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GEOSPATIAL ASSESSMENT OF RUSLE MODELING FOR SOIL EROSION RISK IN NUWARA ELIYA, SRI LANKA

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ABSTRACT

In the tropical highlands of Sri Lanka, especially in the Nuwara Eliya District, steep slopes, intensive agriculture, and heavy rainfall contribute to the accelerated degradation of the land, and soil erosion is one of the major environmental issues prevalent in this area. Although the occurrence of soil erosion in Sri Lanka has been investigated in earlier studies, the present study is an attempt to carry out a detailed soil erosion assessment on the Nuwara Eliya Highlands using GIS techniques, and the Revised Universal Soil Loss Equation (RUSLE) has received less attention in the local context for mapping and spatial prioritization of soil erosion conservation practices. The objectives of this study are to evaluate the potential soil erosion on Nuwara Eliya Highlands and to map the soil erosion risk by using the RUSLE model in combination with GIS techniques. The CHIRPS rainfall dataset, SoilGrids and ESDAC datasets, Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data, Landsat 9 imagery, and land use data were used to derive Rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practice (P) factors in Google Earth Engine and ArcGIS 10.8. These RUSLE factors were combined to calculate soil loss in a year and provide an erosion risk map at a spatial level. The model output shows that 546 km² (32%) of the district experienced moderate erosion, 460.62 km² (30%) experienced high erosion, and 307.08 km² (20%) experienced severe erosion, which indicates that a significant area of the district is highly prone to soil erosion. The spatial distribution of erosion risk was further analysed by comparing it with topographic conditions, land cover characteristics, and documented erosion-prone locations, where erosion hotspots were identified, thereby offering qualitative validation of the hotspots. The study provides a localised soil erosion assessment using GIS data, which can support evidence-based land management and conservation planning in the Nuwara Eliya Highlands.

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1. INTRODUCTION

1.1 Background

Worldwide, soil erosion is considered one of the most significant environmental issues affecting land degradation, ecosystem quality degradation, and agricultural productivity. The loss of fertile topsoil compromises soil structure, water infiltration, deposition of sediments in rivers and reservoirs, and hydrological stability, thereby impacting food security (Borrelli et al., 2021). The effects are most pronounced in tropical highlands, where steep slopes, high rainfall and heavy agricultural burdens lead to higher rates of soil erosion (Senanayake, 2023). Surface runoff and sediment transport can be significantly increased by even slight changes in vegetation cover or changes in soil surface condition, which in turn can greatly accelerate soil erosion. There is a high economic reliance on plantation and smallholder farming in many tropical highlands of the developing world. Natural forests act as a buffer between the soil surface and rain by intercepting and holding water, and their roots hold the soil together, which makes them more resistant to the impact of rain and overland flow. Converting forests to monoculture plantations or intensively grown annual crops decreases the water buffering capacity of the canopy and soil cohesion of roots, making soil surfaces more susceptible to impact from rain and overland flow (Morgan, 2009). In addition, the rainfall during the rainy seasons is sometimes beyond the erosion levels, causing rapid soil loss periods, but of short duration (Fenta et al., 2023). Soil erosion in these areas over time will lead to loss of land productivity as well as reservoir sedimentation, lower hydropower production, and a higher risk of flooding. The Central Highlands in Sri Lanka are one of the most environmentally fragile areas in the country. It is a significant commercial agriculture hub, such as cultivation of tea, vegetable farming, and mixed farming of livestock, particularly dairy. Concurrently, the area is prone to soil erosion due to its steep terrain, shallow soils, and high seasonal rainfall of more than 2500 mm per year (Bandara et al., 2001). The Nuwara Eliya District is at a higher elevation and is heavily dependent on agriculture, making it the most vulnerable area within this zone. Tea plantation establishment during the colonial era has reduced the natural land cover, replacing deep-rooted montane forest with shallow-rooted planted monoculture plantations, which offer comparatively lower protection from soil erosion (Piyathilake et al., 2021). Additionally, intensive vegetable farming on steep gradients, frequently with poor terracing and mulching, also puts the soil at risk from rain erosion and contributes to sediment load in major river catchments. The soil erosion assessment in these complex highland areas needs a quantitative as well as spatially integrated assessment approach. The Revised Universal Soil Loss Equation (RUSLE) is a widely used empirical equation to estimate soil loss accounting for the effect of rainfall erosivity, soil erodibility, slope length and steepness, vegetation cover and soil conservation practices (Nuskiya et al., 2025; Renard et al., 1997). The RUSLE model can be used in conjunction with Geographic Information Systems (GIS) and remote sensing data to map the erosion risk at a spatial level and identify areas of priority for soil conservation (Panagos et al., 2015). The model has been widely used in soil erosion studies, particularly in the tropical highlands of Africa, South Asia and South-East Asia, where land use and topography are important drivers of the soil erosion process (Phinzi & Ngetar, 2019). The results are a soil erosion baseline on a high-resolution basis to facilitate soil conservation planning, land-use zoning, watershed management and sustainable agricultural decision-making in the region.

1.2 Problem Statement

There are several environmental issues that are prevalent in the Nuwara Eliya Highlands, particularly soil erosion, which is caused by steep slopes, heavy agricultural pressure and frequent seasonal rains. So far, the soil erosion assessments in Sri Lanka have been based on coarse resolution data sets and on average parameters, thus unable to adequately describe the spatial variability at the district level. Hence, high-resolution GIS-integrated RUSLE is needed to delineate erosion-prone areas and to help in proper soil conservation and sustainable land management.

1.3 Objectives

1.3.1 General Objective

To estimate and georeference soil erosion hazard in Nuwara Eliya Highlands using a GIS-based Revised Universal Soil Loss Equation (RUSLE) model.

1.3.2 Specific Objectives

1. Estimate the rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practice (P) factors through the use of remote sensing and GIS data.
2. To create spatial distribution maps for each RUSLE factor.
3. To estimate soil loss per year and zone soil erosion hazard.
4. To determine the areas of erosion hot spots to be conserved first.
5. To give recommendations for sustainable soil conservation and land management in the Nuwara Eliya Highlands.

