

Spatial Estimation of Soil Erosion Using RUSLE Modeling: A case study of Dolakha District, Nepal

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Research

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Spatial Estimation of Soil Erosion Using RUSLE Modeling: A case study of Dolakha District, Nepal

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Abstract:

- **Background:** Soil erosion causes topsoil loss, which decreases fertility in agricultural land. Spatial estimation of soil erosion essential for an agriculture-dependent country like Nepal for developing its control plans. This study evaluated impacts on Dolakha using the Revised Universal Soil Loss Equation (RUSLE) model; analyses the effect of Land Use and Land Cover (LULC) on soil erosion.
- **Results:** The soil erosion rate categorized into six classes based on the erosion severity, and 5.01% of the areas found under extreme severe erosion risk (> 80 Mg ha⁻¹yr⁻¹) addressed by decision-makers for reducing its rate and consequences. Followed by 10 % classified between high and severe range from 10 to 80 Mg ha⁻¹yr⁻¹. While 15% and 70% of areas remained in a moderate and low-risk zone, respectively. Result suggests the area of the north-eastern part suffers from a high soil erosion risk due to steep slope.
- **Conclusions:** The result produces a spatial distribution of soil erosion over Dolakha, which applied for conservation and management planning processes, at the policy level, by land-use planners and decision-makers.

Keywords: Soil Erosion; Land Cover; Land Use; Mountainous Region; Topography

1. Background

Last few decades, soil erosion impacts natural resources and agricultural production globally [1]–[3]. In Mountain regions, soil erosion causes severe hazards, such as heavy rainfall, surface water flow on bare lands that contribute to land degradation [4]–[6]. The primary soil erosion is onsite consequences impacts on soil fertility loss and degradation of soil resources quality, whereas pollution on water bodies and settling sediments are an offsite [7], [8]. It directly impacts on the environment, economy, and agriculture in mountain areas [9], [10]. Its rate increased through the change in precipitation and temperature pattern and eventually altering the runoff and land use, which causes flood, drought, and famine [11]–[13]. On the other hand, the deposition of sediments on the river affects reservoir and dams, increases their costs of maintenance, and in the long run, makes them unusable [14]. There have been several studies to understand this situation; their findings control soil erosion and ecological restoration [14], [15]. Although some attention regarding erosion modeling essential for inaccessible mountainous areas.

Mountain region is highly vulnerable to resource degradation caused by landslides, soil loss from steep slopes, and deforestation [16]. In Nepal, approximately 45.5% of land erodes from the water in steeper areas [17]. One study shows that soil loss of agricultural land in the hills through surface erosion, other finds in 1992 and 1993 of Likhu Khola watershed soil loss and slightly degraded secondary forest [18], [19]. Several models exist for prediction of soil erosion from empirical (USLE/RUSLE,) and considerably varies in its data input. The RUSLE represents raindrop impacts on climate, soil, topography, and land use affect rill and inter rill soil erosion [26]. This method is widely used to estimate soil erosion loss and risk, which provides a guideline for the development of conservation plans and controlling erosion under different land-cover conditions, such as croplands, rangelands, and disturbed forest lands [27].

The remote sensing and GIS techniques are feasible for soil erosion estimation and spatial distribution in larger areas [27], [28]. The remote sensing, GIS, and RUSLE provide the potential to estimate soil erosion loss on a cell-by-cell basis [27]. The RUSLE model with GIS used for estimation of the spatial distribution of soil erosion in Dolakha; however, the model is applicable only in the prediction of sheet and rill erosion, unable to estimate the rate of gully erosion [29]. It provides a framework for decision-makers for planning activities to control erosion and contributes toward filling a gap of soil loss information of a particular district.

2. Materials and Methods

2.1. Study Area

The study area is the Dolakha District, Nepal, situated in the northeast part of Kathmandu [30]. It's fragile in the last few years for soil erosion, deforestation, and terrace farming on steep slopes and rapid population pressure on natural resources [31], [32]. Other significant contributors are land use and land cover change caused by a human that increases the erosion rate here [33].

