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Land Management and Utilization
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ARTICLE

Spring Vulnerability to Environmental Degradation Necessitates Sustainable Land Management in the Khyber Pakhtunkhwa Province, Pakistan

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ABSTRACT

Environmental degradation is creating serious challenges for the spring water security in the mountainous region of South Asia. The freshwater springs meeting the growing water demands of the numerous mountain communities are under a high strain due to changing climate and land degradation in the region. The current study aims to assess the spring distribution and vulnerability to land degradation in Khyber Pakhtunkhwa province of Pakistan using geospatial modeling techniques coupled with ground information. The study revealed a total of 2564 springs with a density of about 0.06 springs/km^2 in the study area. More than fifty percent of springs were observed in the 1000–1400 mm rainfall regime, pointing towards a high influence of precipitation in recharging the springs. The mean soil loss of over 48.8 tons/ha/yr was predicted in the area, the risk of which was found to be very high (> 100 tons/ha/yr) over 12% and high (50–100 tons/ha/yr) over 8.1% of the area. Based on the land degradation analysis, over 20.4% of the springs appear to be highly vulnerable, 28.4% medium vulnerable, and 51.1% low vulnerable in the region. The restoration of the forest cover over mountain slopes and highland pastures can lessen overland flows and improve groundwater and spring resources. In-depth investigations of the hydrogeology and environmental implications could be helpful for sustainable management of the springs in the region. The study

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ARTICLE INFO
Received: 20 April 2025 | Revised: 27 May 2025 | Accepted: 3 June 2025 | Published Online: 15 June 2025
DOI: https://doi.org/10.54963/lmu.v1i2.1529

CITATION
Ashraf, A., Ahmad, I., Tahir, U., et al., 2025. Spring Vulnerability to Environmental Degradation Necessitates Sustainable Land Management in the Khyber Pakhtunkhwa Province, Pakistan. Land Management and Utilization. 1(2):65–79. DOI: https://doi.org/10.54963/lmu.v1i2.1529

would provide a base for developing viable land and water conservation strategies to improve spring water security in the region in future.

Keywords: Aquifer Recharge; Groundwater Management; Land Degradation; Spring Hydrology

1. Introduction

The water resources in the mountainous regions are under increasing pressure owing to an increasing population and the frequency of extreme climatic events [1]. Groundwater is a significant source of water supply for drinking and other uses worldwide [2], and is assumed to be more dependable than surface water [3]. Natural springs are known to support sustenance and livelihoods of many mountain communities and freshwater ecosystems, worldwide [4]. The local communities rely on the spring water for drinking and household use since they believe it to be a safer source for drinking and domestic use than surface flows [5]. The management of freshwater springs is important to achieve several Sustainable Development Goals (SDGs), such as reviving water resources (SDG-6), alleviating poverty (SDG-1), taking action against food insecurity (SDG-2), and reducing climate change effects (SDG-13) and enhancing health and well-being (SDG-3). The agriculture sector in the Khyber Pakhtunkhwa (KPK) province of Pakistan is facing poor growth performance owing to sector's main problems, such as inefficient use of surface and groundwater resources, inadequate land management and climate change. Significant efforts and investments are required in the land and water development in the province to increase agricultural growth to keep up with population growth [6]. Human activities such as deforestation, land excavation, and overexploitation, besides extreme climate events, affect the quantity and quality of the subsurface water, consequently creating food insecurity issues [7]. Land degradation owing to soil loss affects not only the soil's fertility and the water quality but also the recharge sources of groundwater and springs [8].

On a local to global level, there are knowledge gaps and a dearth of data on actual water use [9]. Even with the critical water needs, the majority of springs remain inadequately surveyed, and little is known about their conservation status [10]. Although several studies exist on spring resources of the Himalayas [11,12], currently no study has been reported on spring distribution and their response to environmental risks in this Hindu Kush region. There is a need to assess the potential of spring resources and their response to land degradation risks for future water resource management. The risk of land degradation due to soil loss can be predicted by estimating the intricate relationships between geology, topography, climate, soil, land use, and land cover [13]. A number of soil erosion modeling techniques have been developed to forecast soil erosion in highland areas and assess the movement and deposition of sediments. These equations were later modified, and numerous additional variables and factors were included. A few of the models used to study soil erosion include the Modified Universal Soil Loss Equation (MUSLE) [14], Universal Soil Loss Equation (USLE), Unit Stream Power-based Erosion Deposition (USPED) [15], and the Revised Universal Soil Loss Equation (RUSLE) [16]. A computer-based variant of the USLE is called the RUSLE, which includes a new set of guidelines and algorithms for calculating the cover factor, slope length, and steepness factors [17]. It is hypothesized that the spring distribution is influenced by several biophysical factors and land degradation risk that need to be addressed to improve spring water security in this region.

The present study aims to assess spring distribution and vulnerability to land degradation risk owing to soil erosion in the upper KPK province of Pakistan using geospatial techniques coupled with ground information. The Revised Universal Soil Loss Equation (RUSLE) model was used to evaluate the risk of soil erosion influencing mountain ecosystem in the study area. The study would provide a base for developing viable land and water conservation strategies to improve spring water security in the region in future.

2. Geographical Setup

The study area extends over 46,278 km^2 within an elevation range of 366–7,708 m in the northern half of Khyber Pakhtunkhwa province in Pakistan (**Figure 1**). The overall population is around 16.4 million persons, and there are about 2.4 million households with an average household size of about 7 [18]. The major agro-ecologies consist of northern dry mountains, sub-humid valleys, and high rainfall zone. The climate in the north is subtropical continental highland, with warm, dry summers and frigid, snowy winters. In the southern part, the climate is humid subtropical, with warm summers and chilly winters. During the summer (May to September), temperatures vary between 25 °C and 35 °C. The rainfall generally occurs within range of 400–1500 mm per annum. The summer rains are usually received during the monsoon season from June to September, whereas winter rainfall occurs from westerly systems during November to February. Majority of precipitation in the highlands is in form of snowfall that occurs during the winter season. The whole area drains into the Indus River, with the exception of the Kunhar River in Mansehra District, which drains into the Jhelum River after flowing down the Kaghan valley. The spring water meets the irrigation and household requirements of a large number of local communities who are responsible for the management and maintenance of the spring resource under their purview [5].

