Application of the RUSLE Modeling Tool for Quantification of Soil Erosion towards Sustainable Planning: The Case of Kosi River Basin, Bihar, India

Rakesh Kumar
Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India
ar.rakeshkumar2011@gmail.com (corresponding author)

Jagdish Singh
Department of Architecture and Planning, Maulana Azad National Institute of Technology, Bhopal, Madhya Pradesh, India
singhj@manit.ac.in

Received: 25 September 2024 | Revised: 22 October 2024, 15 November 2024, and 02 December 2024 | Accepted: 13 December 2024

 DOI: https://doi.org/10.48084/etasr.9088

ABSTRACT

Soil erosion is a pressing global issue, affecting approximately 2.6 billion people across over 100 countries. It occurs from natural processes and human activities such as intensive agriculture and deforestation. In India, the National Bureau of Soil Survey and Land Use Planning estimates that around 146.8 million hectares of soil have been degraded. Preliminary analysis indicates an average soil erosion rate of 16.4 tons per hectare per year, leading to an annual loss of 5.3 billion tons nationwide. The Kosi River, which frequently shifts its course, exacerbates soil erosion issues in Northern Bihar. This study employs the Revised Universal Soil Equation (RUSLE) to estimate soil loss in the Kosi Basin, covering an area of 1,370,873.485 hectares, utilizing a 30-year rainfall dataset from the Indian Meteorological Department (IMD). Furthermore, various remote sensing data reveal that 0.20% of the area is at very high risk, while 65.88% is classified as having low to shallow risk for soil erosion. These results intend to guide regional planning and land use management in Bihar, emphasizing the importance of the soil erosion prevention model for effective environmental management.

Keywords-soil erosion; Arc GIS; RUSLE; Kosi Basin; Bihar

I. INTRODUCTION

Soil erosion, a critical global issue, poses significant challenges in numerous countries, impacting food security, water quality, and ecosystem health. As the world's population grows, the demand for arable land has intensified, increasing pressure on fragile soil resources [1]. The effects of soil erosion on crop productivity have been extensively studied, revealing alarming trends. The United Nations' Sustainable Development Goals, established in 2015, offer a framework for a more sustainable future, recognizing the interconnectedness of environmental, social, and economic well-being. Meeting the SDGs related to food, health, water, and climate will likely increase pressure on land resources, highlighting the need for sustainable land management practices [2].

River-floodplain systems, among the most productive ecosystems globally, are extensively cultivated and serve as vital sources of income, particularly in Southeast Asia [3]. These dynamic systems are subjected to seasonal and periodic modifications due to rivers' lateral and vertical mobility, influencing land use patterns. Globally, riverine floodplains cover more than 2 × 106 km^2, making them some of Earth's most extensive and vulnerable ecosystems [4]. Soil erosion, the degradation and displacement of soil, is driven by both natural phenomena (e.g. water, wind, and snow) and human activities (e.g. intensive and extensive agriculture) acting together [5, 6]. The National Bureau of Soil Survey and Land Use Planning estimates that India's approximately 146.8 million hectares of land are degraded. Soil erosion is India's most serious degradation problem, resulting in topsoil loss and terrain deformation. Based on the first approximation analysis of existing soil loss data, the average soil erosion rate was approximately 16.4 tons/ha.year, resulting in an annual total soil loss of 5.3 billion tons throughout the country. Of the total eroded soil, approximately 29% is permanently lost to the sea, 61% is redistributed within the landscape, and 10% is deposited in reservoirs [5].

