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Research Article

Impacts of land use change on soil erosion in a Himalayan watershed: Implications for sustainable watershed management

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ABSTRACT
Soil erosion is a major environmental challenge in Nepal's Middle Hills, threatening agricultural productivity and watershed sustainability. This study aims to quantify long-term land use/land cover (LULC) changes and assess spatial patterns of soil erosion risk in the Karra River watershed, Makawanpur District, over a 20-year period. Multi-temporal Landsat imagery from 2003, 2013, and 2023 was used to analyse LULC dynamics, while soil erosion was estimated using the Revised Universal Soil Loss Equation (RUSLE) integrated with Geographic Information Systems (GIS) and remote sensing. The RUSLE model incorporated rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practice factors. The watershed was further subdivided into 29 sub-watersheds to prioritize areas for conservation intervention. The results reveal substantial LULC changes between 2003 and 2023, including a 357.1% expansion of built-up areas, a 6.1% increase in forest cover, and a 10.2% decline in cropland. Estimated annual soil loss ranged from <5 to 463 t/ha/yr, with a watershed-wide mean of 8.32 t/ha/yr. Approximately 66.9% of the watershed experienced low erosion (<5 t/ha/yr), while 21.87% was classified as high to very severe erosion (>20 t/ha/yr). Sub-watershed prioritization identified SW12 as the most erosion-prone unit, with an average soil loss of 40.2 t/ha/yr. Areas experiencing rapid urban expansion and agricultural land conversion exhibited localized but elevated erosion risks. The study concludes that integrating LULC change analysis with RUSLE-based modelling provides a spatially explicit framework for identifying erosion hotspots and supporting targeted soil and water conservation planning in data-scarce mountainous regions.

Keywords: Land Use Change, Soil Erosion, RUSLE, Remote Sensing, GIS, Watershed Prioritization, Nepal

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INTRODUCTION
Land degradation, driven primarily by soil erosion, poses a significant threat to food security and ecosystem sustainability, particularly in mountainous regions such as Nepal (Pimentel, 2006; Chalise *et al.*, 2019). Water-induced soil erosion is a predominant form of land degradation in the country, affecting approximately 45.5% of its land area, largely through sheet and rill erosion (Thapa, 2020). The Middle Hills of Nepal, characterized by steep

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topography and intensive agricultural practices, are highly susceptible to soil loss, which diminishes soil fertility, reduces agricultural yields, and contributes to sedimentation of water bodies (Ghimire *et al.*, 2013; Sah & Lamichhane, 2019).

Land Use/Land Cover (LULC) change is a major anthropogenic factor accelerating soil erosion rates (Parveen & Kumar, 2012). In Nepal, ongoing urbanization, deforestation, and agricultural expansion have significantly altered land cover patterns, increasing the vulnerability of watersheds to erosion (Koirala *et al.*, 2019). Accurate assessment of LULC dynamics and soil erosion risk is therefore essential for developing effective watershed management and soil conservation strategies.

Empirical models, particularly the Revised Universal Soil Loss Equation (RUSLE), integrated with Geographic Information Systems (GIS) and remote sensing (RS), provide a robust and cost-effective framework for predicting soil erosion over large areas (Renard, 1997; Dabral *et al.*, 2008). The RUSLE model, which estimates average annual soil loss as a product of rainfall erosivity (R), soil erodibility (K), topographic factors (LS), cover management (C), and conservation practices (P), has been widely applied in diverse environments, including the Himalayan region (Koirala *et al.*, 2019; Dahal, 2020).

While several studies have assessed soil erosion in Nepal, there is a lack of detailed, spatially explicit studies for specific watersheds such as the Karra River in Makawanpur district. This area is experiencing rapid land cover change due to urban expansion, yet its soil erosion risk remains unquantified. Recent regional assessments have highlighted the acceleration of erosion due to LULC change, but few have linked decadal LULC transitions directly to sub-watershed scale erosion hotspots in rapidly urbanizing Himalayan catchments (Borrelli *et al.*, 2017; Keesstra *et al.*, 2018). Furthermore, the integration of moderate-resolution satellite imagery with global datasets for erosion modeling in data-scarce regions requires validation of its applicability for local conservation planning (Alewell *et al.*, 2019).

