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Research Article

Quantification of Soil Erosion by Integrating Geospatial and Revised Universal Soil Loss Equation in District Dir Lower, Pakistan

Abdullah Khan*, and Atta-ur-Rahman

Department of Geography, University of Peshawar, Peshawar, Pakistan

Abstract: This study is aimed to estimate soil erosion risk by integrating Revised Universal Soil Loss Equation (RUSLE) and geospatial tool in District Lower Dir, Eastern Hindu Kush. Soil erosion is among the biggest threats to agricultural production. Mountainous areas of Pakistan are exposed to erosion hazards due to immature geology, fragile slope, and deforestation. RUSLE factors were derived from data acquired from various sources. The Rainfall erosivity (R) factor was derived from monthly data obtained from Pakistan Meteorological Department, Peshawar. The soil erodibility (K) factor was prepared from the map of soil, Survey of Pakistan. The topography (LS) factor was calculated from 12.5 m DEM downloaded from the Alaska Satellite Facility. The cover management (C) factor was calculated from the Red and Near-Infrared band of Landsat 8 satellite image downloaded from USGS earth explorer. The Digital Elevation Model (DEM) and Landsat image were integrated to prepare the Support practice (P) factor. These factors were combined to assess soil erosion in the study area. The estimated soil erosion ranges between 0-25407 tons/hectare/year, with a mean soil loss of 230 tons/hectare/year. The erosion zonation map was then prepared and was classified as very low, low, moderate, high, and very high erosion. 22 % of the district was affected by low to moderate erosion while 67 % area is affected by very high erosion. The areas having more rainfall and steep slopes are more exposed to erosion hazards. Therefore, Erosion control activities are essential in those areas where erosion is high to assure a viable ecosystem.

Keywords: Soil Erosion, RUSLE, Deforestation, GIS, Lower Dir.

1. INTRODUCTION

Anthropogenic activities like the cutting of trees, overgrazing, construction activities, and extensive farming accelerate the process of soil erosion and degradation of the natural environment [1]. Several natural activities like extensive rainfall, running water, forest and vegetation cover, detachment of soil, and its transportation by several agents also play a major part in the process of erosion [2].

The magnitude and influence of erosion is a major issue especially in developing nations [3, 4], where most people rely on small-scale farming [5]. It is one of the major concerns of the 20th century and will also be top challenge in the 21st century [6]. Each year around 0.90–0.95 mm of the topsoil is eroded due to erosion in the world [7]. Nearly 10 million hectares of cultivable land is washed away by soil erosion annually [8]. In the previous four decades, around one-third of agricultural land has been affected by erosion, while the world's population is increasing a quarter of a million daily, which means demand for agricultural production is increasing daily while its production is decreasing [9]. In the last five decades, agricultural production has been declined from approximately 11.9 to 13.4 % due to the deterioration of cultivable land [10].

Soil degradation also causes various effects on the natural ecosystem and economy of a region [11, 12]. Consistent soil loss results in the decline of soil fertility [10] and crop production [13, 14]. It causes the blocking of river channels and raising the level of dams which poses a high flood risk [15], disturbs

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*Corresponding Author: Abdullah Khan <abdullah.geo47@gmail.com>

reservoirs, increases its maintenance cost, and makes it dysfunctional [16].

Though soil erosion is a global challenge however the developing nations face more threats due to the less available resources to restore and reclaim the eroded soils and lost nutrients [17]. Highland areas are more exposed to erosion hazards due to slope gradient, intense precipitation, gushing rivers, and surface overflow [18]. Pakistan has no exception, soil erosion has affected 11 million hectares of the topsoil and nearly 40 million tons of sediments are carried to the Indus River annually [19]. These sediments are filling the Tarbela and Mangla dams which have cut down the volume and life span of these dams. It also reduces the electricity generation and supply of water [20].

Soil protection and water conservation are identified by the United Nations (UN) as a crucial land-use problem and is one of the main considerations of the UN Sustainable Development Goals [21, 22]. Conventionally, assessment of the erosion hazard offers a foundation for water and soil protection [23]. Combating land degradation, desertification, and soil erosion have drawn much attention of land conservationists, decision-makers, agronomists, and politicians all-round the globe [24]. Erosion models provide soil loss estimation qualitatively and quantitatively in several physical and environmental conditions [25]. It also provides guidelines for framing and implementing strategies for soil and water conservation [26-28].

