



Identification and Prioritization of Sub-watersheds to Soil Erosion and Sediment Yield Susceptibility Using RUSLE, Remote Sensing, and GIS (Case Study: Abbay—Awash Basin in Wollo Area, Ethiopia)

Tewodrose Desale¹ · Girum Metaferia^{1,2} · Eshetu Shifaw^{1,2} · Shawel Abebe^{1,2} · Wondye Molla^{1,2} · Metafet Asmare^{1,2}

Received: 18 April 2022 / Revised: 1 November 2022 / Accepted: 14 December 2022 / Published online: 26 January 2023
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Abstract

The effects of soil erosion are most horrible in developing countries, where agriculturalists are very unable to recover soil fertility using purchased inputs. Evidence on soil loss is vital for encouraging farming productivity and natural resource management. Simulation models are the most active way to predict soil loss processes and their result by using geographic information system and remote sensing. Soil erosion modeling used mathematical equations that require many data measurements as well as physical description of the erosion phenomena. The main goal of this research was to delineate areas that require prior soil conservation measures and to predict the amount of soil loss at the Abbay-Awash basin. The soil loss was assessed by using the Revised Universal Soil Equation (RUSLE) model. The layers were then overlaid and multiplied pixel by pixel, using the RUSLE model and raster calculator-reprocessing tool in Arc GIS 10.1 environment. Annual soil losses range from 0 in the lowlands of the watershed to more than 500 tons ha⁻¹ year⁻¹ in much of the steeper slopes on tributaries. Based on the analysis, the amount of soil loss in the Abbay basin from Wollo area is about 3.52 million tons per year from 1.765 million hectares and also in the Awash basin from the Wollo area about 0.58 million tons per year from 0.787 million hectares area. A detailed examination showed that the most pronounced RUSLE factor that worsened soil erosion and caused a high soil loss rate was the slope length (L), steepness (S) factors, and low vegetation cover. Thus, planners should adapt their soil and water conservation measure implementation strategies by devoting in the very urgent part of the watershed first and then progressively to the needed part to prevent the influence of runoff at its start point.

Keywords Geographic information system · Remote sensing · RUSLE · Soil loss

Introduction

The key factor affecting the sustainability of farming production is soil degradation. Soil erosion is a major threat, among others, to the conservation of the soil and water resources [1]. Although soil erosion can be caused by geomorphological processes, anthropological or accelerated erosion, which is mainly driven by human activities, is the main trigger for biodiversity loss of soil and water resources. Soil erosion has accelerated in most countries of the world, especially in developing countries, due to various socioeconomic and demographic factors and limited resources [2]. Soil erosion is a common phenomenon in the East African highlands, where it causes widespread soil degradation. Rapid population growth, cultivation on steep slopes, clearing of vegetation, and overgrazing are the main factors that accelerate soil erosion in Ethiopia [2]. Such unsustainable and exploitative land use practices due to an increasing demand for food,

✉ Girum Metaferia
girumm121@gmail.com
Tewodrose Desale
tewodrose0933@gmail.com
Eshetu Shifaw
eshetushifaw@yahoo.com
Shawel Abebe
shawl2078@gmail.com
Wondye Molla
Wondye.molla@wu.edu.et
Metafet Asmare
metafet0918@gmail.com

¹ Kombolcha Institute of Technology, Wollo University, Kombolcha, Ethiopia

² Wollo University, Dessie, Ethiopia

fiber, and fodder by the growing human and livestock populations are responsible for accelerated soil erosion in many parts of Ethiopia. Those practices reduce the protective plant cover, thereby exposing the soil surface to the destructive impact of high-intensity rainfall. In the study area, high population growth leads to intensified use of stressed resources and expansion of agricultural land.

Identifying critical sediment source areas, or erosion hotspots, is often cited [3] as a good strategy for directing resources to areas of high risk rather than spreading them equally across the landscape. Earlier studies measured and modeled soil erosion rates from watersheds, using data collected at their outlets, to identify and prioritize the critical watersheds [4].

The sound effects of soil destruction are most severe in developing countries, where agriculturalists are highly contingent on land proprietorship and are not able to advance fruitfulness through the use of purchased inputs [5]. In Ethiopian uplands only, a yearly soil loss reaches 200–300 tons per hectare, while the soil loss drive can reach 23,400 million tons per year [6]. These highlands account for 43% of the countries and are dominated by high soil fertility that covers 95% of the cultivated land. The impact of this loss of fertile soil in Ethiopia is multi-layered. It is still affecting 50% of the agricultural area and 88% of the total population of the country [7]. Therefore, there is a serious need for political involvements and soil conservation that should be carried out to alleviate soil degradation in these zones. Even if it is improbable to measure and investigate with soil erosion measures in every tarnished area in the country, the spatial soil erosion model provides an energetic tool in the design of these interventions [8]. Considering the severity of soil erosion and its impacts, it is necessary that appropriate management measures be undertaken. To achieve this, a sound knowledge of spatial variations in soil erosion is necessary when planning conservation efforts [9]. Because of the high cost of conservation and the competing production objectives such as population increase, infrastructure development, and land degradation, there is a need to target responses and resources to areas of high risk (“hotspots”), rather than spreading them equally across the landscape [10]. Different management and land use planning scenarios can then be implemented to deal with the various land degradation problems.

Simulation models are the most active way to predict soil erosion processes and their effect by using GIS (geographic information system) and RS (remote sensing). GIS and RS investigation could help analyze soil erosion speedily and accurately [11]. The aims of this study are to analyze spatial soil erosion using USLE, to delineate areas that need prior soil conservation measures, and to calculate the amount of soil loss in the Abbay-Awash basin. Inside a raster-based GIS, the RUSLE model can calculate erosion probable on

a cell-by-cell. This has different advantages when trying to find the spatial patterns of soil loss extant within a large region. The GIS can be used to detach and request these locations to yield dynamic information about the hero of individual variables in donating to the detected erosion potential rate.