This study aims to address these gaps by testing the hypothesis that rapid built-up expansion and cropland conversion are primary drivers of increased soil erosion risk in the Karra River watershed. The specific objectives are to: (1) analyze the spatio-temporal dynamics of LULC from 2003 to 2023; (2) estimate soil erosion risk using the RUSLE model integrated with GIS/RS; and (3) identify and prioritize critical sub-watersheds for conservation intervention. The justification for this work lies in providing a spatially explicit, evidence-based tool for local land-use planners and policymakers to implement targeted soil conservation measures in a watershed undergoing rapid transformation. A recognized limitation is the reliance on multi-source geospatial data of varying resolutions, which may affect the precision of absolute erosion estimates but is suitable for identifying relative risk patterns for prioritization purposes.

MATERIALS AND METHODS

Study Area

The study was conducted in the Karra River watershed, a left-bank tributary of the East Rapti River located in the Makawanpur district of Bagmati Province, Nepal (Figure 1). The watershed lies between 27°24'23"N and 27°35'N latitude and 85°3'29"E and 85°15'E longitude, covering an area of approximately 98.27 km². The elevation ranges from 426 to 1,302 meters above sea level. The climate is subtropical monsoon, with mean annual rainfall of about 2,274

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mm and temperatures ranging from 5°C in winter to 36°C in summer. The dominant vegetation includes Tropical Deciduous and Sub-Tropical forests, with key species such as *Shorea robusta* (Sal). The area is characterized by agricultural land, with crops including paddy, maize, wheat, and vegetables.

The Karra River watershed was selected for this study due to its representative vulnerability and under-studied status within Middle Hills of Nepal. While the region is broadly susceptible to erosion, the Karra watershed exhibits accelerated land-use changes specifically rapid urbanization and agricultural conversion that are not yet widely quantified in the literature. This combination of dynamic anthropogenic pressure and a lack of prior focused research made it an ideal case study to assess the impacts of land-use change on erosion and to develop management insights applicable to similar watersheds in the Himalayan region.

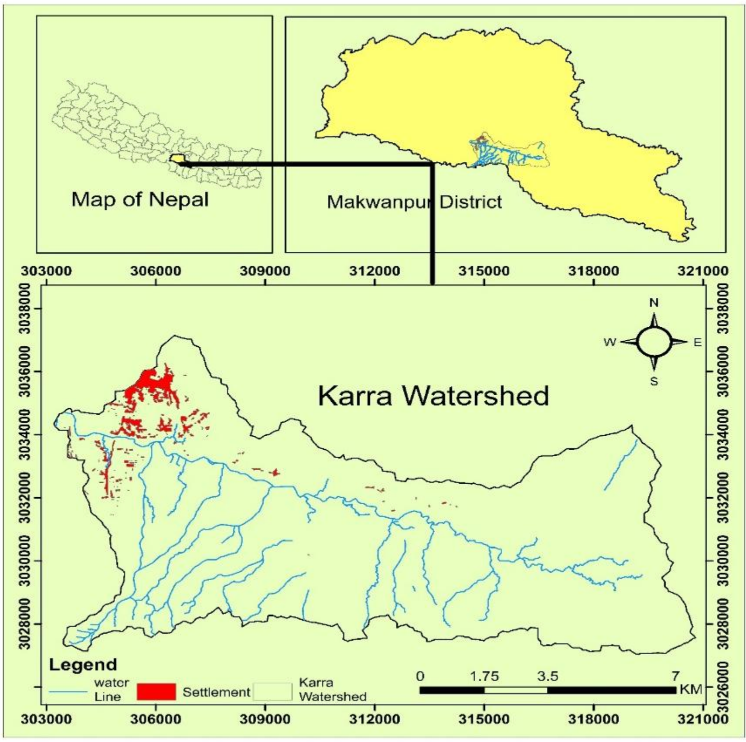

Figure 1: Location map of the Karra River watershed, Makawanpur district, Nepal

The socio-economic and land-use context of the Karra River watershed is characterized by rapid urbanization driven by broader regional development, resulting in a 357.1% increase in built-up areas from 2003 to 2023 (this research), primarily through the conversion of cropland.This transformation is occurring within a traditionally agricultural landscape that supports crops such as paddy, maize, wheat, and vegetables, raising concerns about local food security as productive land diminishes. Despite some forest recovery due to community forestry initiatives, the dominant trend is a shift from managed agricultural and natural systems to urban and impervious surfaces, increasing localized erosion risk and underscoring the need for balanced land-use planning and conservation in a transitioning Himalayan economy.

