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Identifying Potential Erosion-Prone Areas in the Indian Himalayan Region Using the Revised Universal Soil Loss Equation (RUSLE)

Dorje Dawa and Vairaj Arjune[1*]
Centre for Interdisciplinary Studies of Mountain and Hill Environment, University of Delhi, New Delhi – 110007, India
[1]Department of Environmental Studies, University of Delhi, New Delhi – 110007, India
✉ varjune24@gmail.com

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Abstract: Soil erosion is one of the most critical environmental issues with severe consequences. Hence, it continues to be a significant limitation in the progress of many developing countries. Prediction and assessment of soil loss are, therefore, of utmost importance for soil fertility conservation, land and water management. Recent technological advances have provided useful models through which remotely-sensed data for a large scale area can be analysed and interpreted. The present study adopts a physiographically, biologically and climatically unique model for the assessment of soil erosion in the Indian Himalayan Region. The Revised Universal Soil Loss Equation model was applied in conjunction with Geographic Information System to estimate the average annual rate of soil erosion at both state and district levels in India. The model was deployed using coarse resolution datasets to identify specific areas vulnerable to soil erosion. In determining the spatial distribution of average annual soil erosion within the study region, all cell-based parameters of the model were multiplied in the specified 500 m × 500 m spatial resolution. The spatial pattern of annual soil erosion indicates that maximum soil loss occurs in northern and eastern states whereas low rates of erosion is observed in the eastern-most part of the study area.

Key words: Erosion, geographic information system, land cover, remote sensing, soil loss.

Introduction

Soil erosion is a pressing global environmental issue that threatens agriculture and the natural environment, especially in countries where population growth and hence, the need for land is rapidly increasing (Kouli et al., 2008; Pimentel, 1993, 2006; Terranova et al., 2009). Severe soil erosion is also affecting global regions of agricultural practices where more marginal lands are used for cultivation. This is disturbing the soil replenishment cycles by reducing crop residues. Since the Indian agricultural system focusses on ensuring food security for over 1.2 billion people and considering that about 99% of the world's food (calories) is through land cultivation (Pimentel et al., 2004), therefore, productivity of land becomes a crucial factor for agricultural sector. Obstacles in this sector arises due to on-site and off-site damages manifesting in economic, political, environmental and social factors (Ananda and Herath, 2003; Morgan, 2005). Over the years, several anthropogenic activities have played a significant role leading to erosion of soil, which means fertile lands have turned unproductive and sometimes forsaken (Pimentel et al., 1995). In addition to this, offsite damages of upland soil erosion in watersheds have increased the effects of siltation, reduced irrigation,

*Corresponding Author

irregularities in water flow, water pollution, and agro-chemicals run-off. Thus, the capacity of irrigation channels for agriculture and dam reservoirs would be affected due to enhanced soil accumulation (Ananda and Herath, 2003). The assessment of environment and land degradation policy for sustainable agriculture and development analyses that soil loss by erosion is being increasingly recognised as a hazard being more severe in mountainous areas (Angima et al., 2003; Dabral et al., 2008; Jasrotia and Singh, 2006; Millward and Mersey, 1999; Sharma, 2010).

Proper planning, policy and decision making and designing of conservation measures have become a dire need in soil erosion estimation at the regional level (Fistikoglu and Harmancioglu, 2002). Quantitative models present a useful way to assess areas where erosion rates would have exceeded some threshold limit; estimate erosion for data-deficient location, or to predict erosion rates for the future conditions based on modification on land cover and climatic factors (Boardman, 2006). The results of quantitative assessment can be used to understand the extent and magnitude of erosion problems which can be incorporated in management decisions and strategies. Also, advances in spatial technology have improved existing methods of modelling earth resources. The use of Digital elevation model (DEM) along with the advancement of satellite Remote Sensing (RS) and Geographic Information System (GIS) can be applied to provide a detailed assessment of soil erosion (Jain et al., 2001; Kouli et al., 2008). However, the problem of soil loss assessment and conservation practices in developing countries lies in the lack of field data or the ability to obtain high-resolution data to be used as an input for soil loss models (Phillips, 1989).