Methodology

Description of the Study Area

A basin is the portion of land drained by a different river and its tributaries. It encompasses all areas of the land surface dissected and drained by many streams and creeks that flow downhill into one another, and eventually into one river. The Abbay-Awash basin which is of strategic importance to Ethiopia is located in the Northern Eastern part of Ethiopia between 10.033° N and 11.55° N latitude and 38.5° E and 40.083° E longitude. The basin area coverage near Wollo is 25,515.78km². The basin occupies 7868.18 km² of Awash basin and 17,647.6 km² of Abbay basin (Fig. 1).

Rainfall

The climate of Abbay-Awash in Wollo differs from cool highland to tropical type climates. Generally, rainfall ranges between 1207.25 at maximum and 745.33 mm at minimum per year. The Ethiopian highlands have the highest rainfall ranging from 1500 to 2200 mm; however, this area has lower rainfall. The lowest rainfall recorded was less than 1000 mm in most parts of the area. The main annual rainfall over the catchments is 976.3 mm and most of which is concentrated in the main rainy months last from July to September and contributes about 84% of the annual rainfall (Figs. 2 and 3) [12].

Temperature

The climate of Abbay-Awash differs from cool highland to tropical type climates. The climate in the basin is subjugated by two main factors: the near-equatorial location, and the altitude, from about 841 m to more than 4000 m above sea level. The effect of these factors determines a rich variety of local climates, ranging from hot and nearly desert along the Afar region to temperate cold on the mountain peaks. Temperature variation spatially and seasonally depends on altitude, humidity, and wind regime. The mean highest temperature is observed in the Eastern part of the basin 22.1 °C and the minimum temperature 16.1 °C which corresponds to December and June respectively (Fig. 4).

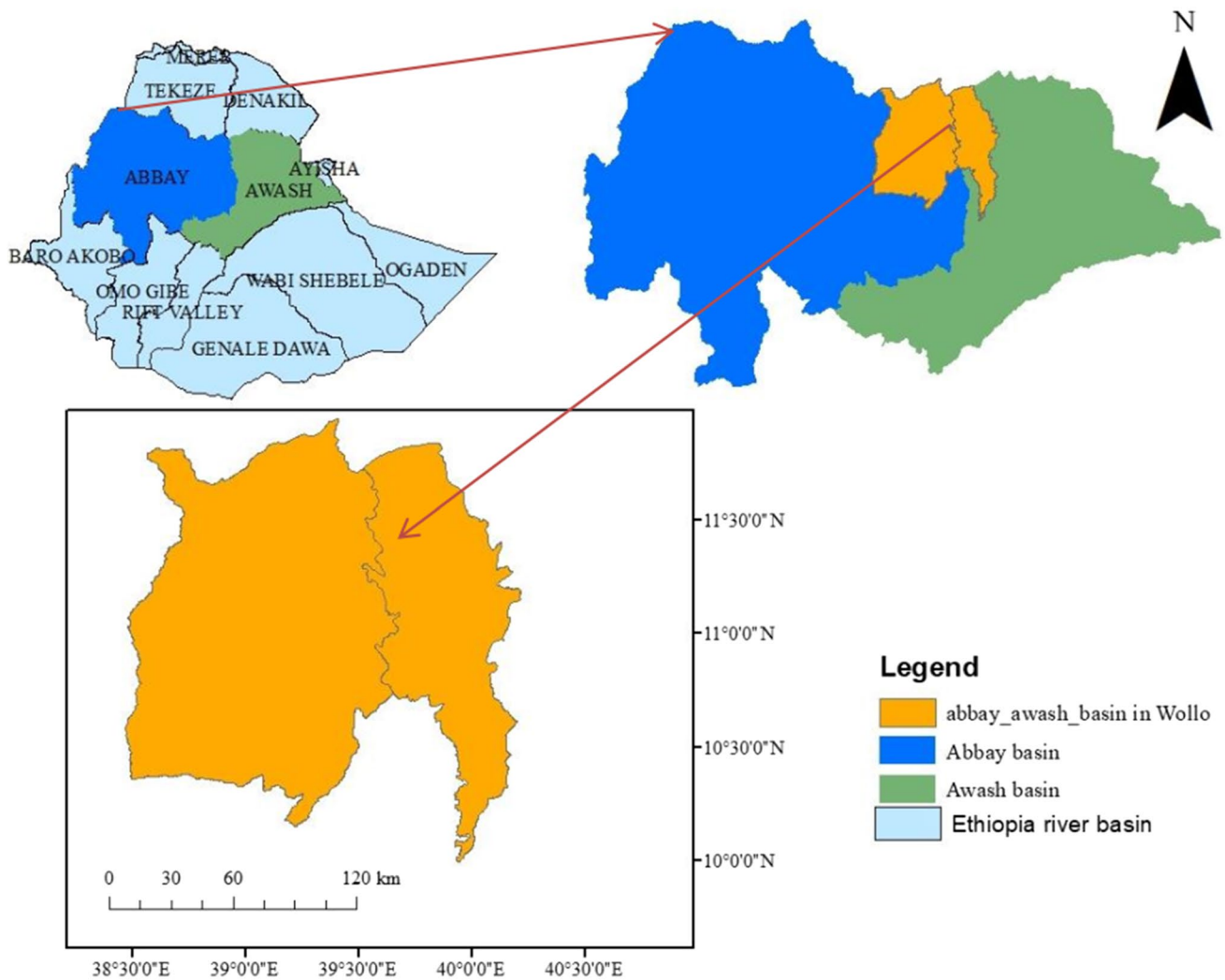


Fig. 1 Location map of the Abbay-Awash basin in Wollo

Topography

The topography of the Abbay basin signifies two distinct features: the highlands, rugged mountainous areas in the center and western part of the basin, and the lowlands in the eastern part of the basin. The topography of the basin ranges from the lowest about 841 m.a.s.l to 4246 m.a.s.l the highest elevation. Sixty percent of the total land of the basin has a slope of less than 20% while the remaining 40% has greater than 20% (Fig. 5).

Land Cover

Moreover, the use of woods for fuel consumption and as a construction material is influencing the land use land cover pattern of the area. Mainly for these reasons, the catchments are getting degraded from time to time [13]. The vegetation cover of the area includes trees, shrubs,

grassland, cropland, regularly flooded, lichen/sparse vegetation/bare land, built, and water. It is obvious that much of the land in the basin is arable. Figure 6 shows the percentage of the land coverage.