Protecting soil by applying suitable and sustainable agricultural practices and land management strategies are the most appropriate method for controlling soil erosion in the world [29]. For this purpose, monitoring and assessment of the potentially vulnerable erosion areas become very important for controlling and managing this problem [30]. Out of numerous erosion models, Revised Universal Soil Loss Equation (RUSLE) is used widely around the globe [31], for the better estimation and quantification of soil loss [32].

2. MATERIAL AND METHODS

2.1 The Study Area

District Lower Dir is situated in the north-eastern Hindu Kush region, Khyber Pakhtunkhwa province. Geographically it stretches 34° 37′ 27″ to 35° 4′ 23″ N latitude and 71° 30′ 37″ to 72° 11′ 30″ longitude (Figure 1). Relatively, it is bounded by the Upper Dir district in the north, district Swat on the east, and district Malakand on the southeast while district Bajaur is situated to the south-western side of the Lower Dir. It also shares an international border on the western side with Afghanistan. The study region occupies a 1, 585 km^2 area and has 1, 435, 917 inhabitants [33]. It is drained by the Panjkora River. The climate is mild to hot in summer mostly warm during May-July when the temperature reaches a maximum of 38 °C whereas in the winter season the temperature decreases to 0 °C. December-March are the coldest months where occasional snowfall also occurs. Mean annual rainfall ranges between 700 to 1200 mm, most of which occur from December to April. Largely the physiography of the study region is occupied by the offshoots of the Hindu Kush Mountains. The altitude of the district ranges from 524 meters to 3268 meters. The highest altitude is found in the northern region of the district whereas in the southern region the height decreases forming a slope gradient. The gradient increases the impact of rain splash and gully erosion. The degree of erosion can be determined from a large amount of silt found in the river [34].

2.2 Methodology

RUSLE model offers an excellent methodology for measuring soil erosion and its causal factors. Like USLE, RUSLE retains the same factors and formula for assessing soil loss [35]. These factors are rainfall erosivity, soil erodibility, slope length and steepness, cover management and support practice. To facilitate the process of erosion, RUSLE has been computerized [36]. Mathematically it is denoted as;

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

Where A is the rate of average annual soil erosion (t.ha^{-1}.yr^{-1}), R represents rainfall erosivity (MJ.mm.ha^{-1}.h^{-1}.yr^{-1}), K is the soil erodibility (t.ha.J^{-1}.mm^{-1}), LS is slope length and steepness, C represents the cover management, while P represents the support practice factor. LS, C, and P are dimensionless factors.