2. LITERATURE REVIEW

Among the most devastating soil degradation processes in the tropical highlands are soil erosion, which occurs when soil particles are trapped, slip, and get blown into the air, due to steep slopes, heavy monsoonal rainfall, and intensive farming practices (Morgan, 2009; Borrelli et al., 2021). In conclusion, sheet, rill, and gully erosion not only lower the productivity of crops and soil fertility, but also increase sedimentation downstream (Jisna et al., 2021; Alewell et al., 2019). Mountain land use changes impact vegetation cover and erosion based on the effects of land use on soil protection. Soil erosion is regulated by soil retention by the vegetation, rooting, and surface protection. Clearing of vegetation from cultivated areas during the seasons exposes the soil to rain (Renard et al., 1997). Spatial assessment of soil erosion risk in topographically complex tropical watersheds is possible using GIS, remote sensing, and Digital Elevation Models (DEMs). The use of GIS, remote sensing, and Digital Elevation Models (DEMs) has added much in the way of spatial information to the spatial assessment of vegetation cover in complex tropical watersheds. High-resolution GIS terrain models can be used for estimating terrain slopes, and satellite-derived vegetation maps can be used for spatial assessment of vegetation cover (Panagos et al., 2015; Papaiordanidis et al., 2019). Papaiordanidis et al. (2019) highlighted the importance of cloud-based GIS processes in the study of soil erosion modelling, while Alewell et al. (2019) focused on the importance of vegetation cover in decreasing erosion. The significance of topography, rainfall, and land use was discussed in the context of Sri Lanka, to the extent of what was demonstrated using GIS-based RUSLE studies, and most studies have been based on larger datasets or national surveys, providing little insight into conservation planning at the district level. Therefore, there is a need to have a detailed spatial evaluation that can fuse recent geospatial data to detect erosion hotspots and apply evidence-based soil conservation in environmentally sensitive areas like the Nuwara Eliya Highlands. The accuracy and efficiency with which soil erosion assessments are made have greatly improved over the last few years, owing to the technological progress in geospatial data. GIS and remote sensing, as well as cloud platforms like Google Earth Engine, facilitate the processing of large-scale geospatial data of large scale and can be used to create high-resolution erosion maps (Zahir et al., 2025; Papaiordanidis et al., 2019). The Digital Elevation Models (DEMs) supplied by satellite give an accurate estimate of the slope length and steepness, while the vegetation indices from Landsat give an indication of the vegetation cover and conservation efforts (Panagos et al., 2015). These approaches allow us to identify erosion hotspots and provide spatial information for sustainable watershed management and soil conservation planning in topographically complex tropical landscapes (Alewell et al., 2019).

3. MATERIALS AND METHODS

3.1 Study Area

Nuwara Eliya District lies in the Central Highlands of Sri Lanka and it is located between 6°58′–7°10′ N latitude and 80°46′–81°00′ E longitude and has a total surface area of approximately 1,741 km2. The district has a cool mountain climate with an average annual rainfall of 2,000–2,500 mm from the Southwest and Northeast monsoon systems (Department of Meteorology, 2022). The district is mountainous with steep slopes, valleys, peaks, and elevations ranging from 1,000 to 2,500 m above sea level. Approximately 25% of the district has a slope over 30°, contributing to rapid surface runoff and soil erosion. The district is also an important headwater catchment, including the Mahaweli and Kelani Rivers that supply water to the hydropower sector, irrigation, and houses (Department of Census and Statistics, 2023). The district has a well-developed drainage system, characterised by a dense drainage system in the upper catchments that allows fast runoff and fast transport of sediment during intense rainfall events.

The district is comprised of Precambrian high-quality metamorphic rocks containing charnockites and gneisses weathered into Red Yellow Podzolic, Lithosols, and Alluvial soils with moderate to high erodibility, especially when vegetation has been removed (NBRO, 2021). Land use is dominated by tea plantations (42%), followed by natural forests (28%), vegetable cultivation accounts for approximately 18%, grasslands (7%), and other land uses (Department of Agriculture, 2018). Intensive cultivation on steep mountain slopes, together with periodic pruning in tea plantations and inadequate soil conservation practices, has accelerated land degradation and soil erosion in many parts of the district (Dharmasena, 2026). The combination of steep terrain, highly erodible soils, intense monsoonal rainfall, dense drainage networks, and intensive agricultural land use makes the Nuwara Eliya District highly suitable for evaluating soil erosion risk using the GIS-integrated

Revised Universal Soil Loss Equation (RUSLE) model.

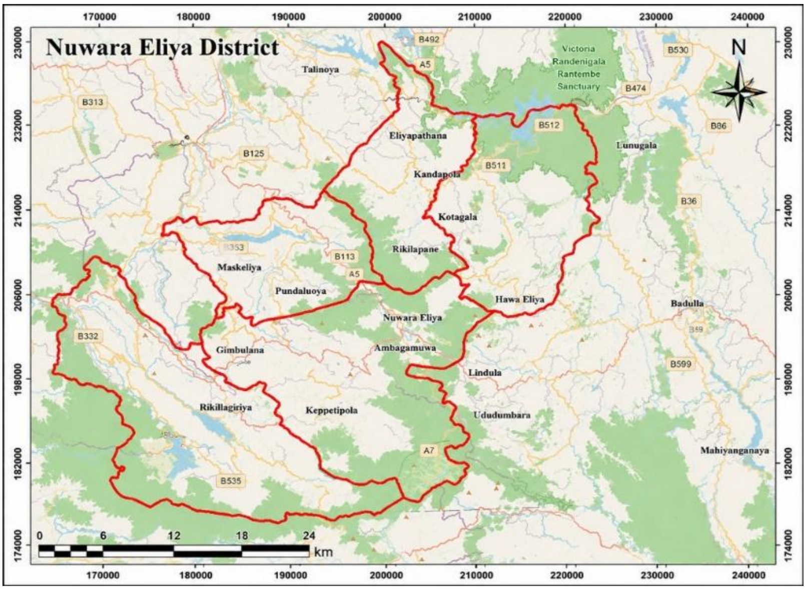

Figure 1: Study Area Map of the Nuwara Eliya District, Sri Lanka
Source: Generated by Author Using ArcGIS 10.8

3.2 Experimental Design and Procedures

A systematic GIS-integrated Revised Universal Soil Loss Equation (RUSLE) was employed for the study to map soil erosion in Nuwara Eliya Highlands. The analytical sequence consisted of the following steps: (i) data acquisition, (ii) data preprocessing, (iii) preparation of the layers of the RUSLE model (R, K, LS, C, and P), (iv) raster overlay analysis, (v) soil loss estimation, and (vi) mapping of the soil erosion risk (Figure 2). The data used include geospatial data including Landsat 9 Operational Land Imager-2 (OLI-2) imagery (30 m), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model (DEM) (30 m), Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) rainfall data processed in Google Earth Engine (GEE) (30 m), and soil property data from ISRIC SoilGrids v2.0 (30 m) and the European Soil Data Centre (ESDAC) (30 m). Some long-term CHIRPS rainfall data processed in Google Earth Engine were used to compute the R factor, while the K factor estimation was done using the soil texture and organic carbon data from SoilGrids and ESDAC.

