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Modeling Soil Erosion Vulnerability Using RUSLE: A Case Study Upstream of Nangal Reservoir, India

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Abstract

Simulation of soil erosion is an important phenomenon in watershed management studies because of the dynamic nature of soil. The present study demonstrates the capabilities of remote sensing coupled with GIS to extract soil erosion vulnerabilities using RUSLE model. Therefore this study understands spatial distribution of soil erosion at a macro-watershed scale. The input parameters for RUSLE model include the rainfall and erosivity (R) derived using the TRMM satellite precipitation product for a long term implementing regression model. The soil erodibility (K) factor is estimated using available soil map, and the topographic factor (LS) from 12m ALOS PALSAR DEM. The management practice information was extracted from the land use / cover map based on 30m multi spectral LANDSAT-8 of three season datasets. The RUSLE model predicted very low, low, moderate, high and very high erosion in 84.8%, 7.9%, 4.4%, 2.3% and 0.7% of reviewed area, respectively. The results were validated with ground information and NDVI, being the main identifiers of soil erosion. As presence of high vegetation indicates higher strength to hold the soil particles together and prevent soil erosion, correlation coefficient was generated to find accuracy of the results with NDVI of the area. The strong positive correlation (0.5) provided scientific support that prediction of soil erosion by RUSLE can be effectively used for watershed management and combating action plan for soil erosion.

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1 INTRODUCTION

Climate change is expected to impact on soil erosion to greater extent (Gupta and Kumar, 2017) because spatial and temporal patterns of long term soil erosion and deposition dynamics are results of complex interactions. Several natural processes of the Earth system dynamics such as rainfall, flowing water, underground water, vegetation growth, soil detachment, transport etc. has a great role in soil erosion. Erosion processes driven by hydrological factors are extremely complicated therefore over the years researchers are trying to find solutions to predict soil erosion quantitatively over large landscapes (Finlayson and Montgomery, 2003). Soil erosion has currently evolved as a global environmental issue which is responsible for nearly 85% of land degradation around

the globe, reducing over time the global crop productivity by 17% (Nyesheja et al., 2019). Soil erosion therefore adversely affects the rate of crop yield and water quality (Lal, 1998). Due to this worldwide rise in concern, estimating soil erosion by different models at catchment levels has become very popular because it helps to provide both quantitative and qualitative estimation (Phinzi et al., 2019). Models developed till date to calculate soil erosion can be broadly divided into (a) empirical, (b) conceptual and (c) those based on physical processes (Aksoy and Kavvas, 2005; Kinnell, 2010). Universal Soil Loss Equation (USLE) is an empirical model introduced in the mid-1960s, this model gained wide popularity

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over time (Wischmeier and Smith, 1965). Over the past few decades, USLE has undergone several significant modifications and up gradation resulting to improved versions of empirical model such as the Modified USLE (MUSLE) developed by Williams and Berndt, 1977, then came Soil Loss Estimation Model for Southern Africa (SLEMSA) developed by Elwell (1977), Revised USLE (RUSLE) proposed by Renard et al., (1991) and Renard et al. (1997), European Soil Erosion Model (EuroSEM) (Morgan et al., 1998), USLE-M (Kinnell and Risse, 1998), and RUSLE (Foster et al., 2003). Amongst these models, RUSLE has been proven to be the most frequently used empirical model because it is also computer based model which provides a clear perspective for understanding the interaction of erosion and its causative factors (Alexakis et al., 2013). The biggest advantage of RUSLE is that it can be stimulated in the Geographic Information System (GIS) environment where satellite based datasets are used to derive several factors for the model as input parameters. Annual soil loss is estimated from the combination of the six factors contained in RUSLE: rainfall erosivity (R), soil erodibility (K), slope length (L), slope steepness (S), soil use and management (C) and support practices (P).

Remote sensing provides several important inferences from the earth observation data and allow us to gain insights into interactions between physical processes and environmental conditions that control erosion and landform evolution. Satellite derived images are preferred than traditional methods which are related to field measurements because although they gave detailed and accurate measurement at plot scale but

employing this methods at catchment levels are really difficult and require considerable amount of time, money, and effort. RUSLE provides an ideal framework for assessing soil erosion and its factors (Ganasri and Ramesh et al., 2016). The RUSLE model can identify soil loss possibility in GIS environment by pixel cell-by-cell method which helps to recognize individual spatial classes of the soil erosion in a big area effectively (Shinde et al., 2010). RUSLE model can be calculated at different geospatial scales in the digital platform. The research objectives of this study are: (1) to develop a methodology that combines remote sensing data and GIS with RUSLE to estimate spatial distribution of soil erosion at a macro-watershed scale with validation of the results using rigorous field work over the study area.

2 MATERIALS AND METHODS

2.1 Study Area

The present study was carried out over a macro-watershed upstream of Nangal reservoir with a total area of 8390 ha, selected mainly because of the spatial diversity of plant cover and the variety of soil classes and slope (Figure 1). The climatic characteristics indicate generally dry hot summer (except in the south-west monsoon season) and a bracing cold winter. The temperature ranges from minimum of 4°C in winter to 45°C in summer. The study area lies in the foothill regions of the Siwaliks where potential soil erosion rate is maximum. The point of interest in the study was to see whether RUSLE integrated in GIS environment was being able to be captured the soil erosion at this spatial scale and variation.

