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Research Article

A geoinformatics and RUSLE model-based soil erosion assessment in a tropical mountainous area of Chite watershed, Mizoram, India

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Abstract

Soil erosion remains a persistent menace to the sustainability of agriculture and the environment in tropical mountainous regions. Soil erosion assessment is therefore necessary to identify degraded land areas for implementing effective conservation and management strategies. Hence, this study focuses on estimating potential soil erosion and analyzing their spatial patterns in the Chite watershed, situated in the Eastern Himalayas, India, using the Revised Universal Soil Loss Equation (RUSLE) model in Geographic Information System (GIS) platform. Various datasets encompassing remote sensing, ground observations, and laboratory analysis were employed to prepare the model's input factors. The estimated mean erosion rate of the study area is 6.10 t ha^{-1} $year^{-1}$, which produces a total soil loss of about 357580.90 t $year^{-1}$. Spatial analysis reveals that about 5.79% of the watershed is under a relatively severe erosion category, contributing 70.13% of the total soil loss. Soil erosion appraisal with respect to the land use/ land cover (LULC) indicates a considerable consequence of various anthropogenic activities in the watershed. Higher rates of soil erosion are mainly observed on the bare land, cropland, and settlement areas which are characterized by steep and continuous slopes. The present findings were also validated with previous work undertaken in some comparable regions. This research can serve as a reliable tool towards the development of successful soil conservation measures and for promoting sustainable land use planning in this ecologically sensitive tropical mountainous region.

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Introduction

Soil erosion presents a significant challenge to agricultural and environmental sustainability (Mosavi et al., 2020). As a natural phenomenon, erosion has been operating steadily on the earth's surface, and the associated influence appears benign and manageable. However, it may turn into a disaster when several anthropogenic activities induce an accelerated rate of soil loss, outpacing the natural rate (Chen et al., 2021). This intensified erosion can remove massive topsoil and vital nutrients, contributing to land degradation and disrupting food security. Moreover, it can also lead to several off-site consequences, such as water pollution, floods, reduced reservoir lifespan, and interruption of the riverine ecosystem. Thus, soil erosion is a critical economic and environmental issue that has been substantially escalated by human activities during the past century (Angima et al., 2003)

Globally, mountainous watersheds in tropical regions are more prone to severe water erosion due to the intricate interplay of climate, topography, land use systems, and agricultural practices (El-Swaify, 1997; Avwunudiogba and Hudson, 2014). Likewise, the

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mountainous regions of northeast India or the eastern Himalayas are also highly vulnerable to soil erosion, as the area has delicate environmental characteristics such as rugged hilly terrain, steep slopes, copious rainfall, weak geology, etc. Coupling this fragile environment, the predominant form of land use system, i.e., shifting cultivation, along with the rapid rate of deforestation, has produced a sizable soil erosion rate, attaining about 200 t ha^{-1} $year^{-1}$ in the region (Saha et al., 2012). Consequently, water erosion has become the most prominent type of land degradation that affects 4.60 million hectares of land areas in northeastern India (Choudhury et al., 2022). Hence, assessing soil erosion becomes imperative for developing reliable strategies for soil conservation and sustainable land management.

For executing a practical assessment of soil erosion, regional information regarding the amount of soil loss and their spatial distribution is essential (Parveen and Kumar, 2012). However, due to a lack of conventional methods for soil loss estimation, such as erosion plots, field observed data are not available for most mountainous regions across the country (Prasannakumar et al., 2012). In addition, localized field measurements cannot accurately portray the spatial dynamics of soil erosion processes (Lu et al., 2004). Accordingly, soil erosion modeling emerges as a valuable approach to predicting erosion rates and identifying priority areas to address these challenges for successful conservation efforts (Karaburun, 2010).

Among various models, the Universal Soil Loss Equation (USLE) and its updated version, the Revised Universal Soil Loss Equation (RUSLE), have been the most commonly utilized erosion models globally for over 80 years. Their universal application arises from their remarkable flexibility across diverse regions worldwide and the instant accessibility of numerous data to formulate inherent factors for the model (Alewell et al., 2019). Moreover, development in remote sensing and GIS technology has significantly enhanced the capacity of the RUSLE model in estimating the soil erosion rate as well as their spatial mapping. Hence, the model, besides being originally developed for use in a temperate region, can be successfully applied in tropical mountainous watersheds with minor adjustments (Angima et al., 2003). Furthermore, they facilitated precise and cost-effective soil erosion monitoring and modeling on a watershed scale (Millward and Mersey, 1999).

The present study was conducted in the Chite watershed, Mizoram, which represents an intensively degraded watershed due to excessive alteration of the natural environment by various anthropogenic activities. These cultural influences impose prominent consequences, enhancing the possible occurrences of severe soil erosion and subsequently reducing the long-term sustainability of natural resources. Hence, this study aimed to determine the rate of soil erosion along with their spatial variability in the watershed based on the RUSLE model using GIS technology. This research is expected to provide a lucid depiction of the current soil erosion status in the watershed, contributing valuable insight that will enhance the formulation of impactful soil conservation strategies and sustainable land use planning in the region. Moreover, this research represents the first attempt to estimate soil erosion and the identification of spatially distributed erosion severity in the watershed.

