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Soil Erosion Risk Assessment using RUSLE (Revised Universal Soil Loss Equation) and GIS

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Abstract

The devastating effects of soil erosion on ecosystems, water quality, and agriculture make it one of the world's most pressing environmental crises. Soil erosion likelihood for a specific watershed will be determined using GIS and the Revised Universal Soil Loss Equation (RUSLE). The variables of C: cover management, P: support practices, LS: slope length and steepness, K: soil erodibility, and R: rainfall erosivity were derived using satellite imagery, digital elevation models (DEMs), land cover maps, and field data. The components were analysed spatially in a GIS environment, which enabled the calculation of average soil erosion over a year inside the area's boundaries by adding or developing risk layers individually. Erosion is primarily influenced by geology, vegetation, and land management techniques. The most likely places to find critical conditions are those with sparse vegetation and exposed rocks. The purpose of this research was to create a soil erosion risk assessment map that managers and planners could use to zero in on the most efficient ways to

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prevent soil erosion. When data is lacking, as is often the case in vast areas, combining GIS with RUSLE provides an accurate and cost-effective way to assess soil erosion and control tactics.

Keywords:

RUSLE, GIS, management of watershed, remote sensing, spatial analysis, soil loss estimation, soil erosion.

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Introduction

Soil erosion has continued to be a great concern to agricultural activities in regions with large population and highly unpredictable weather conditions (Pimentel et al., 1995). Erosion will lower the agricultural productivity greatly besides escalating the velocity of sedimentation as well as erosion of nutrients in the water bodies (Danková et al., 2021; Lal, 2001; Vasquez & Mendoza, 2024). RUSLE planning and research on GIS Special Areas of Concern preservation areas have been made easier with the new technology, including maintenance and planning (Fernandez et al., 2003; Silva et al., 2025; Baros, 2020; Abishek et al., 2023). Numerous attempts have been made to enhance GIS integration into RUSLE with land cover (C), conservation (P), soil erodibility (K), rainfall erosivity (R), and time-space interactions to get more accurate results (Kavitha, 2023; Prasannakumar et al., 2011). There have been various efforts to quantify the erosion of forest, agriculturally exploited, and watershed regions employing a RUSLE-GIS approach (Chatterjee, 2020; Angima et al., 2003; Rahman & Lalnunthari, 2024). Numerous problems that artificial intelligence faces in estimating parameters, ensuring data quality, and verifying actual values in erosion rate estimation pose significant challenges (Prabhu & Sujai, 2022; Kouli et al., 2009). Especially when little attention is given to change-induced land degradation (Anaya Menon & Srinivas, 2023), regional calibration erosion models require precise and tailor-made bespoke attention (König et al., 2020; Panagos et al., 2015; Anand, 2024). The principal erosion hot spot locations will be identified. This study topic is ideal for GIS research since it applies the RUSLE model to the area under investigation. This will aid in the formulation of policies and strategic decisions regarding spatial planning (Devaki et al., 2024; Pandey et al., 2009). This is one of the successful instances of the practical integration of empirical modeling and GIS in soil erosion control in data-poor areas (Renard, 1997; (Ganasri & Ramesh, 2016).

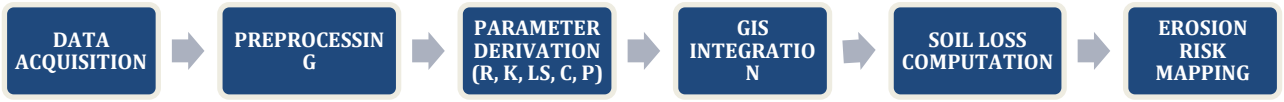

Figure 1. Framework architecture for RUSLE–GIS-Based soil erosion modeling

As seen in Figure 1, a methodical approach to evaluating soil erosion vulnerability can be achieved by integrating GIS with the Revised Universal Soil Loss Equation (RUSLE) (Shum, 2024). The initial step in every procedure is to gather crucial data, including weather conditions, soil type, terrain, and land use. Before moving on to the next phase of parameter creation, a validation process is carried out to ensure the spatial representation is accurate and homogeneous. In the process of deriving the parameters of RUSLE, factors such as cover management and soil erodibility, slope length and steepness, support practice, and R, K, LS, C, and P are calculated. In order to see the soil loss progress in each location inside the target area, the derived parameters are put into the GIS. Next, numerical values are generated from the soil loss computation; these will be used to determine the severity of the erosion condition, which will then be mapped spatially to locations

