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Research Article

GIS Based Modelling of Soil Erosion in Panjkora River Basin Using Revised Universal Soil Loss Equation (RUSLE)

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Abstract: Research work was conducted to identify the effect of soil errosion on agriculture practices in Panjkora river basin, Khyber Pakhtunkhwa, Pakistan. It is situated in the Eastern Hindu Kush mountain of Pakistan, with an area of 5905 km^2. Geo-informatics strategies (GIS) and Revised Universal Soil Loss Equation (RUSLE) were collectively applied to investigate soil degredation. The outcomes reveal that the R factor was in the range of 38.83 to 111.9 MJ mm/ha/h/year, with the minimum values in the Southeastern part, and maximum values in the northern-western part of the basin. For the entire basin, the Topographic Factor (LS) went from 1.34 to 31.20. Besides, the precarious developed slopes are isolated by groove-formed valleys and fundamentally contribute to the sediment supply in the Panjkora River Basin. The review confirms that a high pace of erosion (1-5 ton/ha/yr) is found near the riverbank which reveals that water caused excessive erosion, adversely affecting the land productivity in the agricultural area. It is suggested that viable management methodologies such as terracing, and stream banks stablization are necessary, to decrease the erosion rate in the area where the people mainly relied on agricultural activities for their livelihood.

Keywords: GIS, Remote Sensing, RUSLE, Soil Erodibility Factor, Panjkora River Basin.

1. INTRODUCTION

Globally, land degradation and soil erosion are very critical issues [1-3]. Besides, it is among the very troublesome natural issues that has expanded during the twentieth (20th) century [4, 5]. A Large number of land degradation is recorded in the Asia, Africa and south America, with a typical 30-40 ton/ha/yr making gigantic loss to the worldwide economy and agricultral productivity [6]. This phenomenan is commonly situtated more, where soil is sloping and shallow, for example the highland of Ethiopian [7]. This can prompt an irreversible loss of soil and land debasement. Not withstanding other natural issues looked by ranchers in Pakistan, the land and soil erosion are of primary concern. Moreover, the soil erosion might adversely affect the soil fertility. These issues are noted for the most part in farming area in tropical and semi dry nations. It is likewise a danger to maintainable farming creation and water quality in the region. Pakistan is dominatingly a dry-land country where 80% of its property region is dry or semi-dry and around 12% is dry sub-moist while the excess 8% is humid [8]. Around 16 million hectares (Mha) of land - 20%, in Pakistan is impacted by soil erosion while its 70% (around 11.2 Mha) is by water erosion [9]. There are different factors that largely affects soil erosion, as they are connected to land use, vegetation type, soil properties and topography etc. The flooding unfavorably affects soil fertility that subsequently eliminates the nutrient rich surface of soil, in result decreases the plant development rate. Furthermore, the more penetrable earth layers are set off to increase run off, in outcome low accessibility of water for plants development. Consequently, observing of soil erosion is significant to evaluate and assess various issue [10].

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Geographic information system (GIS) is considered to be a fundamental tool which can gives spatial soil erosion model. The previously mentioned model shows quantitative soil loss in light of erosion plots though; have a few limits like expense, representativeness, and sureness of the resultant data. This model couldn't give a spatial scattering of soil erosion loss because of the limitation of restricted samples in multifaceted conditions for a geospatial investigation of natural intricacy, possibility and unconventionality [11].

Further, utilizing these traditional techniques to evaluate the soil erosion is practically a tedious work. A number of numerical procedures and models have been attempted to estimate the soil loss [12]. Most normal and generally utilized conditions are Revised Universal Soil Loss Equation (RUSLE) and the Universal Soil Loss Equation (USLE) [13]. The RUSLE gauges that how the environment, soil, topography and land use will influence the inter-rill and rill soil erosion brought about by raindrop effect and surface overflow [14]. It has been broadly used to evaluate assess the soil erosion hazards and soil erosion loss while guide the development and protection of projects to relieve soil erosion under different land-cover circumstances [15]. Meanwhile, utilizing conventional methodologies, it is practically difficult to evaluate soil erosion at the watershed scale. While, the current methodologies for finding soil erosion regions depend on physical surveys, which are costly and time-consuming to complete projects of small scale. Soil erosion and land degradation evaluation is a complicated course of geology that requires multidisciplinary and long-term knowledge. Considering its convenience in application and closeness the digital elevation model (DEM), remote sensing data and detailed evaluation of erosion risks can be examined by utilizing GIS effectively [16]. The most recent advances in spatial information technology have expanded the applicability of current techniques. It has given efficient strategies for monitoring, management, and analysis of earth resources [15].