Materials and Methods

Study area

The Chite watershed is drained by the Chite River, which originates at an altitude of approximately 875 meters above mean sea level (MSL). Geographically, it extends between 23º38' to 23º45' N latitudes and 92º42' to 92º47' E longitudes, covering an area of about 52.16 km^2 (Figure 1). Steep slopes characterize this tropical mountainous watershed, and almost one-third of the area has a slope inclination of above 30º. It receives a substantial amount of annual rainfall, about 2086 mm, during the south-west monsoon season. Generally, the mean temperature for the summer months may reach approximately 29º C, while it usually falls to about 17º C during the winter months. The region exhibits a young geological formation comprising sedimentary rocks that mainly comprise sandstone, siltstone, and shale. This ecologically sensitive watershed is highly urbanized, as a majority of the rapidly expanding urban areas, Aizawl city falls within its ambit. Agriculture dominates the major land use system, where shifting cultivation is the primary agricultural method, and the entire cropland covers about 22.42% of the total geographical area.

Data used and their sources

Remote sensing datasets such as Sentinel-2 image (10 m resolution) and SRTM-DEM (Shuttle Radar Topography Mission Digital Elevation Model) were acquired from the official online data portals of Copernicus, European Space Agency (ESA) and Earth Explorer, United States Geological Survey (USGS), respectively. Rainfall data were obtained from three recording stations, viz., State Meteorological Centre, Govt. of Mizoram (SMC), HQ CE (P) Pushpak, Aizawl (HQP) and BDO Office, Thingsulthliah (TBDO) (Figure 2(a)), covering a period of 12 years (2010-2021) each. Soil samples were collected through field surveys where 90 sites were selected at a regular interval of 1 km in the study area (Figure 2b). The particle size distribution of each soil sample was determined through the Bouyoucos Hydrometer Method as outlined by Motsara and Roy (2008), and the soil textural classes were identified with the USDA (United States Department of Agriculture) Soil Textural Triangle and the USDA -Soil Survey Manual handbook (USDA, 2017). A replica of soil samples was also sent to the State Soil Testing Laboratory, Aizawl, to ascertain the organic carbon content.

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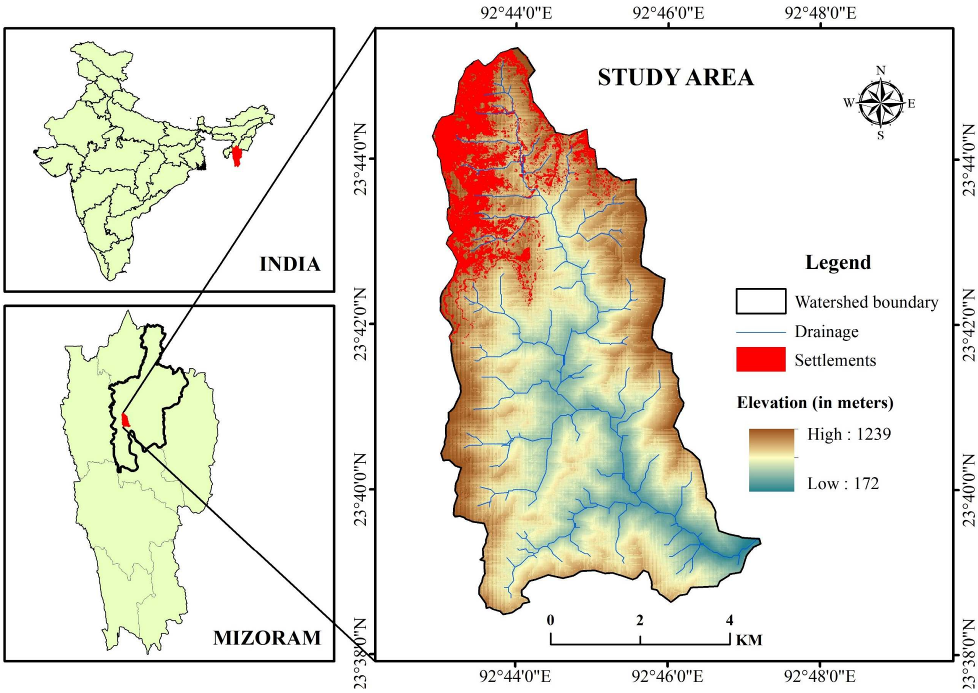

Figure 1. Location map of Chite watershed.

