

# Soil erosion risk assessment using RUSLE in the upper Baitarani river basin, Odisha

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## Abstract

*Soil, a critical non-renewable resource essential for the overall survival of earth's diverse species, faces significant threats from accelerated erosion, adversely impacting both ecology and the economy. This study in this context assesses the soil loss within the Upper Baitarani Basin in the Keonjhar district of Odisha with the help of available geospatial data using open-source or licensed remote sensing and geospatial technology. The widely recognized RUSLE model was employed to quantify soil loss in the study area. The R-factor, influenced by rainfall, was calculated by an Indian scale analysis, considering typical meteorological conditions and IMD outputs for India. The results of the study indicate that soil erosion rates increased phenomenally over the past two decades, with average values rising from 2.21 tons per hectare in 2000 to 7.89 tons in 2020. The study attributes the growing threat of soil erosion due to changing rainfall patterns and land use, particularly in steep, mining-prone areas. The findings imply that suitable mitigation of erosion methods needs to be used to decrease soil erosion risk.*

**Keywords:** *Soil erosion, RUSLE, remote sensing, and GIS*

## Introduction

Water-induced soil erosion is a significant environmental issue impacting ecosystems, human livelihoods, and economic sustainability. Soil formation is an incredibly slow process that takes centuries to form and is a nonrenewable resource of great significance for the sustenance of life on Earth. Therefore, soil conservation has gained global attention. The European Union (EU) hence identifies soil erosion as a key environmental concern. It also plays a critical role in attaining the United Nations' Sustainable Development Goals (SDGs), particularly those related to hunger, clean water, and climate action (Montanarella *et al.*, 2016). The impact of soil

erosion on agriculture is particularly severe due to the loss of nutrient-rich topsoil which is essential for plant growth. Additionally, soil loss negatively impacts carbon sequestration; when eroded soil releases stored carbon, it increases atmospheric CO<sub>2</sub>, intensifying global climate change (Borrelli *et al.*, 2017).

Soil erosion modeling, especially the Revised Universal Soil Loss Equation (RUSLE), is an important tool in predicting and addressing soil loss by incorporating factors like rainfall, soil type, slope, and land cover (Renard *et al.*, 1997). Combining RUSLE with Geographic Information Systems (GIS) enhances the accuracy of soil

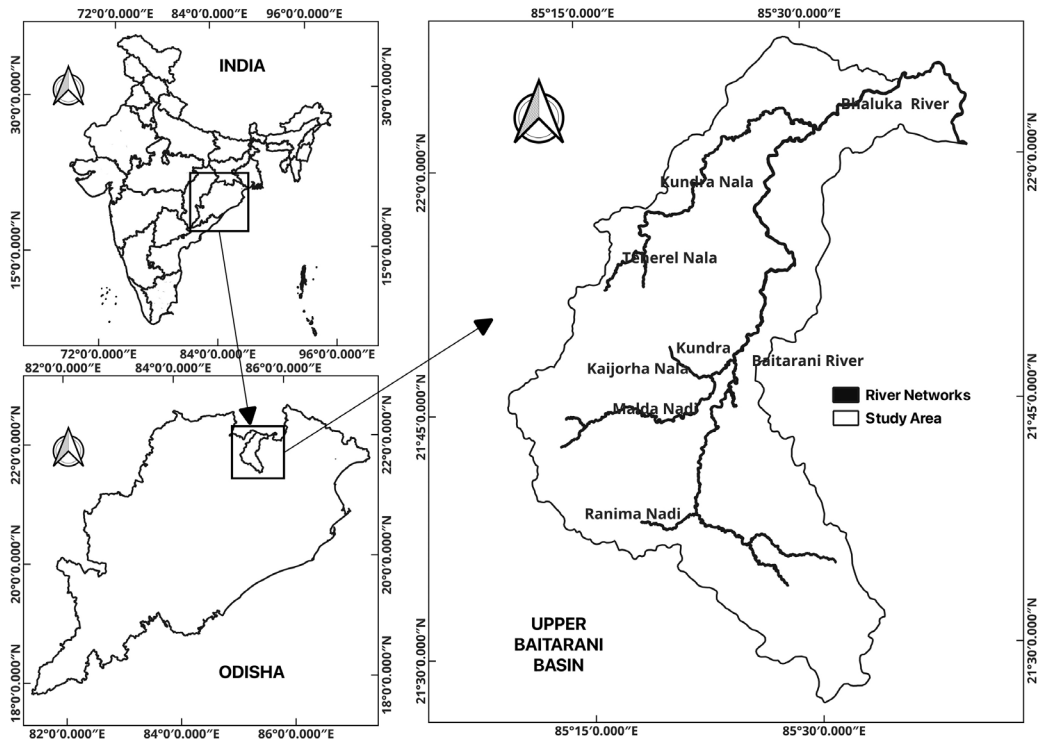


Fig. 1: Location of the study area

erosion predictions by integrating multiple spatial data layers such as rainfall, soil properties, topography, and land cover. GIS allows for the precise mapping of these factors across different terrains, providing a spatial understanding of erosion hotspots. This spatial analysis capability enables RUSLE to not only estimate soil loss more accurately but also identify areas most vulnerable to erosion, facilitating targeted conservation efforts (Sathiyamurthi *et al.*, 2023; Behera *et al.*, 2023). These models are particularly useful in developing regions where soil erosion can reduce land productivity and worsen poverty.