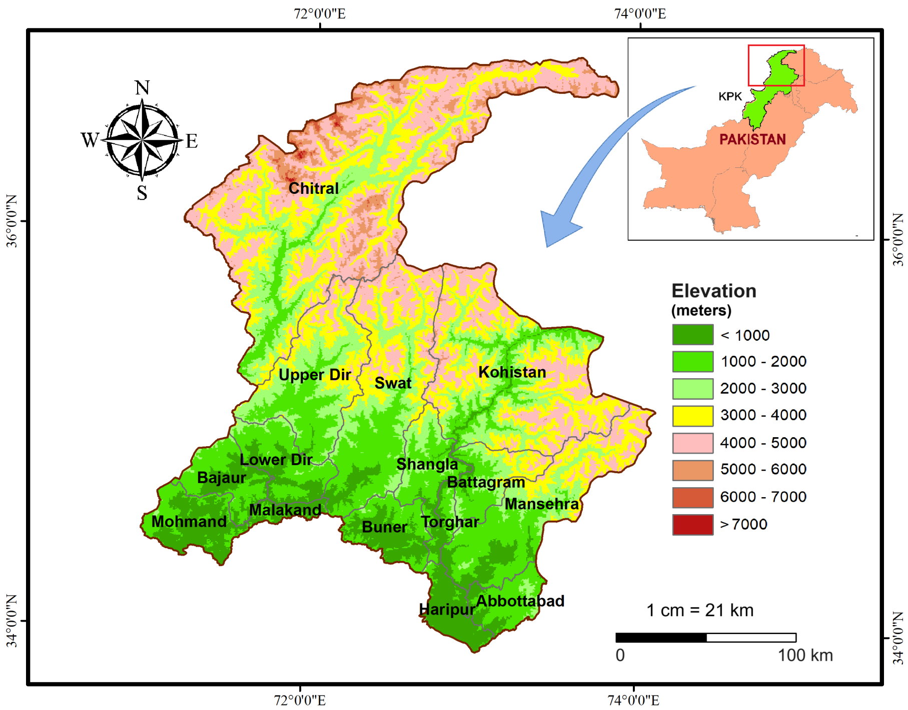

Figure 1. Study Area with Districts in the KPK Province of Pakistan.

The region is rich in biodiversity and forest resources. The coniferous forest is mostly found between 1000 and 4000 meters above sea level in the Chitral, Swat, Upper Dir, Lower Dir, Malakand, Kohistan, Mansehra, and Abbottabad districts [19]. Popular coniferous forest types include chir pine (*Pinus roxburghii*), deodar (*Cedrus deodara*), blue pine (*Pinus wallichiana*), Pindrow fir (*Abies pindrow*), and Morinda spruce (*Picea smithiana*). The subtropical dry forests, including phulai (*Acacia modesta*), kau (*Olea cuspidata*), and hopbush (*Dodonaea viscosa*) species, exist up to a height of 1,000 m in the districts of Mansehra and Abbottabad. Trees of Olive, Phulai, Dodonia, and Berberis, as undergrowth, are observed in the natural flora, which are mainly used as firewood by the local people. Two different farming systems exist here: in the leveled valley bottom like in Swat and parts of Buner, adequate water supplies are available from rain and snow, as well as surface and groundwater for irrigation. In other parts, irrigation supplies are seasonal due to harsh agro-climatic conditions, especially in parts of Shangla and Dir, groundwater plays a significant role [6]. Raising of food crops, forage and trees simultaneously on the same piece of farmland is the characteristic feature here. The primary crops grown include potatoes, wheat, barley, turnips, spinach, and various vegetables [20]. The main sources of income in the area are crop farming, livestock rearing, trade, business, employment, and tourism.

3. Geology and Hydrogeology

The geology of the area consists of igneous and metamorphic rocks mainly in the north and center, and sedimentary rocks towards south [21]. Metamorphic rocks with igneous rock intrusions make up the mountainous region. They are separated into the Kohistan sequence to the north of the Main Mantle Thrust (MMT) and the alkaline intrusion-related metasediments to the south of the MMT [22]. Major landforms include alluvial valleys, weathered bedrock, glacier moraines, and gravelly fans. The soils are somewhat deep, medium-textured, and gravelly in the valleys, and sporadic, gravelly, and well-drained on the mountain slopes. Groundwater mainly occurs in rock formations having favorable porosity and permeability. Primary porosity is typically very low in crystalline rocks, such as igneous and metamorphic complexes, unless the rock is entirely weathered at places. Secondary porosity can manifest as more or less dense joint patterns brought on by cooling or tectonism, or it can manifest as isolated fractures and fault zones. Secondary porosity by solution generally occurs in easily soluble carbonate rocks like limestone and dolomite, which are present in various parts of the area. The majority of sedimentary rocks consist of saturated zones that can be categorized as aquifers. Unconsolidated sand and gravels, permeable sedimentary rocks like limestone and sandstone, and crystalline rocks that are severely weathered or fractured are the prevalent types of aquifers in the region. The folding and faulting of the underlying rock formations in the majority of the region [23] result in patchy and irregular aquifers. Major spring types in the area include artesian springs, fracture springs, gravity/depression springs, and thermal springs [24]. Thermal springs release warm water even during severe cold winters (e.g., 'Garam Chashma' in Chitral district). There are perennial springs that run continuously throughout the year and intermittent springs that run during precipitation and snowfall seasons only. The primary recharge factors for groundwater and springs are snow precipitation, rainfall, stream and river flows, and irrigation return flows. In addition to climate change, human activities like unplanned urbanization, deforestation, and over-extraction have an impact on spring recharge. Spring discharge is affected by precipitation recharge, aquifer water pressure, and springshed size [5].

4. Data and Methodology

4.1. Preparation of Baseline Data

The thematic data of springs, landforms, land use, geology, and climate was gathered from various sources, such as the Survey of Pakistan, Geological Survey, Soil Survey Department, and Pakistani Meteorological Department, Islamabad. The GPS (global positioning system) surveys were conducted to collect land use, soil, hydrological, and socioeconomic data for the study during the 2019–2022 period. The spatial data layers of physiography, climate, landforms/soils, land use, and administrative boundaries were generated for overlay analysis in ArcGIS 10.5.1 software. The spring data was studied under different physiographic regions, slopes, district administrative units, and rainfall zones in the area. The Shuttle Radar Topography Mission (SRTM) DEM (Digital Elevation Model) data of 90 m resolution was used to create the elevation map and physiographic zones, such as high mountains (> 3000 m), middle mountains (2000–3000 m), low mountains (1200–2000 m), siwaliks (700–1200 m), and hilly areas (300–700 m) for spring distribution analysis. A slope map was developed and classified into different classes, such as > 30° (steep), 15°–30° (moderate to steep), 5°–15° (gentle to moderate), and < 5° (flat to gentle) slope for springs' association and land degradation analysis [25]. About 11% of the study area has a flat to gentle slope (< 5°), 31.8% has a gentle to moderate slope (5°–15°), 43.4% has a moderate to steep slope (15°–30°), and 13.7% has a steeper slope (> 30°).

An annual rainfall map was prepared through interpolation of rainfall data of the 1990–2019 period at the selected station using the Inverse distance weighted (IDW) method. In meteorological applications, IDW can fully comprehend the rainfall pattern through interpolation of discrete rainfall data between scattered rain gauges throughout a region [26]. IDW uses the measured values around the prediction location to predict a value for any unmeasured location and assigns higher weights to points that are closest to the prediction location. It assumes that the local influence at each measured point decreases with distance. Due to accessibility limitations in the mountainous terrain, obtaining spring discharges was challenging; therefore, approximations from earlier research conducted in this region were used. The typical spring discharge in the Himalayan region is between 0.01 and 10 liters per second, with 73% of springs having a discharge of less than 0.01 liters per second [27].