Erosional floodplains are formed as streams cut deeper into their channels and laterally into their banks. Material is added to the floodplain during floods, which is called overbank deposition. India has vast floodplain wetland resources of 0.5 million hectares distributed in the Eastern and Northeastern States [7]. The Kosi River exhibits distinctive hydrological and morphological characteristics in northeastern India. The basin is characterized by its mountainous origin [8], influencing its hydrology and sediment transport. The basin is a complex and diverse region due to its wide range of climatic, soil, vegetation, and socioeconomic zones [9]. The Kosi River, often called the "Sorrow of Bihar," [10] is known for its destructive floods and for transporting massive sediment loads into the Ganga River approximately 135 million tons per year [10-12]. This region is prone to natural hazards, as exemplified by the devastating Kosi floods in 2008 [13]. Besides its notable hydrological and ecological importance, the Kosi River basin is also entangled with food and nutritional security concerns. The Kosi River flows through the north Bihar plains in eastern India and is a major tributary to the Ganga River system. It has long been considered a problematic river due to its recurrent and extensive flooding and the frequent changes in its course. The available records indicate that the Kosi River has shifted westward, undergoing a lateral displacement of 150 km in the last two centuries [14] This lateral displacement and recurrent inundation contribute to soil erosion in the region.

This study uses the Revised Universal Soil Loss Equation (RUSLE) model to estimate soil erosion. This model calculates soil loss based on rainfall, soil erodibility, land use and land cover, slope length and steepness, cover management, and support practices. The research question for this study is the spatial patterns and rates of soil erosion within the Kosi River basin. The objectives of the research is to quantify and map soil erosion rates within the Kosi River basin using the RUSLE model, to assess the spatial distribution of soil erosion risk zones within the basin, and to evaluate the potential impacts of soil erosion on land productivity and ecosystem services in the Kosi River basin. Like all models, the limitation of the RUSLE model relies on simplifying assumptions. Factors not explicitly accounted for in the model (e.g. gully erosion, subsurface flow) could lead to an underestimation or overestimation of the actual soil loss in certain areas. At the temporal scale, this study provides a snapshot of soil erosion patterns based on data from a specific period. Long-term erosion trends and the influence of inter-annual climate variability might not be fully captured.

II. MATERIALS AND METHODS

A. Brief Description of the Study Area

The Kosi River basin spans a total area of 74,030 km^2. While a significant portion, 62,620 km^2, lies within Tibet and Nepal, the remaining 11,410 km^2 fall within the borders of India [15]. The Kosi basin is situated in the eastern part of India, nestled between the Himalayas to the north and the Ganges River to the south. It borders the Mahanada basin to the east and the Burhi Gandak basin to the west. The basin encompasses a significant portion of Bihar state, spanning across eight major part of districts: Madhubani, Saharsa, Supul, Purnea, Khagaria, Katihar, Madhepura, and Araria as seen in Figure 1. The Kosi River ultimately flows into the Ganga River in the Katihar district of India, near Kursela. A portion of the Kosi basin lies within India.

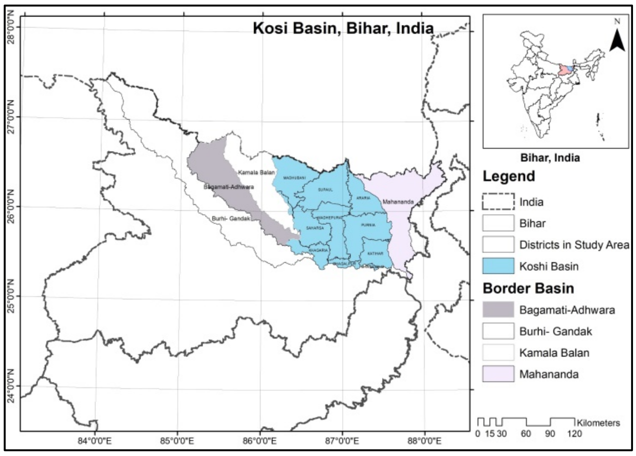

Fig. 1. The basin of the Kosi River.

