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Estimation of soil erosion using the Revised Universal Soil Loss Equation (RUSLE) in Relation to Landslides in Mid-hills of Nepal

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Abstract

An attempt has been made in this research to assess soil erosion and its spatial distribution by the revised universal soil loss equation (RUSLE) model at Rangun Khola Watershed, western Nepal. The erosion factors were acquired from multiple sources (Satellite images, ALOSPALSAR DEM, SOTER soil database, Esri 2020 land cover map, rainfall database of DHM) and an integrated analysis was carried out in raster format of GIS. A landslide inventory was generated on the basis of satellite images and past literature to validate soil erosion intensity in the area. The result map of the RUSLE model was categorized into six levels based on the erosion severity, and 9.06 % of the area was found to be under extremely severe soil erosion risk (> 80 ton $ha^{-1}year^{-1}$) indicating urgent consequences. The frequency ratios for each level of potential erosion susceptible to landside exhibited a linear relationship depicting reasonable and satisfactory level of agreement between the landslide event/location data and the erosion map that validates the model result. The result of this study will be helpful to detect the sensitive zones presenting a priority of protection and offer valuable information that aids decision-makers and user agencies in creating adequate conservation planning programs to stop soil erosion and maintain the natural balance.

Keywords: *Soil erosion, Landslides, RUSLE, Mid-hills*

Introduction

Land degradation is one of the major global issues that affect agricultural output and natural resource availability (Gomiero, 2016). Among the many forms of land degradation (soil truncation, loss of fertility, slope instability), soil erosion is the most significant phenomenon and is greatly influenced by land use and management practices (Abdulkareem et al., 2019). Erosion reduces the ability of the soil to hold water and support plant growth, thereby reducing its ability to support agro-biodiversity (Pimentel, 2006). It is also believed that, as a result of the erosion over the past four decades, 30% of the world's arable land has lost its fertility (Hossain et al., 2020).

In recent years, climate change impacts have accelerated the rate of erosion and related consequences (Eekhout & De Vente, 2020). Accelerated erosion can degrade the quality of land resources, leading to major environmental catastrophes (such as deposition, drought, and floods), impairing regional sustainability through detrimental ecological and social effects and having a significant impact on human survival and economic development (Lin et al., 2012). Soil erosion is a severe environmental concern in Nepal as well, with an estimated 25 ton ha^{-1} yr^{-1} national mean annual soil loss (Koirala et al., 2019). The rate and severity of the erosion also vary in different physiographic regions of the country, and approximately 45.5% of land erodes from the water in steeper areas of the hilly region (Chalise et al., 2019). Thus, studying soil erosion is crucial for scientifically predicting and controlling soil erosion as well as exploiting land resources(Koirala et al., 2019; Pan & Wen, 2014).

In the Rangun Khola watershed of western Nepal, environmental hazards like landslides contribute to a higher rate of erosion and vice versa in the monsoon seasons (Bhandari et al., 2021). There have been a number of landslide events recorded over the last decades, leading to erosion (Pathak & Devkota, 2022a). In this watershed, the natural elements, particularly the weather elements, are highly erosive (Dhital, 2015). Because of the high intensity of monsoon rainfall over short periods of time, the erosivity of rain and run-off are major drivers of soil loosening, slope weakening, and finally mass movements of solid and semi-solid materials such as soil creep, landslips, and landslides (Bhandari et al., 2021; Koirala et al., 2019; Pathak & Devkota, 2022b). Like many of the hilly areas that are on the way of being developed, this watershed is also in the growing phase of development. There are numerous such developmental activities such as the construction of roads and other linear infrastructure are found to be associated with higher amounts of erosion and associated hazards (Chalise et al., 2019). With the ongoing developmental activities and some other development projects in the pipeline for future developments, the risk of soil erosion and landslide events (Bhandari et al., 2021; Pathak & Devkota, 2022a). As a result, the Rangun Khola watershed can be assumed to be under constant pressure for various agricultural and urban developments. In such a scenario, the quantitative information on soil erosion at the watershed scale is extremely useful in planning for soil conservation, erosion control, and watershed management(Pan & Wen, 2014).

There are several models for analyzing soil erosion, but the most often used is the Universal Soil Loss Equation (USLE), which is an empirical model assessing long-term averages of sheet and rill erosion based on plot data gathered in the eastern United States (Morgan et al., 1998). Other models used to assess soil loss include the Erosion/ Productivity Impact Calculator (Williams, 1990), the European Soil Erosion Model (Morgan et al., 1998), and the Water Erosion Prediction Project (Flanagan & Nearing, 1995). The Revised Universal Soil Loss Equation (RUSLE) was created as a result of substantial improvements to the USLE as well as its database in order to more correctly assess soil erosion (Renard et al., 2017).