This study adopts an erosion model that is unique to the physiography, biological and climatic conditions of the Indian Himalayan Region (IHR). The Revised Universal Soil Loss Equation (RUSLE) model deployed in this study predicts the average annual rate of soil erosion for ungauged catchments by incorporating existing knowledge of the location characteristics and climatic conditions (Renard et al., 1997). Recognising the conditions of the region, RUSLE was applied in conjunction with Geographic Information System (GIS) for estimating soil loss in five states of the IHR: Jammu Kashmir, Himachal Pradesh, Uttarakhand, Sikkim, and Arunachal Pradesh as shown in Figure 1.

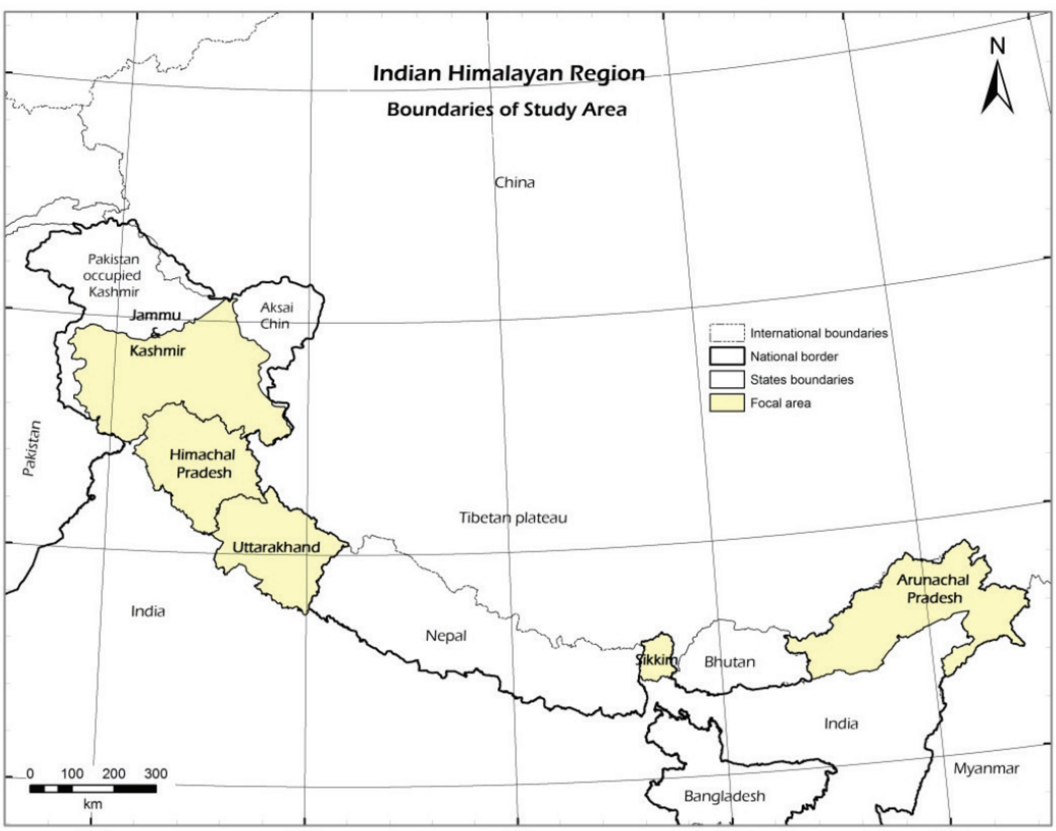

Figure 1: Map showing the political boundaries of the study area.