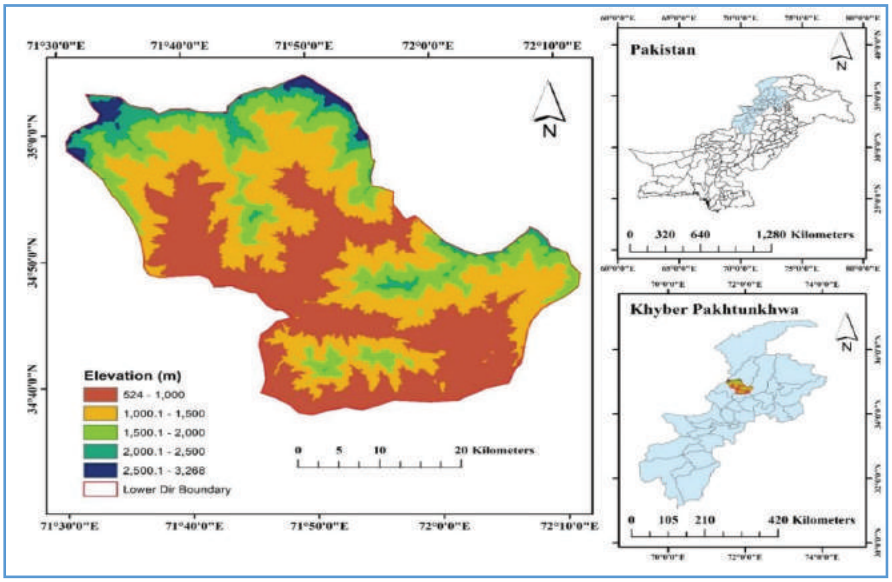

Fig. 1. Location of district Lower Dir

2.2.1 Rainfall Erosivity (R) Factor

The intensity and amount of rainfall are the most important contributor to water erosion to start [37]. The more the intensity and amount of rainfall, the more erosion will occur, related to EI_{30} (the product of kinetic energy and 30 minutes intensity of a rainfall) [38]. Calculation of R factor needs long term continuous precipitation data but in most of the countries, this EI_{30} data is not available. If sufficient data is available still it is a difficult and time-consuming process. However, some simplified methods have overcome this difficulty in numerous countries for R factor calculating from monthly rainfall data. The main advantage of these simplified procedures is that monthly rainfall data are easily available and reliable [39]. A good correlation has been identified by several researchers between rainfall erosivity and monthly data in different parts of the globe [40-43].

R factor was calculated for the study region from monthly rainfall data obtained from Pakistan Metrological Department, Peshawar. Only one met station is there in the district Lower Dir (Timergara met station), so for the accurate estimation of the R factor, the rainfall data was acquired for the seven met stations near the study area (Chitral, Dir, Darosh, Kalam, Malam Jabba, Saidu Sharif, and Timergara met stations) from Pakistan Meteorological Department, Peshawar.

A point map was generated from this data and then interpolation was applied in the ArcMap. (Table 1) shows the average annual rainfall and rainfall erosivity values calculated for each met station using equation 2 established by [41].

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

Where R is rainfall erosivity and P is average annual rainfall.

There is no specific equation in Pakistan for the estimation of the R factor, therefore [41] equation was used for the study area because of the similarity in the rainfall pattern of Pakistan and India (Figure 2a).

2.2.2 Soil Erodibility (K) Factor

Soil of different textures demonstrates a varying degree of vulnerability to water erosion. Erodibility is the resistance of soil to erosion from the impact of rainfall and runoff [44]. It is influenced by a variety of both chemical and physical attributes of soil. But only the physical properties of soil are considered by the RUSLE model for instance soil structure, organic matter, particle size, and permeability are the main components of soil influencing the soil erodibility [45]. District Lower Dir soil map acquired from the soil survey of Pakistan was digitized and four types of soil texture (Figure 2b) have been identified. This map was used to establish the erodibility factor assigning K values (Table 2) extracted from different literature.

2.2.3 Slope Length and Steepness (LS) Factor

The LS is a combination of two topographic factors i.e., length (L) and steepness (S) of a slope, [34], which highly influence the process of soil erosion [48]. On a steep slope, the water rushes at a higher speed which results in increased pressure on the surface consequently increasing the transport of a large number of sediments [49, 50]. Slope length also contributes to erosion, which is the area from the origin of overland flow to the place where either the slope reduces so that deposition occurs or the place where the water moves into distinct channels [49].

Nowadays, in all research studies, DEM is used to calculate the LS factor [51, 52]. In the present study, DEM with the 12.5-meter spatial resolution was used which was downloaded from the Alaska Satellite Facility (Figure 2c), using [53] established equation for the calculation LS factor in the GIS environment (eq. 3).

LS = (Flow accumulation * cell size /22.13)^{m} 0.065+ 0.045 S+ 0.0065^{2}…..............................Eq. 3

Where the value of exponent m ranges from 0.2 to 0.5 based on the slope percentage suggested by [49] (Table 3). 0.5 was taken as the m value from (Table 3) for eq. 3 because most of the area in the study region has a steeper slope than 5º.

Table 3. Values of m for different slopes

m-value	Slope (%)
0.2	<1
0.3	1-3
0.4	3-5
0.5	>5

2.2.4 Cover Management (C) Factor

C factor reflects the combined impacts of both cover and management activities on soil loss [54, 55]. Vegetation can significantly decrease the speed of runoff and also safeguard the soil surface. This factor is mostly altered by anthropologic actions [56]. The plant cover greatly influences the process of soil erosion because it intercepts the rainwater, reduces the velocity of rainfall and runoff, and increases the infiltration rate [57]. Remotely sensed satellite image offers the latest and up-to-date information of the land surface, which can be very beneficial for earth surface dynamics and is extensively used in natural resource assessments and management [56].

The Normalized Difference Vegetation Index (NDVI) is greatly associated with the quantity of plant cover, and hence can effectively be employed to give knowledge of the plant dynamics [58, 59]. Numerous scholars and experts have calculated the C factor from NDVI using different equations [56, 59, 60]. In this study, [60] suggested equation (eq. 4) was applied to compute the C factor (Figure 2d).

