236

Estimation of water-induced soil erosion levels across the rangelands of Ethiopia: an integrated RUSLE and GIS analysis

Worqlul, AW [1]; Yigezu, YA [2]; Louhaichi, M [1]; Haddad, M[3]; Govind, A[4]

[1] International Center for Agricultural Research in the Dry Areas (ICARDA), Tunis, Tunisia

[2] International Center for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt

[3] International Center for Agricultural Research in the Dry Areas (ICARDA), Amman, Jordan

[4] International Center for Agricultural Research in the Dry Areas (ICARDA), Cairo, Egypt

Key words: K-factor; rainfall erosivity; soil erodibility; soil loss; sustainable land management

Abstract

Soil erosion poses a significant global threat, leading to widespread land degradation and the depletion of nutrient-rich topsoil. Understanding the spatial distribution of soil erosion is crucial for implementing effective management practices and preventing further erosion. This study utilized an analytical tool integrating the Revised Universal Soil Erosion Equation (RUSLE) with geographic information systems (GIS) to estimate water-induced soil erosion across the rangelands and other land use categories in Ethiopia. Rangelands, constituting 68% of Ethiopia's total land area, are essential for the livelihoods of millions of pastoralists and agropastoralists. Input data for the analysis were gathered from multiple sources, including in situ observations and remotely sensed data with various spatial resolutions. The estimated soil erosion rates were validated using previously published data from literature. Our results revealed significant variation in soil erosion, ranging from zero to 250 t ha^{-1} yr^{-1}. The average soil loss across the country was estimated at 13.5 t ha^{-1} yr^{-1}, amounting to an annual soil loss of about 1.5 billion tons, making Ethiopia one of the most severely affected countries by soil erosion worldwide. Disaggregated annual soil erosion estimates indicated that the highest soil loss occurs in rangelands (18 t ha^{-1}), sparsely vegetated (bare land) areas (16 t ha^{-1}), cultivated areas (10 t ha^{-1}), and forest areas (8 t ha^{-1}). These results underscore the urgent need to implement appropriate soil and water conservation practices across rangelands, embracing Sustainable Land Management practices that can significantly reduce soil erosion. Such efforts will support sustainable land resource use and potentially unlock new opportunities for the country.

Introduction

Water-induced soil erosion is a leading cause of land degradation worldwide, resulting in the loss of nutrient-rich topsoil. This process not only diminishes agricultural productivity but also disrupts ecosystems and contributes to reservoir sedimentation (Nathan et al., 2022; Stocking, 2003). Water-induced soil erosion presents significant challenges for sustainable land management and environmental conservation efforts. Although this issue affects regions globally, it is particularly severe in sub-tropical and tropical areas (Lal, 2001). In Africa, the threat of soil erosion poses a substantial risk to food security (Gomiero, 2016; Hossain et al., 2020; Rhodes, 2014). This challenge is further intensified by factors such as climate variability, unsustainable land management practices, and population pressure. Tackling soil erosion requires a comprehensive strategy that includes estimating its current and future spatial distribution, setting priorities, and implementing sustainable land management practices in vulnerable regions. This can be achieved using various models to assess current levels of erosion and forecast future trends.

There are various ways of estimating the spatial distribution of water-induced soil erosion, encompassing both biophysical and empirical statistical models (Borrelli et al., 2021; Golmohammadi et al., 2014; Pal and Chakrabortty, 2019; Wang et al., 2011). These models focus on evaluating the effects of agricultural management practices on several parameters, including plant growth, soil erosion, and surface runoff at various scales and environmental conditions.

Biophysical models require extensive data inputs for accurate parameterization and calibration, such as daily climate and streamflow data, soil properties, and sediment data. This reliance on detailed data can be a limitation in areas with limited data availability. In contrast, empirical models, like the Universal Soil Loss Equation (USLE) and its updated version, the Revised Universal Soil Loss Equation (RUSLE), offer simpler approaches, using fewer input parameters to estimate soil erosion. USLE incorporates core factors influencing soil erosion, such as rainfall intensity, soil type, landscape position, and land use. RUSLE builds on USLE by adding factors that account for erosion control practices and integrates these into computer applications, providing more refined estimates.