The LS-factor was created based on the SRTM DEM, and the C-factor was created based on the Normalized Difference Vegetation Index (NDVI) from Landsat 9 imagery. The P factor was calculated based on land use and on-site practices for soil conservation. All data before analysis via RUSLE were projected to a common coordinate system, re-sampled to a common resolution as needed, and clipped to the extent of the study area and transformed to rasters. The methodology employed is based on the concept of the soil erosion cascade (Papaiordanidis et al. 2019) that identifies soil erosion as a series of interdependent soil detachment events (from raindrop impact), sediment transport (via surface flow), and deposition events. The conceptual framework is used as the foundation for integrating the RUSLE factors to determine soil loss for each individual year and to establish areas in the study area that have potential for erosion.

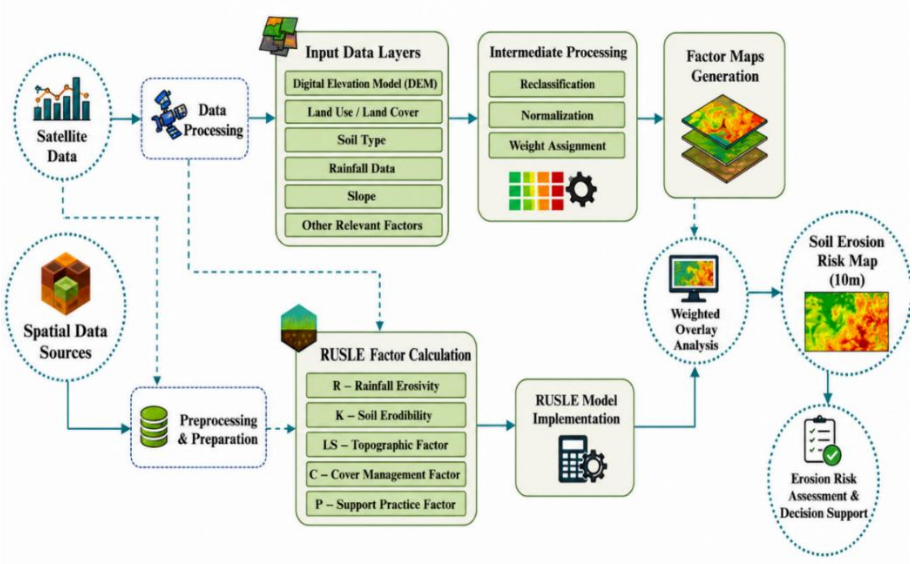

Figure 2: Workflow of the GIS-Based RUSLE Methodology Used for Soil Erosion Assessment
Source: Developed by the authors (2026)

3.3 Data Source and Preparation

The datasets used for this work were Landsat 9 Operational Land Imager (OLI-2), Shuttle Radar Topography Mission (SRTM) Digital Elevation Model, Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS) rainfall dataset, SoilGrids v2.0, and European Soil Data Centre (ESDAC) soil database. Maps of Land Use/Land Cover (LULC) and Normalised Difference Vegetation Index (NDVI) were created using Landsat 9 data collected in January 2025. The slope (LS) factor was calculated using the 30 m SRTM DEM, and rainfall data (CHIRPS) were processed in Google Earth Engine to derive the rainfall erosivity (R) factor for the 2015-2024 time period. Soil texture and organic carbon information obtained from SoilGrids and ESDAC were used to calculate the soil erodibility (K) factor. Conservation practice (P) was determined by land use classes and existing conservation practices. The RUSLE model was applied to all datasets in Google Earth Engine and ArcGIS 10.8. Each dataset was projected to a common coordinate system and processed in Google Earth Engine and ArcGIS 10.8 before application of the RUSLE model.

Table 1: Satellite imagery and geospatial datasets used in the study

Analysis	Satellite/ Dataset	Sensor/ Product	Acquisition Year	Spatial Resolution	Retrieved Year	Access Date
NDVI	Landsat 9	(OLI-2), Collection 2 Level-2	2025	30 m	2025	15 January 2025
Land Use/Land Cover (LULC)	Landsat 9	(OLI-2), Collection 2 Level-2	2025	30 m	2025	15 January 2025
Slope	SRTM DEM	Shuttle Radar Topography Mission (Version 3)	2025	30 m	2025	15 January 2025

LS-Factor	SRTM DEM	Shuttle Radar Topography Mission (Version 3)	2025	30 m	2025	15 January 2025
Rainfall (R-Factor)	CHIRPS Version 2.0	Climate Hazards Group InfraRed Precipitation with Station Data	2015–2024	0.05° (5 km)	2025	15 January 2025
K-Factor	European Soil Data Centre (ESDAC)	European Soil Database	2024	250 m	2025	15 January 2025
K-Factor	SoilGrids v2.0	ISRIC Global Soil Information	2024	250 m	2025	15 January 2025
P-Factor	ESA WorldCover v200	Global Land Cover Product	2024	10 m	2025	15 January 2025

Source: Compiled by the authors (2026) using data obtained from USGS Earth Explorer (Landsat 9 and SRTM DEM), Google Earth Engine (CHIRPS rainfall data), ISRIC SoilGrids v2.0, European Soil Data Centre (ESDAC), and ESA WorldCover v200

3.4 RUSLE Model Framework

Soil erosion was estimated using the (Borrelli et al., 2021) Revised Universal Soil Loss Equation (RUSLE):

$$\boldsymbol{A = R \times K \times LS \times C \times P} \qquad \textbf{(1)}$$

Where:
A = Average annual soil loss (t ha^{-1} yr^{-1})
R = Rainfall erosivity factor
K = Soil erodibility factor
LS = Length of slope and steepness factor.
C = Management factor of vegetation cover.
P = Conservation support practice factor.

