Soil loss estimation and prioritization using geographic information systems and the RUSLE model: a case study of the Anger River Sub-basin, Western Ethiopia

Mitiku Badasa Moisa, Indale Niguse Dejene, Biratu Bobo Merga and Dessalegn Obsi Gemeda

ABSTRACT

Soil erosion is a major environmental problem that affects people’s livelihoods and environmental health, particularly in developing countries. The present study aimed to identify soil erosion hotspot areas and prioritization in the Anger River Sub-basin for conservation planning. The Revised Universal Soil Loss Equation model and geospatial technologies were adopted to identify soil erosion hotspot areas and prioritization of the sub-watershed for conservation planning. Key parameters such as rainfall data, soil data, slope length and steepness factor, cover management, and conservation practices were used to estimate potential soil erosion risk in the sub-watershed. The results showed that the annual soil loss rate in the Anger River Sub-basin ranged between 0 and 932.6 t/ha/year with a mean annual soil loss of 83.7 t/ha/year. About 1,140.7 km² (43.6%) and 220.6 km² (8.4%) were categorized under very severe and severe soil loss types, respectively. The mid- and upstream areas, as well as the steeper parts of the sub-watershed, were highly exposed to soil erosion. This research provides tangible evidence in the decision-making process for soil and water conservation practices at a sub-watershed scale. Moreover, further research should be conducted at a micro-watershed scale to minimize the effects of soil erosion on the health and sustainability of the watershed.

Key words: geographic information systems, prioritization, remote sensing, soil loss, sub-watershed

HIGHLIGHTS

- The method of integration of the RUSLE model and geospatial techniques was used in the estimation of soil loss in the study area.
- The estimated average annual soil loss in the Anger River Sub-basin is 83.7 t/ha/year.
- Of the 23 sub-watersheds, 14 sub-watersheds are categorized under very severe soil erosion risk.
- About 43.6 and 8.4% of the study area were exposed to very severe and severe soil loss, respectively.
1. INTRODUCTION

Soil erosion is one of the environmental problems that hinder the implementation of the first (No poverty) and second (Zero hunger) United States Sustainable Development Goals by providing declining soil fertility (OFID 2016). Soil erosion is defined as the detachment of soil particles of topsoil by air or water (Maity & Mandal 2019; Aslam et al. 2021). It is a common problem in highland areas of the world like East African countries (Girmay et al. 2020). The more protected the environment, the more the agricultural yield. Research conducted in the Ethiopian highlands proved that steep slope cultivation, land-use land-cover (LULC) changes, and population growth are the major driving forces behind soil erosion problems (Shiferaw 2011; Tesfaye et al. 2018; Atoma et al. 2020; Girmay et al. 2020). Ethiopian highlands experience severe soil erosion (Mhiret et al. 2019). Ethiopia is highly exposed to erosion during the heavy rain season between June and September. A study by Krisnayanti et al. (2021) in Indonesia reported that a large volume of rainfall exceeds the soil infiltration capacity, resulting in excess erosion.

Land degradation has a negative effect on economic growth and environmental sustainability (Panditharathne et al. 2019; Girma & Gebre 2020). The negative impacts of soil erosion on people’s livelihoods and the natural environment are expected to increase in the future, especially in the Ethiopian highlands (Niang et al. 2014). Considerable studies have been conducted so far on soil erosion risk assessment in several countries (Jeevan et al. 2016; Woldemariam et al. 2018; Olika & Iticha 2019; Atoma et al. 2020; Balabathina et al. 2020). Although the problem of soil erosion is common across Ethiopia, no research has been done yet on soil loss estimation and prioritization for soil and water conservation in the Anger River Sub-basin.

A study conducted by Negassa et al. (2020) in the East Wollega Zone (western parts of Ethiopia) highlights that LULC conversion, firewood collection and charcoal exploitation from forests for energy consumption, and overgrazing by livestock are some of the major contributing factors to soil erosion. Hurni et al. (2015) reported that the western parts of Ethiopia have the highest soil erosion rate. However, the report of Hurni et al. is too general to design appropriate conservation planning at the watershed level.
It is undeniable that the sub-watershed scale is more effective and efficient than large-scale area assessment for conservation actions (Belayneh et al. 2019). Thus, a knowledge and information gap exists on the status and severity of soil loss in the Anger River Sub-basin. To fill this gap, we adopted the RUSLE model and a geographic information system (GIS) as previously used (Haile & Fetene 2011; Thomas et al. 2018; Zerihun et al. 2018; Amah et al. 2020; Mohammed et al. 2020; Kebede et al. 2021; Moisa et al. 2021) to estimate the amount of soil loss in the Anger River Sub-basin. A majority of the previous studies, including the recent study of Moisa et al. (2021), emphasized on the impact of LULC change on soil erosion with prioritization of sub-watersheds for conservation planning. However, the present study aimed to forward some recommendations for policymakers to work on high erosion hotspot areas through conservation actions.