Data Collocation and Availability

Primary and secondary data sources were used for this study. Primary data were collected via field survey and/or ground truth verification and reflection using Global positioning system (GPS) instruments. This gives concrete information about what is going on in the study area.

The different data sources were arbitrated to investigate the soil loss in the study area. A digital elevation model (DEM) with 0-m resolution developed by NASA was implemented for analyzing the slope length and slope gradient of the study area. The land cover classification map, which was taken from the Ministry of Water and

Fig. 2 Average rainfall pattern of some stations on a monthly scale of the watershed

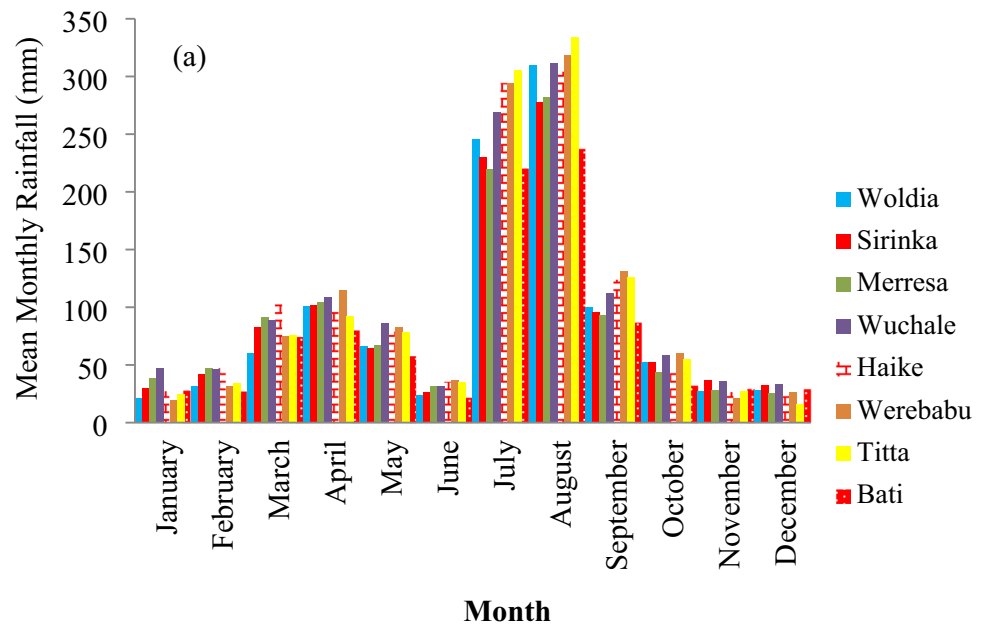
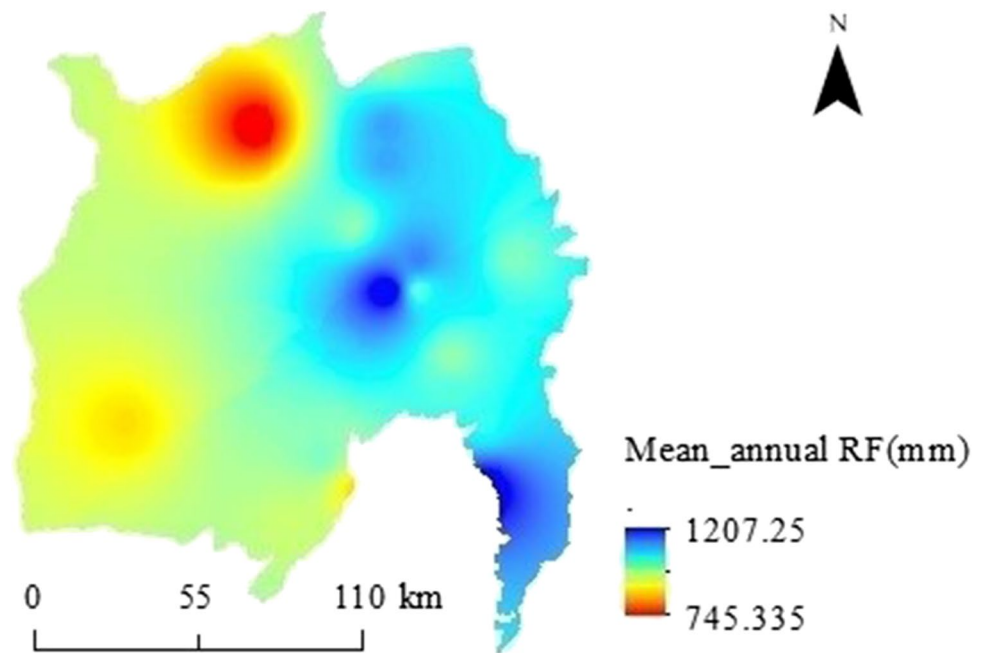


Fig. 3 Spatial distributions of the mean annual rainfall of the basin



Energy, was used for the analysis of crop management factor (*C*-value). Analysis of soil erosivity factor (*R*-value) was derived from annual rainfall data from Ethiopia’s meteorological agencies. A soil map made by FAO was also used for analyzing the soil erodability factor (*K*-value). In addition to the aforementioned secondary data, published and unpublished materials such as research reports, census reports, and journals obtained from different sources were used.