This paper will further the theoretical knowledge on landscape-level interaction effects on erosion patterns in complex landscapes within the Nuwara Eliya District by analyzing these factors using a Geospatial Analysis.

3.5 Spatial Distribution of RUSLE Factors

3.5.1 Soil Erodibility (K-Factor)

The K-factor map (Figure 3-d) has divided the district into three main soil groups, which are Red Yellow Podzolic (RYP), Red-Yellow Latosol (RYL), and Alluvial (AL). The RYP soils, which are mainly found in the district's plantation area, have the highest erodibility with their characteristics of being shallow, weakly aggregated, and low in organic matter. RYL soils found in the upper eastern parts of the district are classified as having moderate erodibility, while the Alluvial (AL) soils, only in the narrow valley bottoms, have less erodibility due to their fine texture and greater cohesion. The prevalence of RYP soils on the slopes for planting is an indication that the district's erosion potential is partly natural and not only a matter of land management practices. Determined using the Wchmier and Sit (1978).

$$\boldsymbol{K} = \frac{2.1\times10^{-4}(12-OM)M^{1.14}+3.25(s-2)+2.5(p-3)}{100} \qquad \textbf{(02)}$$

Where:
OM = Organic matter (%)
M = (% Silt + % Very Fine Sand) (100 – % Clay)
s = Soil structure class code
p = Soil permeability class code

In this study, soil texture and organic matter content were extracted from Soil Grids 250m and resampled to 30 m in ArcGIS 10.8. Dominant Red Yellow Podzolic soils displayed the highest K values.

Table 2: Soil Erodibility Properties and K-Factor Classification

Soil Type (FAO/Local Classification)	Dominant Landscape Occurrence	Key Soil Properties Influencing Erodibility	Assigned K-Factor (t ha h ha^{-1} MJ^{-1} mm^{-1})	Reference
Red Yellow Podzolic (RYP)	Mid- to upper-slope tea plantation zones and cultivated uplands	Shallow profile, weak aggregate stability, low organic carbon	0.022 – 0.025	Wischmeier & Smith (1978); Hengl et al. (2017)
Red-Yellow Latosols (RYL)	Eastern mid-elevation slopes; moderately weathered landscapes	Moderate clay content, moderate structure stability	0.018 – 0.021	Department of Agriculture (2018)
Alluvial Soils (AL)	Valley floors and lower slope accumulation zones	Higher silt–clay balance and organic matter; stronger aggregation	0.015 – 0.018	Morgan (2005)

Source: Developed by the authors (2026) using output K-factor maps, SoilGrids v2.0, ESDAC datasets, and published reference values

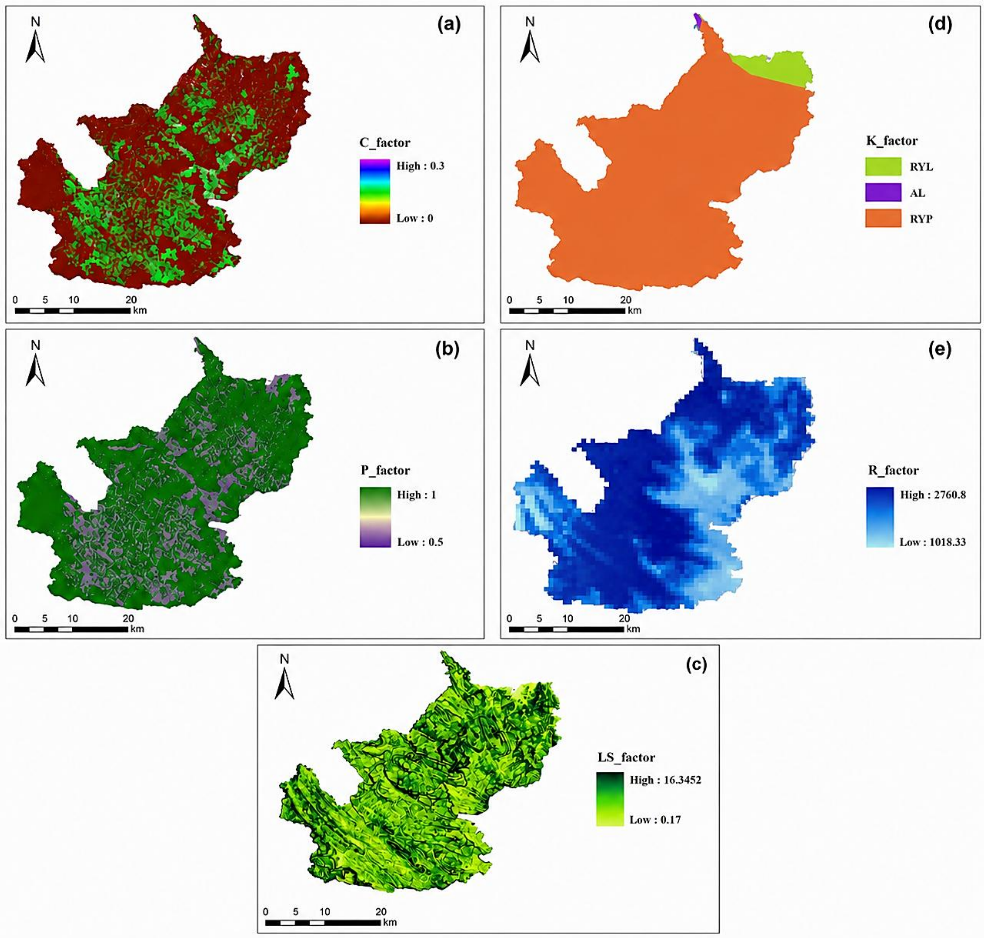

Figure 3: (a) C-factor map, (b) P-factor map, (c) LS-factor map, (d) K-factor map, and (e) R-factor map used for soil erosion estimation in the Nuwara Eliya District.
Source: Developed by the authors (2026) using Landsat 9 OLI-2, SRTM DEM, CHIRPS rainfall data, SoilGrids v2.0, ESDAC, and ESA WorldCover datasets processed in Google Earth Engine and ArcGIS 10.8

3.5.2 Cover Management (C-Factor)

The C-factor map (Figure 3-a), derived from NDVI, ranges from 0.00 in extremely thick forest cover to 0.30 in very dry open land for agriculture. The high C-factor values are mainly found in places such as intensively farmed vegetable fields, Tea plantations during branch cutting, Human settlements, and places where the soil is not covered. These sites have very little tree cover, so the rain can directly hit the ground, and the soil can be washed away easily. The low C-values, which correspond to forest and well-shaded tea that is not cut, are a sign of good surface protection (Senanayake, 2023). The drastic C-factor change across different land types supports the argument that the vegetation structure and crop maintenance practices are the main causes of erosion. This vegetation-induced seasonal exposure is the reason why erosion intensity is greater in the periods of cultivation and pruning.