The RUSLE with GIS is employed in this research to assess the soil erosion potential, which is one of the major environmental problems in the Rangun Khola watershed. Along with this association, another equally significant and related environmental concern landslides, was carried out, which directly impacts and is influenced by soil erosion. It is anticipated that the findings of the study would give planners and decision-makers crucial information they may use to develop effective land management plans in the watershed.

Materials and Methods

Study area

This study was carried out in Rangun watershed situated in Sudurpaschim province, western Nepal covering the area of 48,939 hectare (489.39 sq. km) (Fig. 1). It is one of the major watershed of the Mahakali River Basin, which is an international boundary between Nepal and India(Pathak et al., 2020).The altitude range between 258 to 2,500 m asl, forming the steep slope susceptible to soil erosion. Numbers of landslide events from very past can be observed in the due to natural topographic setting along with the anthropic activities such as, land use and cover change, deforestation, terrace farming on steep slopes and rapid developmental activities (Bhandari et al., 2021; Pathak & Devkota, 2022b).

The average annual temperature ranges between 10°C to 25p C, and annual average rainfall in the watershed is about 1,346.6 mm, which concentrates in June-September mainly in and causes massive erosion each year (Bhandari et al., 2021). Along with various percentages of pasture land and sporadic patches of trees, bushes, and shrubs, the two main crops that make up the majority of the land use are forest and arable. Mudstones, shale, sandstones, siltstones, and conglomerates make up the majority of the rock types (Bhandari et al., 2021). Several instabilities can be observed within the different geological formations white to milky white calcareous quartzite, dolomitic limestone, shales and fine grained cross-bedded quartzite can be observed (Dhital, 2015). Surficial deposits such as alluvium, boulder, gravel, sand, silt, and clay are also common in the region. Thus the combined and cumulative impacts of natural as well as anthropic activates have created a complicated and unique environment for soil erosion.

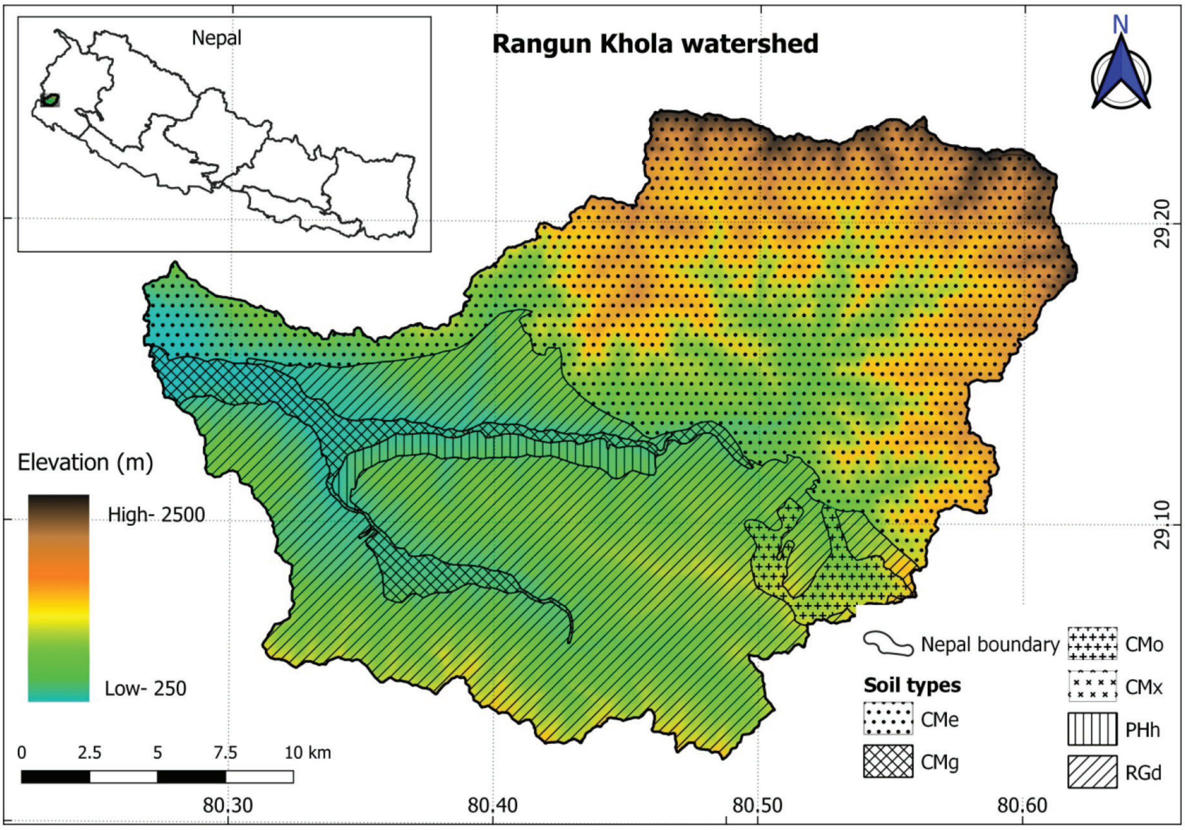

Figure 1: Study area depicting elevation range (250 to 2500 m) and different soil types (CMe- Eutric Cambisols, CMg- Gleyic Cambisols, CMo- Ferralic Cambisols, CMx- Chromic Cambisols, PHh- Haplic Phaeozems, RGd- Dystric Regosols)

Data set and sources

The spatial datasets for this study were obtained from various sources, as shown in Table 1. The data sets were all converted to raster format with the same resolution as the DEM.

