Estimation of Soil Loss by Revised USLE model using Geospatial Techniques: A Case Study of Sainj Valley, Northwestern Himalaya, India

ABSTRACT

Soil erosion is a severe environmental problem. The current study is being conducted in Sainj valley of Himachal Pradesh. An increase in soil erosion rates has significant effects on land degradation, biodiversity loss, productivity and other factors. The Revised Universal Soil Loss Equation (RUSLE) model along with, Geographic Information System (GIS) and Remote Sensing (RS), was used in current study to quantify soil loss in the Sainj valley. Five important parameters like, Runoff rainfall factor (R), Soil erodibility factor (K), Slope length and steepness (LS), Cropping management factor (C), and support practice factor (P) have been used to estimate the amount of soil loss in the study area. All these maps were created in GIS and RS using a variety of data preparation methods. The rainfall erosivity factor ranged between 501.19 to 1097.23 mt ha^{-} cm^{-1}. Spatial distribution of conservation support practice on soil loss indicated the variability (0–1) where lower value represents the higher conservation practice. The results show that average annual predicted soil loss is between 0 to 541.52tons/ha/yr and the predicted Average soil erosion rate was 11.15 tons/ha/Yr. Predicted soil loss was classified into six Erosion intensity classes Negligible (0-5), Low Erosion (5-10), Moderate Erosion (10-25), Moderately high (25-75), High Erosion (75-100), Extremely High Erosion (>100) From soil loss estimation it was observed that 62 % of the area is having very low erosion intensity and 0.37% of the study area having Extremely High erosion intensity. These findings can help the decision makers further in developing a suitable conservation program to prevent soil erosion.

Keywords: Soil erosion, RUSLE, Runoff rainfall factor, Cropping management, Support practice factor, Erosion intensity

1. INTRODUCTION

Soil erosion is a natural process associated with geomorphic processes or agents such as running water, winds etc. Soil erosion is a widespread and serious threat to survival and well being. Since soil formation is a very slow process, once removed completely, soil will take thousand and millions of years to form again and meantime land will be unproductive. In order to assess soil loss and identify watershed areas most likely to experience critical erosion, RS and GIS techniques are used [1]. The biophysical environment which includes soil, climate, terrain, ground cover, and interaction between them, affects how soil erosion occurs. Slope length, aspect and shape of the terrain are significant terrain characteristics influencing the mechanism of soil erosion [2].The evaluation of soil erosion in developing countries is a difficult task primarily because the crucial data are insufficient of occasionally unavailable [3].In study of Admankar and Patil [4]the relationship between C factor and soil loss is Good (R2=0.99). This implies that the influence of crop management factor on soil loss is higher. Lee suggested in their study [5] R factor will be used to identify areas at risk of soil disasters and to establish soil conservation plan. The topsoil is more susceptible to soil erosion due to the frequency of higher intensity rainfall erosivity [6]. Soils in the regions of cultivation are susceptible to erosion because of their low organic matter content and poor soil structure, according to the relationships between soil properties, land-use systems, and erodibility [7]. Important factors affecting soil erosion by water include soil characteristics, heavy rainfall, unusual weather patterns, complex terrain, and land use [8].On these aspects, numerous studies have been carried out globally using the GIS and the USLE and RUSLE approaches [9]. The estimated annual soil loss in Kashmir's Lidder catchment area ranges from 0 to 61 tonnes per hectares. Agricultural areas experienced the highest average soil loss (26 tones ha^{-1} yr^{-1}) whereas forest witnessed the lowest soil loss rates (0.99 tons ha^{-1} yr^{-1}) [10]. Lower Himalayan regions's Suketi watershed is situated in a region of moderated to high runoff and erosion risk. The study's results will benefit a wide range of stakeholders, which include farmers, water resource manager and decision maker in order to improve management procedures and decision making [11]. In the study of Tariq and Li [34] the finding shows that fpr the water year 2020, the estimated total annual potential soil loss of 4,67,064.25 tones ha^{-1}.year^{-1} is comparable to the observed sediment loss of 11,631 tones ha^{-1}.year^{-1}. An increase in agricultural area is expected to result in a predicted soil erosion rate of about 164,249 tones ha^{-1}.year^{-1}. The ability of regions to develop sustainably is severely hampered by soil erosion, which frequently results in land degradation, decreased agriculture production, and environmental deterioration. Major finding of this study demonstrates that machine learning approach's superior capacity for modeling soil erosion and investigating its causes [35].RUSLE, enhanced by GIS and RS, assessed soil loss in

Nagavangala watershed, Karnataka, aiding conservation planning. Dominant land uses were cropland (41.81%) and agricultural plantation (41.5%). Average annual soil loss was 9.80 t/ha/year, highest in scrubland (10.58 t/ha/year) and cropland (10.2 t/ha/year). The resulting erosion map guides strategic soil and water conservation efforts for sustainable resource management [36].

1.1 Study area

Present study was conducted at Sainj valley in district Kullu of Himachal Pradesh. Sainj is 49 Kilometers far from the district headquarter in Kullu. Sainj valley falls under the left bank of upper Beas river system in the lesser Himalayan alpine zone [12].The Sainj valley comprises of Area 528.99 Km^2 in size (Fig. 1). Study area lies within the altitudinal range of 981m to 5366m. The study area (528.99 km^2) located between latitudes 31°43′3″ and 31°54′51″N and longitudes 77°13′28″ and 77°35′48″E. Sainj experiences 1,387 mm of rainfall annually, with an average annual temperature of 20.6 °C. Sainj valley situated in the Great Himalayan national park's lower ranges. The primary rock types in the study area are granites, colluviums, slate, quartzites, dolomites, alluviums, and glacial deposits. The Sainj river is the main river that flows through the Sainj valley. Sainj River originates from the Raktisar glacier (+5500m) and there after it flows toward the South-west direction to join the Beas River at Larji village. The river Sainj and its tributaries are home to a diverse range of cold water fish, with trout reigning supreme. During the winter season, the region's average annual snowfall is about 345 mm, and it is mostly restricted towards the upper reaches of the Sainj river catchment.