that are prone to erosion. This methodology shows how a set of empirical models, including the RUSLE and spatial analysis based on GIS, improve the understanding, accuracy, and visualisation of soil erosion studies for use in conservation planning and land management (Panagos et al., 2015; Abioghli, 2017; Poornimadarshini, 2024).

What is already understood about soil conservation is greatly enhanced by this work in several ways. A geographical map of erosion risks with varying levels of risk combined is shown in the first part of the report using GIS and the RUSLE model (Ulkilan et al., 2024). In addition, it simulates how various human and hydrologic factors, such as rainfall and land use, affect erosion rates. Furthermore, it delves into the importance of pinpointing and classifying areas that could be prone to soil erosion in order to implement strategies for management or mitigation. Research uses GIS and data to look at the RUSLE parameters of the area as a countermeasure (Salehi, & Nowrouzi, 2025; Chen et al., 2011).

There are five sections that make sense together and form the framework of this document. The first section, "Introduction," lays out the background, goals, and significance of the study, and it talks about soil erosion and how it's tried to be quantified using RUSLE and a GIS. In Section II, the paper's scope is justified and the research that addresses the gaps is reviewed. The literature applies spatial techniques and RUSLE to various non-exploitative land use case studies. In Section III, The Methodology describes the process of information gathering, preparation of RUSLE constituents, GIS-geared analysis, and the system designed to assess soil loss. In Section IV, the comparison of the character of the credibility of an erosion-prone region control by led land use versus topographic control on soil is juxtaposed with relevant literature in the Results and Discussion section. As such, in Section V, the primary outcomes are outlined in tandem with strategic regulated land use planning, advanced modeling-based monitoring, or persistent and intensive research opportunities for the study, which is later concluded.

Related Work

On a worldwide scale, RUSLE with GIS has been used to evaluate soil erosion concerns and develop solutions for managing them. Research by (Phinzi et al., 2021) in the Eastern Cape Province of South Africa demonstrated the model's ability to pinpoint areas prone to land use conflicts. Plant cover and slope greatly govern erosion severity, according to Biswas et al. (2015) in their RUSLE-GIS study on South Africa (Chatterjee et al., 2014). When it comes to mapping erosion risk in the (Kouli et al., 2009) also make the case that hydrology and topography are crucial. It was written by Jebari et al. In their 2009 study, Karydas, Panagopoulos, and Mitas enhanced the RUSLE model's C-factor computation for Greece using remote sensing (Abdelsamie et al., 2022) studied a region in the Ethiopian highlands where land cover regulations reduce erosion (Gelagay & Minale, 2016), and they found that integrating RUSLE-GIS helps pinpoint erosion-prone locations. Management zoning is essential, say Avwunodiogba and Wai (2014), who studied erosion in the Nigerian rainforest area using RUSLE (Olorunfemi et al., 2020). In their 2019 study, Islam and Miah evaluated the possibility of riverine erosion in Bangladeshi floodplains using a GIS tool and the Revised Universal Soil Loss Equation (RUSLE) (Mahleb et al., 2022). The results of this investigation support the concept that floodplain environments could be a good place to use the approach more frequently (Islam et al., 2024). Using RUSLE in tandem with GIS is a common practice across all of these studies (Velliangiri & Prasath, 2025). By focussing on the watersheds in the Himalayan range, (Pandey et al., 2007) used data from the HIGSS geodatabase to show how flexible the RUSLE model is. These human-made changes are a part of the most current RUSLE-GIS model in Northeast India, which was created and verified by Dabral, Baithuri, and (Pandey et al., 2009; Dabral et al., 2008). It is clear from these studies that RUSLE-GIS is an effective method

for evaluating soil erosion in a variety of geographical, ecological, and climatic contexts (Deepika, 2024; Anand, 2024).