Model Description for soil Erosion

The RUSLE empirical model was used in this study to forecast yearly soil loss in the landslide prone area. According to Renard et al. (2017), this RUSLE model calculates possible average soil loss (A) using the equation (1).

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

Where, A is the average soil loss (ton ha^{-1} year^{-1}) at a point (spatial location of grid cell), R is the rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}), K is the soil erodibility factor (ton ha MJ^{-1}mm^{-1}), LS is slope-length and slope steepness factor (dimensionless), C is the land management practice factor, and P is the conservation support practice factor (dimensionless).

Table 1: Datasets used for the RUSLE modelling and their sources

Datasets	Data source
DEM	ALOSPALSAR DEM obtained from the Alaska Satellite Facility homepage.
Soil map	Soil and Terrain Database (SOTER) for Nepal, acquired from ISRI data hub (https://data.isric.org/geonetwork/srv/eng/catalog.search#/home) (scale 1:50,000)
Land Cover map	Esri's 2020 land cover map with 10m resolution was utilized.
Rainfall map	Mean Annual District Level Precipitation of Nepal Produced by DHM
Landslide inventory	Google Earth Pro, Landsat images, Past studies (Dhital, 2015; Pathak & Devkota, 2022b, 2022a), and field visit

Rainfall erosivity factor (R)

This rainfall erosion factor (R) describes the intensity of precipitation at a particular location based on the amount of soil erosion (Koirala et al., 2019; Thapa, 2020). It quantifies the effect of raindrop amount and rate of runoff associated with rainfall and its unit is expressed in Mj mm $ha^{-1}h^{-1}year^{-1}$. During this study, the rainfall map produced form mean annual district level precipitation of Nepal produced by DHM was used to generate a rainfall erosion factor. This map shows mean annual precipitation over the district, an equation integrated to make the R-factor given by Morgan et al. (1998).

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

Where, R = Rainfall Erosivity Factor, P = Mean Annual Rainfall in mm

Support practice factor (P)

The P factor is the ratio of soil loss caused by a given support method to the loss caused by upslope and downslope tillage (Pijl et al., 2020). The lower the P value, the more effective the conservation measure in reducing soil erosion is thought to be. Contouring, strip cropping (alternative crops on a particular. slope formed on the contour), and terracing are conservation practice components covered in this term. Tables were used to calculate the ratio of soil loss when contouring and contour strip cropping were used to those where no conservation measures were used, with the P factor set to 1.0. Farming operations in sloppy agricultural land in Nepal occur by the development of terraces that closely mimic contour farmland, which is a conservation farming method. The support practice factor used in this study is presented in Table 2.

Table 2: P factor values for slope as per agricultural practice (Kumar and Kushwaha 2013)

Slope %	Contouring
0–7	0.55
7–11.3	0.60
11.3–17.6	0.80
17.6–26.8	0.95
> 26.8	1.00

Soil erodibility factor (K)

The soil erodibility factor K is a function of percentage of silt and coarse sand, soil structure, permeability of soil and the percentage of organic matter. It is the rate of soil loss per rainfall erosion index unit as measured on a standard plot and often determined using inherent soil properties (Radziuk & witoniak, 2021). Soil texture, organic matter, soil structure, and soil profile permeability are the key soil variables that influence K factor (Baskan, 2021). K factors of large soil groups were computed equation (3), and depicted in Table 3 which was previously employed by various earlier researchers in the similar terrain (Koirala et al., 2019; Thapa, 2020).

$$K = Fcsand * Fsi - cl * Forgc + Fhisand * 0.1317 \quad (3)$$

where,

$$Fcsand = [0.2 + 0.3\, exp\, exp\left(-0.0256\, SAN\left(1 - \frac{SIL}{100}\right)\right)]. \quad (4)$$

$$Fsi - cl = \left[\frac{SIL}{CLA + SIL}\right]^{0.3} \quad (5)$$

$$Forgc = \left[1 - \frac{0.25C}{C + exp\, exp\,(3.72 - 2.95C)}\right]. \quad (6)$$

$$Fhisand = \left[1 - \frac{0.070SN1}{SN1 + exp\, exp\,(-5.51 + 22.9SN1)}\right]. \quad (7)$$

where, SAN, SIL and CLA are % sand, silt and clay, respectively; C is the organic carbon content; and SN1 is sand content subtracted from 1 and divided by 100.