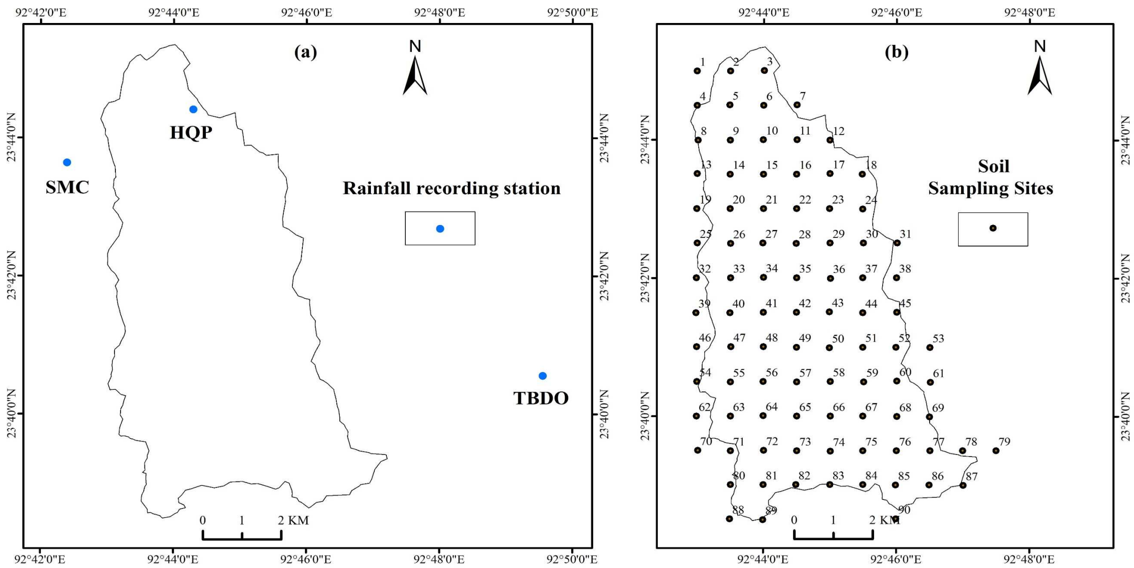

Figure 2. Location of (a) rainfall recording stations and (b) soil sampling sites.

Soil erosion modeling

The illustrated methodological flowchart represents the various datasets, thematic layers, and methodology incorporated in the present study (Figure 3). This study employed the RUSLE model (Renard et al., 1997) to quantify soil loss along with their spatial distribution in the Chite watershed. As an empirical model, the RUSLE integrates five intrinsic factors, encompassing rainfall, soil properties, topography, land cover, and several erosion conservation management practices. Therefore, thematic layers were prepared for all the factors based on remote sensing, ground observation, and laboratory-derived datasets, considering the specific watershed conditions using ArcGIS 10.4 software. Each thematic layers were multiplied in a raster calculator to produce the potential soil loss map utilizing the given equation:

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

where A = estimated mean annual soil erosion in t ha^{-1} $year^{-1}$, R = rainfall erosivity factor, K = soil erodibility factor, LS = slope length and steepness factor, C = cover management factor, and P = conservation management factor.

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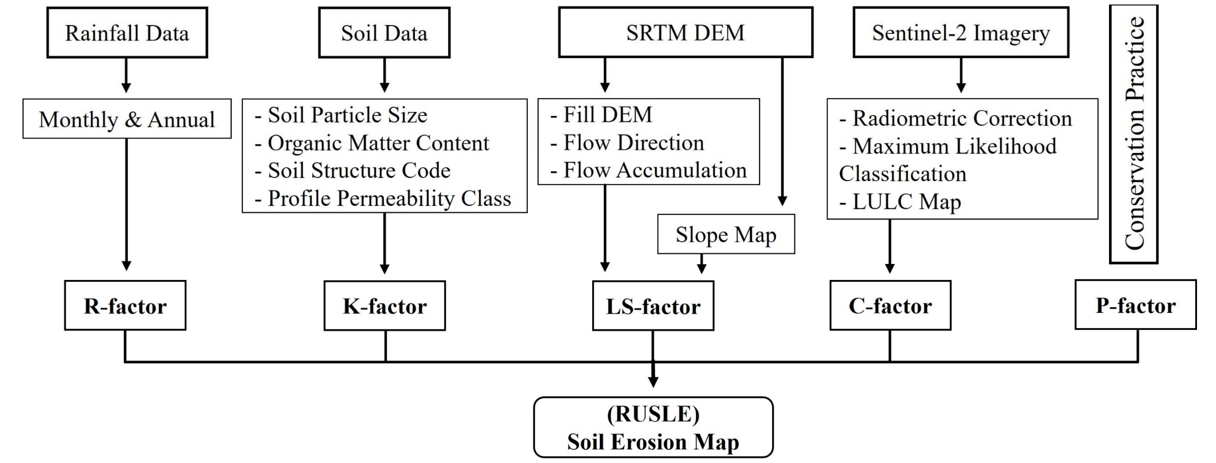

Figure 3. Methodological flowchart for soil loss estimation.