Materials and Methods

RUSLE Model

The Universal Soil Loss Equation (USLE) is a widely used model that predicts the average annual rate of soil loss based on several variables, crop system, management practices, soil type, rainfall pattern and topography. The model mainly computes soil erosion from sheet and rill erosion (Wischmeier and Smith, 1978). However, due to some limitation, RUSLE has emerged as an upgraded alternate to the USLE with changes in the technology for factor evaluation, only the rainfall-runoff factor of the USLE was replaced by the rainfall erosivity factor while all other parameters remain unchanged. The model predicts the long-term average annual soil loss, represented by 'A', on a field slope based on the same factors considered by USLE (Renard et al., 1997). Five (5) factors are used to calculate soil loss for a given area where each factor has a numerical output that reflects the severity of soil erosion (Jung et al., 2004). The RUSLE average annual erosion can be expressed as mass per unit area per year (tons/ha/yr) and is computed as follows (Renard et al., 1997):

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

where:

- A is annual soil loss from sheet and rill erosion in tonnes per hectare per year (t/ha/y)
- R is rainfall Erosivity factor expressed in units of MJ mm ha^{-1} h^{-1} yr^{-1}
- K is soil erodibility factor expresses in units of t/ha/h/ha^{-1}/MJ^{-1}/mm^{-1}
- LS is slope length and steepness factor
- C is cropping and management factor
- P is soil conservation factor

Core Datasets

In executing the RUSLE model, the following prerequisite datasets shown in Table 1 were obtained. For practical use of the GIS-RUSLE integration model, all factors considered by RUSLE should be converted into individual raster-based, evaluated and analysed for various factor values. Maps were digitalised from the associated datasets and then computed for each factor of the RUSLE based on the adopted methodology (shown in Figure 2).

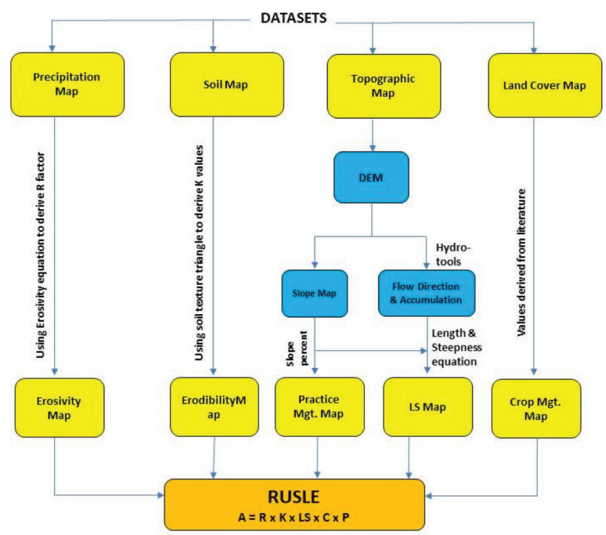

Figure 2: Flowchart depicting the methodology adopted for generating the RUSLE parameters.

Table 1: Summary of spatial datasets and sources

Data type	*Spatial data*		*Source*
	Resolution	*Time*	
Land cover	500 m	2011	LP DAAC, U.S Geological Survey (USGS). MODIS Landcover Retrieved from: http://gdex.cr.usgs.gov
Topography	1 km	-	Global Climate Data (Worldclim) Retrieved from: http://www.worldclim.org
Precipitation	1 km	1950 -2000	Global Climate Data (Worldclim) Retrieved from: http://www.worldclim.org
Soil data	30 arc-second	2009	FAO – Harmonized World Soil Database, v 1.1 Retrieved from: http://www.fao.org
Administrative Areas	-	-	GADM, version 1.0 Retrieved from: http://www.diva-gis.org

Digitalisation of Datasets

Landover

The MODIS Land Cover Type (MCD12Q1) was used in this study for analysing the land use land cover of the Himalayan region. The product incorporates five different land cover classifications derived from the Terra-and Aqua-MODIS satellite data with seventeen (17) land cover classes defined by IGBP. The MCD 12Q1 is essentially a supervised classification method of global land cover with temporal coverage from 2001 onwards. The MCD12Q1 product was first downloaded for the year 2011 and imported into the ArcGIS application where it was reclassified into eleven (11) land cover classes as representative of the study area. The results, as well as areas (in sq. km) covered by each land cover type, are depicted in Table 2.

Soil data

The Harmonized World Soil Database (HWSD) was adopted for mapping the different soil types existing within the study area. HWSD version 1.1 was downloaded from FAO public server and inserted into the ArcGIS 10.0 software. The digital dataset consisted of 16,102 soil mapping units with corresponding attribute table in MS Access format. After projecting and clipping the soil dataset to the boundaries of the study area, 25 soil types were found in the IHR based on FAO-74 and FAO-90 classification system (Table 3). The dominant soil types found within the study area include cambisols and leptosols.

