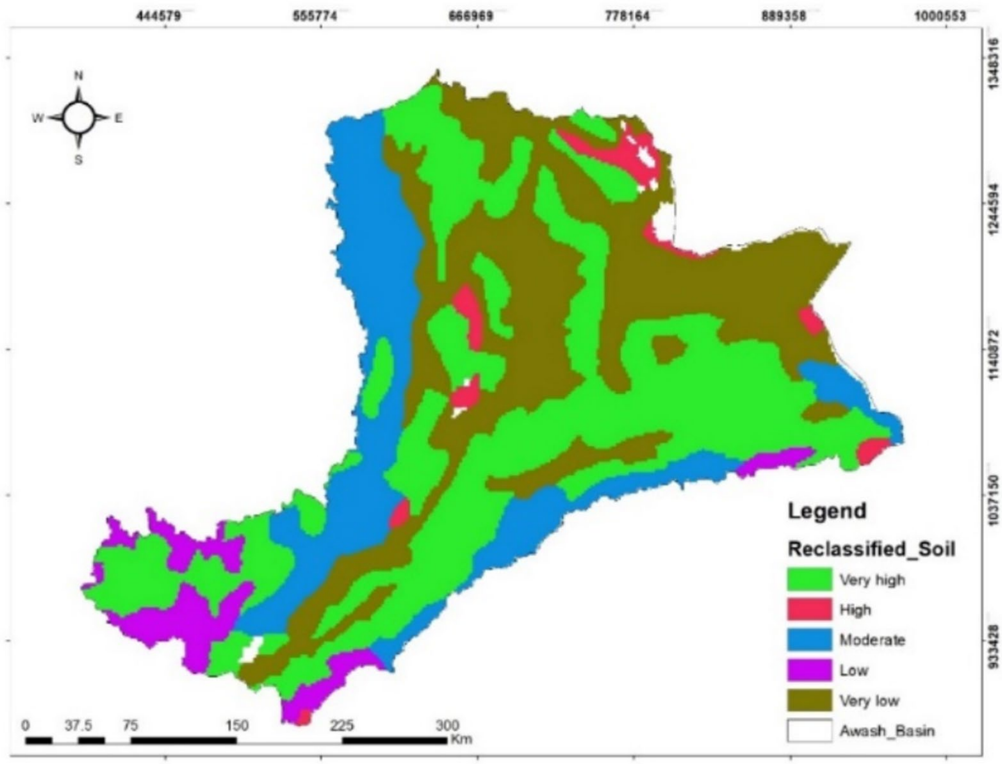

Fig. 8 Reclassified soil map

Table 4 Normalized pairwise matrix (dividing each cell by sum of values of corresponding column)

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type
Elevation	0.4	0.47	0.44	0.4	0.32	0.25	0.23
Slope	0.2	0.23	0.3	0.24	0.23	0.25	0.23
Drainage density	0.13	0.12	0.15	0.24	0.23	0.17	0.17
Rainfall	0.08	0.1	0.05	0.1	0.14	0.17	0.17
Proximity to river	0.06	0.05	0.03	0.03	0.04	0.11	0.12
Land use	0.06	0.03	0.03	0.02	0.01	0.04	0.1
Soil type	0.045	0.026	0.02	0.01	0.01	0.01	0.02

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type	Criterion weight (each pair/N_{total})
Elevation	0.4	0.47	0.44	0.4	0.32	0.25	0.23	***0.36***
Slope	0.2	0.23	0.3	0.24	0.23	0.25	0.23	***0.24***
Drainage density	0.13	0.12	0.15	0.24	0.23	0.17	0.17	***0.17***
Rainfall	0.08	0.1	0.05	0.1	0.14	0.17	0.17	***0.11***
Proximity to river	0.06	0.05	0.03	0.03	0.04	0.11	0.12	***0.06***
Land use	0.06	0.03	0.03	0.02	0.01	0.04	0.1	***0.04***
Soil type	0.045	0.026	0.02	0.01	0.01	0.01	0.02	***0.02***

Bold and italics is used to indicate the significance level of the numbers on the flood hazard map

important erosion-governing characteristics, was used to quantify soil erosion in the study area using the USLE model (Wischmeyer 1978):

$$A = R \times K \times LS \times C \times P$$

Table 5 Final Eigen vector weights of each parameter on the basis of pairwise matrix comparison

	Criterion weight (normalized weight)	Influence (%)
Elevation	0.36	36
Slope	0.24	24
Drainage density	0.17	17
Rainfall	0.11	11
Proximity to river	0.06	6
Land use	0.04	4
Soil type	0.02	2
Total	1.00	100

Numerous sources are used to obtain the USLE model variables. The tropical rainfall measurement mission (TRMM) website and Ethiopian Metrological Agency (EMA) provides annual rainfall data, which are used to calculate the rainfall erosivity factor (R-value). The FAO soil portal database is also used to calculate the soil erodibility factor (K value), which is composed of the organic matter content, texture, and structure of the soil in the research area. The slope gradient factor (LS value) and slope length were derived from the analysis of DEMs with a resolution of 30 m, obtained from United States Geological Survey (USGS). Landsat 7 images and DEMs of the study region were examined to estimate the crop factor (C) and conservation practice factor (P) (Fig. 9).