The primary focal point of this study is to predict the probability of soil erosion inside the Panjkora basin utilizing the Revised Universal Soil Loss Equation (RUSLE); it addresses the method for working out soil erosion for a given site by utilizing five main factors. Various parameters can be utilized to estimate the soil erosion at a specific place. In this manner, the results from the RUSLE address long-term averages more unequivocally. Because of applying GIS, we had the option to map different RUSLE parameters, which were then used to forecast the intensity of soil erosion in the basin. Moreover, a novel evaluation of soil erosion is adopted in the Panjkora River Basin for 2023 using the RUSLE model within a GIS framework. In previous research work Nasir *et al*. [17] the same area has been explored however, it has low precision due to coarse resolution data (30 meter DEM, global land cover satellite imagery), missing rainfall data for one metrological station from 1995 to 2007, and considering the onward data from 2008 to 2016 in comparison with other station's data from 1995-2016. It also neglects the integral soil erosion assessment while selecting the Equation for rainfall erosivity factor for Köppen climate classification. Moreover, the study was conducted for the year 2016 and concluded that annual soil loss in the region ranges from 0 to 3,290 tons/ha/year; however, as per the report if the topsoil is considered 15 cm then there is a maximum of 2000 tons/ha soil available [18-20], which is beyond the maximum limit of the soil available in 1 hectare. Furthermore, Raymond *et al.* [21] elaborated that the top 15 cm (approximately 6 inches) of soil in one hectare weigh around 2,000,000 kilograms (2,000 metric tons) of the maximum soil in one hectare according to Soil Bulk Density using the formula (1).

$$\text{Weight}(\text{kg}) = \text{Area}(\text{m}^2) \times \text{Depth}(\text{m}) \times \text{Bulk density}\left(\frac{\text{kg}}{\text{m}^3}\right) \quad (1)$$

Therefore, the results of Nasir *et al.* [17] seem to be ambiguous. Furthermore, the work on national-scale studies [22], suffers from coarse resolution (500 meter for land cover and 1 km resampled resolution for other parameters) that is unsuitable for the basin's hilly terrain. In contrast, this research employs high-resolution satellite imagery (10 meters spatial resolution) and a finer DEM (2.5 meter) for a more precise analysis. Unlike the previous study, it incorporates the Köppen climate classification for rainfall erosivity using Equation (2) Jain *et al.* [23].

$$R = 81.5 + 0.3P \quad (2)$$

It validates the model's results with detailed field surveys and data collected for sediment discharge at Zulüm Bridge. This focus on high-resolution data, detailed climate considerations, and field validation provides a more accurate and localized assessment of soil erosion in the Panjkora River Basin compared to previous studies.

1.1. Study Area

This study is conducted in the Mountainous Range of Hindukush, in the North-West of Pakistan, that covers an area of 5905 km^2. It stretches at the North Latitude 34°39′30″ to 35°47′17″ and 71°13′8″ to 72°22′13″East longitude. Panjkora River is a significant tributary of the Swat River, a narrow gorge prompts Khal, where it streams toward the south. Nonetheless, downstream from Khal, the stream enters a wide valley. The river passes from the centre of "Dir Valley". The name Panjkora is a blend of two words, "Panj" and "Khwar" that implies to five streams. The name Panjkora is given to the river since it is a blend of five significant streams to be specific, the Barawal stream, Sheringal, Gwaldai, and Kohistan streams. The Panjkora River is joined by a somewhat larger drainage region than the Swat River. Indeed, the stream makes a sharp twist toward the south and enters a little canyon. After arriving at Munda Head Works, it disperses across the plains of the Peshawar Basin. The records of Amandara gauge station suggest a typical summer release of 4,488 cusecs while a colder time of year release of 932 cusecs. The geology of the basin is overwhelmed by the hill and mountains that are the portion of the reaches/part of the Hindu-Kush. The mountain ranges, have some high peaks in the basin where it exceeds than 7,690 meters in level.

