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Spatio-Temporal Patterns of Soil Erosion and Sediment Yield in the UPNM Catchment

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ABSTRACT

This study investigates the issue of soil erosion which, a persistent threat to ecosystem stability. In this study, the Geographic Information System (GIS) technology was integrated with the Revised Universal Soil Loss Equation (RUSLE) model and a Sediment Delivery Ratio (SDR) to determine annual soil erosion and sediment yield within the Universiti Pertahanan Nasional Malaysia (UPNM) catchment. The necessary information parameters for the model were generated, such as soil erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and practise of land management (P) by preparing varied input datasets in ArcGIS software. The final maps were calculated through applying raster calculator in ArcGIS. The results reveal that in 2016, the study area experienced high soil loss at a rate of 1.5328 ton/ha/year, accompanied by a notable sediment yield of 0.5324 ton/ha/year. However, significant progress in erosion management was observed by 2021, leading to a reduced annual soil loss rate of 0.9437 ton/ha/year and a lower sediment yield of 0.3278 ton/ha/year. The findings highlight a positive correlation between soil erosion and sediment yield, underscoring the direct relationship between these two variables. Generally, valuable insights from these findings can be gained for effective erosion management and conservation strategies in the region.

Keywords: Soil erosion; GIS; RUSLE; SDR; sediment yield

INTRODUCTION

Erosion is a natural geological process where soil particles separate and move away from the soil's surface or depth (Zerihun et al. 2018). Human activities such as unrestricted land use, deforestation, excessive grazing, and climate variations contribute to accelerated soil erosion (Ouadja et al. 2022). Changes in temperature, rainfall patterns, and water levels can increase soil displacement. Additionally, human interventions in waterways like channel modification, dam and bridge construction, and uncontrolled animal access exacerbate erosion (Mohammed et al. 2017).

The sediment yield per unit area transported from a watershed measured within a specific time frame, reflecting the level of geomorphic activity (Chuenchum et al. 2019). Soil particles displaced by erosive agents transform into sediments during the early stages of sediment transport. Sedimentation occurs when water-transported degraded materials settle out, reducing water flow. Removing sediment from waterways is challenging and costly, often requiring technical solutions and heavy equipment.

Geographical Information System (GIS) technology is used to gather, store, validate, present, and spatial analyze. GIS integrates location-based (spatial) and database-based (tabular) information, enabling the visualization of patterns, correlations, and trends (Singh et al. 2023). Two common GIS data models are Vector and Raster. Vector data represents geographic information as points, lines, or polygons, while raster data represents information as a grid of cells with attribute values. Unlike vector data, where polygon areas can vary, every cell in a raster dataset has the same size.

The past few centuries, there has existed a significant progress of various erosion models, belonging into various groups, including empirical, conceptual, or physical. Notable examples of these models include the Universal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE), Revised Universal Soil Loss Equation (RUSLE), Soil and Water Assessment Tool (SWAT), and Pan-European Soil Erosion Risk Assessment (PESERA). Throughout the 80-year evolution of erosion modelling, the most employed approaches have relied on algorithms according to the Universal Soil Loss Equation (USLE) framework. It is worth noting that the USLE framework has found application in 109 nations (Alewell et al. 2019). During its evolution, the USLE has undergone modifications, resulting in the development of two related models known as the Modified USLE and the Revised USLE. Both models are built upon a similar conceptual foundation, albeit with some specific variations and improvements.

The aim of this study is to utilize Geographic Information System (GIS) technology integrated with the Revised Universal Soil Loss Equation (RUSLE) and a sediment delivery ratio (SDR) to compute surface erosion and sediment yield. Furthermore, it seeks to ascertain the soil erosion and sediment yield annual spatial dispersion within the UPNM catchment area for year 2016 and 2021.

METHODOLOGY

The current investigation focuses on assessing erosion through the application of RUSLE model by employing GIS with involves the computation of various factors necessary for calculating the mean yearly of soil loss. Yearly soil loss, denoted as ‘A’ and measured in ton/ha/year, is determined by multiplying the values of rainfall erosivity factor (R), soil erodibility factor (K), slope length and slope steepness factor (LS), crop management factor (C), and conservation practice factor (P) in raster format. For generate the yield of sediments (SY) in ton/ha/year, the RUSLE/SDR method was employed by utilizing the ArcGIS tool. SY represents the total amount of sediment discharged from a basin, measured at a specific point and over a designated time. A certain point in the river system’s sediment delivery ratio divided by the average yearly soil loss per unit area upstream of that point is known as the SDR.