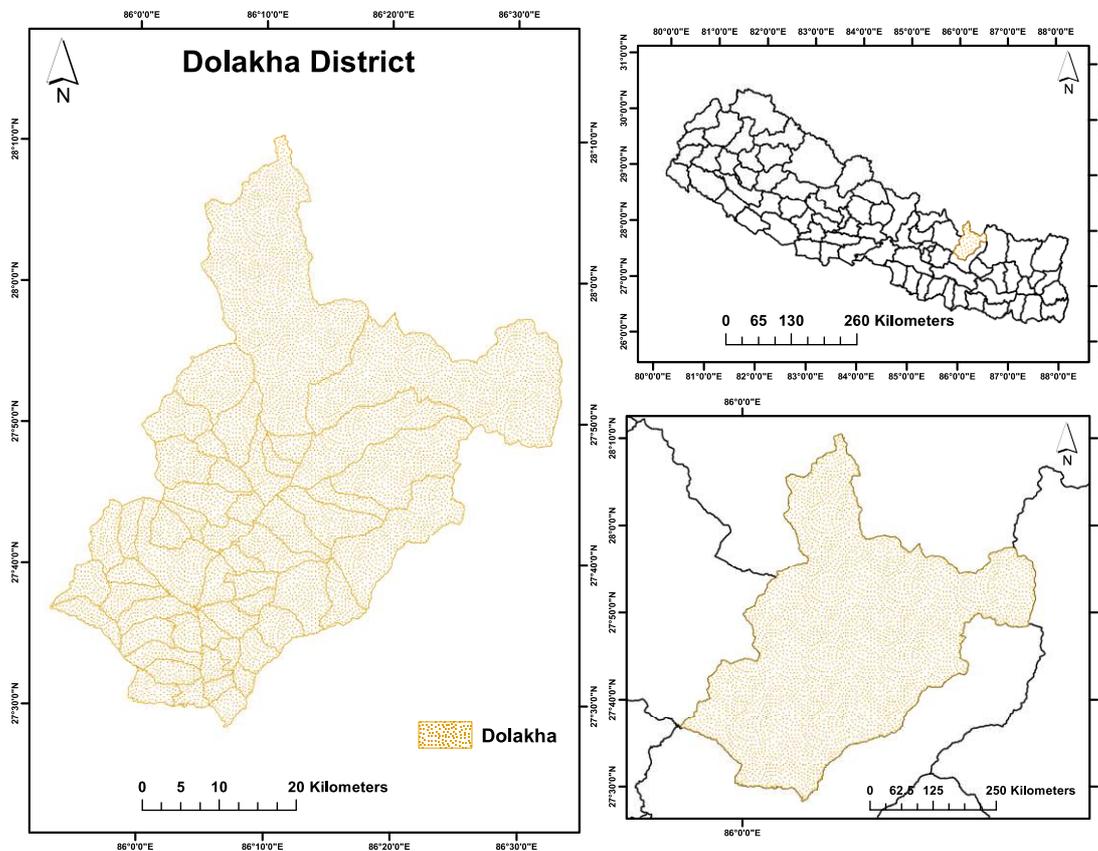


Figure 1: Study area used for estimating soil erosion.

2.2. Data Collection

The spatial datasets for this research are shown in Table 1.

Table 1. The datasets used for the RUSLE modelling.

Datasets	Data Source
DEM*	SRTM DEM [†]
	https://earthexplorer.usgs.gov/
	A product of METI [§] and NASA [#]

Soil Map	Digital Soil Map of the World (2019) www.fao.org/geonetwork/srv/en/metadata.show Produced by FAO-UNESCO (1:5,000,000 scale)
Landcover Map	Landcover Map of Nepal (2010) Produced by ICIMOD [^] TRMM Data [@]
Rainfall Map	https://gpm.nasa.gov/?q=TRMM Produced by NASA

2.3. Methods

The RUSLE model estimates soil damage for ground slopes in Geographic Information System (GIS) platform ([34] Figure 2). A combined equation of geophysical and land cover factors to evaluate the yearly soil loss from a unit of property. It assesses erosion risk in the research area, which has its qualities and application scopes [22], [35]. Its global model to predict soil loss because of its convenience and compatibility with GIS [27], [36]–[38]. GIS and remote sensing technology advancement enabled a more accurate estimation of the factors used for calculation [16], [39]–[41]. Each of the elements derived separately in raster data format and the erosion calculated using the map algebra functions. Figure 2 illustrates the framework for the RUSLE model calculation and expressed by an equation,

$$A = [R] * [K] * [LS] * [C] * [P], \quad (1)$$

where, A = soil loss ($\text{mg ha}^{-1} \text{yr}^{-1}$), R = rainfall erosivity factor ($\text{mm ha}^{-1} \text{yr}^{-1}$), K = soil erodibility factor (mg/ha.yr), LS = slope-length and slope steepness factor (dimensionless), C = land management factor (dimensionless), and P = conservation practice factor (dimensionless).