The Revised Universal Soil Loss Equation (RUSLE) is an empirically based model that has the ability to predict the long-term average annual rate of soil erosion on a field slope as a result of rainfall pattern, soil type, topography, crop system, and management practices (Renard et al. 1997). Previous studies used the RUSLE model and GIS technology to assess the loss of soil in different watersheds in Ethiopia (Gashaw et al. 2018; Belayneh et al. 2019; Tessema et al. 2020; Moisa et al. 2021; Negash et al. 2021). The method of the integration of RUSLE and GIS is widely used across the world due to its effectiveness to estimate the loss of soil at different scales. Moreover, it is also applicable for the prioritization of the severity of soil erosion for conservation actions. Therefore, this research attempted to estimate soil loss and prioritization using GIS and the RUSLE Model. This may draw the attention of decision-makers to formulate effective soil and water conservation strategies.

2. MATERIALS AND METHODS

2.1. Study area descriptions

The Anger River Basin is situated between 9°27′00″ and 9°59′30″ N and 36°33′30″ and 37°6′00″ E. The Anger River Sub-basin is located in two zones of Wollega: Horo Guduru Wollega Zone and East Wollega Zone in Oromia National Regional State (Figure 1). The study area covers 2,613.4 km², with elevations ranging from 1,292.17 to 3,180.57 meters above sea level.

2.1.1. Land-use types of the study area

According to Dawit et al. (2020), of the different land-use types of the Anger River sub-basin, agricultural land constitutes the largest portion of the basin (58%), followed by bare land (27%) and shrublands (14%). Other land-use types also dominate the area, such as woodlands and forests, constituting 40% of the area. The remaining land-use areas can be categorized as built-up areas and water bodies.

2.1.2. Climate

The mean annual rainfall of the Anger River Sub-basin ranges from 1,246 to 2,067 mm. The mean annual maximum and minimum temperatures differ from 22.6 to 31.2 °C and 11.57 to 15.52 °C, respectively, over the Sub-basin (Boru et al. 2019).

2.1.3. Major soil types of the study area

There are 14 major soil types in the study area, and these are as follows: Calcic cambisols, Calcic xerosols, Chromic cambisols, Dystric gleysols, Dystric nitisols, Eutric cambisols, Eutric nitisols, Haplic xerosols, Leptosols, Orthic acrisols, Orthic luvisols, Orthic solonchaks, Phaeozems, and Vertic cambisols. Of these soil types, dystric nitisols is the most predominant one with an area of 601.1 km², followed by vertic cambisols (429 km²), Eutric nitisols (317 km²), and chromic cambisols (260.5 km²).

2.2. Data sources and methods

A Landsat image of 2020 with path 170 and row 53 was downloaded from the United States Geological Survey (USGS) and used for classifying the LULC types of the Anger River Sub-basin, while topographic information was obtained from the Shuttle Radar Topographic Mission (SRTM), which was downloaded from the USGS and used to analyze slope and flow length. A digital soil map of the study area assembled by the Food and Agriculture Organization (FAO) was obtained from the Ethiopian Ministry of Water and Irrigation Engineering. Rainfall data for 30 years (1991–2020) were obtained from the Ethiopian National Meteorological Agency (Table 1). The methodological framework used for soil loss estimation and prioritization is shown in Figure 2. We used different parameters such as annual rainfall data, soil type, slope and flow length, land use, and land cover as recently used by Negash et al. (2021) and Moisa et al. (2021) for the Chogo and Temeje Watersheds, respectively. Materials used for the study include Handled GPS, as well as software like ArcGIS 10.3, ERDAS 2015, Arc SWAT, and Google Earth Pro, which were applied for analyzing the results.
2.2.1. Soil loss estimation

To estimate the amount of soil loss in the Anger River Sub-basin, the RUSLE model (Wischmeier & Smith 1978) was adopted to estimate the annual soil erosion (Equation (1)). This model can be easily applied at a regional or local level (Ganasri & Ramesh 2016).

\[ A = R \times K \times LS \times C \times P \]  

(1)
where \( A \) = average soil loss per unit area (t/ha/year), \( R \) = rainfall – runoff erosivity factor (MJ/m/m/h/ha/year), \( K \) = soil erodibility factor (t/ha/MJ/mm), \( LS \) = slope length and steepness (number), \( C \) = cropping and management systems (number), and \( P \) = Erosion control practice factor (number).

