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Assessment of soil erosion in the Chambal River Basin, India using RUSLE model – implications for agricultural sustainability

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Abstract

Soil erosion is the most concerning issue for agricultural sustainability by decreasing the soil quality. The soil erosion within the Chambal River Basin was assessed using the Revised Universal Soil Loss Equation (RUSLE), satellite-derived datasets such as CHIRPS for precipitation (R factor) and MODIS for vegetation cover (C factor). The study spans from 2001 to 2023, highlighting how changes of MODIS derived LULC in permanent wetlands, agriculture land, urban, vegetation, barren land, and water bodies which influences soil erosion. Results show that croplands consistently dominated over 97% of the study area, increasing from 1,25,613 hectares in 2001 to 1,44,774 hectares in 2023. The spatial variability in erosion, with approximately 50% of the area experiencing slight erosion (<10 t/ha/year) and 30% under moderate erosion (10-20 t/ha/year). Severe erosion (>40 t/ha/year) affects 5% of the basin, particularly in steep slope regions. From 2001 to 2023, mean annual soil loss decreased from 9.66 t/ha/yr to 8.98 t/ha/yr, suggesting minor improvements in land management practices. Rainfall erosivity increased from 351.76 mm in 2001 to 388.09 mm in 2023, correlating with intensified rainfall events due to climate variability. The study highlights the importance of integrating remote sensing and RUSLE for understanding erosion dynamics and promoting sustainable land management in the Chambal Basin.

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INTRODUCTION

Soil erosion is a significant environmental issue, which has a profound impact on ecosystems, agricultural output, and the sustainability of land. Globally, it is estimated that approximately 23 to 42 billion tons of soil is lost annually due to erosion ([Borrelli et al., 2020](#)), driven by factors such as deforestation, unsustainable agricultural practices, and climate change.

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In agricultural areas, soil erosion poses a direct threat to crop productivity and food security. The nutrient-rich topsoil layer, which is essential for soil fertility and plant growth, is lost due to erosion. The removal of topsoil reduces the land's capacity to sustain crops, which results in reduced yields and a greater reliance on fertilizers to sustain output. Soil erosion can reduce agricultural yields by as much as 25%, depending on the severity of erosion and the crop type. In addition, the loss of organic matter and the decline in soil structure due to erosion exacerbate the risk of land degradation, desertification, and the long-term unsustainability of agricultural systems ([Smith et al., 2021](#)). Monitoring soil erosion, particularly in agricultural regions, is essential for the development of sustainable land management strategies.

The Revised Universal Soil Loss Equation (RUSLE) model has been widely applied to assess soil erosion risk by incorporating rainfall patterns, soil characteristics, topography, and land use factors ([Dabral et al., 2008](#)). Changes in LULC, especially in agricultural areas, play a crucial role in determining soil erosion patterns. Agricultural expansion often leads to the removal of natural vegetation, which otherwise acts as a protective barrier against erosion by stabilizing the soil and reducing runoff. LULC changes, especially the conversion of natural vegetation into croplands, significantly contribute to increased soil erosion rates, particularly in areas with intense agricultural activities and inadequate conservation measures. Monitoring these changes is essential for devising soil conservation strategies aimed at mitigating erosion risks.

In recent years, concerns regarding soil degradation and the impact of climate variability on crop yields have heightened, prompting the need for sustainable agricultural practices and water management strategies to combat drought and erosion in the basin. Many studies have highlighted the limitations of traditional soil conservation methods, such as Soil erosion, especially under changing climatic conditions, poses a significant threat to agricultural sustainability in the Chambal River Basin. Large-scale soil moisture estimation is crucial for understanding soil vulnerability in rain-fed areas, where variations in soil moisture influence erosion rates ([B. M. Rao et al., 2001](#)). Additionally, climate variability, as observed in the Ramganga catchment, directly affects rainfall patterns, increasing soil erosion risks during critical periods of reduced rainfall ([Sudhishri et al., 2016](#)). Changes in hydrological cycles, such as increased runoff and altered evapotranspiration, further intensify soil erosion, making climate monitoring essential for effective land management ([Swagatika et al., 2024](#)). The lack of region-specific data and limited monitoring capabilities. By utilizing satellite data, this approach supports the estimation of soil vulnerability and loss under various climatic conditions ([B. M. Rao et al., 2001](#)). By using modern remote sensing techniques and applying the RUSLE model, this study overcomes these limitations, providing a more accurate and timely assessment of soil erosion risk.