Methodology

This study aimed to combine RUSLE and GIS to create a projected erosion risk map and evaluate the erosion risk in the area. The algorithm now incorporates RUSLE-based soil erosion estimates from precipitation and surface runoff. This paradigm is best described by an empirical equation.

RUSLE Model Equation

The RUSLE model estimates annual soil loss (A) using the formula:

$$A = R \times K \times LS \times C \times P \qquad (1)$$

This is where:

- The average yearly loss of soil, measured in tonnes per hectare, is represented by A.
- In units of tons/hour/hectare/megajoule/millimeter, K is the soil erodibility factor.
- The LS factor is the product of the slope's length and steepness.
- C stands for the dimensionless cover management factor.
- The dimensionless support practice factor is represented by P.

To learn about the unique aspects of each characteristic, researchers used digital elevation modelling, fieldwork, and remote sensing. Data processing and analysis made use of ArcGIS and QGIS.

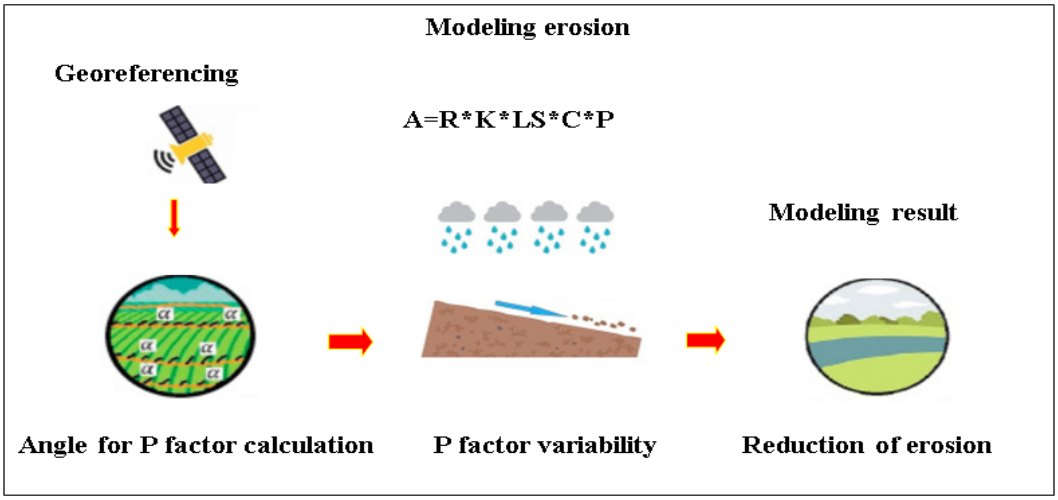

Figure 2. Visual framework for erosion modeling using the rusle equation and geospatial analysis

The RUSLE equation and the SIS linkage, which automate the modelling of soil erosion, are shown in Figure 2 of the flow diagram. The steps to be followed, starting with satellite imaging, are shown in the flow diagram. Not only does this imaging take a picture of the whole area, but it also helps find the P factor and the angle of slope. Through the application of R, K, LS, C, and P—primary productivity—the methodical procedure facilitates the computation of A. An all-encompassing picture of how the control and area management spheres affect soil erosion and loss is provided by this model. Last but not least, these models define and show the goals for sustainable land resource management and soil erosion reduction.

Factor Derivation

Rainfall Erosivity Factor (R)

R-factor is used to represent the erosive effect of rainfall. It has been calculated over a number of years based on the records of weather stations in terms of precipitation. For cases where records were absent, this empirical formula was used as per Freimund and Renard's 1994 study.

$$R = 38.5 + 0.35 \times P \quad (2)$$

Mean annual precipitation (mm) is defined as P.

Soil Erodibility Factor (K)

The k-factorThe is one of the measures of soil erosion, based on the erosion of organic matter, concentration concentration, permeability, and the soil's texture and structure. As Wischmier noted, values related to K could be computed according to the relation after conducting tiered soil surveys:

$$K = \frac{2.1 \times 10^{-4}(12 - OM)M^{1.14} + 3.25(S - 2) + 2.5(P - 3)}{100} \quad (3)$$

Where:

OM means organic matter as a proportion. Soil physiology also employs the following notations: M, which is defined as (% silt + wonderful sand) × (100 - % clay), P for permeability class, and S for soil structure code.