STUDY AREA

The Universiti Pertahanan Nasional Malaysia (UPNM) is a university located in the Federal Territory of Kuala Lumpur (WPKL), Malaysia. It is distinguished by a topography that ranges in elevation from 196 meters at the highest point to 51 meters at the lowest point (Figure 1).

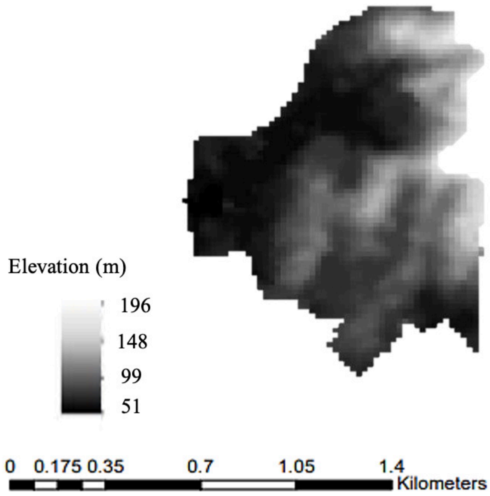

FIGURE 1. The elevation map

The study focuses on the UPNM catchment, covering an area of approximately 235 hectares. The primary soil types in this area are tropical acrisols, which exhibit high weathering, leaching, and substantial clay build-up (Suif et al. 2022; Suif et al. 2024). There are both evergreen and deciduous trees in the catchment. Forests and some steep slopes make up 33% of the area. Rainfall averages 80% to 90% every year throughout the May to October wet season. Starting in November, dry season lasts until April. Rainfall ranges from 2000 mm on average each year to a maximum of 4000 mm.

Understanding the specific characteristics of this catchment is crucial for accurately assessing soil erosion patterns and sediment transport. Elements like land use, topography, human activities and changing climate within the catchment significantly influence erosion and sediment yield processes. By studying in UPNM catchment, valuable insights can be gained for effective erosion management and conservation strategies in the region.

DATA SOURCES

Sources of data utilized were outlined within Table 1, providing a comprehensive overview. The research methodology employed a data-driven approach, leveraging sensed data to facilitate a spatialized comprehension of the various factors contributing to erosion. Additionally, GIS tools were employed to analyze and model erosion and deposition processes. This approach enabled a comprehensive investigation into the dynamics of erosion, allowing for a more in-depth understanding of the phenomenon.

TABLE 1. Principal data and various factors in the RUSLE model

Data	Source
DEM	USGS
Landsat 8	USGS
Soil database	Harmonized World Soil Database (HWSD) (FAO)
Rainfall data	UPNM weather station
C Factor	Landsat 8
K Factor	HWSD
P Factor	Aster DEM
LS Factor	Aster DEM

This study will encompass two primary components: data preparation and simulation work. The data collection process will be meticulously planned to ensure the acquisition of all necessary information. Notably, field data collection is not required since the study will heavily rely on pre-existing data and databases, such as the comprehensive USGS Database. This approach offers several advantages, including cost-effectiveness, time efficiency, and access to a wealth of previously collected data (Negese et al. 2021). By leveraging these valuable resources, the study can focus on the simulation work, where the collected data will be utilized to model and analyze various phenomena of interest.

RUSLE FACTOR

The combination of the RUSLE model and GIS was employed to evaluate the ratio of gross soil erosion and evaluate ratios of erosion distribution throughout various use of land. The equation was expressed as stated below.

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

where A is the mean yearly rate of soil erosion (ton/ha/year); the erosivity factor is represented by R (MJ mm/ha/h/year); K denoted the erodibility factor (ton ha h/ha/MJ/mm); LS expressed the dimensionless topographic factor, composed of the slope length (L) and slope steepness (S) factors (both dimesionless); the impacts of crop management techniques and vegetation cover are represented by the dimensionless component C; and P is a variable used to be held responsible on soil preservation techniques (Ouadja et al. 2022).