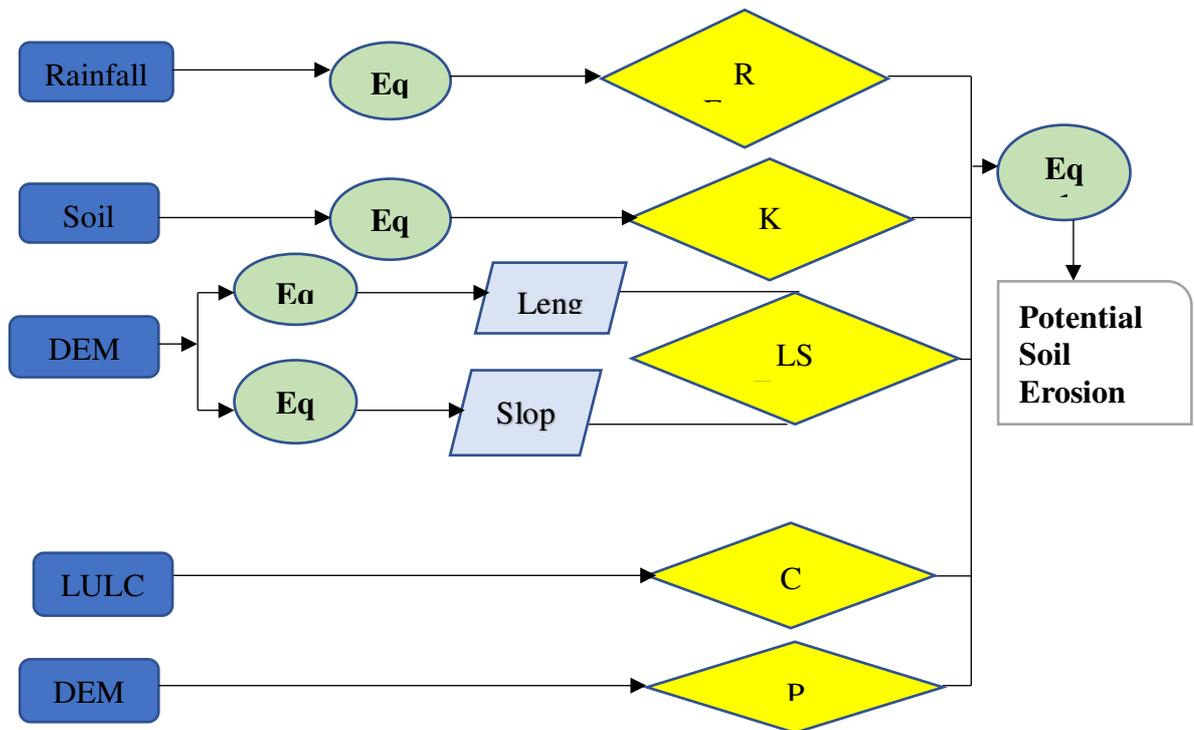


Figure 2: The methodological framework for potential soil erosion using RUSLE model.

2.3.1. RUSLE Parameters Computation

(a) Rainfall Erosivity Factor (R)

This rainfall erosion factor (R) describes the intensity of precipitation at a particular location based on their amount on soil erosion [42], [43]. Essential for soil erosion risk assessment under future land use and climate change [44]. It quantifies an effect of raindrop amount and rate of runoff associate with rainfall and its unit expressed in mm ha⁻¹ h⁻¹ yr⁻¹. During this study, the rainfall map produced by the National Aeronautics and Space Administration (NASA) used to generate a rainfall erosion factor [45]. This map shows mean annual precipitation over the district, equation integrated to make the R-factor given by reference [7].

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

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

(b) Soil Erodibility Factor (K)

The soil erodibility factor (K) measures the susceptible soil types and their particles to detachment and transport by rainfall and runoff. The K factor influenced by soil texture, organic matter, soil structure, and permeability of the soil profile [46]. The equation provided by reference used to estimate the soil loss [47].

$$K = Fcsand * Fsi-cl * Forge * Fhisand * 0.1317, \quad (3)$$

where,

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

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

$$Forge = [1.0 - \frac{0.25 C}{C + \exp(3.72 - 2.95 C)}], \quad (6)$$

$$Fhisand = [1.0 - \frac{0.70 SN1}{SN1 + \exp(-5.51 + 22.9 SN1)}], \quad (7)$$

where, SAN, SIL and CLA are % sand, silt and clay, respectively; C is the organic carbon content; and

SN1 sand content subtracted from 1 and divided by 100.

Fcsand = low soil erodibility factor for soil

Fsi-cl = low soil erodibility factor with high clay to silt ratio.

Forge = factor that reduces soil erodibility for soil with high organic content.

Fhisand = factor that reduces soil erodibility for soil with high sand content.

(c) Topographic Factor (LS)

The topographic factor (LS) created from two sub-factors: a slope gradient factor (S) and a slope-length factor (L), both determined from the Digital Elevation Model (DEM). The slope-length and gradient parameter is crucial in the soil erosion modeling for calculating overland flow (Surface runoff) [21]. The L and S represent the effect of slope length and steepness respectively on erosion, also when it increases soil loss per unit area rises. These calculated from the DEM and combined to result in the topographical factor grid using relation [41].

$$L = (\frac{\lambda}{22.13})^m, \quad (8)$$

where, L = slope length factor, λ = slope length (m), m = slope-length exponent

$$m = \frac{F}{1+F'}, \quad (9)$$

$$F = \frac{\sin\beta/0.0896}{3(\sin\beta)^{0.8+0.56}}, \quad (10)$$

where, F = Ratio between rill erosion and inter rill erosion, β = slope angle (°)

In ArcGIS, L was calculated as,

$$L = \frac{flow_{acc} + 625)^{(m+1)} - flow_{acc}^{(m+1)}}{25^{(m+2)} * 22.13^m}, \quad (11)$$

For slope gradient factor,

$$S = \text{Con}((\text{Tan}(\text{slope} * 0.01745) < 0.09), (10.8 * \text{Sin}(\text{slope} * 0.01745) + 0.03), (16.8 * \text{Sin}(\text{slope} * 0.01745) - 0.5)), \quad (12)$$

$$\text{Final, LS} = L * S, \quad (13)$$

(d) Cover Management Factor (C)

