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Estimating Annual Soil Loss in the Arequa Watershed, North Ethiopia: An Integrated GIS and RUSLE Model

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ABSTRACT

The removal of soil by runoff is a major ecological concern, exacerbated by human-caused land degradation. A detailed procedure that combines the Revised Universal Soil Loss Equation (RUSLE) with Geographic Information System (GIS) methods was used to estimate soil erosion in Arequa watershed. The RUSLE components were applied to evaluate the average annual soil loss due to runoff in the region. The fundamental GIS data layers for RUSLE, encompassing precipitation, soil properties, topography, land use, and agricultural management approaches, were compiled in raster format. The raster calculator was utilized with these layers as input to ascertain the spatial distribution of yearly soil erosion throughout the watershed. A large portion of the drainage area had extremely low (0-6.7 t/ha/yr) to low (6.7-11.2 t/ha/yr) erosion rates, although a considerable segment also indicated moderate (11.2-22.4 t/ha/yr) to elevated (22.4-33.6 t/ha/yr) erosion rates. In certain locations in the study area, the model identified significant erosion rates. Therefore, the combined RUSLE and GIS methodology facilitates a relatively straightforward, rapid, and cost-effective estimation of spatial distribution of sediment output and soil loss, and it aids in determining which watershed areas should be prioritized and receive early treatment, taking into account time and budget limitations. Therefore, to lessen the consequences of erosion on agricultural areas, different cropping patterns and conservation support techniques should be put into place.

Keywords: *Soil Erosion, Watershed, Raster calculator and RUSLE .*

Introduction

Soil erosion caused by runoff is intensified by human activities, which is a significant environmental concern affecting 56% of the global landscape [2]. The highly increasing population, removal of forest lands, improper agricultural practices, as well as excessive grazing have led to increased soil loss, mostly in the less developed nations like Ethiopia [27]. A variety of elements, including slope steepness and length, land cover patterns, climatic change, and the inherent soil characteristics contribute to soil loss, making the soil elements more susceptible and vulnerable to destruction and removal. The profitable concerns of soil erosion are highly pronounced in less industrialized nations such as Ethiopia due to their limited capacity to cope with the impacts and replenish lost nutrients [16]. The rural areas of Ethiopia have experienced high removal of forests, causing to decreased productivity of the soil. These problems have reduced the ability to generate enough food and other biotic assets, accelerated soil erosion, and made the effects of drought more severe [3].

Fifty percent of the country's agricultural land and eighty-eight percent of its people are still affected by soil erosion and the ensuing sedimentation [14]. More than 1.5 billion tons of soil are lost in Ethiopia every year at national level [8], averaging 42 tons per hectare, while around 25,000 hectares of land are lost each year 45% of which comes from cultivated land alone. In the highlands, soil erosion is even more severe, with estimates ranging from 200–300 tons per hectare annually, contributing to a yearly removal of 23,400 million tons [5]. This erosion results in significant economic costs, estimated at nearly 1 billion USD [8]. The aforementioned issues define the Arequa watershed, which is a portion of the Tekeze watershed. Farmers' agricultural output in the watershed may decrease if the existing patterns of soil erosion continue.

Soil loss data is crucial for planning and prioritizing watershed management strategies, as well as for understanding erosion processes and their interactions. Developing efficient soil and water protection strategies and environmental controlling techniques within the drainage area is also aided by evaluating soil removal and locating regions susceptible to soil loss. The RUSLE could be used in determining the mean yearly soil erosion data per unit land area [25]. The Arequa watershed was chosen for this study because there was a dearth of data on erosion and assessment of possible soil loss, and GIS and remote sensing methods were not used. Therefore, using the RUSLE modeled through GIS, an attempt was made to evaluate and depict the spatial distribution of yearly erosion rates induced by water.

Materials and Methods

Study Area Description

The research was carried out in the Abergelle Yechila district, a sub-watershed of the Tekeze basin. The watershed is located in the central portion of Tigray region, approximately 130 km west of Mekelle, the capital city. The district has a mono-modal rainfall pattern, with a two-month wet season in July and August. Geographically the area is located at a latitude of 13^0 14' 07'' N and 38^0 58' 51'' E longitude. The area is characterized by warm, sub-moist lowland (SM1-4 b) below 1500 Mean above sea level. The district's average annual rainfall ranges from 350 to 700 mm with a temperature randing from 24 and 41 degrees Celsius.

It features a variety of soil types with low organic matter concentration, predominantly sandy loam (63.70%), with significant amounts of clay loam (30.4%) and a minor fraction of silt loam (5.9%). (Unpublished data of the BoARD of the Wereda, 2018).

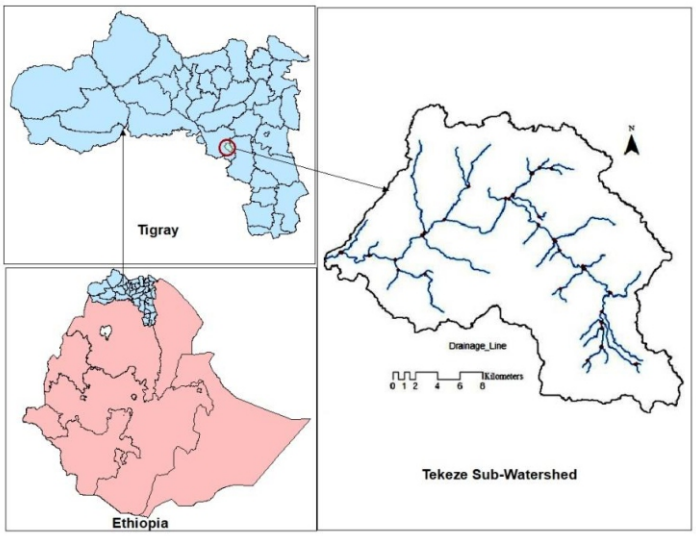


Figure 1: The Geographical Location of the Study Area.