C = (–NDVI + 1) /2 ……....................……… Eq. 4

Where

NDVI= NIR – RED / NIR + RED ………… Eq. 5

2.2.5 Support Practice (P) Factor

Generally, the P factor and C factor are related to each other because both of these factors are used to reduce soil erosion [61, 62]. But the P factor is different from the C factor because it specifies the influence of management activities by controlling the runoff by changing its direction, pattern and reducing the speed [62, 63]. P factor can be estimated in various ways such as from direct investigation of the land use type at the fields and to recognizing the particular farming methods which are particularly time consuming and expensive. It can be calculated from satellite imageries classifications or previous research investigations and also from the knowledge of experts [52]. Several scientists proposed that the values of the P factor are relatively reliant on the slope gradient [49, 64, 65], whereas some others have suggested the use of farming activities to compute the P factor value [66]. In this study, Landsat classified image was used to develop land cover classes (Table 4; Figure 2e).

The land cover classes were overlaid over the

Table 1. Average annual rainfall of the selected met stations

S. No	Meteorological Station	Average annual rainfall	Time interval	Rainfall Erosivity
1	Chitral	458 mm	37 years	245.254
2	Dir	1362 mm	38 years	573.406
3	Darosh	568 mm	37 years	285.184
4	Kalam	1038 mm	16 years	455.794
5	Malam Jabba	1647 mm	16 years	676.861
6	Saidu Sharif	1050 mm	45 years	460.15
7	Timergara	796 mm	11 years	367.948

Table 2. Soil texture and K factor values of the study area

Soil Texture	Area (km^2)	% Area	K values	Erodibility	Reference
Rock outcrop loamy	765.6	48.3	0.25	Low	[46]
Mainly loamy soil	560.7	35.8	0.25	Low	[46]
Eutric cambisols	98.6	6.2	0.34	Low	[47]
Lithosols	160.1	10.1	0.2	Low	[47]