The central area elevation varies from 3,000 to 2,000 meters in height. In the south, at the juncture of the Panjkora and Swat streams, the height declines rapidly to about 600 meters. The ranges have mostly been cut by the Panjkora River and its tributaries. It is these narrow gorges that most people reside in and raise agriculture. There is plenty of water in the rivers and nallahs, but is not calm to use for irrigation because the mountains are on either side of the river banks. The majority of the area is rugged. The farming occurs on mound slopes and in the gorges. Wheat, maize, and rice are the principal crops grown in the Basin. Fruits and vegetables of many varieties are also grown. The weather of the basin in the summer is mild and warm during the day and cold during the night in the north of the basin. June and July are very hot months in the central and southern areas of the basin. In June, the mean limit and extreme temperature were recorded at 32.52 °C and 15.67 °C, respectively. During the spring season, the hurricane from Lowari Top known as Badama, emerges in the evening making the weather hard and unendurable. The colder season is cold and unadorned. The temperature quickly decreases in November and onward. December, January, and February are freezing months when the temperature decreases near or below to freezing point with 3 to 11 feet of snowfall on high mountains. The mean limit and extreme temperature in January were noted as –10 °C to 11.22 °C. The study area is highlighted in Figure 1.

The purpose of this research is the Spatio-temporal analysis of soil erosion in the Panjkora River Basin. To identify its effect on farming practices in the study area and to limit its effects. In the future, it would provide insight for government and non-government organizations dealing with soil erosion, particularly in Khyber Pakhtunkhwa.

More than 80 percent of the global agricultural land experiences moderate to severe erosion, leading to productivity loss, as well as an array of environmental concerns [24]. This erosion has also been proven as a danger to sustainable agriculture production as well as water quality. Determining the extant of soil erosion problems requires a quantitative evaluation to develop appropriate management styles.

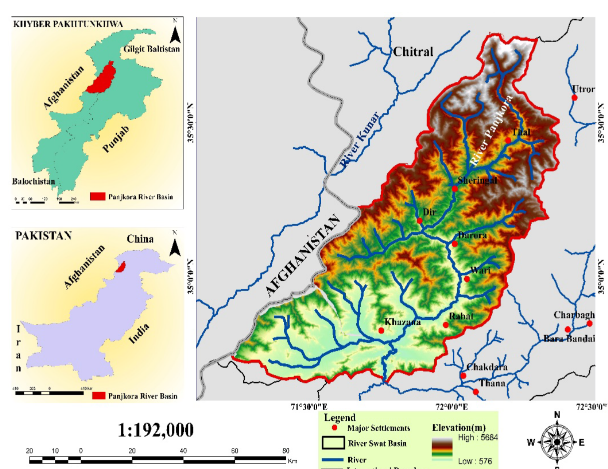

Fig. 1. Study area map (Panjkora River Basin).

2. MATERIALS AND METHODS

2.1. Data Set

Data collected from primary as well as secondary data sources were exported to the ArcGIS Platform for RUSLE model parameters, that are LS factor (Steepness Factor and Slop Length), R factor (the rainfall-runoff erosivity factor), K factor (soil erodibility factor), C factor (cover-management factor) and P factor (support practice factor). DEM (digital elevation model) was generated from Google Earth. The slope for the study area was generated from DEM. Flow direction and flow accumulation were generated through DEM for the extraction of the LS factor. The slope was converted to a vector; grid codes were merged, based on % slope values of the P factor [25] to obtain the P factor Map. Rainfall data from PMD (Pakistan Metrological Department) was obtained from the metrological station within the river basin and the R factor was generated. K factor was calculated from Digital Soil Map of World (DSMW) Food and Agriculture Organization, United Nations. The classified imagery was converted to polygon, gird codes of each land use class were merged to 9 grid codes as per land use classes, and a Cover management factor was generated.