Research Methods

The parameters for the RUSLE model were derived from several data sources: soil maps, rainfall records, a land use/cover map, and a 30-meter ASTER Digital Elevation Model (DEM). After defining the watershed, direction of the flow, accumulation, and stream flows were developed, and the watershed was then analyzed using GIS software, notably Arc Hydro tools. Additionally, the watershed's slope was determined using the DEM model's spatial analysis capabilities. The annual soil loss was calculated using the RUSLE model within the ArcGIS raster calculator [15].

$A = R*K*LS*C*P$ ..... (1)

The equation calculates the mean annual soil loss (A, in t/ha/yr) based on several variables: rainfall erosivity, soil erodibility (K), the crop and management factor (C), slope length, and slope steepness. The RUSLE parameters were spatially interpolated using Wischmeir Ordinary Kriging [7].

Data Analysis

Rainfall Erosivity (R)

The rainfall erosivity parameter is determined by how much rain falls, how intense it is, and how it is distributed over time. Rainfall and soil loss are strongly linked, in part because of the removing force of rain hitting the ground surface and in part because rain contributes to runoff [18]. The R-factor values were computed using the equation taken from [12] for Ethiopian settings, even though there are several techniques to analyze the R based on the specific characteristics of the area.

$R = -8.12 + 0.562 * P$ ..... (2)

Where, R is the Rainfall erosivity, and P is the mean annual rainfall (mm/yr).

The R factor was calculated using data from six meteorological locations. Half of the stations (Agbe, Yechila, and Tekeze) were located inside the Wereda, while the other half (Samre, Gijet, and Finaruwa) came from neighboring Weredas. Following the computation of each station's average rainfall, the rainfall erosivity was calculated and converted into a raster by using standard Kriging interpolation techniques in GIS [17].

Soil Erodibility (k)

A Nomo graph was employed to derive the K factor. In order to understand the K value at the intersection point of the three textures, this Nomo graph requires the percentages of sand, clay, and silt (Figure 2). Soil texture data were sourced from Digital Soil Map of the World (DSMW) of the FAO, which includes relevant basic soil files in Excel format. An conventional Kriging approach was then used to spatially interpolate the obtained K values [20].

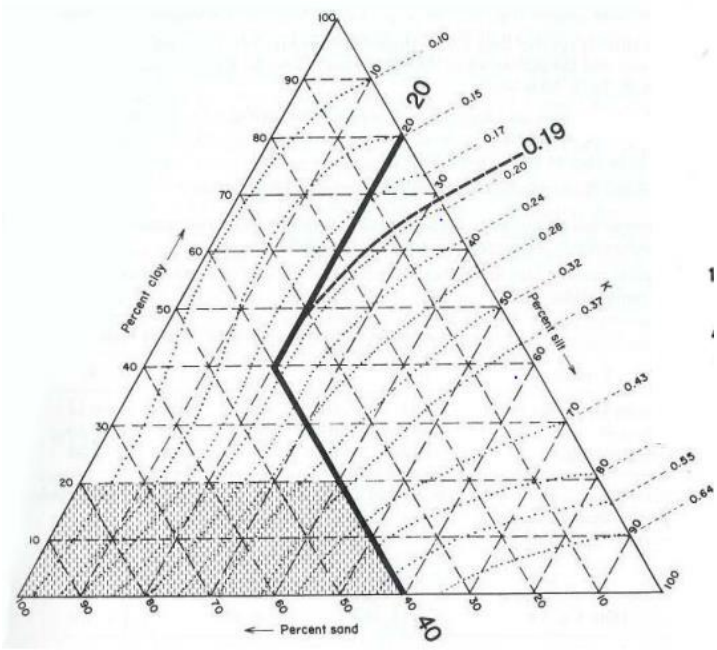


Figure 2: Soil K value Adopted from [26] Nomo graph

Slope Length and steepness (LS)

The slope length and slope steepness in a generic RUSLE model computation can be computed using various formulas. The Unit Stream Power Erosion and Deposition (USPED) technique, which uses raster based calculations combining watershed slope data and stream flow accumulation, was used to calculate the LS factor for this study. The slope data were obtained by analyzing topographic maps through Geographic Information Systems (GIS) to determine percentage values. Arc GIS was also applied to estimate the slope length and slope steepness from DEM. The L factor was calculated using the formula below because, according to [21], the L and S factors are integrated into a single catalog. The following formula was applied to calculate the LS factor.