Despite its significance, research on soil erosion in the Upper Baitarani basin is limited. While RUSLE has been widely used in other

parts of India (Shit *et al.*, 2015; Chakraborty *et al.*, 2020; Kashiwar *et al.*, 2022; Sharma *et al.*, 2023), few focus on mining-affected regions like the Upper Baitarani basin. This is a crucial gap because mining dramatically alters landscapes and influences erosion patterns (Sodnomdarjaa *et al.*, 2023). Moreover, the integration of RUSLE with GIS for high-resolution erosion mapping has not been thoroughly explored in this region, leaving a gap in localized assessment.

### Objective

The Primary objective of this study is to assess and quantify soil erosion in the Upper Baitarani basin using the RUSLE model with the support of GIS.

## Study area

The study area is situated in the north-western part of the Baitarani River basin, within the Keonjhar district of Odisha. Geographically, the basin extends between latitudes 21° N to 22° 5' N and longitudes 85° E to 86° E (Fig. 1), covering an area of approximately 1,812.83 km<sup>2</sup>. The region is part of the mountainous catchment of the Eastern Ghats, with elevations ranging from 375 meters to 1,116 meters above mean sea level, contributing to its varied topography. The area was chosen for this study due to its unique combination of agricultural dependency and extensive mining activities, both of which are key factors influencing soil erosion.

Agriculture is the primary livelihood for most of the population, with large portions of the land used for farming. However, certain areas within the catchment, particularly around Joda, Barbil, and Gandhamardhan, are characterised by iron ore mining operations. These activities have led to significant land degradation, deforestation, and changes in the landscape, which accelerate soil erosion. The region's mining sector contributes substantially to the local economy but also poses severe environmental challenges, including increased runoff and sedimentation. The extent of mining and the associated degradation in these areas make them critical for assessing soil erosion risk.

The climate of the basin ranges from tropical to subtropical, characterized by hot summers, heavy monsoon rainfall, and cool winters. May is the hottest month, with average temperatures reaching up to 40.6°C, while January is the coldest, with temperatures dropping to around 5°C. The monsoon rains, starting in June, play a pivotal role in the area's hydrological patterns, further

contributing to soil erosion, especially on the steeper, mined slopes. These climatic and geographic conditions, combined with the pressures from agriculture and mining, make the Upper Baitarani basin an ideal location for studying soil erosion dynamics.

## Methodology

This study uses the Revised Universal Soil Loss Equation (RUSLE) to assess soil erosion in the Upper Baitarani River basin, a widely validated model for estimating soil loss due to water erosion. Originally developed by Wischmeier and Smith, 1978 and later revised by Renard *et al.*, 1997, RUSLE integrates various environmental factors into a single predictive framework, making it a robust tool for helping soil conservation. In this research, RUSLE is used alongside GIS to analyze erosion patterns across different terrains in the basin.

Data including rainfall were collected from multiple sources, to calculate the rainfall erosivity factor (R), which is crucial for understanding soil detachment and transportation. Satellite imagery from Landsat 5 and Sentinel 2, with resolutions of 30m and 10m respectively, were used to assess land cover and vegetation indices, contributing to the calculation of the cover-management factor (C). Soil texture data helped analyse the soil erodibility factor (K), while topographic data provided slope factors (L and S), essential for understanding terrain influences on erosion. Data were collected for three-time points (2000, 2010, and 2020) to enable temporal analysis of erosion trends.

Using ArcGIS, all datasets were geo-referenced to ensure spatial consistency and integrated into thematic layers for comprehensive analysis. GIS tools such as

raster calculation and spatial interpolation were applied to generate maps that visually represent erosion risks. This approach offers a detailed understanding of erosion dynamics, contributing to more effective watershed management and soil conservation strategies in the study area.

The RUSLE model was used to estimate average annual soil loss by integrating several factors that contribute to soil erosion. The equation is expressed as:

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

Where:

*A* = Estimated average annual soil loss (tons per hectare per year)

*R* = Rainfall erosivity factor

*K* = Soil erodibility factor

*LS* = Slope length and steepness factor

*C* = Cover management factor

*P* = Support practice factor

### Rainfall Erosivity (R) Factor

The R factor quantifies the impact of rainfall on erosion and is calculated using long-term rainfall data. In this study, the rainfall data were sourced from the Climate Hazards InfraRed Precipitation with Station (CHIRPS) dataset and processed using the ArcGIS platform. The erosivity index was computed by applying the formula:

$$R = 50 + (0.389 \times X_s)$$

Where:

*R* = Erosivity index for the season, and

*X<sub>s</sub>* is the annual rainfall in millimeters.

Spatial interpolation of the rainfall data was performed using the Inverse Distance Weighted (IDW) method, ensuring that

erosivity values were accurately represented across the study area.

### Soil Erodibility (K) Factor

The soil erodibility factor *K* represents the susceptibility of soil particles to detachment and transport by rainfall and runoff. The *K* factor is calculated based on soil properties, including soil texture, organic matter content, structure, and permeability.

The formula used for determining the *K* factor is:

$$K = \left( \frac{2.1 \times 10^{-4} (12 - OM) \times M + 3.25(\text{structure} - 2) + 2.5(\text{permeability} - 3)}{100} \right)$$

Where:

*OM* = Percentage of organic matter

*M* = Particle size parameter, calculated as percent Silt + percent Very Fine Sand (100 - percent Clay)

Structure = Soil structure code

Permeability = Soil permeability code

### Slope length and steepness (LS) factor

The topographic factor *LS* represents the influence of slope length (*L*) and slope steepness (*S*) on erosion rates. The *LS* factor is calculated using the following equation:

$$LS = \left( \frac{\text{Flow Length}}{22.13} \right)^m \times \left( \frac{\sin \theta}{0.0896} \right)^n$$

Where:

Flow Length = Slope length in meters

$\theta$  = Slope angle in degrees

*m* and *n* are coefficients that vary based on the slope gradient.