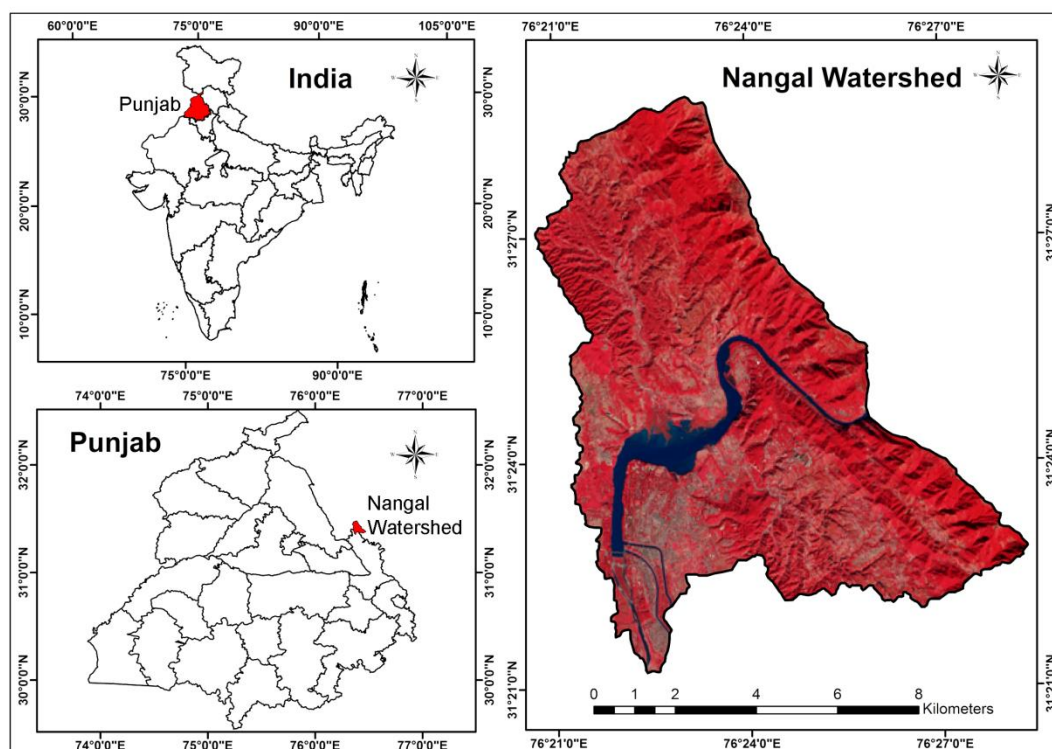


Figure 1. Study area: Nangal watershed of Punjab, India

2.2 Data Used

Three sets of Landsat-8 images (Kharif, Zaid and Rabi) were used in this work for generating thematic layers of land use / land cover (Table 1). ALOS PALSAR digital elevation model was used to derive elevation data. Rainfall data used for deriving R factor used in RUSLE was generated using Tropical Rainfall Mapping Mission (TRMM) datasets of last 18 years. Available soil map on 1:50000-scale was used for soil erodibility (K) extraction. Field survey was also conducted in three different seasons for validation of the final output by collecting GCPs.

2.3 Analysis and Visualization

Implementation of the RUSLE model in GIS involves creating a work flow in computer based environment that includes input data processing, model computation, and analysis of results (Figure 2). The GIS provided powerful tools for analysis, visualization of modeling

and specialized tools to perform model calibration and validation.

2.4 RUSLE Model

RUSLE is often used to monitor soil erosion in agriculture watersheds ranging from macro to mini watersheds across the world (Udayakumara et al., 2010). This model was particularly selected for this study because of its demonstrated effectiveness. The RUSLE (Renard et al., 1997) model can be expressed as equation (1) and the methodology followed to map soil erosion.

$$A = R \times K \times LS \times C \times P$$

A = Computed soil loss per unit area per year (t/ha per year); R = Rainfall erosivity factor (MJ mm ha⁻¹h⁻¹year⁻¹); K = Soil erodibility factor (t ha MJ⁻¹mm⁻¹); LS = Slope length and steepness factor (dimension less); C = Cover management factor (dimension less); P = Support practice factor (dimension less).