The cover-management factor (C) reflects the effect of cropping and other practices on erosion rates [17]. It's the most spatiotemporal sensitive as it follows plant growth and rainfall dynamics [11]. This factor defined as a non-dimensional number between zero and one representing a rainfall erosion weighted ratio of soil loss for specified land and vegetated conditions to the corresponding loss from continuous bare fallow [45]. In this study, LULC produced by the ICIMOD used for preparing a C-factor map [48]. The raster map converted to polygon through raster to polygon tool and the attributes with the same land use type merged into a single class using ArcGIS 10.5 software, the study used eight types of land use (Table 2). Each land-use example, C values assigned through reference ranges from 0 to 1, where lower C means no loss, while higher indicates uncover and significant chances of soil loss [46], [49].

Table 2: Cover Management Factor.

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
Snow Glacier	0.00

(e) Support Practice Factor (P)

The support practice factor indicates the rate of soil loss according to agricultural practice. There are three methods, such as contours, cropping, and terrace, and vital elements to control erosion [39]. This contouring method used with P values ranges from 0 to 1, where the value 0 represents proper anthropic erosion, and the value 1 indicates a non-anthropic erosion facility (Table 3 [47]). It values for particular types of land cover used from published sources [23], [50].

Table 3: P factor values for slope [51].

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

2.3.2. Potential Erosion Map

The different data input processed in ArcGIS created five-factor maps: R, K, LS, C, and P (Figure 3). These raster maps integrated within the ArcGIS environment using the RUSLE relation to generate composite maps of the estimated erosion loss on the study area [40], [41]. Zonal statistics tool and calculating geometry used for computing an area-weighted mean of the potential erosion rates for its generated to explore the relationship between slope and LULC on erosion [52]. The slope map of Dolakha created from DEM in ArcGIS and then reclassified into eight classes [53].

3. Results

3.1 Factor Maps

The results showed that the Topographic factor (LS) value range between 0 and 12073 (Figure 3 a); Rainfall Erosivity Factor (R) value ranges between 87.4938 and 1541.42 mm ha⁻¹ yr⁻¹ (Figure 3 e); Soil Erodibility Factor (K) value ranged from 0.2 to 0.32 (Figure 3 d). The Support Practice Factor (P) value for the entire area ranged from 0.55 to 1 (Figure 3 c). The Cover Management Factor (C) value ranged between 0 and 0.45 (Figure 3 b).

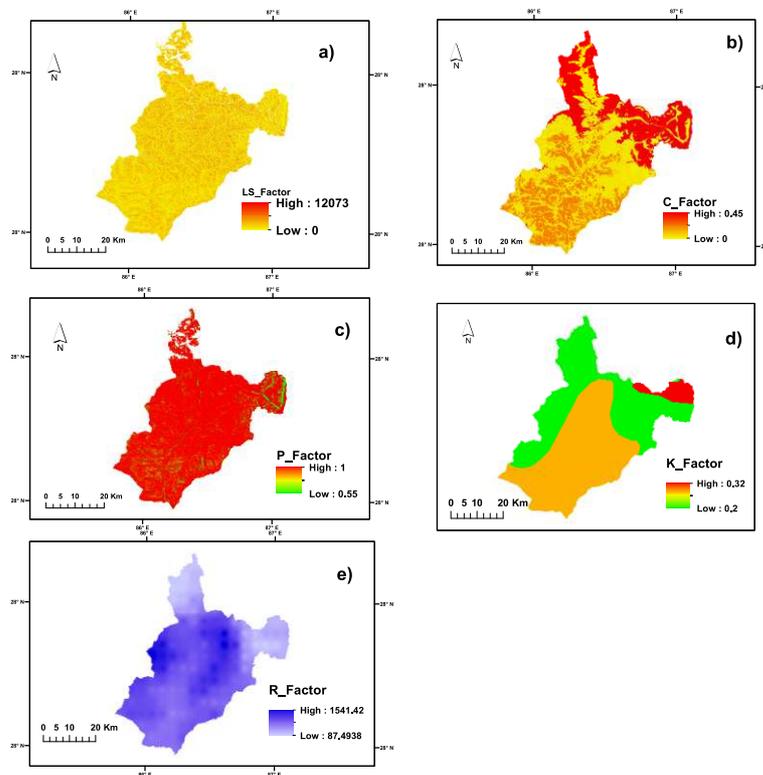


Figure 3: Five factor maps of soil erosion of Study area(a) Topographic factor Map (b) Cover Management factor map (c) Support Practice factor (d) Soil Erodibility factor Map (e) Rainfall erosivity factor map.