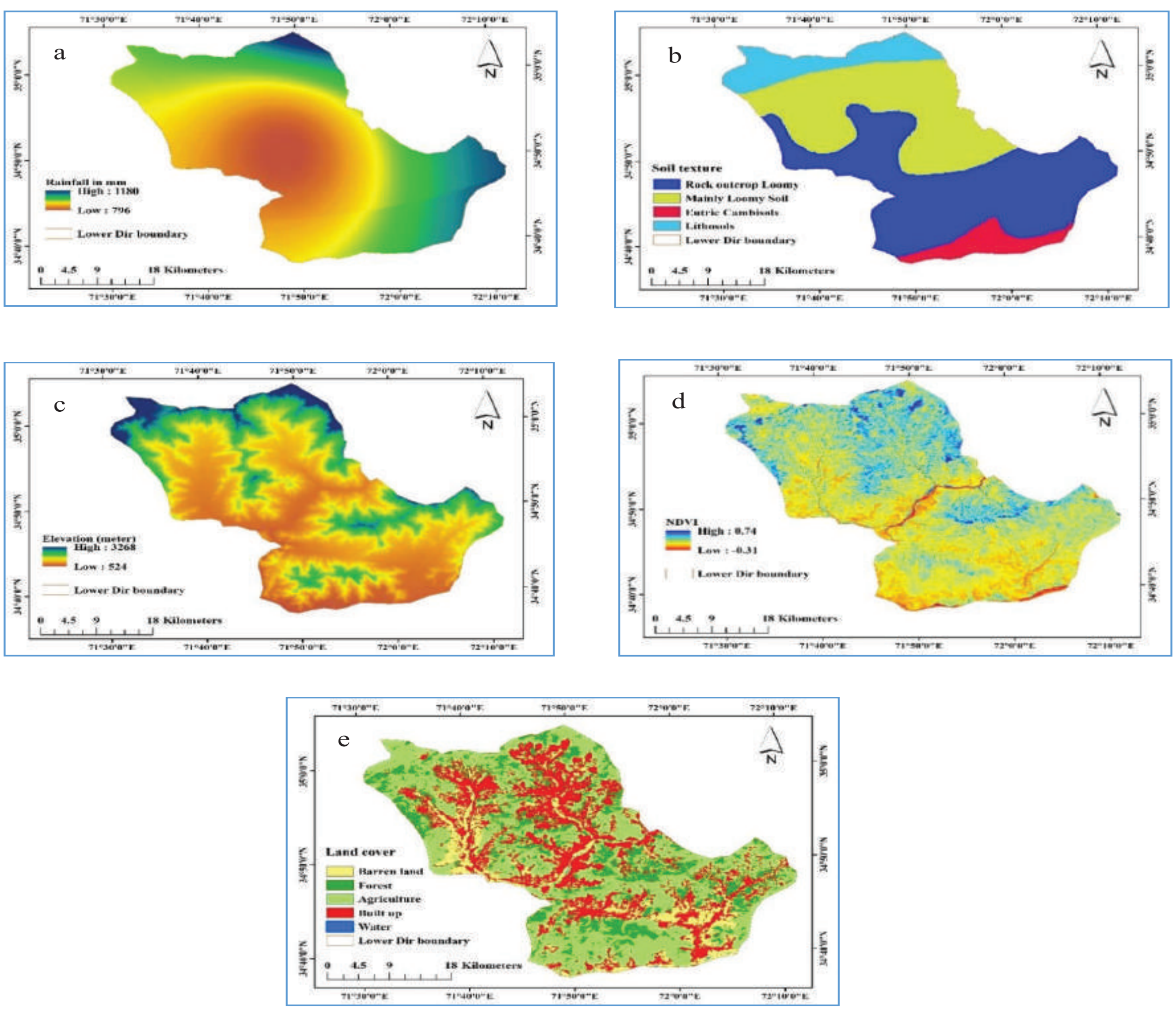

Fig. 2. District Lower Dir showing a; Mean Annual Rainfall, b; Soil texture, c; Elevation, d; NDVI, e; Land cover classes

Table 4. Landcover classes, area and percentage

Land cover	Area (km^2)	% Area
Vegetation	498.2	31.4
Forest cover	426.4	26.9
Barren land	296.4	18.7
Water bodies	39.6	2.5
Built-up area	324.4	20.5

Table 5. P values after [49]

Land cover	Slope %	P values
Agriculture	0-5	0.10
	5-10	0.12
	10-20	0.14
	20-30	0.19
	30-50	0.25
	50-100	0.33
Other lands	All	1

slope map to prepare a P factor map bored on the values based by [49] (Table 5).

2.2.6 Soil Loss Estimation

The factors of the RUSLE model were prepared in the ArcGIS environment. RUSLE formula was employed and all the layers were multiplied to calculate annual erosion for the district Lower Dir. The annual erosion map was further subdivided into erosion categories: very high, high, moderate, low and very low, less than 5 tons/hectare/year was defined as very low, while more than 75 tons/hectare/year as very high erosion. The result of the analysis shows that 12 % of the study exhibit very low and low erosion, while 67 % of the study region is affected by very high erosion (Table 6; Figure 4).

Table 6. Amount of soil erosion, categories and area

Erosion tons/hectare/year	Erosion categories	Area (km^2)	% Area
<5	Very low	63.4	4
5.1 -25	Low	126.8	8
25.1- 50	Moderate	158.5	10
50.1- 75	High	174.3	11
>75	Very high	1062	67

3. RESULTS AND DISCUSSION

The assessment and estimation of soil erosion hazards are very helpful in controlling and managing erosion in the District Lower Dir. GIS is a very effective means of assessing soil loss but the contribution of remote sensing cannot be ignored because it is a very important data source for soil loss assessment. Overall RUSLE model coupled with remote sensing and GIS were employed in this study to calculate the quantity of soil erosion and also to categorize the areas with high erosion.

3.1 R Factor

R factor is a very sensitive factor in computing soil erosion risk. Inverse Distance Weighted (IDW) interpolation method was employed to create a rainfall map and then eq. 1 was used to compute the rainfall and runoff erosivity (R) factor map. The interpolation process is essential when there is more met station data. As the study area, Lower Dir has only one meteorological station so a better estimation of the R factor data was also acquired for the surrounding meteorological station (Table 1). The mean monthly rainfall data were averaged for each met station to find out the mean annual rainfall. The areas having a high amount of rainfall have a high amount of erosivity. The northern and eastern region of the district receives more amount of rainfall while the amount of rainfall decreases going from the north to the southern and western part of the district. The same is the case with the erosivity values, it is high in the northern and eastern part of the district making it more susceptible to erosion while the risk of erosion decreases as the erosivity values decrease in the southern and western part of the district. The erosivity values ranges between 368 to 478 $Mj.mm.ha^{-1}.h^{-1}.yr^{-1}$ in the Lower Dir (Figure 3a).