Data Sources

The data used in this study are summarized in Table 1.

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Table 1: Data sources and their purposes

Data	Purpose	Source	Resolution/Specs
Landsat 8 OLI/TIRS	LULC classification (2023)	USGS EarthExplorer	30 m
ALOS PALSAR DEM	Topographic factor (LS) derivation	Alaska Satellite Facility (ASF)	12.5 m
WorldClim Precipitation	Rainfall Erosivity (R) factor	worldclim.org	~1 km
FAO Digital Soil Map	Soil Erodibility (K) factor	FAO GeoNetwork	1:5,000,000 scale
Field GPS Points	Accuracy assessment of LULC	Field Survey (2023)	-

Land Use/Land Cover Change Analysis

Supervised classification using the Maximum Likelihood algorithm in ArcGIS 10.5 was performed on Landsat images for 2003, 2013, and 2023. Seven LULC classes were identified: Forest, Cropland, Built-up area, Riverbed, Waterbody, Grassland, and Other Woodland (OWL). Post-classification change detection was conducted to analyze the transition between classes over the 20-year period. Accuracy assessment was performed using ground truth points and Google Earth imagery, achieving an overall accuracy of >83% and a Kappa coefficient >0.78 for all classified images.

Soil Erosion Modeling using RUSLE

The average annual soil loss (A) was calculated using the RUSLE model (Equation 1):

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

where A is the computed soil loss (t/ha/yr), R is the rainfall-runoff erosivity factor (MJ mm ha/h/yr), K is the soil erodibility factor (t ha h ha/MJ/mm), LS is the slope length and steepness factor (dimensionless), C is the cover-management factor (dimensionless), and P is the support practice factor (dimensionless).

- **R-factor:** Calculated using the formula $R = 38.5 + 0.35P$, where P is the mean annual precipitation (mm) obtained from WorldClim data (El-Swaify *et al.*, 1985).
- **K-factor:** Derived from the FAO soil map based on soil texture and organic carbon content using the equation proposed by Neitsch *et al.* (2000).
- **LS-factor:** Computed from the 12.5 m DEM using the flow accumulation and slope gradient functions in ArcGIS, following the method of Desalegn *et al.* (2018).
- **C-factor:** Assigned based on the 2023 LULC map, with values referenced from literature (Panagos *et al.*, 2015; Koirala *et al.*, 2019) (e.g., Forest=0.0, Cropland=0.21, Built-up=0.0).
- **P-factor:** Assigned based on slope classes and the presence of terraces, which are the common conservation practice in the area (Shin, 1999).
  All factor maps were resampled to a 30 m resolution and combined using the Raster Calculator tool in ArcGIS to generate the final soil erosion map.

Sub-watershed Delineation and Prioritization

The watershed was delineated into 29 sub-watersheds using the ArcSWAT tool. The average annual soil loss was calculated for each sub-watershed, which were then prioritized into classes (I-XXIX) based on the severity of erosion, with Class I representing the highest conservation priority.

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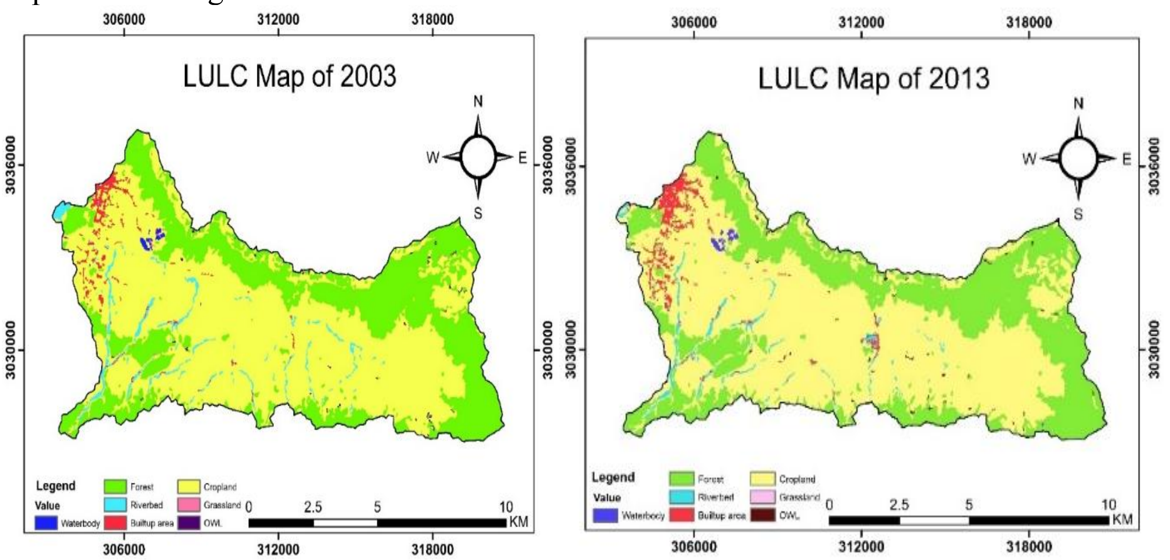
A key limitation of this study is the use of multi-source data with varying spatial resolutions. The coarse resolution of the global climate (WorldClim, ~1 km) and soil (FAO, 1:5,000,000) datasets may not capture local heterogeneities, introducing uncertainty into the R and K factors. While all layers were resampled to a common 30 m grid for analysis, this necessarily generalizes finer-scale variations. Future studies would benefit from utilizing downscaled climate products, detailed soil surveys, and higher-resolution DEMs to improve the spatial accuracy of the estimates. Nevertheless, the primary findings regarding the spatial pattern of erosion risk and the identification of critical sub-watersheds are based on relative contrasts that are likely to be valid for conservation prioritization.

