Soil Erosion Assessment Using the RUSLE Model and Geospatial Techniques (Remote Sensing and GIS) in Kalyani River Watershed of Uttar Pradesh,India

Abstract

Soil erosion significantly impacts environmental sustainability, agriculture, and water quality. This study examines soil erosion in the Kalyani River within the Nindoora and Fatehpur blocks of Barabanki District, Uttar Pradesh, India, where seasonal fluctuations and steep banks exacerbate the issue.The region experiences severe soil degradation due to uncontrolled land use, deforestation, over-cultivation, overgrazing, and biomass exploitation driven by population growth. To address this, GIS and Remote Sensing technologies were utilized, employing the Revised Universal Soil Loss Equation (RUSLE) model to identify erosion-prone areas. The RUSLE model involves calculating parameters such as the runoff-rainfall erosivity factor (R), soil erodibility factor (K), topographic factor (LS), cropping management factor (C), and support practice factor (P). Layer-wise thematic maps of each factor were generated using a GIS platform, incorporating various data sources and preparation methods.The study's results indicate that value of K factor is found to be 0.025 indicates that the soil is relatively resistant to erosion.Higher LS factor values are scattered across the area, especially near the Kalyani River. The southeastern regions show higher C factor values, indicating less effective soil cover and management against erosion. It has also been estimated that 90% of the Kalyani River watershed faces low soil erosion risk (0–10 ton/ha/yr), while 0.20% primarily near riverbanks experiences high to very high erosion risk (10–40 ton/ha/yr). Sandy and sandy loam soils near riverbanks, exacerbated by seasonal water level fluctuations and steep slopes, are highly prone to erosion. The RUSLE-based GIS approach allowed for the precise identification of erosion hotspots, facilitating the development of targeted soil conservation strategies to mitigate soil degradation and promote sustainable land management.

Keywords: Revised Universal Soil Loss Equation (RUSLE), Geographic Information System (GIS), Remote Sensing (RS), digital elevation models (DEMs).

1. Introduction

"Soil is an important non-renewable and useful resource that supports 95% of food production through plant growth and agriculture" (FAO, 2015a, 2015b). Sustainable agriculture depends on soil quality (Acton and Gregorich, 1995), but overuse of land has increased soil erosion, lost biodiversity, reduced productivity, and ultimately ecosystem damage (Pimentel and Kounang, 1998; Pimentel et al., 1995; Ganasri and Ramesh, 2016;). Soil erosion results from over land use, agricultural expansion, international climate trade, and changing agricultural techniques (Yang et al., 2023).

Estimating soil erosion on a global scale is critical for addressing multiple environmental, agricultural, and socio-economic challenges.Global soil erosion estimates have increased significantly over time. In 1984, Brown and Wolf estimated annual losses at 25.4 billion tons, while Myers in 1993 suggested a much higher figure of 75 billion tons per year. Recently it has been estimated approximately 24 billion tons of soil erosion globally.However, Lal and Stewart (1990) reported that India experiences an annual soil loss of 6.6 billion tons which has increased to 16.4 tons per hectare per year as reported by the Ministry of Agriculture (or other relevant authority based on recent studies).Since it can take up to 1,000 years for just a single centimetre of soil to form (FAO, 2015a), the rapid rate of soil loss 10 to 40 times faster than soil formation poses a significant threat to food security and environmental quality (Pimentel, 2006). Additionally, soil erosion exacerbates deforestation, as the loss of agricultural land often leads to further forest clearing to compensate for the decline (Myers, 1989).

Accurately quantifying soil loss is essential for implementing effective soil conservation measures due to the significant environmental and economic impacts of rapid soil erosion (Lal, 1998). Two primary models are used to quantify soil erosion: physically based models and empirical models (Bhattarai and Dutta, 2007). Physically-based models require many parameters and datasets, while empirical models, like the Universal Soil Loss Equation (USLE) and its revised version (RUSLE), are simpler and widely used for estimating sediment yield and surface soil loss (Renard et al., 1991). The Revised Universal Soil Loss Equation (RUSLE) is popular for estimating soil loss at various spatial scales and is effective when integrated with GIS and remote sensing for predicting soil erosion and its spatial distribution (Jasrotia and Singh, 2006). Due to its ease of use and compatibility with GIS, RUSLE can estimate soil loss on a cell-by-cell basis, allowing the delineation of the spatial pattern of soil loss over large areasand at watershed level(Tang et al., 2015; Ganasri and Ramesh, 2016; Kushwaha and Bhardwaj, 2016; Kushwaha and Yousuf,2017; Ghosal and Bhattacharya, 2020;Sharma and Sharma, 2022; Salazar et al. 2024).Also, Dash et al. (2023) studied watershed of Chilika Lake, the RUSLE model combined with remote sensing and GIS tools provided detailed assessments of soil loss, aiding in the development of targeted soil conservation strategies. The Reddy et al. (2024) demonstrated the comprehensive approach employing RUSLE and GIS was used to evaluate soil erosion risk, identifying critical zones requiring immediate intervention in Karnataka's Ganjigatti sub-watershed. This study aims to use the Revised Universal Soil Loss Equation (RUSLE) with GIS and remote sensing to quantify annual soil erosion rates in the Kalyani River watershed.

