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GIS-Based Assessment of Soil Erosion Hazard to Support Sustainable Watershed Management in the Mangkang Watershed, Indonesia

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Abstract: Climate change and land-use change have intensified soil erosion risks in many tropical watersheds, including the Mangkang Watershed in Semarang, Indonesia. This study aims to assess the spatial distribution of soil erosion hazard and identify priority conservation measures using a Geographic Information System (GIS)-based approach integrated with the Universal Soil Loss Equation (USLE). Spatial data on rainfall, soil type, topography, land use, and conservation practices in 2024 were processed in ArcGIS to estimate annual soil loss and classify the Erosion Hazard Index (EHI). The results show that erosion risk varies across the watershed, with high and very high hazard classes mainly concentrated in steep upstream areas, agricultural land, and land-use transition zones with limited vegetation cover. The very high EHI class covered 15.74 km², representing 36.00% of the watershed area. These findings indicate that slope steepness, rainfall erosivity, land-cover conditions, and inadequate conservation practices are the main factors controlling erosion risk. Spatially targeted conservation measures are recommended, including reforestation in degraded upstream areas, terracing and contour farming on steep agricultural slopes, agroforestry development, and riparian buffer restoration along river corridors. This study demonstrates that GIS-based USLE modelling can support sustainable watershed management by identifying erosion-prone areas and guiding site-specific conservation planning.

Keywords: Erosion hazard index; Erosion modelling; GIS; USLE; Watershed management

Introduction

Climate change has become a global environmental issue that affects hydrological processes, land stability, and watershed sustainability, including in Indonesia (Li et al., 2025). One of the most significant impacts of climate change is the alteration of rainfall patterns, particularly the increasing intensity, frequency, and uneven distribution of extreme precipitation events. These changes increase surface runoff and the kinetic energy of rainfall, thereby accelerating soil detachment and transportation processes. As a result, soil erosion has become a major concern in watershed management because it can reduce soil fertility, degrade land productivity, increase sediment input into river systems, and intensify downstream flood risks.

Soil erosion in watershed systems is increasingly influenced by the combined effects of rainfall erosivity, land-use change, and declining vegetation cover. At the global scale, land-use change has been recognized as one of the major drivers of accelerated soil erosion, while rainfall erosivity remains a key factor controlling soil particle detachment and transport (Borrelli et al., 2017; Panagos et al., 2017). Recent studies also indicate that climate-related rainfall variability may intensify erosion risk and alter watershed responses over time (Dash et al.,

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2023). In Indonesian watersheds, land-cover change has been shown to reduce water catchment capacity and increase hydrological pressure, making erosion assessment important for sustainable watershed management (Amini et al., 2025; Fajri et al., 2025).

Soil erosion is influenced by the interaction of climatic, topographic, pedological, land-use, and conservation practice factors. In watersheds experiencing rapid land-use conversion, erosion risk may increase significantly due to the reduction of vegetation cover and soil protection. Human activities such as deforestation, intensive agricultural practices, and urban development can accelerate erosion rates beyond natural conditions. Therefore, erosion assessment is important not only to estimate soil loss but also to support land-use planning, conservation prioritization, and sustainable watershed management.

Geographic Information System (GIS) has become an important tool in environmental assessment and spatial modelling because it enables the integration, processing, and visualization of various spatial datasets. In erosion studies, GIS can be used to combine rainfall, soil, slope, land-use, and conservation practice data to identify erosion-prone areas more effectively (Jalhoum et al., 2024; Sadewo et al., 2023).

The use of GIS and remote sensing has become increasingly important in watershed assessment because these tools can identify spatial patterns of land-use change, hydrological risk, and environmental pressure. Previous studies have demonstrated that GIS-based spatial modelling is effective for mapping flood risk, watershed vulnerability, and environmental changes in different Indonesian catchments (Dottori et al., 2017; A. Purwanto et al., 2023; Virgota et al., 2024). Multi-temporal Landsat analysis has also been used to evaluate long-term land-use change and urban expansion, providing important information for sustainable watershed planning (Ferynandari et al., 2026; Zahrani et al., 2026).