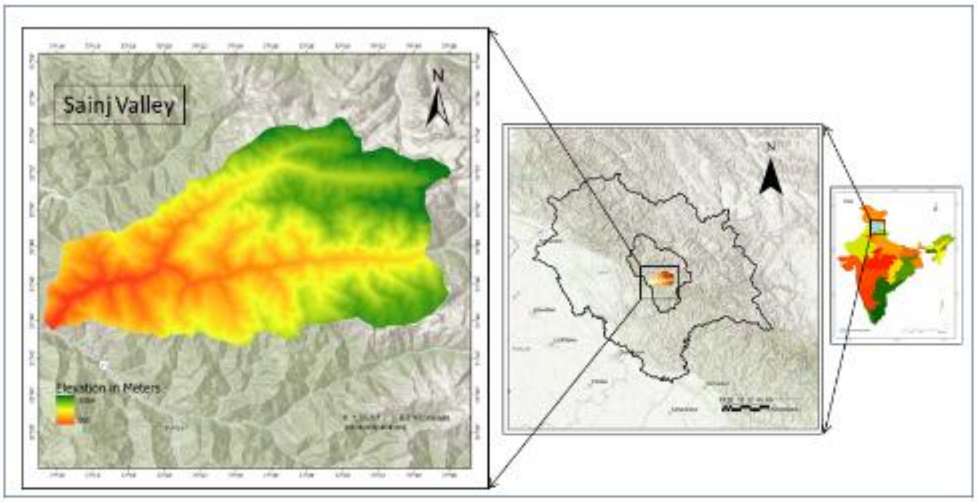

Fig. 1. Study area map of Sainj valley

2. MATERIAL AND METHODS

The USLE was developed by Weishmeier and Smith [13] and is used in many countries all over the globe. For the estimation of soil erosion by Revised Universal Soil Loss Equation (RUSLE) we have used five parameters which is depicted in (Fig. 2)
The USLE soil loss equation is:
A=R*K*LS*C*P
In this equation:
A = Potential Average Annual Soil Loss
R=Rainfall- Runoff Erosivity Factor
K= Soil-Erodibility Factor
L=Slope Length Factor
S= Slope Gradient Factor
C= Cropping Management Factor
P= Support Practice Factor

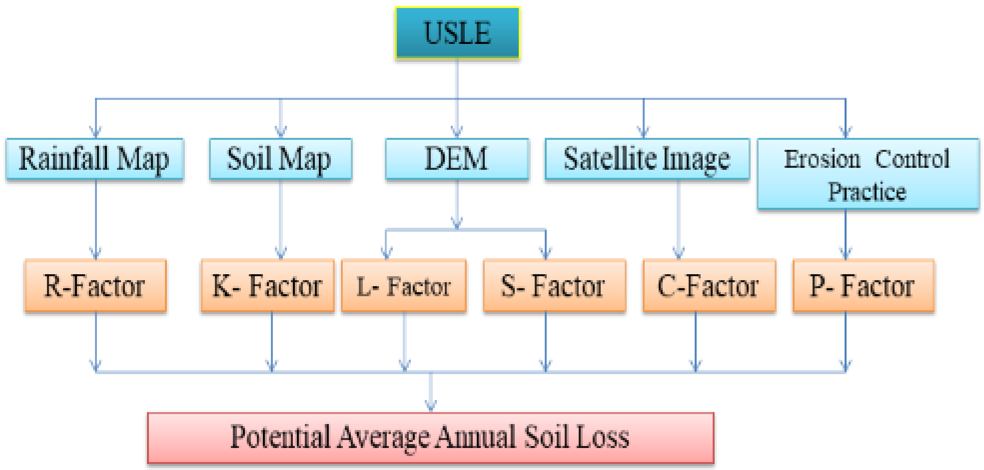

Fig. 2. Flow chart of the study area

2.1 Rainfall Erosivity

Rainfall and soil erosion are interlinked with each other through the combined effect of detachment of raindrops striking the soil surface and by runoff [14].The primary causes of soil erosion by water in forestland are wildfires and logging [15]. Rainfall erosivity factor (R) is calculated from the Rainfall erosivity equation given by Wischmeier and Smith in 1978 [11]

R= 0.5 * P *1.73

Here R is the Rainfall erositivity Factor and P is the Mean annual rainfall in mm. In Sainj valley values of rainfall ranges from 579.41 to 1268.48mm (Fig. 3). Rainfall data was downloaded from Terra climate lab's website for 2021 year in netcdf file format. Downloaded netcdf was then imported to the Arc GIS pro in raster form (using netcdf to raster tool) then the raster file was converted to point vector file. Furthermore, the point data was used to generate the map for the basin extent using IDW interpolation technique.