2. Methodology

2.1 The Study Area

Nindoora and Fatehpur blocks, located in the Barabanki District of Uttar Pradesh, lie approximately 29 km east of Lucknow within the Ayodhya division of the Awadh region. These blocks are primarily agricultural, benefiting from fertile alluvial soil due to their proximity to rivers like the Kalyani and Ghaghra. The topography is predominantly flat to gently undulating, characteristic of the Indo-Gangetic Plains, with elevations ranging between 100 and 150 meters above sea level. The steep banks of the Kalyani River create narrow valleys and occasional floodplains, which influence soil erosion and agricultural practices. The region has a subtropical monsoon climate, with hot, dry summers (March to June) where temperatures range from 28°C to 45°C, and a monsoon season (July to September) bringing significant rainfall between 800 to 1,200 mm annually. Winters (November to February) are mild, with temperatures ranging from 5°C to 20°C. The fertile alluvial soil supports diverse crops, including wheat, rice, sugarcane, and pulses, while sandy loam and clayey soils are found along the riverbanks. Land use is dominated by agriculture, interspersed with small patches of natural vegetation and water bodies. The total study area of these blocks encompasses approximately 124 SqKm for Nindoora Block and 840 SqKm for Fatehpur Block, providing a vast and diverse landscape ideal for investigating soil erosion, agricultural productivity, and the application of geospatial techniques in watershed management.

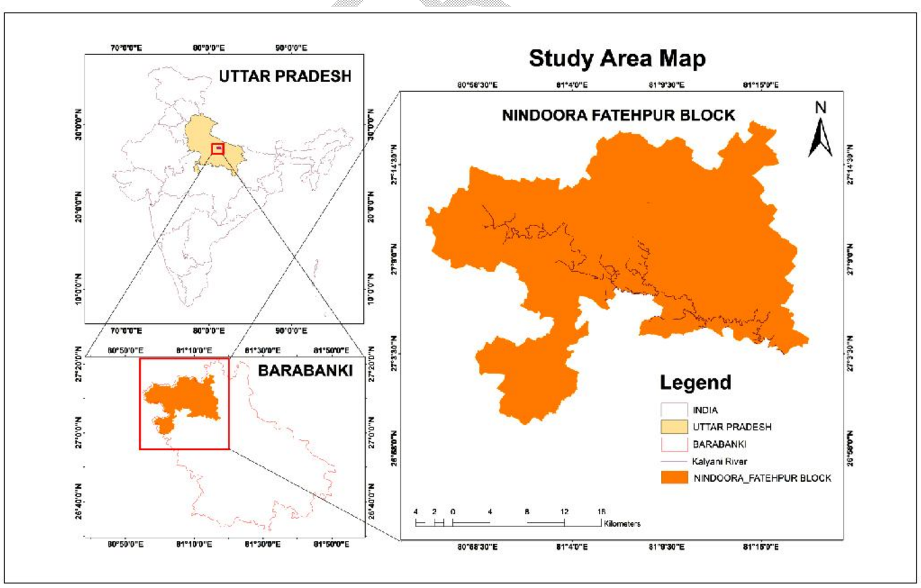


Figure 1. Location map of the study area ~~Study area.~~

2.2 Data Source Processing

The analysis utilized open-source data acquired through remote sensing techniques and secondary databases (Table 1). The SRTM DEM was sourced from the U.S. Geological Survey's Earth Explorer (https://earthexplorer.usgs.gov/), while Annual Mean Rainfall data was obtained from NASA Power (https://power.larc.nasa.gov/).Slope and flow accumulation were derived from DEM data, crucial for identifying erosion-prone areas and mapping runoff pathways in the RUSLE model. Vector data for the Digital Soil Map of the World is acquired from (https://data.apps.fao.org/map/catalog/srv/eng/catalog.s.).The cover management factor (C) was derived from high-resolution land use/land cover data obtained from the ESRI Land Cover dataset (https://livingatlas.arcgis.com/landcover/). The P factor map was created in ArcGIS by combining slope data with the land use/land cover map to evaluate spatial variations in conservation efficiency. For spatial analysis, all geospatial datasets were projected to the WGS 1984 Northern Hemisphere Zone 45 North coordinate system. The datasets, which originally had varying spatial resolutions, were resampled to a 30-meter resolution using the nearest neighbour technique in ArcGIS 10.8 and then clipped to the study area extent.