With this background, the objectives of the present study are: (i) to estimate the spatial and temporal variation of soil loss by integrating remote sensing data processing and analysis and (ii) to analyze the influence of key environmental factors (rainfall, cover management, and LULC changes on soil erosion and (iii) to assess the impact of agricultural expansion and land use practices on soil stability and suggest strategies for sustainable soil conservation. The findings from this research will contribute to the development of sustainable land management practices that can enhance soil stability and ensure the continued productivity of agricultural land in the Chambal River Basin.

METHOD

Study Area

The Chambal River, an important tributary of the Yamuna, spans approximately 1,013 kilometres and is a crucial part of the Ganga River basin. Originating in the Janapav Hills of the Malwa plateau, it covers an area of 141,578.2 km² and the geographic coordinates of the Chambal River basin range from 22°29'17.67" to 27°33'5.27" N latitude and 73°22'17.431" to 79°14'3.07" E longitude that includes parts of Madhya Pradesh, Rajasthan, and Uttar Pradesh (Figure 1). The

basin experiences a semi-arid climate with an average annual rainfall of about 900 mm, primarily during the monsoon months from June to September, although some areas receive over 1,000 mm. Temperature extremes vary significantly, ranging from summer highs of 45°C to winter lows around 5°C. Soils in the basin are diverse, including alluvial, black cotton, and red soils, with black soils in the Malwa plateau being particularly fertile for agriculture. Major crops cultivated in this region include wheat, barley, gram, and mustard, reflecting the agricultural significance of the area. However, soil erosion remains a challenge, especially in the lower basin, where ravines and gullies complicate farming activities.

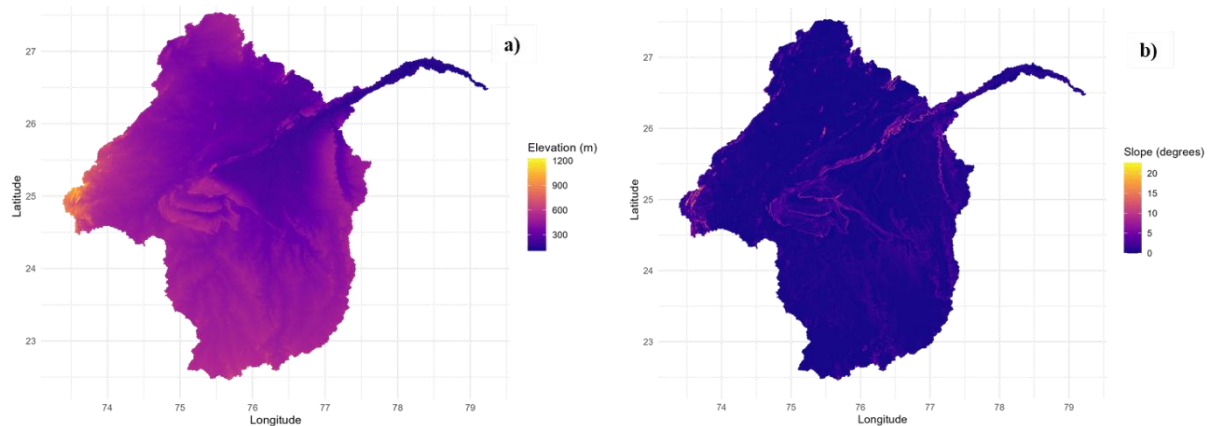


Figure 1. Study area of a) Elevation and, b) Slope of Chambal River Basin (CRB)

In this study, yearly average rainfall data from Climate Hazards Centre InfraRed Precipitation with Station data (CHIRPS) at 0.05° spatial resolution, soil texture data from OpenLandMap Soil Texture Class (USDA System), Digital Elevation Model from Shuttle Radar Topography Mission (SRTM) at 30 m spatial resolution and MOD13Q1 V6.1 product provides a Vegetation Index (VI) 16 days at 250 meter spatial resolution data have been used to create thematic layers in GIS platform (Table 1).