2.2. RUSLE Parameters

By manual digitization and control passage, the data and their associated properties for the model were input into ArcGIS. With a grid cell design data sources were coordinated into ArcGIS. Each portrayed cell (pixel) had a unique region, in space fixed on by grid orientation. To process the review region of the potential erosion rate for the area-weighted mean, the zonal statistical tool was utilized. In the following segment subtleties on processing strategies and on data under particular (RUSLE) factors are given.

Topographic Factor (LS): also known as Steepness Factor (LS) and Slope Length, mirrors the influence of geography on soil erosion. Higher overland stream speed is caused by the incline length and a rising slope, consequently increasing the soil erosion [26]. The detail is shown pictorialy in Figure 2. The LS factor was developed as follows using Equation (3) in raster calculator:

$$LS = (\text{Flow Accumulation} \times 1.375)^{0.5} \times (0.065 + 0.045 \times \text{Slope} + 0.0065 \times (\text{Slope} \times \text{Slope})) \quad (3)$$

In this study a consistent (m) of 0.5 was utilized in above Equation, because of the mean slope more noteworthy than 25% (15°) noticed for the survey area [27].

Support Practice Factor (P): it refers to the soil Conservation Practices carried out to lighten soil erosion. Contour cultivating, terracing, and strip trimming are the ordinarily indexed and archived control measures (Table 1) [28]. It range from 0 to 1, 0 addresses a generally excellent human-centered erosion resistance facility, and one demonstrates a non-human-centered resistance erosion facility. The P factor is illustrated in Figure 3.

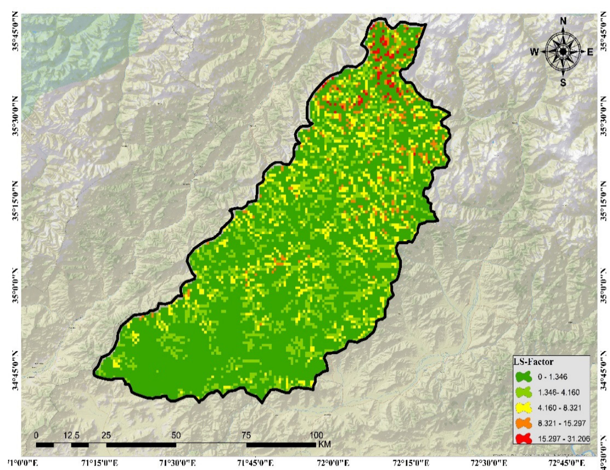

Fig. 2. Slope length and steepness LS-factor of Panjkora River Basin.

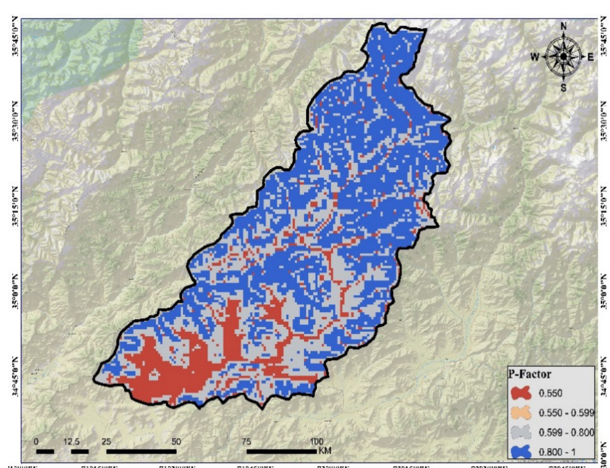

Fig. 3. Shows support practice (P-Factor) of Panjkora River Basin.

Table 1. Support practice factor values as per soil conservation practice [28].

