Geospatial Assessment of Soil Erosion Risk Under Different LULC Categories in the Silabati River Basin

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Abstract

Soil erosion is an ongoing environmental challenge majorly caused by changes to land use and land cover (LULC). Acknowledging how LULC drives soil erosion rates is vital to effective land management and conservation planning. Geospatial technologies, such as remote sensing (RS) and geographic information systems (GIS), offer highly accurate, cost-effective, and time-efficient ways of assessing soil erosion. This study indicates that barren land is particularly susceptible to soil erosion, with an Erosion Susceptibility Index (ESI) score of 4.39, followed by agricultural land at 1.28, further emphasizing the need for effective soil conservation measures as soon as possible. Other LULC categories, including built-up areas, vegetation cover, and river and water bodies, have an Erosion Susceptibility Index (ESI) score below one, signaling minimal erosion risk. To reduce soil degradation, it's essential to employ sustainable land management strategies like afforestation, contour farming, and watershed management. Continuous monitoring with advanced geospatial techniques will significantly enhance erosion prediction and enable informed decision-making, underlining the significance of incorporating technological advancements into conservation policies to maintain long-term soil health and productivity.

Keywords: Soil erosion, Geospatial, Land use and land cover, Erosion Susceptibility Index, Silabati River Basin

1. Introduction

Soil erosion is an increasing environmental challenge threatening water quality, land productivity, and ecosystem health worldwide. Soil erosion is driven mainly by natural factors like rainfall, wind, and topography; however, human activities have further compounded this issue (Pimentel & Burgess, 2013). Assessing soil erosion risk using geospatial techniques provides an in-depth knowledge of erosion dynamics, helping develop sustainable land management strategies (Mishra et al., 2019). Silabati River Basin in eastern India is particularly vulnerable to soil erosion due to its varied topography, climate conditions, and human intervention (Ghosh et al., 2020). This study seeks to conduct a geospatial evaluation of erosion risk under different LULC categories in the Silabati River Basin for use in conservation planning strategies.

Soil erosion results in the loss of fertile topsoil, decreasing agricultural productivity, increasing sedimentation in rivers and reservoirs (Lal, 2001), and leading to soil health and aquatic habitat degradation (Borrelli et al., 2017). Borrelli et al. (2017) reported that global soil erosion rates have escalated as a result of deforestation, urban expansion, and unsustainable agricultural practices, especially in regions in India with dynamic land use and land cover (LULC) changes, which makes analyzing erosion risks at basin level essential.

Geospatial technologies like remote sensing (RS) and geographical information systems (GIS) are important tools for assessing the risk of soil erosion. The Revised Universal Soil Loss Equation (RUSLE) model can effectively estimate soil erosion rate on a local scale by incorporating important soil erosion conditioning factors including rainfall, soil condition, surface slope, vegetation concentration, management practices, etc. (Renard et al., 1997). Many studies have demonstrated how accurate geospatial models, such as RUSLE, can assess soil loss in various LULC situations (Panagos et al., 2015). Applying this model to the Silabati River Basin could offer significant insights into the areas susceptible to erosion and help implement research-based land management methods. Understanding the relationship between LULC and soil erosion in the Silabati River Basin will help identify high-risk zones and prioritize conservation efforts.

Land use and cover modifications have a massive impact on soil erosion rates. Forest areas generally show less risk due to their dense vegetation cover, which helps to buffer the impact of rainfall while stabilizing the slopes (Morgan, 2005). Barren and agricultural land suffer higher erosion rates because of a lower vegetation cover and greater vulnerability to forces of erosion (Zhou et al., 2020). Urbanization can further increase erosion rates through changing natural draining patterns as well as increasing impervious surfaces resulting in increased drainage and sediment transport (Ganasri & Ramesh, 2016).

The study will provide an evidence-based method for assessing erosion risk and forming sustainable land-use strategies. The results of this research will offer important insights to policymakers, environmentalists, and land managers to reduce soil erosion within the Silabati River Basin. By studying the interplay between various LULC categories and erosion dynamics within the Silabati River Basin, this study is designed to aid in sustainable land management and conservation efforts in the environmental field. Furthermore, this study will aid in the overall discussion on the conservation of the environment and resilience to climate change, emphasizing the significance of integrated land management in reducing erosion-related degradation.