Rainfall erosivity factor (R)

This is an index to quantify the impact of rainfall towards soil erosion. Hence, its calculation requires information on the kinetic energy produced by storm events and its intensity for 30 minutes (Renard et al., 1997). As such data are scarce in many regions, monthly data as well as annual rainfall data are widely utilized to formulate the R-factor worldwide. In India, Babu et al. (2004) advanced a linear relationship for computing the R-factor value considering the regional conditions, which is as given below:

$$R = 81 + 0.38P \quad \text{For } 340 \leq P \geq 3500 \text{ mm} \tag{2}$$

Where: R = rainfall erosivity in MJ mm ha^{-1} h^{-1} $year^{-1}$, and P = average annual rainfall (mm). The R-factor map was derived through the Inverse Distance Weighted (IDW) interpolation method in ArcGIS software.

Soil erodibility factor (K)

The K-factor reveals how susceptible various soil characteristics are to erosion under specific rainfall erosivity (Millward and Mersey, 1999). It is mainly associated with diverse soil physico-chemical attributes, including soil texture, structure, permeability, and organic matter content. The K-factor was then calculated using these specific soil properties based on the nomograph prepared by Wischmeier and Smith (1978). It is the most commonly applied method and is calculated using the given mathematical expression:

$$K = [2.1 \times 10^{-4} (12 - OM) M^{1.14} + 3.25 (a - 2) + 2.5 (b-3)] / 100 \tag{3}$$

where K = soil erodibility in t h MJ^{-1} mm^{-1}, OM = organic matter content of the soil (%), M = soil particle size distribution ((% Silt + % Very fine sand) (100 - % Clay)), ‘a’ and ‘b’ = soil structural and permeability code, respectively. Here, the OM was derived by converting the organic carbon content as suggested by Pribyl (2010), while M was calculated using the analyzed particle size distribution of soil. The specific values for ‘a’ and ‘b’ were obtained from the categorization framework based on soil textural class, as highlighted by Bagarello et al. (2009) (Table 1).

Table 1. Soil structural and permeability code.

Soil textural class	‘a’	Soil textural class	‘b’
Sandy, Loamy sand and Sandy loam	1	Sandy loam, Loamy sand and Sand	2
Sandy clay, Sandy clay loam, Loam, Silt loam and Silt	2	Silt loam, Loam, Sandy clay loam	3
Clay loam and Silty clay loam	3	Clay, Silty clay loam, Clay Loam, Sandy clay and Silt	4
Clay and Silty clay	4	Silty clay	5

Source: Bagarello et al., 2009. Note: ‘a’ soil structural code, ‘b’ soil permeability code.

Slope length and steepness factor (LS)

The LS-factor plays a crucial role in estimating soil loss as it represents the influence of topography and surface run-off on the soil erosion process. Steeper slopes with longer lengths correspond to the increased amount and velocity of run-off, enhancing the chances of soil erosion (Alexakis et al., 2013). A DEM image with ample resolution is considered a dependable means for topographical analysis. Hence, the present study employs the algorithm established by Mitasova et al. (1996) using SRTM-DEM images in ArcGIS software.

$$LS = \text{Power}([\text{Flow Accumulation}] \times \text{Cell Size} / 22.13, 0.6) \times \text{Power}(\text{Sin}[\text{Slope}] \times 0.01745 / 0.0896, 1.3) \tag{4}$$

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where LS = dimensionless slope length and steepness factor, cell size is the resolution of the DEM image, Sin Slope = slope in degrees layer, and 0.01745 is the conversion factor for slope in degrees to radians. Thematic layers for flow accumulation were prepared using hydrology tools in Spatial Analyst extension, and a slope map was developed through 3D Analyst tools under the ArcGIS platform (Figures 4a and b).