Cover-management factor (C)

The cover-management factor (C) is used to reflect the effect of cropping and other management practices on erosion rates. It measures the combined effect of all the interrelated cover and management variables, (Mukharamova et al., 2021). It was derived from a land use/cover classification obtained from Esri's 2020 land cover map (Karra et al., 2021). First, the raster map was converted to polygon and the attributes with same land use type were merged in ArcGIS. From this, six types of land use were

Table 3: Soil classification and computation of K-factor

Soil	Carbon (g/kg)	Sand (%)	Silt (%)	Clay (%)	F_{csand}	$F_{si\text{-}cl}$	F_{orgc}	F_{hisand}	K
Eutric Cambisol	9.6	40	40	20	0.741	0.885	0.929	0.980	0.079
Endosodi-Gleyic Cambisol	11.9	70	10	20	0.399	0.719	0.877	0.996	0.033
Skeleti-Ferralic Cambisol	6	80	10	10	0.358	0.812	0.980	0.998	0.037
Eutri-Chromic Cambisol	3.2	70	10	20	0.399	0.719	0.995	0.996	0.037
Calcaric Phaeozem	13.8	70	10	20	0.399	0.719	0.834	0.996	0.031
Siltic Phaeozem	46.8	10	70	20	1.126	0.927	0.750	0.941	0.097
Humi-Leptic Regosol	27.3	40	40	20	0.741	0.885	0.751	0.980	0.064

obtained (Table 4). For each land use type, C values were assigned through reference (Panagos et al., 2015). The C factor ranges from 0 to approximately 1, where higher values indicate no cover effect and soil loss comparable to that from a tilled bare fallow, while lower C means a very strong cover effect resulting in no erosion.

Table 4: Cover management factor(Panagos et al., 2015)

Land use	C factor
Forest	0.03
Shrubland	0.03
Grassland	0.01
Cultivated area	0.21
Barren land	0.45
water body	0.00

Topographic factor (LS)

The total topography of the RUSLE adds two variables to soil erosion: the length factor (L) and the steepness factor (S) (Lu et al., 2020; Sabzevari & Talebi, 2019). The LS factor is obtained by adding the L and S factors by using the equation used by Pan & Wen (2014) to determine the LS factor was implemented in this study.

$$LS = 1.07\left(\frac{\lambda}{20}\right)^{0.28} * \left(\frac{\alpha}{10^0}\right)^{1.45} \quad . \quad (8)$$

Where L is the slope length factor, S is the slope steepness factor, k is the field slope length in meters, and a is the slope angle in degrees. The % slope was calculated using the DEM, and the field slope length was calculated using a grid size of 12.5 m. The LS factor was calculated using ArcMap 10.5.

Potential Erosion Map and Correlation with Landslides

Five different factor maps were then input and processed to prepare raster map in ArcMap 10.5 and these raster maps were integrated using RUSLE relation to generate potential erosion map. Zonal statistics tool was also used for computing an area-weighted mean of the potential erosion between slope and LULC classes. Due to the absence of models or procedures to evaluate soil erosion intensity values in the study region, the soil erosion intensity map was correlated with landslide inventory map developed from satellite imagery, previous research (Pathak & Devkota, 2022b, 2022a) and a comprehensive field survey. Landslide sites over the last 20 years are overlaid with a soil erosion map generated by the RUSLE model and the frequency ratio-based statistical approach was used to examine correlation.

Results and Discussion

Factor maps

The results showed that the Rainfall Erosivity Factor (R) value ranges between 300 and 1300 Mj mm $ha^{-1}h^{-1}yr^{-1}$ with the highest rainfall in southern part of the study area (Fig. 2a). Soil Erodibility Factor (K) value ranged from 0.033 to 0.097 ton ha MJ^{-1} mm^{-1} (Fig. 2b). The Support Practice Factor (P) value ranged from 0.55 to 1 where a higher value indicates there is no any support practice such that erosion is at its maximum due to the absence of any practice (Fig. 2d). The value of the Cover Management Factor (C) ranged between 0 and 0.45 (Fig. 2e).

Potential Soil Erosion Rates

The potential soil erosion map of the Rangun Khola watershed produced utilizing RUSLE model and classified into six classes (Fig. 3, Table 5). It has been observed that the erosion ranges from 0 to 151 t $ha^{-1}yr^{-1}$ in the study area.