Precipitation

In regions of complex topographical features and harsh climatic conditions, based on their location, the accessibility of weather stations are limited to valley bottoms (Geneletti and Dawa, 2009). Additionally, spatially distributed meteorological data were unavailable from weather stations in the IHR. Thus, to map precipitation, information on the monthly and annual precipitation for each state was extracted from the WorldClim database version 1.4 (Figure 3).

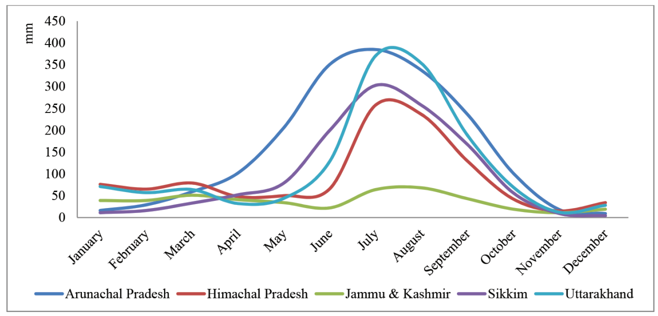

Figure 3: Average precipitation distribution derived from WorldClim Precipitation dataset.

Table 2: Area size (km^2) occupied by the different land cover classes in the Indian Himalayan Region

Land cover	*States*				
	Jammu & Kashmir	*Himachal Pradesh*	*Uttarakhand*	*Sikkim*	*Arunachal Pradesh*
Agriculture	11,266	5,406	6,856	19	522
Barren	51,434	10,272	2,333	44	190
Built-up	321	27	236	-	19
Forest	11,306	14,739	22,107	3,270	71,617
Grassland	14,688	10,750	9,612	2,481	7,221
Shrub land	776	453	381	45	667
Snow & ice	11,533	7,092	4,080	908	1,731
Water	382	282	89	9	142
Wetland	89	45	51	5	241
Woodland	1,965	4,567	6,099	194	1,730
Vegetation	2,279	2,098	1,771	238	1,584
Geographical area	101,387	55,672	53,483	7,096	83,743

Note: State-wise area covered by each land cover type was calculated based on the defined administrative areas derived from GADM spatial database version 1.0.

Table 3: Soil mapping unit symbol and State-wise spread of soils (km^2)

Soil Group	*Symbol*	*Jammu & Kashmir*	*Himachal Pradesh*	*Uttarakhand*	*Sikkim*	*Arunachal Pradesh*
Acrisols	AC	5890.23	na	na	196.56	21219.24
Alisols	AL	na	na	na	na	15517.82
Anthrosols	AT	na	na	na	na	0.25
Arenosols	AR	na	na	na	115.28	2.75
Cambisols	CM	29246.86	30268.66	25949.64	1991.09	1070.57
Ferralsols	FR	na	na	na	na	4606.61
Fluvisols	FL	535.16	279.33	2917.11	na	na
Leptosols	LP	44445.33	11136.78	17584.93	3690.59	11401.61
Luvisols	LV	3734.60	2830.83	na	na	29466.67
Nitisols	NT	na	na	na	na	5.50
Podzoluvisols	PD	na	Na	na	na	249.32
Regosols	RG	na	4428.80	4303.27	na	na
Rock Outcrop	RK	9131.69	na	218.31	na	1227.11
Water Bodies	WR	469.89	na	na	na	141.54
Glaciers	GG	12419.91	6690.97	2515.49	1188.85	510.65

Note: Rock Outcrop, Water Bodies, and Glaciers are considered non-soil areas. (na – not applicable)

Topography

Topographic modelling rely either on spatially distributed or lumped characterisation of local slope and the drainage per unit contour length, with digital elevation models (DEM) commonly used for such applied environmental application (Zhang and Montgomery, 1994). The elevation and derived topographical features used in this study area were derived from WorldClim. For maintaining consistency in the overall dataset (soil – 1 km, precipitation – 1 km, and land cover 500 m), a 30 arc-second or equivalent 1 km elevation was employed.