3.2 K factor

In the present study, soil map acquired from soil survey of Pakistan was utilized to establish the K factor assigning K values from (Table 2) extracted from different kinds of literature. (Table 2) reveals that rock outcrop loomy is the largest soil group that approximately occupies 50 % of the study region. This type of soil is mostly found in the central part of the district. Besides this, 35 % of the district has loomy soil. The erodibility values range from 0.2 to 0.34 t.ha.h/ha/MJ/mm (Figure 3b). Though the erodibility values are low in the whole district, it increases from north to south.

3.3 LS Factor

The LS factor was calculated for the study area from the ALOS PALSAR 12.5 m DEM. Figure 2c shows the slope map and elevation of district Lower Dir. This map depicts that elevation ranges between 524 to 3268 meters. The highest altitude is found in the northern and eastern part of the district, while the slope decreases from north to south and reaches 524 meters.

The topography is divided into different slope categories based on the slope percentage (Table 7), which shows that 3.5 % of the study area has a steep slope, and has more than 40 % slope percentage. Most of the study area (45 % area) has strongly undulating.

Figure 3c shows the LS factor of the study region. The LS values range from 0 to 1303. Like the altitude, the high values are found in the northern and eastern part of the Lower Dir, while these values drop to 0, which are mostly found in the south-western valleys. The LS and slope map depict that more than 50 % of the study region is vulnerable to erosion due to its topography.

3.4 C Factor

Spectral indices like NDVI and land use land cover classified maps are preferred nowadays over the orthodox methods due to their low cost and relative accuracy. In the current study, the C factor was computed from Landsat 8 satellite imagery downloaded for the year 2020. The higher the NDVI values means high vegetation cover while low values show sparse or no vegetation. In district Lower Dir, The NDVI values decrease towards the south from 0.74 to -0.31. The higher values are found in the north of the district where the coniferous forest is found at higher altitudes with some weed species and shrubs while in the lower valleys' agriculture activities are practiced. The C factor values are inverse to the NDVI. The areas with high NDVI values have low C factor values, which means these areas have more protection against soil erosion. In the study area, the C factor value ranges from 0.12 to 0.65. The high C values are found in the southern part of the district due to low vegetation cover while it decreases towards the northern part of the district (Figure 3d).

3.5 P Factor

The P factor is computed based on farming activities on different slopes from the land use map of the study region acquired from the classification of Landsat image for the year 2020 from USGS open source. The Landsat satellite image was classified by supervised classification techniques into different land use classes i.e., Built-up area, forest, water bodies, agriculture, and barren land. The classified image reveals that agriculture and forested land have largely occupied the study region combined form 58 %, while nearly 19% area is barren land and 22 % area is occupied by built-up area (Table 4). The land use map was overlaid over the slope map and values were assigned to agricultural land on different slopes from [49] proposed values from (Table 5) while P-value 1 was assigned to all the non-agricultural land use classes (Figure 3e).

Table 7. Slope categories, percentage, and area

Slope categories	Slope %	% Area
Flat	0-2	3
Gentle undulating	2.1-5	10.9
Moderate undulating	5.1-10	11.7
Undulating	10.1-20	25.2
Strong undulating	20.1-40	45.7
Mountainous	> 40	3.5