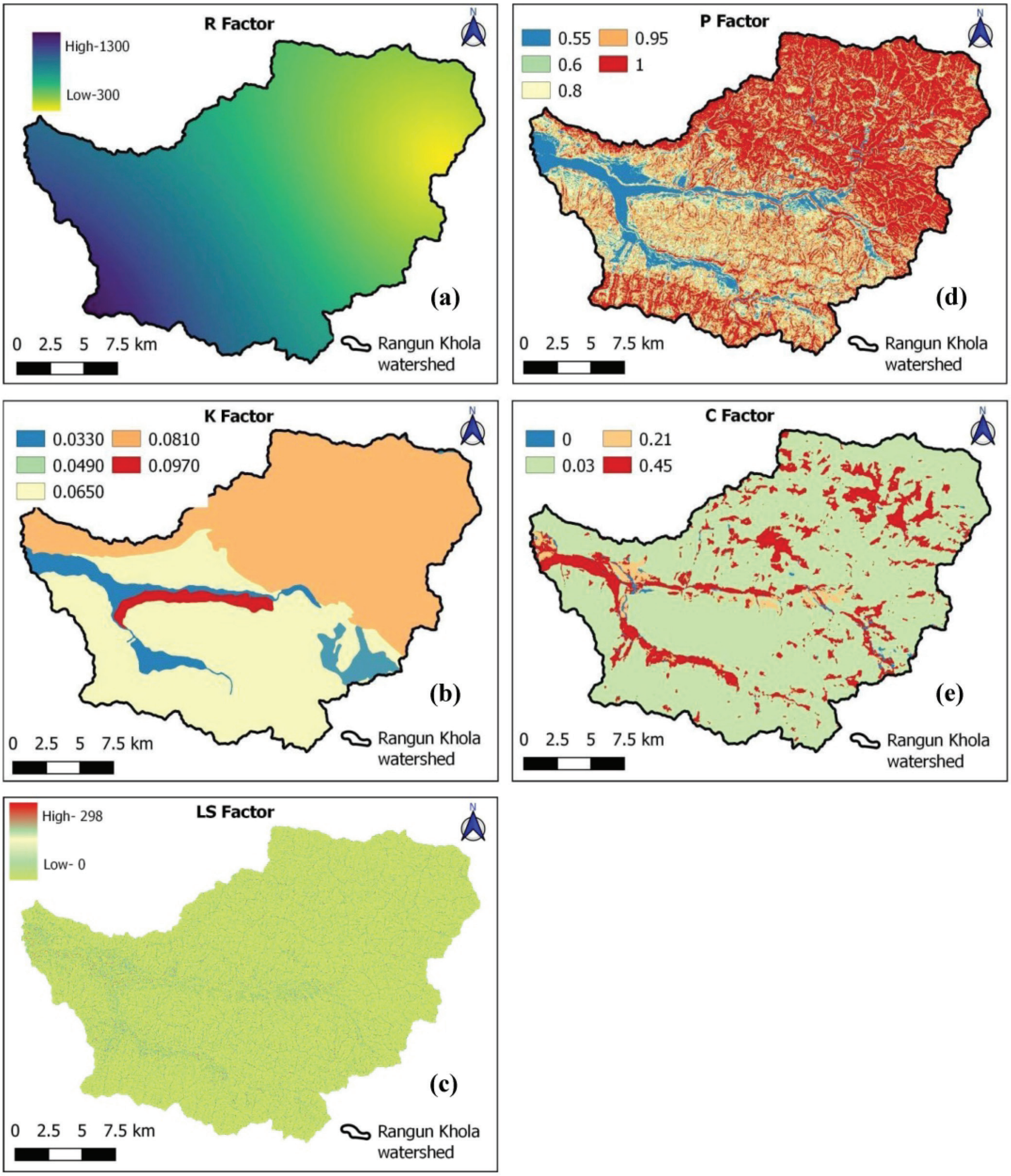

Figure 2: Five factor maps of soil erosion of study area, a Topographic factor map, b cover management factor map, c support practice factor, d soil erodibility factor map, e rainfall erosivity factor map