$LS = \sqrt{L}/22.13\ (.065+.045S+0.0065s^2)$ ..... (3)

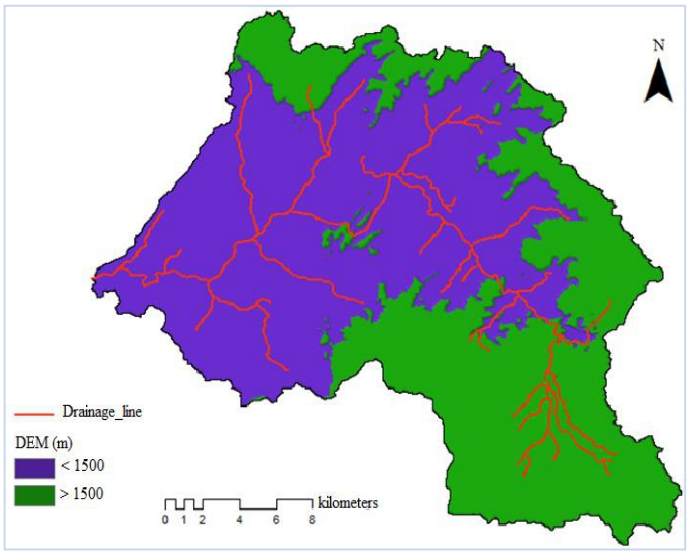
Crop Management Factor and Conservation Practice

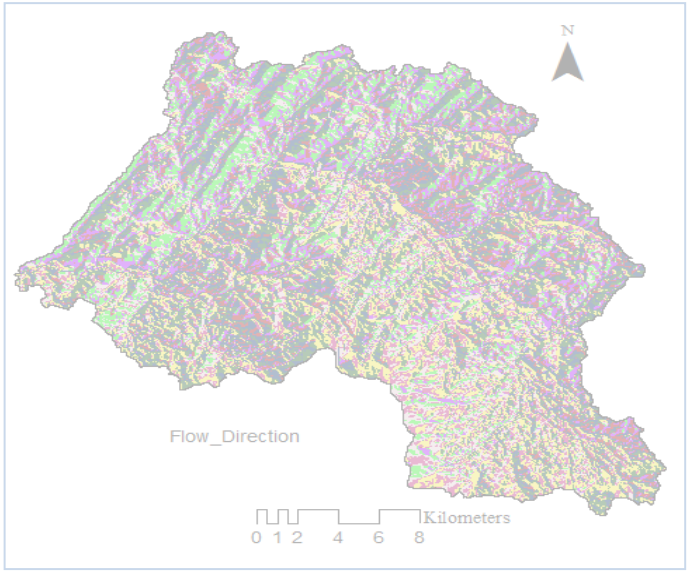
In the RUSLE model, the conservation practice (P) represents the proportion of soil erosion occurring within a particular protection measure compared to the amount of soil lost under fluctuating gradient farming, where the P factor is set to one. The P value (ranging from 0 to 1) is determined by the soil management practices applied, which are themselves strongly influenced by the slope of the land. The FAO's land use/cover map served as the basis for C and P practices. After cross-referencing this with the field, the values from [21] and [10] were applied to calculate the CP values. Within Arc GIS, the calculated C and P values for each cropping method and conservation practice were exported as raster layers.

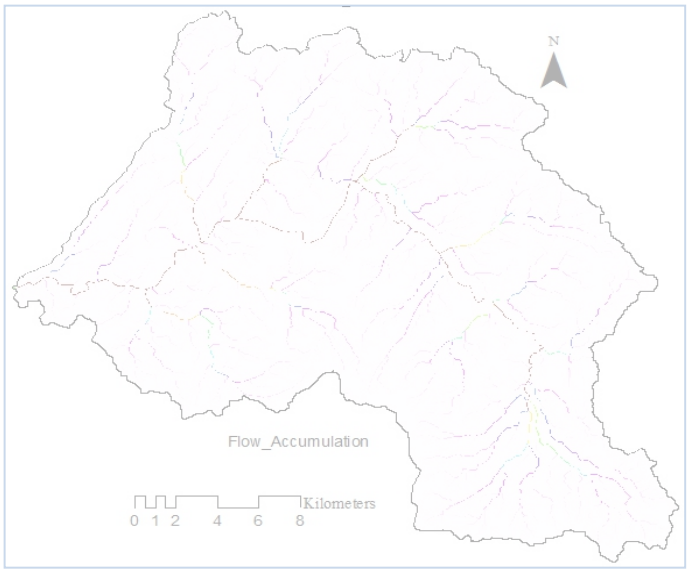
Results and Discussion

Watershed Delineation and Processing

The chosen watershed has an elevation range of 1149 to 2392 m a.s.l. The processed surface drainage patterns such flow direction, flow accumulation and drainage lines are illustrated in figure (3). The DEM and its generated data were used to create stream networks and define watersheds after preprocessing. The terrain preprocessing menu's phases were carried out top to bottom in a sequential fashion (Figure 3).