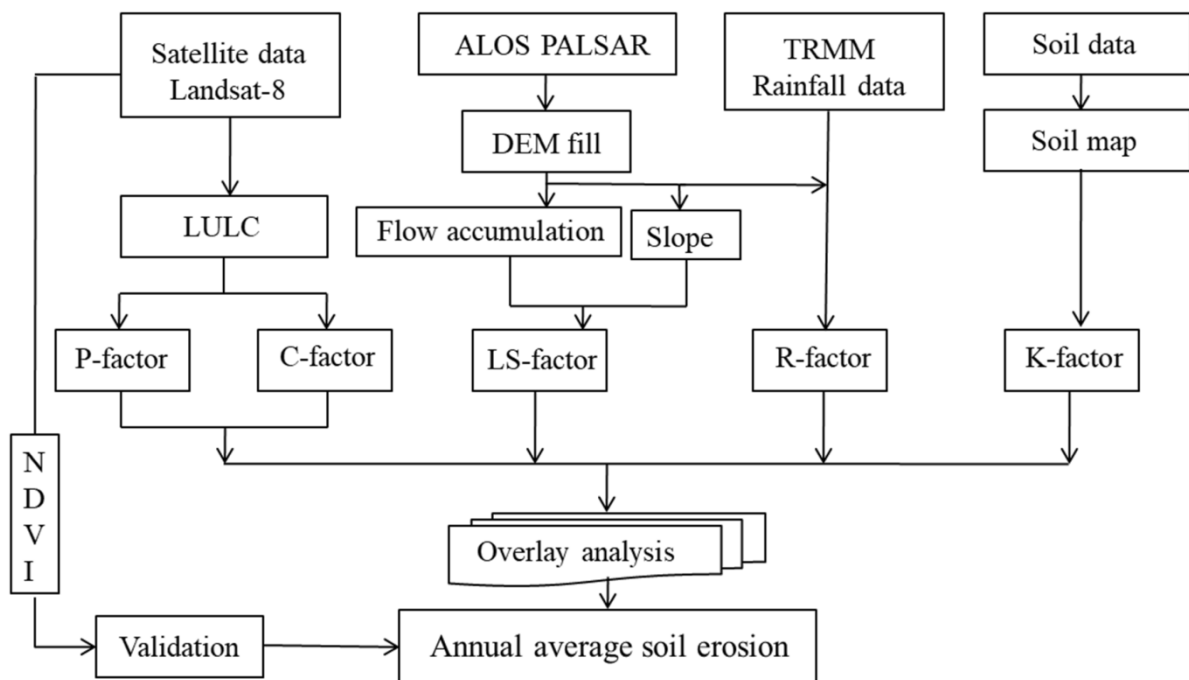


Figure 2. Methodology

Table 1. Data

Data	Source	Resolution
Digital Elevation Model	https://urs.earthdata.nasa.gov/	12.5 m
LANDSAT 8-OLI	www.earthexplorer.com	30 m
Soil data	Soil and Land Survey of India	1:50000
Rainfall data	TRMM (Monthly Data) https://pmm.nasa.gov/data-access/downloads/trmm	0.25°×0.25°

2.4.1 Rainfall Erosive Factor (R)

The rainfall erosivity factor is measured by rainfall intensity thus R basically explains the effect of raindrop on the ground. The modeling of R factor in GIS environment requires continuous satellite retrieved precipitation data. Therefore, monthly rainfall data product of TRMM satellite was downloaded over the study area for 18 years (1998-2015) and used to calculate the R-factor. Random 50 points were plotted over the study area. The locations and altitude of each point was calculated. Multiple regression models were used to derive a coefficient against each point's altitude, longitude, latitude and rainfall. Finally rainfall intensity was calculated using the equation given by Van der Kaniff *et al.* (1998).

$$R = a \cdot p_j$$

p_j is rainfall intensity in mm, a = coefficient derived from the multiple regression model.

2.4.2 Soil Erodibility Factor (K)

Soil erodibility is a function of soil texture, structure (e.g., macro porosity, aggregate properties), organic matter content, hydraulic properties and wetness of soil due to rain water and runoff (Blanco-Canqui and Lal, 2008). In this study available soil map was used to derive the soil erodibility (K) classes using standard classification scheme (Table 2). Since this watershed has thick forested layer whereas detailed field survey were not possible.

2.4.3 Slope Length and Steepness Factor

The topographical factors slope length (L) and the slope steepness (S) represents a ratio of soil loss below specified condition to any site (Ganasri and Ramesh., 2016), it is a unit less factor. The highest and the lowest slope represent the maximum potentiality of soil erosion as LS factor generate high overland flow velocity and similarly higher runoff (Zhao *et al.*, 2020). To obtain slope length (L) and slope steepness (S), ALOS PALSAR DEM data was used. This resolution was chosen by accurately defining flow direction in the watershed, using the "flow direction" tool of the Arc GIS software. Slope length corresponded to 10.0 m, when water flow was perpendicular to the pixel line and 14.14 m when it was diagonally oriented. The slope length factor was computed using the equation below:

$$L = (\mu/22.1) m$$

Where, L = Slope length factor, μ = horizontal projected slope length (m)

m = slope length exponent, (μ =flow accumulation $\times$ cell size)

In this equation 'm' slope length varies based on slope steepness, m equals 0.5 if the slope is 4.5% or

more; 0.4 if the slope is 3-4.5%; 0.3 if the slope is 1-3% and 0.2 of uniform gradient of less than 1% (Wischmeier and Smith, 1978).

2.4.4 Cover Management Factor (C)

The C-factor is important because it helps to indicate how soil loss potential will be distributed in time under different land use/land covers and during crop rotations, construction or other management activities (Thomas *et al.*, 2018). To identify the C-factors, GIS techniques were used to extract thematic layer of land use / land cover of the study region from the satellite imagery. Then the literature based C-factor values were assigned for different land use / land cover in the study area according to Table 3.