### 2.2.2. Rainfall erosivity factor

The rainfall erosivity \( (R) \) factor reflects the effect of rainfall intensity on soil erosion (Wischmeier & Smith 1978; Ganasi & Ramesh 2016; Koirala et al. 2019; Thapa 2020). This factor indicates the intensity of precipitation at a specific location based

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**Figure 2** Conceptual framework of soil loss estimation and prioritization at a sub-watershed scale.
on the amount of soil erosion (Thapa 2020). The $R$-factor, as shown in Equation (2), was used following that of Gelagay & Minale (2016). Data on 29 years of annual rainfall in five stations (Shambu, Anger Gute, Sibu Sire, Haro, and Nekemte) were used to estimate the $R$-factor. For each meteorological station, the Inverse Distance Weight (IDW) interpolation technique in ArcGIS software was applied (Figure 3).

$$R = -8.12 + (0.562 \times P)$$  \hspace{1cm} (2)

where $R$ = rainfall erosivity factor, and $P$ = mean annual rainfall (mm).

2.2.3. Soil erodibility factor

The soil erodibility ($K$) factor is used to estimate the susceptibility of the soil particles to detachment and transport by water erosion (Haile & Fetene 2011; Prasannakumar et al. 2012; Atoma et al. 2020). A soil type was used to determine the $K$-factor value (Yesuph & Dagnew 2019) for the Anger River Sub-basin as suggested by Hurni (1985) for Ethiopian conditions (Table 2; Figure 4).

2.2.4. Slope length and steepness factor

The slope length and steepness (LS) factor was extracted from SRTM DEM with 30 m resolution (Figure 5). The equation developed by Hurni (1985) was adopted to calculate the LS-factor as indicated in Equation (3):

$$LS = \frac{\lambda^{0.5}}{22.1} \times (S/9)^{1.3}$$  \hspace{1cm} (3)

where $\lambda$ = flow length and $S$ = slope (%).

2.2.5. Cover management factor

Cover management ($C$-factor) is used to associate the relative impact of management strategies on conservation plans (Renard et al. 1997; Fayas et al. 2019). The Anger River Sub-basin was classified into five LULC categories and the
C-factor value was assigned (Table 3; Figure 6) based on the existing literature (Fayas et al. 2019; Olika & Iticha 2019; Yesuph & Dagnew 2019).

2.2.6. Erosion control practice factor

The erosion control practice ($P$) factor is also called the support and conservation practices factor (Renard et al. 1997; Fayas et al. 2019). The $P$-factor for different land-use categories was assigned as from the existing literature (Figure 7) as previously used by Prasannakumar et al. (2012), Fayas et al. (2019), and Olika & Iticha (2019).

| No. | Soil types       | Area (km$^2$) | $K$-factor |
|-----|------------------|---------------|------------|
| 1   | Calcic cambisols | 201.4         | 0.05       |
| 2   | Calcic xerosols  | 3.5           | 0.2        |
| 3   | Chromic cambisols| 260.5         | 0.28       |
| 4   | Dystric gleysols | 71.5          | 0.35       |
| 5   | Dystric nitisols | 601.1         | 0.25       |
| 6   | Eutric cambisols | 40.2          | 0.34       |
| 7   | Eutric nitisols  | 317.7         | 0.25       |
| 8   | Haplic xerosols  | 117.3         | 0.2        |
| 9   | Leptosols        | 198.0         | 0.3        |
| 10  | Orthic acriosols | 17.5          | 0.22       |
| 11  | Orthic luvisols  | 104.8         | 0.2        |
| 12  | Orthic solonchaks| 248.0        | 0.15       |
| 13  | Phaeozems        | 2.4           | 0.2        |
| 14  | Vertic cambisols | 429.4         | 0.24       |

Figure 4 | Soil types (a) and a $K$-factor map (b).
3. RESULTS AND DISCUSSIONS

3.1. LULC analysis

In the present study, LULC in the Anger River Sub-basin was classified into five categories by using the supervised classification technique with maximum algorithm, and these were forest land, shrubland, grassland, cultivated land, and bare land (Figure 8). The overall accuracy and kappa coefficient of LULC were 95.6% and 0.93, respectively. An analysis of the LULC result showed that 73.4% of the study area is covered by cultivated land, while 12.5% is covered by forest land. These findings are comparable with the work of Moisa et al. (2021) in the Temeji Watershed, who report that cultivated and forest cover

![Figure 5](image_url) | Slope (a), flow length (b), and LS-factor (c) map.