The flow length and slope were derived from a Digital Elevation Model (DEM) using GIS tools, allowing for spatially variable calculations across the study area.

### Cover management(C) factor

Vegetation cover significantly impacts soil erosion by protecting the soil surface from raindrop impact and runoff. The C factor was assessed using the Normalized Difference Vegetation Index (NDVI), derived from Sentinel-2 satellite imagery. The NDVI was calculated using the formula:

$$NDVI = \frac{NIR - Red}{NIR + Red}$$

Where:

NIR and Red is the reflectance recorded in the near-infrared and red spectrum, respectively.

Based on the NDVI image, the following equation, which gives better results than assuming a linear relationship, is used to generate a C-factor surface from NDVI values

$$C = \exp \left[ -a \left( \frac{NDVI}{b - NDVI} \right) \right]$$

Where:

$\alpha$  equals 2 and  $\beta$  equals 1, which are unitless parameters that determine the shape of the curve relating to NDVI and the C-factor.

### Support practice (P) factor

The P factor is a dimensionless index that represents the effectiveness of soil conservation practices in reducing soil erosion. It measures how different land management strategies, such as contouring or terracing, help in minimizing erosion by influencing water flow and reducing runoff. In this study, different P values were assigned based on land use patterns observed in the watershed, with a particular distinction between paddy fields and non-paddy agricultural fields (Singh, 1989). GIS tools were used to overlay land use data on the RUSLE model to determine the P factor,

allowing for an assessment of how these management practices impact erosion rates.

Soil loss was calculated by spatially integrating the RUSLE model components: R (rainfall erosivity), K (soil erodibility), LS (topographic factor), C (cover management), and P (support practice). Each factor was represented as a thematic layer within the GIS, and the overall potential soil loss (A) was computed using the formula  $A=R \times K \times LS \times C \times P$ . This calculation was facilitated by the Raster Calculator tool in ArcGIS, which performed pixel-by-pixel multiplication of the layers to yield a comprehensive map of annual soil loss rates across the region.

The next important task was generating risk maps and analyzing soil erosion severity. The resultant soil loss data were classified into categories (e.g., low, moderate, high) based on threshold values established in the literature and adapted to local conditions. This classification helped in identifying areas most at risk of severe erosion, thereby enabling targeted soil conservation efforts. Risk maps were then generated to visualize these categories, highlighting areas of critical concern that require immediate intervention.

GIS tools were also employed to perform advanced spatial analyses, such as hotspot analysis, which identifies clusters of high erosion within the landscape. This analysis was crucial in understanding the spatial patterns of erosion and the effectiveness of existing land management practices. Additionally, the use of GIS facilitated the overlay of soil erosion data with other environmental and socio-economic layers, such as biodiversity hotspots and agricultural productivity zones. This multidimensional analysis aids stakeholders in making informed

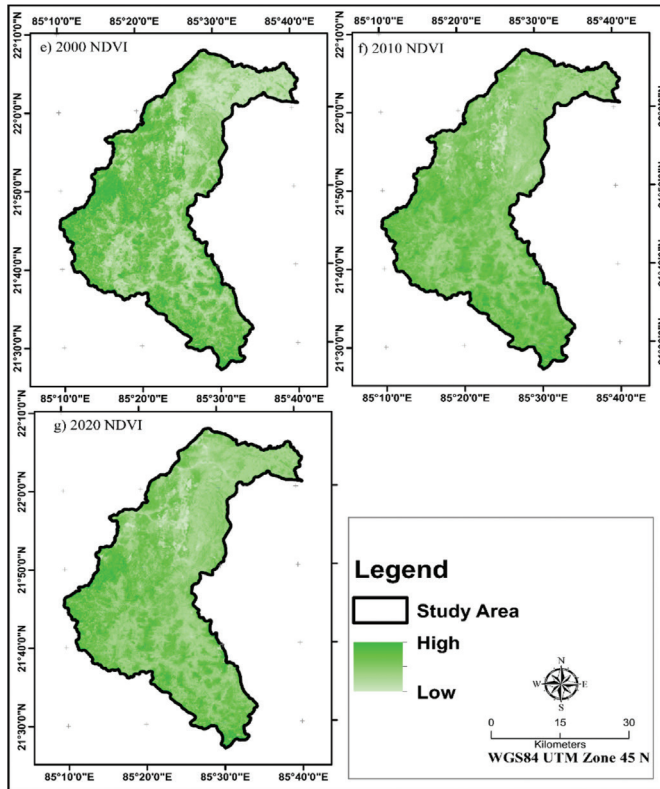


Fig. 2: Temporal NDVI variation from 2000-2020

decisions regarding land use planning and erosion control measures.

## Results

### *Rainfall erosivity assessment*

The rainfall erosivity (R) factor, a critical determinant of soil erosion in the RUSLE model, exhibits significant variation across the temporal scale from the year 2000 to 2020 in the Baitarani River basin (Fig. 4, 5 and 6). Data derived from CHIRPS precipitation measurements indicated a pronounced increase in erosivity with recorded values escalating from 134.9 to 144.6 MJ mm/ha/h/y in 2000, to a substantial range of 571.3 to 1747.05 MJ mm/ha/h/y by 2020.