RAINFALL EROSIVITY FACTOR (R)

R, which denotes an erosive power due to rainfall, considers the rain intensity. When it is prolonged and heavy, causes to a more crucial soil degradation. By assessing the total amount of rainfall and the duration of storms, it becomes possible to identify the substantial potential area for erosion. For this study, the precipitation data was thoroughly analyzed with a grid resolution to achieve the highest level of precision (Swarnkar et al. 2018). The rainfall data utilized in the analysis covered the period between 2016 and 2021, ensuring a comprehensive understanding of the erosive rainfall patterns. The Equation (2) was utilized to determine the erosivity of rainfall (Mengie et al. 2022).

$$R = \sum_{i=1}^{12} -8.12 + (0.562 \times P) \qquad (2)$$

where the rainy erosivity factor is denoted by R (MJ. mm/ha.hr.y), and P representing the monthly rainfall (mm).

SOIL ERODIBILITY FACTOR (K)

Soil properties significantly influence the K factor, which is crucial for estimating soil erodibility (Balabathina et al. 2020). These properties include soil texture and structure, organic matter content and permeability index (Telkar et al. 2015). To estimate soil erodibility, soil maps by the Department of Agriculture (DOA) Malaysia can be used. These maps provide valuable information for assessing soil erodibility. Alternatively, the formula produced by Wischmeier and Smith in 1978 are used to estimate the erodibility factor. This equation serves as a useful tool for quantifying soil erodibility based on available data (Chuenchum et al. 2019):

$$f_{sand} = (0.2 + 0.3\, exp\ [-0.256 \times m_{sand} \times \left(1 - \frac{m_{silt}}{100}\right)]) \qquad (3)$$

$$f_{cl-si} = (\frac{m_{silt}}{m_{clay} + m_{silt}})^{0.3} \qquad (4)$$

$$f_{org.C} = (1 - \frac{0.0256 \times orgC}{orgC + exp[3.72 - 2.95\, orgC]}) \qquad (5)$$

$$f_{silt} = \left(1 - \frac{0.7\left(1-\frac{m_{sand}}{100}\right)}{\left(1-\frac{m_{sand}}{100}\right)+exp\left[-5.51+22.9\left(1-\frac{m_{sand}}{100}\right)\right]}\right) \quad (6)$$

$$K = f_{sand} + f_{clay} + f_{orgC} + f_{silt} \quad (7)$$

The equation for soil erodibility factor (K) considers various functions related to soil composition. These functions include f_{sand} for coarse sand content, f_{cl-si} for clay and silt content, f_{silt} for high sand content, and f_{orgC} for organic carbon content. The variables ms_{and}, m_{silt}, and m_{clay} represent the respective percentages of sand, silt, and clay fractions, while orgC represents of organic carbon content. By incorporating these functions and variables, the equation estimates K based on specific soil characteristics.

TOPOGRAPHIC FACTOR (LS)

Topography affects soil erosion rates. LS stands for the proportion of soil loss from a field slope per unit area to the overall loss of soil from a standardized slope length (72.6 ft or 22.13 m) with a uniform gradient of 9% under identical conditions. Topographic characteristics greatly affect soil erosion rates. A Digital Elevation Model (DEM) was integrated utilizing GIS and remote sensing methods to calculate LS components. This integration allowed for determining the appropriate LS value. The study employed the simplified approach by incorporating DEM data and employing GIS and remote sensing (Moore &Wilson, 1992). The goal of the investigation deserves accurately check the contribution LS factor to erosion. This approach provided insights into the relationship among soil erosion and topography by analyzing terrains impact on erosion rates as Equation (8).

$$LS = \left(\frac{A_s}{22.13}\right)^{0.6} \times \left(\frac{\sin\beta}{0.0896}\right)^{1.3} \quad (8)$$

where LS represents the factor obtained by combining the length and steepness of slope. *As* represents the specific area in square meters per meter, and β denotes the angle of slope (degrees).

CROP MANAGEMENT FACTOR (C)

The component that poses the greatest challenge in achieving the desired outcome is the factor of management cover. Vegetation cover acts a crucial function in mitigating the impact of precipitation, reducing the velocity, and preventing erosion. C value of the crop management factor is impacted by various elements, including the plant species, growth stage, and extent of land coverage. The C factor, representing the effectiveness of land cover, ranges from 0 to 1, depending on the specific type of vegetation present (Parmar, 2019). Additionally, categorization of the C factor varies depending on the specific land use, as demonstrated in Table 2 (Yang et al. 2003).