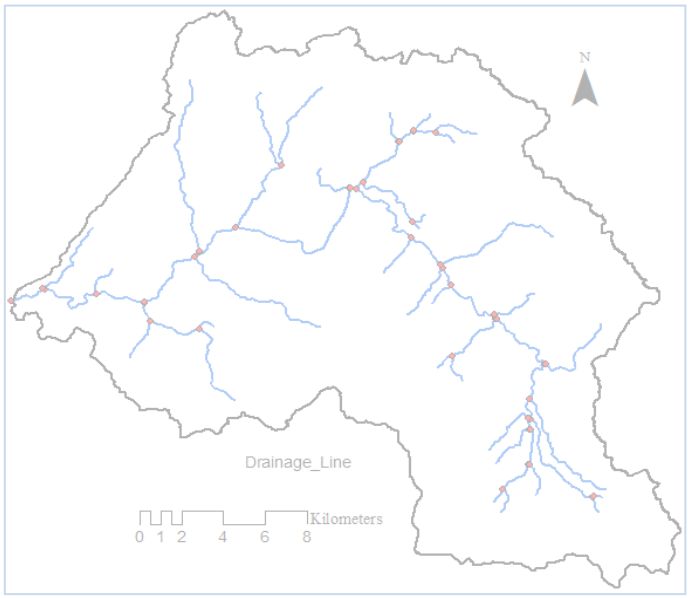


Figure 3: Digital Elevation Model Out puts of the Watershed

Flow direction shows where water flows from each cell (along the steepest drop), while flow accumulation shows how much water flows to each cell (based on the number of upstream cells).

Estimation of RUSLE Factors

Slope Length factor

A flow accumulation dataset is used in the LS calculation approach described here. According to the results, the predominant length for overland flow ranges from zero to approximately 58 meters. According to Figure (4), the greatest overland flow length is 58.1 meters, while the minimum value is zero. The standard deviation is 1.2 meters, while the mean value is 0.53 meters. But the image also makes it clear that lower LS values are seen in greater areas. It is evident from Figure (4) that the valleys with steep slopes have LS values higher than the mean.

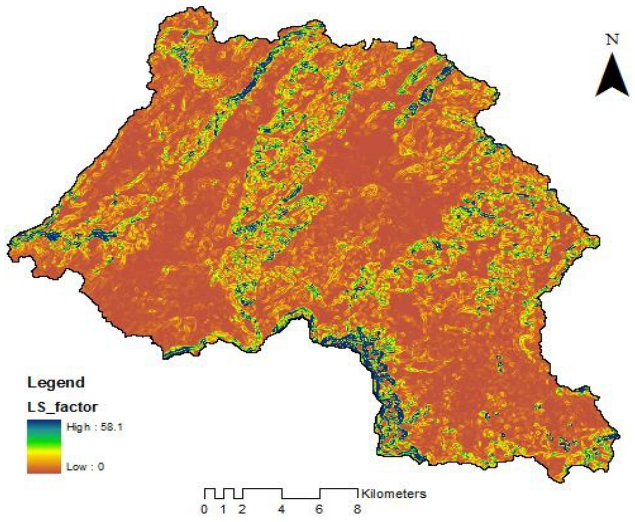


Figure 3: Slope length of the Selected Sub-Watershed at Tekeze Basin

Rainfall Erosivity and soil Erodibility

Figure (5) displays regional distribution for soil erodibility (K) and rainfall erosivity (R) parameters. According to the findings, the R values for the study area range from highest 357 to the lowest 183 MJ/ha.mm/h respectively. The average rainfall erosivity was 269.7 MJ/ha.mm/h, with a standard deviation of 38.7.