Methods of Data Analysis

Soil Loss Estimation

Soil erosion modeling used mathematical equations that require many data measurements as well as physical description of the erosion phenomena. The universal soil loss equation was active to assess the amount of soil loss that existed in the Abbay-Awash basin. The universal soil loss equation

Fig. 4 Maximum and minimum temperature

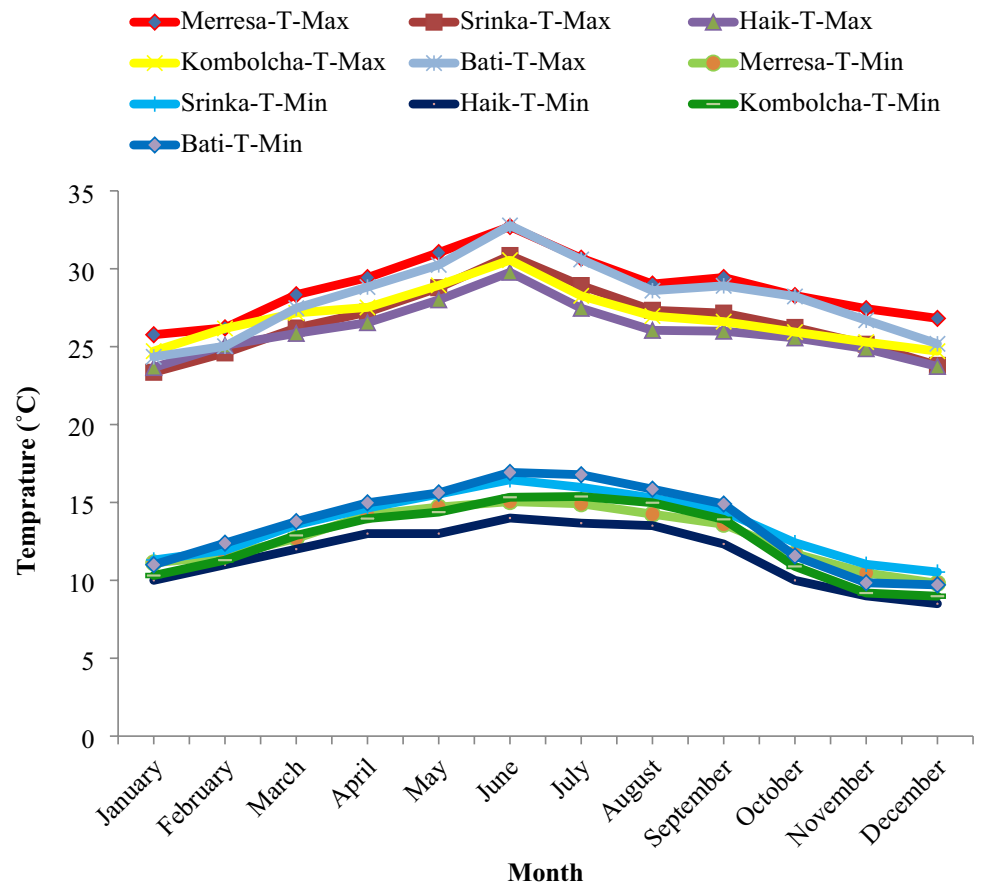


Fig. 5 Slope map of Awash-Abbey basin in Wollo area

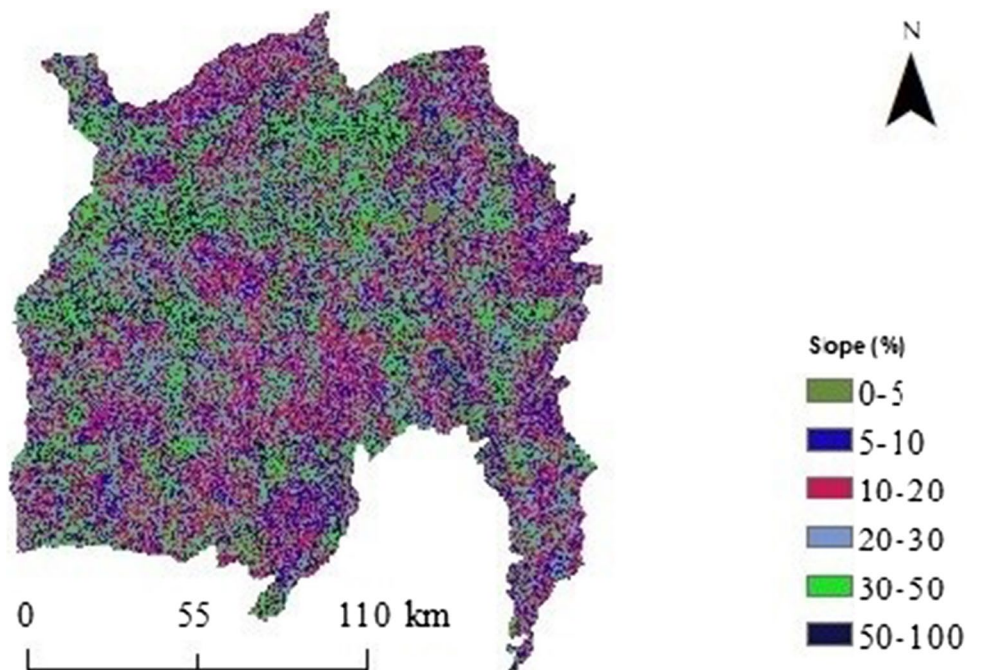
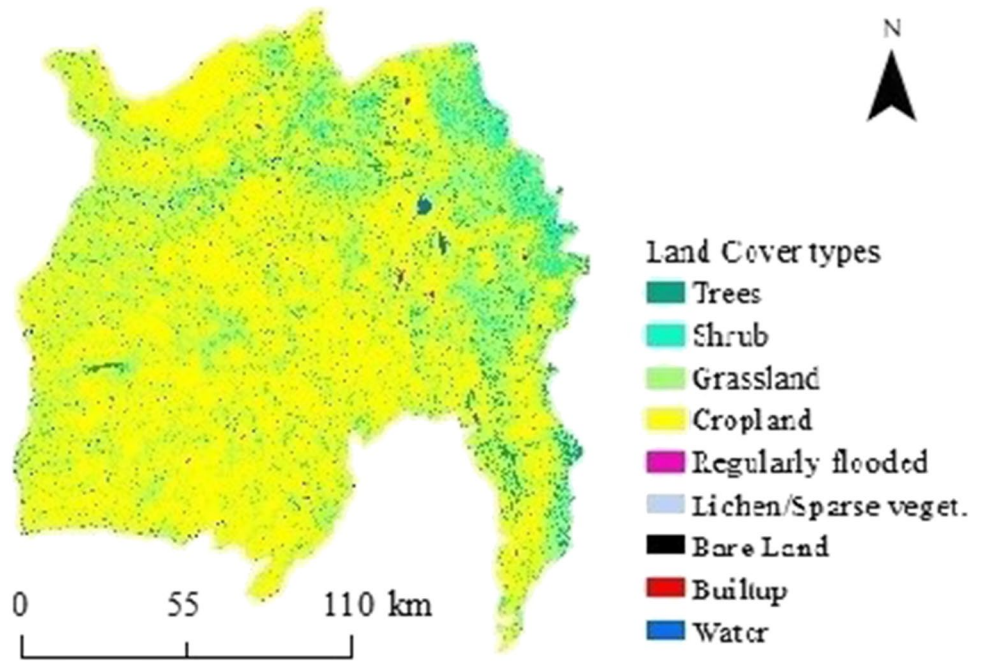