4.2. Preparation of RUSLE Input Data

The RUSLE was used in this study to evaluate the risk of soil erosion, which is a popular empirical model that has the capability to forecast the long-term average annual soil loss from sheet and rill erosion brought on by rainfall and runoff [28]. The RUSLE is a popular empirical model that has the capability to forecast the long-term average annual soil loss from sheet and rill erosion brought on by rainfall and runoff. It is a widely used tool for evaluating soil erosion, which provides decision support for sustainable landscape management in the degraded lands [29]. The factor maps of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover management (C), and conservation practice where '$flowacc$' stands for flow accumulation map and 'slope' is the slope of the area in degrees. It is predicated on the idea that soil erosion rises with slope length and steepness [36]. The cover management C-factor representing impact of cropping and management techniques on runoff and soil erosion rate, is thought to be the second most significant factor affecting soil erosion after to-
(P) were integrated in the RUSLE model following

$$A = R \times K \times LS \times C \times P \tag{1}$$

where 'A' stands for average annual soil loss in tons/ha/yr, 'R' for erosivity in MJ·mm/(ha·h yr), 'K' for soil erodibility in t·h/(MJ·mm), and slope length and steepness 'LS', cover management 'C', and support practice factor 'P' are dimensionless. The factor map layers were prepared and integrated in the GIS software to create a risk map of soil erosion. The amount of soil lost from the cultivated areas is directly related to the intensity and energy of each rainstorm event, which is represented by the rainfall erosivity (R-factor). The link between the R-factor and Fournier index as given in Equation 2 was used to compute the R-factor [30].

$$LogR = 1.93log\frac{pi^2}{P_a} - 1.52 \tag{2}$$

where 'P_a' stands for average annual rainfall and 'p_i' for monthly rainfall. The composition of sand, silt, clay, and organic matter in the soil was used to calculate the erodibility K-factor, which represents the susceptibility of soil particles to detach by rainfall and runoff water [31–33]. It is crucial to estimate the topographic element accurately since it has a very unpredictable effect on erosion [28]. Slope is one of the main determinants of the growing risk of soil loss and landslide occurrence [34]. Steeper slopes are typically more affected by soil erosion than gentler slopes. In a similar vein, longer slopes are more likely to experience erosion than shorter ones. The slope length and steepness LS factor was computed using the ArcGIS software's spatial analyst extension in accordance with Equation 3 to investigate the topography on soil erosion [35].

$$\begin{aligned}[LS] = Pow([flowacc] \times \frac{resolution}{22.1}, 0.4) \times \\ Pow\left(\frac{Sin([slope] \times 0.01745)}{0.09}, 1.4\right) \times 1.4\end{aligned} \tag{3}$$

pography [37]. The risk of high erosion rates is typically decreased by vegetation cover, which dissipates the kinetic energy of raindrops before they reach the soil surface. Although long-term field experiments are necessary for the estimation of the C-factor, the lack of experiments has led to the development of several methods in the literature to quantify the C-factor. The RUSLE model typically uses referencing studies with C-factor values for comparable land use/land cover (LULC) as direct input. The C-factor values were assigned to the LULC map, which represents the intensity of various vegetation types in the study area, as vegetation cover provides security to soil against intense rainfall conditions. Since there are no widespread preservation practices in the study area, the support practice (P) factor was given a value of 1.

Five risk classes of soil erosion were characterized, i.e., very low (< 5 tons/ha/yr), low (5–25 tons/ha/yr), moderate (25–50 tons/ha/yr), high (50–100 tons/ha/yr), and very high (> 100 tons/ha/yr)[38]. The risk of soil erosion was assessed under various slope classes, physiographic regions, land cover types, and districts of the study area. The flowchart of major steps followed in the study is shown in **Figure 2**. The risk map of soil erosion can help decision-makers create plans and strategies for reducing soil erosion risk in particular zones[17]. The vulnerability of springs was assessed based on risk of erosion, i.e., high vulnerability (risk area with > 50 tons/ha/yr erosion), medium vulnerability (area with 5–50 tons/ha/yr erosion), and low risk (area with < 5 tons/ha/yr erosion) (**Table 1**). Finally, options for restoration of the degraded lands and sustainable water resource management were identified based on ground information, literature review, and community perception.

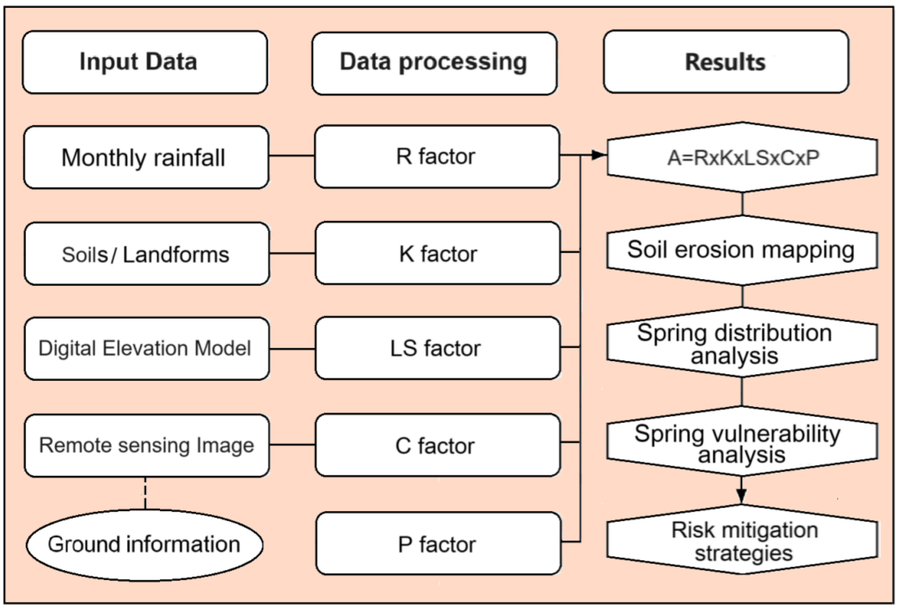

Figure 2. Major Steps Followed for Assessment of Soil Erosion Risk and Spring Vulnerability in the Study Area.

Table 1. Index of Spring Vulnerability to Land Degradation in the Study Area.

Class	Soil Erosion (tons/ha/yr)	Spring Vulnerability
1	> 50	High
2	5–50	Medium
3	< 5	Low

5. Results and Discussion

5.1. Spatial Data Analysis

The springs showed a varied distribution by physiography, LULC, slopes, and rainfall zones of the region. The maximum area is covered by the high mountains zone (i.e., about 47.1%), followed by middle mountains (18.3%) and low mountains (17.4%), while the minimum area is contributed by the hilly area (3%), followed by the Siwaliks zone (14.2%). Of the 2564 springs found in the study area, the maximum was observed in low mountains, i.e., 805, while the least number of springs were found in the hilly area, i.e., 48 (**Table 2** and **Figure 3**). The high concentration of springs observed in the low mountains is due to presence of extensive forest cover and receiving higher summer rains than other regions. About 22.7% and 28.1% springs were identified in the middle and high mountains lying north of the province, respectively. Overall, spring density was observed to be 0.06 springs/km^2 in the study area.