One of the most widely used empirical models for estimating soil erosion is the Universal Soil Loss Equation (USLE), which was originally developed by (Wischmeier et al., 1958). The USLE estimates average annual soil loss by considering rainfall erosivity, soil erodibility, slope length and steepness, cover management, and conservation practice factors. Previous studies have also demonstrated the usefulness of USLE-based erosion assessment in different watershed conditions (Devatha & Renukaprasad, 2015; Purba et al., 2020; Yustika et al., 2019).

The integration of USLE with GIS has improved erosion assessment by providing spatially distributed erosion information at the watershed scale. This approach is more efficient than conventional field-based assessment because it can cover broader areas and produce erosion hazard maps that are useful for planning and decision-making. Several studies have shown that GIS-based USLE applications are effective in identifying erosion hotspots and supporting site-specific conservation planning (Karakoyun et al., 2022). However, the USLE model also has limitations. It primarily estimates sheet and rill erosion and does not directly represent other processes such as gully erosion, riverbank failure, sediment routing, or sediment deposition. Therefore, the results of USLE-based modelling should be interpreted as potential soil loss and erosion hazard information, not as a direct simulation of sediment movement. More comprehensive hydrological models, such as the Soil and Water Assessment Tool, may be required for studies that aim to simulate runoff, sediment transport, and sediment deposition in greater detail (Alia et al., 2021; Maurya et al., 2024; UNISDR, 2002).

The Mangkang Watershed in Semarang is a relevant area for erosion hazard assessment because it is influenced by a combination of physical and anthropogenic pressures. The watershed has varied topographic conditions, including steep upstream areas that are sensitive to runoff concentration and soil detachment. At the same time, land-use conversion from vegetated and agricultural areas into residential, industrial, and other developed land uses has reduced natural soil protection and increased surface runoff (Bappeda, 2022). These pressures are further intensified by high rainfall, erodible soil characteristics, and limited conservation practices in several parts of the watershed. Consequently, soil erosion in vulnerable zones may contribute to sediment input into river channels, reduce drainage capacity, and increase downstream hydrological pressure, including flood risk (Lyddon et al., 2018; Marchand et al., 2008; Samuels et al., 2008; Yoga et al., 2020).

Although previous studies have discussed the environmental impacts of land-use change and erosion in watershed systems, site-specific investigations that integrate GIS-based erosion modelling, Erosion Hazard Index classification, and conservation priority zoning remain limited in the Mangkang Watershed. This research gap is important because watershed management requires not only information on the magnitude of soil loss, but also spatial evidence regarding where erosion risk is concentrated and which areas should be prioritized for conservation. Therefore, a more detailed spatial assessment is needed to support evidence-based watershed planning, particularly in areas experiencing rapid land-use change and increasing hydrological pressure.

In response to these issues, this study employs a GIS-based erosion assessment framework integrated with the Universal Soil Loss Equation to estimate spatial soil erosion rates and classify erosion hazard levels in the Mangkang Watershed. However, this study recognizes that the USLE primarily estimates sheet and rill erosion and does not directly simulate sediment transport, gully erosion, riverbank erosion, or sediment deposition. Therefore, the model is used specifically to identify potential soil loss and erosion-prone areas, while the conservation recommendations are directed toward reducing erosion sources rather than directly modelling sediment movement.

The novelty of this research lies in the integration of GIS-based USLE modelling, Erosion Hazard Index classification, and spatially targeted conservation prioritization at the local watershed scale. Unlike general erosion assessments that only estimate soil loss, this study translates erosion hazard information into practical conservation directions based on spatial characteristics. High and very high erosion hazard zones can be linked with appropriate soil conservation measures, such as reforestation in degraded upstream areas, terracing and contour farming on steep agricultural slopes, agroforestry development in land-use transition zones, and riparian buffer restoration along river corridors. This approach strengthens the connection between erosion modelling results and practical watershed management needs.