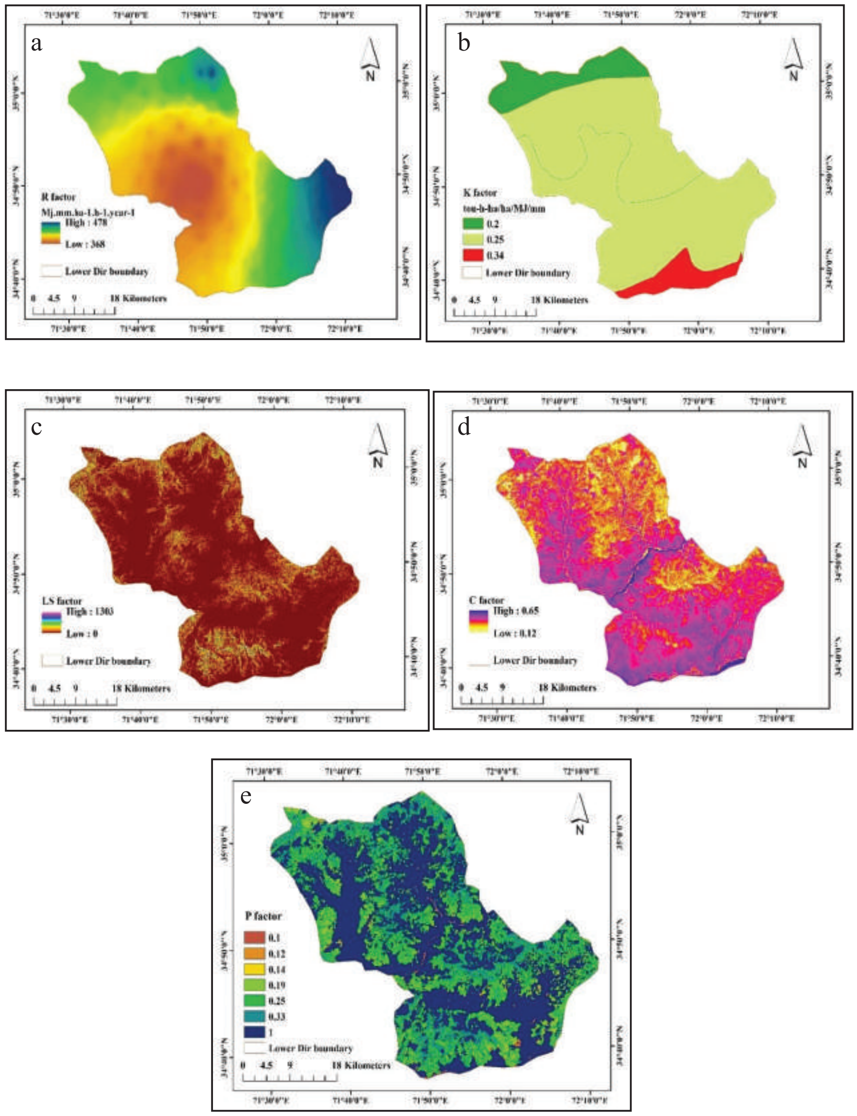

Fig. 3. District Lower Dir showing a. R factor, b. K factor, c. LS factor, d. C factor, e. P factor

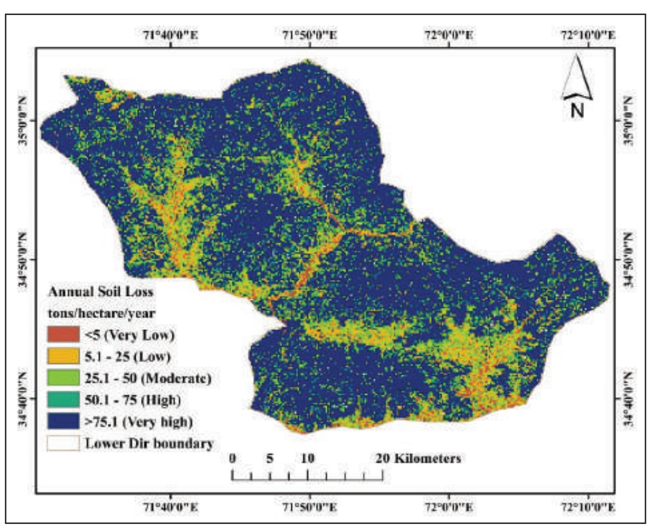

Fig. 4. District Lower Dir annual soil loss map

4. CONCLUSION

Excessive soil erosion not only reduces the productivity and fertility of land but also supplies a large amount of sediment to the reservoirs and dams which reduces its capacity and efficiency. Estimation and spatial extant of soil erosion hazards are time-consuming and difficult tasks but the combination of RUSLE and geospatial techniques are very helpful tools in quantification and mapping of erosion from an area.

This study is very important for providing firsthand information on the high erosion areas and may assist the planners and environmentalists in mitigating and monitoring the soil loss. The conservation and management of soil erosion will help increase agricultural production as well as reduction of sediments will increase the life span of dams and reservoirs. The outcome of this study would help padologist, irrigation departments, Directorate of Soil and Water Conservation as well as decision-makers for effective watershed and sediment management in the headwater region of River Panjkora.

5. CONFLICT OF INTEREST

The authors declared no conflict of interest

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