TABLE 2. Classification of Land Cover and C and P Factors

Land Cover of the RUSLE	C Factor	P Factor
Urban Area	0.1	1.0
Bare Land	0.35	1.0
Dense Forest	0.001	1.0
Sparse Forest	0.01	1.0
Mixed Forest and Cropland	0.1	0.8
Cropland	0.5	0.5
Paddy Field	0.1	0.5
Dense Grassland	0.08	1.0
Sparse Grassland	0.2	1.0
Mixed Grassland and Cropland	0.25	0.8
Wetland	0.05	1.0
Water Body	0.01	1.0
Permanent Ice and Snow	0.001	1.0

The Normalized Difference Vegetation Index (NDVI) were utilized to evaluate the factor of C from remote sensing data (Almagro et al. 2019). These methods were chosen for their simplicity, ease of use, and widespread availability of data input. The NDVI is calculated by comparing the spectral reflectance of a satellite image's red and near-infrared bands (Negewo & Sarma, 2021). It quantifies the absorbed radiation required for photosynthesis. In this study, the NDVI were employed to evaluate the factor of C following an approach outlined (Durigon et al. 2014).

$$NDVI = \frac{(NIR-RED)}{(RED+NIR)} \quad (9)$$

$$C = \frac{(-NDVI+1)}{2} \quad (10)$$

CONSERVATION PRACTICE FACTOR (P)

The impact of land cover and use on soil erosion is measured by the support practice factor. The P variable shows how conservation techniques like terrace contour farming, buffer strips, and contouring affect erosion caused by water. The P factor is 1.0 reveals the lack of erosion control actions as in Table 2 (Chuenchum et al. 2019).

A descending P factor implies a decrease in water volume and velocity, as well as a reduction in surface sediment deposition intensity. The value of factor P was estimated according on cover of land types specified by the factor of C as in Table 2 by considering various constraints (Yang et al. 2003).

DETERMINATION OF SDR AND SY

Since RUSLE is a terrain-scale model, it is unable to determine downstream sediment levels directly since eroded soil may settle before it reaches the watershed outflow or site of interest. Therefore, RUSLE cannot provide precise sediment quantity information. However, the SDR approach enables the estimation of sediment yield, which is an important metric often unavailable in hydrological and erosion studies. The SDR approach allows for the measurement of net soil erosion rates, facilitating the determination of sediment yield. The sediment yield was calculated by the SDR and mean potential soil erosion per year (A). The sediment yield formula is as follows (Wu et al. 2005):

$$SDR = \frac{(0.1406A^2 - 0.1253A + 0.4065)}{(0.3995A^2 + 0.8735A + 0.7176)} \quad (11)$$

where SDR represents the ratio of sediment delivery, which refers to proportion transported sediment pertaining to the watersheds area, denoted as A.

RESULTS AND DISCUSSION

After estimating the potential for soil erosion, the contrastive elements of the RUSLE equation were computed and spatialized.

RAINFALL EROSIVITY FACTOR (R)

The formula in Equation (2) calculates rainfall erosivity, providing a range of values that indicate the intensity of rainfall events. Lower values signify lower intensity, while larger values indicate higher intensity. These values are valuable in understanding the potential for erosion caused by rainfall within the field of study. Figures 2 and 3 illustrate significant variations in rainfall erosivity between 2016 and 2021 respectively. The result shows that rainfall erosivity was higher in 2016 compared to 2021, suggesting fluctuating intensity and patterns of rainfall during the specified timeframe.