Results and Discussion

Individual GIS Layers

All factors considered by RUSLE were built by using various equations and values available in the literature and later aggregated using geospatial modelling in ArcGIS 10.0. The spatial output cell size resolution for each layer was downscaled to 500 m, except the Land Cover Map.

Erosivity Factor (R)

The erosivity factor is calculated as the sum of individual storm EI-values for a year averaged over 20 years to accommodate apparent cyclical rainfall patterns (Renard and Freimund, 1994). EI means energy multiplied by intensity and equals the product total storm energy (E) times the maximum 30-min intensity (I_{30}) for a given rainstorm intensity (Wischmeier and Smith, 1978). Recognising that such rainfall intensity data may not be readily available for different parts of the world, many studies were conducted at various locations across the globe in an attempt to estimate the *R*-factor as a function of mean annual precipitation (Cooper, 2011). For example, Renard and Freimund (1994) found that by segregating weather stations based on the monthly distribution of annual precipitation, the *R*-factor can be successfully achieved; thus, they proposed equations for calculating the *R*-factor based on data with the totals of annual precipitation. These equations can be expressed as follows:

$$R = 0.04830\ P^{1.610} \text{ for precipitation below 850 mm} \quad (2)$$

$$R = 587.8 - 1.219\ P + 0.004105\ P^2 \text{ for precipitation above 850 mm} \quad (3)$$

where:

R is *R*-factor in units of MJ mm ha^{-1} h^{-1} year^{-1}

P is mean annual precipitation (mm)

Equations (2) and (3) show limitations in estimating the *R*-factor with a coefficient of determination value 0.81 and 0.72, respectively. Hence, it was recommended that equation (2) can be used for locations where the mean annual precipitation is below 850 mm whereas equation (3) for locations exceeding 850 mm (Renard and Freimund, 1994). The mean annual precipitation derived from WorldClim was imported into ArcGIS and with the help of a Microsoft Excel spreadsheet, the *R*-factor was computed for all the grid cells within the study area. When equations (2) and (3) were modelled using the spatial analyst tool with the relevant constraints; the derived *R*-factor values range from 27 to 65,180 in units of MJ mm ha^{-1} h^{-1} $year^{-1}$.

Erodibility Factor (K)

The soil erodibility factor is usually determined using the empirical equations and the soil erodibility nomograph for farmland and construction sites since direct measurements of the soil erodibility factor is both costly and time-consuming (Wischmeier and Smith, 1978). The K factor for the soils found within the study area was calculated based on the following relationship (Renard et al., 1997):

$$K = [[2.1 * 10^{-4} (12 - OM) M^{1.14} + 3.25 (s - 2) + 2.5 (p - 3)]/100]/7.59 \quad (4)$$

where:

- K is SI units of t * ha * h * ha^{-1} * MJ^{-1} * mm^{-1}
- M is product of the primary size fractions: (% modified silt) × (100 – clay)
- OM is percent organic matter content
- s is soil structure code used in soil classification
- p is profile permeability class

The values of K range from 0 to 1 with the highest values for soils showing high silt content. According to HWSD data, 25 soil types exist within the study area with three non-soil types (glacier, water bodies, and rock outcrop). Due to the lack of soil particle size in the HWSD database, calculations for estimating the K-factor was carried out using the percent silt and clay. Dabral et al. (2008) conducted a similar study in North-Eastern India considering only silt and clay in calculating '*M*', where there was a negligible content of fine sand. The individual percentage of sand, silt and clay was plotted along the USDA soil texture triangle to derive soil texture within the study area. The soil textures found to be present were clay, clay loam, loam, loamy sand, sandy clay loam, sandy loam, and silt loam. The magnitude and spatial distribution of the soil erodibility factor are given in Figure 5, where the value ranges from 0.01 to 0.04. These values indicate that soil particles are moderately susceptible to detachment and produce moderate rates of runoff.