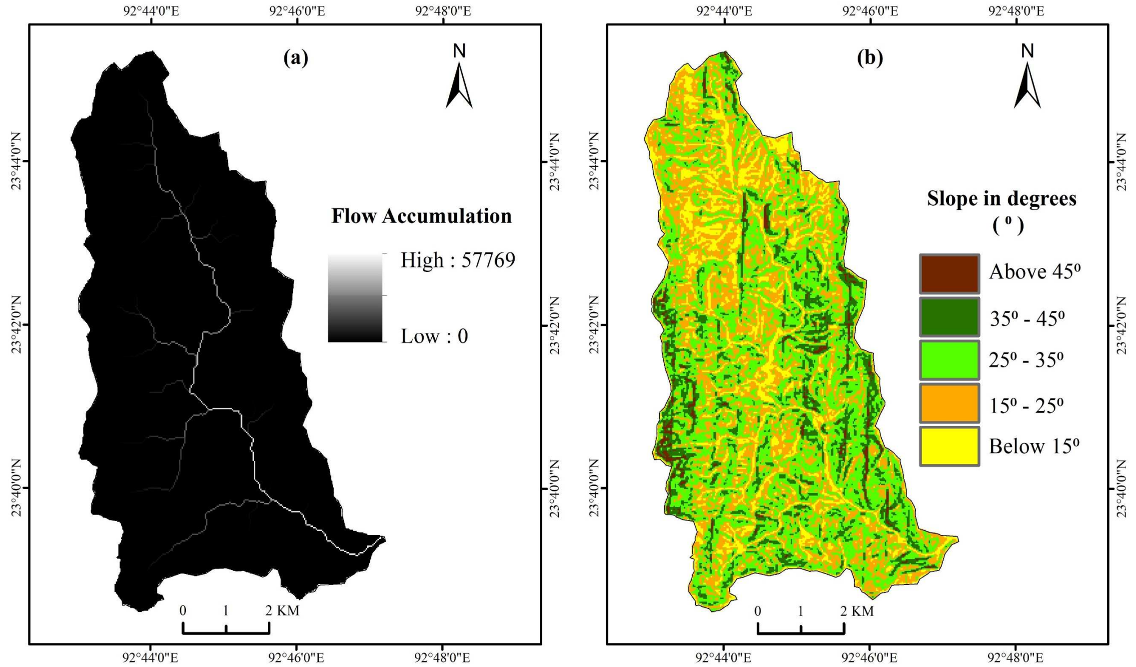

Figure 4. (a) Flow accumulation and (b) Slope (in degrees) map.

Cover management factor (C)

This factor manifests how various cropping practices and management strategies have an impact on the rates of soil erosion. In common practice, the land use/ land cover (LULC) classes are assigned their respective C-factor values, as they mainly reflect the influence of various anthropogenic activities (Karaburun, 2010). Hence, a radiometrically corrected Sentinel-2 Image was used to prepare the LULC layer through a Supervised-Maximum Likelihood Classification (MLC) method, which produced a kappa coefficient of 0.88 and an overall accuracy of 87% (Figure 5). Different LULC classes were then assigned their respective C-factor values based on several studies undertaken in India (Chatterjee et al., 2013; Biswas and Pani, 2015; Ganasri and Ramesh, 2015).

Conservation management practice factor (P)

The P-factor indicates various practices that support soil conservation, which were developed by humans and are intended to reduce soil erosion. These practices embody designs that can minimize soil removal by alleviating the amount and velocity of surface run-off. Some of the conservation support practise include contouring, terracing, strip-cropping, subterranean drainage, etc. (Renard et al., 1997). Generally, a numerical value of 1 is used to represent those areas that lack artificial structures to support soil conservation. In contrast, those areas with conservation practices are assigned lower values up to 0, depending on the adequacy of such practices implemented (Morgan, 2005). The lesser the value, the better the practices. However, due to the lack of any artificial conservation management practices developed throughout the entire watershed, the value of 1 has been adopted to represent a P-factor in the study area.

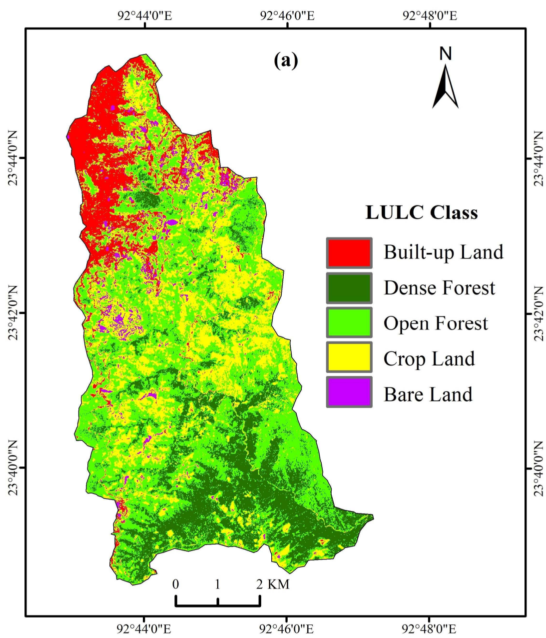

Figure 5. Land use/land cover (LULC) map.

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Results and Discussion

The RUSLE factors

The calculated R-factor in the study area ranges from 816.51 to 851.71 MJ mm ha^{-1} h^{-1} year^{-1} (Table 2). It is the single most dominant factor for soil loss estimation. However, besides the high R-factor values of the region, their spatial variability is not so significant due to the small watershed's size (Figure 6a). Soil erodibility was calculated for each identified soil textural class, and the K-factor was observed extending between 0.40 and 0.57 t h MJ^{-1} mm^{-1} (Table 3). Loamy sand has the highest K-factor and occupies the mid-eastern corner of the watershed, while fine sandy loam, sandy loam, and coarse sandy loam representing a relatively lower K value are uniformly distributed across the entire watershed (Figure 6b). On the other hand, sandy clay loam is the least erodible and occupies a small portion on the western parts of the watershed. The calculated LS-factor varies between 0 and 41.34, and about 90% of the total geographical area is observed to have a value below 0.25. Higher LS-factors are generally observed along the main river channel and its tributary streams, which are characterized by a continuous slope graduation (Figure 7a). The derived C-factor of the research area extends from 0.003 to 1 (Figure 7b). Areas with more vegetation cover, like dense forests and open forests, are well protected and, therefore, conform to a lower C-factor. At the same time, higher C-values are found in built-up land, cropland, and bare land, revealing intensive alterations of the natural environment by various anthropogenic activities. The region lacks artificial conservation practices as traditional shifting cultivation dominates the agricultural system. Consequently, the absence of such significant conservation support practices is indicated by a P-factor value of 1 (Chatterjee et al., 2013).