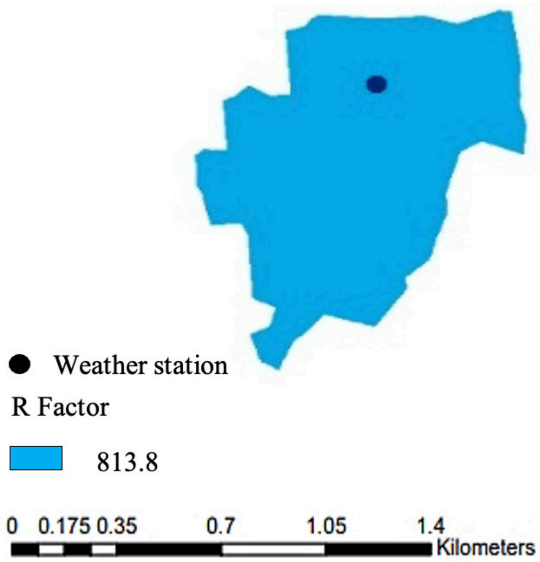

FIGURE 2. Rainfall erosivity factor for 2016

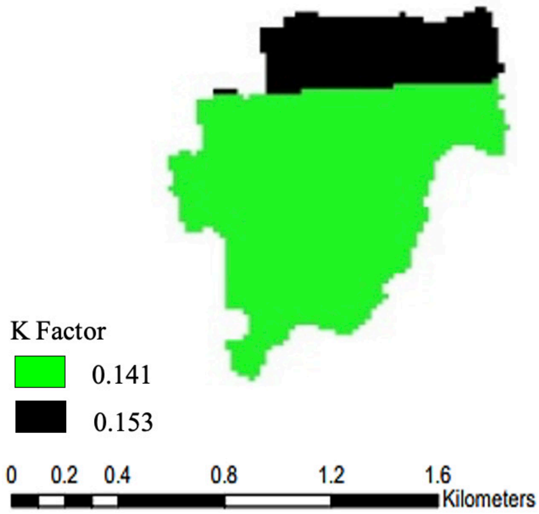

FIGURE 3. Rainfall erosivity factor for 2021

The visual representation of the map reveals a predominant color, indicating a relatively even distribution of rainfall across the UPNM watershed. Understanding rainfall erosivity is crucial as it provides insights into the erosive impact of precipitation. Comparing rainfall erosivity over different time periods helps in understanding the variations in erosive potential over time (Taloor et al. 2025). These insights can guide land use planning, agricultural practices, and the development of erosion prevention techniques to ensure the long-term health and sustainability of the watershed ecosystem.

SOIL ERODIBILTY FACTOR (K)

The K value evaluated by equations from the previous chapter and ranged from 0.141 to 0.153. Figure 4 highlights the highest K value, emphasizing its importance in understanding erosion vulnerability in the research area. It is noteworthy that the magnitudes of the K factor vary across the region, indicating distinct soil traits and conditions. Soils with low antecedent soil moisture and poor permeability have lower K factor values at the lower end of the spectrum. These factors result in reduced infiltration rates and limited water-holding capacity, making the soil less susceptible to erosion.

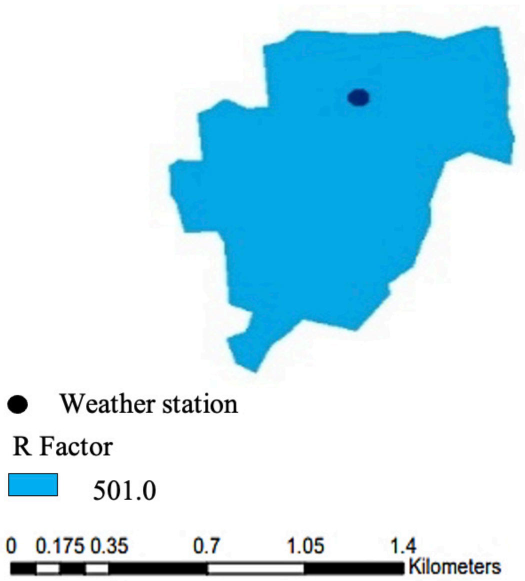

FIGURE 4. Soil erodibility factor

TOPOGRAPHIC FACTOR (LS)

Figure 5 illustrates the slope distribution in the UPNM area, exhibiting a wide range from 0 to 62.62 percent. This variation highlights the diverse geography of the region. The slope factor, measured in a dimensionless manner, is crucial for evaluating the steepness of the terrain rather than providing a specific unit of measurement. Flow accumulation in the UPNM area, representing the water accumulation across the landscape, ranges from 0 to 1. It is a significant parameter in determining the LS factor. As both slope and flow accumulation increase, the LS factor also increases, indicating a positive correlation between these variables. The LS factor has a broad range of values, starting at 0 on flat terrain and gradually increasing to 0.000262 on hilly terrain. Higher LS factor values indicate a higher risk of erosion due to steeper slopes and greater water flow accumulation. In contrast, areas with lower LS factor values, such as flat terrain, are less prone to erosion.