2.4.5 Support Practice Factor (P)

Support practice factor represents the positive impacts of support practices on the soil it is often described as the ratio of soil loss by a support practice to that of straight-row farming up and down the slope (Renard and Foster, 1983). The P-factor indicates conservation practices adopted in the watershed including terracing, bunding, strip cropping, check dam etc. The value of P-factor ranges from 0-1, in which 0 values represent high-quality preservation practice and the value resembling one indicates poor protection practices (Morgan *et al.*, 1998). In catchment areas often several mitigation practices like terracing and contour tillage among other practices cannot be reflected in land use maps (Fu *et al.*, 2005). Therefore, P-factor information was calculated through empirical method proposed by (Wener, 1972):

$$P = 0.2 + 0.03 \times S$$

Where, S = Slope steepness, P = P-factor

2.4.6 Annual Soil Loss (A)

Soil loss determined using the RUSLE model using the Arc GIS software, was classified into five classes of soil loss: 0-2; 2-4; 4-6; 6-8 and >8 t/ha/yr.

3 RESULTS AND DISCUSSIONS

3.1 Rainfall Erosivity Factor (R)

Since many studies often indicate that rainfall is the main indicator of soil erosion in any region therefore the pattern of rainfall in this region needs to be studied carefully. The monthly rainfall datasets were summed up to get the annual rainfall of each year over the study area. More than 400 mm of rainfall is witnessed in all the years and an average of 800 mm has been observed in this region over 18 years (Figure 3). In the present analysis average annual rainfall was used for R-factor calculation (Figure 4a).

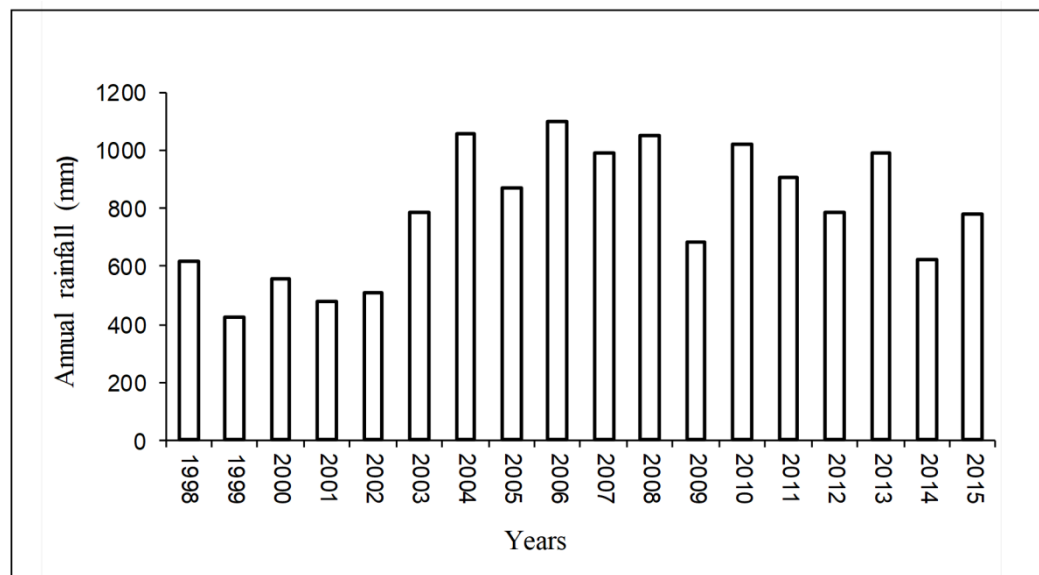


Figure 3. Rainfall pattern (1998-2015)

Table 2. Classification scheme for K-factor

Texture class	Average	Less than 2%	More than 2%
Clay	0.22	0.24	0.21
Clay loam	0.30	0.33	0.28
Coarse sandy loam	0.07		0.07
Fine sand	0.08	0.09	0.06
Fine sandy loam	0.18	0.22	0.17
Heavy clay	0.17	0.19	0.15
Loam	0.30	0.34	0.26
Loamy fine sand	0.11	0.15	0.09
Loamy Sand	0.04	0.05	0.04
Loamy very fine sand	0.39	0.44	0.25
Sand	0.02	0.03	0.01
Sandy clay loam	0.20		0.2
Sandy loam	0.13	0.14	0.12
Silt loam	0.38	0.41	0.37
Silt clay	0.26	0.27	0.26
Silt clay loam	0.32	0.35	0.3
Very fine sand	0.43	0.46	0.37
Very fine sandy loam	0.35	0.41	0.33

Table 3. Classification scheme for C-factor ([Kent, 1972](#))

Land use/land cover	C-factor
Degraded forest	0.0006
Dense forest	0.003
Double cropped	0.20
Fallow	0.80
Single cropped	0.62
Steeply sloping	0.80
Undulating land with or without grass	0.14
Water body	1.00