Table 2. Spring Distribution in Various Physiographic Regions.

Elevation (m)	Coverage		Springs		Density (Springs/km^2)
	km^2	%	Number	%	
Hilly area	1408.8	3.0	48	1.9	0.03
Siwaliks	6558.6	14.2	409	16.0	0.06
Low mountains	8044.7	17.4	805	31.4	0.10
Middle mountains	8489.4	18.3	581	22.7	0.07
High mountains	21776.5	47.1	721	28.1	0.03
Total	46278.0	100.0	2564	100.0	

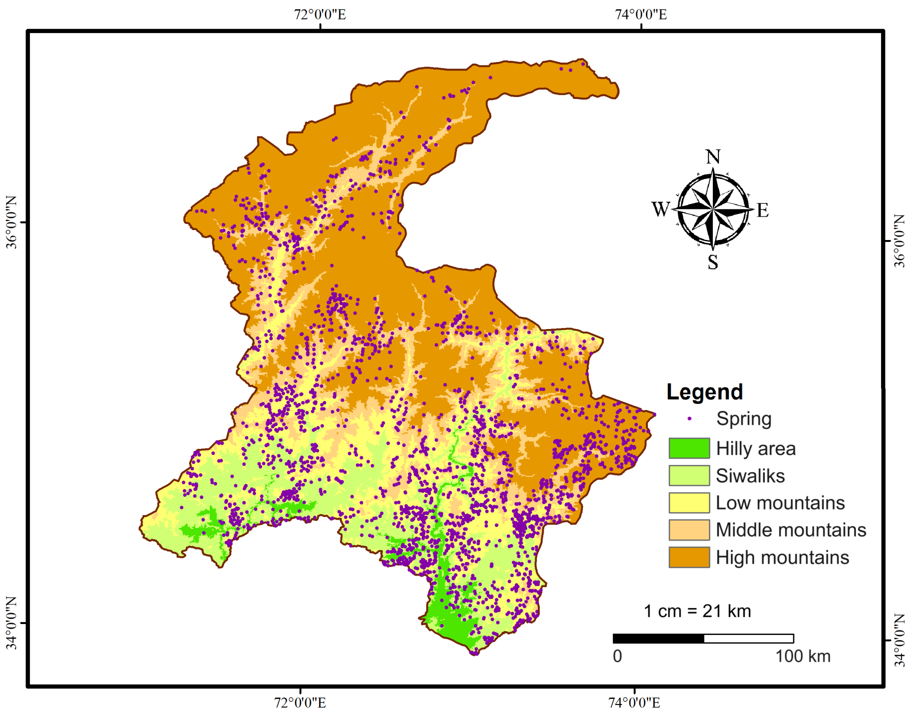

Figure 3. Spring Distribution in Different Physiographic Regions.

Major LULC types identified in the study area include 12% forest cover, 50% rangeland, and about 19% bare ground, i.e., exposed rocks/soils. About 61% of the springs were identified in the rangeland, 18.4% in the forest, and 11.1% in the exposed rocks/soils (**Table 3**). The forest class indicated a spring density of over 0.09 springs/km^2, while the rangeland exhibited a density of about 0.07 springs/km^2. The higher spring densities in the vegetation classes than in other land use types suggest that vegetation cover favors moisture conservation and recharging the spring resource.

About 7.5% (192) of the springs were found over flat to gentle slopes, 37.2% (954) over gentle to moderate slopes, 45.2% (1158) over moderate to steep slopes, and 10.1% (260) over steeper slopes. The steeper slopes can create risks of landslide, rockfall and erosion, which could have an impact on the source of spring water. There were 708 springs identified in the 1,000–1,200 mm rainfall zone, 637 in the 1,200–1,400 mm zone, and 365 in the 400–600 mm zone (**Table 4**). **Figure 4** displays the rainfall and spring distribution pattern in the study area. The spring concentration was less than 300 each in the 1,400–1,600 mm and 600–800 mm zones. The maximum spring density, i.e., 0.17 springs/km^2, was observed in the 1,400–1,600 mm zone, followed by 0.11 springs/km^2 in the 1,200–1,400 mm zone (**Figure 5**). The higher spring densities observed in the high-rainfall zones suggest a significant role for precipitation in the formation, distribution, and recharge of springs. The study of Negi and Joshi also highlighted the relation of rainfall with spring discharge in the western Himalayan region [11]. However, the complex geology, topography, climate, and surface hydrological conditions in the region all contribute to the variations in spring distribution.

Table 3. Spring Distribution in Various LULC Classes in the Study Area.

Land Use/Cover	Coverage		Springs		Density (Springs/km^2)
	km^2	%	Number	%	
Forest cover	5,534.1	12.0	473	18.4	0.09
Rangeland	23,231.3	50.2	1563	61.0	0.07
Agriculture land	1,540.5	3.3	27	1.1	0.02
Bare ground	8,848.6	19.1	285	11.1	0.03
Built-up land	2,768.2	6.0	173	6.7	0.06
Snow/glacier	4,112.2	8.9	43	1.7	0.01
Water bodies	243.2	0.5	-	-	-
Total	46,278.0	100.0	2,564	100.0	

Table 4. Spring Distribution in Various Rainfall Zones.

Rainfall (mm)	Coverage		Springs		Density (Springs/km^2)
	km^2	%	Number	%	
200–400	25.9	0.1	-	-	-
400–600	14,231.0	30.8	365	14.2	0.03
600–800	7,703.7	16.6	278	10.8	0.04
800–1,000	7,545.0	16.3	364	14.2	0.05
1000–1,200	9,796.9	21.2	708	27.6	0.07
1,200–1,400	5,701.8	12.3	637	24.8	0.11
1,400–1,600	1,273.6	2.8	212	8.3	0.17
Total	46,278.0	100.0	2,564	100.0	