3.2. Potential Soil Erosion Rates of Nepal

The potential soil erosion map of the Dolakha district produced multiplying the factor maps in ArcGIS (Figure 4; Table 4). The soil erosion higher than 80 percent consists of a 5.01 percentage area (Table 4). It shows that around 10% of high, very high, and severe risk zones need conservation to reduce the risk of soil erosion. The mean erosion rate high in barren lands, followed by agricultural lands, shrubs, grasslands, and forests, and the highest soil loss rates observed in steep slopes.

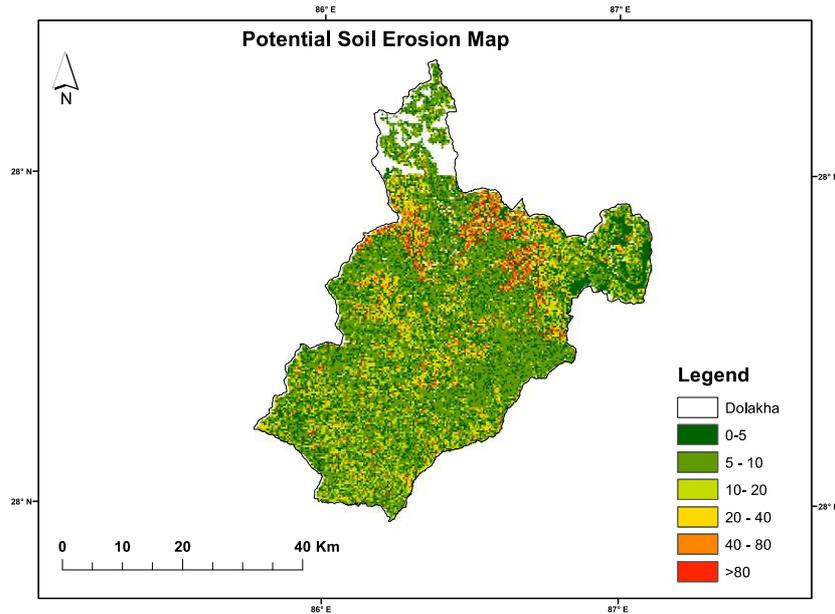


Figure 4: Potential Map of Soil Erosion Rate of Dolakha District.

The study area classified into six classes that remained constant in the different erosion classes shown bold in the diagonal cells. Greater than 80% of the study area remained in the high severe erosion risk class. The proportion area at low and moderate risk of erosion is 70% and 15%, respectively, while the space between the upper and very severe, around 15%, indicates a chance increasing.

Table 4: Potential Soil Erosion Rate of Dolakha District.

Class	Rate of Erosion (Mg ha⁻¹yr⁻¹)	Area (Km²)	Percentage of Area	Severity
1	0-5	1730.105	70.01	Low
2	5-10	249.429	15.40	Moderate
3	10-20	28.327	2.41	High
4	20-40	2.937	4.15	Very High
5	40-80	0.446	3.02	Severe
6	>80	0.157	5.01	Very Severe

4. Discussion

RUSLE is an empirical-based modeling approach that predicts the long-term average annual rate of soil erosion on slopes using five factors. It estimates soil loss with similar terrain and meteorological conditions [3]. This research, a potential soil erosion rate map of Dolakha generated using different sources (Table 1) for the RUSLE model using ArcGIS software. Its the first time that such an approach to assess erosion risk across an entire mountainous region, and the methodology still has certain limitations. Again, it identifies priority areas for reducing soil erosion. Other research studies having similar geographic characteristics also used the same method [3], [49], [51]. In an erosion model, proper consideration of R-factor, LS-factor, K-factor, P-factor, and C-factor should minimize the uncertainties. The LS-factor with a maximum slope in the study area used as original RUSLE formulations [54]. According to the many research results, Nepal is vulnerable to soil erosion hazards due to five major factors, high annual precipitation, the soil characteristics, mainly texture and steep slopes, land covers, and soil conservation practices along the slopes [54], [55]. Its total soil erosion is comparatively

higher than in other countries of the world [42]. This study also found that around 15 % of the total area in district was between upper and very severe region, which is common in rates of erosion of countries like India, Ethiopia, United Kingdom, Europe, and Africa in their steeper slope area [7], [44], [45]. Here, the suggested range of erosion is almost equal to that of Australia, China, as estimated by reference [56]. The higher erosion rates in China and Australia indicate the vulnerability to an erosion of the semi-arid and semi-humid areas of the world [57]. The soil erosion rates in the mountainous regions, like Nepal, also rise with an increase in slope [58].

RUSLE is the most commonly applied soil loss estimation model[59]–[62]. Moreover, RUSLE model strength lies in giving predicted soil loss using limited information, especially in developing countries where data are scarce [63]–[65] although RUSLE widely used in mountainous terrain with steep slopes still questionable [66], [67]. Some models, such as AGNPS or ANSWER, are unsuitable in Nepal due to large amounts of data and AGNPS, non-applicable to this Middle hill area [68], [69]. On the other hand, modeling results are impressive but difficult to interpret and validate because of its complexity [70]. Overall, such models include errors because they based on empirical rules. This model identifies areas at risk, where management actions needed [71], [72]. It's simple, flexible, and physical base for predicting the relative soil loss pattern; however, the high hills are heterogeneous on precipitation patterns and topography. It assesses soil erosion accuracy estimates from the models using ground observations. It's impossible to validate the assessments and analyze error and bias by comparing model prediction with field-based measurements over a set of sites. There have been very few field-based studies in the area. However, the output compared with the estimated erosion levels of different studies from published articles and with other model-based results of mid and high hill areas in Nepal with similar characteristics to the Dolakha [73], [74].