B. Data and Methods

This study utilized a variety of datasets to quantify soil erosion within the study area. Rainfall erosivity was determined using a 30-year (1993-2023) dataset collected from six stations belonging to the India Meteorological Department. Soil erodibility was derived from the Food and Agriculture Organization's Digital Soil Map of the World [16]. A 12.5 m resolution digital elevation model acquired from ALOS PALSAR [17] provided information for the calculation of the slope length and the steepness factor. Finally, the cover management and the soil conservation practices factor were determined using data from the ESRI Sentinel-2 Landcover Explorer [18], which provides 10 m resolution imagery. Table I provides a detailed summary of the datasets used in this study.

C. Methodology Used

The RUSLE was used to estimate the average annual soil loss (A), represented in ton/ha.year. This equation incorporates five key factors:

$$A = R \times K \times LS \times C \quad (1)$$

where R is the rainfall/runoff erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}) representing the erosive force of rainfall, K is the soil erodibility factor (ton.H.MJ^{-1}.mm^{-1}) reflecting the susceptibility of soil to erosion, LS is the slope length and steepness factor (dimensionless) accounting for the effects of topography, C is the cover factor (dimensionless) representing the influence of vegetation and land management, and P is the support practice factor (dimensionless) reflecting the impact of erosion control measures.

1) Rainfall Erosivity (R) Factor

The R-factor (MJ mm ha^{-1} h^{-1} year^{-1}) is a crucial component of the RUSLE model. It quantifies the erosive potential of rainfall. This study focuses on a region with distinct Indian climatic conditions, necessitating a tailored approach to R-factor calculation:

$$R = 81.5 + 0.375\,AAP \quad (2)$$

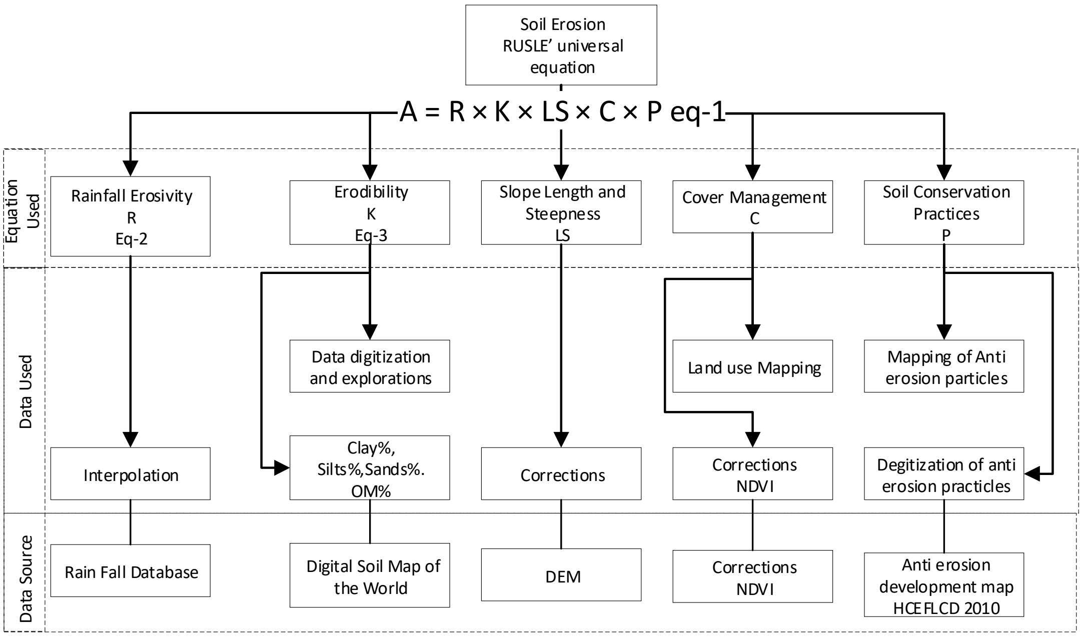

Fig. 2. Methodology.