Previous GIS-based erosion studies have demonstrated the usefulness of spatial modelling for estimating soil loss and identifying erosion-prone areas at watershed scale (Ali et al., 2016; Gia et al., 2018) In Indonesia, basin-wide erosion assessment using the USLE method has shown that spatial erosion analysis can support watershed-scale environmental management (Kardhana et al., 2024). However, recent studies emphasize that erosion assessment should not stop at soil loss estimation but should also be linked with spatial prioritization for conservation planning (Ahmad, 2017; Anley et al., 2024; Campos et al., 2025). Therefore, this study contributes by integrating GIS-based USLE modelling, Erosion Hazard Index classification, and spatially targeted conservation prioritization for the Mangkang Watershed.

This study aims to estimate the spatial distribution of soil erosion rates in the Mangkang Watershed using a GIS-integrated USLE approach, classify erosion hazard levels based on the Erosion Hazard Index in 2024, and identify priority zones for spatially targeted soil conservation planning. The importance of this research lies in its contribution to sustainable watershed management by combining geospatial technology with conservation planning approaches. Through GIS-based analysis and empirical modelling, this study provides scientific evidence to support government institutions, urban planners, watershed managers, and environmental stakeholders in designing adaptive policies and implementing effective land and water conservation programs (Azzahra et al., 2024; Gia et al., 2018).

Method

This study applied a GIS-based erosion hazard assessment framework integrated with the Universal Soil Loss Equation (USLE). The research procedure was systematically developed to ensure that all spatial and non-spatial input data were processed consistently before erosion modelling.

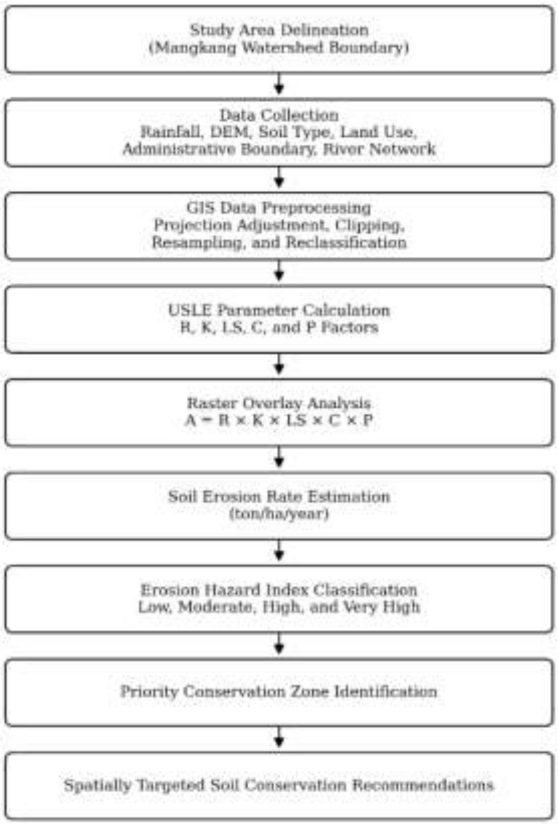

Figure 1. Research workflow for GIS-based soil erosion hazard assessment

The workflow involved study area delineation, spatial and rainfall data collection, GIS data preprocessing, USLE parameter calculation, erosion rate estimation, Erosion Hazard Index classification, and identification of priority areas for conservation planning. This sequence was designed to improve the reliability of spatial analysis and to provide a clear basis for interpreting erosion-prone zones within the Mangkang Watershed. The overall methodological workflow is presented in Figure 2.

Study Area

This research was carried out in the Mangkang Watershed, which is situated in the western region of

Semarang and covers an area of approximately 43.98 km². The watershed is characterized by diverse topographical conditions and varying land-use patterns that influence its environmental dynamics (Bappeda, 2022). High rainfall intensity, particularly during the wet season, has become one of the dominant factors contributing to soil erosion and sediment deposition within the river network. These conditions have increased environmental pressure on the watershed and affected downstream hydrological stability. A general overview of the study area is presented in Figure 2.

Considering these physical and climatic characteristics, this study adopted a methodological framework centered on spatial modeling approaches. Spatial datasets consisting of topography, rainfall distribution, soil characteristics, and land-use conditions for 2024 were compiled and processed using Geographic Information System. The Universal Soil Loss Equation was integrated within the GIS environment to estimate annual soil loss and identify the spatial distribution of the Erosion Hazard Index (EHI) throughout the watershed area (Li et al., 2025; Liu et al., 2026).