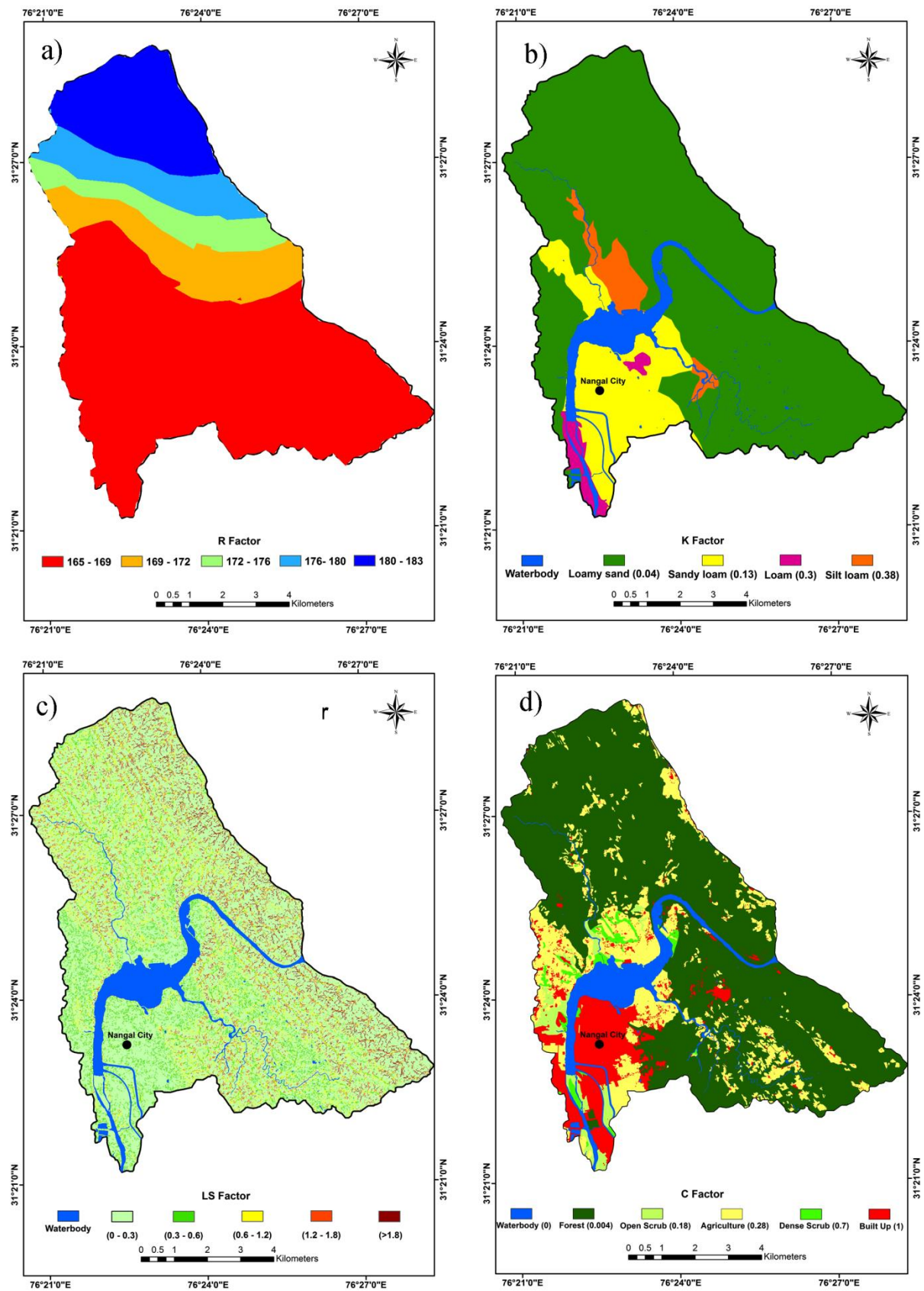


Figure 4. Thematic maps: (a) Rainfall erosivity factor, (b) Soil erodibility factor, (c) Slope length and steepness factor and (d) Land cover management factor