RESULTS

Land Use/Land Cover Change (2003-2023)

Analysis of land use/land cover (LULC) in the Karra watershed over 20 years revealed notable transformations (Table 2, Figure 2). The most prominent change was a substantial expansion of built-up areas, increasing by 357.1% from 136.08 ha in 2003 to 622.08 ha in 2023, reflecting rapid urbanization in the watershed. Forest cover increased by 6.1%, from 3,273.30 ha to 3,473.64 ha, suggesting some forest regeneration or afforestation efforts. In contrast, cropland, the dominant land use class, declined by 10.2%, decreasing from 6,146.01 ha to 5,516.28 ha, indicating conversion to built-up areas and other uses.

Other land cover classes also exhibited notable reductions. Riverbed areas decreased by 26.2% (from 218.79 ha to 161.46 ha), and grassland declined by 31.0% (from 12.78 ha to 8.82 ha), reflecting both natural processes and anthropogenic influences. The LULC change matrix revealed that the most significant transitions occurred from cropland to built-up areas (475.65 ha) and from forest to cropland (89.91 ha), highlighting the dynamic interaction between urban expansion and agricultural land use.



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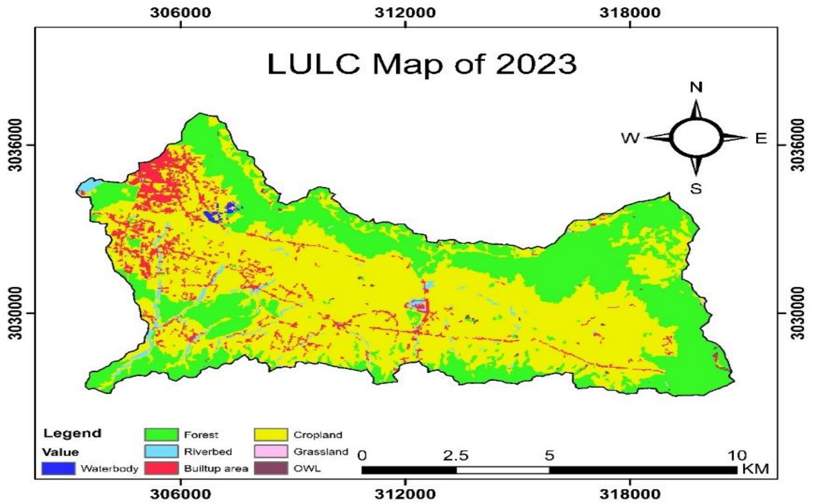

Figure 2: Land use/land cover maps of the Karra watershed for the years 2003, 2013, and 2023

Table 2: LULC change statistics (2003-2023)

LULC Class	2003 Area (ha)	2023 Area (ha)	% Change (2003–2023)
Built-up Area	136.08	622.08	357.1
Forest	3273.3	3473.64	6.1
Cropland	6146.01	5516.28	−10.20
Riverbed	218.79	161.46	−26.20
Grassland	12.78	8.82	−31.00
Mean	1957.39	1956.46	59.16
Minimum	12.78	8.82	−31.00
Maximum	6146.01	5516.28	357.1
Standard Deviation (SD)	2710.98	2437.73	167.19