Figure 2. Mangkang watershed

To improve the reliability and consistency of the analysis, the study utilized a Digital Elevation Model (DEM) with a spatial resolution of 30 meters and land-use classification data at a scale of 1:25,000. Rainfall erosivity was estimated using the Bols equation due to its suitability for regional climatic conditions in Java. However, this study also recognizes that more advanced approaches, such as the Revised Universal Soil Loss Equation (RUSLE) and the Soil and Water Assessment Tool (SWAT), may provide broader analytical capabilities and are recommended for future investigations. Furthermore, model validation was conducted using observed sediment yield data from field monitoring locations, while sensitivity analysis was performed to evaluate the stability and robustness of key model parameters.

Data Collection

This study relies on secondary data as the primary source of information for conducting the analysis. Various datasets were compiled to ensure a comprehensive assessment of the research objectives and to support accurate spatial evaluation. The data utilized in this study include annual rainfall records from 2015 to 2024, Digital Elevation Model data for terrain analysis, soil type information, land-use data for 2024, as well as administrative boundary maps and river network data. These datasets were integrated to provide a more detailed understanding of erosion conditions within the study area.

Erosion Analysis

Soil erosion rates in the Mangkang Watershed were estimated using the Universal Soil Loss Equation integrated within a ArcGIS environment. This model was applied to calculate average annual soil loss by considering six key parameters expressed in the following equation:

$$A = R.K.L.S.C.P \quad (1)$$

In Equation (1), Arepresents the estimated annual soil loss expressed in ton/ha/year, while Rrefers to the rainfall erosivity factor that describes the erosive power of rainfall. The Kfactor indicates soil erodibility, which reflects the susceptibility of soil particles to detachment and transport. The LS factor represents the combined influence of slope length and slope steepness on runoff and erosion processes. Furthermore, Cdenotes the cover management factor, which describes the effect of land cover and vegetation protection, whereas P represents the conservation practice factor that reflects the effectiveness of soil and water conservation measures

The spatial analysis process was conducted using ArcGIS to model each parameter individually and integrate them through overlay analysis in order to identify areas that are highly vulnerable to erosion (Anley et al., 2024). This approach also supported the classification of erosion hazard levels and helped determine priority zones that require immediate conservation and mitigation measures.

Rainfall Erosivity Factor (EI30)

The rainfall erosivity factor (R-factor) represents the effect of rainfall intensity and surface runoff on soil erosion. It is influenced by the kinetic energy of raindrops and rainfall intensity, both of which determine the ability of rainfall to detach and transport soil particles (Kardhana et al., 2024). Higher rainfall intensity and longer storm duration generally increase erosion potential, particularly when soil conditions are already saturated. In this study, rainfall erosivity was calculated using the Bols Equation due to its suitability for regional conditions:

$$EI_{30} = 6{,}119\,(RAIN)^{1{,}21}(DAYS)^{-0{,}47}(MAXP)^{0{,}53} \quad (2)$$

In Equation (2), EI_{30} represents the annual rainfall erosivity factor, $RAIN$ refers to the average annual rainfall expressed in centimeters, $DAYS$ indicates the average number of rainy days per year, and $MAXP$ denotes the maximum daily rainfall recorded within a 24-hour period, also expressed in centimeters.

Soil Erodibility Factor (K)

The soil erodibility factor (K) represents the susceptibility of soil to erosion based on its physical and chemical characteristics. This factor is influenced by several properties, including soil permeability, organic matter content, texture, and particle composition. Soil erodibility is closely related to weathering processes, soil structure, and local geographic conditions. Which determine how easily soil particles can be detached and transported during rainfall events and surface runoff (Kinnell, 2025; Sodoke et al., 2025; Yang et al., 2024).

