

LAND USE AND CLIMATIC FACTORS IN SOIL EROSION
DYNAMICS: A CASE STUDY OF HAZARA, PAKISTAN
WITH RUSLE AND GIS

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Abstract

Soil loss was quantified along with essential erosion factors within Hazara region of Khyber Pakhtunkhwa, Pakistan using the RUSLE model through ArcGIS[™], QGIS, and Excel. Five soil loss classes were identified, with erosion rates ranging from 6.11 to 111.5 t/ha/year. Central and southwestern regions had the highest erosion due to steep slopes, high rainfall (763 MJ mm/h ha/yr), and sparse vegetation. Southern Hazara showed moderate to high erodibility (K-factor: 0.127–0.155) due to bare land, while northern areas had lower erosion risk. These findings highlight the need for immediate soil conservation and sustainable land management strategies.

Key words: soil conservation, erosion modelling, geospatial analysis, land management, environmental sustainability

Introduction. Soil serves as an essential factor for both ecological sustainability and foundation of life on earth [1]. Human activity during the initial agricultural revolution began to harm soil negatively which created soil erosion. Soil erosion stands today as a worldwide environmental problem especially in developing nations [2]. A substantial amount of land worldwide falls under the categories of fair, poor, and very poor as per global classification [3]. Widespread land degradation projected a 56% global estimate during the early 1990s while researchers assessed diverse levels of water-induced erosion across these territories [4]. Soil

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erosion generates adverse effects on both soil productivity and agricultural sustainability and causes environmental degradation by sedimentation together with pollution and flooding. The situation requires immediate attention to both erosion control measures and land conservation efforts [5].

Soil loss in the Hazara region, Pakistan becomes worse because of deforestation and negligent management practices that include vegetation removal and overgrazing which causes soil erosion along with the depletion of natural resources [6]. Vital topsoil nutrients get depleted through erosion which results in major agricultural productiveness decline and leads to changes in land use [7]. Soils lose valuable water quality attributes because of erosion which both spoils water bodies and creates harm to aquatic habitats [8]. The area has faced multiple natural disasters including the 2005 earthquake that caused significant landslides together with soil movement particularly in Mansehra and Kashmir regions [9]. Multiple monitoring systems in use for soil erosion prediction and evaluation of control measures include the Universal Soil Loss Equation (USLE) and its upgraded version (RUSLE) [10]. Global predictions of soil erosion together with land management strategies receive better insights through these predictive models as they work best when connected with Geographic Information Systems (GIS) [11]. Recent studies applying RUSLE in Pakistan estimated annual soil loss at 97.81 million t/ha in Chakwal [12], 58 t/ha in the Chitral River basin [13], and 148 t/ha in the Potohar region [14]. However, limited research has examined the combined effects of land use and climatic factors on soil erosion in Hazara. To address this gap, the present study employs RUSLE within a GIS framework to estimate annual soil loss and provide insights for sustainable land management in the region.

Geographic setup. The Hazara Region in Khyber Pakhtunkhwa (KPK) Pakistan ($33^{\circ}44' - 35^{\circ}10' \text{ N}$, $72^{\circ}35' - 74^{\circ}6' \text{ E}$) covers $17\,064 \text{ km}^2$ while having a population of approximately 6.2 million people (Fig. 1). Haripur receives the least annual rainfall of 845 mm while Balakot receives the highest of 1750 mm and these amounts fall primarily in July through August. Temperatures range from -2°C in Abbottabad during winter to 45°C in Haripur in summer. The region's soil textures include loam, silt loam, and sandy loam, supporting diverse vegetation from coniferous forests to agricultural land, which plays a critical role in water retention, nutrient availability, and soil fertility.

Materials and methods. Soil erosion, significantly influenced by rainfall, topography, soil properties, and vegetation cover, is assessed using the Revised Universal Soil Loss Equation (RUSLE) [15]:

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

where A represents annual soil loss, R is rainfall erosivity, K is soil erodibility, LS accounts for slope length and steepness, C represents land cover effects, and P reflects conservation practices. A list of the resources used in the current study are presented in Table 1, where Rainfall erosivity (R) quantifies the impact