Slop (percent)	Strip cropping	Contour cropping	Terrace cropping	
			Bench	Croad-based
0-7.0	0.27	0.55	0.10	0.12
7.0-11.3	0.30	0.60	0.10	0.12
11.3-17.6	0.40	0.80	0.10	0.16
17.6-26.8	0.45	0.90	0.12	0.18
>26.8	0.50	1.00	0.14	0.20

Cover Management Factor (C): it addresses the soil erosion proportion from land tillaged under specific circumstances. It concludes how normal vegetation or yield cover reduces precipitation energy and overflow or captures precipitation energy and increments penetration. It is the second most critical element near precipitation erosivity and topography that controls the threat of soil erosion [29]. The Figure 4 shows Land Use Land Cover map of the study area while the Figure 5 illustrates C factor map for the study area.

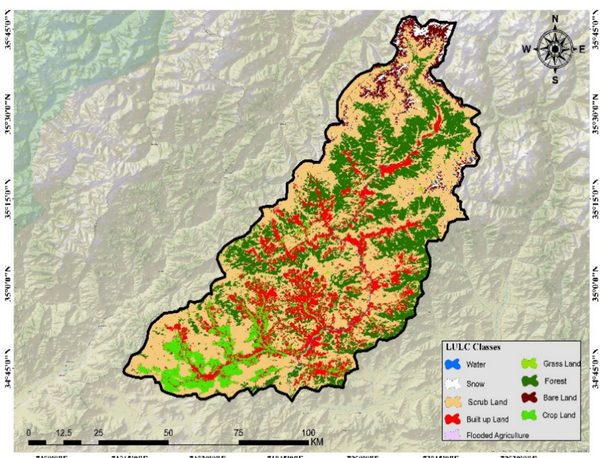

Fig. 4. Land use/land cover distribution.

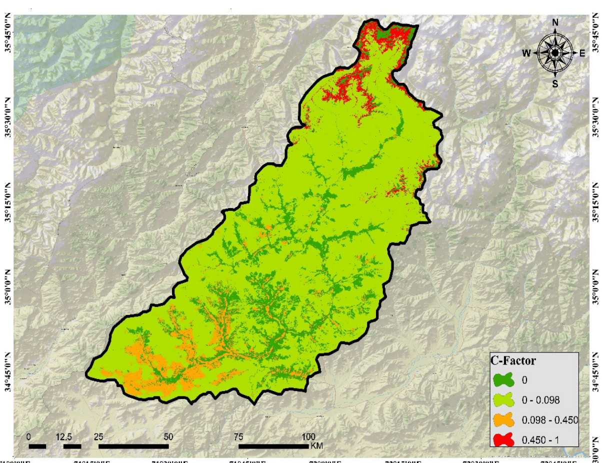

Fig. 5. Cover management (C factor) of Panjkora River Basin.

Table 2. Cover management factor.

S. No.	Land use	C Factor
1	Forest	0.03
2	Shrubland	0.03
3	Grassland	0.01
4	Agricultural Land	0.21
5	Barren Land	0.45
6	Built-up	0.00
7	Snow Glacier	0.00
8	Water body	0.00

Rainfall Runoff Erosivity Factor (R): Rainfall Erosivity Factor "R" considers how much rainfall to introduce the peak intensity sustained over a lengthy period, showing the expected capacity for rainfall to causes soil loss. It depicts the idea of rainfall erosivity as a collaboration between the kinetic energy of raindrops and the soil surface [30]. R factor essentially affects soil loss [31] as shwon in Figure 6. The R factor is calculated using Equation (4):

$$R = 81.5 + 0.38P \tag{4}$$

Where,
R addresses the Rainfall Erosivity Factor,
P is the Mean Annual Rainfall in mm.

Soil Erodibility Factor (K): it is alluded to as the defenselessness of a soil molecule type to erosion by precipitation and overflow. All small parts of the topsoil layer comprise organic carbon, silt, sand, and clay which makes the soil erodibility factor (Figure 7) expected to estimate the K factor utilized by the following numerical relations depicted in [3]. Numerous researchers consider the topsoil layer to compute the K factor since it is impacted directly by the raindrop energy. The K factor values for the DSMW soil layers of the study area were acquired using the following Equations (5), (6), (7), (8), and (9), based on which the soil layers are developed as a K factor map.