Table 1. Details of the factors derived and the datasets used

Factor derived	Dataset used	Data source	Spatial Resolution
Rainfall erosivity (<i>R</i>)	Rainfall	Climate Hazards Centre InfraRed Precipitation with Station data (CHIRPS) (https://www.chc.ucsb.edu/data/chirps)	0.05°
Soil erodibility (<i>K</i>)	Soil texture	OpenLand Map Soil Texture Class (USDA System) (https://zenodo.org/records/2525817)	250 m
Crop management (<i>C</i>)	NDVI	Moderate Resolution Imaging Spectroradiometer (MODIS) (https://earthexplorer.usgs.gov/)	250 meter
Support practices (<i>P</i>)	DEM	SRTM (https://portal.opentopography.org/raster?opentopoID=OTSRTM.082015.4326.1)	30 m

The methodology employed in this study integrates multiple satellite products and geospatial datasets to estimate soil loss in the Chambal River Basin using the Revised Universal Soil Loss Equation (RUSLE) model. The RUSLE model, developed by [Renard et al. \(1997\)](#), is an empirical tool designed to estimate long-term average annual soil loss rates based on rainfall patterns, soil characteristics, topography, land cover, and conservation practices in Figure 2.

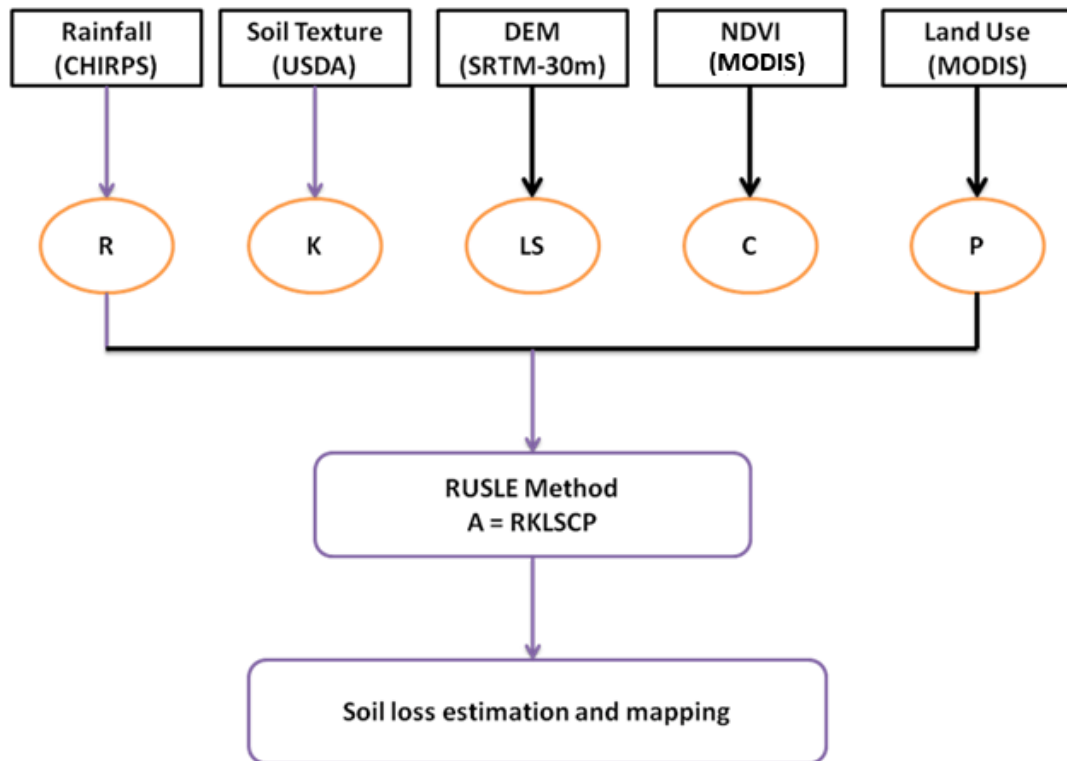


Figure 2. Flow chart for the calculation of RUSLE factors and their integration

R factor (Rainfall-Runoff Erosivity Factor)

The R factor represents the erosive force of rainfall and its capacity to cause soil erosion. In this study, the CHIRPS dataset was used to calculate the R factor. The total annual precipitation was computed using CHIRPS data, and the R factor was calculated using the following formula, derived from empirical studies for Indian conditions:

$$R = (P \times 0.363) + 79 \quad (1)$$

Where P represents the total annual precipitation in millimeters. This formula emphasizes the role of rainfall intensity and duration in soil erosion, aligning with established methodologies for soil loss estimation.