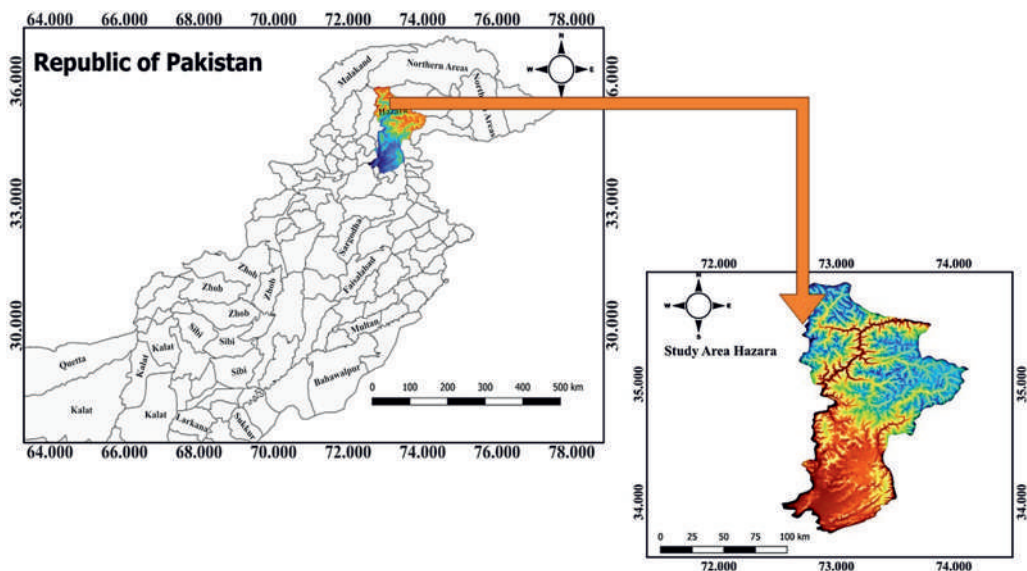


Fig. 1. Location and topographic overview of the Hazara region within Pakistan: study area highlighted with elevation gradient

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Data sources, soil properties, LULC classes, and soil erosion classification

Type	Description	Processing	Key parameters
DEM	SRTM DEM (30 m resolution)	Extract, reproject	Slope, flow direction, LS factor
Soil	FAO DSMW soil map for K factor	Extract, reproject	K values: Cambisols (0.153), Gleysols (0.160), Regosols (0.127), Lithosols (0.155)
LULC	Landsat 8, MODIS land cover classification	Atmospheric correction, reclassify	C values: Water (0), Trees (0.025), Bare (1), Rangeland (0.4), Flooded Vegetation (1), Crops (0.05)
Rain	TRMM rainfall erosivity for R factor	Extract, rasterize	Rainfall intensity, erosivity index
Erosion	Derived from RUSLE model	Classify erosion severity	Soil loss (t/ha/yr): VL (0–10, mean 6.11), L (10–30, mean 20.1), M (30–50, mean 38.4), H (50–80, mean 60.2), VH (> 80, mean 111.5)

of precipitation on soil displacement. In this study it was determined that the most suitable equation is the one which had been used in Lower Dir District,

Pakistan [16]:

$$(2) \quad R = 79 + 0.363 \times P.$$

The measurement tool utilizes P to represent precipitation intensity. Researchers applied this algorithm to measure R -factor values across each pixel centre which created detailed maps depicting the spatial effects of rainfall on soil erosion. The R -factor raster identifies assessment areas prone to increased erosion severity thus functioning as a guiding instrument for conservation planning and land management practices [17].

On the other hand, Soil erodibility (K) reflects the susceptibility of soil to erosion, influenced by physical and chemical properties. Due to data limitations, soil colour was used as a proxy, with K -values assigned based on FAO/UNESCO soil classifications. Values range from 0.127 for Eutric Regosols (least erodible) to 0.155 for Lithosols (most erodible).

The topographic factor (LS) represents the influence of slope and length on erosion. Derived from a Digital Elevation Model (DEM) in ArcGIS, LS values are computed using [18]:

$$(3) \quad LS = \left(FA \times \frac{\text{Cell size}}{22.13} \right)^{0.4} \times \left(\frac{\sin(\text{Slope of DEM} \times 0.01745)}{0.09} \right)^{1.3} \times 1.6,$$

where LS is the slope length and slope steepness factor and FA is flow accumulation. This factor highlights erosion-prone slopes.

The cover management factor (C) accounts for vegetation's protective role. Land use/land cover (LULC) maps were processed, assigning C -values based on vegetation density, soil type, and management practices. Raster conversion enabled spatial analysis of soil protection levels.

The conservation practice factor (P) reflects erosion mitigation measures. It ranges from 0 to 1, with cultivated land receiving specific values based on management practices. For non-agricultural areas, P was set to 1 due to the absence of conservation practices. By integrating these parameters, RUSLE provides a comprehensive assessment of soil erosion risk, guiding conservation planning and land management strategies.