Normalised Difference Vegetation Index (NDVI) was calculated from Landsat 8/9 satellite images:

$$\boldsymbol{NDVI} = \frac{(\boldsymbol{NIR-Red})}{(\boldsymbol{NIR+Red})} \qquad \textbf{(3)}$$

The NDVI values were converted to C-factor using the formulation by Van der Knijff et al. (2000):

$$\boldsymbol{C} = \mathbf{exp}[-\mathbf{2}(\frac{\boldsymbol{NDVI}}{\mathbf{1-NDVI}})] \qquad \textbf{(4)}$$

3.5.3 Conservation Practice (P-Factor)

The P-factor (Figure 3-b) demonstrates the differences in soil conservation practices in terms of space (Dharmasena, 2026). The tea plantations made in terraces and the perennial crops aligned with the contour have the lowest P-values (0.50), which suggests that there is a partial reduction in the concentration of runoff. On the other hand, the smallholder vegetable farms on steep slopes often have P-values close to 1.00, which indicates that no erosion control measures are in place. Runoff in the direction of the slope that is not terraced leads to an increase in the formation of rills and gullies because of the quickness of the downslope movement of water. Consequently, the P-factor differences bring to light the impact of the land management strategy on the erosion process, whether it is by way of suppression or promotion, and this is irrespective of the prevailing conditions of climate or soil. The P-factor has a range between 0 and 1; a number that is very close to zero indicates a very good conservation practice, and one that is very close to one indicates an eceptionally poor conservation practice.

The formula is the p-factor as:

$$\frac{\boldsymbol{Conservation\ Practice}}{\boldsymbol{Slope\ Management\ Condition}} \qquad \textbf{(5)}$$

3.5.4 Rainfall Erosivity (R-Factor)

The R-factor map (Figure 3-e) presents a distinct spatial gradient influenced by both the elevation and the monsoon rains (Renard et al., 1997). The highest erosivity values (up to 2760.8 MJ mm ha^{-1} yr^{-1}) are found in the southeastern and central mountain slopes, where orographic uplift raises the intensity of rains. These places experience the heaviest storms; thus, the raindrops have the highest kinetic energy, and the soil is the most easily detached. On the contrary, lower erosivity values (around 1018.33 MJ mm ha^{-1} yr^{-1}) are found in the northwestern and valley-floor regions, where the rainfall is more evenly distributed over the year. This observation supports the conventional view of the rainfall–elevation interaction being the main climate factor controlling erosion in the district, which is a characteristic of Sri Lanka's central highlands. Rainfall erosivity was computed based on mean annual precipitation using the empirical equation developed for tropical highlands (Hurni, 1985):

$$\boldsymbol{R = 0.739 \times P^{1.847}} \qquad \textbf{(6)}$$

Where:
P = Mean annual rainfall (mm)

For conducting this research, the CHIRPS rainfall data and climatological records data from the Department of Meteorology, Sri Lanka, were processed through Google Earth Engine (GEE) to yield the R-factor map, which varied from 1018.33 to 2760.8 MJ mm $ha^{-1}\ h^{-1}\ yr^{-1}$.

3.5.5 Slope Length and Steepness (LS-Factor)

The LS-factor map (Figure 3-c) clearly indicates that topography is the main factor controlling erosion (Papaiordanidis et al., 2019). The values of the map go from 0.17 in areas with low slopes to more than 16.3452 in areas with steep ridges and escarpments. The highest LS values are found in a continuous orographic strip that goes through the Ragala Uplands, Hakgala Slope Complex, and Moon Plains Transition Belt. In these areas, the slope angles are more than 30°, and the runoff velocity goes up rapidly with the descent. The topography in these regions facilitates the occurrence of sheet and rill erosion, especially if the vegetation cover is limited. The LS-factor is thus the leading physical force that causes erosion, and this is in line with the highland geomorphological characteristic in humid tropical climates. The LS-factor was derived from the DEM using the formulation:

$$\boldsymbol{LS} = \left(\frac{\mathbf{FlowAcc \times CellSize}}{\mathbf{22.13}}\right)^{\mathbf{0.4}} \left(\frac{\mathbf{\sin(\theta)}}{\mathbf{0.0896}}\right)^{\mathbf{1.3}} \qquad \textbf{(7)}$$

Where:
Flow Acc: Flow accumulation (number of contributing cells)
θ = Slope angle in radians
Cell Size: DEM spatial resolution (Desmet and Govers, 1996)

The LS-factor values were in the range of 0.17 to 16.3452, and steep escarpment slopes in Ragala, Hakgala, and Moon Plains were the places where the highest values were mainly found.

3.6 GIS Processing and Map Production

NDVI estimation was done using GEE, rainfall statistics were calculated using GEE, factor surface generation was done using GEE, and Area statistics (km^2/ percentage per erosion) were done using ArcGIS 10.8. Raster overlay analysis, RUSLE computation, Severity class reclassification, and Area statistics. Final soil erosion values were classified as Low, Moderate, High, and Severe risk. The spatial patterns were compared with slope maps, land-use layers, and previously released erosion thresholds to ensure consistency and interpretive validity of the map.

4. RESULTS

4.1 Analysis of Site Factors Influencing Soil Erosion

The site factors illustrate how land use, vegetation cover, and soil characteristics, together with hydrology, play an interconnected role in soil erosion and deposition in the Highlands of Nuwara Eliya. According to the (LULC) Land Use/Land Cover map (Figure 4-e), tea plantations that cover approximately 42% of the district are mainly in mid- and upper-slope positions. These areas usually go through periodic pruning cycles and have limited understory management, thereby exposing the soil to raindrop impact. Natural forests occupy 28%, and this coverage is mainly along ridges, within protected reserves, and in small, isolated patches. Vegetable farming and residential areas (18%) found at places with slope breaks and near valleys are the most disturbed, particularly during the land preparation seasons. The rest of the area, which is 12%, includes water, bare earth, and wetlands. The above land use distribution observed suggests that human activities have a strong influence on the erosion susceptibility. High-intensity cultivated and settlement areas are more disturbed at the surface and are more susceptible to soil erosion and sediment movement during heavy rainfall.