RUSLE's ability to capture the effects of soil and water conservation practices allows it to assess management strategies' effectiveness in reducing soil erosion. The choice between biophysical and empirical models depends on the purpose of the study and data availability: while biophysical models require extensive, high-resolution data, empirical models need fewer inputs and deliver reasonably precise results. Additionally, empirical models like RUSLE are compatible with spatial applications, making them advantageous for mapping soil erosion.

Researchers and land managers use RUSLE to assess and manage soil erosion risks, guide land-use planning, and develop erosion control strategies. The model is particularly valuable in identifying areas vulnerable to soil erosion, understanding the impact of different factors on erosion rates, and evaluating the effectiveness of soil conservation practices. RUSLE has been widely applied in agricultural and environmental research, contributing to sustainable land management practices and erosion prevention strategies.

This specific study concentrates on assessing the spatial distribution of soil erosion in the rangelands and other land use groups of Ethiopia. The objective of this study is, therefore, to integrate RUSLE within GIS and evaluate the spatial distribution of soil erosion across Ethiopia. This study will contribute to the body of knowledge on soil erosion, which has limited comprehensive studies across Ethiopia.

Methods

The spatial distribution of soil erosion across the rangelands and other land use groups of Ethiopia were estimated using the RUSLE method. The methodology involved mapping essential factors such as rainfall intensity, soil texture and organic carbon content, landscape position, land use, and conservation practices, which significantly contribute to soil erosion. Those factors under RUSLE were represented with rainfall erosivity factor (R-factor), soil erodibility factor (K-factor), slope length and slope steepness factor (LS-factor), land cover management factor (C-factor), and conservation practice factor (P-factor). Input data required to estimate RUSLE factors, including annual average rainfall from 2000 to 2020, were collected from ground observation stations and Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) when there is no or limited gauged rainfall data. Additionally, information on soil texture and organic matter, digital elevation model (DEM), and land use/cover were gathered from diverse global data sources with various spatial resolutions. The diverse factors were mapped, resampled, and overlaid using the ArcGIS platform to compute the spatial distribution of soil erosion. The validation of the estimated soil loss across the three countries was undertaken through a thorough literature review, which involved an examination of existing scientific studies and reports. This process aimed to assess the accuracy and reliability of the soil loss estimates generated using the RUSLE integrated with GIS. Finally, the soil erosion was disaggregated across the different land use groups and reported.

Results

Spatial Distribution of the Soil Erosion Factors

Rainfall erosivity (R-factor) in Ethiopia ranged between 64 and 1,388 MJ mm ha^{-1} hr^{-1} yr^{-1}, averaging 510 MJ mm ha^{-1} hr^{-1} yr^{-1}. The southeastern region exhibits the highest rainfall erosivity, while lowland areas that receive less than 300 mm of annual rainfall experienced the lowest rainfall erosivity. High R-factor values indicate strong rainfall energy, which can lead to significant soil erosion.