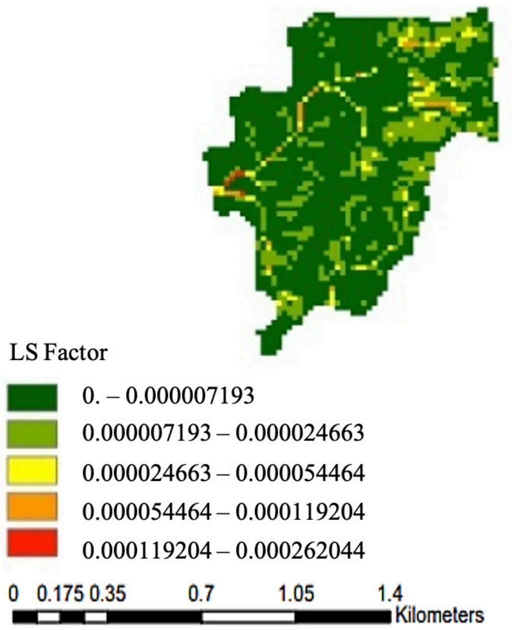

FIGURE 5. Topographic factor

CROP MANAGEMENT FACTOR (C)

The study found a range of C factors from 0 to 0.35, indicating varying levels of influence on soil erosion. Barren land in the UPNM region contributed to higher C factor values.

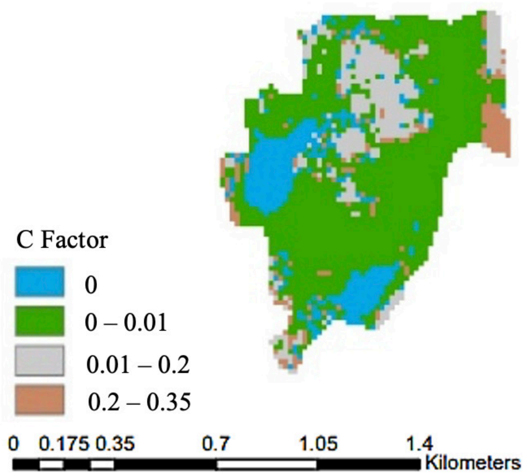

FIGURE 6. Landuse factor 2016

Analysis of the C factor distribution in year 2016 (Figure 6) and in Figure 7 as for year 2021 revealed spatial patterns and changes in land cover over time, potentially due to land use changes or urbanization. Understanding the distribution of the C factor helps identify areas susceptible to soil erosion and enables targeted soil conservation measures. Areas with higher C values require erosion prevention efforts, while areas with lower C values, such as water bodies, necessitate water resource protection strategies.

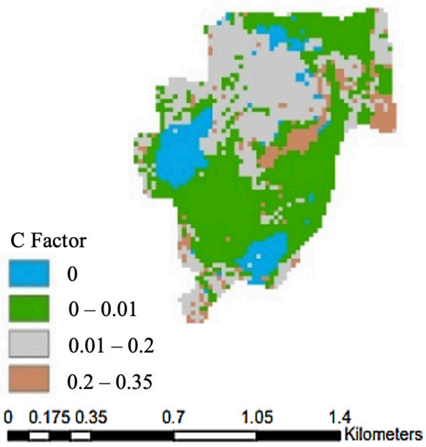

FIGURE 7. Landuse factor 2021

SUPPORT PRACTICE FACTOR (P)

The C values from Table 3 were used to calculate the P factor, indicating the potential for soil erosion. Figures 8 (year 2016) and 9 (year 2021) show a significant distribution range of P values in the UPNM region, ranging from 0.5 to 1.

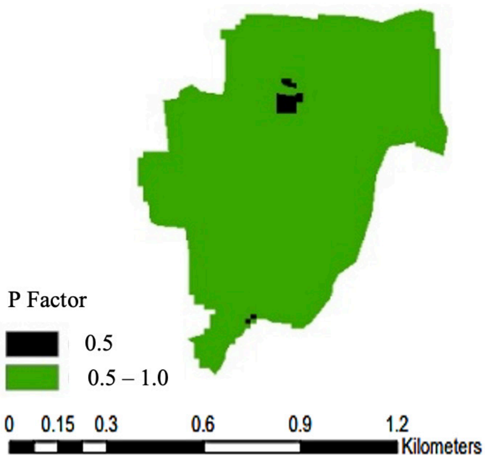

FIGURE 8. Practice factor 2016

Higher P values indicate a greater probability of soil erosion, while lower values indicate decreased erosion potential. Comparing data from 2016 to 2021, there are only minor differences in P factor values. The UPNM watershed's vulnerability to soil erosion is exacerbated by limited vegetation cover. Vegetation plays a crucial role in preventing erosion by holding soil together and intercepting rainfall. Insufficient vegetation cover leaves the soil exposed and susceptible to erosion, leading to increased sediment load in water bodies due to the erosive pressures of flowing water.