Methodological limitations

Remote sensing has provided us with adequate information for both flood hazard and USLE mapping analysis; however, it is important to realize a number of limitations. The accuracy of remote sensing data was greatly impacted by atmospheric conditions, sensor calibrations, and varying land cover characteristics. Furthermore, biases may occur during classification due to overlap in spectral signatures among various land cover types, which could distort the land use classification. Therefore, the quality and data accuracy of subsequent research can be greatly improved by integrating high resolution imaging with ground truth validation, including field surveys.

Result and discussion

The flood hazard analysis results (Table 8 and Fig. 10) revealed that the majority of the basin, which accounts for 5,855,130.12 Ha (51.4%), is vulnerable to high flood hazards, and the second highest area coverage is subjected to moderate vulnerability to flood hazards,

Table 6 Derived consistency ratio (CR)

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type
Elevation	1* (0.36)	2* (0.24)	3* (0.17)	5* (0.11)	7* (0.06)	7* (0.04)	9*(0.02)
Slope	0.5* (0.36)	1* (0.24)	2* (0.17)	3* (0.11)	5* (0.06)	7* (0.04)	9*(0.02)
Drainage density	0.33* (0.36)	0.5* (0.24)	1* (0.17)	3* (0.11)	5* (0.06)	5* (0.04)	7*(0.02)
Rainfall	0.2* (0.36)	0.33* (0.24)	0.33* (0.17)	1* (0.11)	3* (0.06)	5* (0.04)	7*(0.02)
Proximity to river	0.14* (0.36)	0.2* (0.24)	0.2* (0.17)	0.33* (0.11)	1* (0.06)	3* (0.04)	5*(0.02)
Land use	0.14* (0.36)	0.14* (0.24)	0.2* (0.17)	0.2* (0.11)	0.33* (0.06)	1* (0.04)	3*(0.02)
Soil type	0.11* (0.36)	0.11* (0.24)	0.14* (0.17)	0.14* (0.11)	0.2* (0.06)	0.33* (0.04)	1*(0.02)
Criterion weight	0.36	0.24	0.17	0.11	0.06	0.04	0.02

	Elevation	Slope	Drainage density	Rainfall	Proximity to river	Land use	Soil type	Weighted sum value	Criterion weight	Ratio
Elevation	0.36	0.48	0.51	0.55	0.42	0.28	0.18	**2.78**	*0.36*	***7.7***
Slope	0.18	0.24	0.34	0.33	0.03	0.28	0.18	**1.58**	*0.24*	***6.6***
Drainage density	0.12	0.12	0.17	0.33	0.3	0.2	0.14	**1.38**	*0.17*	***8.1***
Rainfall	0.07	0.07	0.05	0.11	0.48	0.2	0.14	**1.12**	*0.11*	***10.2***
Proximity to river	0.05	0.048	0.034	0.036	0.06	0.12	0.1	**0.45**	*0.06*	***7.5***
Land use	0.05	0.03	0.034	0.02	0.02	0.04	0.06	**0.25**	*0.04*	***6.25***
Soil type	0.03	0.02	0.023	0.015	0.012	0.013	0.02	**0.13**	*0.02*	***6.5***

The asterisk (*) signifies the multiplication of specified numbers, weighted by a given criterion or number placed within brackets

Table 7 Random inconsistency value (RI)

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI value	*0.00*	*0.00*	*0.58*	*0.90*	*1.12*	*1.24*	***1.32***	*1.41*	*1.46*	*1.49*

Bold and italics is used to indicate the significance level of the numbers on the flood hazard map

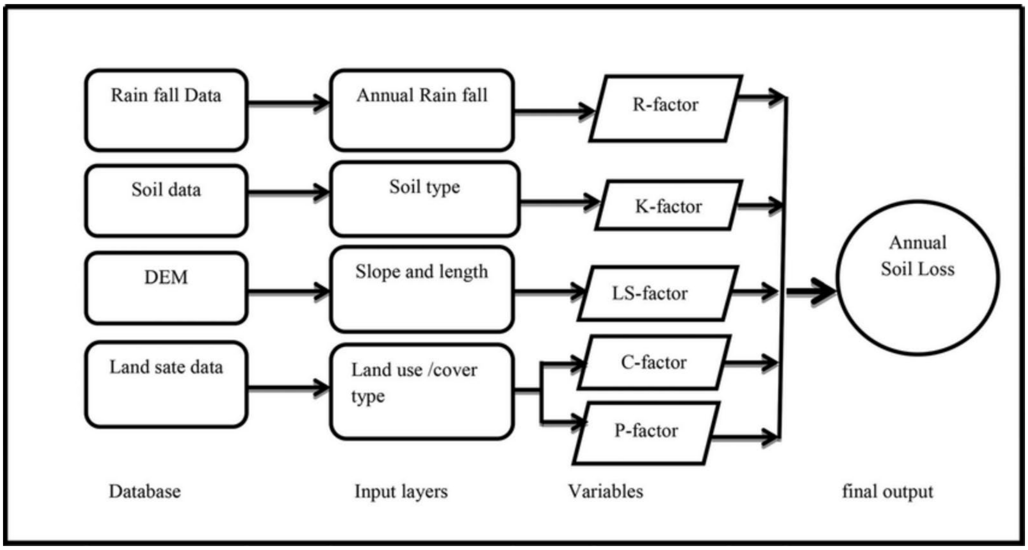

Fig. 9 Methodological workflow for estimating soil loss: image source (Endalamaw et al. 2021)