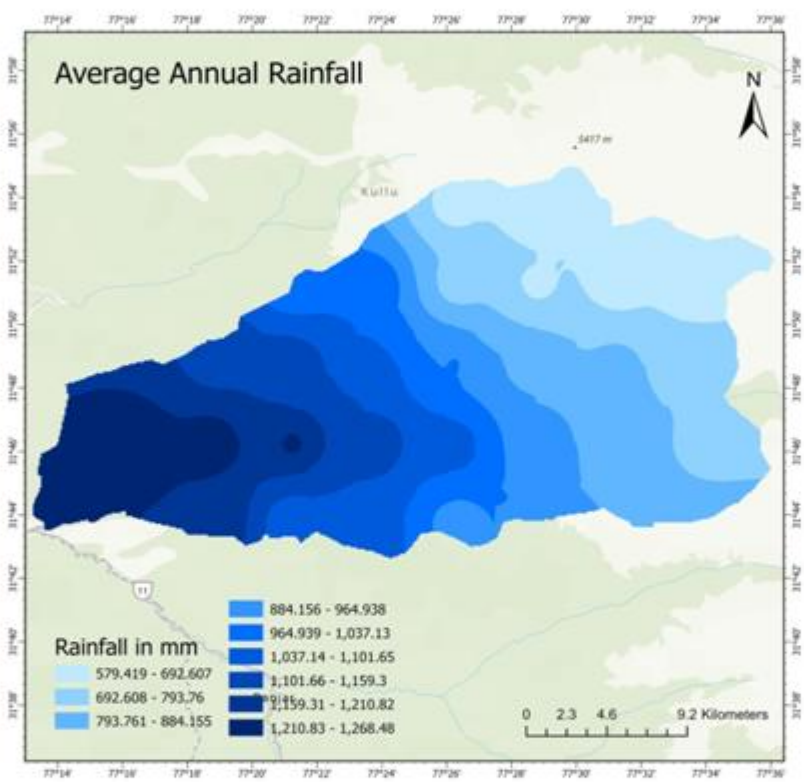

Fig. 3. Annual average rainfall in Sainj

2.2 Soil Erodibility Factor

One of the most significant factors required to determine or estimate soil loss globally is soil erodibility, which has been proven to be strongly correlated with the soil loss [16]. Soil erodibility refers to the association between the combined impacts of rainfall, runoff and infiltration on soil loss as well as the effect of soil qualities and soil profile characteristics on soil loss [17]. Based on topographical and lithological properties, soil type differs from one region to another. The Erodibility of soil (K) is an important index; it aids to determine the soil's erodibility. The USLE nomograph was used to estimate the K-Values of various soil types [13]. There are 4 type of soil within the Sainj valley Loamy, Rock outcrop, Glacier and rock crop, Sandy. Soil map shows only 4 soil classes viz Loamy, Rock outcrop, Glacier and rock outcrop, Sandy (Fig. 4) which covers almost 37.57%, 8.12%, 8.54%, 45.74% of the study area respectively (Table 1)

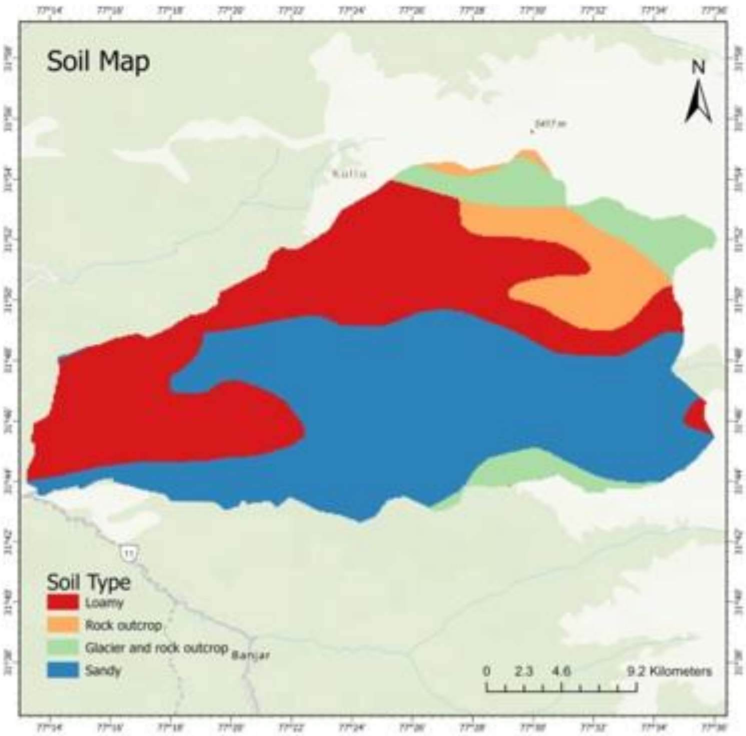

Fig. 4. Soil map of Sainj valley

Table 1. Soil classification in Sainj valley

Soil Type	Area in Km^2	% of Area
Loamy	197.12	37.57
Rock outcrop	42.64	8.12
Glacier and Rock outcrop	44.84	8.54
Sandy	239.96	45.74

2.3 Topographic Erosivity Factor (LS)

Topographic factors (LS) are gradient slope length factors that include slope length (L) and slope steepness (S) [18].One of the most important parameter in the RUSLE analysis is the topographic erosivity factor (LS). When the length of slope increases, because of the increased accumulation of surface runoff, soil erosion by water increases. The flow accumulation and slope values are used to calculate the slope gradient and slope length factor. GIS and RS are nowadays generally viewed as essential tools for the natural management studies; therefore almost all researchers use DEM and GIS tools to measure LS in soil erosion studies [19].The Topographic erosivity factor (LS) map was created using the Arc GIS Pro .LS depend upon Slope and Length of slope of the area is computed from the DEM by the Following formula [20]