Fig. 6 Land cover of Abbey-Awash basin



is an empirical model developed by Wischmeier and Smith [14] to estimate soil erosion from fields. Mathematically the equation is denoted as

$$A(\text{tons/ha/year}) = R \times K \times L \times S \times C \times P \quad (1)$$

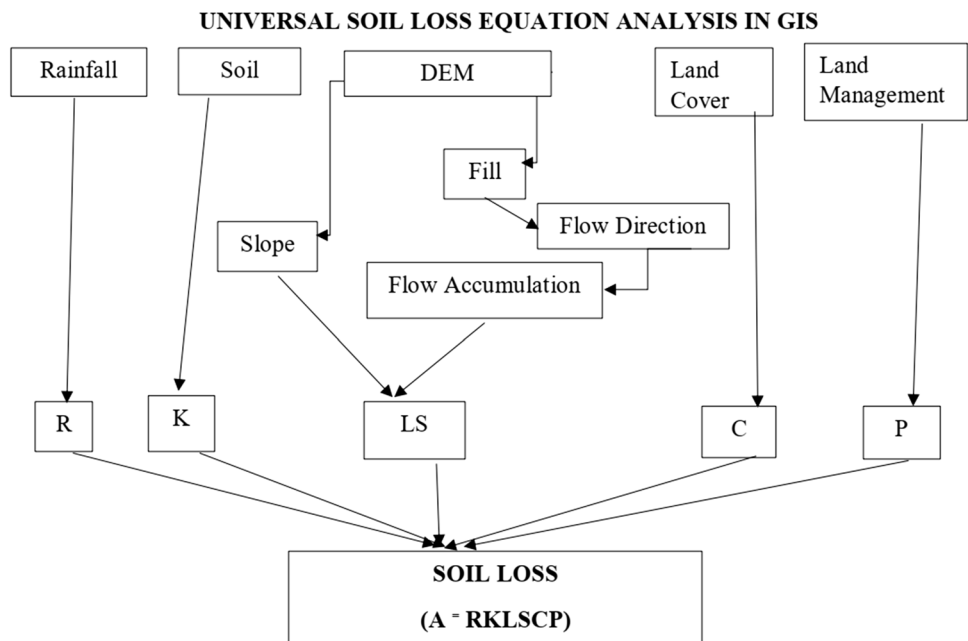
where A is the mean annual soil loss, R is the rainfall erosivity factor, K is the soil erodability factor, L is the slope length factor, S is the slope steepness factor, C is the crop management factor, and P is the erosion control practice

or land management factor. The USLE was applied in GIS based on the flow chart as shown in Fig. 7.

RUSLE Parameter Estimation

For the valuation and mapping of the spatial distribution of soil loss in the study area, all the five parameter maps (having the same coordinate system) were discretized to a grid with $20 \text{ m} \times 20 \text{ m}$ cell size. The layers were then overlaid and multiplied pixel by pixel, using the above

Fig. 7 Flow chart showing analysis of soil loss based on GIS application [14]



equation and raster calculator geoprocessing tool in Arc GIS 10.1.

Rainfall Erosivity (R) Factor The rainfall erosivity factor enumerates the effect of rainfall impact and also reflects the amount and rate of runoff likely to be associated with precipitation events [2].

The most suitable expression of the erosivity of rainfall is an index based on the kinetic energy of the rain. There are different ways of analyzing the R factor. For instance,

- A. $R = 9.28 \times P - 8838$. Mean annual erosivity ($KE > 25$), where P is the mean annual precipitation [[15] cited in [16]]
- B. $R = 0.276 \times P \times I30$. Mean annual EI30, where P is the mean annual precipitation [16]
- C. $R = 0.5 \times P$ (in US unit) and $R = 0.5 \times P \times 1.73$ (in metric unit) [4]

These formulas are functional in different parts of the world. The first equation appears to work well for Peninsular Malaysia, whereas the application for other countries is less satisfactory. Particularly with the annual rainfall below 900 mm, like part of the study area, the equation yields estimates of erosivity, which are obviously meaningless [16]. In connection with this, the second equation requires an I30 value for calculating of erosivity factor, which is difficult to get in the context of the study area. Therefore, in this study, we preferred to use the third equation for the determination of the R-value. Hence, each grid cell of mean annual rainfall was calculated based on the third equation to get the R-value using GIS software, ArcGIS10.1

Soil Erodability Factor (K) Soil erodibility is the indicator of the inherent resistance of soil particles to the flaking and conveying power of rainfall [17]. This factor quantifies the cohesive character of a soil type and its resistance to dislodging and transport due to raindrop impact and overland flow shear forces. The value of K ranges from 0 to 1 (Table 1).

Table 1 Estimated K -values for some soils in Ethiopia [2]

Soil color	Name	Estimated K -value (metric/ha MJ mm)
Black	Andosols, Vertisols, etc	0.15
Brown	Cambisols, Regosols, etc	0.20
Red	Lixisols, Nitisols, etc	0.25
Yellow	Fluvisols, Xerosols, etc	0.3

Slope Length and Slope Steepness (LS) The slope length and slope steepness can be used in a single index, which expresses the ratio of soil loss as defined by [17]

$$LS = (X/22.1)^m(0.065 + 0.045S + 0.0065S^2)$$

where X is the slope length (m) and S is the slope gradient (%).

The values of X and S were derived from DEM. To calculate the X -value, flow accumulation was derived from the DEM after conducting FILL and flow direction processes in ArcGIS.

$$X = (\text{flow accumulation} \times \text{cell value})$$

By substituting the X -value, LS equation will be as follows: $LS = (\text{flow accumulation} \times \text{cell value}/22.1) \times m \times (0.065 + 0.045 s + 0.0065 s^2)$.