Table 8 Flood hazard area coverage

Hazard class	Area coverage in Ha	Percentage (%)
Very low	10,428.67	0.1
Low	866,358.09	7.6
Moderate	4,625,378.51	40.6
High	5,855,130.12	51.4
Very high	23,481.11	0.2
Total		100

accounts for 4,625,378.51 Ha (40.6%) of the total awash river basin area coverage. An area of 866,358.09 Ha (7.6%) in the basin is exposed to low flood hazard threats. The drainage density, elevation and slope level contribute more to flood hazard exposure comparing with the other parameters, and many previous studies have also supported this stipulation. The drainage density is directly linked to flooding; as the drainage density increases, the probability of flooding also increases, whereas a decrease in drainage density leads to a lower flood risk. Furthermore, high drainage density results in greater surface runoff, which in turn increases flood risk in areas with elevated drainage density (Paul et al. 2019; Das 2019).

The likelihood of flooding is minimal in elevated regions but significantly greater in low-lying areas (Das 2019; Khosravi et al. 2019). Additionally, flatter slopes are more susceptible to floods and flood events (Radmehr and Araghinejad 2015; Khosravi et al. 2018).

Riaz and Mohiuddin (2025) also reiterate that slope is important characteristic that determines flood-prone surface zones, according to the results of the AHP techniques, which prioritize pertinent aspects of flood occurrences.

The volume of registered rainfall in the area facing a higher flood risk is very low; thus, the more significant rainfall observed in the upper basin has led to considerable flood hazard impacts in the lower basin area. Furthermore, various studies stipulate that flood hazards in the Awash River basin, particularly in major cities such as, Dire Dawa, are strongly interlinked with rainfall patterns. Factors such as the duration, magnitude and intensity of rainfall affect flood formation (Erena and Worku 2018; Hong et al. 2018; Sahana 2019; Das 2019).

Certain portions of the Awash River Basin, such as the area near Dubti down to Lake Abe, the area between Debele and Gewane around Lake Yardi, and the area 30 km north of Awash town, have reported repeated flooding following the main rainy season, as stated by the Ministry of Water and Energy (Girma Taddese 2010).

Most downstream parts of Awash River basin are exposed to severe flood hazards due to urbanization and the expansion of agricultural lands. Scholars have highlighted that, urban areas adjacent to rivers face heightened flooding risks because of their valuable economic assets, critical infrastructure, and high population density (Khosravi et al. 2016a, b; Das 2018). According to Bishaw (2012), a shift in land use, which includes increasing agricultural production, raised the overflow magnitude and created a high flood hazard zone in the river basin downstream regions. Hence, in the Awash River Basin, recurrent floods have become more frequent every year, resulting in significant financial losses as well as related