Length and Slope Factor (LS)

Topographic conditions play an important role in influencing soil erosion through slope length (L) and slope steepness (S). Longer slopes tend to increase soil loss because surface runoff accumulates as water moves downslope. Likewise, steeper slopes accelerate runoff velocity and enhance its erosive force, resulting in higher erosion rates (Campos et al., 2025; Kucuker et al., 2022). In this study, the LS factors were analyzed using Digital Elevation Model within a GIS environment. Slope gradients were classified into five categories: 0–8% (flat), 8–15% (gentle), 15–25% (moderate), 25–45% (steep), and >45% (very steep).

Crop Management and Soil Conservation Factor (CP)

The cover management factor (C) reflects the influence of land cover conditions and management practices on soil erosion. This factor represents how vegetation cover, crop residues, soil surface conditions, and cultivation activities affect the ability of land to resist erosion (Liu et al., 2026; Zhu et al., 2022). It is commonly expressed as the ratio of soil loss from land under specific cover conditions compared with bare or continuously cultivated land. Meanwhile, the conservation practice factor (P) measures the effectiveness of soil conservation efforts by comparing erosion rates on land with conservation treatments to those without such measures under similar conditions. Higher (CP) indicate limited vegetation protection and ineffective conservation practices, which increase the vulnerability of land to erosion.

Result and Discussion

Results

The results and discussion section presents the spatial distribution of erosion parameters, estimated erosion rate, Erosion Hazard Index classification, and interpretation of erosion-prone areas in the Mangkang Watershed. To improve the clarity and reliability of the results, all tables were reformatted using consistent units and international decimal notation. Research maps and data figures were also prepared using high-resolution GIS outputs rather than scanned images. Supporting literature and field documentation were added to strengthen the interpretation of erosion patterns and conservation priorities.

Rainfall Erosivity Factor (EI30) Calculation

The erosive potential of rainfall is strongly influenced by the kinetic energy generated by raindrops, which is closely related to rainfall intensity, rainfall amount, and spatial-temporal distribution patterns. These characteristics directly determine the ability of rainfall to detach and transport soil particles from the land surface (Fernández-Raga et al., 2010; Risal et al., 2018). In the Mangkang Watershed, rainfall erosivity was estimated using the Bols equation, which incorporates three primary variables: average rainfall, number of rainy days, and maximum daily rainfall within a 24-hour period. Rainfall records from 2015 to 2024 were used to provide a more representative assessment of long-term climatic conditions in the study area. The cumulative erosivity value for 2015–2024 was presented to describe rainfall erosivity during the observation period. However, the value used as the rainfall erosivity factor in the USLE model was the average annual erosivity value, because the USLE estimates annual soil loss. Therefore, using cumulative ten-year erosivity as the model input would overestimate erosion rates. The calculated erosivity values were subsequently used as an important parameter in estimating soil erosion rates, and the detailed results are presented in Table 1.

Table 1. Rainfall Erosivity Values

Station	Cumulative erosivity 2015–2024 (kJ/ha)	Average annual erosivity used as R factor (kJ/ha/year)
Gunung Pati	17,862.60	1,786.30
Plumbon	11,097.20	1,109.70
Ahmad Yani	10,507.20	1,050.70

Rainfall erosivity is a key component in erosion modelling because it represents the potential of rainfall to detach and transport soil particles. Global rainfall erosivity assessment has shown that rainfall intensity and temporal distribution strongly influence soil erosion potential (Panagos et al., 2017). In addition, climate-related rainfall variability may intensify erosion risk, particularly in watersheds where high rainfall coincides with steep slopes and reduced vegetation cover (Dash et al., 2023; Maulana et al., 2025).

Soil Erodibility Factor (K) Calculation

The soil erodibility factor describes the susceptibility of soil to detachment and transport by rainfall energy and surface runoff. This factor is influenced by soil permeability, organic matter content, texture, structure, and particle size distribution. Soil structure and weathering conditions also contribute to variations in erodibility levels across different soil types (Kaffas et al., 2021). In the Mangkang Watershed, six soil types were identified, each showing different K values that reflect varying levels of erosion vulnerability, as presented in Table 2.