Table1 Datasets used for the RUSLE modelling and their sources

Data	**Spatial Resolution**	**Temporal**	**Source**
Digital Elevation Model	30 m	23 August, 2016	SRTM-1 Arc Second Global downloaded from USGS Earth Explorer (https://earthexplorer.usgs.gov/).
Land Use Land Cover	10 m	2023	ESRI Land Cover Dataset (https://livingatlas.arcgis.com/landcover/).
Annual Mean Rainfall	0.5 x 0.625 degree	January 1 2003 to December 31, 2022	Nasa Power (https://power.larc.nasa.gov/).
Digital Soil Map	1:5,000,000 scale	—	The Food and Agriculture Organization (FAO) vector data of the Digital Soil Map of the World https://data.apps.fao.org/map/catalog/srv/eng/catalog.s.)

2.3 Methods

Soil erosion, as well as sediment movement and deposition in rivers, lakes, and estuaries, have been ongoing challenges throughout geologic history, exacerbated by contemporary human activity. Many techniques such asUniversal Soil Loss Equation (USLE), Modified Universal Soil Loss Equation (MUSLE), Water Erosion Prediction Project (WEPP), Soil and Water Assessment Tool SWAT models have been used to find out the Soil Loss Erosion Map. In this study,the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS was used to estimate annual soil loss in the part of Kalyani River which lies in the Nindoora and Fatehpur. RUSLEis one of the most widely applied and universally accepted empirical models used to estimate average annual erosion potential (A) which includesrainfall-runoff erosivity factor (R), soil erodibility factor (K),slope length factor (L) and slope steepness factor (S), cover management factor (C) andconservation practice factor (P).The primary equation of the RUSLE method for predicting annual soil loss is as follows:A=R×K×C×P×LSoverall methodology of this study is shown in Fig.2.

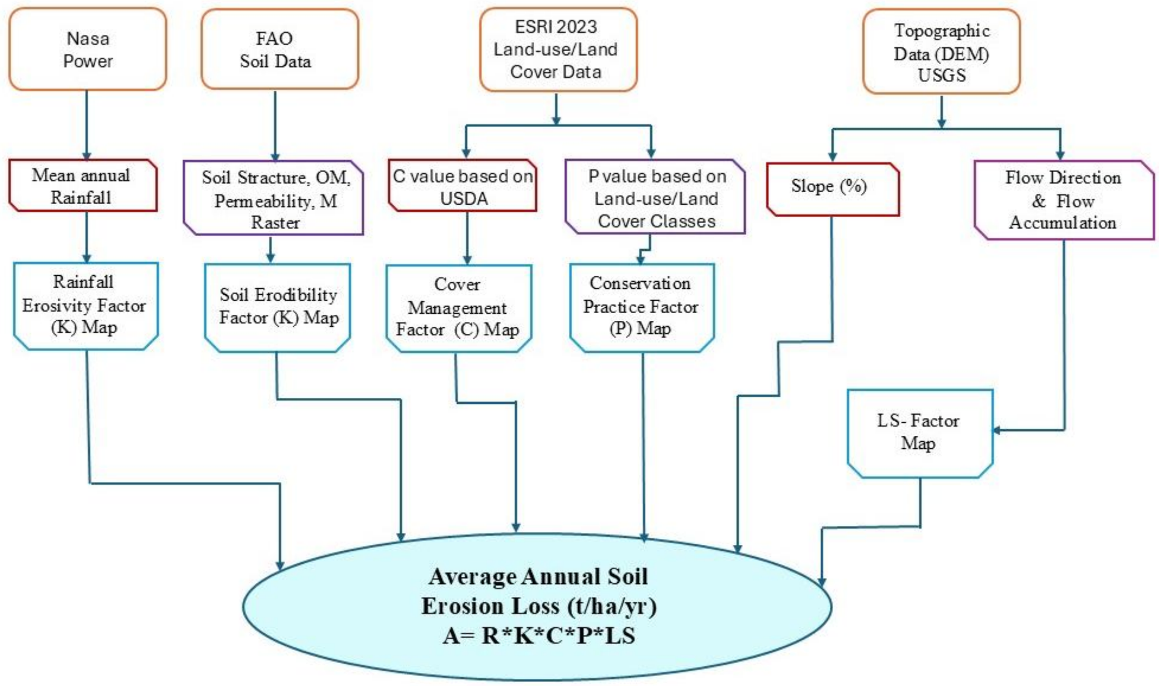


Figure 2. Flow chart showing the methodology adopted for soil loss estimation.

2.3.1 RainfallErosivity Factor (R)

The R factor was estimated using the formula adapted for Indian conditions by Babu et al. (2004). Similar formula has also been used by many researchers to find out the Rainfall Erosivity Factor(Jain et.al 2010;Ganasri et al. 2016; Patel et al. 2016; Saha et al. 2022)

$$R=81.5+0.375\times MAP \quad \textbf{(i)}$$

R is the Rainfall Erosive Factor, and MAP is the Mean Annual Precipitation (mm). Mean annual rainfall data was collected over 20 years from eight meteorological stations which is shown in Table 2. After that IDW interpolation techniques were used to generate the R factor map.