Slope Length and Steepness Factor (LS)

The LS factors considered by RUSLE, account for the effect of topography on erosion. Both slope length and steepness substantially affect the rate of rill and sheet erosion measured by RUSLE. As slope steepness and length increase so do the rate of erosion (Renard et al., 1997; Wischmeier and Smith, 1978). The LS factor computes the ratio of soil loss under given conditions to that from a field slope with the "standard" slope steepness of 9% and a slope length of 22.1 m (Geneletti and Dawa, 2009). Both the USLE and RUSLE do not include the influence of flow convergence in the LS factor. Hence, the models usually predict relatively low erosion in areas with convergent waters and higher erosion in areas where water flow is dispersed (Mitasova et al., 1996). Therefore, to incorporate the effect of flow convergence in RUSLE, a replacement of the slope length by the upslope contributing area per contour width was needed. The modified LS factor at any point on a hill slope is (Mitasova et al., 1996):

$$LS(r) = (m + 1)\left[\frac{A(r)}{22.13}\right]^m \left[\frac{\sin \beta (r)}{0.0896}\right]^n \quad (5)$$

where:

- $A(r)$ is the upslope contributing area per unit width
- $\beta(r)$ is the steepest slope angle
- r is x, y
- m, n are parameters dependent on the type of flow

Equation (5) was used to approximate the LS factor for the study area and estimation of soil loss using RUSLE. The combined LS factor was computed for the study area using ArcGIS – Arc Hydro tools and spatial analyst extension using the DEM. However, the computation of LS requires factors such as flow accumulation and slope steepness. Using the spatial analyst extension, the slope of the study area was derived from the DEM. Sinks in the DEM were then identified and filled. The filled DEM was used as an input to determine the flow direction which was used to further derive the flow accumulation using Arc hydro tools. Finally, the LS factor was computed using the raster calculator to build an expression for estimating LS based on flow accumulation and slope degree.

Cover Management and Support Practice Factor (C, P)

Cover Management factor values are assigned to land cover classes from the USLE and RUSLE guide tables or field observations. The C factor values range from 0 to 1 with the highest values reflecting standard fallow conditions. With more and more vegetation being added to the soil, the C factors approach zero (Ashiagbor et al., 2013). In this study, the land use land cover (LULC) map was derived from the MODIS global supervised land use land cover map. The reclassify land use land cover map was used in the allocation of *C* and *P* values for various land cover classes. The *C* and *P* factor values for the study area were obtained from available literature on studies conducted in the Himalayas (Dabral et al., 2008; Jain et al., 2001; Jasrotia and Singh, 2006).

State-wise Erosion Impact

The modelling of rainfall-runoff erosivity factor shows that the highest intensity and duration of the rainstorm occurs in Eastern Himalayas (Figure 4). As the topography changes from steep mountainous areas to nearly flat areas, the erosivity factor increases from 100 to just over 25000 MJ mm ha/h yr^{-1}. Figure 5 presents the results of modelling the soil erodibility. As given in Figure 6, the results indicate that the soil is easily detached within the study area by rain splash erosion or by surface runoff , which indicates that steep slopes of land would accelerate erosion. The vegetation cover management is modelled and the results are shown in Figure 7. The results indicate that vegetation has a tremendous impact on soil erosion by cushioning the effect of rainfall impact; thus, lowering rainfall kinetic energy and increasing filtration. For example, in the case of Arunachal Pradesh, the high soil erodibility is mitigated by dense and pristine forest cover.

The RUSLE model was successfully executed within the ArcGIS software to derive the average annual soil loss erosion at State and District level. Soil loss at the district level after data processing had a mean value of 363 t ha^{-1} yr^{-1}. Maximum soil loss occured in the districts of Shimla, Sirmaur, Chamba,

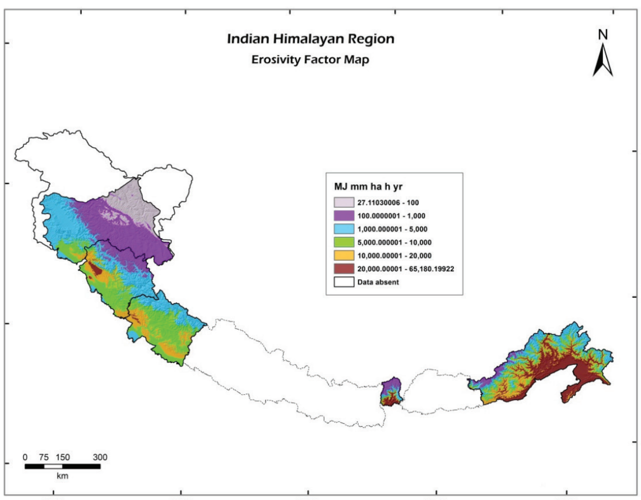

Figure 4: Spatial distribution of rainfall erosivity.