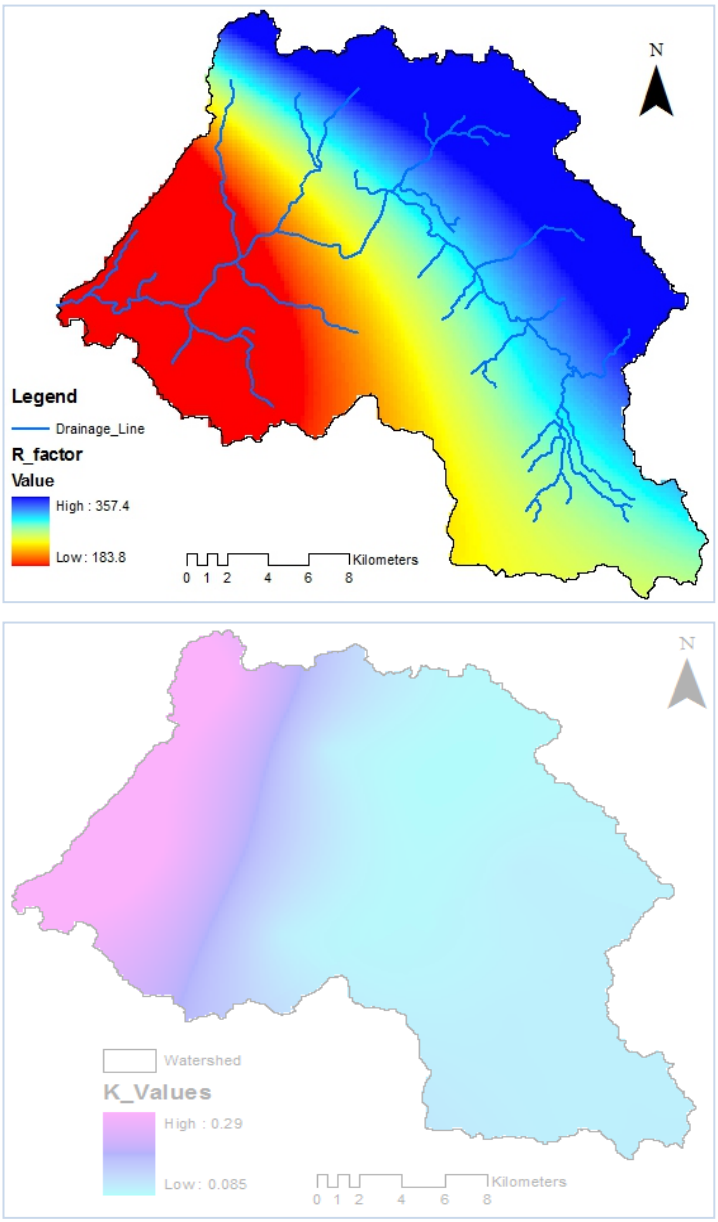
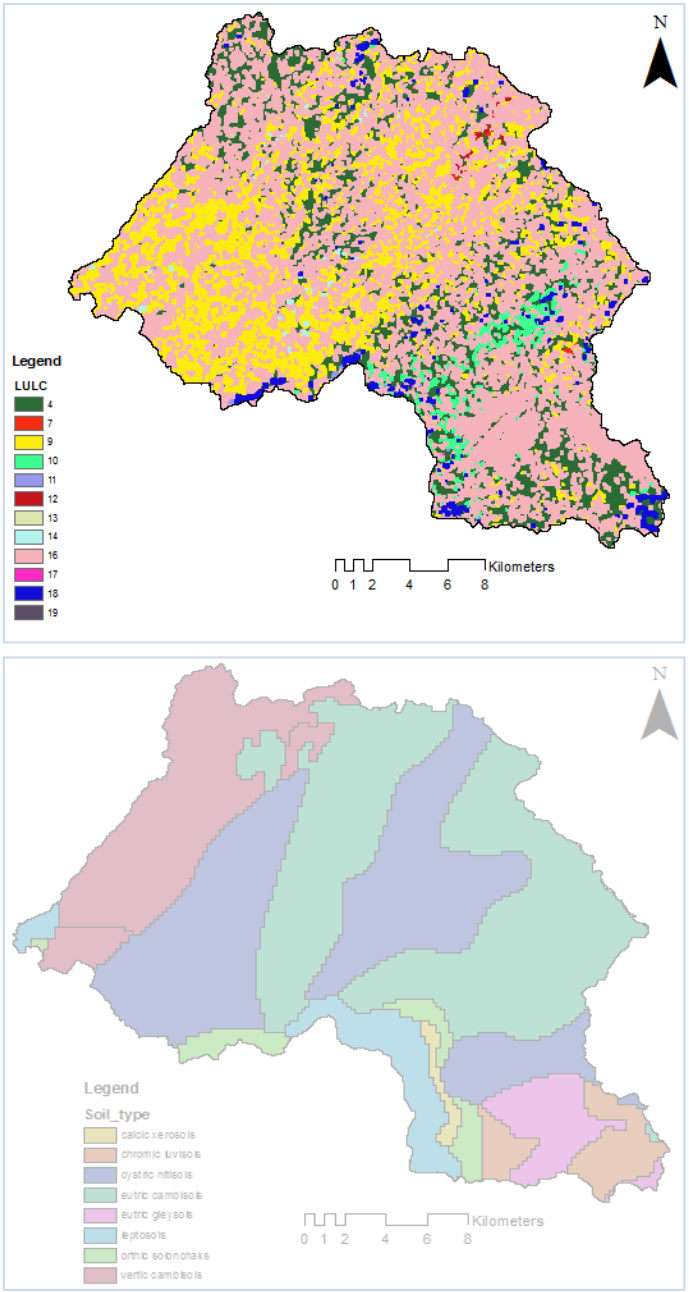


Figure 5: Map of the Rainfall Erosivity and Soil Erodiblity of Arequa Watershed.

Based on [26], the complex interaction of the physio-chemical features of the soil determines the K factor. According to [17], this factor is the mean yearly removed soil per unit of R in particular baseline circumstances: naked soil on a 5° slope with a 22-meter slope length, freshly plowed up and down the slope, and no erosion management measures. Soil erodability is primarily determined by the soil's capacity to absorb rainfall and its structural stability. Soil structure, texture, depth, soil organic matter concentration, and other physio-chemical qualities of the upper soil all have an impact on these properties. This watershed's soil erodibility varies from the greatest at 0.29 to the smallest at 0.085. The lower watershed exhibits considerable soil erodibility, a characteristic linked to its dominant dystric nitisols and vertic cambisols as shown in Figure 5.

Land Use Land Cover (LULC) and Soil Type

The processed LULC categories consist of agricultural areas, barren or grazing land, open forests, and shrubs/bushes Figure (6). The study watershed was found to contain seven principal soil types according to the FAO soil classification: Vertic cambisols, Calcic xerosols, Eutric cambisols, Chromic Luvisols, Dystric Nitosols, Leptosols, Orthic solon chaks and Eutric gleysols. Nonetheless, dystric nitosols, Eutric cambisols, and Vertic cambisols are the watershed's predominant soil types. The C factor indicates how much soil is lost under specific land cover compared to bare soil [18]. Land cover significantly influences erosion and sedimentation processes. Protective layers like vegetation or crop residues can lessen the impact of raindrops, improve water absorption, decrease runoff speed, and weaken the flow's ability to carry soil particles. The LULC map was first converted from raster to vector format. Subsequently, each land use class received a C-value corresponding to the cover values recommended by [12]. Finally, the LULC map was reclassified and converted to a raster to create the C factor map (Figure 6).