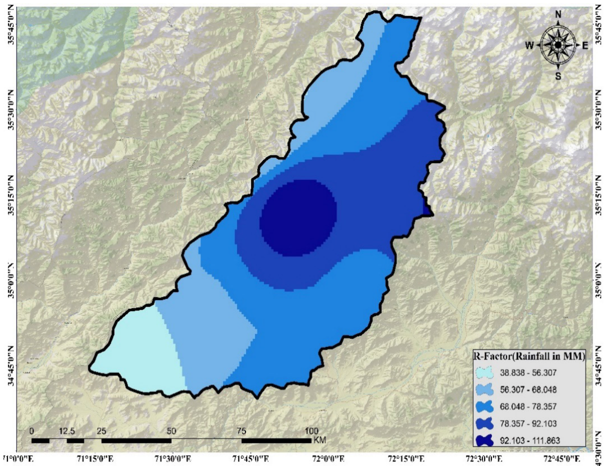

Fig. 6. Rainfall-runoff erosivity (R Factor) of Panjkora River Basin.

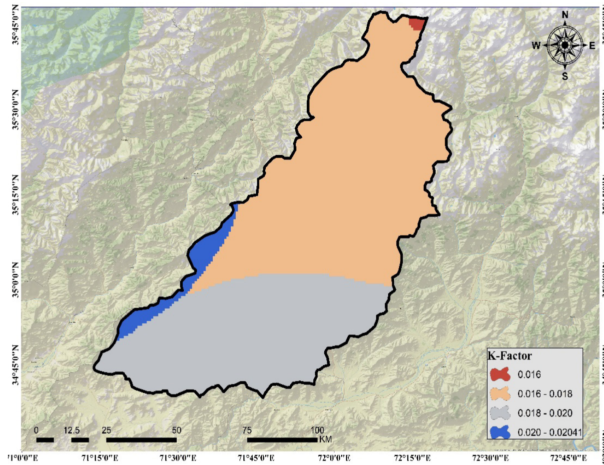

Fig. 7. Soil erodibility (K Factor) of Panjkora River Basin.

$$K_{Factor} = f_{Sand} \times f_{Clay} \times f_{OrgC} \times f_{Silt} \times 0.1317 \quad (5)$$

$$f_{Sand} = \left(0.2 + 0.3 \times \exp\left[-0.256 \times m_{Sand}\left(1 - \frac{m_{Silt}}{100}\right)\right]\right) \quad (6)$$

$$f_{Clay} = \left(\frac{m_{Silt}}{m_{Clay} + m_{Silt}}\right)^{0.3} \quad (7)$$

$$f_{Orgc} = \left(1 - \frac{0.0256.OrgC}{Orgc + \exp[3.72 - 2.95.OrgC]}\right) \quad (8)$$

$$f_{Silt} = \left(1 - \frac{0.7\left(1 - \frac{m_{Sand}}{100}\right)}{\left(1 - \frac{m_{sand}}{100}\right) + \exp\left[-5.51 + 22.9\left(1 - \frac{m_{Sand}}{100}\right)\right]}\right) \quad (9)$$

The proposed study is conducted step wise using the following methodology. Firstly, data was collected from Sentinel-2A Multi Spectral Instrument (MSI) and Climate data repository. DEM is obtained from google earth. The C factor and R-Factor were obtained from satellite and climate data while LS and P factor were obtained from DEM data respectively. Moreover, K factor was obtained using DSMW, detail is shown in Figure 8. Finally, the developed RUSLE model is executed in model builder of ArcGIS version 10.8.

3. RESULTS AND DISCUSSIONS

All the layers were combined in Raster Calculator according to the Equation (10) as mentioed by Koirala *et al*. [29].

$$A = R \times LS \times K \times C \times P \quad (10)$$

The erosion was classified into five classes Low Erosion (>0), Moderate Erosion (1-5), High Erosion (5-10), Very High Erosion (10-20) and Severe Erosion (20-37.43). The Study reveals that the maximum area near the Panjkora River is under moderate erosion ranging from 0 to 5 tons/ha/yr in 2021. Residents of the area live near the Panjkora River as the rest of the area is mountainous and agriculture practices are affected by the erosion leading to a loss in productivity and food quality. It is also identified that the maximum erosion in the study area is by water as shown in Figure 9.