Table 2 Mean annual rainfall for the study area

DISTRICT	BLOCK	Stations	LONGITUDE	LATITUDE	Mean Annual Rainfall (mm) (2003-2022)
BARABANKI	NINDOORA	ANWARI	81.02333333	27.00111111	1043.775
BARABANKI	NINDOORA	JAFARPUR	81.10916667	27.23611111	1043.775
BARABANKI	NINDOORA	KASTURI KALAN	81.22777778	27.16694444	1043.775
BARABANKI	NINDOORA	KURSI	81.18611111	27.17222222	1043.775
BARABANKI	NINDOORA	NIGOHAN	81.025	27.22222222	1043.775

BARABANKI	FATEHPUR	BISHUNPUR	81.26111111	27.20277778	1043.775
BARABANKI	FATEHPUR	MOHAMMED PURKHAL	81.225	27.11111111	1043.775
BARABANKI	FATEHPUR	RAMPUR	81.18055556	27.25	1156.239

2.3.2 Soil Erodibility Factor (K)

The soil erodibility factor (K) is one of the most dominant factors impacting the determination of soil erosion using the RUSLE model. This factor depends on the soil's geological aspect such as soil permeability, soil structure, and organic matter content (USDA, 1951; Schwab et al., 1993). The greater the value of the Soil erodibility factor, the greater its vulnerability to erosion. In this study, the K factor was calculated using the model equation developed by Wischmeier et al. (1971)which was moreover utilized by numerous researchers (Das 2012; Saha et al 2022).

$$\boldsymbol{K} = \frac{(2.1\times10^{-4})(12-\mathrm{OM})\times M^{1.14}+3.25\,(\mathrm{Structure}-2)+2.5\,(\mathrm{Permeability}-3)}{100} \qquad \textbf{(ii)}$$

Where,

K is the soil erodibility factor.

OM is the percentage of organic matter.

M = is the product of the primary particle size fractions (% silt + % very fine sand) × (100 - % clay).

S = Soil structure code.

P = Permeability is a code for the soil permeability.

The soil data have been derived with the Food and Agriculture Organization (FAO) vector data of the Digital Soil Map of the World. The soil erodibility factor map (K) has been derived based on different soil types, textures, and organic matter composition (percent of humus) of the soils as shown in (Table: 3). The particle size parameter (M) was calculated using the percentage of silt with very fine sand and the percentage of all soil fractions other than clay. In (table 3) Higher K values indicate more erosion-prone soil.

$$\mathbf{M} = (\mathbf{M\%_{Silt}} + \mathbf{M_{Vsand}}) * (\mathbf{100} - \mathbf{\%_{clay}}) \qquad \textbf{(iii)}$$

The K factor in RUSLE represents soil erodibility, with higher values indicating greater erosion susceptibility. It is calculated using the percentage of silt (M%_Silt) and very fine sand (M_Vsand), excluding clay (%_clay),to reflect topsoil composition and assess soil's erodibility.

Table 3. Parameters used for Soil erodibility

Soil Map Unit Value	3685
% Sand	42
% Silt	36
% Clay	22
Organic Carbon % weight	1
Soil Unit Name	EutricCombisols
Organic Matter Contant (OM)	1
M	2808
Soil Structure	2
Soil Permeability	3
K_FACTOR	0.025

2.3.3 Topographic Factor (LS)

This study calculates the LS factor using the Unit Stream Power Erosion and Deposition (USPED) approach developed by Wilson et al. (2000). This method integrates flow accumulation and slope data to estimate potential soil erosion. By using flow accumulation and slope values from Digital Elevation Models (DEMs), the USPED approach effectively captures the influence of terrain on erosion patterns, helping to map and quantify areas at higher risk of erosion.

$$\mathbf{L = (m+1)\left(\frac{\lambda_A}{22.1}\right) m \quad (iv)}$$

Where:

L is the slope length factor
λ_A is the area of upland flow,
M is an adjustable value depending on the soil's susceptibility to erosion,
22.1 is the unit plot length.

$$\mathbf{S = \frac{Sin\,(0.01745 * \theta^0)}{0.09} n \quad (v)}$$

Where:

θ is the slope in degrees,
0.09 is the slope gradient constant, and
N is an adjustable value depending on the soil's susceptibility to erosion.

The combined LS factor is then calculated as:

LS=Power (“Flow Accumulation” ×{cellsize}/22.1,0.4)×Power(sin”(sloperasterdeg”×0.01745)/0.09,1.4×1.4(vi)

In this formula, flow accumulation derived from DEM using ArcGIS tools such as fill, flow direction, and flow accumulation represents the number of upstream cells contributing to the flow into a specific cell. The cell size corresponds to the grid resolution used to model the landscape. Following this, the LS factor map (Figure 3c) was generated using Equation (VI) through the raster calculator function in ArcGIS.