$LS = (\text{Flow accumulation} * \text{Cell values} / 22.13\ m) * (\sin\beta / 0.0896)n$

The accuracy of estimation is determined by the resolution of the DEM. Topographic factor was calculated in Arc GIS Pro's spatial analyst module using a 30 m resolution SRTM DEM. Terrain of Sainj valley having very dense stream system and therefore "m" and "n" were respectively assigned 0.5 and 1.3 (Table 2) [21]

Table 2. The variation of m-exponent and S- slope of variation

m-Value	Slope degree
0.5	**>5**
0.4	**3-5**
0.3	**1-5**
0.2	**<1**

2.4 Cropping management factor (C-Factor)

"C" is the Crop management factor. The majority of researchers reported using these two factors as distinct factors when computing for USLE [22]. Majority of the study area is covered in numerous types of vegetation. The C factor ranges from 0-1(Bare land). To calculate C factor NDVI of year 2021 has been used which is produced by using Google earth engine. NDVI of 2021 had been generating by using the Sentinal-2 10m for 1 January 2021 to 31 December 2021. NDVI map is the median for all the Tiles of year 2021 by using filtered scene with criteria i.e Cloudy Pixel percentage <=30%. NDVI was computed using equation suggested by Rouse [23] and shown in figure 5.

NDVI = (NIR – Red)/ (NIR + Red)

The regression equation [24] was found as

C factor = 1.02 - 1.21 * NDVI

Final C factor map was generated by using this regression equation in Arc GIS Pro software.

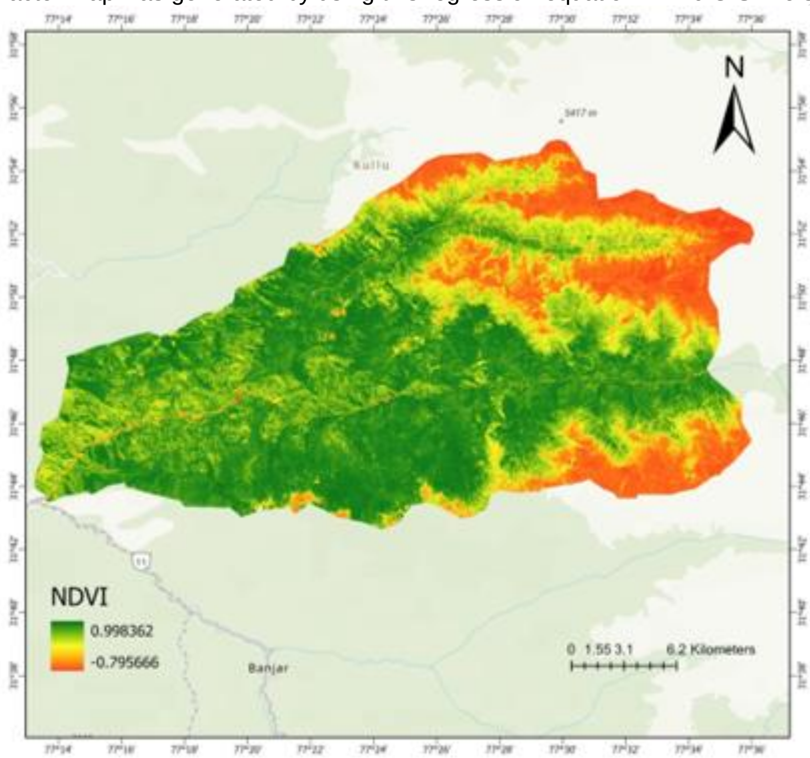

Fig. 5. NDVI Map of Sainj valley (2021)

2.5 Support Practice Factor (P-Factor)

"P" is the erosion control practice or conservation factor. P factor depends upon the soil land use practices and also implementation of any soil erosion protection measures in the area (Such as Afforestation, slope stabilization, vegetative erosion traps etc.). To calculate P-Factor Sentinel- 2, 10m Land use land cover map (2021) has been used which is produced by ESRI, Microsoft and impact observatory (Fig. 6). The typical values of P-Factor (Table 3) based on the land use type and the erosion protection measures [25] presented in Table 3.

Table 3. P-factor values according to the Land use type

Land Use Type	P factor	Area(Km^2)	% of Area
Water body	0.0	0.52	0.10
Tree	1.0	233.67	44.54
Grassland	0.9	14.85	2.83
Agricultural land	0.5	0.36	0.06
Shrubs	0.8	209.65	39.96
Settlements	0.1	1.11	0.21
Barren land	1	53.32	10.16
Snow/ Glacier	1.0	11.65	2.10