Volume- 2, Issue- 1 | 2025 ISSN: 3048-9938

2. Database and Methodology

2.1 Study Area

The study area (Fig. 1) was delineated by digitization from fifteen merged topographical maps (73I/12, 73I/16, 73J/13, 73M/4, 73M/8, 73N/1, 73N/2, 73N/3, 73N/5, 73N/6, 73N/7, 73N/9, 73N/10, 73N/11, and 73N/14). The Silabati River begins its journey in the Purulia district of West Bengal (23° 14' 10" N, 86° 38' 37" E) and flows for roughly 217.28 kilometers before meeting with Dwarakeswar River near Ghatal in Paschim Medinipur (22° 40' 14" N, 87°, 46' 41" E). Together, they form the Rupnarayan River at a junction angle of 230° with a slope of 00°11'55.03" (Das & Bandyopadhyay, 2015), covering 4011.70 km^2 across Purulia (55.58 km^2), Bankura (1389.18 km^2) and Paschim Medinipur (2566.94 km^2). This region experiences tropical monsoon climate conditions with average annual rainfall averaging 1342.39 mm with temperatures ranging between 6°C in winter to 50°C in summer (Bhunia et al., 2021). The river is characterized by a sinuous course with a sinuosity index of 1.94 (Pal 2016). Additionally, the River features an undulating course, often flooding the Ghatal and Daspur areas which act as an important geomorphological transition zone (Das & Bandyopadhyay, 2015).