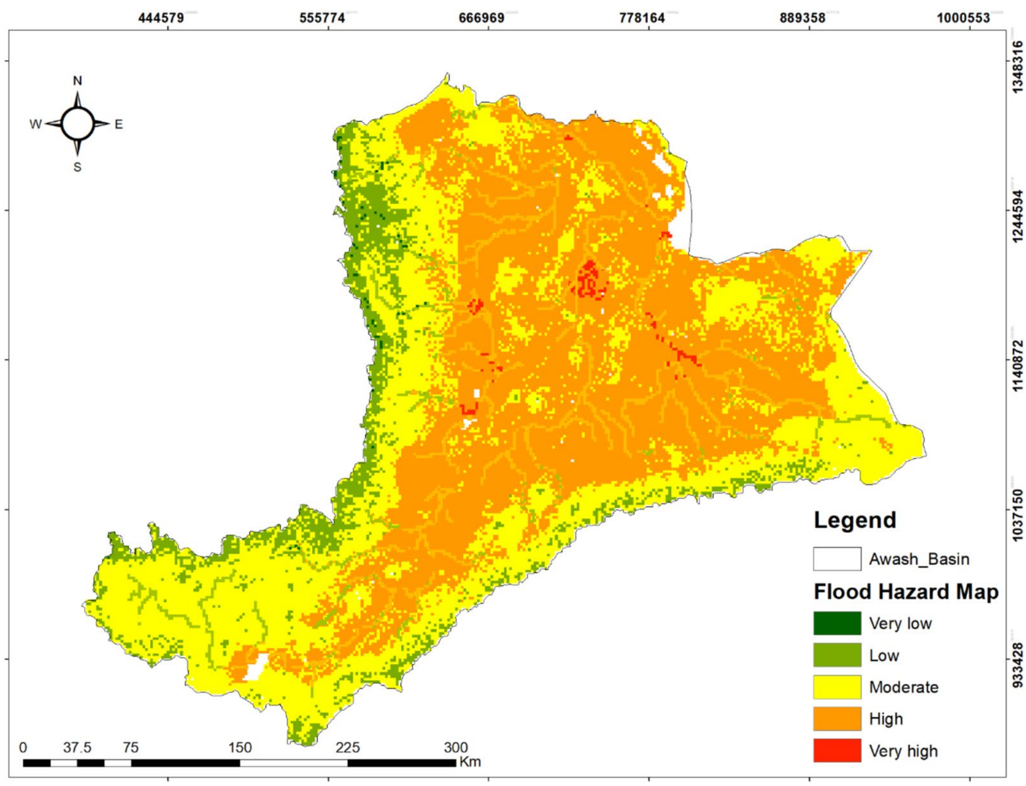

Fig. 10 Flood hazard map of Awash River basin

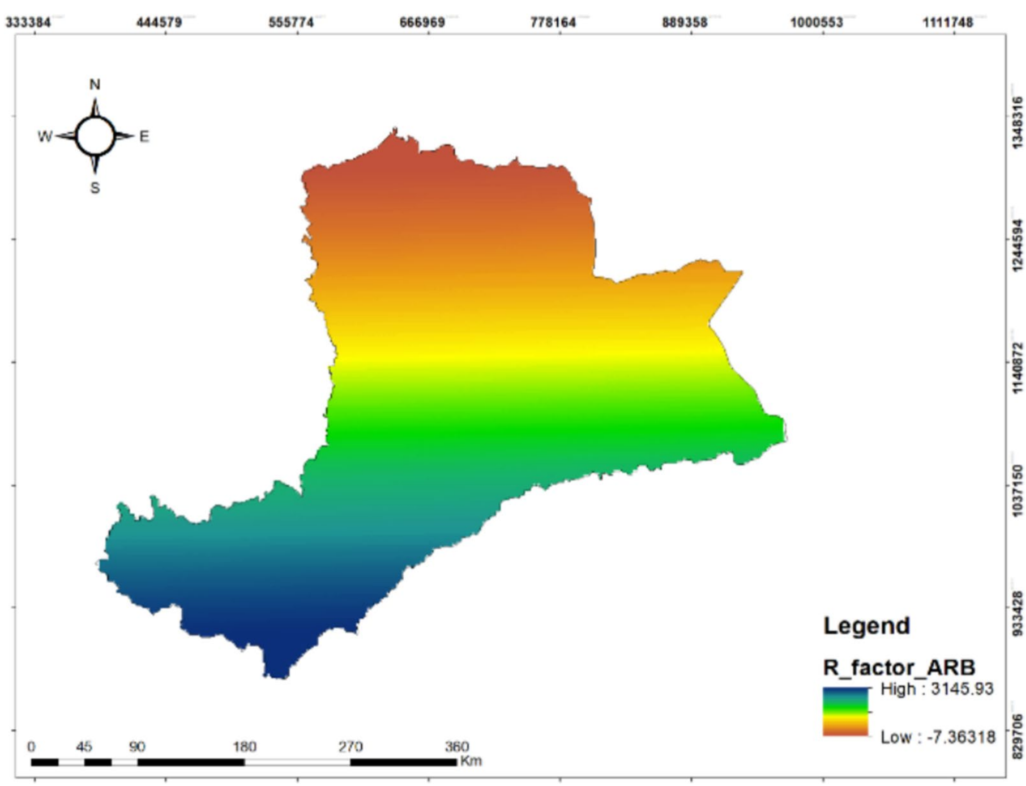

Fig. 11 R factor

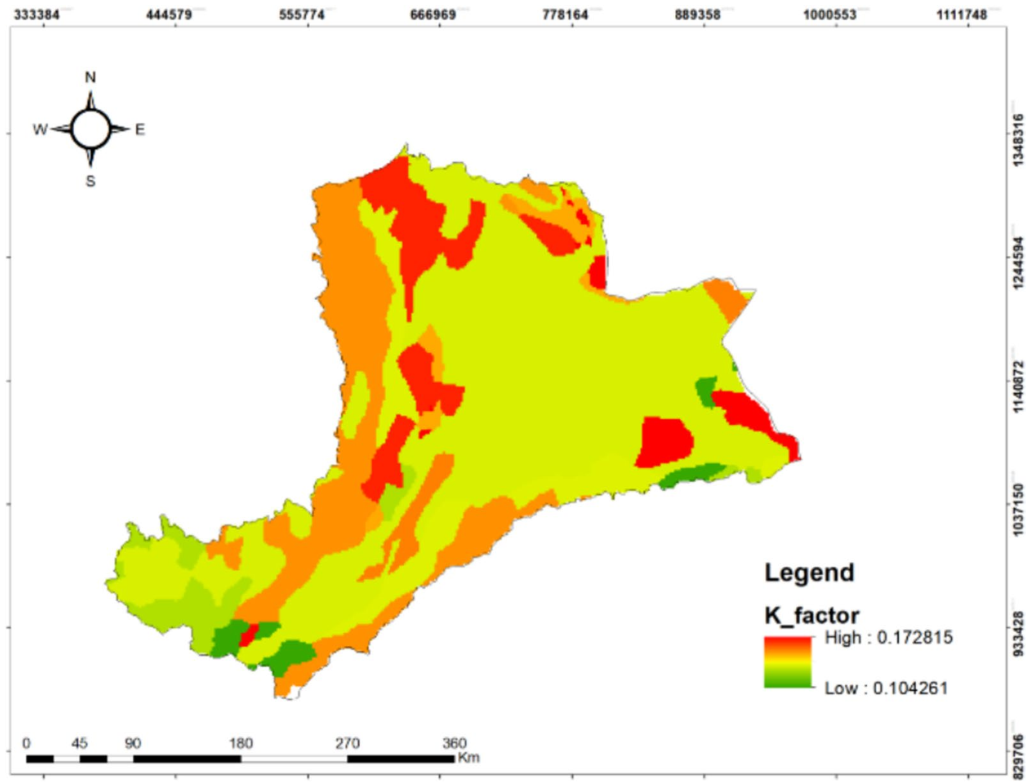

Fig. 12 K factor

societal effects. The climate and other related factors are the main reasons for this. The basin has experienced increases in urbanization, agriculture, and grazing areas, all of which drastically decrease the permeability of the ground and improve overland flow. As a consequence, the basin experiences floods every year.

Soil erosion estimation parameters

The value of the rainfall erosivity factor (*R*) in the Awash River basin, which was estimated to range from − 7.36318 to 3145.93 MJ mm ha^{-1} h^{-1} $year^{-1}$ (Fig. 11), is greater than many other findings because of the higher rainfall intensity in the study area, especially in the upper catchment and winter seasons. When the *R*-value is lower, the research area experiences less intense rainfall and rainfall that is less likely to erode the soil (Asmamaw 2019). The *K*-value of the study area ranged from 0.104261 to 0.172815 (Fig. 12), which is similar to findings of the *K* value in tropical soils, which ranges from 0.06 to 0.48 EI-Swaify (1982), and according to the FAO–UNDP (1984), the majority of Ethiopian soils have K values between 0.05 and 0.6. The LS factors of the study area range from 0 to 50,773.1 (Fig. 