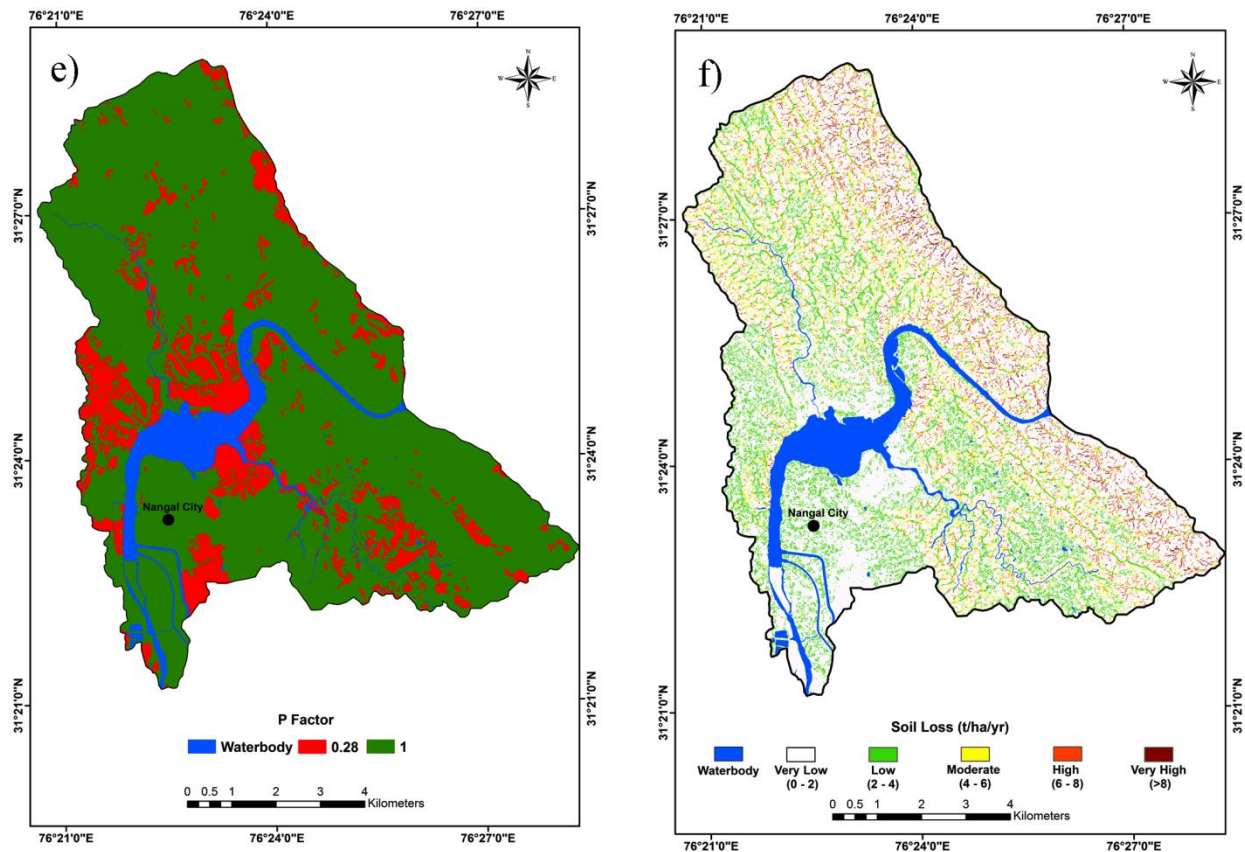


Figure 4. Thematic maps: (e) Support practice factor and (f) Soil loss estimations

The estimated R-factor ranges from 165 to 183 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ in the study area. The R-factor calculated has been divided into five major zones as seen in Table 4 and Figure 4(a). 165-169 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ covers 5307 ha, 169-172 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ covers 667 ha, 172-176 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ covers 563ha, 176-180 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ covers 526ha and 180-183 $\text{mm.ha}^{-1} \text{hr}^{-1}/\text{year}$ covers 1327 ha. This region experiences orographic type of rainfall, the foot hill region in the northern part of the study area experiences heavy rainfall and gradually the erosivity rate decreases as the land slopes down towards the plain.

Table 4. Rainfall erosivity factor

R-factor	Area (ha)
165-169	5307
169-172	667
172-176	563
176-180	526
180-183	1327
Total	8390

3.2 Soil Erodibility Factor (K)

The study area is classified into four major soil erodibility classes based on soil texture. The study area comprises of four major soil textural classes i.e. loamy sand, sandy loam, silt and loam (Figure 4b). Maximum area is covered by loamy sand with an average soil

erodibility factor of 0.3. The sandy loam soils possess an average erodibility factor of 0.13. Silty loam soils found in small patches provides an average of 0.38 soil erodibility factor. Very small patches of loam soils are found in the southern part of the study area. The silt loam soils K value as 0.38 occupies 328 ha of land, whereas sandy loam soils and occupies 1504 ha of land. Table 5 shows the distribution of the soil erodibility factor.

3.3 Slope Length and Steepness Factor (LS)

Topographic factor represents the basic influence of slope length and slope steepness on erosion process. LS-factor was calculated in ARCGIS by considering the flow accumulation and slope in percentage as the input factors. From the analysis, it is observed that the value of topographic factor increases as the flow accumulation and slope increases. The general slope of the region ranges between 0 and 1.8 from east to west. Maximum slope of the area is between 0 and 0.3 which occupies 6895 ha of land in the study area. Only 53 ha of land is under very high steepness factor influence which is in the hilly forested region bounded on the right hand part of the study area. Table 6 shows the distribution of slope length and steepness factor and Figure 4c demonstrates slope steepness factor.

3.4 Cover Management Factor (C)

Land use and land cover helps to understand land utilization pattern of any region and in turn land utilization helps to understand the erosion rate of that

particular land cover. Thus, cover management is one of the crucial factors. The study region is mainly covered by dense forest, which is around 5448 ha in the eastern part and 0.004 is the C-factor in this region because the rainforest in this region contains huge tall trees with high density canopy cover which protects the ground below from random erosion factors (Figure 4d). Around 1301 ha land is covered by crop land which is vulnerable because this region goes under three cropping season thus soil particles are open to more erosion this region has a cover factor of around 0.28. Urbanization has contributed towards erosion to a great extent and it is most vulnerable land use because it spoils the top soil totally and covers an artificial concrete floor. Thus, 787 ha of land in the study area gave C-factor of 1. A very small part of the land is bare which are almost a waste lands it covers an area of 183 ha and has a C-factor of around 0.18 this land is affected only by natural geomorphic agents and not by any other external agents. Land without scrub has been given 0.7 C-factor because scrub does not have much of canopy cover to protect the soil. Water body in this region covers around 554 ha which is 0 C-factor because it is the least receptive land cover towards erosion. Table 7 shows crop management factor distribution.