Table 3: LULC Classification Table

Category	Area (km^2)	Percentage (%)
Cultivated	716.52	42
Natural Forest	477.68	28
Built- up	307.08	18
Water Bodies	119.42	7
Barren Land	51.18	5

Source: Developed by the authors (2026) based on Landsat 9 OLI-2 imagery processed in Google Earth Engine and ArcGIS 10.8.

The NDVI-based assessment of vegetation conditions reveals that the risk of exposure is seasonal and driven by land use. The NDVI values of less than 0.25 were recorded by almost 38% of the district area, which indicates that the area has a very sparse vegetation cover comprised of agricultural fields and pruned tea estates. The low NDVI areas are very much related to the areas where erosion susceptibility is high, since the interception loss at the canopy stage enhances the rainfall's kinetic energy, which is then passed on to the soil surface. On the other hand, the forests that are not very thick and the tea canopies that are partially covered showed NDVI values greater than 0.50 and are thus termed natural erosion control areas through root cohesion, organic matter, and moisture regulation. The trend exhibited indicates the montane vegetation - erosion relationship, which has been found in tropical highland systems around the world (Alewell et al., 2019).

Moreover, the slope characteristics further point out the spatial vulnerability of the landscape. A terrain analysis result indicates that 25% of the area of the district is covered in slopes of more than 30°, and these slopes are mainly scattered over the Ragala ridge, Hakgala upper escarpment, and Moon Plains transitional belts. The steep slopes result in fast runoff, a short infiltration time, and high particle detachment. Moderate slopes (10° to 30°) make up 44% of the area, most of which are found in tea estates and upland vegetable cultivation areas. The erosion potential of these slopes is reported to be moderately to highly susceptible to erosion; that is, when these slopes are cleared of vegetation and groundcover is inadequate, sheet and rill erosion occur at a higher rate. The lowest gradient valley bottoms make up the remaining 31% of the area, which is characterized by lower erosion potential but may still serve as sediment deposition areas.

Erosion from rainfall is also influenced by elevation, and it is one of the factors that determine the erosivity patterns. The district, which has a mean altitude of 1,624 m, is subjected to very heavy orographic rain mainly due to the lifting of moist air over the mountains. The R-factor map shows that the areas with the highest rainfall erosivity values are the windward slopes and high mountain watersheds, where the rain is heaviest. The situation is thus similar to that of the monsoon season in the highlands of Sri Lanka (Department of Meteorology, 2022). Of the areas analysed, the flow accumulation pointed out the major runoff paths that were overlapping, particularly along the transitions of slopes and valleys. Those hydrological convergence points are in the very cultivated areas, thus creating local regions where the formation of rills and gullies is very likely. The networks of runoff at the landscape scale indicate the dependence of erosion not only on slopes but also on drainage structures.

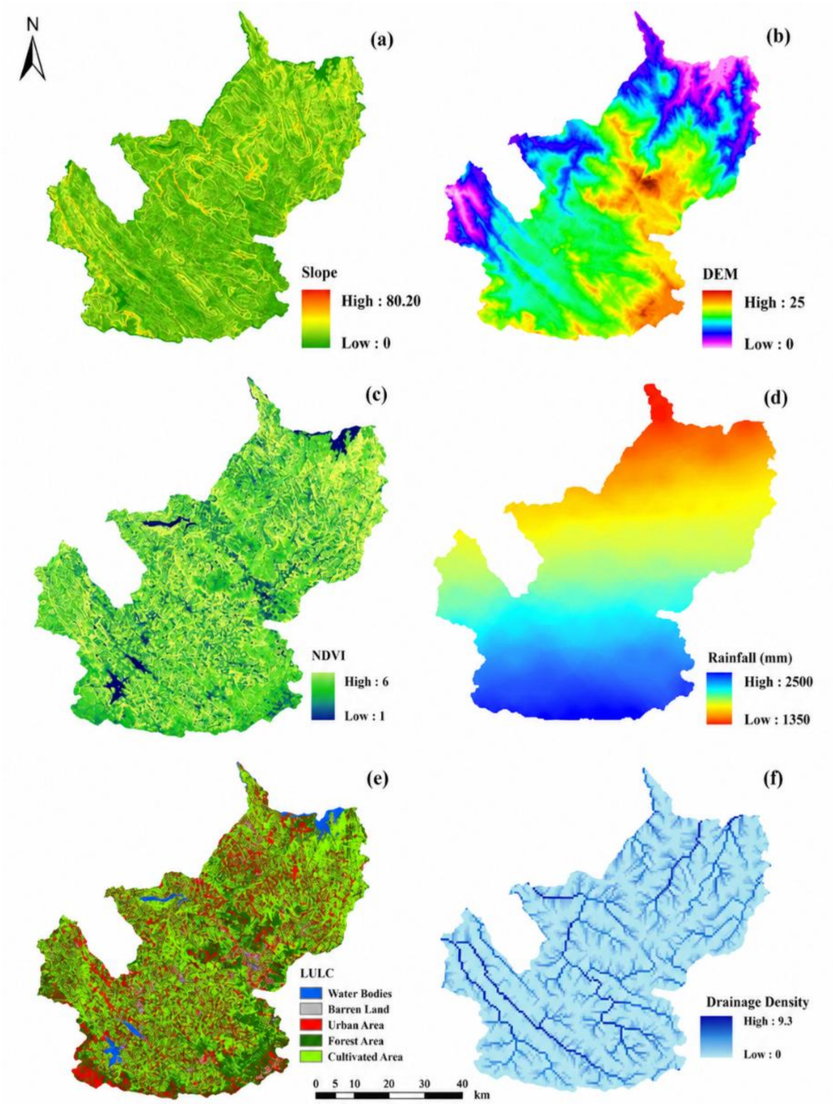

Figure 4: (a) Slope map, (b) DEM map, (c) NDVI map, (d) Rainfall distribution map, (e) Land Use/Land Cover (LULC) map, and (f) Drainage density map of the Nuwara Eliya District