13), and scholars have reported that higher LS values indicate greater erosion vulnerability due to high velocity and runoff accumulation. The C-factor of the Awash River Basin ranges from 0 to 1 (Fig. 14); a relatively high C value indicates increased exposure to soil loss. The area coverage of each land use class is clearly identified. The p factor for the study area ranged from 0.55 to 1 (Fig. 15). A higher P value indicates greater erosion vulnerability in the specified watershed or basin.

Soil loss potential

The average annual soil loss was estimated via analysis of the rainfall Erosivity factor (R), soil erodibility factor (K), slope degree factor (LS), cover management (C), and support factor (P) using the ArcGIS 10.8. The USLE map shows that the annual average soil loss potential (A) in the Awash River Basin is displayed in (Fig. 16). The results illustrate that the annual average soil loss in the basin ranges from 0 to 31,049,739 ton ha^{-1} $year^{-1}$. The highest coverage region of the research area has the lowest result, which ranges from 0 to 121,502 ton ha^{-1} $year^{-1}$, indicating that soil erosion in this part of the basin is minimal. The second-highest area coverage registered 121,502 ton ha^{-1} $year^{-1}$ and 852,091.1036 ton ha^{-1} $year^{-1}$ soil losses, which indicate that soil erosion is largely present and is thought to be of moderate severity.