Cover Management Factor (C)

With the help of the C-factor, you can figure out how different farming methods and systems affect the rate of soil loss. Landsat and other satellite images were used to create maps of land cover and use, which were then used to develop CULC. C-values were assigned based on unpublished empirical data to fill gaps in published studies and to note gaps in various land cover types.

GIS Integration and Soil Loss Mapping

Each geographic information system (GIS) layer associated with the R, K, LS, C, and P variables was built and organised geographically. To multiply these layers, we turned to ArcGIS's raster calculator:

$$A(x, y) = R(x, y) \times K(x, y) \times LS(x, y) \times C(x, y) \times P(x, y) \quad (4)$$

The provided raster displays the study area's soil erosion estimation in tons per hectare per year, which has been color-coded for ease of use. To clarify the results, they were compared to some observable features and validated against the erosion intensity classifications.

Figure 3 shows the risk assessment of soil erosion using GIS tools and the RUSLE model, which is a method for addressing soil erosion. Gathering information about the present management practices, land use, terrain, precipitation, and soil properties is the initial stage of this approach. Parameters R, K, LS, C, and P, which represent soil erosion and precipitation, are then computed using GIS code in the RUSLE model. By creating a soil erosion risk map, this study will help identify which areas necessitate more advanced land management strategies.

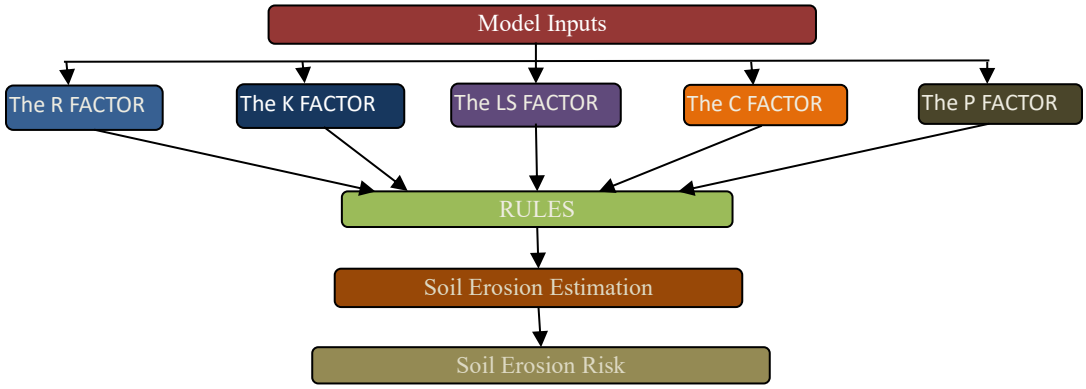

Figure 3. Proposed RUSLE-GIS model workflow for soil erosion risk assessment

Results and Discussion

Spatial Distribution of Soil Erosion

When soil erosion estimates were derived from the RUSLE model using GIS Spatial Data, the research broke down. A somewhat wide standard deviation of about 10 tons/ha/year was observed, with a maximum estimate of 150 tons/ha/year and an average of 12.4 tons/ha/year. The hill regions in the centre and northwest saw the most severe soil erosion since those locations had the steepest, least vegetated, and most exposed soil slopes. There are five separate categories for soil loss on the erosion map:

- Almost 40 percent of the area is left with super low level of erosion (less than 5 tons/ha/year).
- Low areas yield 5-10 tons/ha/year, accounting for 22% of the regions.
- Moderate erosion, or 10% to 25 tons/ha/year, is also considered 'average.'
- High, at 12%, is 25 – 50 tons/ha/year.
- Very High: the only category with 10% of the area where erosion is 'very high' as greater than 50 tons/ha/year or >10.

Considering that almost twenty percent of the area is at moderate to high risk of loss, the information above indicates that conservation efforts should commence immediately.