The average erosivity over the period was calculated at 539.45 MJ mm/ha/h/y, with a standard deviation of 126.44 MJ mm/ha/h/y. This trend is indicative of increasing rainfall intensity, which is consistent with broader climatic shifts attributed to global warming (Smith *et al.*, 2018). The geographical distribution of the R factor further delineates the stark contrast between the core region's steep terrains, particularly in the northern and central parts of the basin, where areas like Joda, Barbil, and the surrounding mountainous regions exhibited higher R values. This disparity can be attributed to the steep slopes, increased rainfall intensity, and extensive mining activities in these regions,

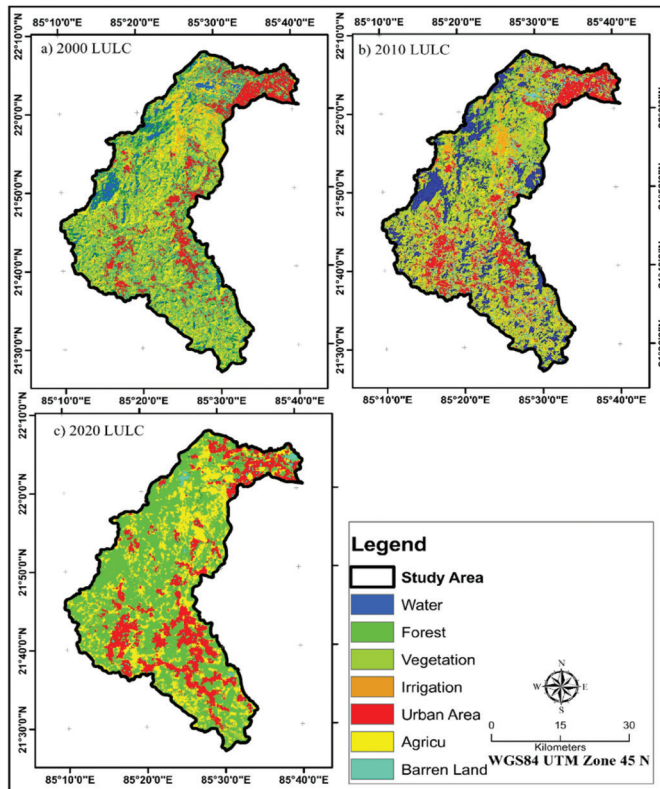


Fig. 3: LULC a) 2000 b) 2010 c) 2020

which amplify the erosive power of rainfall. In contrast, the southern and lower-elevation areas of the basin, which are predominantly agricultural, tend to have lower R values due to gentler slopes and better land management practices.

### ***Soil erodibility dynamics***

Soil erodibility (K), influenced by the intrinsic properties of soil types within the basin, showed a range from minimal (0.0) to 1.82 MJ mm/ha/h/y. The average K value stood at 1.05 MJ mm/ha/h/y with a standard deviation of 0.58 t ha-h ha/MJ/m/m reflecting moderate variability. These findings highlight the heterogeneous nature of soil composition across the basin and its impact on erosion

processes. The variations in K values across different geological formations within the basin suggest the need for differential management practices that cater to the specific erosion risks of various soil types.

### ***Topographic influence on soil erosion***

The topographic factor (LS) has shown an upward trend in the values from 2000 to 2020 (Fig. 4, 5 and 6), with maximum values increasing markedly from 552.78 in 2000 to 1199.37 in 2020. The mean LS value over this period was calculated at 5.17, with a variance of 7.82. The increase in LS values is indicative of the exacerbating impact of topography on erosion risk, particularly on steeper slopes which are more prone to