Furthermore, slope (%) is also directly derived from the DEM using the same software. The value of m varies from 0.2 to 0.5 depending on the slope as shown in Table 2 [17].

Crop Management Factor (C) The crop management factor represents the ratio of soil loss under a given crop to that of the base soil [16]. The land use map was used for analyzing the C -value (Table 3). After changing the coverage to the grid, an equivalent C -value was allocated to each land use class using Re-class method in ArcInfo as given by D. D. S. Wischmeier W.H. [17].

The crop management factor signifies the ratio of soil loss under a given crop to that of the base soil [16]. The cover management factor (C -values) reflects the effect of cropping and management practices on the soil erosion rate [18].

Erosion Management Practice Factor (P-value) The erosion management workout, P -value, is also one factor that governs the soil erosion rate. Factor expressing the protection

Table 2 m -value [17]

m -value	Slope (%)
0.5	>5
0.4	3–5
0.3	1–3
0.2	<1

Table 3 C factor values for the catchment were taken from different studies [17]

Land use land cover	C factor
Water body	0.00
Cultivated land	0.1
Forest land	0.01
Shrub land	0.014
Grazing land	0.05

of soil from agricultural practices, erosion control practices of soil (P) says human intervention in creating practices that conserve soil and reduce land degradation, such as crops curves level in alternating strips or terraces, reforestation benches, mounding and ridging are the most effective soil conservation practices. The *P*-value ranges from 0 to 1 depending on the soil management activities working in the specific plot of land. These management activities highly depend on the slope of the area. Wischmeier W.H. [17] calculated the *P*-value by delineating the land into two major land uses, agricultural land and another land. The agricultural land is sub-divided into six classes based on the slope percent to assign different *P*-values (see Table 4). In this study, we employed this same technique assigns the *P*-value of the basin which has a value from 0.1 to 1.

Results

RUSLE Parameter Mapping

Rainfall Erosivity (R) Factor

In this study, we chose to use the third equation for the determination of the *R*-value. Hence, each grid cell of mean annual rainfall was calculated based on the third equation to get the *R*-value using GIS software, ArcGIS10.1

The erosivity factor estimated by the above equation ranges from 410.76 to 670.35 mm. The point rainfall data obtained from four stations were interpolated by the inverse distance weighted (IDW) method to estimate the *R*-value of each grid cell. The *R* factor is directly proportional to the annual rainfall of the study area, as shown in Fig. 8A.

Soil Erodability Factor (K)

The *K*-value varies from 0 to 1, where the former suggests less and the latter implies high susceptibility to erosion risk, respectively [11]. The soil erodibility map of the basin is shown in Fig. 8B. Soil loss was spatially correlated to the vegetation, slope, gradient, altitude, and

rainfall. It is reasonable to understand that soil erosion is mostly dependent on the topography, runoff, and land cover of the study area. Average annual soil losses for watershed were estimated for each grid cell. Results indicate that soil erodibility value in the study area ranges from 0 to 0.3 t ha⁻¹ MJ⁻¹ mm⁻¹.

Slope Length and Slope Steepness (LS)

The biggest relief parameters which determine the intensity of the water erosion in the watershed are the gradient and slope length. The combined effect of the gradient of the slope and its length is taken up by the topographic factor (LS) [19]. Furthermore, the computed LS factor in the watershed ranged from 0 to 7838.22. The soil erosivity by runoff increases with the velocity of the runoff water on the steeper slopes. Thus, in steeper slopes, the runoff water will attain accelerated velocity, resulting in an increased shear force on the soil surface.

Crop Management Factor (C)

It is used to determine the relative effectiveness of soil and crop management systems in preventing soil loss. The *C*-value is a ratio comparing the soil loss from land under a specific crop and management system to the corresponding loss from continuously fallow and tilled land. The result of the analysis is shown in Fig. 8D, which the value ranges from 0 to 0.75. The lowest *C* factor value was assigned for the water body (0), and the highest value was assigned for the settlement (0.75). The areas with a high *C* factor value can be changed to enhance their infiltration by changing the cropping and surface management.

Erosion Management Practice Factor (P-Value)

The value of *P*=1 is given to the land on which none of the cited practices are used and *P*-values less than or equal to 1 when there is an intervention to fight against erosion. The distribution of *P* factor classes in the study area is shown in Fig. 8E.