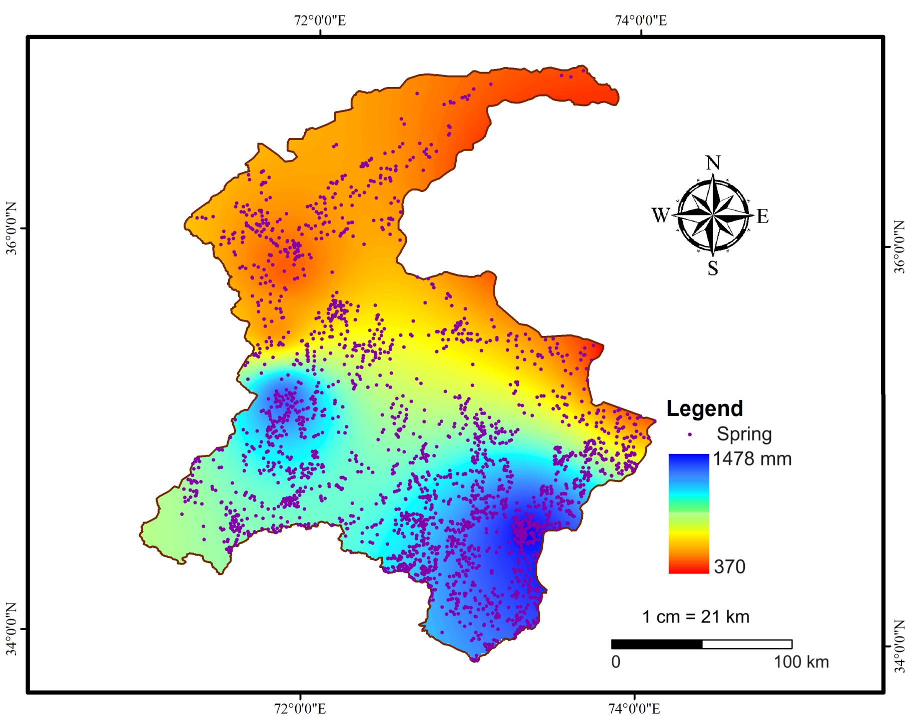

Figure 4. Spring Distribution in Variable Rainfall Pattern in the Study Area.

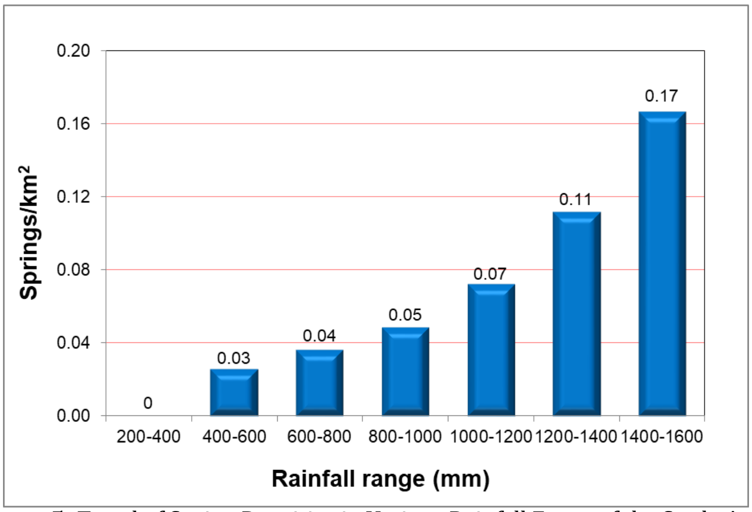

Figure 5. Trend of Spring Densities in Various Rainfall Zones of the Study Area.

5.2. Risk Assessment of Soil Erosion

The study area showed R factor values ranging between 54 and 972 MJ/ha mm/year, increasing towards the southeast (**Figure 6**). Higher R values indicate a greater capacity of rainfall to erode fields and hillslopes. The K factor values exhibited variations between 0.15 and 0.18 in the area (Higher erodibility K values indicate greater likelihood of erosion). The LS values ranged from 0 to 533 (higher values indicate a greater effect of slope length and steepness on erosion). The high mountainous terrain of the Upper Dir, Chitral, Swat, and Kohistan districts exhibited the highest LS values, which indicate greater susceptibility of the sloppy/steeper terrain to soil erosion (**Figure 6**). In accordance with Fernandez et al. and Ashraf[25,39], the C-factor values allocated to different LULC classes are as follows: forest 0.008, rangeland 0.02, agricultural land 0.13, exposed rocks/soils 0.2, built-up land 0.05, and snow/glacier and water 0.001 each. More likelihood of erosion from the corresponding LULC class is indicated by a higher C factor value.

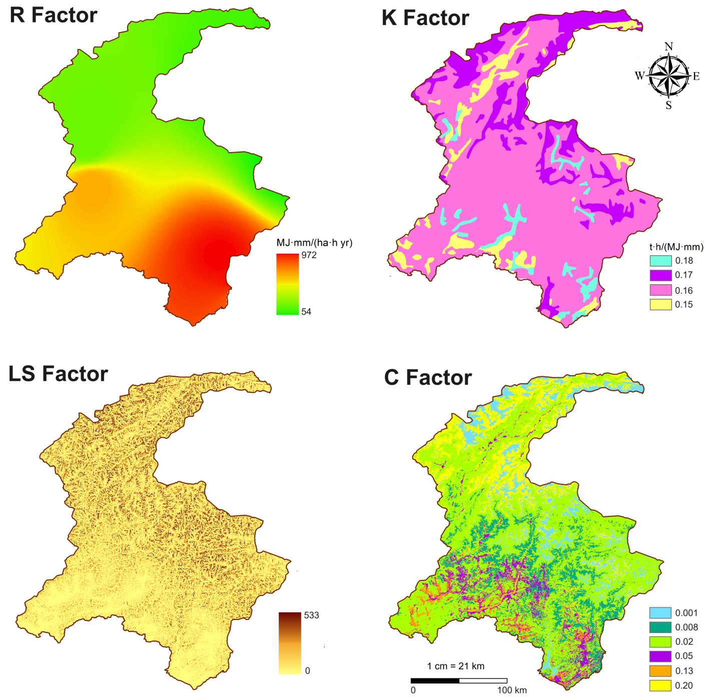

Figure 6. Input Factors of RUSLE for Predicting Soil Loss in the Study Area.

The risk of soil erosion was predicted high (50–100 tons/ha/yr) over 8.1% and very high (> 100 tons/ha/yr) over 12% of the area, with mean erosion rate of about 48.8 tons/ha/year in the study area. The low (5–25 tons/ha/yr) and very low risk (< 5 tons/ha/yr) were noticed in 15.1% and 53.6% of the area, respectively (**Table 5** and **Figure 7**). The soil erosion at an average rate of about 48.8 tons/ha/year in this area is consistent with the findings of Tariq and Mahmood [13], according to which soil loss ranges from < 50 to over 276 tons/ha/year in the Hind Kush, depending on variations in the topography and land use. Tahir et al. assessed change in average soil erosion from 26.5 tons/ha/year in 2000 to 33.7 tons/ha/year in 2023 in the Mansehra district of KPK province [40]. Joshi et al. estimated soil loss of about 25 to 42 tons/ha/year in selected watersheds of the Nepal Himalayas [41]. Whereas, George et al. predicted erosion rates from 14 to > 40 tons/ha/year (low in the high vegetation cover and high in the steeper areas) in different river basins of the Indian Himalayan region [42]. The mean soil loss was assessed over 35 tons/ha/year in the hilly area, 36.2 tons/ha/year in the Siwaliks, and 53.7 tons/ha/year in the low mountains. It was 52.3 tons/ha/year in the high mountains and 46.9 tons/ha/year in the middle mountains. The mean erosion was estimated to be more than 50 tons/ha/year in the Chitral, Shangla, and Battagram districts, and between 30 and 50 tons/ha/year in the Upper & Lower Dir, Swat, and Kohistan districts. The higher erosion rates observed in different physiographic regions and districts are likely due to the presence of less extensive vegetation cover and steep topographic terrain associated with fragile geology.