Results and discussions. Rainfall erosivity factor. The calculated erosivity for the Hazara region (Fig. 2a) ranges from 0 to 763 MJ mm/h ha/yr. The average rainfall erosivity across the study area was 763 MJ mm/h ha/y, indicating moderate to high erosivity in certain areas. The findings revealed that rainfall variation in the region was higher in the southern region. In addition, the data showed that the R -value increased with the quantity and intensity of rainfall and decreased in areas with less rainfall. Furthermore, the northern areas of Hazara, including Kohistan, experienced higher rainfall erosivity due to intense precipitation, leading to higher R values. Consequently, these regions are at a higher risk of soil erosion.

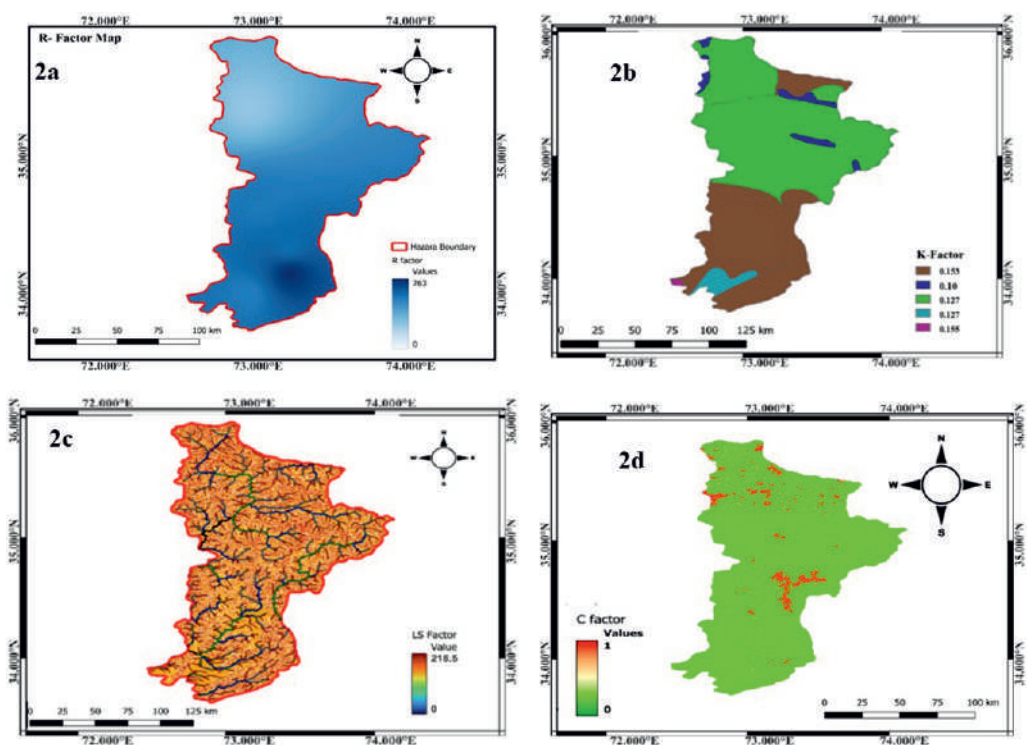


Fig. 2. Spatial distribution maps of RUSLE parameters:
(a) *R*-Factor, (b) *K*-Factor, (c) *LS*-Factor, and (d) *C*-Factor

Soil erodibility (*K*-factor). The *K*-factor (soil erodibility factor) for the Hazara region shows a range of 0.10 to 0.155 t ha h/ha MJ mm, indicating low to moderate soil erodibility (Fig. 2b). The northern regions, particularly Kohistan, exhibit lower *K* values (0.10 to 0.127), suggesting reduced vulnerability to erosion, as detailed in Table 1. Conversely, the southern areas, including Abbottabad and Haripur, display higher *K* values (0.127 to 0.155), indicating greater susceptibility to erosion due to weaker soil structure or higher permeability. This distribution highlights the importance of recognizing soil erodibility variations in determining erosion risks. The northern regions, despite having steeper slopes, are less prone to erosion due to their lower *K* values. Understanding these variations is critical for targeting effective soil conservation strategies, especially in regions with high erosion risk.

***LS*-factor (Length-Slope factor).** The Length-Slope (*LS*) factor quantifies the influence of topography on soil erosion by considering both slope length and steepness (Fig. 2c). Results showed that the Middle and Lower Hazara regions exhibit steeper slopes exceeding 13°, making them more susceptible to erosion due to increased runoff. In contrast, areas with slopes below 3° experience reduced runoff and, consequently, a lower erosion risk. The *LS*-factor map indicates *LS* values ranging from 0 in low-lying areas to a maximum of 218.5 in regions with

steeper slopes and extended slope lengths, particularly in the central and eastern parts of the study area. These elevated *LS* values highlight pronounced soil loss, emphasizing the strong correlation between slope steepness and erosion potential. Since slope is a key determinant of erosion rates, an increase in slope angle accelerates runoff and soil displacement, whereas a decrease in slope mitigates erosion by reducing runoff intensity.