Table 2. Rain gauge locations, calculated average annual rainfall, and R-factor.

Stations	**Latitude**	**Longitude**	**Elevation (m)**	**Average annual rainfall (mm)**	**R-factor (MJ mm ha^{-1} h^{-1} year^{-1})**
SMC	23° 43′ N	92° 42′ E	971	2099.39	841.08
HQP	23° 44′ N	92° 44′ E	925	2128.69	851.71
TBDO	23° 42′ N	92° 51′ E	955	2031.71	816.51

Note: SMC (State Meteorological Centre), HQP (HQ CE (P) Pushpak, Aizawl) and TBDO (Thingsulthliah BDO Office).

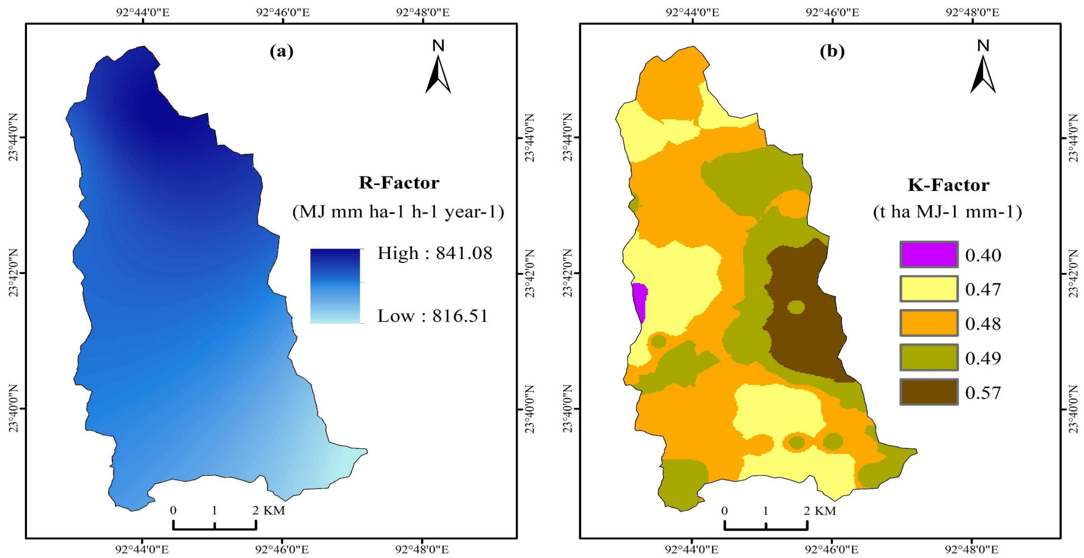

Figure 6. (a) R-factor map and (b) K-factor map.

Table 3. Determined soil properties and the calculated K-factor.

Soil textural class	**'a'**	**'b'**	**Average values**					
			Sand (%)	**Silt (%)**	**Clay (%)**	**OM (%)**	**'M'**	**'K-factor' t h MJ^{-1} mm^{-1}**
Sandy clay loam	2	3	58.98	19.09	21.93	3.21	6095.19	0.40
Fine sandy loam	1	2	57.94	31.94	10.12	3.12	8080.66	0.47
Sandy loam	1	2	62.98	28.23	8.79	3.28	8323.59	0.48
Coarse sandy loam	1	2	68.40	24.26	7.33	3.43	8588.16	0.49
Loamy sand	1	2	78.06	15.77	6.17	2.43	8804.22	0.57

Note: OM (organic matter content), 'a' (soil structural code) 'b' (soil permeability class), 'M' (particle size parameter).