Table 5. Spring Distribution in Different Risk Zones of Soil Erosion in the Study Area.

Soil Erosion (tons/ha/y)	Risk	Area		Springs	
		km^2	%	Number	%
< 5	Very low	24,791.9	53.6	1311	51.1
5–25	Low	6,970.8	15.1	348	13.6
25–50	Moderate	5,203.8	11.2	381	14.9
50–100	High	3,766.3	8.1	271	10.6
> 100	Very high	5,545.3	12.0	253	9.9
Total		46,278.0	100.0	2,564	0.06

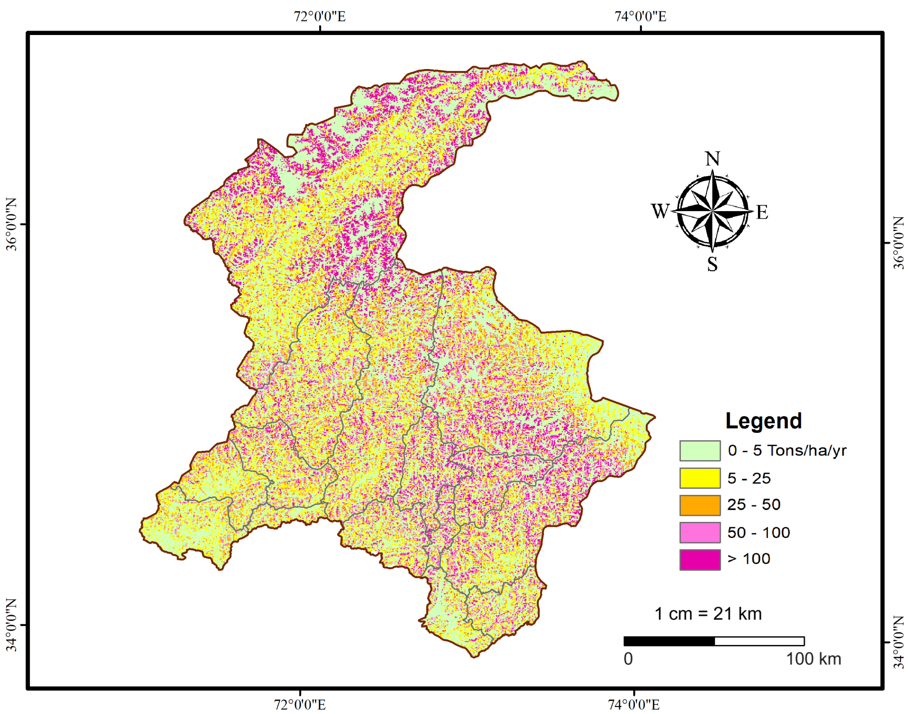

Figure 7. Soil Loss Severity in Various Districts of the Study Area.

About 51% of springs (1311) were found under the very low risk class of erosion, 13.6% (348) in the low risk class, and 14.9% (381) in the moderate risk class of erosion (**Table 5**). The percentage of springs in the high- and very-high-risk classes of soil erosion was approximately 10.6% and 9.9%, respectively. Overall, 20.4% of the springs were deemed highly vulnerable, 28.4% medium vulnerable, and 51.1% low vulnerable, per the vulnerability assessment based on the soil degradation analysis (**Table 1**).

5.3. Resource Management Options

In the past, the springs used to provide significant water security to ecosystems and dependent populations. The environmental degradation brought on by changing climate, urban developments, and overexploitation of natural resources has rapidly altered the situation. Numerous restoration initiatives were started in different parts of the world. For instance, reintroducing native tree species in Ghana, promoting farmer-managed natural regeneration in Ethiopia and Niger [43], and stabilizing terraced farmland in Rwanda by planting fruit and fodder trees [44]. In an effort to encourage conservation and enhance livelihoods, the United Nations declared 2021–2030 to be the "Decade on Ecosystem Restoration" [45]. There are currently no significant practices underway to restore the highly eroded land other than encouraging small-scale social forestry and growing farm trees in the area.

The higher risk zones of erosion are characterized by steep slopes, heavy rainfall, a dearth of vegetation, and highly erodible soils (such as silty or sandy soils with weak structure) that accelerate soil loss. The recharge source of groundwater has been diminished due to a steady reduction in coniferous and scrub forest cover and a notable increase in urban development [46]. Rainstorms typically result in significant erosion, including landslides on mountain slopes with less vegetation [47]. In severely degraded soils, a reversal might not be feasible. However, the degraded soils can be adequately restored through increasing the amount of organic matter in the soil, protecting exposed soil surfaces, improving soil structural qualities, and managing surface runoff [48]. In the medium risk zones of erosion, reforestation can potentially stop soil degradation by providing resilience against topographic and climatic effects [49]. Plantations on barren slopes can promote soil biodiversity in addition to reducing soil erosion and averting landslides [50]. In the low-risk zones of erosion, it is necessary to maintain ecosystem health, which can provide resiliency against the negative impacts of climate extremes and the risk of land degradation [51]. As the findings of this study are based on the geoinformatic analysis performed within limited time and financial resources. However, the research can be improved through conducting detailed field surveys for comprehensive planning and management of the spring resources. Future strategies and policies that need to be promoted for sustainable land and water management in this region are given as follows:

- ❖ In the wake of increasing rainfall trends observed in this region [52], an evaluation of the effects of changing climate on the springs would be helpful in spring resource management.
- ❖ Thorough hydrogeological studies coupled with effective community involvement in reviving the springs are essential for a sustainable supply of spring water.
- ❖ There is a need to find ways to improve spring water recharge and prevent water loss. Farm ponds and wetlands may be built for groundwater and spring recharge, as well as improving the ecosystem health. Proper land use planning and ecosystem management are necessary to preserve water supplies from the spring resource.
- ❖ The spring discharge may be recorded in response to precipitation and growing environmental changes to gain insight into the hydrodynamic operation of springs in the region.
- ❖ Appropriate governance and water policy may be ensured for protecting spring resources, maintaining water supplies and equitable use of spring resources.
- ❖ Improved land management techniques, such as sustainable farming methods, water management, soil conservation, rotational grazing and use of precision farming technologies are essential to mitigate negative environmental impacts in the region.
- ❖ Terrace farming and contour bunding (barriers built at the slope's edge to slow down water) should be em-

phasized for cultivation on sloping lands vulnerable to high risk of soil erosion.

- ❖ The soil's ability to retain and absorb water is reduced when forests are cleared for agriculture or urbanization. Therefore, deforestation should be controlled due to its serious negative impacts on both the environment and society.
- ❖ Capacity building of the local communities and institutions is necessary in water resource management and efficient water use.