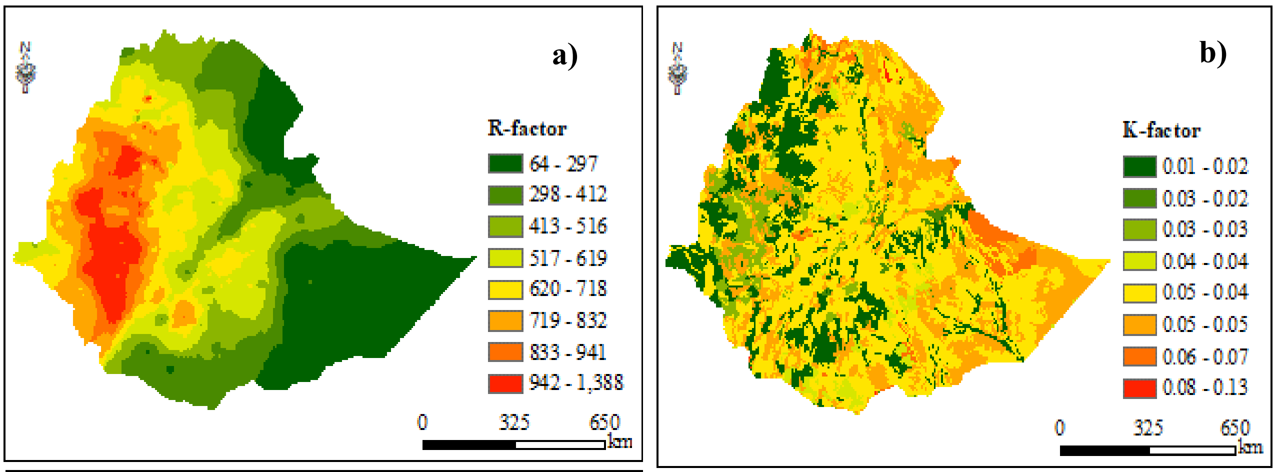

Figure 1. a) Rainfall erosivity (R-factor) [MJ mm ha^{-1} hr^{-1} yr^{-1}] and b) Soil erodibility (K-factor) [t ha hr ha^{-1} MJ^{-1} mm^{-1}] of Ethiopia.

The soil erodibility factor values estimated across Ethiopia ranged from 0.01 to 0.13 t ha hr ha^{-1} MJ^{-1} mm^{-1}, averaging about 0.04. The result of the analysis, in general, indicated that soil textures, including clay, silty clay, and silty clay loam, have lower K-factor values since those soils are resistant to particle detachment. Meanwhile, coarse-textured soils with lower resistance to detachment, such as sand, loamy sand, and sandy loam, were characterized by a higher K-factor value, signifying higher erosion rates.

The slope length and slope steepness factor (LS-factor [unitless]) estimated across Ethiopia exhibited the most significant variability with a coeffect of variation of 606%. The average LS-factor value for Ethiopia was approximately 13.2. The average C-factor for Ethiopia, determined from land use/cover conditions was approximately 0.15. A higher C-factor value signifies a higher potential for soil erosion under the current land cover and management condition. The conservation practice factor (P-factor) value estimated using slope class and land use condition indicated an average value of 0.66 across the country.

RUSLE Estimated Annual Soil Loss.

The estimated annual soil erosion rate in Ethiopia varied from zero to more than 250 t ha^{-1} yr^{-1}, with a coefficient of variation of 380%, showing a significant variation due to the largest range in rainfall, soil, and altitude. The average soil loss across the country was 13.5 t ha^{-1} yr^{-1}, which amounts to an annual soil loss of about 1.5 billion tons, making Ethiopia one of the most severely affected countries by soil erosion worldwide (Tamene and Vlek, 2008; Tsegaye, 2019). Levels of soil erosion estimated across the major land use groups indicated that the highest soil loss is estimated in the rangelands (18 t ha-1), sparsely vegetated (bare land) areas (16 t ha^{-1}), cultivated areas (10 t ha^{-1}) and forest areas (8 t/ha). Soil erosion was classified based on severity classes as indicated in Haregeweyn et al. (2017); the results show that 21% of the country is experiencing "Moderate" to "Excessive" soil erosion risk, of which 4% is "Severe" and 6% is "Excessive". The remaining 79% of the country is experiencing "Low" and "Very Low" erosion risk. The finding of this work is consistent with Tsegaye (2019) and Tamene and Vlek (2008). From among the 72 administrative zones in Ethiopia, the highest soil erosion is estimated in Hadiya (45 t ha^{-1}), Dawuro (38 t ha^{-1}), and Wolayita (27 t ha^{-1}), located in the Southern Nations and Nationalities region, and in Wag Hemira (32 t ha^{-1}) and East Gojam (30 t/ha) in the Amhara region. Soil erosion in Ethiopia is one of the most serious causes of soil degradation, which has been directly linked to a substantial decrease in soil fertility and crop yield (Aleminew and Alemayehu, 2020; Taddese, 2001; Yebo, 2015). This underlines the urgent need for soil conservation measures across the country.

Discussion and Conclusions

This study highlights the urgent soil erosion risks affecting Ethiopia's rangelands, revealing critical insights for sustainable land management in regions essential to the livelihoods of pastoralists and agropastoral communities. The RUSLE-GIS-based analysis illustrates that rangeland, covering the majority of Ethiopia's land, face the highest rates of soil erosion, estimated at 18 t ha^{-1} annually. Given that these areas are vital for livestock and agriculture, the findings underscore a pressing need for targeted soil and water conservation practices in Ethiopia's rangelands to mitigate erosion and its adverse effects on land productivity and environmental health.