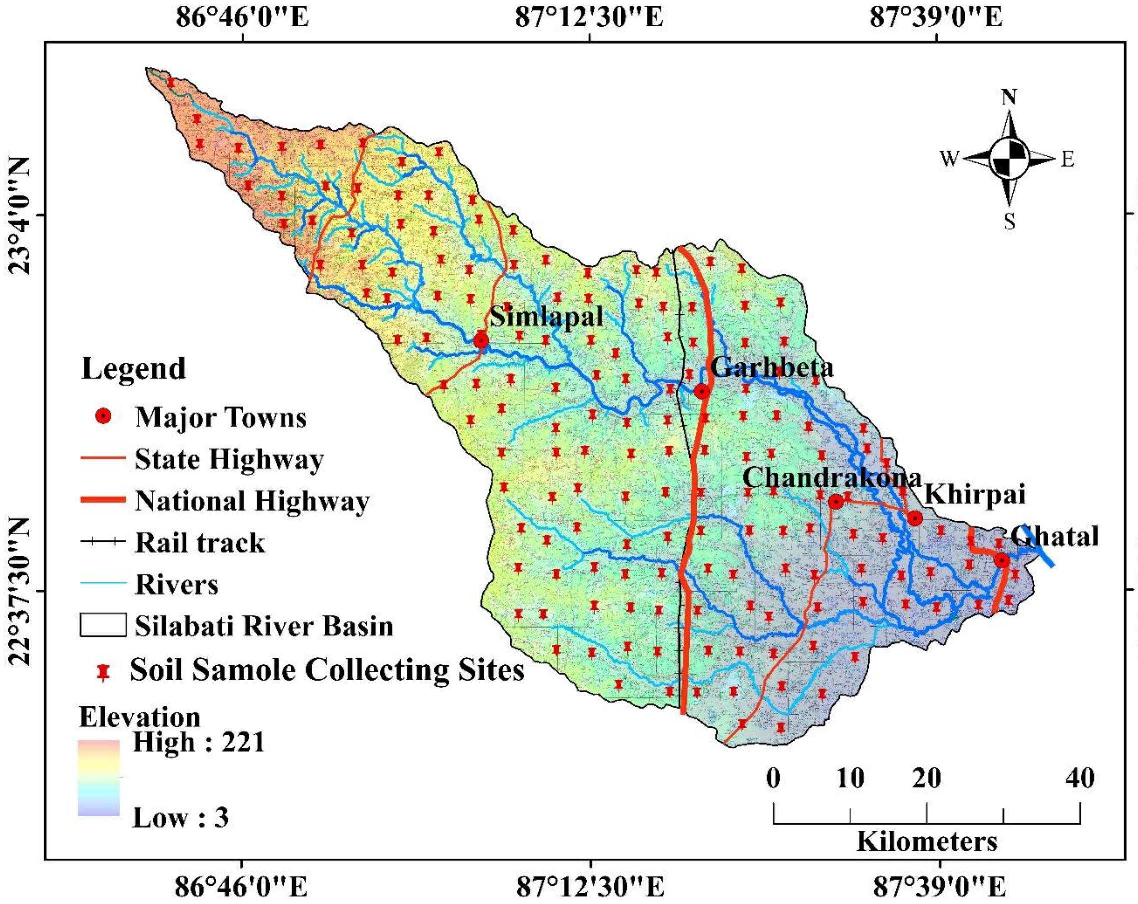

Fig. 1: The Study area

2.2 Data used

Rainfall records spanning from 1981 to 2021 were acquired from NASA POWER to facilitate the generation of rainfall and R-factor maps. The ALOS PALSAR DEM, obtained from the Alaska Satellite Facility (ASF), was utilized for deriving elevation, slope, and other terrain-related parameters. Landsat 8 OLI/TIRS imagery, acquired on February 9, 2023, from the United States Geological Survey (USGS), with a spatial resolution of 30 meters with a cloud cover of 1.9%, was employed for the derivation of NDVI, land use and land cover (LULC), as well as C and P factor maps. Soil properties, including the concentrations of sand, silt, clay, and soil organic carbon (SOC), were assessed through primary field surveys and laboratory analyses to map their spatial distribution and derive the K-factor. Additionally, topographical maps sourced from the Survey of India were utilized for delineating the study area and supporting geospatial analyses.

2.3 Methodology

2.3.1 Estimation of Soil Erosion

The average yearly rainfall data was mapped using the Inverse Distance Weightage (IDW) method. The land use and land cover (LULC) categories are identified by analyzing satellite image using the Maximum Likelihood Classification method. The average rate of soil erosion is estimated using the Revised Universal Soil Loss Equation (Eq. 1).

$$A = R \times K \times LS \times C \times P \qquad \text{(Eq. 1)}$$

where A is the average annual rate of soil erosion (t/ha/y), R is the rainfall-runoff erosivity factor (MJ.mm/(ha.h.yr)), K is the soil erodibility factor (ton·ha·h/(MJ·mm), LS is the slope length and steepness factor, 'C' is the cover-management factor, and 'P' is the support-practice factor (Pal et al., 2024)

2.3.2 Identification of Critical Erosion Areas Across LULC Categories

The Maximum Permissible Soil Erosion Rate, also referred to as Soil Erosion Tolerance Limit (T), serves as an essential parameter in identifying critical erosion-prone areas. Mandal and Sharda (2011) established a 'T' value for the study area that has been adopted here and applied accordingly. Once identified as critical erosion zones, their spatial distribution across various Land Use Land Cover (LULC) categories was identified.