Where: 4) Indicates Swamp Forest, 7) Savanna Forest, 9) Deciduous Wood Land, 10) Deciduous Shrub Land with Scarce Trees, 11) Open Deciduous Shrub Land, 12) Closed Grass Land, 13) Open Grass Land with Sparse Shrubs, 14) Open Grass Land, 16) Swamp Bush Land and Grass Land, 17) Crop Lands (>50%), 18) Crop Lands with Open Woody Vegetation and 19) Irrigated Crop Lands.

Figure 6: Soil Type and LULC Change of the Watershed

Crop management Factor and Conservation Practice

Frequent focused interviews and field observations with the district's agricultural office were conducted in order to determine the P factor. Based on this, ploughing in contour line and terracing like stone bunds which were applied on the hillside and mountainous parts of the watershed were considered as a conservation practices. A conservation practice factor map was created in Arc GIS using the watershed's land use/land cover map after the conservation practices and their corresponding values were evaluated (Figure 7).

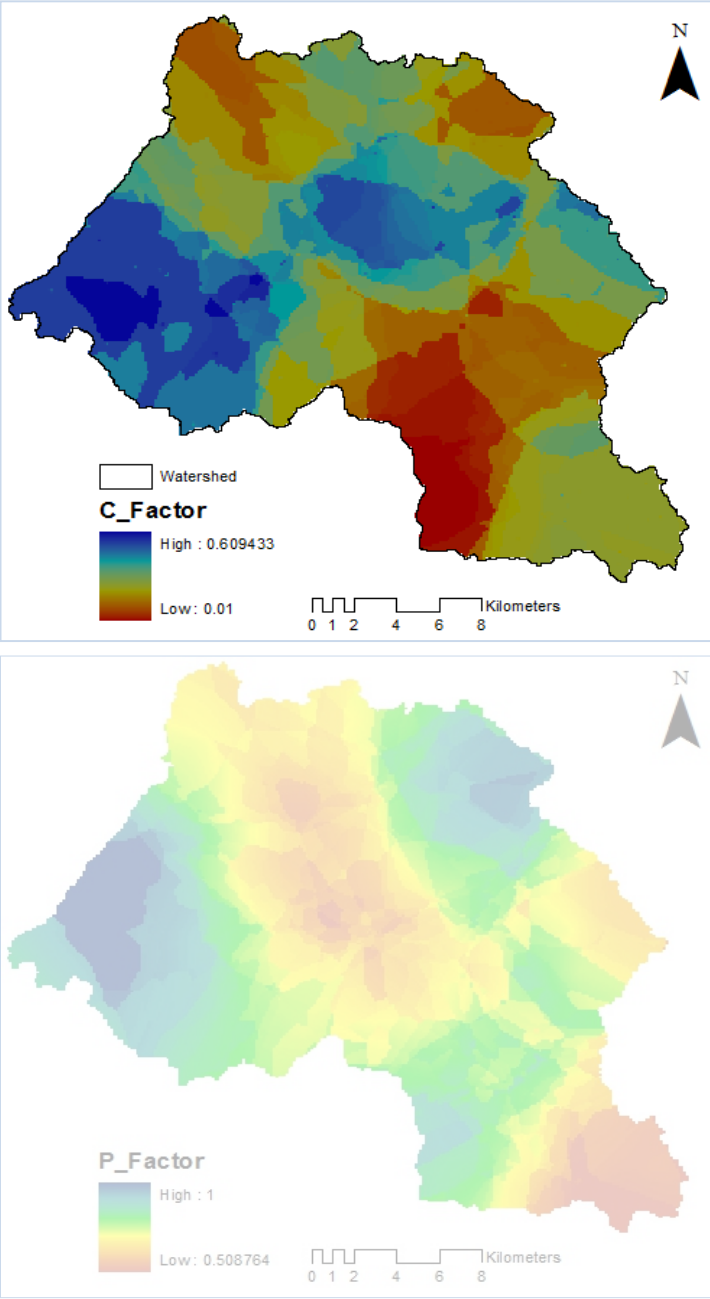


Figure 7: Crop Management Factor and Conservation Practice

The largest crop management factor (C) values were found in the lower and middle portions of the the study area, unlike the steeper upper areas (Figure 7, left). The largest P factor was generally found in the bottom portion of the watershed, much like the C values.

Soil Loss Estimation

The data presented in Figure 8 indicate a wide variation in soil erosion, with annual rates ranges from zero to 283.7 tons per hectare.

However, it was discovered that the steeply sloping riverbanks saw the greatest amount of soil loss. However, Figure (8) makes clear that a significant portion of the watershed has an average yearly soil erosion rate of 6.7 tons and less, which may classified as extremely low erosion rates. A significant area of the watershed, however, experiences moderate (11.2-22.4 t/ha/yr.) to high (22.4-33.6 t/ha/yr.) rates of soil erosion. A very small part of the study area experienced severe erosion, with rates exceeding 33.6 t/ha/yr.