According to the specific details provided in Table 1, areas with dense vegetation and supportive systems have the lowest rate of soil erosion, which is attributed to forested regions. In contrast, agricultural areas with mid-level vegetation and steep slopes have the highest rate of erosion.

Table 1. Average annual soil loss under different land use types

Land Use Type	Average Slope (%)	Cover Management Factor (C)	Support Practice Factor (P)	Average Annual Soil Loss (t/ha/year)
Agricultural Land	12	0.35	0.55	27.6
Urban Area	5	0.15	0.90	12.3
Grassland	8	0.05	0.50	4.7
Forest Area	10	0.01	0.40	1.9

Factor Sensitivity and Influence

The LS factor exhibited the most variation across space and was often paired with areas of high erosion. Soil erosion is not the only risky topographic feature; landforms and other surviving characteristics also play a role.

The rate of erosion was quite high, particularly in the alpine regions due to the extensive deforestation and the long, steep slopes (more than 15°). In addition to cropland and bare land undergoing erosion, the rate in these areas was four times higher than in forested or grass-covered regions, which his C-factor calculation using the LULC dataset proved. In these heavily vegetated protected areas, erosion was less prominent, indicating effective management of soil erosion. Average soil erosion control was found to be more prominent where contour farming and terracing were practiced, as expressed by the P-factor; the average loss was reduced by 35 percent.

Table 2. Monthly variation in estimated soil loss (t/ha/year)

Month	Rainfall (mm)	Vegetation Cover Index (NDVI)	Estimated Soil Loss (t/ha/year)
January	45	0.62	1.2
February	30	0.71	0.9
March	55	0.59	1.4
April	80	0.48	2.0
May	110	0.41	2.3
June	95	0.45	1.8
July	120	0.43	1.5
August	105	0.50	1.7
September	90	0.53	1.6
October	70	0.56	1.3
November	60	0.60	1.1
December	40	0.65	1.0

You may see a summary of the soil loss estimates by month, rainfall, and NDVI in Table 2. The intensity of rainfall has a positive correlation with soil loss, but the density of vegetation cover has a negative correlation. Soil loss is greatest in May (2.3 t/ha/year) when rainfall is at its highest and vegetation cover is lowest, and it is lowest in February (0.9 t/ha/year). Together, precipitation and vegetation density govern erosional dynamics, which is why these two factors are important.

Comparison with Previous Studies

Estimates of soil loss align with earlier studies undertaken in the same agroecological zones. Tebebu et al. (2010), for example, observed that similar area systems in Ethiopia had erosion rates of over 50 tons/ha/year on degraded land, while Ganasri and Ramesh (2016) noted these erosional losses in Southern India at 10-30 tons/ha/year.

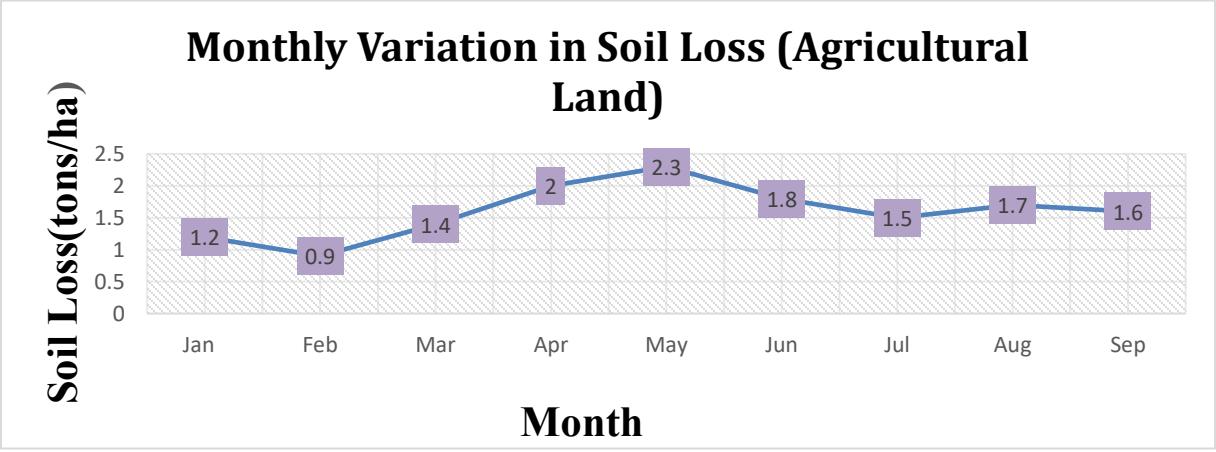

Figure 4. Estimated annual soil loss under different land use types using RUSLE and GIS