TABLE I. DATABASES USED FOR ESTIMATING SOIL LOSS WITH THE RUSLE MODEL

Data Base	Purpose	Duration	Scale of Resolution	Source
Rainfall	Rainfall erosivity Factor	1993–2023	Six Station Dataset	India Metrological Department
Soil	Soil Erodibility	2012	30 Arc Sec	[16]
Elevation	Slope Length Steepness Factor	2008	12.5m	[17]
LULC	Cover management and soil Conservation practices factor	2022	10m	[18]

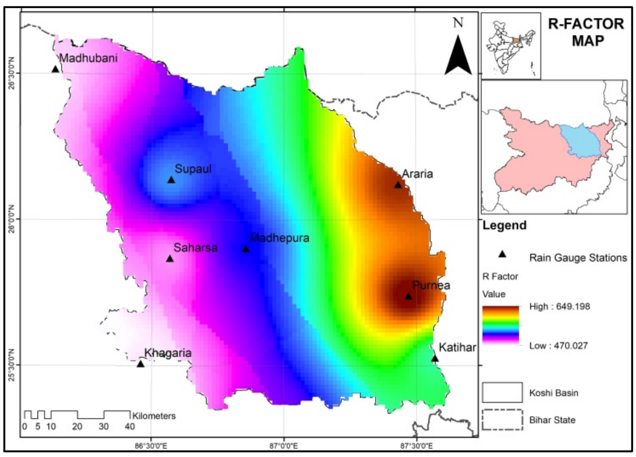

Fig. 3. R-factor.

This study employed a modified formula specifically designed for the Indian context [19]. This formula incorporates both monthly and annual rainfall patterns to provide a comprehensive assessment of rainfall erosivity. Previous research efforts in India, notably by [19, 20], have sought to establish a correlation between annual average precipitation and the R-factor. Authors in [19] proposed various equations for R-factor estimation, as summarized in Table II. They further refined these equations, proposing specific formulas for Dehradun and Jharkhand. Ultimately, this study adopted (2) to determine the R-factor. This equation, tailored for the specific region under investigation, ensures a more accurate representation of local rainfall erosivity dynamics.

2) K Factor

The soil erodibility factor quantifies the inherent susceptibility of a given soil to erosion. It reflects how readily soil particles can be detached and transported by the forces of rainfall and runoff [21]. Defined as the erosion rate per unit erosion index from a standardized plot, the K-factor provides a standardized measure of soil erodibility. Soils with high clay content tend to exhibit low K-values, typically ranging from 0.05 to 0.15, due to their inherent resistance to particle detachment [21]. The calculation of this factor is made by [22]:

$$K_{usle} = \left[0.2 + 0.3 X exp^{-0.256\, X\, ms\left(1-\frac{msilit}{100}\right)}\right] X \left[\left(\frac{\mathrm{msilt}}{\mathrm{mc+msilit}}\right)0.3\right) X\, (1 - 0.25\, X orgc + exp^{3.72-295\,\mathrm{X}\,\mathrm{orgc}}] X \left[1 - \left(\frac{0.7\mathrm{X}\left(1-\frac{ms}{100}\right)}{\frac{1-\mathrm{ms}}{100}}\right) + exp^{-5.51+22.9\mathrm{X}\left(1-\frac{\mathrm{ms}}{100}\right)}\right] \quad (3)$$

where K_{usle} is the soil erodibility factor ms is the percentage share of sand, $msilt$ is the percentage share of silt, mc is the percentage share of clay, $orgc$ is the percentage share of organic matter, and *hisand* is the high sand factor [23].

The soils of the study area are categorized into five distinct classes: Calcaric Fluvisols, Calcic Cambisols, Eutric Fluvisols, Eutric Cambisols, and Orthic Luvisols. Equation (3) was employed to determine the K factor, representing soil erodibility. The resulting K factor values, presented in Table III and visually represented in Figure 4, were then multiplied by a conversion factor of 0.1317 to align with the International System of Units.