Erosion Susceptibility Index (ESI) is a quantitative measure used to compare soil erosion across different land use types and environments. It serves as a way of standardizing erosion rates against an established reference value and assesses the relative risk associated with them (Eq. 2).

$$ESI = \frac{A_E}{A_T} \qquad \text{(Eq. 2)}$$

Where A_E is the area in percent under critical erosion of total critical erosion areas of a LULC type, and A_T is the total area in percent of that LULC type.

3. Result and Analysis

3.1 Estimation of Soil Erosion

Table 1 provides the high, low, and mean values of RUSLE factors in the Silabati River Basin to estimate soil erosion rates and understand its susceptibility to land degradation. It is the R-factor, which is a measure of the runoff energy and energy from raindrops on soil detachment varies from 543.84 to 591.22 MJ·mm/(ha·h·yr), with an average of 566.27 MJ·mm/(ha·h·yr). Its variations reflect the spatial variation in rainfall and distribution within the basin. The K factor is a measure of soil erodibility based on its texture, which ranges from 0.14 to 0.19 ton·ha·h/(MJ·mm), and the average value of 0.17 ton·ha·h/(MJ·mm). Soils with more K values tend to be separated by erosional forces and are more vulnerable to erosion. The LS factor, which measures topographic influences on erosion potential, typically ranges between 0.68 and 30.26; steeper or longer slopes often exhibit higher values as their greater gravitational forces exert force upon surface runoff. Factor C measures the protection effects of the vegetation against erosion, ranging between 0.25 and 0.59, with an estimated average of 0.39. Lower C values suggest better vegetation cover and less soil loss. Higher values indicate barren or poorly managed land, which leads to more erosion and loss of soil. The P factor measures the efficiency of LULC management measures to conserve soil. The range of values is 0.00 to 1.00, with an average of 0.19.