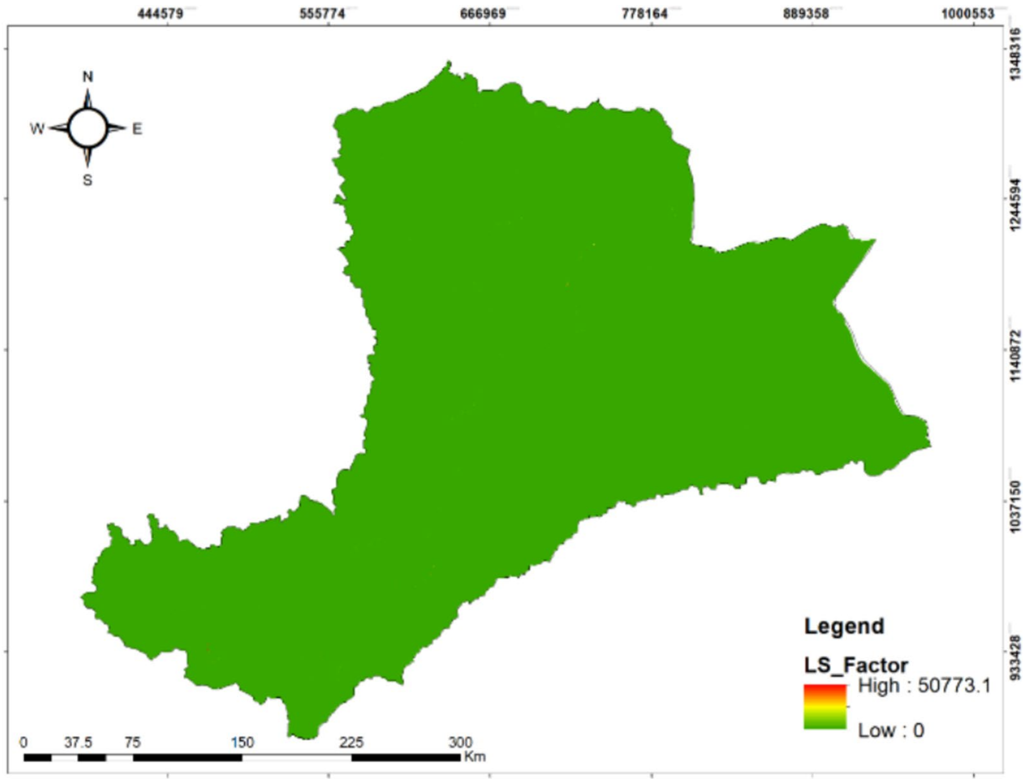

Fig. 13 LS factor

The remaining areas range from 852,091.1036 ton ha^{-1} year^{-1} to 3,165,620.626 ton ha^{-1} year^{-1}, which is considered a high-severity area for soil erosion; the remaining areas range from 3,165,620.626 ton ha^{-1} year^{-1} to 8,766,797.363 ton ha^{-1} year^{-1}, which is considered very high severe; and the remaining 8,766,797.363 ton ha^{-1} year^{-1} to 31,049,739 ton ha^{-1} year^{-1}, which is considered an extremely severe potential area for erosion. The significant reason for this extreme soil erosion is high slope gradient within the Awash River basin; according to Jodhani et al. (2023) LS factor is considered as the main reason for highest soil erosion in Rel River watershed. The large share of the Awash River basin falls under the slope percentage of 0–10%, hence the erosion mainly witnessed in this area is significantly low. Moreover, the presence of forest and grass, which play a vital role in protecting soil from erosion, is also important. According to Kumar et al. (2012), recurrent changes in vegetation cover result in erosion rates, particularly in semiarid regions. Hence, vegetation plays a major role in preventing severe soil erosion.

The total annual estimated soil loss of the Awash River Basin is 31,049,739 ton ha^{-1} year^{-1}, and the mean annual soil loss is estimated to be approximately 28.6 ton ha^{-1} year^{-1}. According to Wolka, Renard and Hurni analysis, this number is above the tolerable limit of soil loss, but, owing to rapid urbanization and the intensive scale of forest degradation, this number is also expected to increase inevitably unless the necessary precautions and measurements take place.

Validation of model results

To make sure the level of accuracy for the utilized hazard model, data calibration and validation is highly recommended by various scholars (Jodhani 2023). While some researchers (Adornado and Yoshida 2010; Nonta Nanandh and Changno 2012) believe that ground trothing is an important tool for improving validation procedures, others (Panagos et al. 2015; Nakil and Khire 2016) recommend comparing the results to other soil erosion results from the same watershed, basin, or at the national or regional scale.

As a result, the validity of this study is assessed by comparing its findings to those of prior studies conducted in the Awash River Basin. Field observations were also conducted to guarantee that the results were accurate, observable, and meaningful. Degife et al. (2021); Yesuph and Dagnew (2019) used comparable approaches. The flood hazard map, which was created by using the Multi-Criteria Decision Analysis (MCDA) method, was