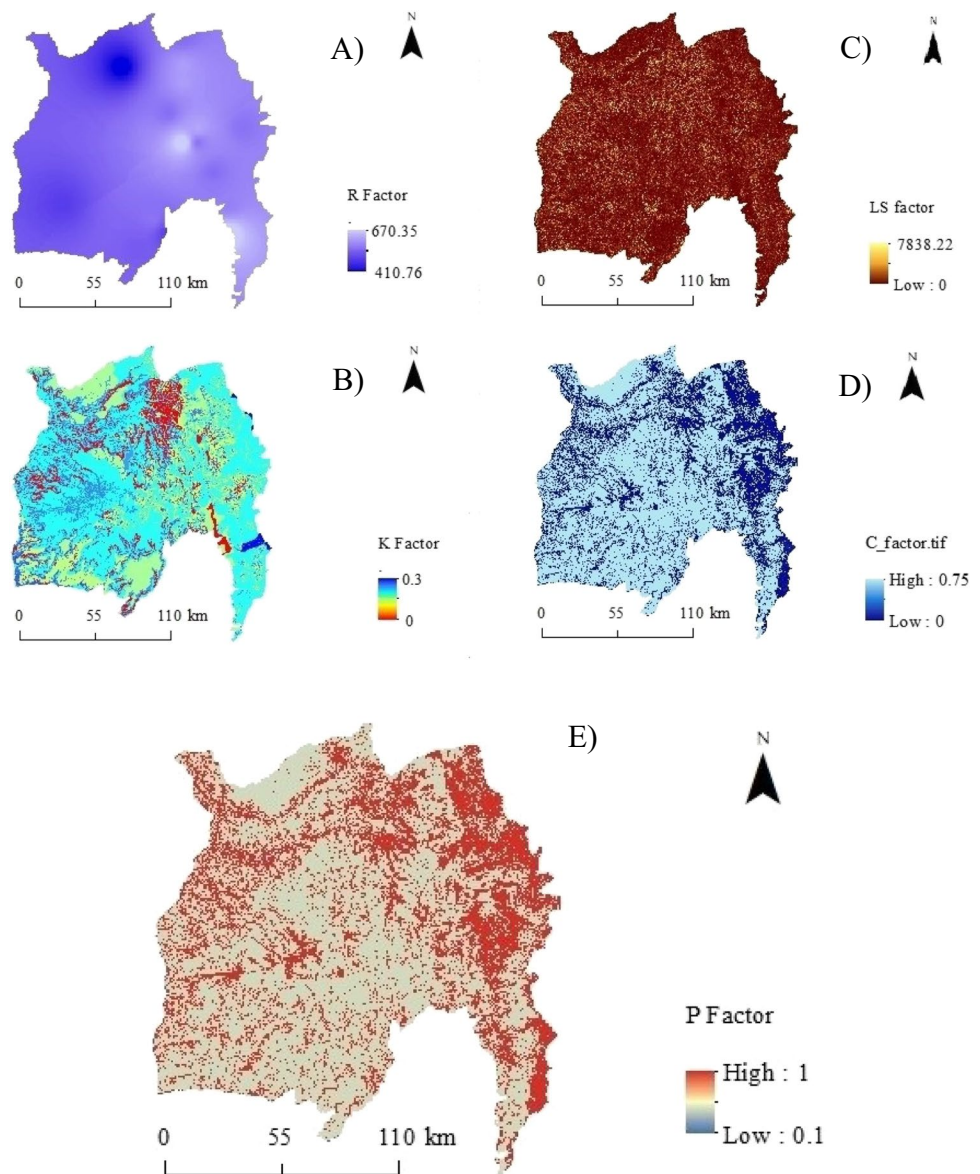
Assessment of Soil Loss Rates

The annual soil loss rate was determined by a cell-by-cell analysis of the soil loss surface by multiplying the respective RUSLE factor values interactively in ArcGIS 10.1 using Eq. (1). Figure 9 shows the resulting soil loss rate map. In order to ease the presentation of the output data, the map showed seven main categories (Fig. 9). Annual soil loss ranged from 0 in the plain area the basin to over 500 metric tons ha⁻¹ year⁻¹ in much of the steeper slope banks of tributaries (Fig. 9). Based on the analysis, the amount of

Table 4 *P*-value [1]

Land use type	Slope (%)	<i>P</i> factor
Agricultural land	0–5	0.1
	5–10	0.12
	10–20	0.14
	20–30	0.19
	30–50	0.25
	50–100	0.33
	All	1.00

Fig. 8 Spatial distributions of **A** rainfall erosivity (R) factor, **B** soil erodability factor (K), **C** slope length and slope steepness (LS), **D** crop management factor (C), and **E** erosion management practice factor (P -value)



soil loss in the Abbay basin from Wollo area is about 3.52 million tons per year from 1.765 million hectares and also in the Awash basin from the Wollo area about 0.58 million tons per year from 0.787 million hectares area.

Prioritization for Soil Conservation Planning

The assignment of a range is subject to the judgment of how much erosion would be harmful to the soil. Figure 9 shows areas with higher soil loss potential. These areas have ranges of the erosion severity classes of severe, very severe, and extremely severe, where conservation priorities of the first, second, and third order are needed. A detailed examination showed that the most pronounced RUSLE factor that worsened soil erosion and caused a

high soil loss rate was the slope length (L) and steepness (S) factors. Prioritization of these areas means ranking in terms of urgency; those areas are shown in Fig. 10.

Discussion

The largest size among soil loss categories was that of 5–25 metric tons ha^{-1} year $^{-1}$ which is under moderate level (Fig. 9). Average annual soil loss for the entire area was estimated at 15.25 metrics tons ha^{-1} year $^{-1}$. The spatial locations of the high spot area for soil erosion in the study revealed that the potential soil loss is typically greater along the steeper slope banks of tributaries. Other high soil erosion areas are dispersed throughout the basin