2.3.4 Cover Management Factor (C)

The cover management factor (C-factor) reflects the ratio of soil loss under specific vegetation cover to baseline soil loss (Morgan, 1994). It reflects how land cover affects erosion by intercepting raindrops, increasing infiltration, slowing runoff, and reducing water flow's transport capacity. In this study,a land use/land cover map was converted from raster to vector, assigned C-values based on USDA (1972)and RAO (1981) (Table 4)as demonstrated by Tirkey et al. (2013)then reclassified and converted back to raster to create the C-factor map.

Table 4. Crop management factor for different land use/land cover classes (source: USDA (1972),Rao (1981)

Land Use Class	**C – Factor**
Settlement	1.0
Vacant land	1.0
Quarry / Brick kilns	1.0
Crop land	0.28
Fallow land	1.0
Plantations	0.28
Dense forest	0.004
Open forest	0.008
Degraded forest	0.008
Land with scrub	0.7
Land without scrub	0.18
Marshy	0
Water bodies	0

2.3.5 Conservation Practice (P) Factor

The P factor quantifies the ratio of soil loss considering the influence of conservation practices, specifically accounting for the area's slope (Renard et al., 1997; Saha et al.2022).For agricultural land, the P factor values range from 0 to 1. If the value of P is approaching 0 indicate good conservation practice (indicating high erosion resistance) whereas value of P is approaching 1 indicate poor conservation practice(indicating no resistance). In other terms, the P factor values vary according to the type of agriculture applied and slope. In this study,P values were estimated based on slope values shown in table 5. High values correspond to areas of high slopes and vice versa. P-factor map was generated in ArcGIS, utilizing the land use/land cover map.

Table 5. Erosion control practice based on slope (Shin 1999; Imajjaine and Belfoul 2020)

Slope %	Contouring
0.7	**0.55**
7-11.3	**0.6**
11.3-17.6	**0.8**
17.6-26.8	**0.9**
26.8>	**1**

3. Results and Discussion

3.1Rainfall erosivity factor (R)

Interpolated maps which were used to calculate the R factor shown in (Fig: 3a) illustrate the spatial distribution of rainfall over the study area, where an increasing trend of the average annual rainfall is evident from the north-western portion towards the north-eastern and south-eastern portions. The average annual rainfall can be as low as 1043.78 mm per year in the west and southeast, increasing to as high as 1156.22 mm per year in the northeast. Since the R factor is directly dependent on the quantity of rainfall, the areas with higher average annual precipitation also accounted for higher values of the R factor.

3.2. Soil erodibility factor (K)

In this study area,the spatial distribution of the K factor was shown in (Fig: 3b).The region is predominantly composed of EutricCambisols (loamy soils), with K-factor values around 0.025 t·ha·h per ha·MJ·mm. The K factor, a measure of soil erodibility, reflects the soil's susceptibility to erosion. A value of 0.025 indicates that the soil is relatively resistant to erosion, which is advantageous for preserving soil health and preventing land degradation.

3.3. Topographic Factor (LS)

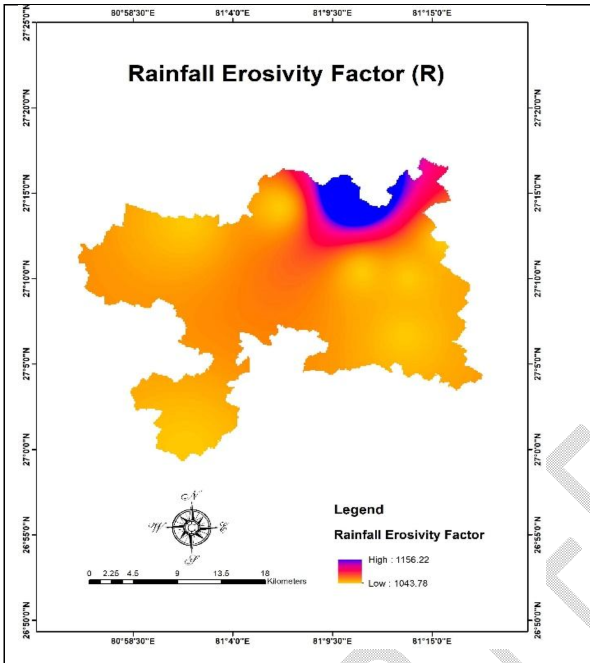
The LS factor represented in (Fig. 3c)which was calculated using Equation (vi), The mapshows the spatial distribution of the topographic factor of the study area. Range of LS factor lies between 0 to 50.46 while lower values ranging from 0 to 0.98 are predominant, higher values ranging from 29 to 50.46 are scattered over the study area and are also present along the bank of the Kalyani River.Higher LS factors indicate stronger runoff energy capable of detaching and transporting soil particles, whereas lower LS factors reflect weaker runoff energy with less potential for soil detachment and transport.