Source: Developed by the authors (2026) using SRTM DEM, Landsat 9 OLI-2, CHIRPS rainfall data, and GIS analysis in Google Earth Engine and ArcGIS 10.8

4.2 Analytical Insight and Key Findings

The interaction between vegetation cover and slope steepness predominantly determines the degree of soil erosion in the district. Areas with low NDVI on steep slopes experience the most soil loss, as the limited canopy protection permits the direct impact of the rain on the exposed soil, thereby detaching it. Even in places where tea is grown, the loss of soil goes up during the period of pruning, when the soil between the rows becomes exposed. Erosion can be made worse by the cultivation of seasonal vegetables for about half a year, when the land is left bare during preparation and harvest. In addition, convergence of slopes leads to increased surface runoff in small channels, which further increases sediment transportation and results in places that are prone to erosion at all times. These associations are in line with the highland erosion behavior described by Phinzi and Ngetar (2019) and Morgan (2005), thus reinforcing the scientific validity and novelty claims.

Table 4: Site Factors Affecting Level

Dominant Driver	Condition in Nuwara Eliya	Resulting Effect
High LS Factor	Steep continuous slopes (25% >30°)	Increases runoff force and detachment
High C Factor	Low vegetation cover (38% NDVI < 0.25)	Exposes soil to raindrop impact
High P Factor	Limited terracing/contouring on smallholder plots	No barriers to flow concentration

Source: Developed by the authors (2026) based on the GIS-integrated RUSLE analysis and the results of the present study.

Table 4 gives a summary of the dominant site factors that are involved in soil erosion in the Nuwara Eliya District. Steep continuous slopes (25%–30°) have a high LS-factor, causing increased detachment and velocity of the sediment. A high C-factor is associated with low vegetation cover (lower NDVI, 38% of the area with NDVI < 0.25), meaning the soil is exposed to raindrop impact and is more susceptible to erosion. Furthermore, smallholder plots have a high P factor due to limited terracing and contouring, which makes conservation measures and flow concentration less effective. All these factors add up to explain the high level of soil erosion in the study area.

4.3 Soil Loss Map of Nuwara Eliya District

The final soil loss map (Figure 4) shows a clear and distinct spatial stratification of the erosion intensity in the whole Nuwara Eliya highlands area. The soil loss was grouped into five classes of erosion severity, namely: Very Low 204 km^2), Low (187 km^2), Moderate (546 km^2), High (460km^2), and Severe (307km^2) using the equal interval classification method. It was mainly the Moderate to Severe erosion levels that were found to be widespread over the majority of the district, thus confirming that the degradation of soil is not a localised issue, but it happens over a wide area. On the other hand, the Very Low and Low erosion zones, when combined, represented about 23% of the total land area, and they were located mainly in dense montane forest blocks, valley bottoms, and the stable perennial tea canopy regions.

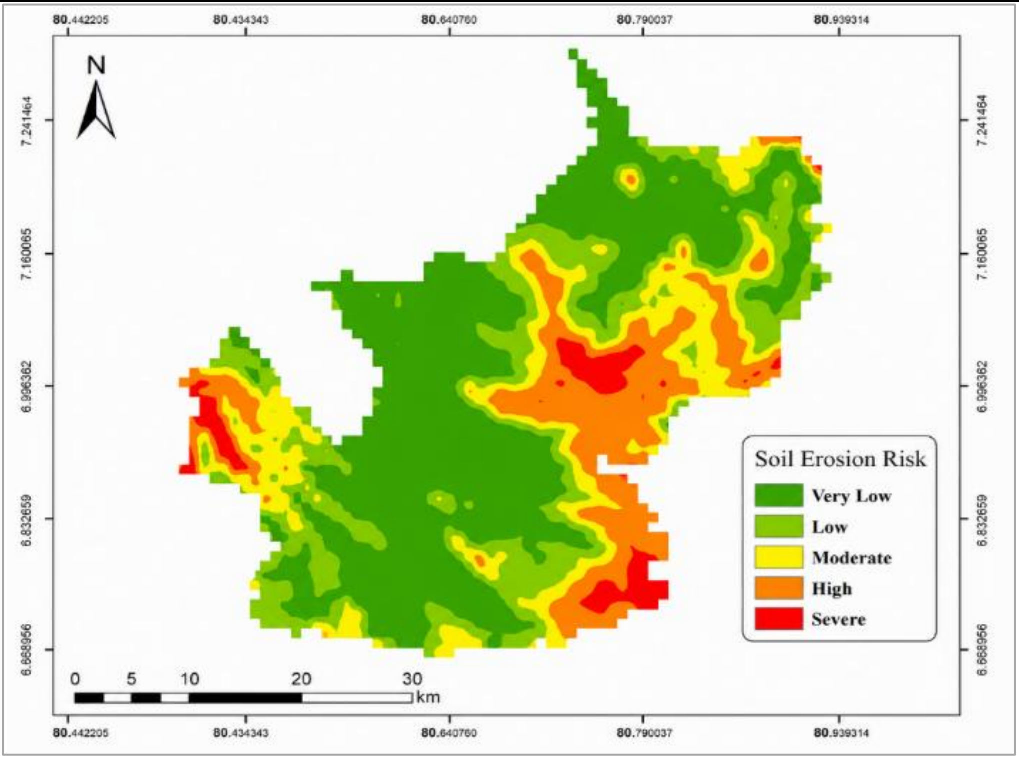

Figure 5: Soil Erosion Risk Map for Nuwara Eliya
Source: Developed by the authors (2026) using the GIS-integrated RUSLE model in ArcGIS 10.8

They have a persistent ground cover, a higher organic matter content, and slower runoff, all of which work to overcome soil detachment and promote infiltration. The Moderate erosion areas (about 32% of the district) were more closely associated with the tea plantations on the mid-slopes, where the pruning cycles and exposure between the rows of the plants periodically reduce soil protection. During seasonal periods, soil loss is increased in these plantations, particularly when the canopy is removed during crop management. High and Severe erosion zones, accounting for 27% and 18%, respectively, formed well-defined continuous belts around steep areas. The Ragala uplands, Hakgala slope complex, and Moon Plains transition escarpment were identified as the main areas of high erosion, where the LS-values are greater than 10, C-values are around 0.30, and P-values are close to 1.0 due to the lack of contouring or terracing. In these regions, intense monsoonal rainfall (R-factor nearing 2760.8 MJ mm ha^{-1} yr^{-1}) interacts with high slope-induced runoff energy, amplifying soil detachment and rapid downslope sediment transport. The patterns observed support the notion that the erosion intensity is mainly determined by the joint effect of the steepness of the slope and the state of the vegetation cover, while rainfall and soil characteristics are not that influential. In areas where high LS, high C, and high P are present together, erosion becomes much more extensive. This interaction is in line with the mechanisms of erosion in humid tropical agro-ecosystems that have been identified, wherein the disturbances caused by topography and vegetation work together to cause soil loss.