Fig. 9 Spatial distribution of soil erosion

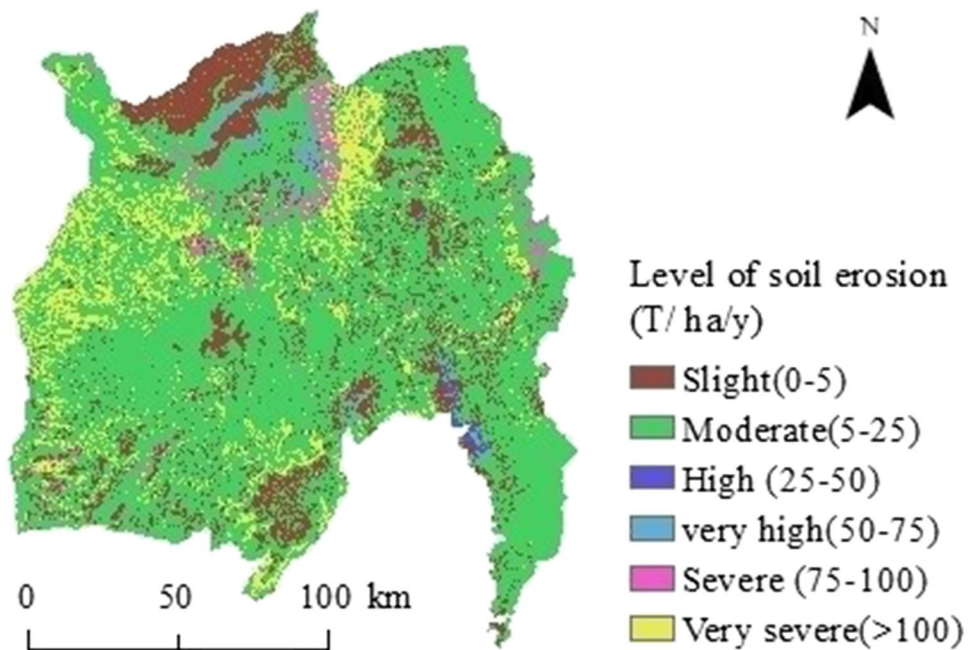
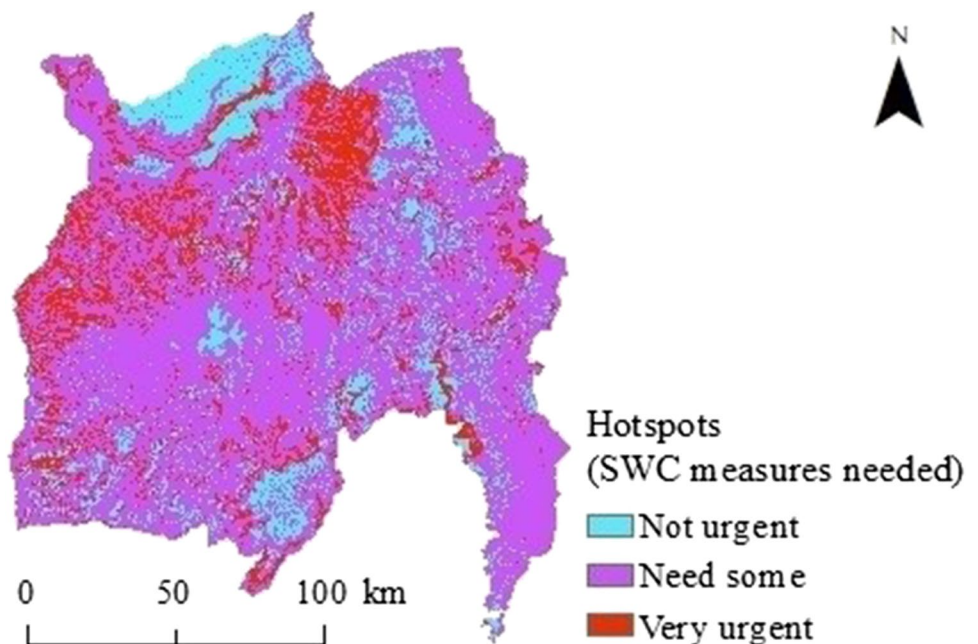


Fig. 10 Soil and water conservation (SWC) intervention areas: not urgent slight, some intervention for moderate; and very urgent for areas suffering from high to very severe soil erosion risks



and are typically associated with high erosion potential land uses. The plain area of the basin shows the least vulnerable to soil erosion.

In the highlands of Ethiopia and Eritrea, soil losses are extremely high with an estimated average of 20 metric tons $\text{ha}^{-1} \text{year}^{-1}$ [20] and measured amounts of more than 300 metric tons $\text{ha}^{-1} \text{year}^{-1}$ on specific plots. Accounting for redeposition of mobilized sediments [4] estimated mean soil loss from cultivated fields as 42 metric tons $\text{ha}^{-1} \text{year}^{-1}$. The average annual soil loss estimated by USLE from the entire Medego watershed of northern

Ethiopia was also 9.63 metric tons $\text{ha}^{-1} \text{year}^{-1}$ [6], and the average annual soil loss for the entire Chemoga watershed in the Blue Nile Basin, Ethiopia, was estimated at 93 metric tons $\text{ha}^{-1} \text{year}^{-1}$ [4]. Based on this study, the estimated soil loss rate and the spatial patterns are approximate realistic; this number needs to validate on the ground because this result seems smaller than what we expected based on the topography.

Their topography and poor vegetation cover contribute to significant erosion in these areas. They are typically associated with high erosion capacity and have the highest and

highest weights of the fourth and fifth conservation priorities. The main causes of soil erosion in these areas are (i) crop erosion caused by plowing and erosion during crop development during the rainy season, and (ii) lack of tree cover, leaving areas vulnerable to rainfall. However, farmers' lack of awareness of soil erosion or lack of participation in conservation measures may limit the application of soil and water conservation technologies to a few priority issues. Applying conservation measures only in areas where resources are scarce will significantly reduce soil erosion in the study area. Therefore, the affected areas need to be treated with proper soil and water conservation and priority given to treatment.

Quantitative and spatial soil loss information obtained through simulation of RUSLE parameters by GIS and remote sensing techniques in a watershed guarantees the handling of spatially variable data and inaccessible areas easily and efficiently where ground-based observation is difficult. The method can therefore be replicated in other parts of Abbay and Awash sub-basin in particular and in Ethiopia in general for the assessment and delineation of erosion-prone areas, conservation prioritization, and for the evaluation of the effectiveness of different land management practices.

Conclusion

Describing basin erosion capacity gives different insights, for example, where to expect the first level based on the level of erosion and the interaction between highland erosion factors. This study provides ways to collect the representation information needed for RUSLE and demonstrates its usefulness for soil waste forecasting and soil conservation planning. The results of the study include a map showing the level of soil waste in the basin and the priority given to conservation area.

The finding of this study incorporates spatially distributed soil loss rate and an erosion risk map of the study area. Annual soil loss ranged from 0 in the plain area of the basin to over 500 metric tons $\text{ha}^{-1} \text{year}^{-1}$ in much of the steeper slope banks of tributaries. Their topographic ruggedness and poor vegetation cover contribute to the high rate of soil erosion in these areas. They are typically associated with high erosion potential land uses and have ranges of severity classes of high and very high in which conservation priority order is needed.

Thus, planners should modify their soil and water conservation measure implementation strategies by investing in the very urgent part of the watershed first and then progressively to the needed some part to avert the influence of runoff at its initiation point.

Acknowledgements The research was implemented under a collaborative partnership between the Awash-Abbay basin director at Wollo University, so the authors would like to thank to these organizations for the financial and other support during this work. We also acknowledge the anonymous reviewers, whose comments greatly improved the paper.

Author Contribution Tewodros Desale conceived and developed the research framework. Tewodros Desalew, Girum Metaferia, and Metafet Asmare undertook the data processing and analysis. Shawol Abebe, Girum Metaferia, and Eshetu Shifaw wrote and revised the manuscript. Eshetu Shifaw and Wondye Molla supervised and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

Data Availability All data generated and analyzed during this study are included in this published article.

Declarations

Conflict of Interest The author declares no competing interests.

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