3.4. Cover management factor (C)

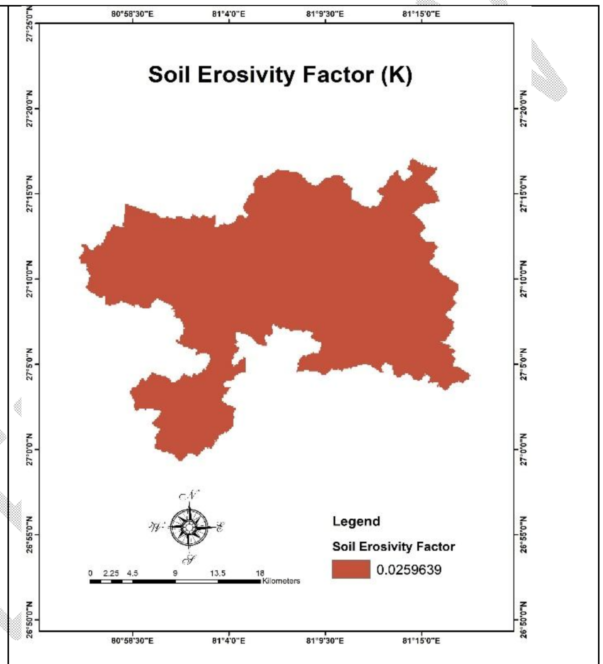
The C factor values in the study area range from 0 to 0.28 represented in (Fig 3d). Higher C factor values are observed in the southeastern regions, indicating areas where soil cover and management practices are less effective in preventing erosion. These higher values suggest increased susceptibility to soil erosion due to inadequate vegetation cover or poor land management strategies. In contrast, lower C factor values are found in the northwestern and northeastern regions, where cover management practices are more effective in minimizing soil erosion. The extensive green areas on the map (Fig: 3d) highlight regions with effective soil conservation measures, likely due to dense vegetation cover or well-implemented land management practices. The spatial variation in C factor values highlights the need for targeted soil conservation efforts, especially in areas with higher values, to improve soil stability and mitigate erosion risks.

3.5. Conservation practice factor (P)

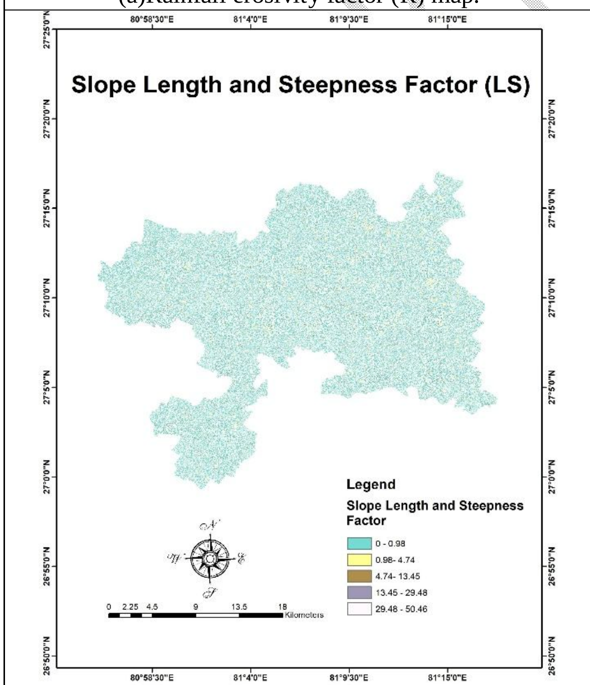
The Conservation Practice Factor (P) map indicates P-factor values ranging from 0.55 to 1, with 0.55 being predominantly associated with agricultural croplands, the most common land type in the study area (Fig 3e). Higher values approaching 1 correspond to areas where conservation measures are less effective, thus more prone to soil erosion. In contrast, lower values (near 0.55) signify regions where effective conservation practices are implemented, reducing soil erosion risk. This highlights the spatial variability of conservation efforts and their impact on soil stability across the landscape.



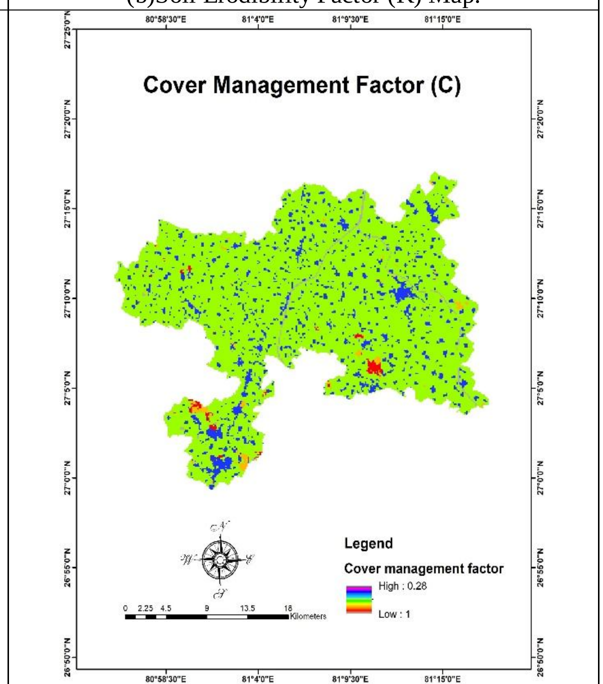
(a)Rainfall erosivity factor (R) map.