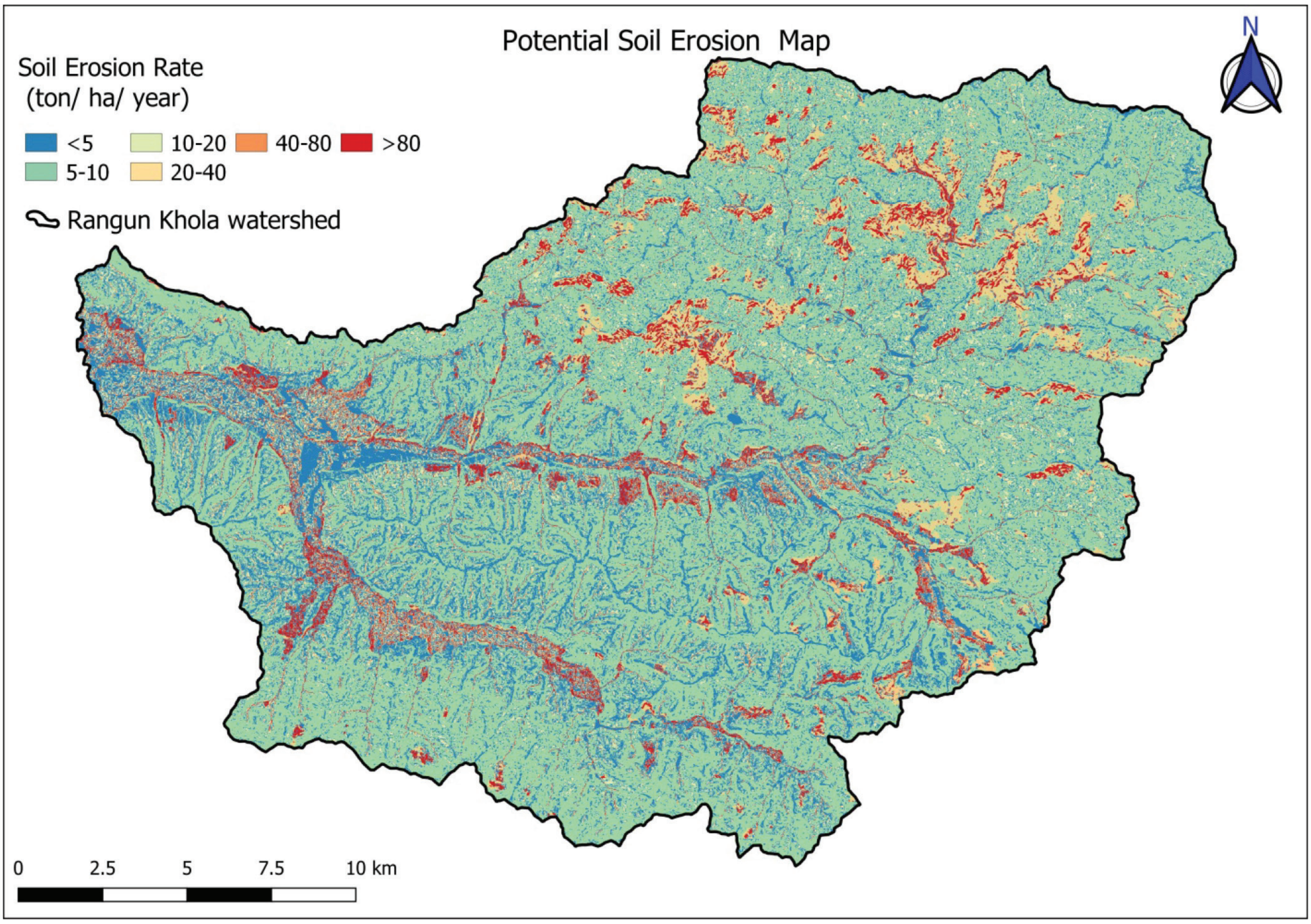

Figure 3: Potential soil erosion prone zone map of Rangun Khola watershed depicting six levels of soil erosion potential

The soil erosion higher than 80% consists of a 9.06% area (Table 5). It also shows that 8.20% of the area consist of very high, 3.18% high and 2.53% of serve risk zones need conservation to reduce the risk of soil erosion. The mean erosion rate high in barren lands, followed by cultivated area, and shrubland , and the highest soil loss rates observed in steep slopes(>26.8%).

Correlation of soil erosion map

Landslide locations, occurred during the past 15 years, are overlaid with the potential soil erosion map of using RUSLE model and are depicted in Fig. 4. In order to determine the association between these two related occurrences in the research region, frequency ratio techniques are based on the observed correlations between distribution of landslides and potential soil erosion.

Table 5: Area and the amount of soil loss in Rangun Khola watershed

Class	Rate of erosion	Count	Area (ha)	Percentage of area	Severity
1	< 5	667513	10429.89	17.8	Low
2	5-10	1954514	30539.28	59.21	Moderate
3	10-20	99600	1556.25	3.18	High
4	20-40	25683	401.2969	8.2	Very high
5	40-80	79242	1238.156	2.53	Severe
6	>80	293767	4590.109	9.06	Very severe