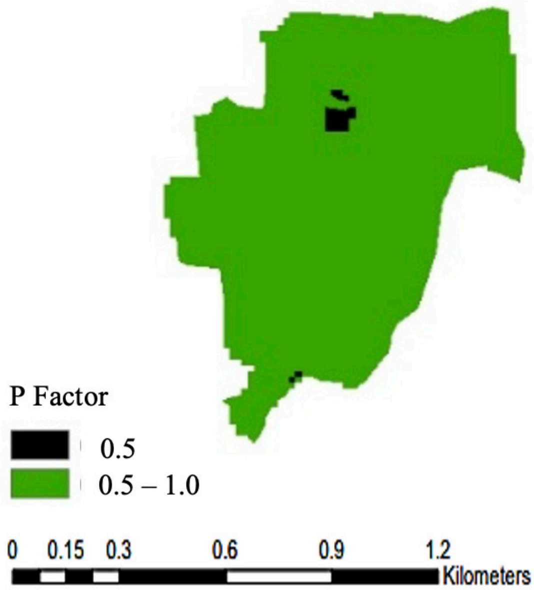

FIGURE 9. Practice factor 2021

THE POTENTIAL SOIL EROSION (A)

Figures 10 and 11 illustrate the presence of regions within the UPNM area that are susceptible to soil erosion in year 2016 and 2021 respectively. These areas are concentrated in locations characterized by steep slopes, insufficient support practices, and shallow soils. The spatial distribution of these vulnerable zones emphasizes the need for targeted conservation measures to mitigate erosion risks. There are notable differences in the annual rate of soil loss between 2016 and 2021. Changes in land use, climate patterns, and human actions may have contributed on varying levels of erosion observed over the defined period.

The map categorizes these locations into different sensitivity groups, ranging from very low to low, moderate, high, and very high erosion potential. By clearly delineating these levels, the map serves as a valuable resource for identifying priority regions that require immediate attention and intervention to effectively manage erosion concerns.

A comprehensive analysis of the findings uncovers significant insights into the projected annual soil loss using the RUSLE model within the UPNM region. The data indicates that in year 2016, the estimated annual soil loss was approximately 1.538 ton/ha/yr, which subsequently decreased to 0.9437 ton/ha/yr in 2021. These estimates offer valuable information regarding the erosive potential and fluctuations in soil loss dynamics over the specified timeframe. Notably, the study identifies terrain and vegetation cover as the primary determinants shaping the extent of erosion in the UPNM region. Understanding the interplay between these factors is crucial for comprehending and managing erosion patterns effectively.

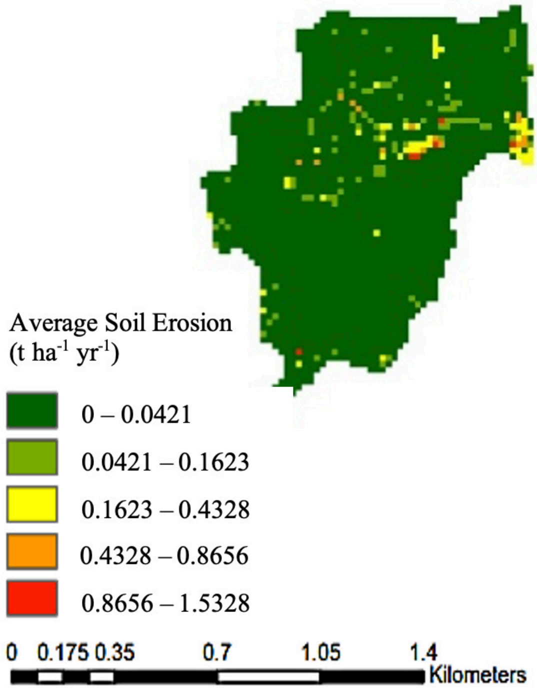

FIGURE 10. Annual soil erosion 2016

Soil erosion is a pressing issue in the UPNM watershed due to various factors that accelerate its progression. Validating soil erosion estimates at regional or continental scales is extremely challenging (Taloor et al. 2025) The conventional methods commonly employed for assessing soil erosion are often impractical and costly when dealing with large spatial areas. Nevertheless, despite these limitations, there are still some viable options available. In the case of validating the soil erosion map generated through the utilization of the RUSLE model approach, the alternative qualitative methods were opted that rely on visual evaluation.