Table 3 | C- and P-factors

| No. | LULC            | C-factor | P-factor |
|-----|-----------------|----------|----------|
| 1   | Bare land       | 0.05     | 0.73     |
| 2   | Cultivated land | 0.18     | 0.9      |
| 3   | Forest          | 0.001    | 0.53     |
| 4   | Grassland       | 0.05     | 0.63     |
| 5   | Shrubland       | 0.014    | 0.6      |
account for about 74.4 and 13%, respectively. The total extent or composition of individual LULC classes is presented in Table 4.

3.2. Soil erosion loss estimation

Soil erosion loss estimation results showed that the annual soil loss rates in the study area range between 0 and 932.6 t/ha/year, producing a mean annual soil loss of 83.7 t/ha/year (Figure 9(a)). Compared with the proposed tolerable range by Hurni

Figure 6 | LULC map (a) and the C-factor (b).

Figure 7 | LULC map (a) and the P-factor (b).
(1985) for different agro-ecological regions of Ethiopia, i.e., 2–16 t/ha/year, the soil losses in the Anger River Sub-basin are higher than those in higher regions. The mean annual soil loss in the study area is 83.7 t/ha/year, which is more than twice that of the findings of Negash et al. (2021) in the Chogo Watershed in the Horo Gudru Wollega Zone. Negash et al. found that the mean annual soil loss in Chogo was 37.96 7 t/ha/year. This variation can be mainly attributed to the topography of the study area.

To get a better understanding, the mean annual soil loss rates were identified and categorized following FAO (2006) guidelines, with some modifications to suit the conditions of the study area (Yesuph & Dagnew 2019). Accordingly, the quantitative output of the actual soil erosion rate for the Anger River Sub-basin was computed and finally graded into five severity classes (Figure 9(b); Table 5) such as very slight (0–5 t/ha/year), slight (5–15 t/ha/year), moderate (15–30 t/ha/year), severe (30–50 t/ha/year), and very severe (>50 t/ha/year) as previously used by Gashaw et al. (2019). The findings

![LULC map of the study area.](image-url)

**Figure 8** | LULC map of the study area.

| No | LULC         | Area (km²) | Area (%) |
|----|--------------|------------|----------|
| 1  | Bare land    | 173.5      | 6.6      |
| 2  | Cultivated land | 1,917.5   | 73.4     |
| 3  | Forest       | 327.5      | 12.5     |
| 4  | Grassland    | 2.6        | 0.1      |
| 5  | Shrubland    | 192.3      | 7.4      |
|    | Total        | 2,613.4    | 100.0    |

**Table 4** | LULC types and their coverage
from the study clearly reveal that about an area of 1,140.7 km² (43.6%) and 220.6 km² (8.4%) fell under the very severe and severe categories, respectively. This result is more consistent with that of the previous research by Tadesse et al. (2017), Belayneh et al. (2019), Kidane et al. (2019), and Balabathina et al. (2020).

### Table 5 | Severity range and severity class of soil erosion

| No | Severity range | Severity class | Area (km²) | Area (%) |
|----|----------------|----------------|------------|----------|
| 1  | 0–5            | Very slight    | 548.8      | 21       |
| 2  | 5–15           | Slight         | 393.8      | 15.1     |
| 3  | 15–30          | Moderate       | 309.5      | 11.8     |
| 4  | 30–50          | Severe         | 220.6      | 8.4      |
| 5  | >50            | Very severe    | 1,140.7    | 43.6     |
|    | Total          |                | 2,613.4    | 100      |

### Figure 9 | Soil loss risk (a) and severity class (b).

#### 3.3. Sub-watershed soil loss prioritization

Anger River Sub-basin prioritization was performed in this study. This prioritization was done at a sub-river basin scale by considering areas with a higher soil loss and increased erosion risk (Tesfaye et al. 2018; Woldemariam et al. 2018; Belayneh et al. 2019; Negash et al. 2021). The loss of topsoil due to erosion can significantly affect agricultural yield and result in food insecurity. From the result of the study, the Anger River Sub-basin has 23 sub-watersheds along the mean annual soil loss and the classified severity class were indicated (Table 6; Figure 10(b)). Out of the 23 sub-watersheds, 14 of them were categorized as very severe in soil loss, while four sub-watersheds were categorized as severe. This result is more in agreement with the previous research of Belayneh et al. (2019) and Atoma et al. (2020). This is mainly because of the steepness of the area in question and deforestation for agricultural activities. When we compare this finding with the work of Negash et al. (2021), the number of watersheds classified under very severe soil erosion risk is extremely high. In the present study, we found 14 watersheds under severe soil risk, while Negash et al. (2021) found that only one watershed could be categorized under high soil erosion risk.
Table 6 | Sub-watershed and mean annual soil loss