High rainfall erosivity and soil erodibility in specific regions further exacerbate the erosion risk, particularly in Hadiya, Dawuro, Wolayita, Wag Hemira, and East Gojam zones, which show some of the highest soil loss rates. This calls for immediate action in these zones through localized erosion control practices, emphasizing sustainable land management practices like reforestation, conservation tillage, and optimized grazing management to protect soil resources.

The study's findings reinforce the need for policy interventions that prioritize soil conservation strategies, particularly in the most vulnerable rangelands. Integrating these practices into Ethiopia's broader environmental policy and development programs could significantly alleviate soil degradation. Further research could refine the model by incorporating additional local data, enabling even more accurate soil erosion mapping and, ultimately, more effective interventions. In conclusion, this study offers a critical foundation for advancing Ethiopia's land conservation efforts, aiming to support sustainable land use while protecting vital rangeland ecosystems.

Acknowledgements

This research was jointly funded by the CGIAR Research Initiative on Livestock and Climate, which is supported by contributors to the CGIAR Trust Fund and the Belgium CGIAR Fund Addressing SDG15 in the Sahel by Building Pathways for Transforming Food and Land Systems in a Climate Crisis through the CGIAR Initiative on Climate Resilience (ClimBeR). CGIAR is a global research partnership for a food-secure future dedicated to transforming food, land, and water systems in a climate crisis.

References

Aleminew, A, Alemayehu, M (2020). Soil fertility depletion and its management options under crop production perspectives in Ethiopia: A review. *Agricultural Reviews* 41, 91-105.

Borrelli, P, Alewell, C, Alvarez, P, Anache, JAA, Baartman, J, Ballabio, C, Bezak, N, Biddoccu, M, Cerdà, A, Chalise, D, et al. (2021). Soil erosion modelling: A global review and statistical analysis. *Science of the Total Environment* 780, 146494.

Golmohammadi, G, Prasher, S, Madani, A, and Rudra, R (2014). Evaluating three hydrological distributed watershed models: MIKE-SHE, APEX, SWAT. *Hydrology* 1, 20-39.

Gomiero, T (2016). Soil degradation, land scarcity and food security: Reviewing a complex challenge. *Sustainability* 8, 281.

Haregeweyn, N, Tsunekawa, A, Poesen, J, Tsubo, M, Meshesha, DT, Fenta, AA, Nyssen, J, Adgo, E (2017). Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the Upper Blue Nile River. *Science of the Total Environment* 574, 95-108.

Hossain, A, Krupnik, TJ, Timsina, J, Mahboob, MG, Chaki, AK, Farooq, M, Bhatt, R, Fahad, S, and Hasanuzzaman, M (2020). Agricultural land degradation: processes and problems undermining future food security. *In* "Environment, climate, plant and vegetation growth", pp. 17-61. Springer.

Lal, R. (2001). Soil degradation by erosion. *Land degradation & development* **12**, 519-539.

Nathan, O. O., Monicah, M.-M., Jayne, M. N., Isaya, S., George, N., and Daniel, M. N. (2022). Nutrient and organic carbon losses by erosion, and their economic and environmental implications in the drylands of Kenya. *Environmental challenges* **7**, 100519.

Pal, S. C., and Chakrabortty, R. (2019). Modeling of water induced surface soil erosion and the potential risk zone prediction in a sub-tropical watershed of Eastern India. *Modeling Earth Systems and Environment* **5**, 369-393.

Rhodes, C. J. (2014). Soil erosion, climate change and global food security: challenges and strategies. *Science progress* **97**, 97-153.

Stocking, M. A. (2003). Tropical soils and food security: the next 50 years. *Science* **302**, 1356-1359.

Taddese, G. (2001). Land degradation: a challenge to Ethiopia. *Environmental management* **27**, 815-824.

Tamene, L., and Vlek, P. L. (2008). Soil erosion studies in northern Ethiopia. *Land use and soil resources*, 73-100.

Tsegaye, B. (2019). Effect of land use and land cover changes on soil erosion in Ethiopia. *International Journal of Agricultural Science and Food Technology* **5**, 026-034.

Wang, X., Kannan, N., Santhi, C., Potter, S., Williams, J., and Arnold, J. (2011). Integrating APEX output for cultivated cropland with SWAT simulation for regional modeling. *Transactions of the ASABE* **54**, 1281-1298.

Yebo, B. (2015). Integrated soil fertility management for better crop production in Ethiopia. *International Journal of soil science* **10**, 1-16.