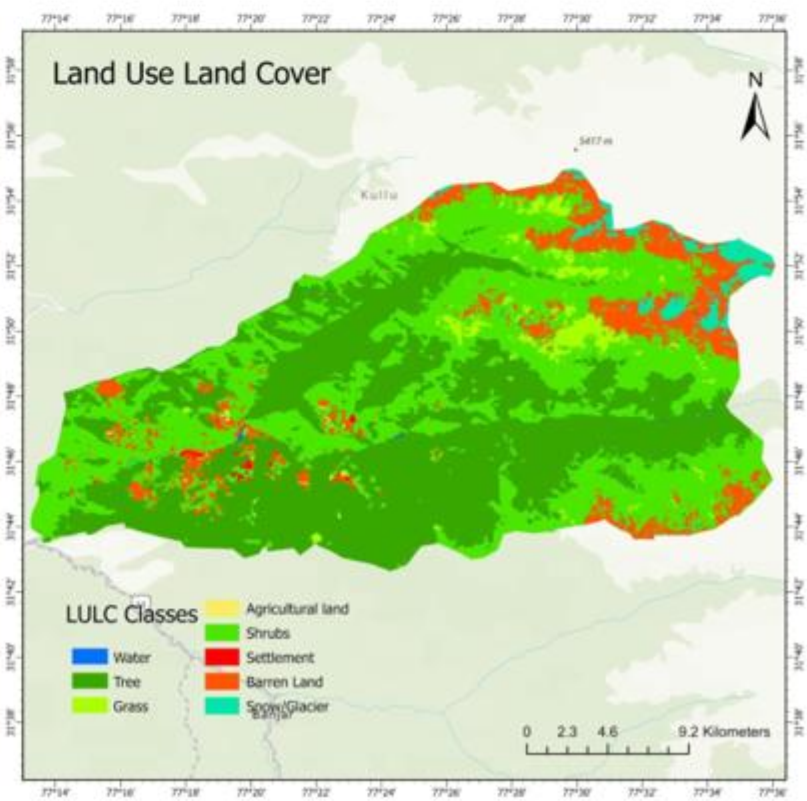

Fig. 6. Land use/ Land cover Map of Sainj valley

3. RESULTS AND DISCUSSION

3.1 Rainfall Erosivity (R)

Rainfall erosivity is the soil erosion factor that has gained most attention during the last decade and a lot of research has been done to improve the Erosivity Indexes [26]. For evaluating and controlling soil erosion, the rainfall erosivity map is important [27].The annual rainfall erosivity factor (R) for the year was found to be in the range of 501.19 to 1097.23 mt ha^{-1} cm^{-1} signifies the variability in erosive potential, with higher values indicating a greater propensity for soil erosion due to rainfall. Calculated rainfall erosivity factor for the study area is shown in figure 7.

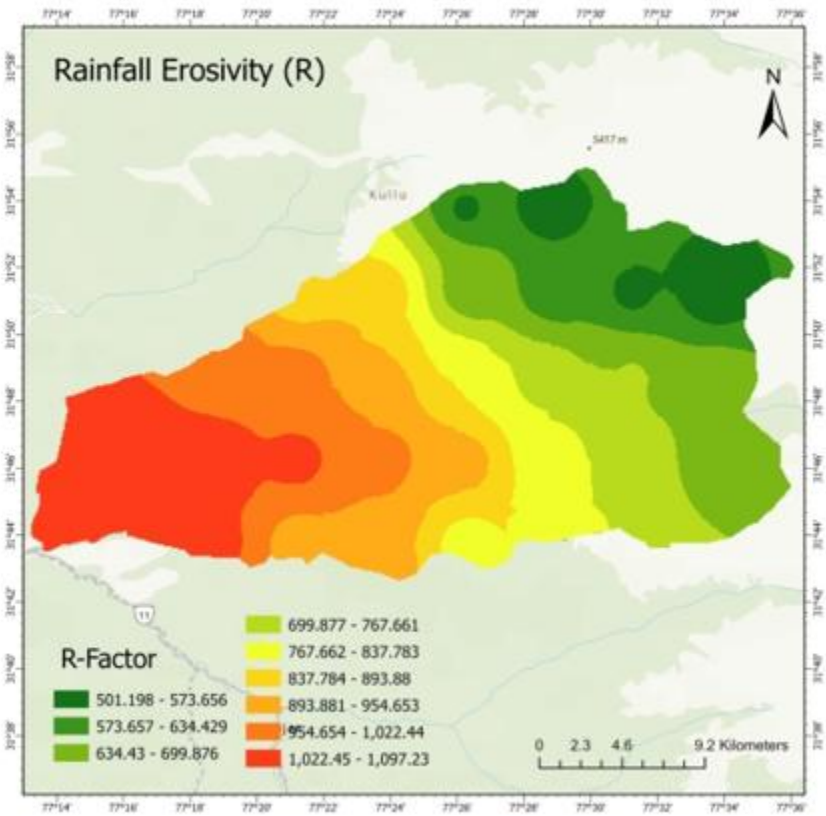

Fig. 7. R- Factor map of Sainj valley

3.2 Soil Erodibility (K)

The soil erodibility index or K-factor is described as the rate of soil loss per unit of R. Texture Organic Matter (OM) content, structure and permeability all have an influence in the soil erodibility [28]. The K factor, which determines the rate of soil loss per rainfall erosion index unit is influenced by six factors, including the organic matter content, permeability, and soil structures as well as the primary soil particles (Silt, Sand, clay) [29]. The K-Factor is quantitative criteria used in USLE model; the index can be interpolated to estimate soil erosion [30]. K factor map shows a maximum value of 0.3 and minimum value of 0 (Fig. 8)