The method contains limitations and potential for factors that drive erosion in the RUSLE model. Precipitation data from TRMM Data used for hill areas to calculate the rainfall erosion factor. Weather stations in the Himalayan region limited, and spatial precipitation data is low resolution. Furthermore, this approach is unable to capture the distribution of massive precipitation events, markedly impacting soil erosion. The Cover Management Factor (C) and Support Practice Factor (P) weighted at soil order level using published results [75]. Better estimates could determine the C-factor by remote sensing, have used vegetation indices such as the Normalized Difference Vegetation Index (NDVI) [76], [77]. Usually, NDVI directly correlated to the C-factor by linear or exponential regression [50], [78]. An alternative approach for an approximation of the P-factor based on empirical equations. For instance, Wener's method assumes that the P-factor linked to topographical features, and slope gradient[49], [79], [80]. The RUSLE method reported overestimating erosion in high terrain [40], [75]. The Rich Mesic Forest (RMF) and Mesic Forest (MF) models better estimates over a slope with ground data [33], [81]. Comprehensive research appropriate for accurate estimation of erosion model and ground measurements.

5. Conclusions

The severity assessment of soil erosion GIS-based RUSLE equation considering rainfall, soil, DEM, land use, and land cover. The soil erosion rate categorized into six classes based on its severity, and 5.01% of the regions found under extreme risk ($> 80 \text{ Mg ha}^{-1}\text{yr}^{-1}$) 70% of areas remained in a low-risk zone. This show area with high elevation along with prompt rainfall susceptible to soil erosion. The predicted severity can provide a basis for conservation and planning processes at the decision-makers. The regions with high to very severe soil erosion warrant special priority and control measures. While this model forms a basis on mapping and

prediction using remote sensing and GIS-based analysis for vulnerability zones, such studies suggested for conservation and refining the model in the future.

6. List of Abbreviations

RUSLE- Revised Universal Soil Loss Equation

ArcGIS- Arc Geographic Information System

DEM- Digital Elevation Model

SRTM DEM- Shuttle Radar Topography Mission, Digital Elevation Model

METI- Ministry of Economy, Trade and Industry, Japan

NASA- National Aeronautics and Space Administration, US

ICIMOD- International Center for Integrated Mountain Development

TRMM- Tropical Rainfall Measuring Mission

Yr- Year

7. Declaration

• Consent for publication

I agreed to submit the final manuscript for Environmental Systems Research Journal.

• Ethics approval and consent to participant

Not applicable.

• Availability of data and materials

The data used for this study mentioned with their sources; if data used in the manuscript are not precise, the author is ready to clarify and even send the dataset on request.

• Competing interests

The author declares that they have no competing interests.

• Funding

No funding was received

• Authors' contributions

The author has conducted all research activities such as data acquisition, analysis, evaluation, and result.

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• Authors' information (optional)