K Factor (Soil Erodibility Factor)

The K factor represents the susceptibility of soil to erosion, depending on its physical and chemical properties such as texture, organic matter content, structure, and permeability. Soil type data for the Chambal River Basin was obtained from soil property maps and reclassified according to soil texture classes. The K factor values were assigned based on the following ranges, adapted from [Wischmeier & Smith \(1978\)](#):

$$K = \text{Soil Erodibility Index} \quad (2)$$

Where the index was derived from the USDA soil erodibility nomograph. Coarser soils, such as sandy soils, have lower K values, indicating lower susceptibility to erosion, while finer soils (clay, silt) have higher K values due to their tendency to form crusts, leading to increased erosion under rainfall.

LS Factor (Slope Length and Steepness Factor)

The LS factor represents the combined effect of slope length (L) and slope steepness (S) on soil erosion. A Digital Elevation Model (DEM) was employed to calculate the slope gradient and derive the LS factor for the basin. The LS factor was computed using the following equation, as recommended by [McCool et al. \(1987\)](#):

$$\text{Slope\%} = \tan(\text{Slope in Degrees}) \times 100 \quad (3)$$

C Factor (Cover Management Factor)

The C factor quantifies the effect of vegetation cover and management practices on soil erosion. In this study, the MODIS dataset was used to derive the NDVI, which is an indicator of vegetation density. The NDVI was calculated from surface reflectance data and applied to estimate the C factor using the following equation:

$$NDVI = (NIR - RED)/(NIR + RED) \quad (4)$$

Where NIR refers to the near-infrared reflectance and RED refers to the red reflectance from the MODIS dataset. This index serves as an indicator of vegetation health and density, contributing to soil stabilization and moisture retention. The C factor is further derived from NDVI values, indicating the potential for vegetation to protect soil from erosion.

P Factor (Support Practice Factor)

The P Factor, which accounts for land use and land cover impacts on erosion, is calculated using the LULC data from MODIS. The analysis employs an expression that incorporates both land use types and slope to derive the P factor. Specific thresholds for land use categories (such as Permanent wetland, agricultural land, urban areas, vegetation, Barren land, and Water bodies) are used to classify the P factor, reflecting how different land uses influence soil erosion processes.

Soil Loss Calculation

After calculating all the factors (R, K, LS, C, and P), the RUSLE model was applied to estimate soil loss for each study year. The final soil loss estimate was calculated using the formula:

$$Soil\ Loss = R \times K \times LS \times C \times P \quad (5)$$

The results were processed in a GIS environment, where maps of soil loss were generated for visual analysis. The spatial distribution of soil loss was classified into five categories: slight (<10 t/ha/year), moderate (10-20 t/ha/year), high (20-30 t/ha/year), very high (30-40 t/ha/year), and severe (>40 t/ha/year). These classes were used to identify areas at risk of severe soil erosion. This detailed methodology provides a comprehensive approach to understanding soil loss dynamics in the context of the Chambal River basin, utilizing remote sensing data and geospatial analysis to inform sustainable land management practices.

RESULTS AND DISCUSSIONS

This study evaluates soil loss trends over the Chambal River Basin using RUSLE. Various factors, including rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and conservation practices (P), were derived from satellite data and other geospatial sources. The integration of these factors provides a comprehensive view of soil erosion rates, which are crucial for sustainable land management in the region.

Distribution of soil loss classes over Chambal River Basin

The analysis shows in Figure 3, the majority of the soil erosion falls within the low to moderate categories and it that approximately 50% of the area exhibits low erosion, with rates generally below 10 tons/ha/year, which aligns with sustainable land use practices. The moderate erosion class covers around 30%, reflecting areas with erosion rates between 10 to 20 tons/ha/year, signalling zones where erosion control measures may be necessary to prevent further degradation. These findings are consistent with studies that highlight moderate erosion as a concern in semi-arid regions, where both natural and human-induced factors contribute to soil loss.

The high erosion category accounts for roughly 15% of the area, with soil loss rates between 20 to 30 tons/ha/year, were indicating regions where soil conservation measures should be prioritized to mitigate land degradation. The most critical areas fall under the severe erosion category, representing about 5% of the basin, where erosion exceeds 40 tons/ha/year. These areas

are prone to severe land degradation and require immediate interventions such as afforestation, terracing, and other conservation practices.