Table 1: Low, high, and mean values of RUSLE parameters

RUSLE parameter	Unit	Low	High	Mean value
R factor	MJ.mm/(ha.h.yr)	543.84	591.22	566.27
K factor	ton·ha·h/(MJ·mm)	0.14	0.19	0.17
LS factor	-	0.00	30.26	0.68
C factor	-	0.25	0.59	0.39
P factor	-	0.00	1.00	0.19

Using these factors (Fig. 2), the estimated average annual soil erosion rate in the Silabati River Basin is 4.35 t/ha/y. However, the erosion rates exhibit a wide range, from 0 to 445.87 t/ha/y, indicating significant spatial variability. The soil erosion map (Fig. 3) reveals distinct spatial patterns across the basin. High erosion occurs in the upper reaches due to steep slopes, high elevation, sparse vegetation, sandy soils, low clay content, and low SOC levels. In contrast, the middle reaches experience minimal erosion, benefiting from dense vegetation cover that protects the soil. The lower reaches exhibit moderate erosion, influenced by low elevations, gentle slopes, and clay-rich soils that reduce erosion but are counteracted by intensive farming practices, sparse vegetation, and urbanization.

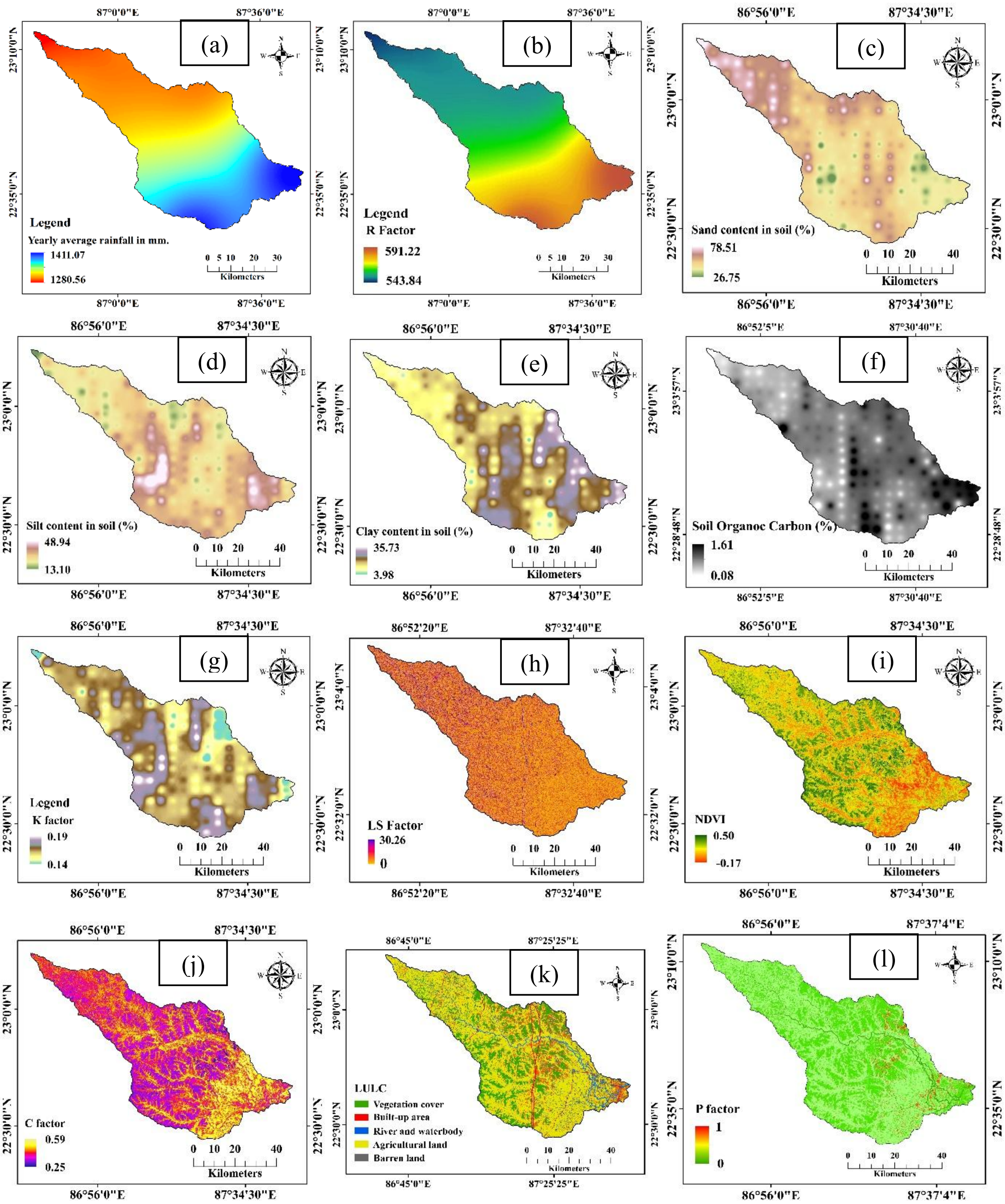

Figure 2: Spatial distribution of the RUSLE factors and their related parameters. a – average yearly rainfall; b - R factor; c – distribution of sand; d - distribution of silt; e - distribution of clay; f - distribution of organic carbon; g – K factor; h – LS factor; i – NDVI; j – C factor; k – LULC; l – P factor

In the Silabati River Basin, approximately 43.72% of the total area experiences a very low rate of soil erosion, with values below 1 t/ha/y. In comparison, 28.53% of the basin falls under the low erosion category, with rates ranging between 1 and 5 t/ha/y. Additionally, 9.42% of the area is subjected to moderate soil erosion, varying from 5 to 10 t/ha/y. Furthermore, high soil erosion rates, ranging from 10 to 20 t/ha/y., affect around 12.01% of the basin, while very high erosion rates, exceeding 20 t/ha/y., are observed in approximately 6.32% of the total area. The overall average soil erosion rate across the entire basin is estimated to be 4.35 t/ha/y., highlighting variations in soil loss intensity across different regions.

Table 2: Class-wise distribution of soil erosion rate

Erosion class	Erosion rate (t/ha/y)	Area (km^2)	Area in %
Very low	<1	1753.76	43.72
Low	1 to 5	1144.43	28.53
Moderate	5 to 10	377.93	9.42
High	10 to 20	481.89	12.01
Very high	>20	253.69	6.32