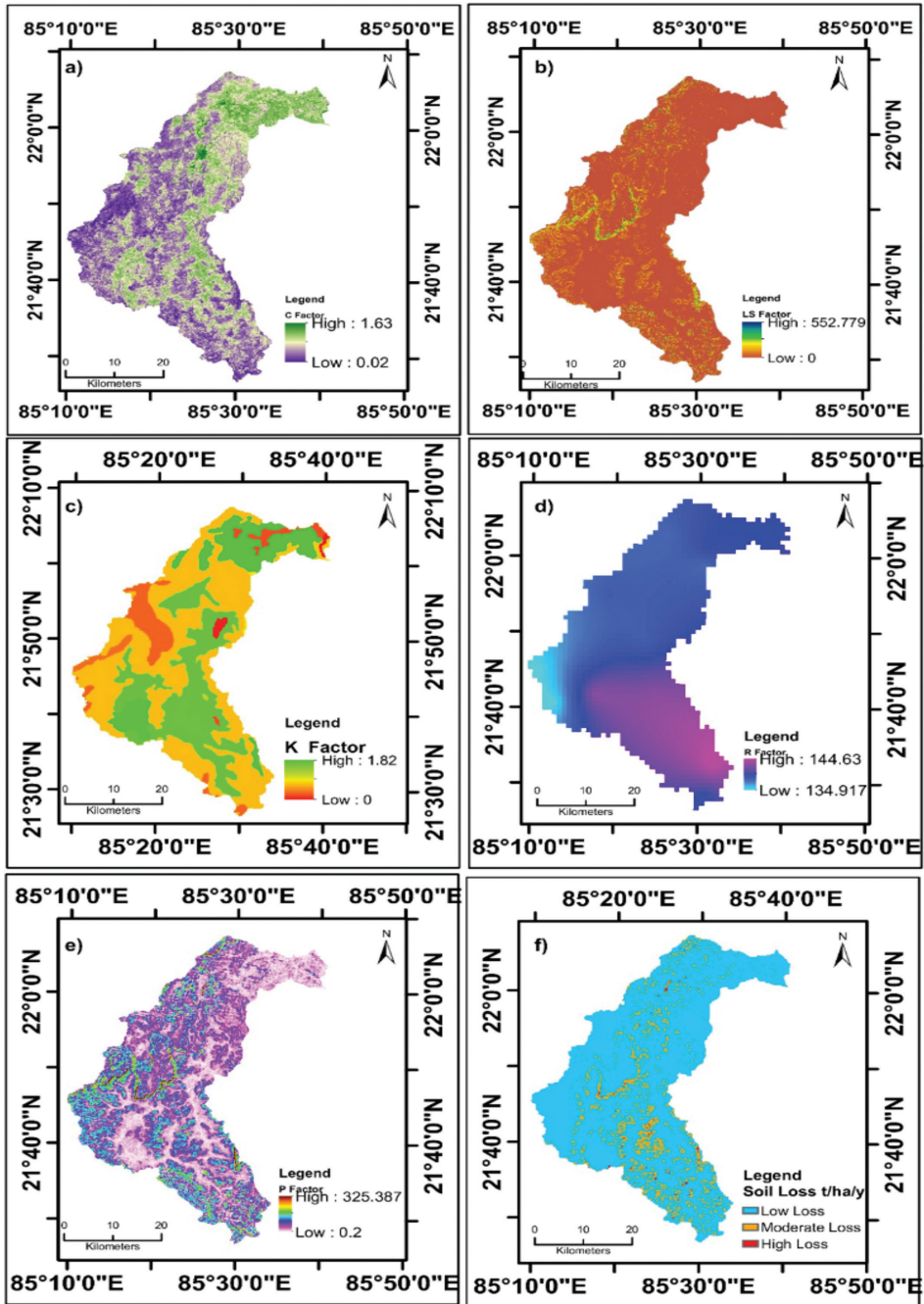


Fig. 4: Spatial Map of (a) C factor cover management (b) LS factor Topographic, (c) K factor soil erodibility, (d) R factor rainfall erosivity, (e) P-factor support practice and (f) soil loss of 2000

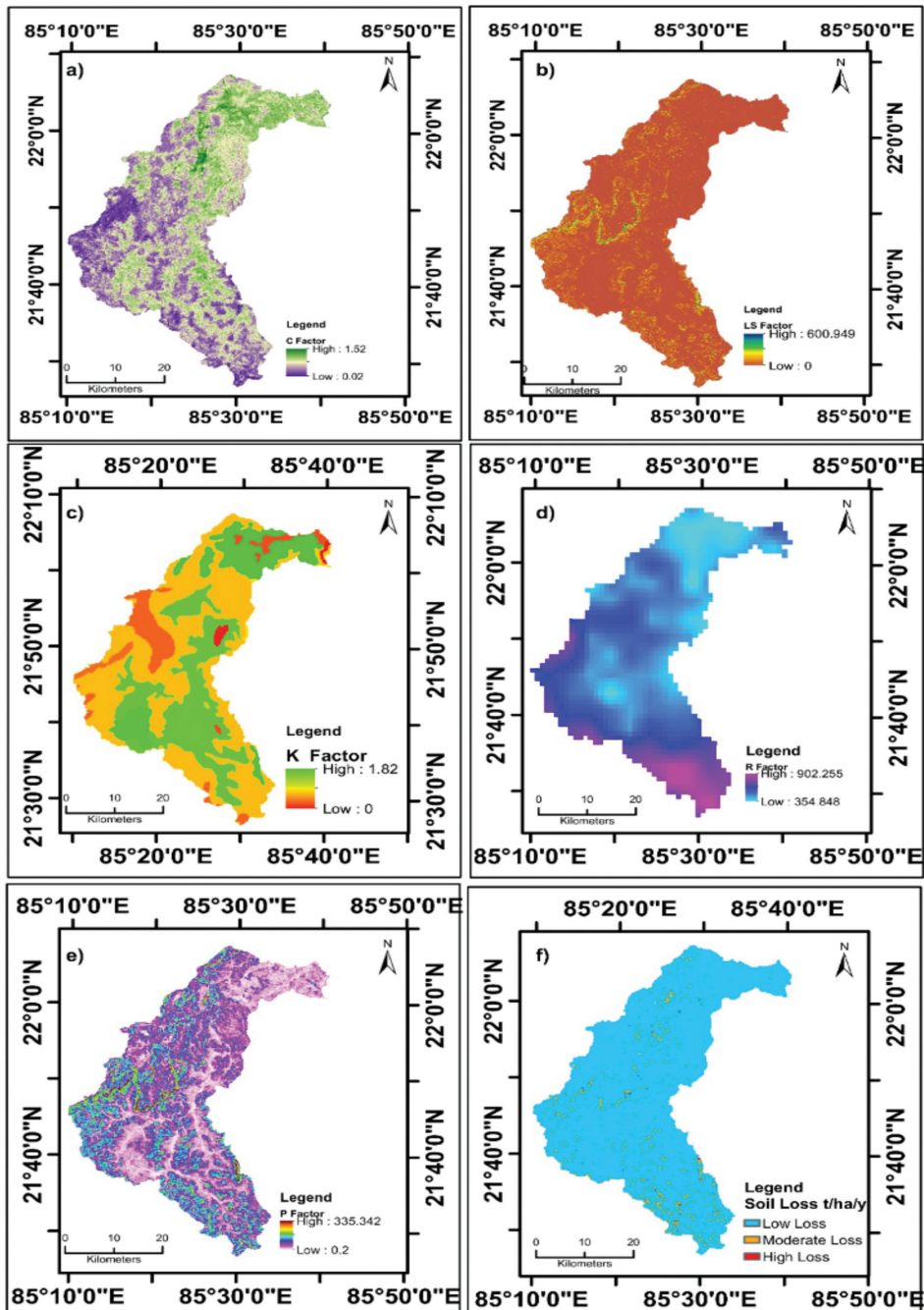


Fig. 5: Spatial Map of (a) C factor cover management (b) LS factor Topographic, (c) K factor soil erodibility, (d) R factor rainfall erosivity, (e) P-factor support practice and (f) soil loss of 2010.