RUSLE-calculated land degradation annauly in the Panjkora basin is presented in Figure 9 through regional distribution. The yearly soil loss falls into five graded classes starting from low erosion through very high erosion to severe erosion. The examined territory experiences yearly soil loss between 0 -37.43 tons per hectare annually. Figure 9 illustrates the extent of land under each soil erosion severity rank in the research area. Research findings demonstrate that soil loss effectiveness presents greater sensitivity to barren lands combined with high-altitude bare granite slopes in comparison to vegetation-covered areas. Panjkora basin presents moderate soil erosion as its primary form (78%) yet high to severe erosion exists in certain upper north areas (5%) and the remaining sections with low erosion make up (17%). The annual sediment output originates from 4.51 million tons of soil that

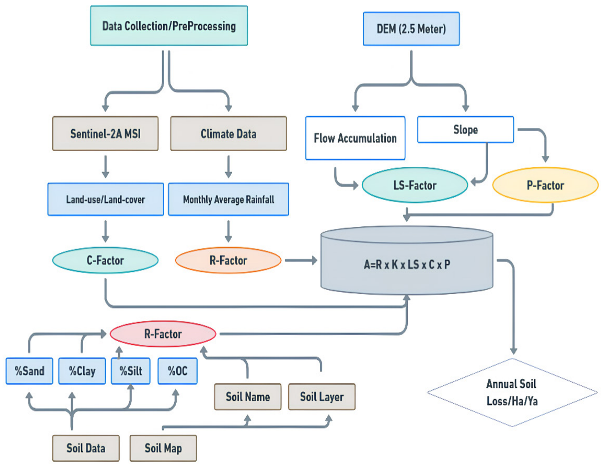

Fig. 8. Flow chart of the proposed study.

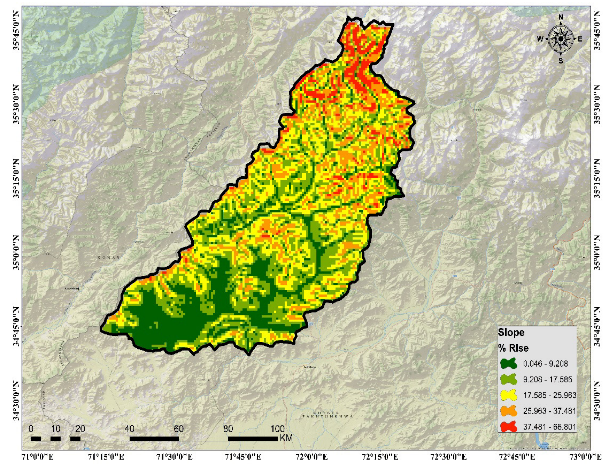

Fig. 10. Shows the slope map for the study map.

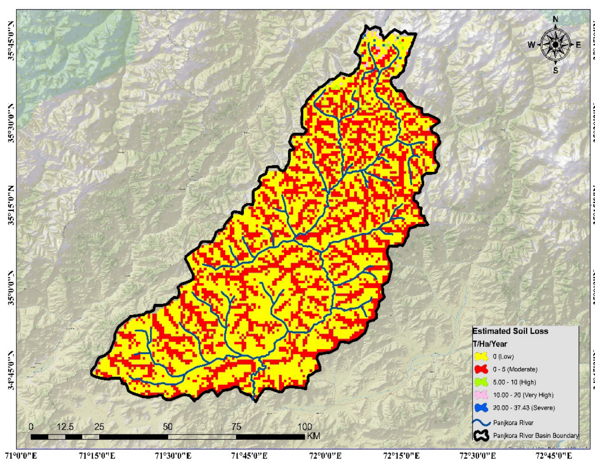

Fig. 9. Annual soil loss in Panjkora River Basin.