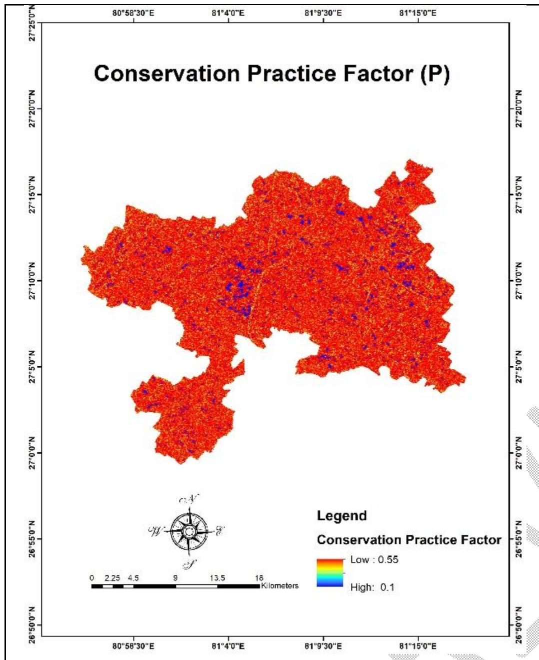
(b)Soil Erodibility Factor (K) Map.



(c) Slope Length and Steepness Factor (LS) Map.



(d)Cover management factor (C-value) map.



(e)Support practice factor (P) map.

Figure 3. Map result showing multiple parameter analysis using the RUSLE model.

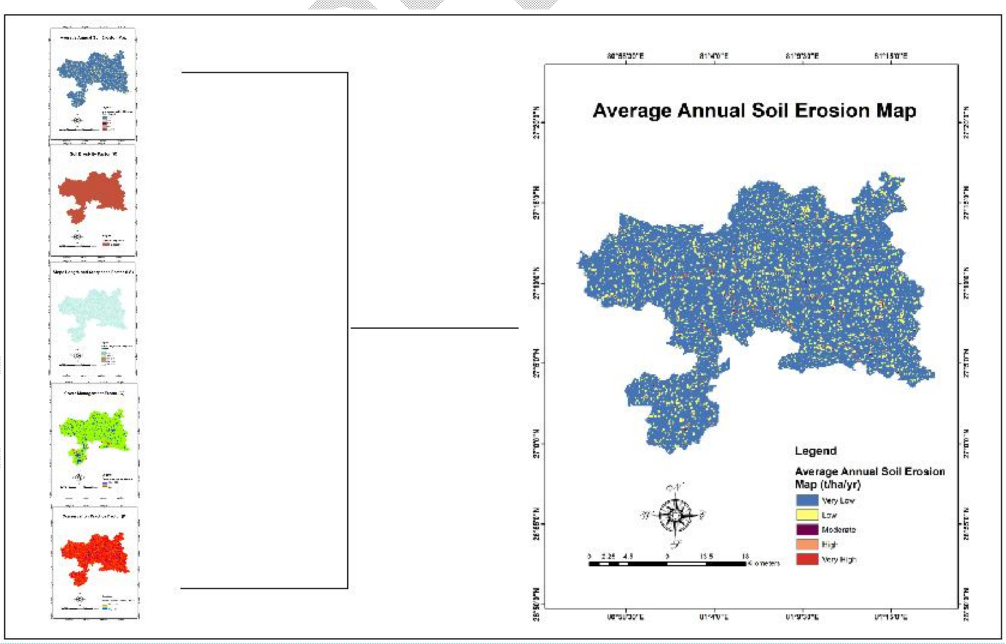


Figure 4. Accumulation of all factors to generate the erosion map of the region.

3.6. Estimation of average annual soil erosion (A)

The Revised Universal Soil Loss Equation (RUSLE) is generally used to estimate average annual soil erosion loss based on sample plot data. The integration of remote sensing and GIS enables mapping the spatial distribution of soil erosion risk. In this study, the RUSLE equation was utilized to calculate the annual average soil loss rate in tons per hectare per year (ton/ha/yr). To predict this rate, the R, K, LS, C, and P factors were multiplied using the raster calculator function tool in ArcGIS. Thematic maps of these parameters and the estimated potential soil erosion were created. This information allows management interventions to be precisely targeted, prioritizing areas with severe erosion along the Kalyani River watershed. The estimated pixel-level soil loss values were categorized into five classes. Results, shown in Table 6 and Fig. 5, indicate that approximately 90% of the study area is classified as low potential erosion risk (0–10 ton/ha/yr), while about 0.20% of the area falls under high to very high erosion risk (10-40 ton/ha/yr). Which is near to the bank River bank.