6. Conclusions

To manage spring resources sustainably, the current study aims to assess the spatial distribution of freshwater springs and their vulnerability to land degradation in Khyber Pakhtunkhwa Province, Pakistan. A total of 2564 springs were identified in the study area, with a density of about 0.06 springs/km^2. Higher numbers of springs, i.e., 708 springs, were observed in the 1000–1200 mm rainfall zone, 637 in the 1200–1400 mm zone, and 365 in the 400–600 mm zone. The density of the springs showed a close relationship with the rainfall zones, pointing towards a high influence of precipitation in recharging the spring resource. A mean soil loss of around 48.8 tons/ha/year was anticipated in the area; the risk of this was found to be high (50–100 tons/ha/year) over 8.1% and very high (> 100 tons/ha/year) over 12% of the area. The low (5–25 tons/ha/yr) and very low (< 5 tons/ha/yr) risks were noted in 15.1% and 53.6% of the area, respectively. The high- and very-high-risk classes of soil erosion were found to include roughly 10.6% and 9.9% of springs, respectively. Based on the soil degradation analysis, over 20.4% of springs were identified as highly vulnerable, 28.4% as medium vulnerable, and 51.1% as low vulnerable in the study area.

It is essential to preserve spring water in storage tanks or ponds for household use and farming of high-value crops like fruits and vegetables, thereby promoting livelihoods and food security in the region. An increase in deforestation and urbanization is anticipated in this region, which may affect the recharge sources of groundwater and springs. A series of check dams may be constructed and plant cover maintained in the higher reaches to boost spring recharge, besides lowering sedimentation downstream. Restoring the forest cover on mountain slopes and highland pastures can lessen overland flows and replenish groundwater and spring resources. A system for documenting broad data on the patterns of spring and stream flows, water budget, and microclimate changes may be developed at the village or district level for effective water resource management. Future research is needed to effectively understand the connections between various watershed features and spring water hydrology to ensure water security in the region.

Author Contributions

Conceptualization, A.A. and I.A.; methodology, A.A.; software, I.A.; validation, U.T. and M.A.; formal analysis, A.A.; data curation, I.A. and U.T.; writing—review and editing, A.A.; supervision, A.A. All authors have read and agreed to the published version of the manuscript.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

The data is available from the corresponding author upon responsible request.

Acknowledgments

We appreciate the data support of Pakistan Meteorological Department and Soil Survey of Pakistan, and the technical support of the scientists of Climate, Energy and Water Research Institute of National Agricultural Research Centre (NARC) for the execution of this study.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Laghari, A.N., Vanham, D., Rauch, W., 2012. The Indus basin in the framework of current and future water resource management. Hydrology and Earth System Sciences. 16(4), 1063–1083. DOI: https://doi.org/10.5194/hess-16-1063-2012

[2] Guppy, L., Uyttendaele, P., Villholth, K.G., et al., 2018. Groundwater and Sustainable Development Goals: Analysis of Interlinkages. UNU-INWEH Report Series, Issue 04. United Nations University Institute for Water, Environment and Health: Hamilton, ON, Canada.

[3] Margat, J., van der Gun, J., 2013. Groundwater Around the World: A Geographic Synopsis. CRC Press Taylor & Francis Group: Boca Raton, FL, USA. pp. 1–376.

[4] Chinnasamy, P., Prathapar, S.A., 2016. Methods to investigate the hydrology of the Himalayan springs: a review. International Water Management Institute (IWMI): Colombo, Sri Lanka.

[5] Ashraf, A., Mustafa, N., 2025. Assessment of springs in different physiographic regions of Pakistan for sustainable resource development. Pakistan Journal of Geology. 9(1), 34–40.

[6] FAO, FAOLEX, 2015. Agriculture Policy-Khyber Pakhtunkhwa-A Ten Year Perspective (2015–2025). 01 Janurary 2015. Available from: https://faolex.fao.org/docs/pdf/pak173417.pdf (cited 25 July 2025).

[7] Huo, J., Peng, C., 2023. Depletion of natural resources and environmental quality: Prospects of energy use, energy imports, and economic growth hindrances. Resources Policy. 86(Part A), 104049.

[8] Rather, M.A., Kumar, J.S., Farooq, M., et al., 2017. Assessing the influence of watershed characteristics on soil erosion susceptibility of Jhelum basin in Kashmir Himalayas. Arabian Journal of Geosciences. 10(3), 59.

[9] Agarwal, A., Bhatnaga, N.K., Nema, R.K., et al., 2012. Rainfall dependence of springs in the Midwestern Himalayan Hills of Uttarakhand. Mountain Research and Development. 32(4), 446–455.

[10] Cantonati, M.L.E., Stevens, S., Segadelli, A.E., et al., 2020. Ecohydrogeology: the interdisciplinary convergence needed to improve the study and stewardship of springs and other groundwater dependent habitats, biota, and ecosystems. Ecological Indicators. 110, 105803.

[11] Negi, G.C.S., Joshi, V., 2004. Rainfall and spring discharge patterns in two small drainage catchments in the Western Himalayan Mountains, India. Environmentalist. 24(1), 19–28.

[12] Poudel, D.D., Duex, T.W., 2017. Vanishing springs in Nepalese mountains: Assessment of water sources, farmers' perceptions, and climate change adaptation. Mountain Research and Development. 37(1), 35–46.

[13] Tariq, Z., Mahmood, S., 2024. Spatial Quantification of Soil Erosion Using Rusle Approach: A Study of Eastern Hindu Kush, Pakistan. In: Mahmood, S. (ed.). Soil Erosion - Risk Modeling and Management. IntechOpen: London, UK.

[14] Smith, S.J., Williams, J.R., Menzel, R.G., et al., 1984. Prediction of sediment yield from southern plains grasslands with the modified universal soil loss equation. Journal of Range Management. 37(4), 295–297.

[15] Mitasova, H., Hofierka, J., Zlocha, M., et al., 1996. Modeling topographic potential for erosion and deposition using GIS. International Journal of Geographical Information Systems. 10(5), 629–641.

[16] Renard, K.G., Foster, G.R., Weesies, G.A., et al., 1991. RUSLE: Revised universal soil loss equation. Journal of Soil and Water Conservation. 46(1), 30–33.

[17] Khan, A., Rahman, A.U., Mahmood, S., 2023. Spatial estimation of soil erosion risk using the RUSLE model in District Swat, Eastern Hindu Kush, Pakistan. Journal of Water and Climate Change. 14(6), 1881–1899.

[18] Hussain, A., Khan, S., Liaqat, S., et al., 2022. Developing evidence based policy and programmes in Mountainous specific agriculture in Gilgit-Baltistan and Chitral Regions of Pakistan. Pakistan Journal of Agricultural Research. 35(1), 181–196.

[19] Nafees, M., Rashid, W., Sultan, H., et al., 2024. Occurrence, probable causes, and management of forest wildfires in the Northern Highlands of Pakistan. Environmental Challenges. 15, 100930.

[20] Hashmi, A.A., Shafiullah, 2003. Agriculture and food security. International Union for Conservation of Nature and Natural Resources: Gland, Switzerland. pp. 1–149.