Land cover management (C-factor). For this study, a Landsat ETM image (30 m resolution) was used for calculating the *C*-factor. A supervised classification technique was applied to generate the LULC map (Fig. 2d). The study area was categorized into six classes: shrublands, grasslands, croplands, urban/built-up, forest, and water bodies. The *C*-factor values for LULC were derived by utilizing NDVI values and field measurements and are presented in Table 1. The results indicated that the *C*-factor was lower in the northern and eastern areas where tree cover dominates, while higher values were observed in the southern and western regions characterized by plain soil and built-up areas. This highlights the significant role of vegetation in controlling soil erosion.

Estimation of potential soil erosion. In this study, we used GIS, remote sensing (RS), and erosion models to assess both the magnitude and spatial distribution of soil erosion in the region. We analyzed key factors that drive erosion, including rainfall erosivity, soil erodibility, slope length and steepness, land cover, and soil conservation practices. The rainfall erosivity model highlighted that higher storm intensity and duration significantly boosted the potential for erosion, as seen in Fig. 2b. Similarly, the slope length and steepness model revealed that steeper slopes tend to generate more runoff over time, which is consistent with the findings of WISCHMEIER and SMITH [19]. The role of land cover in reducing erosion was also evident. Vegetation plays a crucial role by intercepting rainfall, reducing its impact, and helping water infiltrate the soil. In Fig. 2b, the soil erodibility factor helps us understand how the vulnerability of the soil itself, combined with runoff, contributes to overall erosion. Our final soil loss model, shown in Fig. 3, reveals the annual soil erosion across the region, pinpointing areas most vulnerable to significant erosion. This model aligns with field studies from similar regions, where high levels of erosion were found to contribute to downstream sedimentation issues.

Our findings align with [20], who reported erosion rates of 40–80 t/ha/year in Hazara's forested regions, emphasizing deforestation and poor land management as key contributors. Table 1 highlights erosion susceptibility across LULC types, slope categories, and five erosion factors. Erosion rates ranged from 6.11 to 111.5 t/ha/year, affecting 20.14% of the study area. Table 1 shows minimal erosion in most land use categories, with moderate forests experiencing higher losses due to highly erodible soil and heavy rainfall.

Conclusions. This study applied the Revised Universal Soil Loss Equation (RUSLE) integrated with Remote Sensing (RS) and Geographic Information Sys-

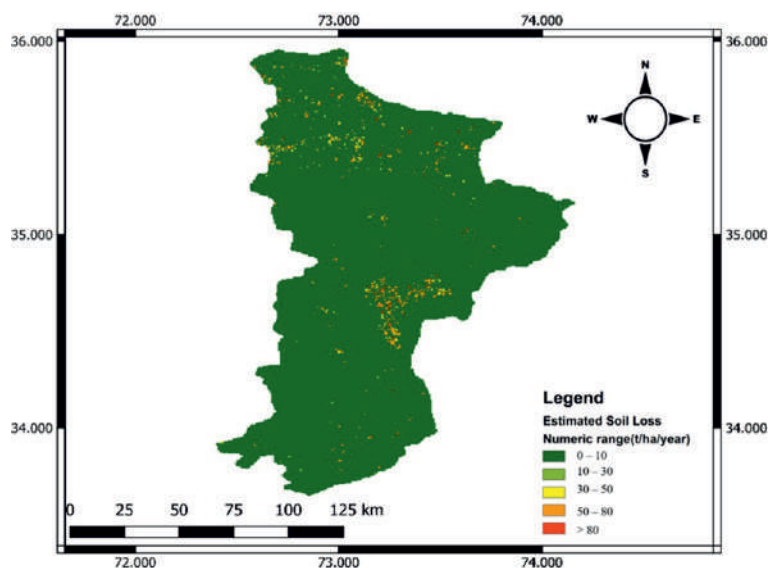


Fig. 3. The potential soil erosion map of the study area with estimated soil loss

tems (GIS) to assess soil erosion risk and identify vulnerable areas in Hazara. The results revealed erosion rates ranging from 6.11 to 111.5 t/ha/year, influenced by topography and land use/land cover (LULC). Natural forests showed the lowest erosion rates, while areas with human activity and steep slopes, particularly in intermediate forest zones, exhibited higher vulnerability. The study highlights the role of vegetation in reducing erosion and emphasizes the need for field-based validation and precise *P*-factor determination for enhanced accuracy. These findings offer valuable insights for targeted erosion control and support the development of sustainable land management strategies to mitigate soil erosion and promote environmental conservation.

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