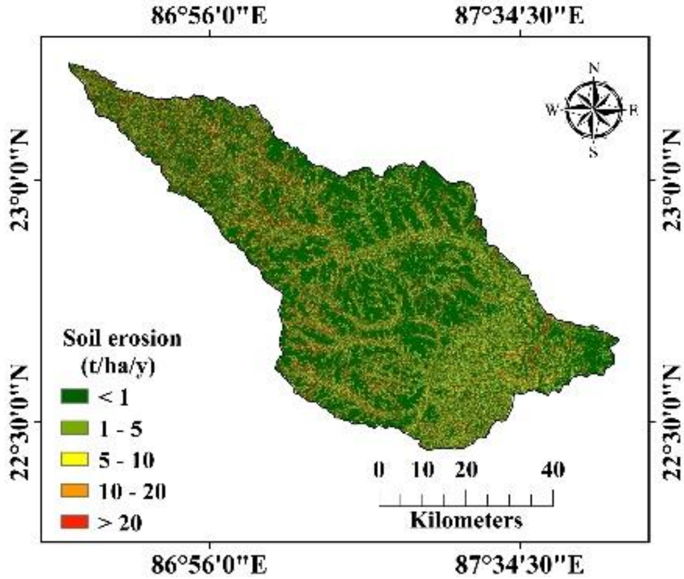

Fig. 3: Spatial distribution of soil erosion

LULC-wise distribution of critical erosion areas

Fig. 4 and Table 3 present the critical erosion areas of the river basin. The total area under critical erosion is 487.52 sq. km., or about 12.15% of the study area. The highest area under critical erosion is observed in the agricultural land which occupies 71.44% of the total critical erosion area while it covers 55.61% of the basin. The vegetation cover occupies 27.52% of the basin but 15.69% of the critical area, the second highest after agricultural land. In terms of total area, barren land occupies only 1.97% but covers 8.64% of the critical erosion areas. The built-up area is the least contributor to critical erosion areas, occupying only 4.23% while it covers 11.95% of the basin. No erosion occurs in rivers and water bodies.

The highest Erosion Susceptibility Index (ESI) was observed in Barren land (4.39), indicating that this land cover type is at the highest risk of soil erosion. This suggests that barren lands are highly vulnerable to soil degradation due to a lack of vegetation cover and minimal soil protection against erosive forces. The second-highest ESI was recorded in agricultural land

(1.28), highlighting that cultivated areas also experience significant erosion risks, suggesting the adaptation of immediate conservation measures. In contrast, other LULC categories exhibit relatively lower erosion susceptibility, with ESI values below 1 (Table 3). This implies that these land cover types, including Built-up areas, Vegetation cover, and River and waterbody, provide better soil stability and are less prone to erosion.

Table 3: LULC-wise distribution of critical erosion area with their contribution to the total area and respective category.

LULC	Total area		Erosion area above 'T' value		Contribution to the total erosion area above 'T' value (%)	Erosion Susceptibility Index (RSI)
	km.^{2}	%	km.^{2}	%		
Built-up area	479.47	11.95	20.64	0.51	4.23	0.35
Agricultural Land	2230.86	55.61	348.27	8.68	71.44	1.28
Vegetation Cover	1104.15	27.52	76.47	1.91	15.69	0.57
Barren Land	78.87	1.97	42.14	1.05	8.64	4.39
River and waterbody	118.35	2.95	0.00	0.00	0.00	0.00
Total	4011.7	100	487.52	12.15	100	

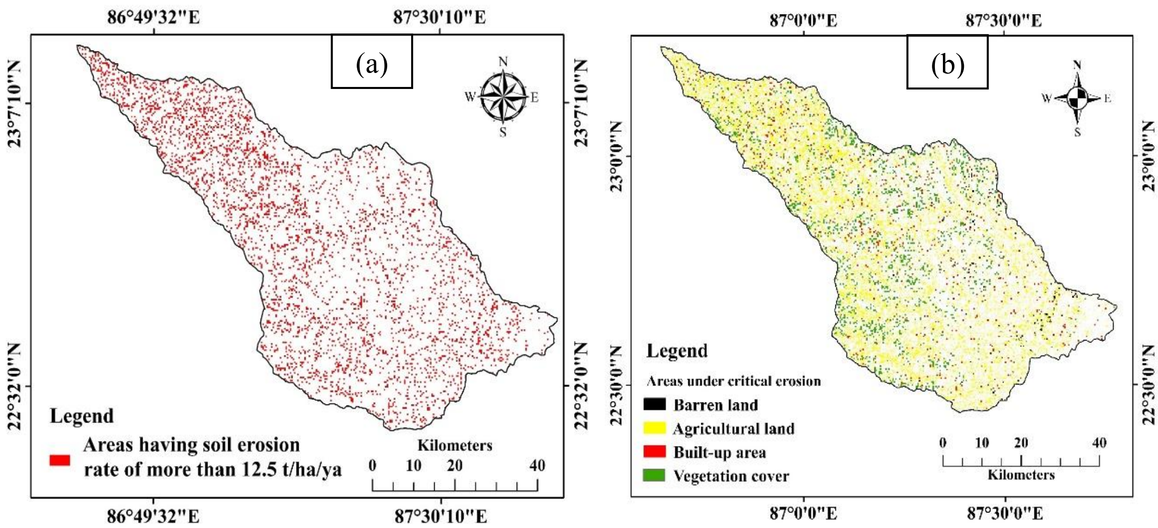

Fig. 4: Critical soil erosion areas (a) and their spatial distribution in different LULC categories (b)