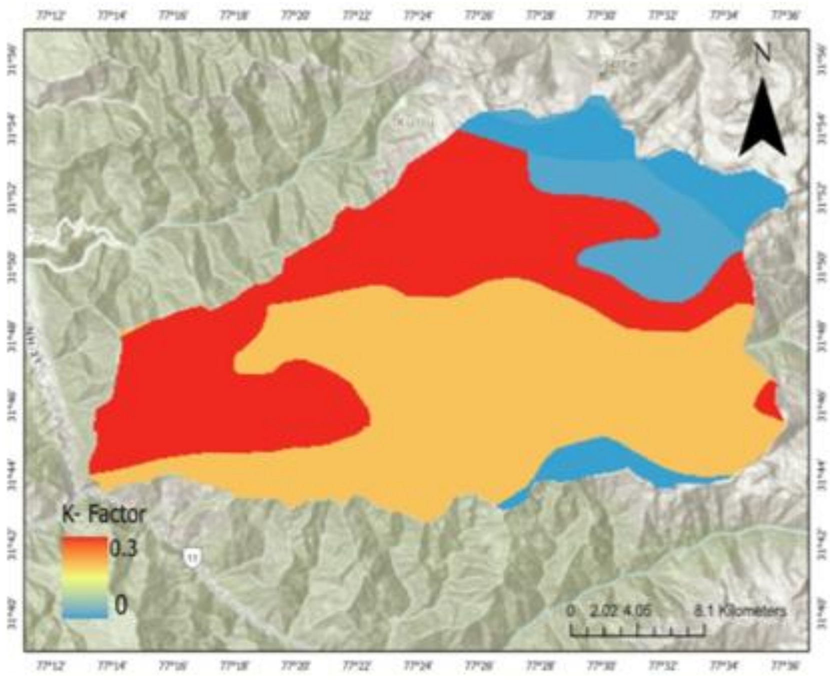

Fig. 8. Soil Erodibility map of Sainj valley

3.3 Topographic Erosivity Factor (LS-Factor)

The LS factor in the study area was found to be in the range of 0 to 8.57(Fig. 9). Steep slopes are defined by higher LS factor value [31]. Relative slope and steepness values (L & S) indicate how erodible a parcel of land is. The lowest value of LS factor was found along the Sainj River that flows toward west direction because the slope values are low near the river. The result demonstrates that the slope is very steep and the slope length is short. The LS factor, spanning 0 to 8.57, signifies the impact of slope length and steepness on soil erosion. Higher values indicate more challenging terrain, highlighting areas with increased erosion vulnerability due to topography. This factor causes a high rain flow rate, which causes severe soil erosion.

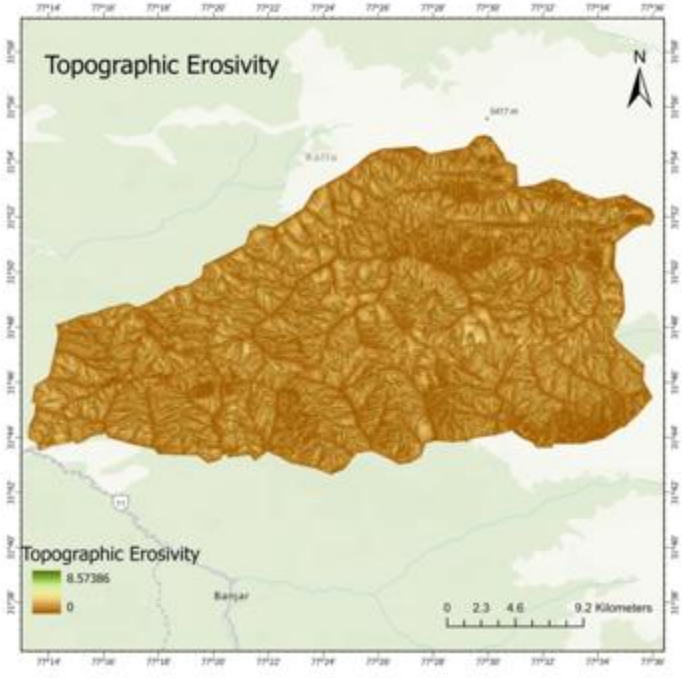

Fig. 9. Topography Erosivity map of Sainj valley

3.4 Cropping Management Factor (C factor)

C- Factor was derived from the NDVI. NDVI is a crucial factor because it indicates the type of soil layer cover. Large scale soil erosion can be predicted and evaluated in a significant way due to the C-Factor [32]. The C factor values in the study area vary from 0.0008 to

0.8978 (Fig. 10). In the study area, higher values in the C-factor represents rocky area or barren land while lower values in the C-factor represents vegetation cover [33]. Lower values suggest effective soil conservation practices, while higher values imply increased erosion susceptibility.