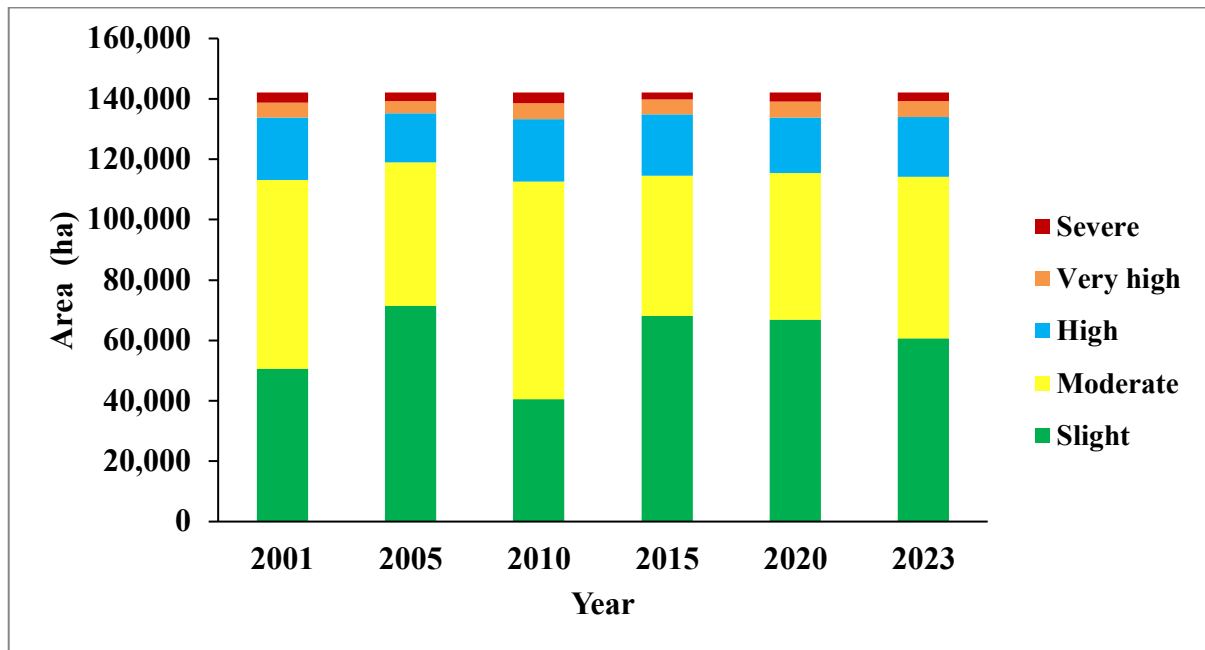


Figure 3. The distribution of soil loss classes (ha) over Chambal River Basin

These findings are supported by recent research, which emphasizes the impact of rainfall intensity, land cover changes, and slope gradient on soil erosion in similar river basins. For instance, observed that regions with high precipitation and steep slopes, such as those in the Chambal Basin, are prone to accelerated soil loss. Additionally, the correlation between land cover and soil loss is evident, as areas with sparse vegetation, primarily under agricultural use, experience greater erosion rates.

The results indicate significant spatial variability in soil loss across the study period (2001–2023). The highest soil erosion rates are found in areas with steep slopes and intensive agricultural activities, while regions with more stable vegetation cover show lower erosion rates. For instance, mean annual soil loss in 2001 was calculated at 9.66 t/ha/yr, while in 2023, it was estimated at 8.98 t/ha/yr. The changes observed between these years suggest fluctuations due to land cover and climatic conditions, with certain years experiencing more severe erosion due to extreme rainfall events ([Arnold et al., 1998](#)).

Between 2001 and 2023, notable trends are observed in the area distribution of soil loss categories in Table 2. The Slight category showed significant variation, peaking at 71,417 ha in 2005, followed by a drop to 60,604 ha in 2023. The Moderate category exhibited a rise from 62,558 ha in 2001 to 72,097 ha in 2010, before stabilizing at 53,656 ha in 2023. High and Very High categories remained relatively stable, while the severe category consistently showed lower values, reaching 2,834 ha in 2023. This trend is consistent with findings noted similar patterns in land use change dynamics in India over the past two decades.

Table 2. Area statistics in the Chambal River Basin under different soil loss categories in ha

Year	Soil Loss Classification				
	Slight (ha)	Moderate (ha)	High (ha)	Very high (ha)	Severe (ha)
2001	50,544	62,558	20,632	5,104	3,284
2005	71,417	47,495	16,269	4,170	2,770
2010	40,526	72,097	20,714	5,200	3,585
2015	68,140	46,374	20,439	4,885	2,284
2020	66,772	48,615	18,504	5,289	2,942
2023	60,604	53,656	19,786	5,242	2,834

From 2001 to 2023 in Figure 4, mean soil loss (t/ha/year) fluctuated, with the highest value recorded in 2010 at 10.57 t/ha/year and the lowest in 2015 at 8.017 t/ha/year. The values remained relatively stable in recent years, with 8.98 t/ha/year in 2023.