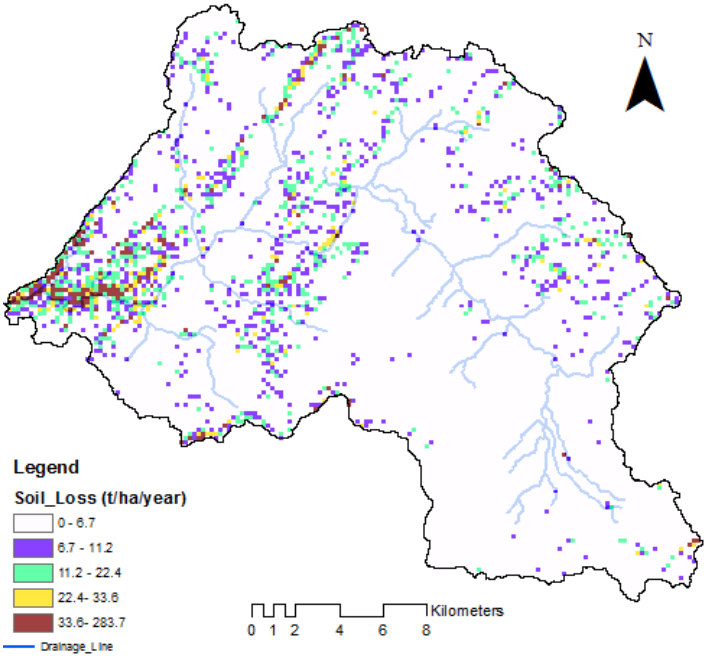


Figure 8: Estimated Annual Soil Loss of the Watershed

The locations with the greatest raster values are those that are most susceptible to soil erosion, while the areas with the lowest raster values are those that are far less susceptible. The Anjeni research unit of [22] reported that the Northwestern Highlands of Gojjam saw an annual soil loss with a potential yield of up to 320 metric tons per hectare, which is significantly greater than this finding. Severe soil erosion in the watershed's steep slopes results from a combination of unsustainable practices, including poor land management, over-cultivation, and overgrazing, which leave the soil bare and vulnerable at the critical onset of seasonal rains. Overall, the study's conclusions were consistent with those of [9, 22 and 23]. According to studies by Solomon Abate [23] and [8], soil loss in Ethiopia's Northern Highlands, including the research site, varies from mild to severe. In the Northwestern Highlands of Gojjam, annual soil loss from farmland and barren areas is reported to be as high as 243 to 320 tonnes per hectare, according to multiple studies [9, 13 and 22]. As expected, farmland experiences the most soil erosion, whereas forestland experiences the least. As a result, this land use was given top priority for conservation planning, which is consistent with the findings of [24]. This implies that compared to farmland, soils covered by grasses and forests are less susceptible to erosion. Furthermore, the results of this study show that in order to guarantee sustainable land use, the vast majority of the study region requires various soil-water conservation interventions [1]. Concentrating land management efforts on important erosion hotspots can significantly lower total soil loss in resource-constrained areas [4]. According to the findings, soil erosion poses a major danger to land productivity and is the most urgent agricultural problem in the research area. Cereal crops like maize, sorghum, and tef are continuously grown on the land due to growing population

pressure. Croplands are more vulnerable to erosion because they frequently lack efficient land management techniques. Because it lessens soil erodibility, minimum tillage practice is a crucial conservation technique in the African sub-Sahara [19]. This type of tillage increases hydraulic conductivity and water retention while maintaining the soil's structure over time.

According to [11], covering the ridges with crops breaks down the stored soil fertility, providing a direct benefit to farmers by releasing nutrients for cultivation. The study area's reduced use of compost and manure could be another factor contributing to the severity of soil loss on farm land. According to a study by [6], adding animal feces to soil improves pore space and water infiltration while reducing bulk density and compaction, which reduces runoff and erosion.

Conclusion and Recommendation

This work allowed for the successful integration of GIS methods with RUSLE parameters to evaluate the degree of soil loss in any watershed. The predicted potential soil erosion and thematic maps of these characteristics were calculated geographically using the RUSLE factors. The watershed's most badly damaged regions can be prioritized and management efforts can be precisely focused using this data. The study's findings generally demonstrate that Revised Universal Soil Loss Equation combination with Geographic Information System is an effective model for both qualitative and quantitative evaluation of soil loss for a particular watershed. According to the findings, the watershed's average yearly soil loss ranges from zero to 6.7 t/ha/yr, indicating a very low danger of erosion. However, a significant portion of the watershed was also evaluated for moderate to high soil erosion by water. According to the study's findings, it is advised that ground surveys should be conducted in regions with a high risk of soil erosion in order to implement appropriate conservation measures to slow down the erosion rates.