3.5 Support Practice Factor (P)

The analysis clearly shows that the area can be divided into two major classes according to support factor. The crop land in this region although is prone to more erosion due to exhaustive agriculture practices but these regions also go for green manuring at frequently after each crop rotation in three different seasons therefore, P-factor in this region is 0.28 (Figure 4e). However, rest of the land use and land covers like water body, dense forest, land without scrub, land with scrub and settlement does not have any managerial practices over this region therefore, 1 is distributed over these areas (Table 8).

3.6 Annual Soil Loss (A)

Integration of soil erosion parameters in RUSLE model in GIS environment provided annual soil loss at pixel by pixel basis to study the spatial distribution of soil erosion in the study area (Table 9, Figure 4f). The area can be

graded into five vulnerability zone like very low, low, moderate, high and very high.

It is seen that 7116 ha area is under erosion rate of $0-2 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$, 663 ha area is under erosion rate of $2-4 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$, 370 ha area is under erosion rate of $4-6 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$, 370 ha area is under erosion rate of $6-8 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$, 186 ha area is under erosion rate of $6-8 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$ and 55ha area is under erosion rate of $6-8 \text{ t}^{-1}/\text{ha}^{-1}/\text{yr}$. Immediate attention needs to be given to the 55 ha of land which is very highly prone to soil loss. Very high erosion rate is witnessed in the lower foothill parts of the hilly mountains because the river gushes down the slope and erodes the slopes by lateral and vertical movement of water downwards. Since Nangal Dam controls the water management factors in two major agricultural states of Punjab and Haryana, it can be affected adversely any time due to the high erodibility in the upper reaches of the study area, thus management practices needs to be implemented properly to save the natural resource in the region.

3.7 Validation of Results

Several workers reported integration of RUSLE in the GIS environment sans validation of soil loss estimation, which needs to be carried out to evaluate the authenticity of the results. The study area was very challenging as most of the places were inaccessible due to geographical hindrances and being upstream of the reservoir. Therefore, validation was done by collecting maximum points possible in the lower reaches on both sides of the river and few points in the lower foothills of the forested hilly areas. Random places were chosen and total of 35 points were visited, and ground information was gathered in correspondence to their latitude and longitude values using GPS. Further a Normalized Differential Vegetation Index (NDVI) map was generated in the GIS environment which included three seasons' datasets to extract the vegetation cover percentage in the study area and a correlation of 0.5 was found between the NDVI and the soil loss erosion map $\text{t}/\text{ha}/\text{yr}$ (Figure 5). This positive strong correlation suggests quite good accuracy level of the soil loss estimation map generated in the GIS environment (Figure 6).

Table 5. Soil erodibility factor

Texture	Average	Less than 2%	More than 2%	Area (ha)
Loam	0.3	0.34	0.26	184
Loamy sand	0.04	0.05	0.04	6374
Sandy loam	0.13	0.14	0.12	1504
Silt loam	0.38	0.41	0.37	328
Total				8390

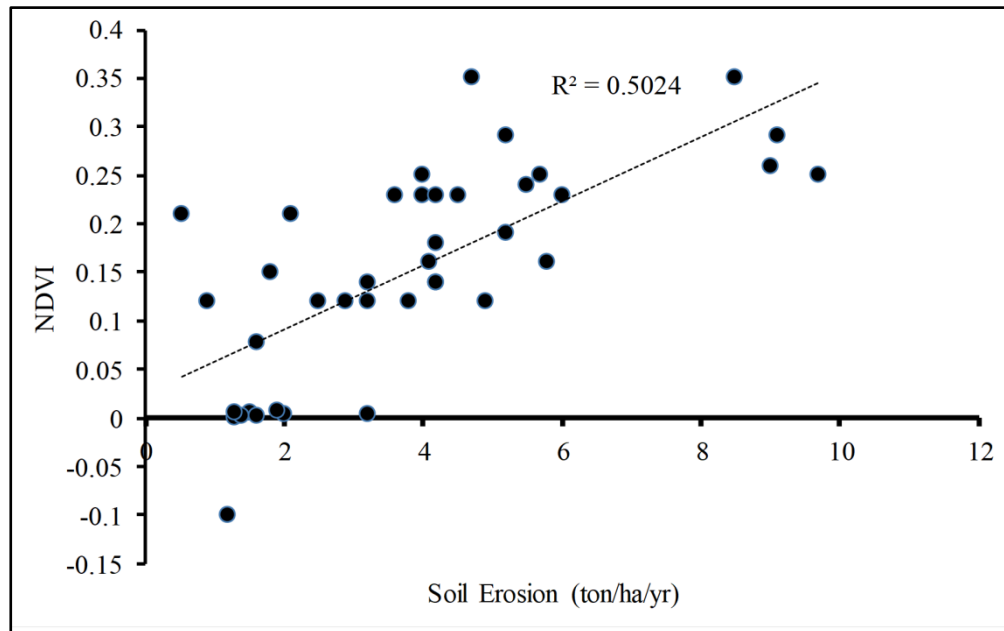


Figure 5. Correlation between vegetation cover and soil losses

Table 6. Slope length and steepness factor

LS-factor	Area (ha)
0 -0.3	6895
0.3 -0.6	785
0.6-1.2	442
1.2 - 1.8	214
>1.8	53
Total	8390