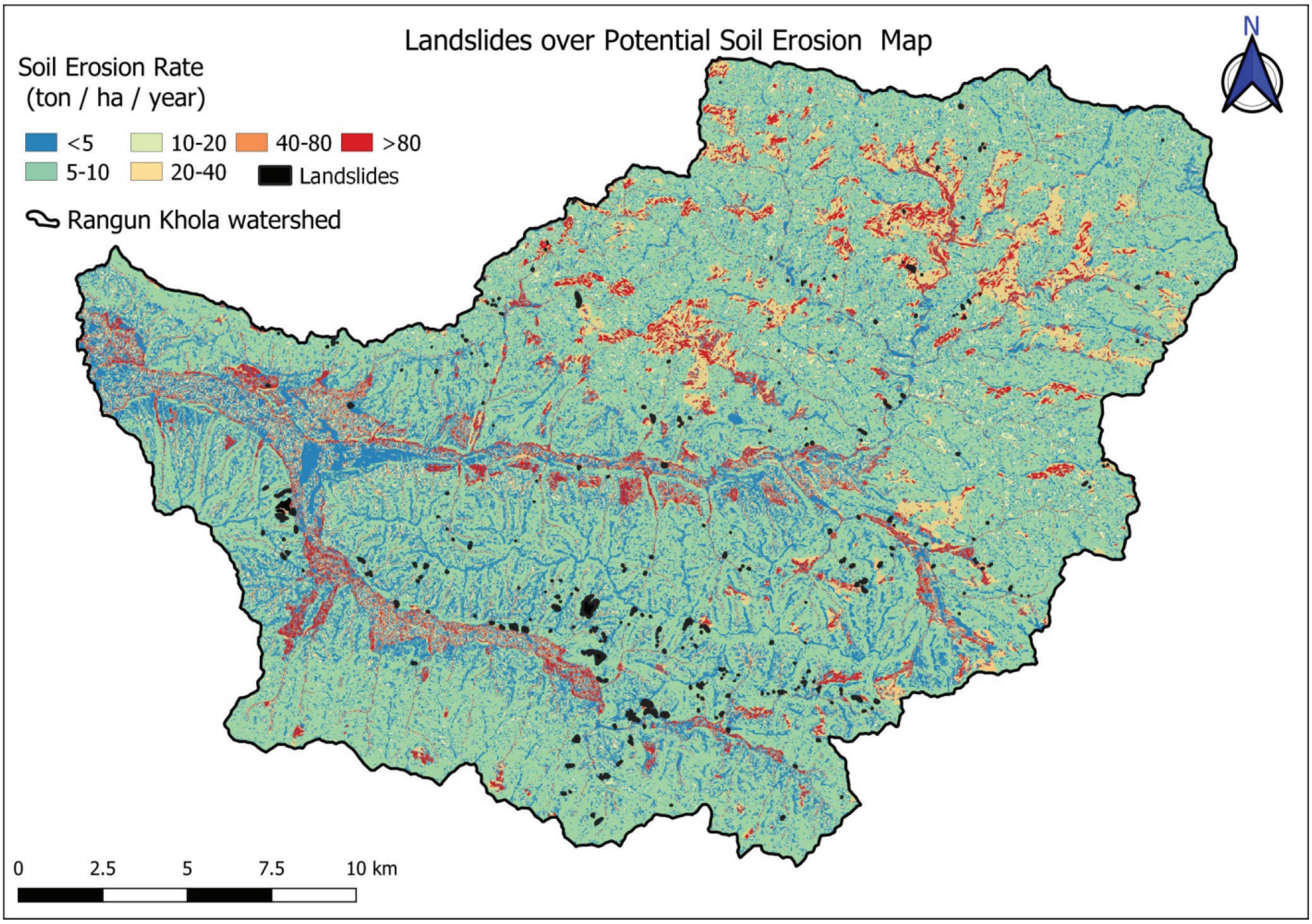

Figure 4: Landslide inventory (polygons) overlaid on potential soil erosion map of Rangun Khola watershed

The frequency was calculated from the analysis of the relationship between landslides and the attribute factors as given in Table 6. In the relationship analysis, the ratio is that of the area where landslides occurred to a particular area of erosion prone zone. A value of 1 is an average value. If the value is greater than 1, it means a higher correlation, and a value lower than 1 means a lower correlation of occurring soil erosion. The relationship between soil erosion and landslides occurrence shows that a very serve erosion level has a higher probability of landslides with frequency ratio of 4.41, which indicates higher probability of landslide occurrences. For serve, very high and high erosion levels, the frequency ratio is 3.49, 2.50 and 2.04, respectively. Similarly for low and moderate erosion levels frequency ratio was 0.46 and 0.50 that indicates it has a low probability of landslide occurrences.

Table 6: Frequency ratio values of landslide occurrences vs. potential soil erosion map

Soil Erosion levels	Pixels in domain	Pixels %, (a)	Landslide pixel count	Landslide occurrence, % (b)	Frequency ratio (b/a)
Low	667513	21.39	609	9.87	0.46
Moderate	1954514	62.64	1923	31.18	0.50
High	99600	3.19	401	6.50	2.04
Very high	25683	0.82	127	2.06	2.50
Severe	79242	2.54	547	8.87	3.49
Very severe	293767	9.41	2561	41.52	4.41
Total	3120319	100	6168	100	1

Fig. 5 displays the frequency ratio for each level of potential erosion susceptible to landside graphically. The frequency ratio and soil erosion levels have a linear relationship depicted in the graph. This correlation result demonstrates a reasonable level of agreement between the landslide event/location data and the erosion map and validates the model result.