Discussion

Analyzing soil erosion across different land use and land cover (LULC) categories within the study area has found significant variations in the susceptibility to erosion across different LULC categories. About 487.52 sq. km or 12.15 percent of the study area falls under critical erosion zones. Agriculture land stands out from the LULC categories, having the highest critical erosion coverage, taking up 71.44 percent of the total erosion areas. The soil disturbances caused by humans, such as plowing, intensive farming practices, and unsustainable conservation efforts, significantly impact erosion. Research done in the past (e.g. Lenka et al., 2014; Sharda et al., 2018) Also suggests this connection that agricultural land is often subject to more erosion due to less vegetation cover and continual soil exposure.

Barren land covers just 1.97 percent of the total land area, but it is responsible for more than four times in crucial erosion areas, with an ESI index of 4.39 further proving the fact that barren land is particularly susceptible to soil erosion because of their absence of vegetation as well as poor structure of the soil. The research done by Wischmeier and Smith (1978) and Jetten et al., (2003) has demonstrated this, revealing areas with low vegetation cover tend to have a more rapid rate of soil erosion which highlights the need for urgent soil conservation measures such as mulching, reforestation and structures for erosion control as the most urgent measures to protect against further erosion of soil.

Vegetation cover, comprising 27.52% of the basin, accounts for 15.69% of critical erosion areas. Yet its erosion susceptibility index (ESI) remains below 1, reflecting reduced susceptibility. Morgan (2005) suggests forested and vegetated areas can play an integral part in mitigating soil erosion by stabilizing it with root systems and mitigating the direct impact of rainfall. The built-up area, covering 11.95% of the basin, contributes only 4.23% to the critical erosion areas, with an ESI below 1. This is consistent with the findings of Pimentel and Kounang (1998), which indicated that urbanized regions generally have lower erosion risks due to impervious surfaces reducing direct soil exposure to erosive forces. However, urban expansion and land use transitions should be monitored closely to mitigate potential erosion risks in future scenarios.

Notably, rivers and water bodies do not contribute to soil erosion, which is expected, as these areas do not undergo direct soil detachment or surface runoff erosion processes. However, bank erosion and sediment transport processes could still be significant in certain hydrological conditions, as noted in studies by Goudie (2006) and Trimble (2010).

The spatial analysis of LULC-wise soil erosion highlights the urgent need for targeted erosion control strategies. The highest priority should be given to barren lands and agricultural areas, where conservation tillage, contour farming, afforestation, and soil stabilization techniques should be implemented to curb erosion rates. Bhattacharyya et al., (2019) suggested that integrating Remote Sensing and GIS-based modeling approaches, such as the Revised Universal Soil Loss Equation (RUSLE) and Soil and Water Assessment Tool (SWAT), can enhance erosion prediction accuracy and inform effective mitigation planning.

4. Conclusion

The present study highlights the urgent need for sustainable land management practices in erosion-prone areas. Barren and agricultural lands are specifically prone to high soil loss, demanding immediate conservation practices. An integrated and multi-layered response can be developed and soil conservation policies can be implemented in these particular regions and environmental conditions. Effective watershed management practices may help to reduce runoff rates and decrease vulnerability to further degradation. Sustainable agricultural practices such as agroforestry and contour farming can play an invaluable role in combatting soil erosion.

By encouraging their adoption, land productivity can be sustained while attenuating environmental harm. Public awareness campaigns give farmers and landowners tools for responsibly managing their lands. An integrated approach encompassing policy, technology, and on-the-ground conservation practices is necessary to halt soil degradation and ensure long-term viability in agricultural and natural landscapes. By adopting such strategies, we can preserve the productivity of our lands as well as safeguard ecosystems for future generations.

Acknowledgments

The authors are thankful to NASA Prediction of Worldwide Energy Resources (POWER), Alaska Satellite Facility (ASF), United States Geological Survey (USGS), and Survey of India (SOI) for providing the required information in digital format. Thanks also to Ramkrishna Ashram Krishi Vigyan Kendra, Nimpith, South 24-Parganas, West Bengal—743338, India, for helping in analyzing soil samples.

Conflict of Interest

There are no conflicts of interest to declare.

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