Soil Erosion Risk Assessment

The estimated annual soil loss in the Karra watershed exhibited considerable spatial variability, ranging from <5 t/ha/yr to 463 t/ha/yr, with a watershed-wide mean of 8.32 t/ha/yr (Figure 3). The distribution of soil erosion showed that 66.9% (6,540.84 ha) of the watershed experienced low erosion (<5 t/ha/yr). Approximately 11.2% (1,096.42 ha) of the area was classified under moderate erosion (5–10 t/ha/yr), while the remaining 21.87%, comprising high, very high, severe, and very severe classes, accounted for the most significant portion of total soil loss, highlighting localized hotspots of concern (Table 3).

Specifically, areas under high erosion (10–20 t/ha/yr) covered 1,040.49 ha (10.64%), very high erosion (20–40 t/ha/yr) covered 663.13 ha (6.78%), and severe erosion (40–80 t/ha/yr) spanned 230.79 ha (2.36%). Very severe erosion (>80 t/ha/yr) accounted for 204.48 ha (2.09%) of the watershed. These high-risk zones were predominantly located on steep slopes and in areas undergoing rapid land-cover change, such as urban expansion and cropland conversion.

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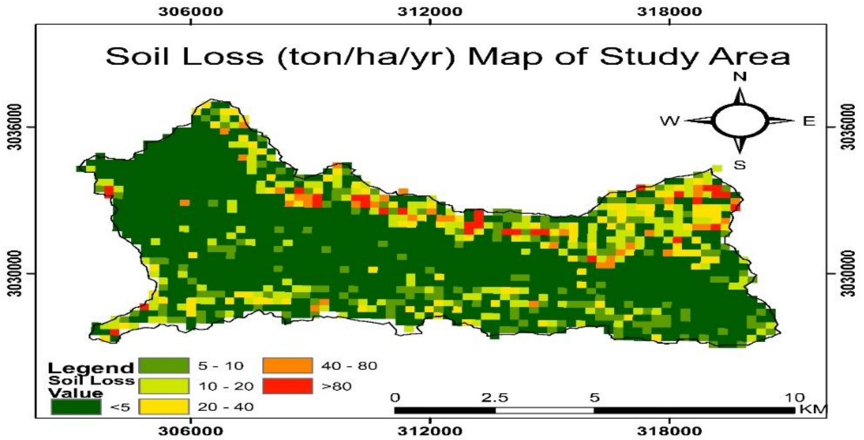

Figure 3: Spatial distribution of estimated annual soil loss (t/ha/yr) in the Karra watershed

Table 3: Area under different soil erosion severity classes

Erosion Severity	Rate (t/ha/yr)	Area (ha)	% of Watershed
Low	< 5	6540.84	66.91
Moderate	5–10	1096.42	11.22
High	10–20	1040.49	10.64
Very High	20–40	663.13	6.78
Severe	40–80	230.79	2.36
Very Severe	> 80	204.48	2.09
Total	—	9776.15	100
Mean	—	1629.36	16.67
Median	—	851.81	8.71
Minimum	—	204.48	2.09
Maximum	—	6540.84	66.91
Standard Deviation (SD)	—	2355.94	24.11

Sub-watershed Prioritization

The prioritization of the 29 sub-watersheds in the Karra watershed highlighted distinct erosion hotspots (Table 4, Figure 4). Sub-watershed SW12 emerged as the most critical area (Priority I), exhibiting the highest average soil loss of 40.19 t/ha/yr and a maximum observed loss of 463 t/ha/yr. Following SW12, SW23 and SW8 were classified as Priority II and Priority III, with average soil losses of 30.67 t/ha/yr and 22.74 t/ha/yr, respectively.

In contrast, sub-watersheds such as SW3 and SW4 experienced negligible erosion, with average losses of <0.3 t/ha/yr, and were accordingly assigned the lowest priority classes (XXVIII–XXIX). The spatial distribution of priorities indicates that the most vulnerable sub-watersheds are generally located on steep slopes and areas undergoing significant land use changes, particularly urban expansion and cropland conversion.

This prioritization provides a spatially explicit framework for targeting soil and water conservation interventions. By focusing on high-priority sub-watersheds such as SW12, local planners and watershed managers can allocate resources more effectively, implement erosion

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control measures, and mitigate downstream sedimentation and land degradation.