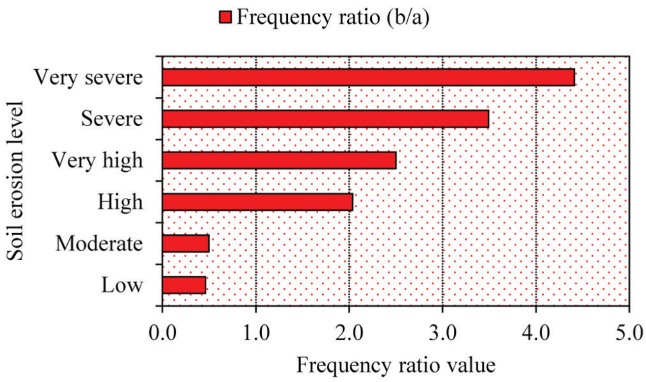

Figure 5: Frequency ration analysis between potential soil erosion map and landslide events between years 2005-2020 AD

RUSLE is the most commonly applied soil loss estimation model (Erol et al., 2015; Kumar et al., 2022). It can predict soil loss using limited information especially in developing countries where data collections are scarce (Thapa, 2020). Although the applicability of RUSLE model in mountainous terrain with steep slopes still questionable (M. Kumar et al., 2022), yet most widely used in similar terrain (Devatha et al., 2015; Koirala et al., 2019; Kumar & Kushwaha, 2013; Thapa, 2020). The potential soil erosion map prepared in this research revealed that the Rangun Khola watershed which is highly susceptible to landslide events (Pathak & Devkota, 2022a, 2022b) is also vulnerable to soil erosion due to five major factors, a high annual precipitation, the soil characteristics, mainly texture and steep slopes, land covers and soil conservation practices along the slopes. The range of potential soil erosion in this region ranges between 0 to 151 t $ha^{-1}yr^{-1}$, with an average (43 ton $ha^{-1}yr^{-1}$) higher than that of national average (25 ton $ha^{-1}yr^{-1}$) and falls in the range (0-273 ton $ha^{-1}yr^{-1}$) estimated for Nepal in the past study (Koirala et al., 2019).

The soil erosion increases with an increase in the steepness, which is also reported by Koirala et al. (2019) and Thapa (2020) in mountain of Nepal. Similarly the results of the potential soil erosion in different land covers were found to be similar to that of (Thapa, 2020) where barren land was highly vulnerable to the erosion. Land-use types with crop cultivation are much more exposed to soil loss than land-use types under semi or natural vegetation such as grassland, rangeland, shrub land, and forest. The erosion rate in undisturbed forestland is usually very low. Studies indicated that the reduction of overstorey canopy (Mohammad & Adam, 2010); removal or alteration of vegetation, destruction of forest (Karamage et al., 2016), land cover change mining (Borrelli et al., 2017) and landslide event (Pathak & Devkota, 2022a) significantly increase soil erosion risk which supports our finding that the forests and grasslands have low erosion rates in comparison with other land use.

The average erosion potential in current study suggests that the soil loss is above the tolerable limits and attention is needed to reduce the soil loss in vulnerable areas. Though there are no standard tolerable limits for soil losses in the mountain terrains, it is suggested that special soil and water conservation measures need to be applied for erosion rate greater than 35t $ha^{-1}yr^{-1}$ (Mandal & Sharda, 2013). In addition to harming the land, erosion causes sedimentation downstream to have a number of detrimental effects. Therefore, it is crucial to plan and carry out erosion control measures. The most vulnerable locations where the impact is expected to be highest must be the focus of the control measures in order to be as successful as possible.

It is necessary to assess the accuracy of the empirical models for the validation of the model outputs. But there are no proper validation techniques for potential soil erosion estimation from the RUSLE models and the results are compared with the field-based measurements over a set of sites for verification (Pradhan et al., 2012) or the results are compared with the estimated erosion from published field data (Koirala et al., 2019; Thapa, 2020). The frequency ratio approach suggested by Pradhan et al. (2012) and Gayen et al. (2020) was utilized. The frequency ratios for each level of potential erosion susceptible to landside exhibited a linear relationship. This can be the meaningful and reasonable level of agreement between the landslide event/location data and the erosion map that validates the model result. However, due to the enormous heterogeneity of the mid-hills of Nepal's geography, soil, cultural practices, and rainfall distribution, there is a wide range of erosion levels. For the model to be properly validated and improved, a one-to-one comparison of the estimates across a range of sites is necessary. Future investigations into places recommended for conservation efforts may include such studies, and the model and suggestions may be improved through an iterative process.

Conclusion

Rangun Khola watershed is very susceptible to soil erosion and landslides; therefore there was a need to study the soil erosion prone zones of this area. The present study demonstrates the application of RUSLE model in potential soil erosion estimation quantitatively. The soil erosion map was compared to the landslide inventory map and verified using the location of landslides by frequency ratio analysis. The results of this correlation showed a satisfactory agreement between the soil erosion intensity map and landslide events. Furthermore, the empirical model RUSLE for assessing soil erosion is used to evaluate soil erosion potentials in this area and to detect the sensitive zones presenting a priority of protection. Potential soil erosion map helps the decision makers to know the maximum erosion that can take place in the watershed and design land use/cover systems to reduce this non-point source pollution. Application of the RUSLE has many advantages: it provides quantitative data for comparison with qualitative assessments in erosion studies; data requirements for RUSLE are not too complex or unattainable and are compatible with GIS and easy to implement and understand from a functional perspective.

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