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References

1. Angima, S., Stott, D., O'Neill, M., Ong, C., and Weesies, G. (2003). Soil erosion prediction using RUSLE for central Kenyan high-land conditions. *Agriculture, Ecosystems and Environment*, 97, 295–308. https://doi.org/10.1016/S0167-8809(03)00011-2
2. Bai, Z. G., Dent, D. L., Olsson, L., and Schaepman, M. E. (2008). Proxy global assessment of land degradation. *Soil Use and Management*, 24, 223–234. https://doi.org/10.1111/j.1475-2743.2008.00169.x
3. Bekele, W., and Drake, L. (2003). Soil and water conservation decision behavior of subsistence farmers in the eastern highlands of Ethiopia: A case study of the Hunde-Lafto area. *Ecological Economics*, 46, 437–451. https://doi.org/10.1016/S0921-8009(03)00166-6
4. Berhan, G., and Mekonnen, K. (2009). Estimating soil loss using Universal Soil Loss Equation for soil conservation planning at Medego watershed, northern Ethiopia. *Journal of American Sciences*, 5, 58–69.
5. Bewket, W. (2003). Towards integrated watershed management in high-land Ethiopia: The Chemoga watershed case study. Internal PhD, Wageningen University. https://doi.org/10.18174/121444
6. Bizoza, A. (2014). Three-stage analysis of the adoption of soil and water conservation in the high-lands of Rwanda. *Land Degradation & Development*, 25, 360–372. https://doi.org/10.1002/ldr.2145
7. Eldrandaly, K., and Abu-Zaid, M. (2011). Comparison of six GIS-based spatial interpolation methods for estimating air temperature in western Saudi Arabia. *Journal of Environmental Informatics*, 18(1), 38–45. https://doi.org/10.3808/jei.201100197
8. FAO. (1986). *Ethiopian High-land Reclamation Study*. Final report of the Food and Agriculture Organization, Rome.
9. Gete, Z. (2000). *Landscape dynamics and soil erosion process modeling in the north western Ethiopian high lands*. African Studies Series A16, Geographic Bernensia, Berne.
10. Schwab, G. O., Fangmeier, D. D., Elliot, W. J., and Frevert, R. K. (1993). *Soil and water conservation engineering* (4th ed.). ISBN: 0471574902.
11. Gowing, J., and Palmer, M. (2008). Sustainable agricultural development in sub-Saharan Africa: The case for a paradigm shift in land husbandry. *Soil Use and Management*, 24, 92–99. https://doi.org/10.1111/j.1475-2743.2007.00137.x
12. Hurni, H. (1985). Erosion-productivity conservation systems in Ethiopia. *Proceedings of the 4th ISCO Conference*, Venezuela, 654–674.
13. Hurni, H. (1993). Land degradation, famine, and resource scenarios in Ethiopia. In D. Pimentel (Ed.), *World Soil Erosion and Conservation* (pp. 27–62). Cambridge University Press. https://doi.org/10.1017/CBO9780511735394.004
14. Keyzer, M. (2011). Evaluating quantitative and qualitative models: An application for nationwide water erosion assessment in Ethiopia. *Environmental Modelling & Software*. https://doi.org/10.1016/j.envsoft.2011.05.002
15. Kin, Y. (2014). Soil erosion assessment using GIS and Revised Universal Soil Loss Equation (RUSLE). *CE 394K GIS in Water Resources*, David R. Maidment.
16. Lulseged, T., and Paul, V. (2006). Reservoir siltation in the semi-arid high-lands of northern Ethiopia: Sediment yield–catchment area relationship and a semi-quantitative approach for predicting sediment yield. *Earth Surface Processes and Landforms*, 31, 1364–1383. https://doi.org/10.1002/esp.1338
17. Meusburger, K., Steel, A., Panagos, P., Montanarella, L., and Alewell, C. (2012). Spatial and temporal variability of rainfall erosivity factor for Switzerland. *Hydrology and Earth System Sciences*, 16, 167–177.
18. Morgan, R. P. C. (1994). *Soil erosion and conservation*. Silsoe College, Cranfield University, Cranfield.
19. Ndah, H. T., Schuler, J., Uthes, S., Zander, P., Triomphe, B., Mkomwa, S., and Corbeels, M. (2015). Potential for conservation agriculture in Africa: A newly developed assessment approach (QATOCA) applied in Kenya and Tanzania. *Land Degradation & Development*, 26, 133–141.
20. Perez-Rodriguez, R., Marques, M. J., and Bienes, R. (2007). Spatial variability of the soil erodibility parameters and their relation with the soil map at subgroup level. *Science of the Total Environment*, 378, 166–173.
21. Morgan, R. P. C. (1986). *Soil erosion and conservation*, pp. 256–295.
22. SCRP. (1988). *Soil Conservation Research Programme: Fifth Progress Report 1985*. University of Bern, Switzerland, in association with the Ministry of Agriculture, Ethiopia.
23. Solomon, A. (1994). *Land use dynamics, soil degradation, and potential for sustainable use in Metu Area, Illubabur Region, Ethiopia*. African Studies Series A13, Geographical Bernensia, Berne.
24. Tripathi, M., Panda, R., and Raghuwanshi, N. (2003). Identification and prioritization of critical sub-watersheds for soil conservation management using the SWAT model. *Biosystems Engineering*, 85, 365–379.

25. Van Remortel, R., Hamilton, M., and Robert, J. (2001). Estimating the LS factor for RUSLE: The slope length processing of DEM elevation data within ArcInfo Grid. 30(1).
26. Wischmeier, W., and Smith, D. (1978). *Predicting rainfall erosion losses: A guide to conservation planning*. Agriculture Handbook No. 537, USDA Agricultural Research Service, Washington, DC.
27. Zemenu, D., and Minale, A. (2014). Adoption of soil conservation practices in North Achefer District, Northwest Ethiopia. *Chinese Journal of Population Resources and Environment*, 12(3), 261–268. https://doi.org/10.1080/10042857.2014.934953