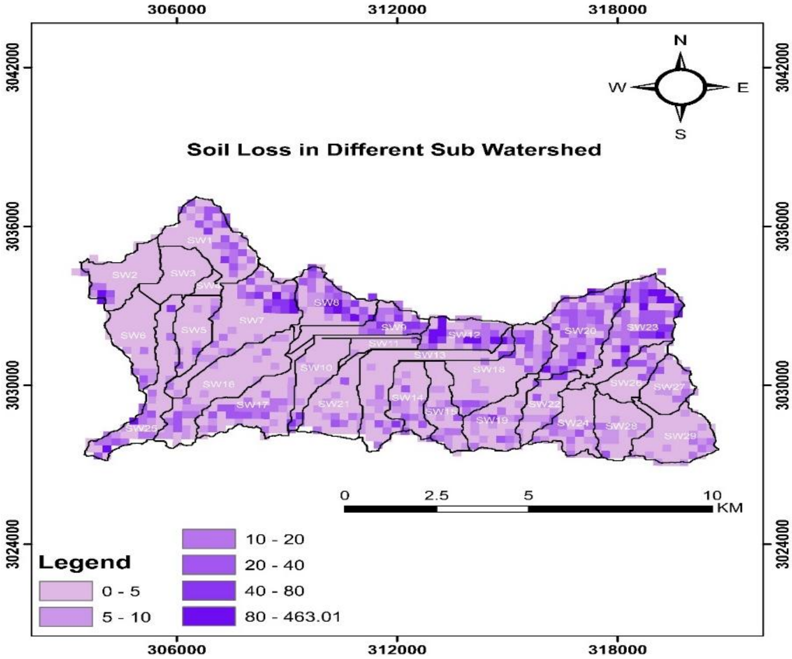

Figure 4: Prioritization map of sub-watersheds based on average annual soil loss

Table 4: Priority classes of selected sub-watersheds based on average soil loss

Sub-watershed	Area (ha)	Avg. Soil Loss (t/ha/yr)	Priority Class
SW12	258.56	40.19	I
SW23	518.32	30.67	II
SW8	329.96	22.74	III
...	...	...	...
SW3	246.4	0.006	XXIX

DISCUSSION

This study demonstrates the significant impact of LULC change on soil erosion risk in a Central Himalayan watershed of Nepal. The rapid expansion of built-up areas (357.1% over 20 years) at the expense of cropland and natural vegetation is a key driver of environmental change, consistent with trends observed in other developing regions (Tolessa *et al.*, 2020). While forest cover increased slightly, likely due to community forestry initiatives, the loss of agricultural land raises concerns about local food security. It underscores the need for balanced land-use planning.

The spatial pattern of soil erosion risk, estimated using the RUSLE model, aligns with the topographical and land cover characteristics of the watershed **(**Figure 3**)**. The highest erosion rates were associated with steep slopes (high LS-factor derived from the DEM in Figure 1**)**, sparse vegetation cover (low C-factor), and areas undergoing land conversion. Specifically, the transition matrix revealed that the dominant LULC change was the conversion of cropland to built-up area (475.65 ha)**,** which exacerbates erosion through two key mechanisms: (1) the construction phase removes vegetative cover and disturbs soil, creating a temporary bare soil condition (C-factor ≈ 1) highly susceptible to monsoonal rains; and (2) the resulting impervious surfaces increase runoff volume and velocity, concentrating flow and its erosive energy

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downstream (Borrelli *et al.*, 2017; Alewell *et al.*, 2019). This process directly links the observed LULC transition to the localized severe erosion classes (>20 t/ha/yr) shown in Table 3 and mapped in Figure 3**.**

The average soil loss (8.32 t/ha/yr) exceeds the commonly cited tolerable limit of 1-5 t/ha/yr for mountainous regions (Pimentel *et al.*, 1995), indicating a significant problem. The estimated range (0-463 t/ha/yr) is comparable to rates found in other Himalayan watersheds (Koirala *et al.*, 2019; Dahal, 2020) but lower than those reported for severely degraded areas such as the Andes, highlighting the relative but concerning severity within the Nepalese context. This aligns with global assessments that identify land-use change as a primary driver of accelerated soil loss (Borrelli *et al.*, 2017).