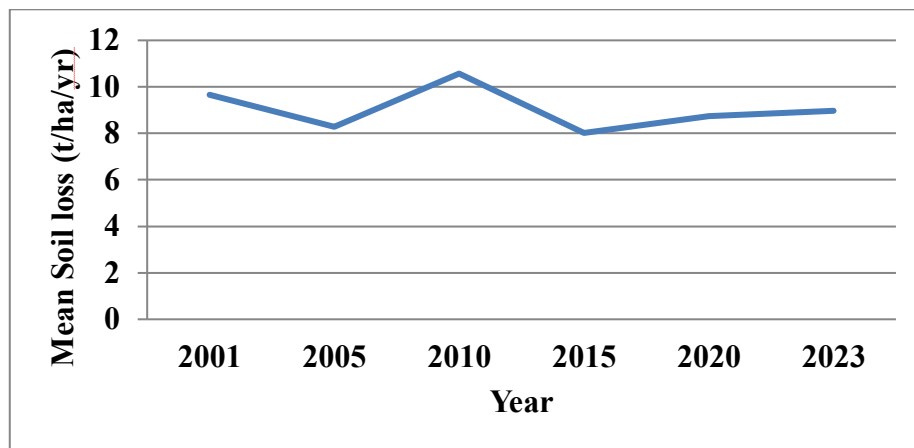


Figure 4. Mean annual soil loss (t/ha/yr) over Chambal River Basin

The comparative analysis of C factor in Figure 5 maps from 2001 to 2023 reveals key trends in land cover and soil erosion risk in the Chambal River Basin. In 2001, the average C factor was 0.31, indicating moderate vegetation cover, with higher values (0.4-0.5) in some regions showing higher erosion risk. By 2023, the average C factor decreased to 0.28, suggesting an improvement in vegetation cover, likely due to conservation efforts. However, localized increases in certain areas highlight on-going land degradation. This aligns with previous findings by [Pandey et al. \(2007\)](#), who noted the importance of vegetation cover in reducing erosion risks across India's landscapes. This spatial distribution aligns similar trends in agricultural land-use changes and erosion risks in Indian basins.

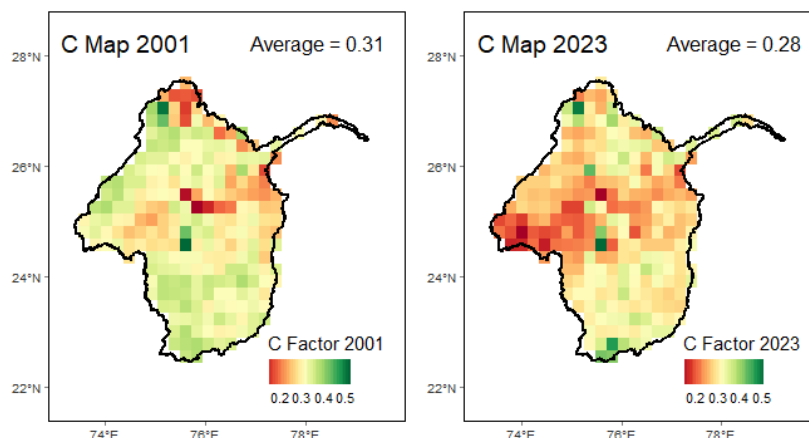


Figure 5. Spatial distribution of Cover management (C Factor) over Chambal River Basin

The maps in Figure 6 depict the rainfall erosivity (R) factor for the years 2001 and 2023 in the Chambal River Basin, as derived from the CHIRPS precipitation products. Rainfall erosivity is a key factor in soil erosion, indicating the potential of rainfall to cause erosion based on the intensity and amount of precipitation. In the 2001 map, the R-factor values are distributed across the basin, with lower values dominating the southern and central parts of the basin. These areas experienced less intense rainfall erosivity, with average R-factor values around 351.76. As we move to the north and north-eastern parts of the basin, the R-factor increases, transitioning to shades, signaling higher erosivity in these regions.