TABLE II. RAINFALL EROSIVITY FACTOR

Applicable Area	Rainfall Erosivity Factor Equation	Source
Entire India	R=79+0.363×AAP	[19, 20]
Dehradun, India	R= 22.8+0.64×AAP	[19]
Jharkhand, India	R=81.5+0.375×AAP	[19]

TABLE III. K FACTOR OF THE STUDIED SOIL

	Abbreviation	K factor	Ton Ha hr h/ha M.J. mm
Eutric Cambisols	BE	0.319731562	0.042109
Calcic Cambisols	BK	1.350997479	0.177926
Calcaric Fluvisols	JC	0.917926151	0.120891
Eutric Fluvisols	JE	0.245708205	0.03236
Orthic Luvisols	LO	1.519143373	0.200071

Source: [19], Calculated for the study area by the author.

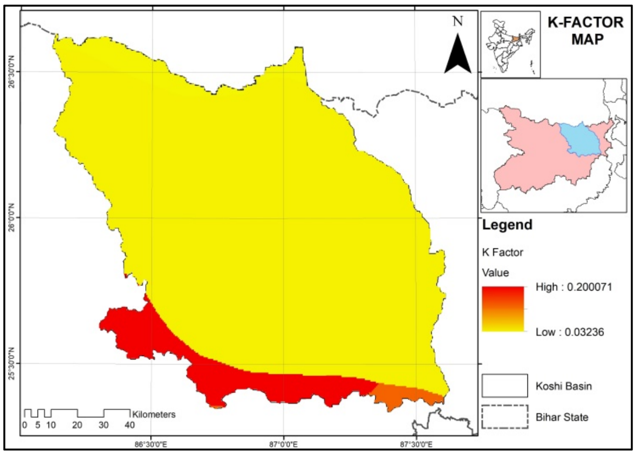

Fig. 4. K factor.

3) *Slope Length and Slope Steepness Factor*

The LS factor in the RUSLE equation represents the impact of slope length and steepness on soil erosion. It is calculated as the ratio of soil loss under given conditions to the soil loss from a "standard" slope with a 9% steepness and a 22.13 m length. As slope length and steepness increase, so does the risk of erosion [24]. This study utilized a 12.5 m resolution digital elevation model to determine the LS factor [17]. Flow direction and accumulation were analyzed to understand the river system's flow pattern. Subsequently, a filled raster image was used to determine the slope and degree of each cell. The calculation of slope length (L) and slope steepness (S) was performed using equations from [25], specifically (4), and further refined using (4.1) as input equation in Map algebra during raster calculation.

$$\text{LS}= power\left(Flowaccumulation \times \frac{cell\ size}{22.1\times 0.4}\right) * power\left(\frac{\sin(slope\ in\ Percentage \times 0.01745)}{0.09\times 1.4}\right)\times 1.3 \quad (4)$$

$$\text{LS} = Power[\frac{Flow\ Accumulation" \times Cell\ Size}{22.13}]\times 0.4\times Power[\frac{0.01745\times\left(Sin\left("slope\ in\ Percentage"\right)\right)}{0.0896}]\times 1.3 \quad (4.1)$$

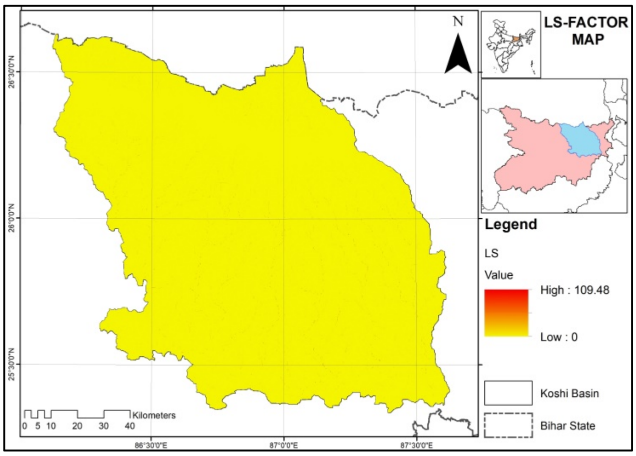

Fig. 5. LS factor.