The integration of GIS with RUSLE proved highly effective for identifying specific critical areas for intervention. The prioritization of sub-watersheds, such as SW12 (Priority I, average loss of 40.19 t/ha/yr, Table 4, Figure 4), provides a scientific basis for allocating limited resources for soil conservation. The high erosion in these areas can be attributed to a combination of factors, including steep topography (high LS factor) and potentially unsustainable land practices (reflected in the C and P factors). The severe erosion in SW12 spatially correlates with both steep slopes (visible in the DEM) and LULC classes or transitions with poor ground cover, supporting the mechanistic link between development and erosion risk. The severe erosion in SW12 correlates spatially with both steep slopes (visible in the DEM) and LULC classes or transitions that offer poor ground cover, supporting the mechanistic link between development and erosion risk. Therefore, conservation efforts should focus on promoting terracing, afforestation, and sustainable agricultural practices in these priority zones. Nature-based solutions, such as agroforestry and riparian buffers, have been shown to effectively mitigate erosion by improving ground cover and soil structure (Keesstra *et al.*, 2018; Poesen, 2018).

A limitation of this study is the use of multi-source data with varying spatial resolutions. The coarse-resolution global climate and soil data (WorldClim, FAO) may introduce uncertainty into the R and K factors, a common challenge noted in regional-scale erosion modeling (Alewell *et al.*, 2019). Future research should incorporate higher-resolution local data and validate model outputs with field measurements of sediment yield. Furthermore, the use of a single-year C-factor map (2023) does not capture dynamic erosion risk during the active conversion period; a multi-temporal C-factor analysis could improve temporal accuracy (Panagos et al., 2018).

Investigating the socio-economic drivers of LULC change would provide a more holistic understanding for developing effective land management policies. Integrating agent-based models with geospatial erosion assessments is a promising frontier for understanding the feedback between human decisions and land degradation.

CONCLUSION

This study provides a spatially explicit assessment of land-use/land-cover (LULC) dynamics and soil erosion risk in the Karra River watershed, Nepal, over 20-year period (2003–2023). The analysis revealed substantial landscape transformations, most notably a 357.1% expansion of built-up areas at the expense of cropland, alongside a modest increase in forest cover. Using

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the Revised Universal Soil Loss Equation (RUSLE) integrated with GIS and remote sensing, estimated annual soil loss ranged from <5 to 463 t/ha/yr, with a watershed-wide average of 8.32 t/ha/yr exceeding the tolerable limit for mountainous regions. Approximately 21.9% of the watershed was classified under high to very severe erosion (>20 t/ha/yr), with sub-watershed prioritization identifying SW12 as the most critical unit (40.19 t/ha/yr).

While the integration of multi-source geospatial data enabled a replicable, watershed-scale assessment, certain limitations must be acknowledged. The use of coarse-resolution global datasets (WorldClim, FAO) and varying spatial resolutions (DEM, Landsat) introduces uncertainty in the RUSLE-derived estimates, particularly for the rainfall erosivity (R) and soil erodibility (K) factors. Furthermore, model assumptions regarding the cover-management (C) and support practice (P) factors rely on generalized values from literature, which may not capture local variability. Despite these constraints, the spatial patterns and relative severity of erosion across sub-watersheds remain robust for conservation prioritization.

The findings offer actionable insights for sustainable watershed management. Immediate interventions such as terracing, contour farming, agroforestry, and check dam construction should be targeted in high-priority sub-watersheds (e.g., SW12, SW23). Long-term policy measures must address the drivers of haphazard urban expansion by enforcing zoning regulations, protecting agricultural land, and promoting community-based forest management. This study underscores the value of integrating LULC change analysis with erosion modeling to support evidence-based, spatially targeted decision-making in data-scarce Himalayan regions. Future efforts should focus on validating model outputs with field sediment measurements and incorporating higher-resolution local datasets to reduce uncertainty and enhance management precision.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript.

Authors' Contribution

S. Gurung Pathak designed the research, conducted the field work, and analyzed the data. S. Gurung Pathak, G. Kafle and H. K. Pathak prepared the manuscript. G. Kafle supervised the overall research, report, and article preparation. All authors read and approved the final manuscript.

Ethics Approval Statement

This study does not involve human or animals. Data were obtained from remote sensing sources, secondary datasets, and non-invasive field observations. Any stakeholder interactions were voluntary and conducted with informed consent. The study complies with institutional and international ethical standards for environmental research.

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