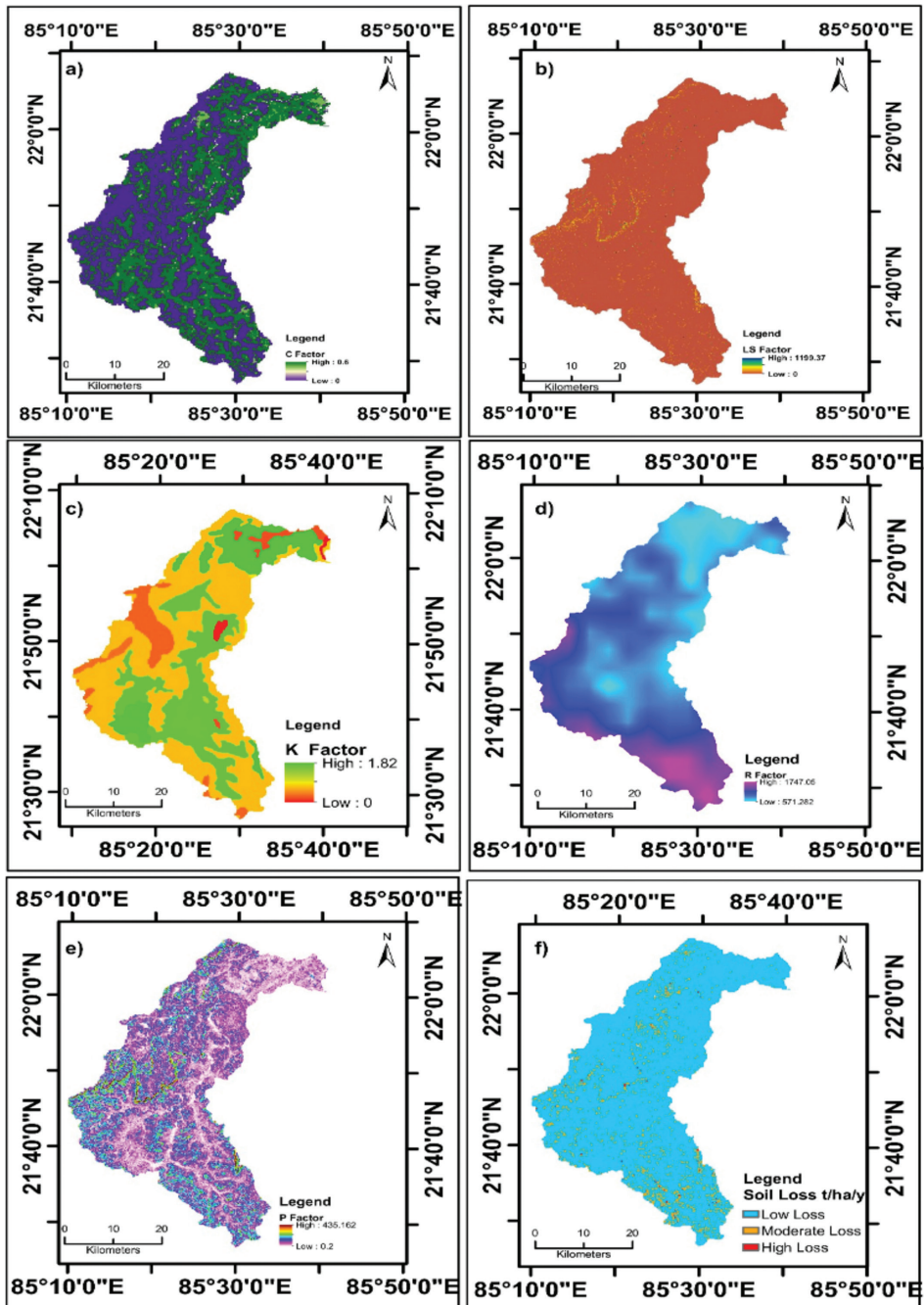


Fig. 6: Spatial Map of (a) C factor cover management (b) LS factor Topographic, (c) K factor soil erodibility, (d) R factor rainfall erosivity, (e) P-factor support practice and (f) soil loss of 2020

runoff and thus higher erosion rates (Nguyen *et al.*, 2020). This trend underscores the escalating challenge posed by topography in soil erosion control, emphasizing the urgency for implementing effective land management strategies that incorporate contour farming, terracing, and vegetation buffers to mitigate erosion (Wang *et al.*, 2023).

**Cover-management factor variation**

The Cover-Management factor (C) in the Baitarani River basin has shown significant temporal variation from 2000 to 2020, which are derived from NDVI maps (Fig. 2) highlighting the dynamic nature of land cover and its impact on soil erosion. Minimum C-factor values were observed in water, vegetation, and agriculture, reflecting their protective role against soil erosion. Conversely, the maximum values were noted in barren land, vegetation, and forested areas in 2000, 2010, and 2020 respectively, with values peaking at 1.63 in 2000 and decreasing to 0.60 by 2020 (Fig. 2). The average C-factor over these years was 0.43, with a standard deviation of 0.18. These trends indicate an overall improvement in land management practices over the two decades, likely due to increased afforestation and improved agricultural practices, which contribute to reducing the C-factor.