4) *C Factor*

The cover factor (C) in the RUSLE equation quantifies the impact of vegetation and land management practices on soil erosion rates [26]. It's a dynamic factor, varying both spatially and temporally, reflecting the complex interplay between plant growth and rainfall patterns [27]. Represented as a dimensionless value ranging from 0 to 1, the C-factor signifies the ratio of soil loss under specific land cover and management practices to the soil loss from a continuously bare fallow condition [28]. This study utilized land use and land cover data from the Sentinel-2 Landcover Explorer for the year 2022 [18, 29]. This application provides a time-series LULC layer derived from ESA Sentinel-2 imagery at a 10 m resolution, enabling a detailed assessment of land cover dynamics.

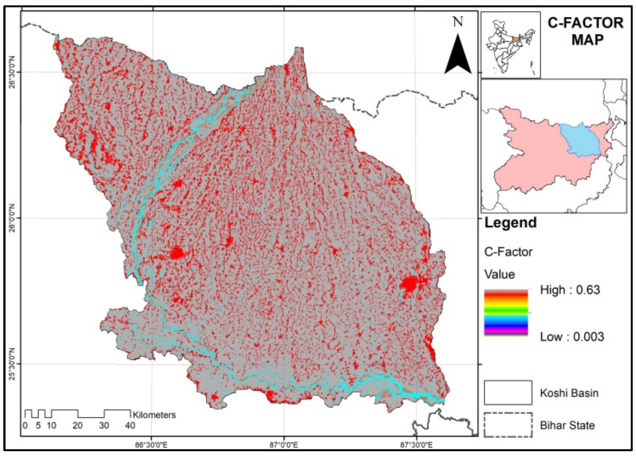

Fig. 6. C factor.

The C-factor, representing the cover management factor, was assigned based on a standardized scale ranging from 0 to 1.

Lower C-values, approaching 0, indicate better soil protection and minimal erosion potential. On the other hand, higher values, closer to 1, suggest inadequate land cover and a heightened susceptibility to soil erosion. Table IV provides a classification of land use types within the study area and their corresponding assigned C-factor values. This classification system facilitates a systematic assessment of land cover's influence on soil erosion potential.

TABLE IV. LAND USE CLASSIFICATION

Land use Classification	C- Value	Source
Water	0.28	[30]
Trees	0.003	
Flooded vegetation/wetland	0.28	
Crops	0.63	
Built area	0.09	
Bare ground	0.50	
Rangel Land	0.525	[31]

5) P- Factor

To determine the P-factor, representing the support practice factor, a contouring approach was employed within the study area. A digital elevation model was used to generate a slope map expressed in percentages. The slope values were then reclassified into five distinct categories with ArcGIS software, as detailed in Table V.

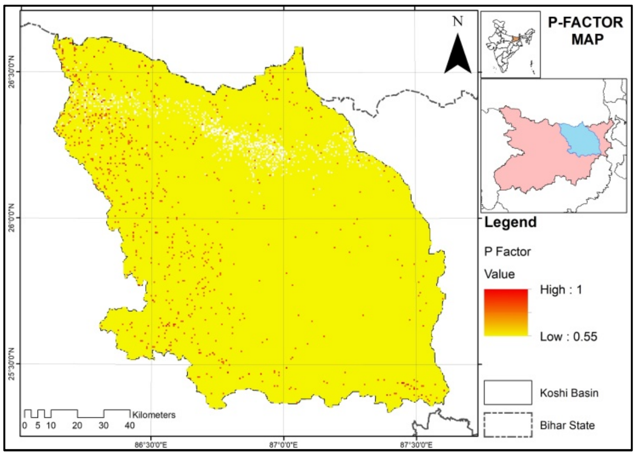

Fig. 7. P factor map.