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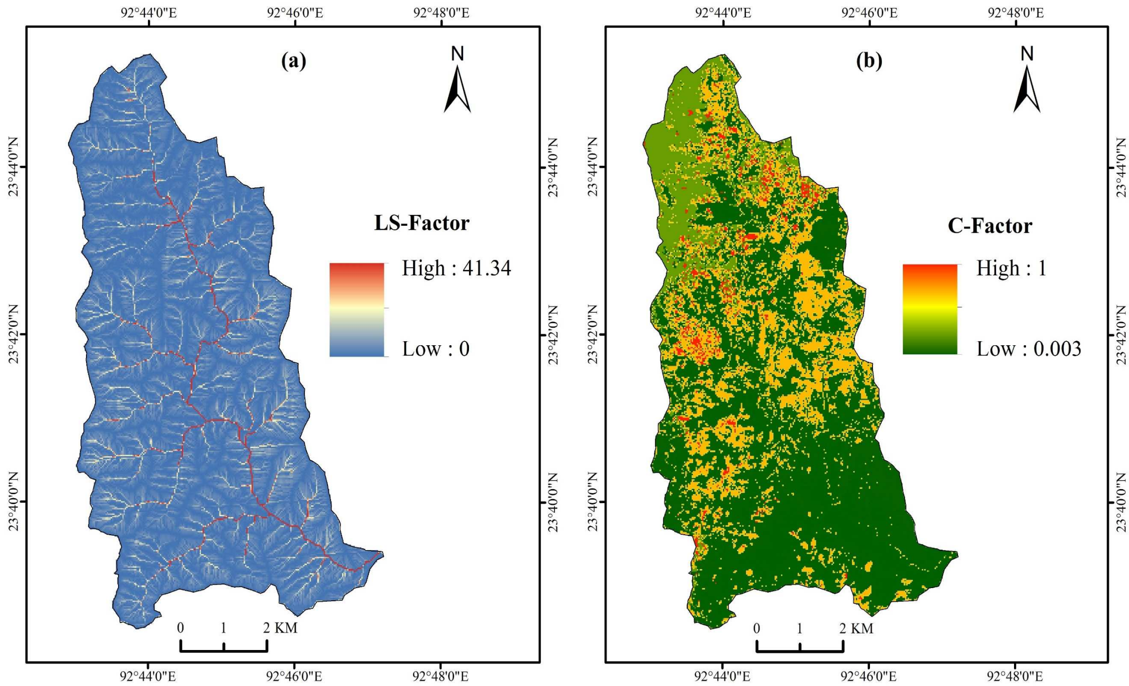

Figure 7. (a) LS-factor map and (b) C-factor map.

Estimated soil erosion and their spatial variability

The estimated mean erosion rate of the Chite watershed is about 6.10 t ha^{-1} $year^{-1}$, while the highest erosion rate reached up to 4928.90 t ha^{-1} $year^{-1}$. With a varying rate of soil erosion, the entire region generated a gross soil loss of approximately 357580.90 t $year^{-1}$. The study area is divided into five erosion categories to show the spatial distribution, following Chatterjee et al. (2013) scheme of classification (Figure 8 and Table 4).

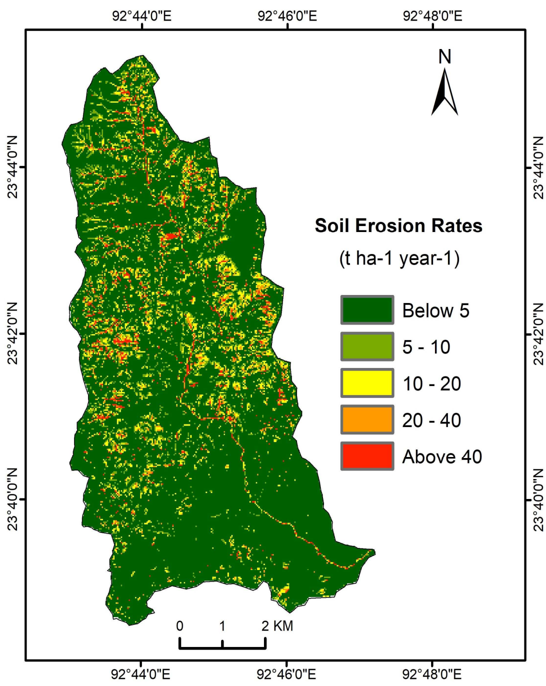

Figure 8. Soil erosion map of Chite watershed.

The area classified under very low categories is mainly observed along the gentler slope in the southern, southwestern, and northeastern parts, covering an area of about 80.51% of the watershed. The low and moderate categories correspond to 7.29% and 6.41% of the watershed area, respectively. They are mostly confined just adjacent to the areas of higher erosion rates. Those regions encountering severe and very severe categories of soil erosion rate together constitute 5.79% of the total geographical area, occupying the central as well as the northern, mid-eastern, and mid-western corners. Generally, higher erosion rates are found along higher LS-factor values, exposing the remarkable influence of topography on soil erosion. Despite their relatively smaller spatial extent, the area under the severe and very severe erosion classes accounts for a considerable soil loss of about 50,621.74 and 200,146.95 t $year^{-1}$, respectively, contributing to 70.13% of the gross soil loss from the region.

Soil erosion was also evaluated with regard to the land use/ land cover classes, as they distinctly characterize the diverse anthropogenic activities of the study area (Table 5). The mean erosion rate is found to be highest in the bare land, followed by cropland, which together occupy 25.61% of the study area, contributing about 81.52% of the total soil loss. With a comparatively lesser vegetation cover, these LULC classes are more vulnerable as the surface is directly exposed to the influence of rainfall and run-off. The bare land embodies locations for various constructions and dumping areas of earth spoils, comprising a huge quantity of unconsolidated sediments. This implies that the regions are significant sources of sediments with higher chances of rapid soil removal.

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Table 4. Estimated soil erosion and their spatial distribution in Chite watershed.