**Soil loss classification and hazard mapping**

The integration of RUSLE components facilitated the generation of soil loss estimates

and the creation of a soil loss hazard map, proving to be vital tools for environmental management and planning. The annual soil loss was categorized into low, moderate, and high classes, detailed in Tables 1, 2 and 3. Remarkably, most of the study area (88.3% in 2000, 90% in 2010, and 93% in 2020) was classified under a very low hazard class, indicating effective soil conservation measures and stable land cover conditions conducive to minimal soil displacement.

However, the trend of decreasing areas classified under 'low' hazard—from 11.3 percent in 2000 to 3.0 percent in 2020—and the consistent appearance of regions under 'moderate' and 'high' hazard classes (peaking at 1.0% each in 2020) signal localized degradation, particularly in coastal zones. These areas are especially prone to high erosion due to the confluence of steep slopes and barren land, which significantly diminishes the resistance of the soil to erosion forces (Liu & Sheng, 2023).

**Discussion**

The shift towards a larger proportion of the region falling under the very low hazard category is a positive indicator of the ongoing efforts in soil conservation and sustainable land management. Nonetheless, the presence of moderate and high erosion hazards in certain areas, especially those characterized by challenging topographic and land cover conditions, calls for targeted interventions. Strategies such as the implementation

Table 1: Soil Loss, 2000

Year	Soil loss (ton/ha/yr)	Category	s/n	Area Change	Total area (%)	Class
2000	1.945	Low Loss	1.	144376.204	88.3	High
2000	12.310	Moderate Loss	2.	18528.9651	11.3	Moderate
2000	24.624	High Loss	3.	547.99156	0.3	Low
Total	2.211			163453.1607	100	

of contour plowing, terracing, and the establishment of buffer zones with dense vegetation could be expanded to mitigate the risk in these high-hazard zones.

Furthermore, the decreasing trend in maximum C-factor values and the broad reduction in areas under higher hazard classes over the years align with global and regional initiatives aimed at combating land degradation and promoting land sustainability. This progression underscores the importance of continuous monitoring and adaptive management strategies to address the evolving challenges posed by environmental and climatic changes.

The results from the RUSLE model for the Baitarani River basin indicate that the average annual rates of soil loss have escalated over the past two decades: from 2.1 t/ha/year in 2000 to 5.05 tons in 2010, and 7.89 tons in 2020 (Table 1, 2 and 3). These figures are slightly lower than the European Union (EU) average but are on a rising trend that aligns with the increasing severity of climatic variables influencing soil erosion. For instance, the rill erosion rates across the EU in 2008 averaged at 2.46 t/ha/y, but countries with challenging topographies like Italy and Slovenia reported much higher rates, underscoring the influence of physical geography on erosion processes (Jain *et al.*, 2010).

Global climate models (GCMs), despite their limitations in resolving regional-scale phenomena, suggest an increase in the severity and frequency of rainfall events, which will exacerbate soil erosion (Giorgi & Lionello, 2008). Dynamic downscaling of GCM data via Regional Climate Models (RCMs) has provided more tailored insights, which are crucial for understanding local responses to global climatic changes. This

approach has been pivotal in predicting future scenarios of rainfall erosivity, particularly in regions like India and Greece, where significant research has been conducted. The insights gained underscore the necessity of integrating climate projections in soil erosion assessments and management plans (Rummukainen, 2009).

The study highlights the varying erosion rates across different land use and land cover (LULC) types, with forests showing minimal erosion due to their protective canopy and root systems. This emphasizes the importance of forest conservation strategies that prioritize ecological functions over economic gains. In contrast, agricultural areas, which showed higher erosion rates, could benefit significantly from sustainable practices such as contour farming, which can reduce erosion by up to 50 percent, and strip farming, which stabilizes the soil through varied vegetation cover (Wang *et al.*, 2001).

The need for new policies that incentivize soil conservation, particularly in high erosion areas is critical. Such policies could include subsidies for farmers practicing conservation agriculture and the construction of erosion control structures like stone walls, which are effective in steep terrains typical of the Mediterranean landscape (Petanidou *et al.*, 2008).

Furthermore, as climate change continues to influence soil erosion dynamics, future research should incorporate both climate and land-use change scenarios to develop more comprehensive soil conservation strategies. The use of advanced technologies such as cloud computing platforms and tools like Google Earth Engine could facilitate large-scale analysis and real-time monitoring of erosion processes.

The Land Use and Land Cover (LULC) analysis based on the supervised classification of Landsat satellite images from 2000, 2010, and 2020 reveals significant changes in the landscape of the Baitarani River basin (Fig. 3). In 2000 and 2010, agricultural land and moderately barren land were the most prevalent cover types, representing approximately 19.7 percent and 19.3 percent of the area respectively. Urban and irrigated areas constituted 16.6 percent and 13.1 percent, while vegetation and water covered smaller fractions at 10.3 percent and 9.0 percent.

By 2020, there was a notable shift in land cover; the area under agriculture and moderately barren land decreased to 11.5 percent and 11.2 percent, respectively (Table 3). Conversely, irrigated areas and urban zones increased slightly to 16.5 percent and 14.7 percent. Most strikingly, vegetation and water bodies saw significant increases, covering 18.4 percent and 17.2 percent of the land, respectively. These changes reflect broader trends in land management and

development pressures, as well as efforts towards conservation and sustainable land use practices.