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Figures

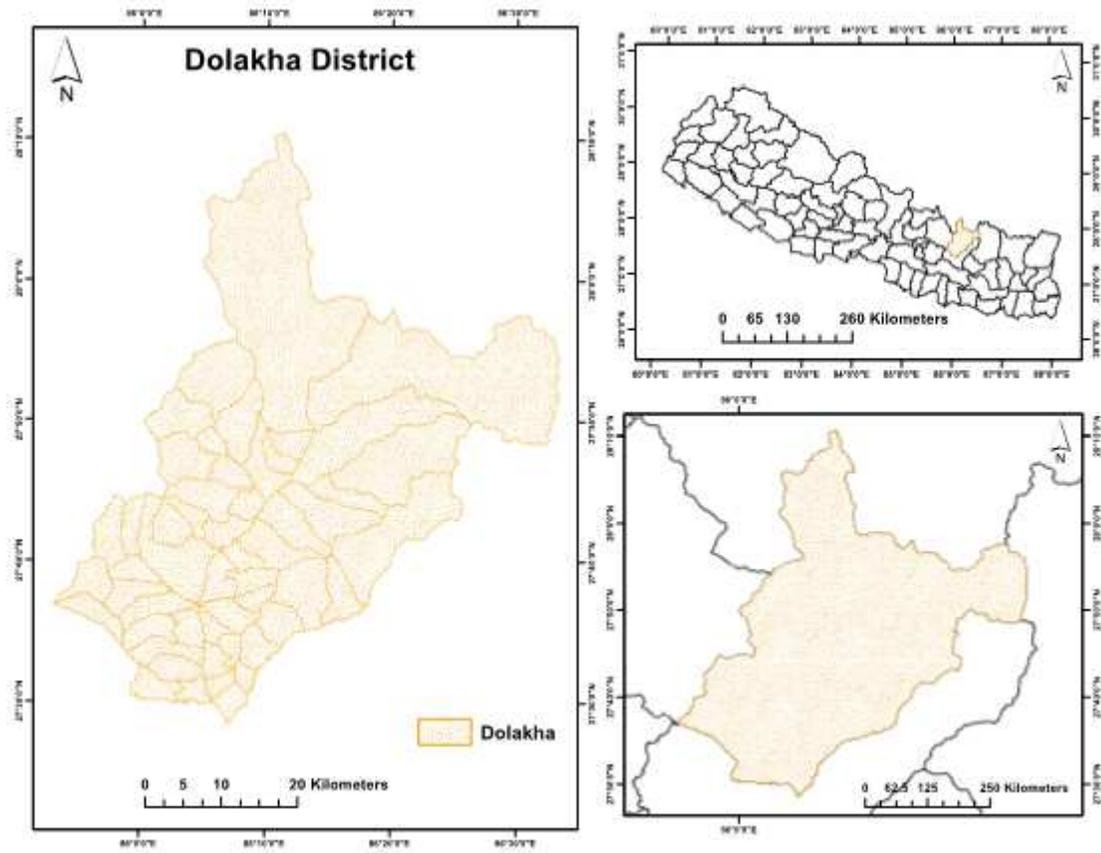


Figure 1

Study area used for estimating soil erosion.

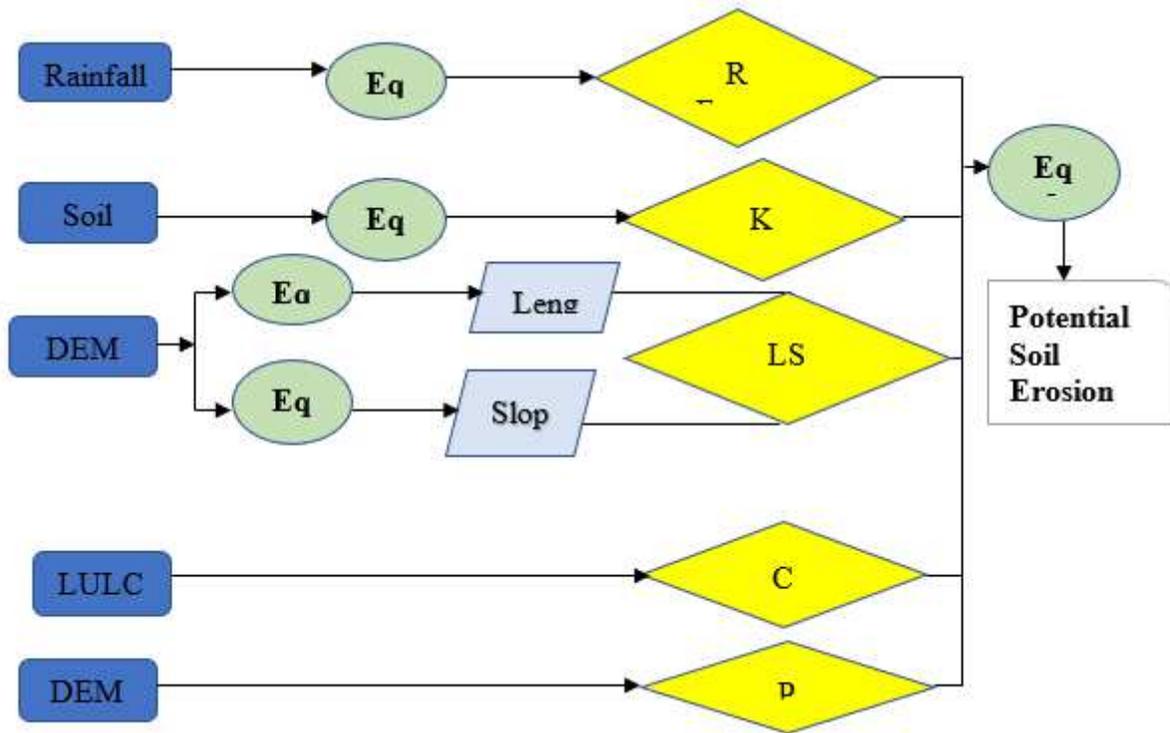


Figure 2

The methodological framework for potential soil erosion using RUSLE model.