Ground truthing was carried out on June 23, 2023, in the areas most severely affected by soilerosion. Specific locations where erosion is most pronounced are highlighted in Figure 6.

Table 6. Area under different categories of soil loss of Kalyani River Watershed

Erosion Risk Class	**Soil loss classes (t ha-1 year-1)**	**Area (%)**	**Location**
Very Low	0–10	86.55	General area, flat or low slopes
Low	10–20	11.85	Gently sloping areas
Moderate	20–40	1.32	Near riverbank moderately steep areas
High	40–60	0.19	Steep slopes near riverbanks
Very High	60 and above	0.07	Very steep slopes, close to riverbanks

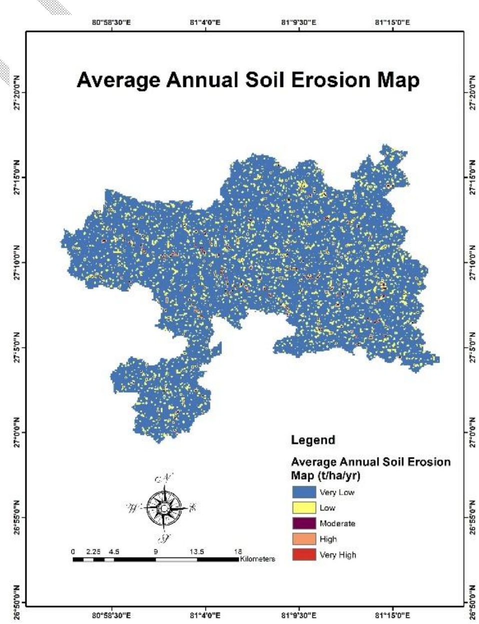


Figure 5. Average Annual Soil Erosion map.

Nindoorablock (Lat: 27.12143611° Long 81.08650278°)

Lat: 27.170647° Long 81.024073°

Lat: 27.133393°Long 81.087523°

Figure 6: Soil erosion sites photograph of the Kalyani River watershed

The study findings reveal that soil composition and landscape features significantly influence soil erosion in parts of the Kalyani River area within the Nindoora and Fatehpur blocks of Barabanki District. Sandy and sandy loam soils near the riverbanks are highly susceptible to erosion due to their loose structure and low cohesion. Seasonal fluctuations in the river's water level and steep banks further exacerbate erosion in these areas. In the 'Uparhar' region, the yellowish clay, despite being more cohesive, still experiences erosion caused by surface runoff and intensive agricultural activities. The basin lands, characterized by sandy soils, are particularly vulnerable to water and wind erosion.

These findings underscore the necessity for effective soil conservation and management strategies that consider the varying soil textures and their respective erosion susceptibilities. Such measures are essential to mitigate soil degradation and promote sustainable land use in the district.

4. Conclusions and Recommendations

This study demonstrates the application of geospatial technology and the RUSLE model to estimate potential soil erosion in the Kalyani River watershed, located near the Nindoor and Fatehpur districts of Uttar Pradesh. The different factor such as the runoff-rainfall erosivity factor (R), soil erodibility factor (K), topographic factor (LS), cropping management factor (C), and support practice factor (P) has been used to find the soil erosion potentials area and to detect the sensitive zones presenting a priority of protection. It has been estimated that approximately 90% of the Kalyani River watershed is characterized by a low risk of soil erosion, with erosion rates ranging from 0 to 10 tons per hectare per year. This indicates that the majority of the watershed is relatively stable, with minimal soil loss occurring under normal conditions. However, a small portion of the watershed, specifically around the riverbanks, faces a higher erosion risk. About 0.20% of the area, concentrated near the river's edges, experiences more significant soil erosion, with rates ranging from 10 to 40 tons per hectare per year. This higher erosion risk is likely due to factors such as increased water flow during rainfall events, land use changes, or the proximity to the river, which can lead to greater susceptibility to erosion. These localized areas of high to very high erosion risk pose a concern for land management and conservation efforts in the region.

Implementation of the best soil conservation strategies accurate estimation of soil loss are necessary, in this context RUSLE model provides quantitative data for comparison with qualitative erosion assessments, is simple and accessible, and easily integrates with GIS. Its straightforward design ensures ease of use and effective implementation. Result of this study can certainly be utilized by the responsible authorities for implementing effective soil conservation strategies as area is situated in the doab region between the Ganga and the Yamuna, the inhabitants of the district used to face acute water crises.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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