These alternative methods provide a means to assess the accuracy and reliability of the soil erosion map without relying solely on technical and financial resources. Instead, visual evaluation allows for a qualitative assessment of the map's results, taking into consideration factors such as the visual appearance of erosion patterns, the consistency of erosion intensity, and any noticeable discrepancies or inconsistencies in the mapped areas.

By employing these alternative qualitative methods, can still gain valuable insights into the performance and validity of the soil erosion map generated using the RUSLE model approach, even when faced with constraints that render the conventional procedures unfeasible for larger spatial extents.

Steep slopes, inadequate vegetation cover, and the erosive power of flowing water contribute to soil particle detachment, runoff, and sedimentation. The steep slopes in the region increase vulnerability to erosion as water flow gains momentum and forcefully removes soil particles. Understanding the interplay of these factors is crucial in addressing soil erosion. Effective measures should be implemented, such as terracing to mitigate steep slopes, promoting afforestation and re-vegetation to enhance vegetation cover, and installing proper drainage systems to manage runoff.

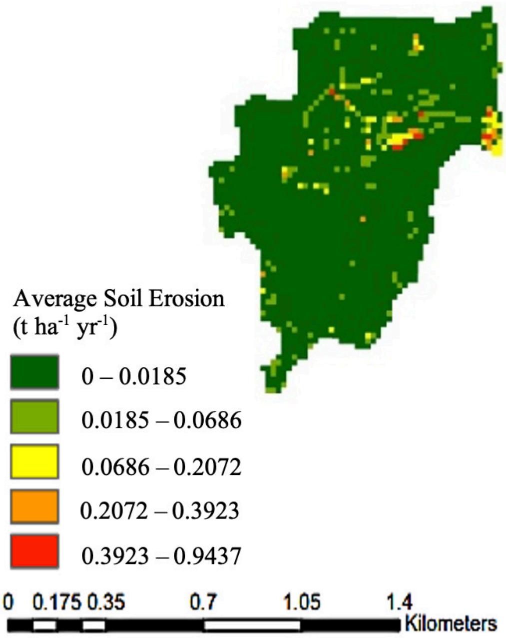

FIGURE 11. Annual soil erosion 2021

CONCLUSION

The integration of the RUSLE model and sediment yield modelling in a GIS environment allowed for a comprehensive examination and analysis of soil erosion and sediment yield in the UPNM region. The findings of this extensive research shed light on the extent of soil loss and sediment yield rates in the study area.

According to the study, the estimated annual soil loss rate was approximately 1.5328 tonne/ha/year in 2016, indicating a significant susceptibility to erosion during that period. Concurrently, the sediment production was calculated to be around 0.5324 tonne/ha/year, representing the amount of eroded material transported and deposited within the watershed. However, in 2021, there was a notable decrease in the annual soil loss rate to 0.9437 tonne/ha/year, suggesting potential improvements in erosion management efforts. Similarly, the sediment yield for 2021 was estimated to be 0.3278 ton/ha/year, indicating a decline in the amount of degraded material carried and deposited.

The study also highlights a strong positive correlation between soil erosion and sediment yield, emphasizing the direct relationship between these two variables. As soil erosion rates increase, there is a corresponding rise in sediment yield within the UPNM region. This underscores the notion that accelerated erosion processes lead to more evident sediment transport and deposition, resulting in higher sediment production.

Furthermore, the study identifies key factors contributing to the region's elevated erosion rates. Poor vegetation cover, steep slopes, and intense rainfall events emerge as prominent drivers of erosion. Insufficient vegetation cover exposes the soil to erosive forces, while steep slopes enhance the erosive potential of runoff. Additionally, heavy rainfall provides substantial kinetic energy to the land surface, leading to increased soil detachment and subsequent sediment transport.

These findings provide valuable insights into the dynamics of soil erosion and sediment production in the UPNM region. They emphasize the importance of implementing effective erosion control methods, such as promoting vegetation development, adopting proper land management practices, and deploying erosion control structures. By addressing these relevant factors, UPNM management can collaborate to reduce erosion rates, mitigate sediment yield, and ultimately preserve the ecological integrity of the region.

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DECLARATION OF COMPETING INTEREST

None.

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