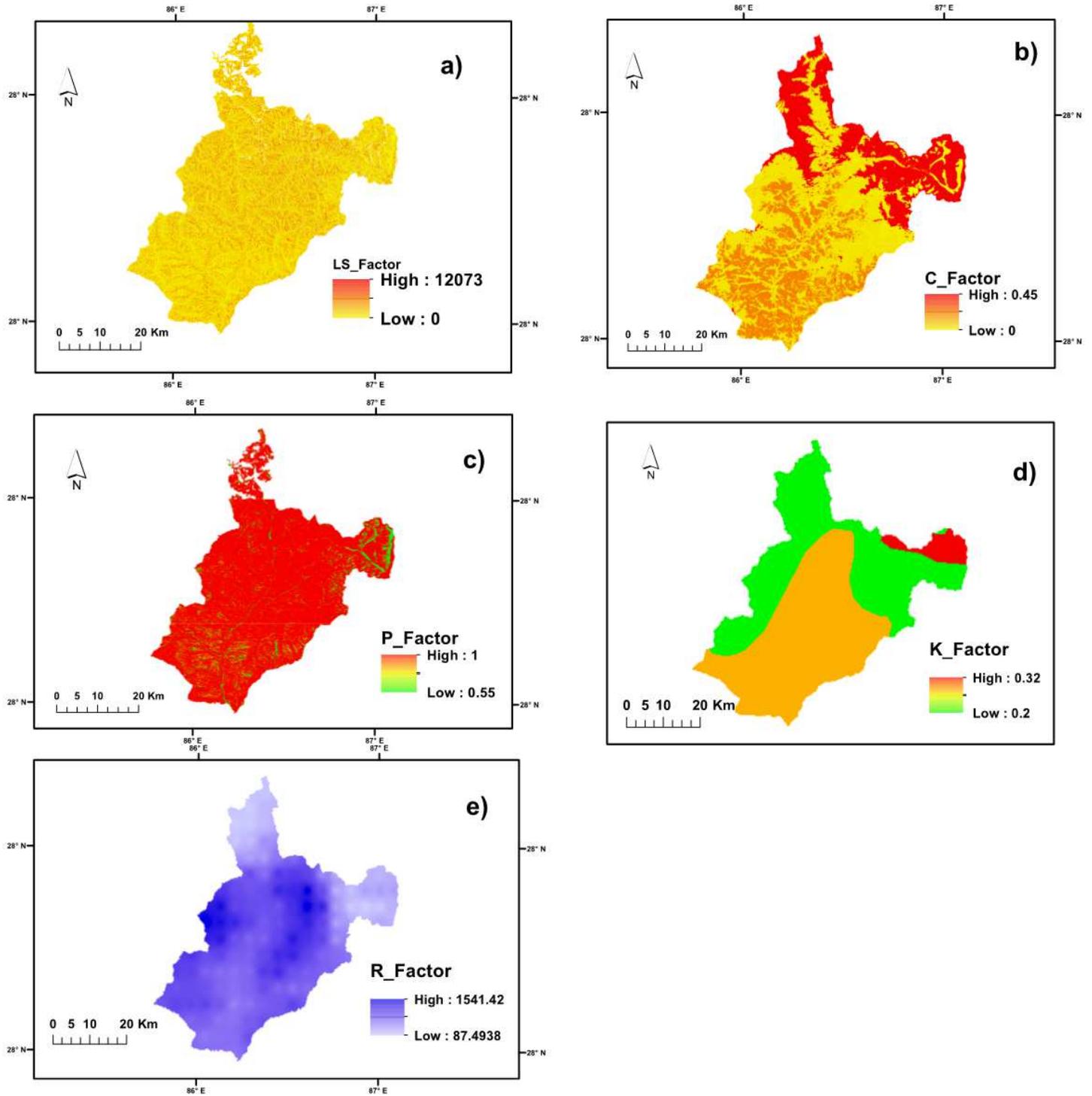


Figure 3

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.

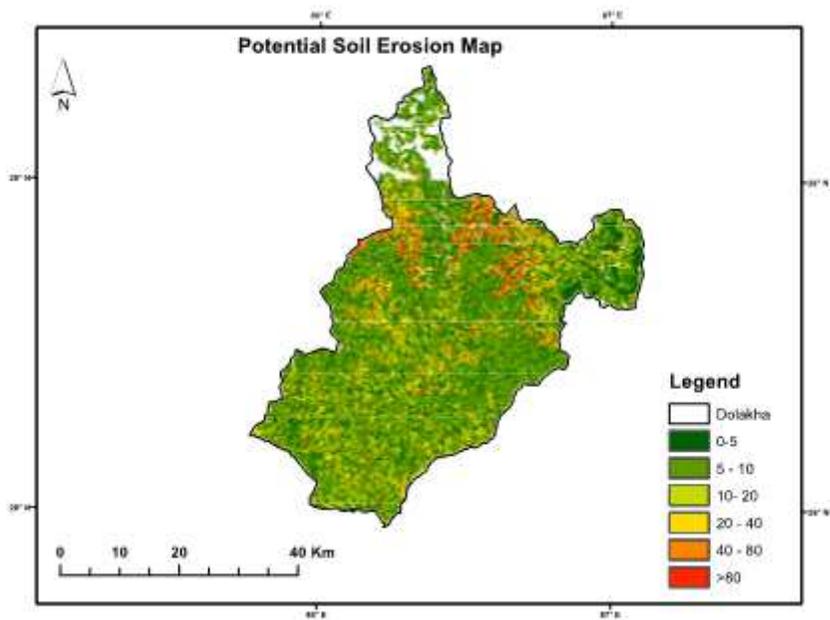


Figure 4

Potential Map of Soil Erosion Rate of Dolakha District.