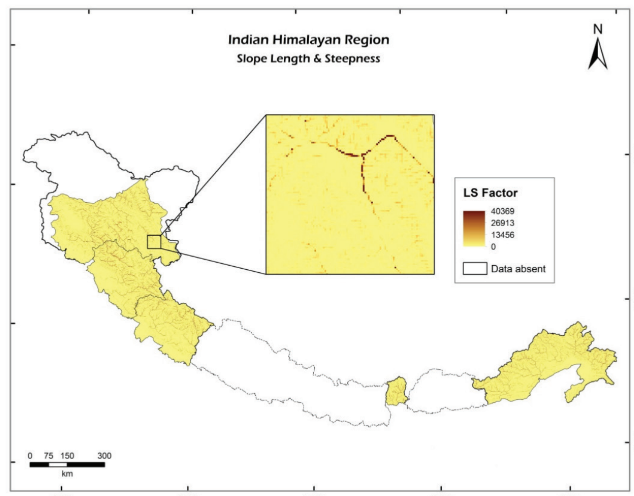

Figure 6: Spatial spread of topographic factor.

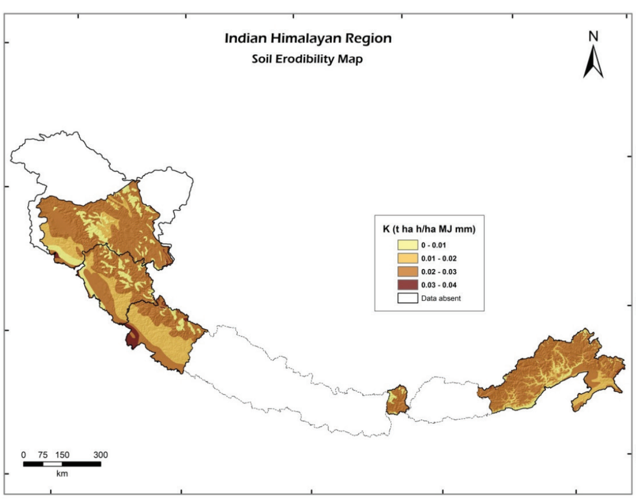

Figure 5: Soil susceptibility to runoff and rainfall.

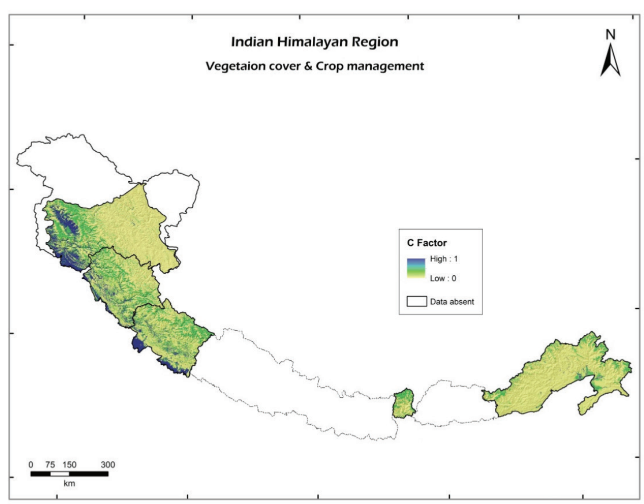

Figure 7: Spatial distribution of cover management factor.