TABLE V. CONSERVATION SUPPORT PRACTICES

Slope (%)	Conservation support practices (P- factor) focused on slope		
	Contouring	Strip cropping	Terracing
0.00-7.0	0.55	0.27	0.10
7.0-11.3	0.60	0.30	0.12
11.3-17.6	0.80	0.40	0.16
17.6-26.8	0.90	0.45	0.18
>26.8	1	0.50	0.20

Source: [32]

The P-factor in the RUSLE model plays a crucial role in accounting for the effectiveness of conservation practices in mitigating soil erosion. It considers the presence and implementation of soil conservation measures such as terraces, contour ploughing, and grassed waterways. The adoption of such conservation practices is reflected in a higher P-factor value, indicating a greater reduction in soil erosion.

III. RESULTS AND DISCUSSION

A. Results

The study's findings, visualized through various maps, reveal the spatial distribution of soil erosion factors and the overall erosion potential within the study area.

- Rainfall Erosivity: The R-factor, ranging from 470.027 to 649.198 MJ mm $ha^{-1}h^{-1}year^{-1}$, exhibits an increasing trend from east to west, as depicted in Figure 3. This suggests a higher erosive potential of rainfall in the western portion of the study area.
- Soil Erodibility: Figure 4 illustrates the spatial variation in K-factor values for different soil types. Calcaric Fluvisols exhibit moderate erodibility while Orthic Luvisols demonstrate higher erodibility.
- Slope Length and Steepness: The LS-factor, ranging from 0 to 109.48, as depicted in Figure 5, highlights the significant influence of topography on erosion potential. Steeper slopes, associated with higher LS-values, are more susceptible to soil loss.
- Cover Management: The C-factor in Figure 6, ranging from 0.003 to 0.63, reflects the protective role of vegetation and land cover. Areas with denser vegetation exhibit lower C-values, indicating better soil protection.
- Soil Conservation Practices: The P-factor, ranging from 0.55 to 1, as shown in Figure 7, underscores the effectiveness of conservation measures in reducing erosion. Higher P-values indicate a greater reduction in erosion due to implemented conservation practices.

Finally, the study integrates all five factors using a raster calculator in ArcMap to generate a comprehensive soil erosion map. This map, with values ranging from <0.5 to >50 as illustrated in Figure 8, provides a spatially explicit representation of potential soil loss within the study area.

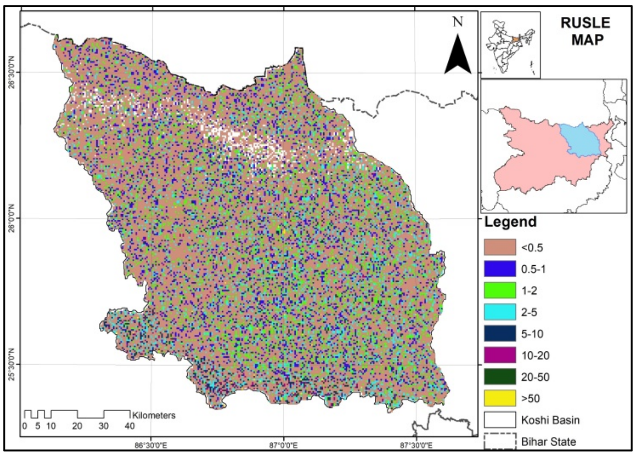

Fig. 8. RUSLE map.