The resulting sedimentary transport to the area of investigation is emphasized by such comparisons even though efforts to preserve productivity have been made and this increases the chronic, unproductive sedimentary problems in the lower parts. This can be used to verify the suitability of RUSLE-GIS estimation method.

The consumption rate of soil loss in agriculture has been changing over time as depicted in Figure 4. May is one of the most distinctive ones with its extremities because this soil has a maximum loss of 2.3 tons/ha. The remaining figures of erosion of April and June are lower yet significant 2.0 and 1.8 tons per hectare, respectively. Soil loss is highest in mid-spring and early summer, possibly due to high precipitation and considerable tillage activities during the growing season. The value of soil loss in February records the lowest value of 0.9 tons/ha, which merits this unique value. This is most likely the case due to the little rainfall, along with a quiescent disturbance of the soil surface, accompanied by some degree of vegetation or residues of vegetation. January and March are noted with somewhat weaker but moderately austere figures of 1.2 and 1.4 tons per hectare, respectively. This means that it can be approached to a pre-planting season. Sensible efforts have been put to explain this phenomenon but unfortunately there is yet no success. Whichever way, the analysis informs that soil erosion will continue to escalate every month, with July, August, and September projected at 1.5, 1.7, and 1.6 tonnes respectively with contrary findings, which are said to have concentrated on the same. This argument is in line with the theory of seasonal erosion cycles, which forecasts high summer erosion of farmlands. This kind of data is required during the formulation of policies to regulate soil resource erosion.

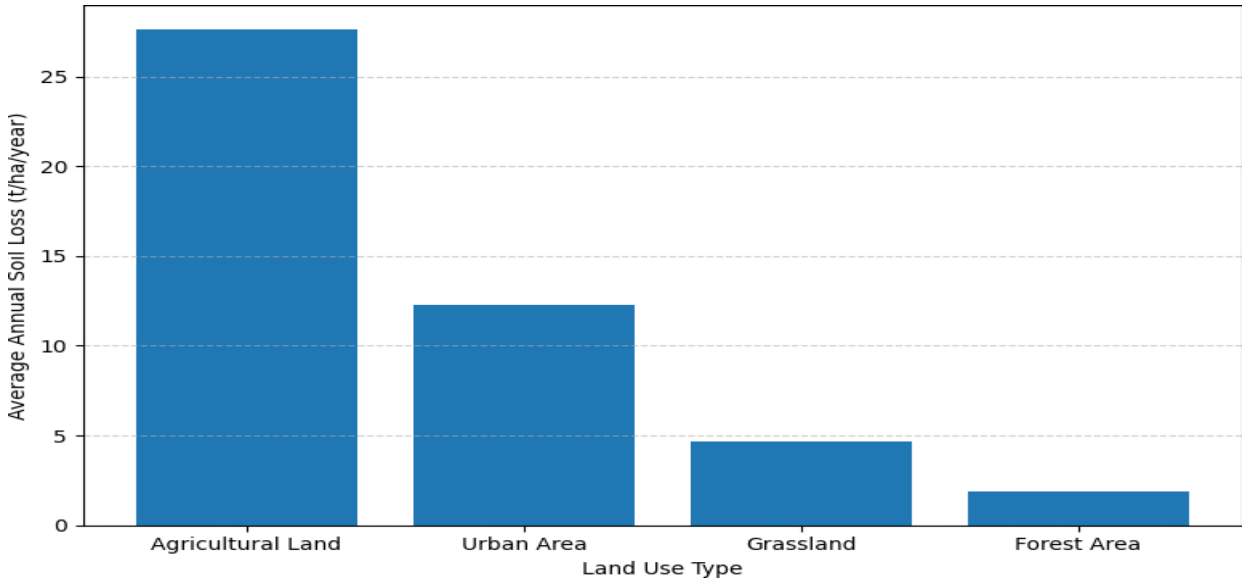

Figure 5. Average annual soil loss by land use type (t/ha/year)