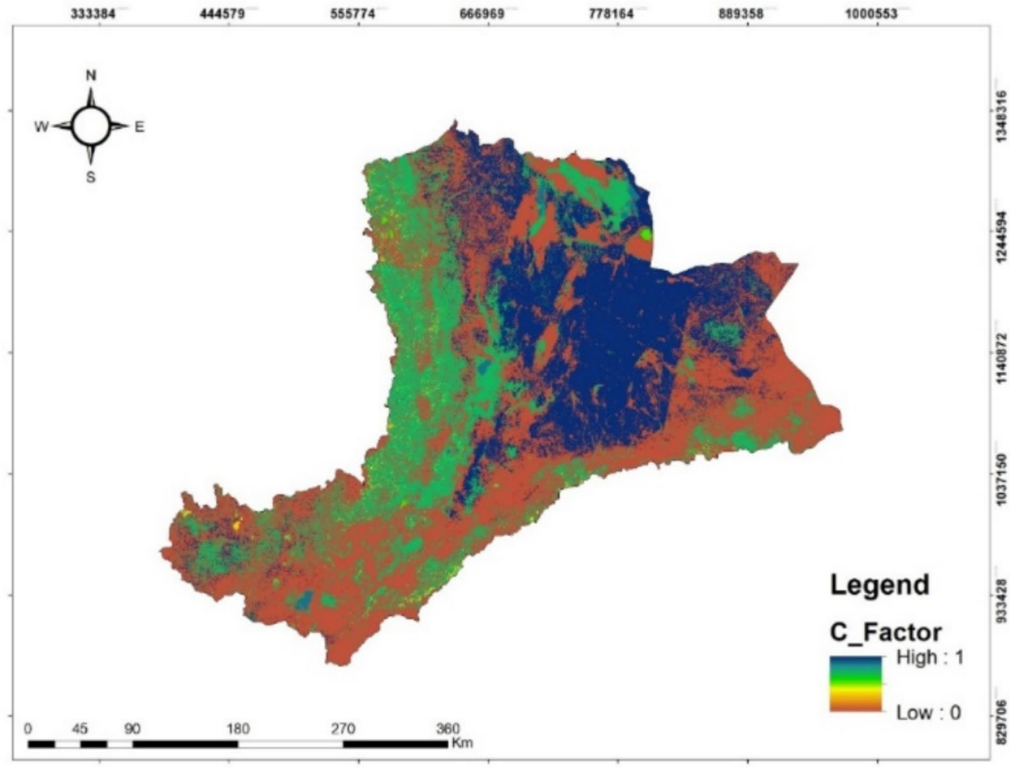

Fig. 14 C factor

thoroughly validated against a historical inundation map based on satellite data. The same techniques are also utilized by Jodhani et al. (2024). To ensure a contextual awareness of the research area, the results from the USLE were also quantitatively compared to those estimated using the revised universal soil loss equation (RUSLE), which is a distinct model used in this paper.

Environmental planning and policy implications

Flood hazard and soil erosion in the Awash River Basin have been modeled and assessed, which supports the critical importance of effective environmental planning and sustainable management of flood hazard and erosion. A systematic approach should be used, including concepts such as integrated land management, community involvement, and effective government policy frameworks. These are concluding studies for land use planning to observe the areas that are most susceptible to flood hazard and erosion, drawing of erosion hazards to guide the region, and ecological restoration regions meant for planting trees and shrubs. Policy measures include supporting programs of likely agro-forestry and likely land use while limiting hazardous activities in weak areas and encouraging monetary support for conservational work (Bewket 2009). The degree of environmental conservation and management will increase if locals are involved through education and agro-ecological methods (Sharma 1999; Bewket and Sterk 2002).

In addition to improving efficient soil and water conservation initiatives that address to their unique demands and concerns, we can readily extract creative and indigenous solutions to flood hazards and soil erosion by collaborating with local people. Farmers can adopt optimal management methods such contour farming, agroforestry, cover crops, reforestation, and afforestation with the active and participatory participation of stakeholders. In the Awash River watershed, community-based conservation initiatives that integrate traditional knowledge can improve resilience against erosion and flood hazards while halting severe soil deterioration. Furthermore, Integrated Water Resources Management and attainment of structures for flood hazard and erosion control ensure substantial soil and water management with the goal of minimizing flood hazard and soil erosion as well as fostering eco-visualization in the basin.

Conclusion

In conclusion, this study effectively utilized Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) to identify and map flood hazard zones