By 2023, a noticeable increase in R-factor values across the basin, with the average R-factor rising to 388.09. The northern and north-eastern regions exhibit a significant increase in rainfall erosivity, with the map shifting more. This suggests an intensification of rainfall in those areas, which could lead to greater soil erosion risks. The southern parts still show relatively lower R-factor values, though they also exhibit an upward trend compared to 2001.

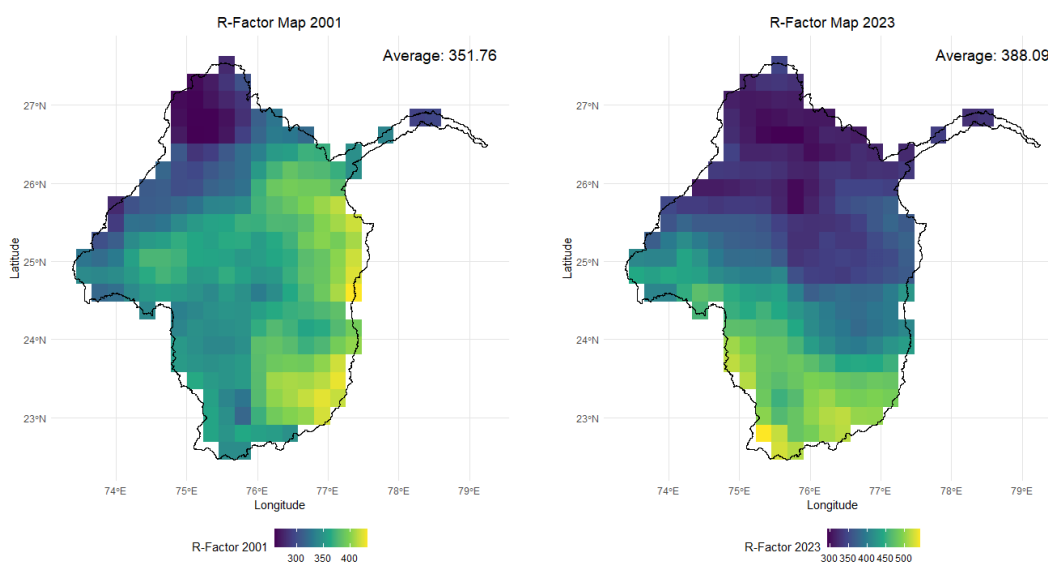


Figure 6. Spatial distribution of Rainfall erosivity (*R Factor*) over Chambal River Basin

The increase in R-factor between 2001 and 2023 aligns with the broader patterns of climate change, where intensified rainfall events become more frequent, increasing the erosive potential of storms. This phenomenon has been explored in studies like those by [Nearing et al. \(2004\)](#), which link rising rainfall erosivity to global warming and changing precipitation patterns.

In 2001, the region's land use was dominated by agriculture, covering 97.49% of the total area, highlighting the region's heavy reliance on farming, which can significantly contribute to soil erosion. Urban areas accounted for 1.88%, while barren land and vegetation were minimal, with 0.24% and 0.13% respectively in Table 3.

Table 3. LULC Classes over Chambal river basin

LULC Class	2001		2023	
	Area (km ²)	Area %	Area (km ²)	Area %
Permanent Wetlands	71.25	0.06	155.5	0.10
Agriculture Land	1,25,613	97.49	1,44,774.75	97.58
Urban	2,425.25	1.88	2,504.25	1.69
Vegetation	173.5	0.13	59.75	0.04
Barren Land	309.25	0.24	236.75	0.16
Water Bodies	249.5	0.19	628.5	0.42

The limited presence of wetlands (0.06%) and water bodies (0.19%) suggests restricted natural buffers against erosion. This LULC distribution aligns with concerns raised by [Montgomery \(2007\)](#) regarding the role of agricultural expansion in accelerating soil degradation. In 2023, the land use/land cover (LULC) classification still shows agriculture as the dominant land use, covering 97.58% of the total area, slightly increasing from 2001. However, there is a small decrease in urban area, now making up 1.69% of the region. Interestingly, permanent wetlands have expanded to 0.10%, indicating some restoration or change in wetland areas. On the other hand, vegetation has significantly reduced to 0.04%, and barren land has also decreased to 0.16%, while water bodies have increased to 0.42%. This shift points to slight changes in land use patterns, with a continuing emphasis on agriculture and urban expansion, yet with some increases in water bodies and wetlands, which could have implications for regional soil and water management.