The rates of soil erosion, as shown in Figure 5, are produced from the RUSLE-GIS model and are classified according to the land use category. The results show that the highest average yearly rates, associated with bare soil, steep slopes, and intensive growing, occur on agricultural land, at 27.6 t/ha/year. Runoff from impermeable surfaces, or those that do not absorb precipitation, likely contributed to the intermediate loss of 12.3 t/ha/year in metropolitan areas. The relevance of vegetation cover in facilitating stability and curbing the power of soil erosion is demonstrated by the much lower average conditions of 4.7 t/ha/year for grass and 1.9 t/ha/year for forest, respectively. These results highlight the need of sustainable land management practices for reducing soil erosion and increasing watershed resilience, including but not limited to contour farming, mulching, and reforesting of sensitive agricultural areas that have been eroded.

Implications for Land Use Planning

The findings attract attention to the fact that there are no management plans designed in relation to the critically degraded agricultural land that requires a serious concentration. Scarpland reinforcement, zonal tillage, mulching and even afforestation should be maximized in the high risk areas. With these maps, planning of concepts becomes easy, and planners, water basin authorities and farmers gain advantages as the sustainability principles can be integrated at grassroots level.

Conclusion

RUSLE and GIS are used together in order to measure soil erosion in terms of degree and dispersion. This method swamps RUSLE in the interdisciplinary model of estimating soil loss. Landscape features (LS), resistance to water runoff (R), soil permeability (K), control of vegetation or land cover (C), and protection (P) are all part of it. Additionally, it was discovered that soil erosion is highly dynamic, and that the problem is worsened when shallow slopes are combined with scant land cover and inefficient land usage. The mitigation measures are in urgent need because more than 40 percent of the land is cumulatively moderately and very likely to be at risk of eroding. C further has overriding importance of control which is not limited to cover management. They were the determining factors together with topography. This shows how it is necessary to manage vegetation cover and control the vegetation cover on the slopes to avoid erosion. The RUSLE together with GIS facilitated the strategic planning of land use in an efficient and cost-effective way by considering the location areas that are prone to erosion. This paper proposes contour farming and reforestation or a mix of harrowing land cover or sustainable actions that should be implemented accordingly. The maps and the existing studies can be used by community members, land managers, and policymakers to solve problems of soil erosion within their areas and to increase agriculture in accordance with their areas. This paper demonstrates the application of RUSLE to a GIS to calculate the potential of soil erosion, whereas it is also evident that the paper is not the ultimate one in the work. First, more precise assessments can be utilized in real-time using remote sensing and time-series images of land use and elevation characteristics, namely, in the cover and topographic parts (C) and (LS). In addition, concentrating more on the impacts of climate change, particularly on the R-factor rainfall erosivity will enable more profound study in future. The reason is that the soil erosion would be aggravated in the long run due to the altered rain patterns. Moreover, the definition of changing land use, hydrological cycle, as well as other anthropogenic activities, and a decrease in the facets of soil sediment yield helps to have much sharper estimates of erosion. When RUSLE is incorporated in complex models like SWAT or WEPP, more knowledge of the processes of erosion and sediment transportation is gained in a watershed, which improves the overall knowledge on the processes. In addition, the combination of artificial intelligence and machine learning in modeling erodibility prediction is a new opportunity in the creation of effective land management strategies. Concentrating on multi-year observational studies that are established by field work is preferable to gain model accuracy and greater policy checking since these are the two main interests of improved model fidelity and model credibility. In formulating and nutritious policies, interdisciplinary measures like socioeconomics, geostatistics, remote sensing, and other solutions should be synchronized in the aim of sustainable development concerning soil erosion.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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