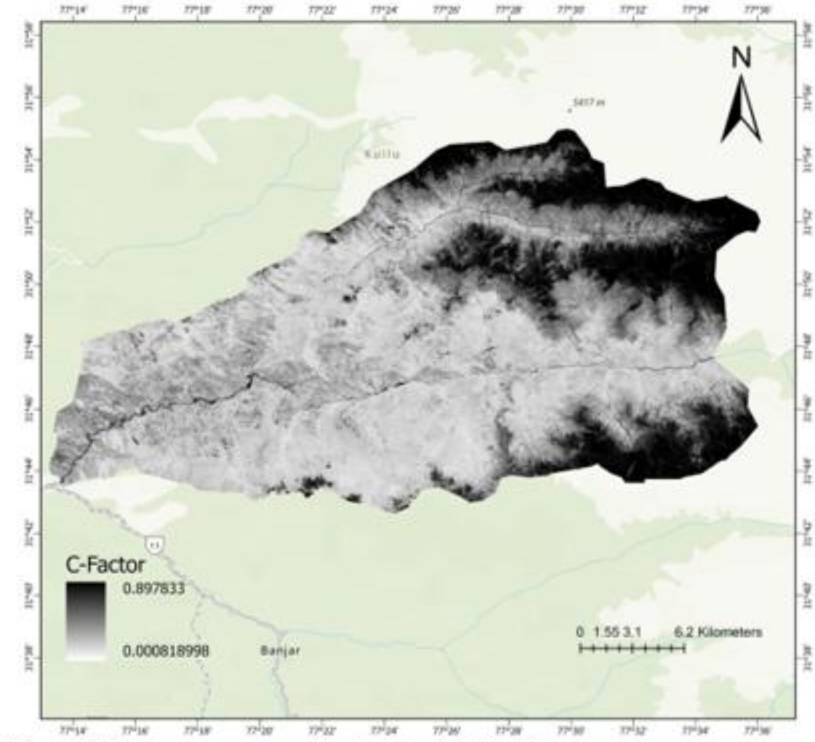

Fig. 10. Crop management factor for Sainj valley

3.5 Support Practice Factor (P)

P factor can differ according to the farming practices and level of conservation practices adopted particularly in the agricultural land. To create the Support practice factor, P values was assigned to the Land use land cover map of the area using Reclassify tool in Arc GIS. Distribution of Conservation support practice on soil loss ranges from 0 to 1(Table 4). Resultant map was classified into 6 support practice classes 0, 0.1, 0.5, 0.8, 0.9, 1(Fig. 11). The higher P-values indicate the lack of available soil conservation measures, while the lower P values indicate the higher conservation practice on the soil [33].

Table 4. P factor classification according to the Area

P Factor	Area in Km^2	% of Area
0	**0.49**	**0.09**
0.1	**1.18**	**0.22**
0.5	**0.39**	**0.07**
0.8	**211.19**	**39.92**
0.9	**14.93**	**2.82**
1	**300.78**	**59.85**

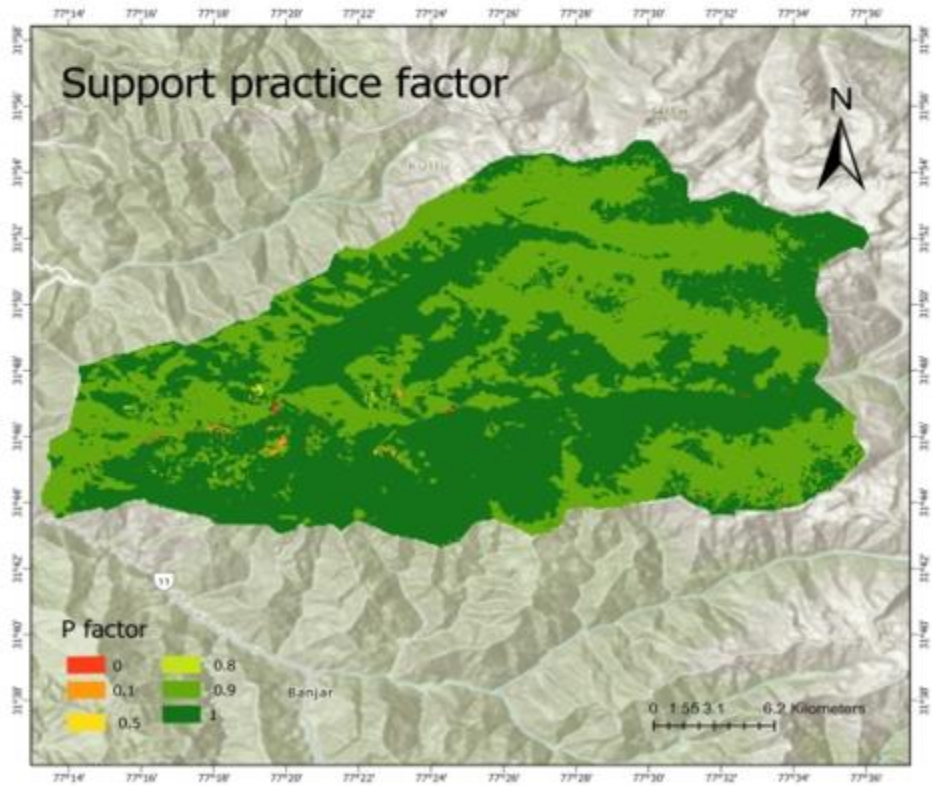

Fig. 11. Map showing spatial variability of Support practice factor

3.6 Average Annual Soil Loss (A)

Annual average soil erosion potential (A) has been computed by multiplying the developed raster data from each factor of RUSLE analysis. The resultant "A" factor map shows the average annual soil loss potential of the Sainj valley. Average annual predicted soil loss ranges between 0 to 541.52 tons $ha^{-1}yr^{-1}$ (Fig. 10). Highest values of estimated soil erosion potential are 541.52 tons $ha^{-1}yr^{-1}$. The resultant map is classified into six classes viz. Negligible erosion (0-5 tons $ha^{-1}yr^{-1}$), Low erosion (5-10 tons $ha^{-1}yr^{-1}$), Moderate erosion (10-25 tons $ha^{-1}yr^{-1}$), Moderately high erosion (25-75 tons $ha^{-1}yr^{-1}$), High Erosion (75-100 tons $ha^{-1}yr^{-1}$), Extremely high erosion (>100 tons $ha^{-1}yr^{-1}$) classes(Table 5). Mean annual soil loss for the entire study area is 11.15 tons $ha^{-1}yr^{-1}$. In Sainj valley soil erosion rates ranged from 0-5 tons/ha/yr accounts for 39.72% of the total area, whereas soil erosion rates greater than 100 tons/ha/yr accounts for 0.37% of the total area.) (Table 5).