exists within coniferous and alpine forest terrain extending from 1,000 - 4,000 m and 4,000+ m mean sea level. The Panjkora basin exhibits steep slopes that mainly exist in its north and northeastern part of the basin shown in Figure 10. When granite feldspar encounters rainwater it transforms into white clay material known as kaolinite due to hydrolysis. The hydrolytic process transforms both biotite and muscovite mica types into kaolinite [31]. Soil erosion risk is high because the area contains steep slopes representing 64 percent of the total space while P-factor reaches 0.599 (Figure 3). This area features slopes exceeding 8.321% that result in these conditions. According to Phinzi *et al.* [32] the annual rate at which soil erosion is happening was strongly correlated with the LS-factor. Also, the panjkora basin suffer from extremely high soil erosion where agriculture is carried out on the apron parts of alluvial fans that extend into the pediments of mountains. The current study predicted a 5.94 million tons sediment output, compared to hydrological station data (5.5 million tons) situted at Zulam bridge, Timargara. The C factor of different parts of the Panjkora basin in terms of vulnerability to soil erosion is depicted in Figure 4. The results show that 78% of the entire area has a moderate soil erosion. The high, very high and severe erosion class comprises of only 5% of the total area of Panjkora basin. These regions are mostly sandy shallow soils and badly eroded steep slopes clad with little vegetation coupled with poor crop and soil conservation practices.

The quantity of annual losses throughout Potohar region reached 97.81 million tons/ha/year according to multiple studies [34, 35]. A 58 tons/ha/year rate of soil loss was determined through research performed on the Chitral river basin. The calculated total yearly erosion rate of soil amounts to 31 million tons per year. The annual soil erosion in Pakistan was estimated in [23] through RUSLE model analysis. The research establishes soil deficit rates for different administrative areas across Pakistan during one year. The research demonstrates that Khyber Pakhtunkhwa experiences annual soil deterioration at a level of 12.84 ± 39.897 tons/ha/yr [22]. The present study adds information to existing knowledge databases through field measurements as it uses high-resolution data while applying RUSLE model. Soil erosion measurements achieved by this methodology define a specific measurement of 37.43 tons/ha/yr for the Panjkora Basin area. The provincial estimate by Gilani *et al.* [22] supports the validity of the proposed study results conducted in Panjkora Basin.

High sediment deposition significantly hinder water resources storage, primarily by decreasing dam storage capacity and causing deposition within water distribution networks. Dutta [33] reported that the current water-holding capacity of major dams in Asia and the Middle East is approximately 1450 x 10^9 m^3, with siltation leading to an annual reduction of 0.8%. Consequently, sediments occupy 40% of the initial capacity in Asian dams, highlighting the substantial negative impacts on the region's long-term sustainability [34]. Notably, the Terbela Dam's anticipated a yearly sediment inflow of 325 million tons [35]. However, sediment accumulation has significantly reduced the reservoir capacity, from an initial 14.34 billion cubic meters to the current 10.04 billion cubic meters. This excessive sedimentation has considerably diminished the water storage and power generation capacity of major dams in pakistan, including Terbela, Warsak, and Mangla.

4. CONCLUSIONS

The proposed study was conducted in Panjkora basin to estiamate land degradation. The result demonstrates that the target area have intermediate vulnerability to soil erosion. Furthermore, the results also depicts that slope exceeding 8.321% with C factor values above 0.450 shows an attentive distribution pattern that leads to high erosion levels. The RUSLE model demonstrates that agricultural regions penetrating the foothills have moderate amounts of soil loss. It also calculates that the annual soil loss from the basin amounts 5.94 million tons. The obtained data will provide essential information that enables planners and policymakers to develop better land management practices. The research findings provide useful data to both land and water resource management authoraties to take proper soil conservation measures, including suitable crop management systems and construction of check dams and streambank stabilization structures. Spatial representations of soil erosion rates, through the generation of soil risk maps, can effectively identify critical erosion hotspots. By pinpointing such areas, efforts and resources can be strategically targeted to mitigate further erosion. The identification of these erosion-prone zones constitutes the initial step towards developing effective soil and water conservation plans, a crucial aspect in addressing food scarcity concerns, particularly within the Panjkora River Basin.

5. ACKNOWLEDGEMENTS

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6. CONFLICT OF INTEREST

Authors declare no conflict of interest.

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