| No | Sub-watershed name | Area (km²) | Mean soil loss (t/ha/year) | Severity class |
|----|-------------------|------------|----------------------------|----------------|
| 1  | SWS1              | 231.6      | 125.3                      | Very severe    |
| 2  | SWS2              | 127.1      | 150.1                      | Very severe    |
| 3  | SWS3              | 121.2      | 58.0                       | Very severe    |
| 4  | SWS4              | 69.0       | 39.2                       | Severe         |
| 5  | SWS5              | 85.5       | 113.6                      | Very severe    |
| 6  | SWS6              | 145.8      | 114.5                      | Very severe    |
| 7  | SWS7              | 156.5      | 119.8                      | Very severe    |
| 8  | SWS8              | 69.6       | 74.1                       | Very severe    |
| 9  | SWS9              | 83.6       | 82.0                       | Very severe    |
| 10 | SWS10             | 115.9      | 87.5                       | Very severe    |
| 11 | SWS11             | 226.7      | 90.5                       | Very severe    |
| 12 | SWS12             | 83.9       | 76.7                       | Very severe    |
| 13 | SWS13             | 48.8       | 110.2                      | Very severe    |
| 14 | SWS14             | 71.6       | 33.6                       | Severe         |
| 15 | SWS15             | 114.7      | 30.9                       | Severe         |
| 16 | SWS16             | 140.9      | 20.2                       | Moderate       |
| 17 | SWS17             | 100.5      | 30.7                       | Severe         |
| 18 | SWS18             | 119.0      | 32.3                       | Severe         |
| 19 | SWS19             | 80.2       | 22.5                       | Moderate       |
| 20 | SWS20             | 65.6       | 22.4                       | Moderate       |
| 21 | SWS21             | 51.7       | 15.0                       | Moderate       |
| 22 | SWS22             | 96.1       | 146.1                      | Very severe    |
| 23 | SWS23             | 208.1      | 133.1                      | Very severe    |

Figure 10 | Map of the Anger River Sub-watershed (a) and soil loss severity class (b).
4. CONCLUSIONS

Soil erosion is a major threat to environmental health and people’s livelihoods. It has huge potential to affect food security by providing declining agricultural yields. In this study, the method of the integration of the RUSLE model and geospatial tools has been used to estimate the potential loss of topsoil by erosion. To estimate the amount of topsoil loss, we used different parameters such as climate, soil, slope length and steepness, cover management, and supportive practices. Our results conclude that the average annual soil loss estimated using the RUSLE model was about 83.7 t/ha/year in the Anger River Sub-basin. The finding from the study clearly reveals that a total of 1,140.7 km² (43.6%) and 220.6 km² (8.4%) fell under very severe and severe categories, respectively. Thus, the stakeholders concerned should take necessary steps to minimize the loss of soil in the watershed. However, if no interventions are made to arrest his trend and the current scenario continues in the future, agricultural production may be affected by topsoil erosion in the watershed. Of the 23 sub-watersheds of the study area, sub-watershed 2 (SWS2) comes under the very severe category, having a mean soil loss of 150.1 t/ha/year. The steepness of the area and clearance of natural vegetation for agricultural activities are the key factors that influence the amount of soil loss. Our results clearly indicate erosion hotspot areas for further research and policy intervention. Further research should be conducted by using high-resolution Landsat images, the digital elevation model, and CHIRPS rainfall data for making policy recommendations and for conservation planning.

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AUTHOR CONTRIBUTIONS

M.B.M. was involved in research design, literature review, data collection, satellite image and document analysis, and manuscript writing. I.N.D. and B.B.M were involved in research design, literature review, and data analysis. D.O.G. was involved in research design, document analysis, data interpretation and document analysis, and manuscript writing and editorial work. All authors read and approved the final manuscript for publication.

CONSENT FOR PUBLICATION

The authors agreed to publish this manuscript on water and climate change.

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CONFLICT OF INTEREST

The authors declare no competing interests.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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