[21] Ogasawara, M., Fukuyama, M., Siddiqui, R.H., et al., 2019. Origin of the Ordovician Mansehra granite in the NW Himalaya, Pakistan: constraints from Sr–Nd isotopic data, zircon U–Pb age and Hf isotopes. Geological Society, London, Special Publications. 481, 277–298.

[22] Kazmi, A.H., Jan, Q., 1997. Geology and Tectonics of Pakistan. Graphic Publishers: Karachi, Pakistan.

[23] Zahid, M., Ahmad, S., Ali, F., et al., 2009. Structural

geometry of a part of the Southeastern Hazara Fold-Thrust Belt, Khyber Pakhtunkhwa, Pakistan. Pakistan Journal of Hydrocarbon Research. 19, 19–28.

[24] Stevens, L.E., Schenk, E.R., Springer, A.E., 2020. Springs ecosystem classification. Ecological Applications. 31(1), e2218.

[25] Ashraf, A., 2019. Risk modeling of soil erosion under different land use and rainfall conditions in Soan river basin, sub-Himalayan region and mitigation options. Modeling Earth Systems and Environment. 6(1), 417–428.

[26] Benmoshe, N., 2025. A simple solution for the Inverse Distance Weighting Interpolation (IDW) clustering problem. Science. 7(1), 30.

[27] Pandit, A., Batelaan, O., Pandey, V.P., et al., 2024. Depleting spring sources in the Himalayas: Environmental drivers or just perception? Journal of Hydrology: Regional Studies. 53, 101752. DOI: https://doi.org/10.1016/j.ejrh.2024.101752

[28] Renard, K.G., Foster, G.R., Weesies, G.A., et al., 1997. Predicting soil erosion by water: A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). Agriculture Handbook no. 703. USDA: Washington, D.C., USA.

[29] Almouctar, M.A.S., Wu, Y., Zhao, F., et al., 2021. Soil Erosion Assessment Using the RUSLE Model and Geospatial Techniques (Remote Sensing and GIS) in South-Central Niger (Maradi Region). Water. 13(24), 3511.

[30] Arnoldous, H.M.L., 1980. An approximation of rainfall factor in the universal soil loss equation. In: De Boodt, M., Gabriels, D. (eds.). Assessment of erosion. Wiley: Chichester, UK. pp. 127–132.

[31] Gao, L., Bowker, M.A., Xu, M., et al., 2017. Biological soil crusts decrease erodibility by modifying inherent soil properties on the Loess Plateau, China. Soil Biology and Biochemistry. 105, 49–58.

[32] Williams, J.R., 1995. Chapter 25: The epic mode. In: Singh, V.P. (ed.), Computer Models of Watershed Hydrology. Water Resource Publications: Woodbridge, VA, USA. pp. 909–1000.

[33] Chuenchum, P., Xu, M., Tang, W., 2019. Estimation of Soil Erosion and Sediment Yield in the Lancang–Mekong River Using the Modified Revised Universal Soil Loss Equation and GIS Techniques. Water. 12(1), 135.

[34] Rahman, A., Khan, A.N., Collins, A.E., 2014. Analysis of landslide causes and associated damages in the Kashmir Himalayas of Pakistan. Natural Hazards. 71(1), 803–821.

[35] Moore, I.D., Turner, A.K., Wilson, J.P., et al., 1993. GIS and land-surface-subsurface process modeling. In: Goodchild, M.F. (ed.), Environmental Modeling with GIS. Oxford University Press: Oxford, UK. pp. 196–230.

[36] Rahman, S.A., Aruchamy, S., Jegankumar, R., et al., 2015. Estimation of annual average soil loss based on RUSLE Model in Kallar Water Watershed, Bhavani Basin, Tamil Nadu, India. ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences. 2, 207–214.

[37] Wischmeier, W.H., Smith, D.D., 1978. Predicting rainfall erosion losses: a guide to conservation planning (No. 537). Department of Agriculture, Science and Education Administration: Washington, D.C., USA.

[38] Ashraf, A., Ahmad, I., 2024. Evaluation of soil loss severity and ecological restoration approach for sustainable agriculture in the Hindu Kush, Karakoram and Himalaya region. Journal of Mountain Science. 21(5), 1509–1521.

[39] Fernandez, C., Wu, J., McCool, D., et al., 2003. Estimating water erosion and sediment yield with GIS, RUSLE, and SEDD. Journal of Soil and Water Conservation. 58, 128–136.

[40] Tahir, U., Ashraf, A., Arif, S., 2025. Risk assessment of soil erosion under different land use changes across the Himalayan ecosystem using GIS & RS techniques in the Rusle model. Journal of Climate and Community Development. 4(1), 139–156.

[41] Joshi, P., Adhikari, R., Bhandari, R., et al., 2023. Himalayan watersheds in Nepal record high soil erosion rates estimated using the RUSLE model and experimental erosion plots. Heliyon. 9(5), e15800.

[42] George, J.K., Kumar, S., Hole, R.M., 2021. Geospatial modelling of soil erosion and risk assessment in Indian Himalayan region—A study of Uttarakhand state. Environmental Advances. 4, 100039.

[43] Reij, C., Garrity, D., 2016. Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. Biotropica. 48(6), 834–843.

[44] Iiyama, M., Mukuralinda, A., Ndayambaje, J.D., et al., 2018. Tree-based ecosystem approaches (TBEAs) as multi-functional land management strategies—evidence from Rwanda. Sustainability. 10(5), 1360.

[45] Rao, K.S., Semwal, R.L., Ghoshal, S., et al., 2021. Participatory active restoration of communal forests in temperate Himalaya, India. Restoration Ecology. 30(1), e13486.

[46] Virk, Z.T., Khalid, B., Hussain, A., et al., 2019. Water availability, consumption and sufficiency in Himalayan towns: a case of Murree and Havellian towns from Indus River Basin, Pakistan. Water Policy. 22(S1), 46–64.

[47] Wulf, H., Bookhagen, B., Scherler, D., 2010. Seasonal precipitation gradients and their impact on fluvial sediment flux in the Northwest Himalaya. Geomorphology. 118(1–2), 13–21.

[48] Blanco-Canqui, H., Lal, R., 2010. Restoration of

Eroded and Degraded Soils. In: Principles of Soil Conservation and Management. Springer: Dordrecht, Netherlands.

[49] Firoozi, A.A., Firoozi, A.A., 2024. Water erosion processes: Mechanisms, impact, and management strategies. Results in Engineering. 24, 103237.

[50] Negi, V.S., Pathak, R., Dhyani, V., et al., 2022. Land restoration in the Himalayan Region: Steps towards biosphere integrity. Land Use Policy. 121, 106317.

[51] Dolidon, N., Hofer, T., Jansky, L., et al., 2009. Watershed and forest management for landslide risk reduction. In: Sassa, K., Canuti, P. (eds.), Landslide: Disaster Risk Reduction. Springer: Berlin & Heidelberg, Germany. pp. 633–649.

[52] Latif, Y., Yaoming, M., Yaseen, M., 2018. Spatial analysis of precipitation time series over the Upper Indus Basin. Theoretical and Applied Climatology. 131(1), 761–775.