Table 5: Soil Loss Classification

Class	Soil loss ($t\ ha^{-1}\ yr^{-1}$)	Area (km^2)	% Area
Very Low	< 4	204.7	12
Low	4–21	187.7	11
Moderate	21–41	546.0	32
High	41–52	460.6	27
Severe	> 52	307.1	18

Source: Developed by the authors (2026) based on the GIS-integrated RUSLE model results generated in ArcGIS 10.8 and GEE.

5. DISCUSSION AND RECOMMENDATIONS

The GIS-based RUSLE analysis showed that the Nuwara Eliya Highlands is mainly dominated by the effects of topography, vegetation cover, rainfall erosivity, as well as land management practices on soil erosion. There is a high risk of soil erosion (Moderate to Severe) in about 77% of the study area. The combined effect of natural and anthropogenic factors on soil loss is apparent from the highest erosion susceptibility observed in areas of the Ragala, Hakgala and Moon Plains where there is high LS-factor, limited vegetation cover and lack of conservation practices. This is in line with earlier research carried out at tropical high elevation sites. Steep slopes and intensive cultivation strongly contribute to high erosion rates (Morgan, 2009), and the combination of GIS with the RUSLE model is a useful tool for delineating erosion-susceptible areas (Panagos et al., 2015). Also, Phinzi and Ngetar (2019) reported that land-use change and vegetation degradation are significant factors affecting soil erosion in the Central Highlands of Sri Lanka, and Piyathilake et al. (2021) identified agricultural expansion and steep terrain as main drivers of soil erosion in the Central Highlands of Sri Lanka. The present study builds on these results by using recent geospatial data to perform a high-resolution spatial evaluation of the erosion risk in the Nuwara Eliya Highlands. The RUSLE model offers many spatial data for evaluating erosion, but there are some restrictions on the results. The model is empirical and relies on the accuracy and spatial resolution of input data, and soil loss was not measured in the field for quantitative validation. Hence, the predicted erosion hazard is not a precise value of soil loss per year, but rather a relative value of susceptibility to erosion. Soil conservation measures should be undertaken in the first place in steep tea plantations and vegetable farming sections where erosion is identified as a hotspot. The use of contour farming, bench terracing, contour bunds, mulching, cover cropping and agroforestry should be encouraged to minimise soil erosion and runoff. Further, the provision of farmer awareness programmes, enhancement of the agriculture extension services and integration of the erosion risk maps in the land-use planning of the districts would add value to sustainable watershed management and long-term soil conservation in the Nuwara Eliya Highlands.

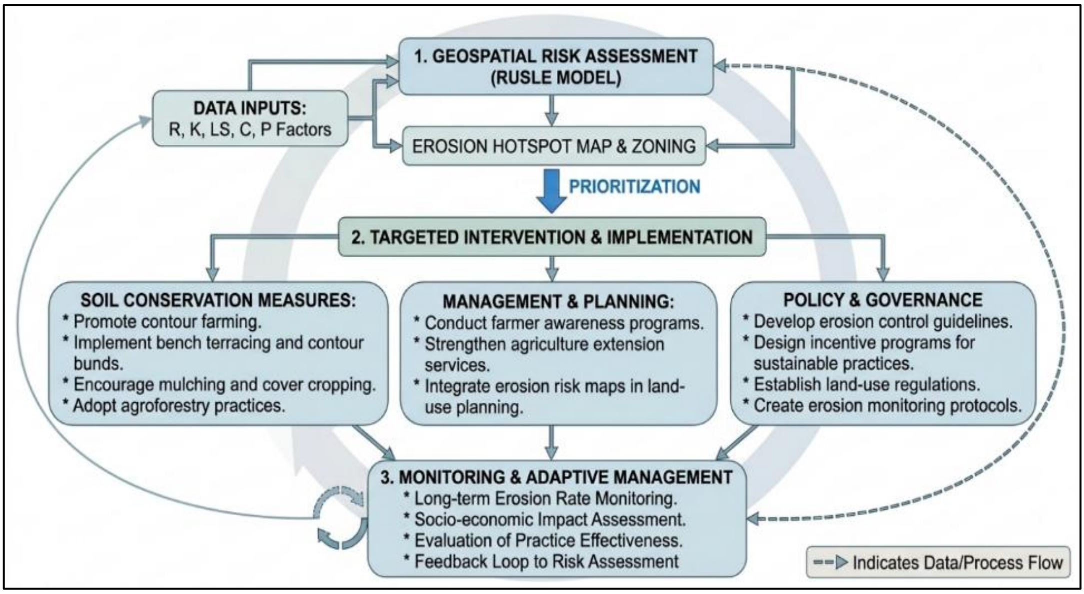

Figure 6: Sustainable Soil Conservation Recommendation Framework
Source: Developed by the authors (2026) based on the findings of the present study

6. CONCLUSION

In this study, a GIS-based RUSLE was used to assess the spatial variability of soil erosion risk in Nuwara Eliya Highlands. The study was able to accomplish its goals of estimating the factors of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practice (P), and producing spatial maps of erosion factors; calculating soil loss potential; and locating areas of high soil loss. The findings indicated that significant portions of the district are at Moderate, High, and Severe erosion risk, while the risk of severe erosion is mainly observed in the Ragala, Hakgala, and Moon Plains areas. Based on the spatial patterns, soil erosion in the study area is mainly influenced by intensive agricultural land use, low vegetation cover, and limited conservation practices in the area. The application of GIS, remote sensing data, and the RUSLE model was a successful tool to map erosion-prone areas at high spatial resolution with erosion risk and to create spatial information to support evidence-based land management. This study provides a scientific basis for future watershed management, soil conservation planning, and sustainable agricultural development.

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