B. Discussion

Soil erosion, a critical environmental concern, leads to soil degradation and topsoil loss, impacting agricultural productivity and ecosystem health. To combat this, conservation planning relies on tools like the RUSLE for estimating soil loss [33]. RUSLE considers factors such as rainfall erosivity, soil erodibility, slope characteristics, crop management, and erosion control practices to provide valuable insights for developing effective soil erosion management strategies. Numerous studies demonstrate the versatility of RUSLE in assessing and predicting soil erosion:

- Ethiopia: A study integrated RUSLE with a spatially distributed soil erosion and sediment delivery model (WATEM/SEDEM) to evaluate its performance. The integration provided valuable information on soil erosion and sediment delivery patterns in the region [33].
- Indonesia: In [34], RUSLE was used to estimate soil loss for conservation planning in the Dolago Watershed. The study focused on determining erosion hazard classifications and creating an erosion hazard map, ultimately aiding in developing a comprehensive soil and water conservation program.
- China: RUSLE, combined with geospatial technologies, facilitated a quantitative assessment of soil erosion in the Upper Minjiang River Basin. The findings contributed to the development of optimal soil erosion management plans for the basin [35].
- India: RUSLE has been extensively applied in India for soil erosion estimation. Studies in a semi-arid watershed in Tamil Nadu and the Banas River Basin in Rajasthan demonstrate its effectiveness in assessing soil erosion for different land uses [30].
- Furthermore, RUSLE's applicability extends to various regions, including the Eastern Himalayan region of India [36] and the Kosi Basin in Nepal [37], highlighting its adaptability in diverse geographic contexts.

The above mentioned studies collectively emphasize the significance of RUSLE as a valuable tool for understanding and mitigating soil erosion. By considering a multitude of factors, RUSLE provides a comprehensive framework for conservation planning and the development of sustainable land management practices.

IV. CONCLUSION

The study utilized the RUSLE model to quantify soil erosion patterns within the Kosi River basin, revealing valuable insights for conservation planning and land management.

A. Quantification and Spatial Patterns

The RUSLE-generated map and the associated data in Table VI provide a high-resolution quantification of soil erosion rates. This information is particularly crucial for the Kosi River basin, a data-scarce region where such insights are essential for guiding sustainable land management practices. The study highlights the spatial variability of erosion, with critical areas concentrated along the confluence of the Ganga and Kosi rivers.

B. Identifying High-Risk Zones

The study identifies approximately 1.55% of the study area as experiencing extremely high to high erosion rates (greater than 10 tons/ha/year). These high-risk zones, primarily located along the Ganga and Kosi River intersection, are particularly vulnerable to accelerated land degradation. This finding emphasizes the need for targeted interventions in these areas to mitigate soil loss and promote sustainable land use practices.

TABLE VI. CLASSIFICATION OF SOIL EROSION AND RISK LEVEL

Risk Level	Erosion in ton /ha/year	Area (Ha)	Area (%)
Very Low	<0.5	944323.5	68.88480303
Low	0.5-1	131061.3	9.560422711
Low medium	1-2	144218.4	10.52018305
Medium	2-5	100020.1	7.296085386
High medium	5-10	29615.45	2.160334292
High	10-20	12473.08	0.909863684
Very high	20-50	6283.079	0.458326685
Extremely high	>50	2878.576	0.209981157
	Total	1370873.485	100

C. Baseline for Management

While a majority of the basin (77.44%) experiences very low erosion rates (0-2 tons/ha/year), the estimated total eroded area of 1,370,873.485 Ha remains a significant concern. This study establishes a critical baseline for monitoring future erosion trends and evaluating the effectiveness of implemented soil conservation measures.

D. Implications for Policy and Future Research

This study provides valuable insights for policymakers and stakeholders in the Kosi River basin by offering a detailed assessment of soil erosion patterns and quantifying erosion rates. The identification of high-risk zones enables targeted interventions and resource allocation for effective soil conservation efforts.

E. Future Research

Future Research should focus on exploring the socioeconomic drivers of land use practices that contribute to erosion in high-risk zones. Evaluating the effectiveness of specific soil conservation strategies in mitigating erosion and promoting sustainable land management within the Kosi River basin.

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