Table 7. Crop management factor

Land use classes	C-factor	Area (ha)
Water bodies	0	554
Dense forest	0.004	5448
Land without scrub	0.18	183
Crop land	0.28	1301
Land with scrub	0.7	117
Settlement	1	787
Total		8390

Table 8. Support factor

Land use/ land cover	P-factor	Area (ha)
Crop land	0.28	1301
Water bodies	1	7089
Dense forest	1	
Land without scrub	1	
Land with scrub	1	
Settlement	1	
Total		8390

Table 9. Soil losses

Soil loss (t/ha/yr)	Area (ha)	Vulnerability
0-2	7116	Very low
2-4	663	Low
4-6	370	Moderate
6-8	186	High
>8	55	Very high

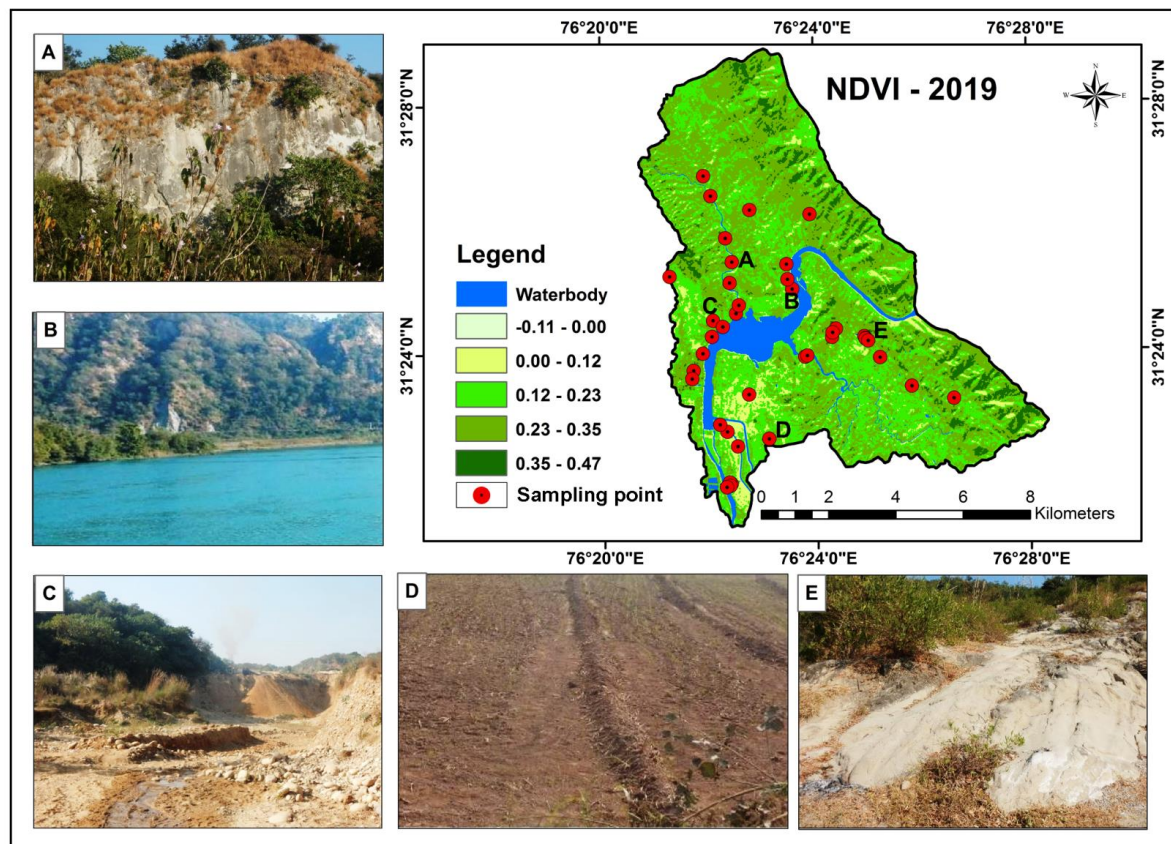


Figure 6. Distribution of ground truth points with photographs

4 CONCLUSIONS

RUSLE can be easily integrated in the GIS platform and the inputs required for this model can be derived from multi-sources like satellite based data, available maps and in-situ observations. The topographic parameters can be readily extracted from DEMs facilitating GIS based erosion modeling. In spite of advances in sensor technologies, uncertainty and coarseness of critical parameters like spatial distribution of soils, and rainfall still remain the weak components of erosion modeling using RUSLE. The model results reasonably match with the observed field survey and majority of the area falls under moderate to low risk of soil erosion. Only, 55 ha of land is under threats of very high erosion rate per year. The results obtained from the study can assist in developing management scenarios and provide options to policy makers for managing soil erosion hazards in the most efficient manner for sustainable management plans.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest associated with this publication. This research article is in compliance with the ethical standards of this journal. This article does not contain any information that requires informed consent.

ABBREVIATIONS

ALOS: Advanced Land Observation Satellite; **DEM**: Digital Elevation Model; **GIS**: Geographical Information System; **NDVI**: Normalised Differential Vegetation Index; **PALSAR**: Phased Array type L-band Synthetic Aperture Radar; **RUSLE**: Revised Universal

Soil Loss Equation; **TRMM**: Tropical Rainfall Measuring Mission.

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