Erosion Class	Soil erosion rate ($t\ ha^{-1}\ year^{-1}$)	Gross soil loss		Area	
		($t\ year^{-1}$)	(%)	(km^2)	(%)
Very Low	<5	23,981.12	6.71	41.99	80.51
Low	5-10	30,487.26	8.53	3.80	7.29
Moderate	10-20	52,343.83	14.64	3.35	6.41
Severe	20-40	50,621.74	14.16	1.66	3.18
Very Severe	>40	200,146.95	55.97	1.36	2.61
Total		357,580.90	100	52.16	100

The majority of the cropland represents areas under shifting cultivation, where forests are completely cleared and burned away for cultivation. Thus, this unsustainable cultivation method along steep slopes is mainly attributed to generating a huge amount of soil loss from the cropland as there are no remarkable soil conservation measures carried out in the study area (Sharma, 2004). The settlement area covering 19.30% of the watershed also has high erosion rates due to the rapid rate of urbanization in the watershed, as urban land use can remarkably enhance the run-off rate, resulting in a huge amount of soil loss in an extended area (Alexakis et al., 2013). On the other hand, surface-bearing vegetation cover is comparatively well protected against soil erosion, which is identical in the case of dense and open forests, covering more than half of the study area. Plant canopies provide shields against the direct impact of raindrops, enabling adequate infiltration and reducing the erosive power of surface run-off (Conforti et al., 2014).

Table 5. Estimated soil erosion based on land use/ land cover in Chite watershed.

LULC	Area		Mean soil erosion	Standard	Gross soil loss
	(km^2)	(%)	($t\ ha^{-1}\ year^{-1}$)	Deviation	($t\ year^{-1}$)
Settlement	10.07	19.30	4.11	19.06	26,988.97
Dense Forest	22.97	44.05	0.43	2.12	4,898.96
Open Forest	5.76	11.04	1.45	27.08	34,189.47
Cropland	11.71	22.45	16.19	84.73	239,822.70
Bare Land	1.65	3.16	33.89	140.25	51,608.35

Validation

Validation becomes a challenging task in the present study, as the Chite watershed lacks field-based recorded data. However, it is necessary to verify the efficiency of a prediction model (Feizizadeh and Blaschke, 2014). Therefore, validation was carried out by comparing the present findings with previously published literature from the Eastern Himalayan regions of India that resemble similar geo-environmental conditions. A comparable soil erosion rate of 5.63 and 5.38 $t\ ha^{-1}\ year^{-1}$ was reported by Jaiswal and Amin (2020) and Kichu and Dutta (2022), respectively. In a similar study, Das et al. (2018) predicted a mean soil loss below 5 $t\ ha^{-1}\ year^{-1}$, while Chatterjee (2020) estimated an erosion rate of 3.4 $t\ ha^{-1}\ year^{-1}$. On the other hand, Dabral et al. (2008), Pandey et al. (2009), Das et al. (2020), and Barman et al. (2020) reported a comparatively higher mean erosion rate of 51, 57.06, 59.94, and 115.4 $t\ ha^{-1}\ year^{-1}$, respectively. Such an extensive disparity may be attributed to regional distinctions in the parameters as well as the varying methodology adopted while preparing these parameters. Nevertheless, comparisons from the previous studies exhibit identical results regarding the influence of various physical and cultural conditions towards the spatial variability of potential soil erosion.

Conclusion

The present study focuses on evaluating potential soil erosion along with their spatial distribution in the Chite watershed using the RUSLE model under the ArcGIS platform. In the study area, the estimated mean soil erosion rate is 6.10 $t\ ha^{-1}\ year^{-1}$. The erosion rate varies between 0 and 4,928.90 $t\ ha^{-1}\ year^{-1}$ in different parts of the watershed, resulting in a substantial soil loss of approximately 357,580.90 $t\ year^{-1}$. The entire watershed is categorized into five classes of erosion severity, ranging from very low to very severe, to recognize the spatial distribution of soil erosion. Although soil erosion of severe categories is noticeable throughout the watershed, covering 5.79% of the total geographical area, they are mostly concentrated along the central, northern, mid-eastern and mid-western corners. Besides the region's vulnerable natural environment, such as undulating topography, copious rainfall, young geology, etc., the spatial pattern of potential soil erosion has clearly depicted the significant impact of various anthropogenic activities in the study area. As distinctly apparent from the soil erosion rate in various LULC classes, large-scale deforestation, rapid urban development, unsustainable agricultural practices, and the absence of soil conservation measures are mainly

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ascribed to remarkably intensifying the process of soil erosion. Validation of the present findings with the previous works has also shown a broadly sensible consistency considering the estimation and spatial distribution of soil erosion. However, field measurements along the areas with varying spatial attributes will provide a more accurate and well-founded baseline for the model's verification in further studies. Overall, the study demonstrates the relevance of soil erosion modeling based on the RUSLE model and GIS technology in a data-scarce mountainous region of Northeastern India. Hence, the present findings will facilitate the immediate implementation of soil conservation measures and sustainable land use planning in the region.

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