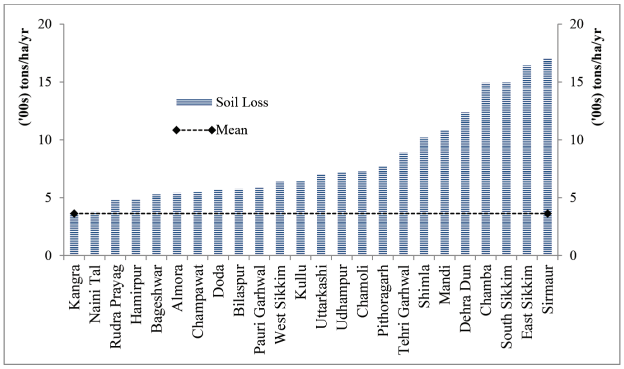

Figure 8: Erosion-prone areas requiring environmental regulations and interventions (soil erosion > mean value).

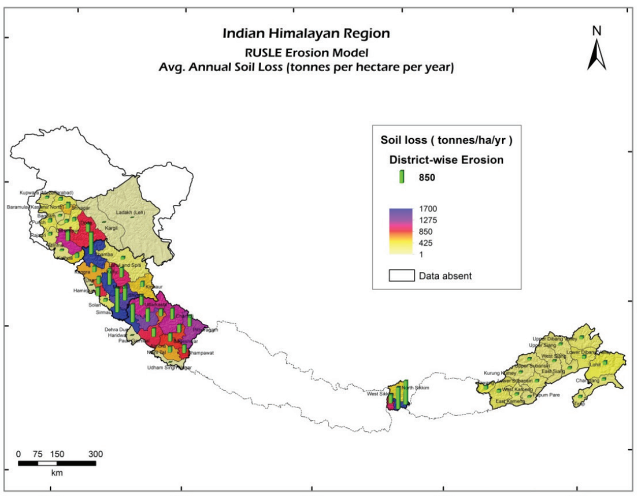

Figure 9: Spatial distribution of district-wise average annual soil loss.

and Mandi of Himachal Pradesh (see Figure 8). The Zonal Statistics tool in ArcGIS was used to extract the mean average annual soil for each district, with a derived value ranging between 1 and 1702 t ha^{-1} yr^{-1}. Figure 9 shows the average annual soil loss rate at the district level for the Indian Himalayan Region. In a study conducted by Shekinah and Saraswathy (2005), results obtained through RUSLE seems to exaggerate the results presented by Narayana, D.V. and R. Babu (1983) depicting the estimation of soil loss by water in the Himalayan Region. This analysis concludes the embedded limitations of using RUSLE in mountainous regions and shows the lack of a detailed erosion estimate in India. State-wise soil loss erosion rate is presented in Table 4. The overall spatial pattern of soil erosion rate indicates that maximum erosion takes place in the north, north-western and eastern regions of the study area while the areas in the eastern-most part of the study area show low soil erosion rates.

Conclusion

The study demonstrates the use of the RUSLE model to estimate the average annual soil loss *A* in tonnes ha^{-1} $year^{-1}$. All factors considered by RUSLE were calculated for the study area using datasets from open sources as well as ArcGIS application. Erosivity, slope length and steepness factor were modified to improve the applicability of the model in an area of mountainous terrain. The inclusion of the modified LS factor in the RUSLE is influenced by the cumulative effect of overland flow on erosivity. Based on the results generated modified RUSLE, the estimated soil loss at State-level varied from 141 to 659 tonnes ha^{-1} $year^{-1}$ and District-wise soil loss averaging between 1 and 1702 tonnes ha^{-1} $year^{-1}$. The model was built using coarse resolution data requirements, with practicality in providing annual soil loss rates for a large study area. It provides a mean to describe specific districts that are vulnerable to soil erosion and render immediate action for soil conservation practices. Additionally, the model can be implemented in regions facing similar topographic, land cover and climatic characteristics.

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Table 4: State-wise erosion assessment for the Indian Himalayan Region

State	*Geographic area in* km^2	*Mean soil loss in tons/ha/yr*	*% contribution to erosion*
Arunachal Pradesh	83,743	150	6.7
Himachal Pradesh	55,672	637	28.7
Jammu & Kashmir	101,387	141	6.4
Sikkim	7,096	659	29.7
Uttarakhand	53,483	632	28.5

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