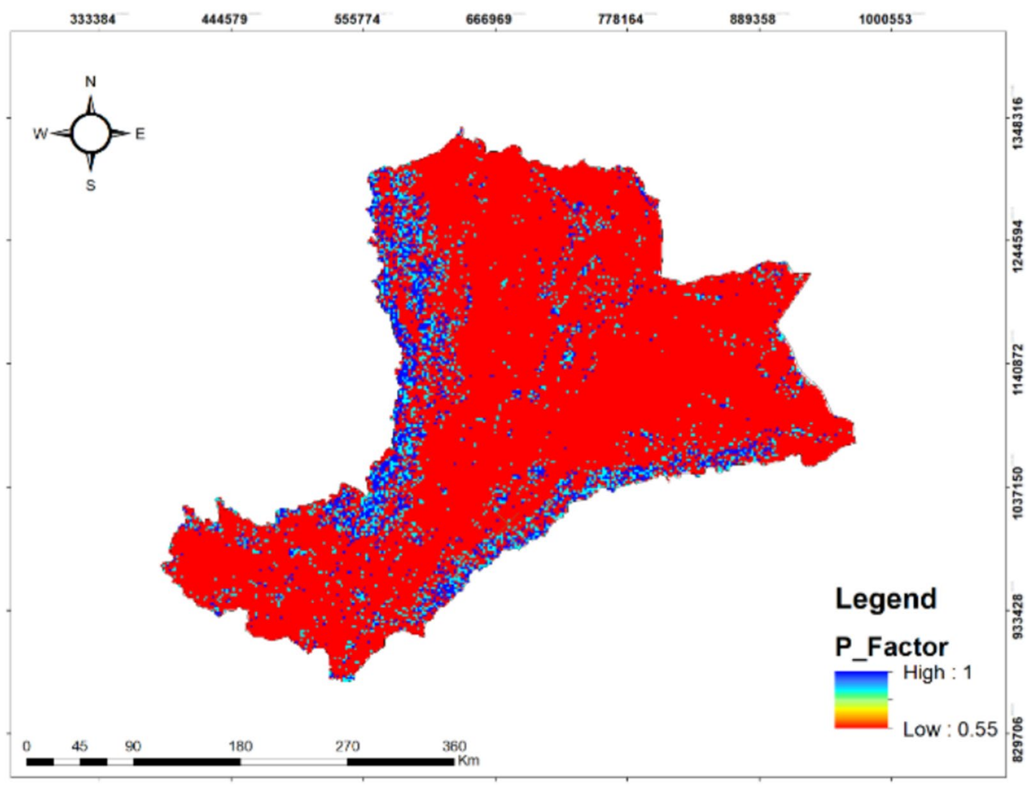

Fig. 15 P factor

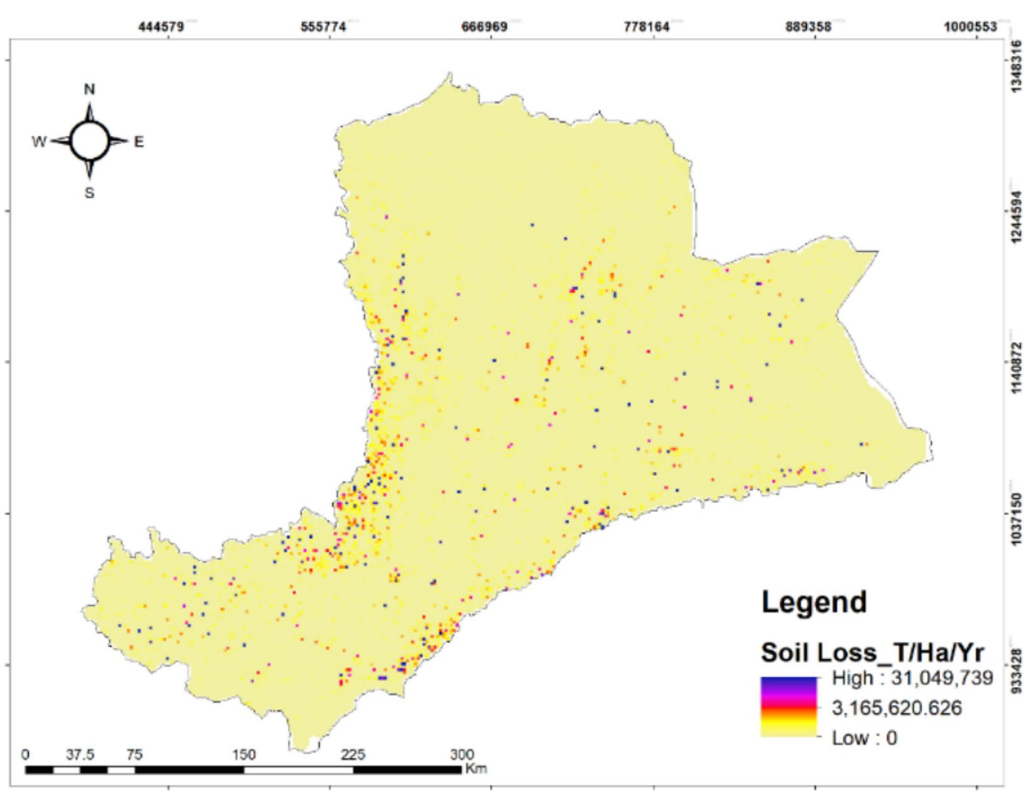

Fig. 16 Soil loss estimation

and assess soil erosion within the Awash River Basin of Ethiopia. The findings reveal that a significant portion of the basin is vulnerable to flooding, with key risk factors including slope, drainage density, and elevation. Urbanization, environmental degradation, and changing climatic patterns exacerbate these flood vulnerabilities, particularly in downstream areas. The accuracy of the flood hazard maps was corroborated by data from the Awash River Basin Authority, thus underscoring the necessity for effective flood management strategies that integrate these maps into urban and regional planning. This should include the establishment of early warning systems and the promotion of sustainable land-use practices that bolster natural drainage systems.

Simultaneously, soil erosion analysis using the Universal Soil Loss Equation (USLE) indicates that the catchment region exhibits low to moderate levels of erosion, with certain areas experiencing extremely high erosion rates, primarily due to heavy runoff from increased rainfall in higher catchments. The majority of the basin's land is slightly prone to erosion, facilitated by well-managed agricultural practices and vegetative cover. However, soil loss can reach alarming levels, with annual losses ranging up to 31,049,739 tons per hectare. Soil loss ranged significantly, emphasizing the need for implementing sustainable land management techniques such as contour farming and agroforestry to enhance soil resilience amidst climate variability. This interrelation between soil erosion and sediment transport significantly impacts both aquatic ecosystems and terrestrial landscapes, necessitating the implementation of sustainable land management techniques such as contour farming and agroforestry to mitigate erosion risks and enhance soil resilience amid climate variability.

The intricate relationship between soil erosion and flooding in the Awash River Basin emphasizes the need for concerted efforts to establish adaptive management strategies tailored to local contexts, ensuring ecological rehabilitation and the sustainability of agricultural systems in vulnerable regions. Future research should enhance predictive models that reflect the impacts of land use, climate change, and anthropogenic activities on these interconnected systems. By integrating scientific insights into policy frameworks and raising awareness among stakeholders, effective measures can be instituted to safeguard the basin's ecological integrity, promote food security, and advance sustainable agricultural practices.

Comprehensive erosion management measures tailored to the specific topography and land use of the Awash River Basin are strongly recommended to mitigate soil loss and promote sustainable agricultural practices.

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Author contributions
A.G. write original manuscript text E.G. and H.D. supervise, edit and validate the manuscript All authors reviewed the manuscript and confirmed.

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Declarations

Ethics approval and consent to participate
This article does not contain any studies conducted by any of the authors that would require ethical approval. This article does not contain any studies involving human participants or animals performed by any of the authors.

Informed consent
Informed consent was obtained from both authors for submission and publication.

Competing interests
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