The spatial distribution of soil loss in the years 2001 and 2023 reveals significant changes in erosion patterns over time. From the Figure 7, it is clear that in 2001, the areas with slight soil loss (0-10 t/ha/year) dominate the landscape. These regions are more widespread and cover a large portion of the landmass. Moving into 2023, the distribution of slight soil loss shrinks noticeably, particularly along the main river channels and towards the lower left part of the region. The increase in moderate soil loss (10-20 t/ha/year), is more prominent in 2023, spreading outwards and increasing the spatial extent compared to the limited appearance in 2001.

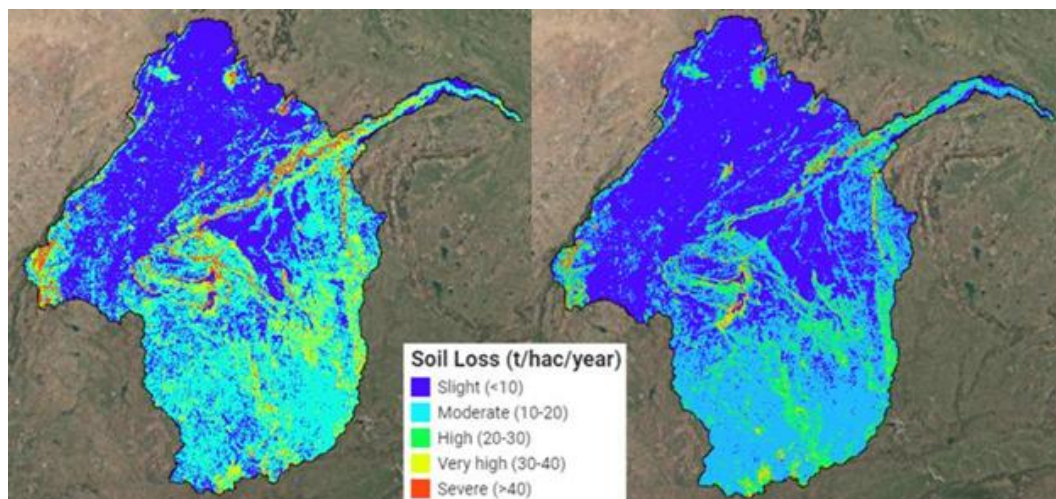


Figure 7. Spatial distribution of soil erosion risk map of the Chambal River Basin

High soil loss class (20-30 t/ha/year), indicated that have also expanded between the two years, becoming more concentrated in the central and upper right regions of the map by 2023. These changes signal an increase in the erosion intensity over two decades. Similarly, regions with very high soil loss (30-40 t/ha/year), depicted also more frequent in 2023, spreading particularly across the central parts of the landscape. In contrast, severe soil loss areas (above 40 t/ha/year), are less pronounced in 2001 but become more common and widespread by 2023.

This overall trend toward higher erosion rates could be attributed to changes in land use, deforestation, or climate change factors affecting the region. Research by [Poesen et al. \(2003\)](#) and [Panagos et al. \(2015\)](#) have emphasized the rising concern of soil erosion due to agricultural expansion and human activities, aligning with the patterns observed in these maps. [Mandal & Sharda \(2011\)](#) have demonstrated similar trends in soil erosion across Indian river basins, emphasizing that regions with steep slopes and sparse vegetation tend to exhibit higher soil loss. Their research, combined with the current findings, suggests that targeted land management strategies are essential to control erosion, particularly in high-risk areas where erosion rates are expected to worsen without intervention.

CONCLUSION

The study provides a comprehensive assessment of soil erosion in the Chambal River Basin over two decades (2001–2023), revealing a gradual decline in mean annual soil loss from 9.66 t/ha/yr to 8.98 t/ha/yr. Despite this improvement, high and severe erosion categories remain prevalent in areas with steep slopes and intensive agricultural activities, particularly in the northern and central parts of the basin. The increase in rainfall erosivity from 351.76 mm in 2001 to 388.09 mm in 2023 suggests that climate variability is exacerbating erosion risks, particularly in the north-eastern regions. The analysis emphasizes the necessity of specific soil conservation techniques, including terracing and afforestation, in high-risk locations in order to increase agricultural sustainability, lessen land degradation, and support sustainable land use management and the achievement of Sustainable Development Goal 15 (SDG-15).

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AUTHOR CONTRIBUTIONS

The author made substantial and independent contributions to the conception and design of the study, data acquisition, analysis and interpretation of data, as well as drafting and revising the manuscript.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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