The evolution of land use and land cover is a pivotal factor affecting soil erosion rates in the basin. Changes in land cover influence soil stability, water infiltration capacity, and surface runoff characteristics, thereby altering the susceptibility of areas to erosion. As shown in the multi-layered vulnerability maps, each land cover type was evaluated based on its potential impact on soil erosion, categorized into different sensitivity groups.

The increase in urbanization (from 13.1 to 14.7%) contributes to soil erosion, though not in a substantial manner at present. While this minor rise in urban areas has slightly reduced permeability and increased runoff, its current impact on erosion remains limited. However, if urbanization continues to expand in the coming years, it could become a more significant factor in exacerbating soil erosion. Conversely, the increase in vegetation cover can be seen as a positive development, as vegetative cover significantly reduces the

Table 2: Soil Loss, 2010

Year	Soil loss (ton/ha/yr)	Category	s/n	Area Change	Total area (percent)	Class
2010	4.6088	Low Loss	1.	147767.514	90	High
2010	27.894	Moderate Loss	2.	15512.271	9	Moderate
2010	36.436	High Loss	3.	137.699	1	Low
Total	5.053			163417.484	100	

Table 3: Soil Loss, 2020

Year	Soil Loss (ton/ha/yr)	Category	s/n	Area Change	Total area (percent)	Class
2020	7.265	Low Loss	1.	151559.0239	92	High
2020	15.275	Moderate Loss	2.	12696.3769	7	Moderate
2020	32.918	High Loss	3.	327.806263	1	Low
Total	7.897			164583.2071	100	

velocity of surface runoff and enhances soil stability through root systems, thus mitigating soil erosion.

The significant rise in water-covered areas also suggests changes in hydrological patterns, possibly due to climate change impacts or alterations in water management strategies. Water bodies can help reduce soil erosion by trapping sediments and slowing runoff during heavy rainfall events.

The observed trends in LULC highlight the need for integrated land management strategies that accommodate both development and environmental conservation. The reduction in barren lands and the increase in vegetative cover are encouraging signs of effective land management practices. However, the continuous monitoring of urban expansion and its impacts on soil erosion is crucial. Urban planning should incorporate green infrastructure and sustainable drainage systems to manage runoff and prevent erosion effectively. Additionally, agricultural practices need to be continually adapted to maintain soil health and prevent erosion. Techniques such as cover cropping, reduced tillage, and contour farming should be promoted among farmers to enhance soil retention and reduce runoff.

## Conclusion

This study provided significant insights into soil erosion dynamics over a twenty-year period in the Upper Baitarani River basin of Odisha. The key findings of our analysis in understanding the challenges and effective management strategies needed in the region are:

a. *Rainfall erosivity increase:* A pronounced increase in the rainfall erosivity factor from 134.9 MJ mm/ha/h/y in 2000 to an alarming range of 571.3 to 1747.05

MJ mm/ha/h/y by 2020 underscores the growing intensity of rainfall events. This trend is aligned with global climatic shifts and highlights the urgent need for enhanced erosion control measures.

- b. *Soil erodibility variability:* The study reveals significant variability in soil erodibility across different geological formations, with values ranging from 0.0 to 1.82 MJ mm/ha/h/y. This variability necessitates tailored soil conservation strategies to address the differential erosion risks presented by various soil types.
- c. *Topographic influences on erosion:* An increase in the topographic factor (LS) from 552.78 in 2000 to 1199.37 in 2020 indicates that steeper slopes are increasingly prone to erosion. This trend emphasizes the importance of integrating landscape management practices such as terracing and contour farming to mitigate erosion risks.
- d. *Land cover management improvements:* The observed decrease in the Cover-Management (C) factor values from a maximum of 1.63 in 2000 to 0.60 by 2020 reflects improvements in land cover management, particularly through afforestation and better agricultural practices which have contributed to reduced soil erosion.
- e. *Soil loss rates and hazard mapping:* The categorization of soil loss into low, moderate, and high classes reveals a significant portion of the area, increasing from 88.3 percent in 2000 to 93 percent in 2020, falls under a very low hazard class. Despite this positive trend, the presence of areas under 'moderate' and 'high' hazard classifications indicates ongoing localized degradation.

f. *Annual soil erosion rates*: The average annual rates of soil loss in the region have shown a worrying increase, rising from 2.1 t/ha/year in 2000 to 7.89 t/ha/year in 2020. These findings indicate a growing severity in soil erosion that, while still below the European Union average, requires urgent and continuous management attention.

The results of this study not only illustrate the evolving nature of soil erosion influenced by multiple factors but also highlight the critical need for adaptive management strategies that incorporate both current findings and ongoing monitoring. The integration of these strategies will be essential for sustainable land management and the prevention of further soil degradation in the Upper Baitarani River basin.

Our soil loss classifications and hazard mapping indicate that despite the increased severity of some contributing factors, a substantial portion of the basin now falls under the very low hazard category. This is a testament to the effectiveness of ongoing soil conservation initiatives. However, the presence of moderate and high erosion hazards in specific locales highlights the continued necessity for targeted interventions.

The study reinforces the critical need for integrated soil erosion management that combines traditional techniques with innovative approaches tailored to the unique challenges of the Baitarani River basin. As climate change continues to influence erosion dynamics, it is imperative that future research and policymaking prioritize sustainable land use and conservation strategies, incorporating advanced technologies for real-time monitoring and analysis. This will ensure the long-term resilience of the land and its capacity to support the region's ecological and economic needs.

## Competing interest

The corresponding author declares that they have no conflict of interest.

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