Table 5. Soil loss classification according to the Area

Erosion intensity classes	Soil Loss(tons ha^{-1} $year^{-1}$)	Area (Km^2)	% of Area
Negligible Erosion	**0-5**	**210.15**	**39.72**
Low Erosion	**5-10**	**120.04**	**22.68**
Moderate erosion	**10-25**	**141.59**	**26.76**
Moderately high Erosion	**25-75**	**52.72**	**9.96**
High Erosion	**75-100**	**2.50**	**0.47**

Extremely High	**>100**	**1.99**	**0.37**

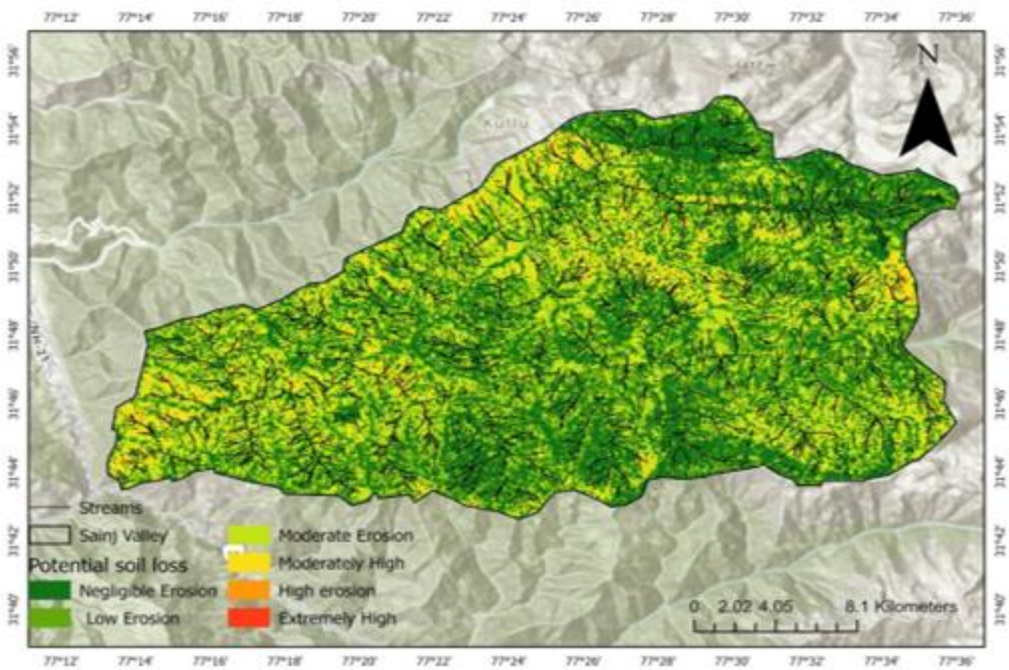

Fig. 12. Potential soil loss (tons/ ha/ yr) in the Sainj valley

3.7 Discussion

Sainj valley is a High altitude valley in Himachal pradesh's district Kullu. The valley's rainfall ranges from 579.419 to 1268.48mm. The study area ranges in elevation from 981 m to 5366 m above mean sea level.Based on the calculations and remote sensing data, the average value of rainfall erosivity factor-R ranges from 501.19 to 1097.23 mt ha^{-1} cm^{-1} indicates varying degree of erosive potential, with higher values signifying more erosive rainfall patterns. The LS factor incorporates slope length and steepness, influencing the potential for erosion. The range of LS factor (0 to 8.57) indicates diverse terrain and topographical conditions, impacting erosion susceptibility. Steeper slopes and longer lengths increase erosion risk. LS have the strongest effect on erosion; when the soil loss rate is high, LS values is also strong. The soil erodibility factor (K) varies between 0 to 0.3. There are two major types of soil in the study area: Loamy and Sandy. C factor has a discernible impact on the A- factor which is the Potential annual soil loss. Lower C- Factor results in lower soil erosion values. "Negligible Erosion" class, constituting 39.72% of the area, signifies areas with minimal soil loss, requiring basic conservation practices. The "Low Erosion" class (22.68%) indicates slightly higher erosion levels, necessitating proactive erosion prevention strategies. The "Moderate Erosion" class (26.76%) represents a significant erosion rate, highlighting the importance of targeted erosion control measures to mitigate soil loss. Moving to higher categories, the "Moderately High Erosion" class (9.96%) calls for immediate and intensive erosion control efforts, while the "High Erosion" class (0.47%) represents areas facing severe erosion, demanding urgent and robust erosion control strategies to prevent irreparable damage. The range of the predicted annual soil loss is 0 to 541.52 tonnes $ha^{-1}yr^{-1}$.This study describes the predicted amount of soil loss and its spatial distribution in the valley, which is useful when planning and implementing conservation program to reduce soil loss from the valley.

4. CONCLUSION

Soil is the major land degradation process. The study was done to address and quantify the soil loss problem in Sainj valley of Himachal Pradesh. The areas having steep slopes are more vulnerable to soil erosion. Soil erodibility increases with increase in slope and predicted average soil erosion rate in the study area is 11.15 tons/ha/yr. RS and GIS are the most effective tools for analyzing spatial distributed information in a vast area now. The all RUSLE parameters R, K, LS, C and P factors maps were combined together for creating the annual soil loss map of Sainj valley. This RUSLE is very helpful for estimating the rate of erosion as well as to identify the erosion prone areas in the Valley. According to the findings, the maximum annual soil loss estimated using RUSLE is Sainj valley is 541.52 tons/ha/yr. According to Soil risk classes it is observed that 0.84% area is at risk under High and Extremely high erosion classes. However there is a need to have the direct field measurements of soil erosion in the watershed to confirm and validate the results of USLE prediction. Therefore future works are required for monitoring and sediment load in the rivers and measurement sediment deposition in river and other water bodies that exists in the valley

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