Table 2 shows that the highest K values were found in brown mediterranean and regosol association and brown mediterranean and litosol association. These soil types are more susceptible to erosion, particularly when located in steep areas or land-use zones with limited vegetation cover. The variation in K values confirms that soil characteristics are important factors controlling erosion processes, especially when combined with high rainfall erosivity and inadequate conservation practices.

Table 2. Soil Erodibility Factor Values

Soil type	K value
Hydromorphic alluvial soil	0.16
Grey alluvial and brown alluvial soil with subdued color	0.19
Grey grumusol and litosol complex	0.19
Brown mediterranean and regosol association	0.27
Red mediterranean and regosol	0.19
Brown mediterranean and litosol association	0.27

Length and Slope Factor (LS) Calculation

The LS factor represents the combined influence of slope length and slope steepness on soil loss. Longer slopes allow surface runoff to accumulate along the flow path, while steeper slopes increase runoff velocity and erosive force. Reduced infiltration capacity on sloping terrain may further increase surface runoff and accelerate soil particle transport (Dutta et al., 2025; Kaffas et al., 2021). Based on Digital Elevation Model analysis, the Mangkang Watershed consists of several slope classes ranging from flat to very steep. The distribution of LS factor values across the study area is presented in Table 3.

Table 3. Length and Slope Factor Values

Slope class	Slope category	LS value	Area (km²)	Percentage (%)
0–8%	Flat	0.40	18.50	42.30
8–15%	Gentle	1.40	9.88	22.60
15–25%	Moderate slope	3.10	8.77	20.05
25–45%	Steep	6.80	5.83	13.32
>45%	Very steep	9.50	0.76	1.73
Total			43.74	100.00

The influence of slope on erosion risk is also supported by morphometric and geospatial watershed studies. Watershed morphology, slope gradient, and terrain characteristics can affect runoff concentration, sediment transport potential, and flood vulnerability (Kaffas et al., 2021; Maulana et al., 2025). Comparative morphometric analysis has also been used to identify sub-watersheds with higher hydrological risk, supporting the prioritization of conservation actions in critical areas (Indrawan et al., 2025; Maulana et al., 2025) Therefore, LS factor analysis is important not only for estimating soil loss but also for identifying topographically sensitive zones that require spatially targeted management (Campos et al., 2025).

Table 3 shows that flat areas dominate the Mangkang Watershed, covering 18.50 km² or 42.30% of the total watershed area. However, steep and very steep areas remain critical because they have greater potential to accelerate runoff and soil particle transport. Although these areas occupy a smaller proportion of the watershed, they may contribute significantly to erosion risk when combined with high rainfall erosivity, erodible soils, and limited vegetation cover. This finding supports the role of topographic factors as one of the main controls in GIS-based erosion modelling.

Crop Management and Soil Conservation Factor (CP) Calculation

The CP factor consists of two main components: the C factor, which represents land cover and land management conditions, and the P factor, which reflects the application of soil conservation practices. The C factor describes the influence of vegetation cover, surface residues, soil surface condition, and land management activities on erosion rates. Meanwhile, the P factor indicates the effectiveness of conservation measures in reducing soil loss (Ali et al., 2016; Tuhepaly et al., 2022). In this study, CP values were determined based on land-use conditions within the Mangkang Watershed. Land-use data from 2024 were analyzed to identify CP value variations and their influence on soil erosion potential. The CP factor values are presented in Table 4 and Figure 3.

Table 4. Crop Management and Conservation Practice Factor Values

Land use	Area (km²)	Percentage (%)	CP value
Water body	6.25	14.32	<0.01
Forest	10.59	24.21	0.03
Dryland agriculture	5.68	12.99	0.02
Paddy field	11.30	25.84	0.28
Bare land or open soil	9.90	22.64	1.00
Total	43.74	100.00	

Land-cover condition strongly affects erosion because vegetation can reduce raindrop impact, improve infiltration, and stabilize the soil surface. Previous studies have shown that cover management and support practice factors play an important role in controlling soil erosion and conservation effectiveness (Ebabu et al., 2022). Land-cover changes in watersheds can also reduce water catchment capacity and increase runoff pressure, particularly when vegetated areas are converted into agricultural or built-up land (Fajri et al., 2025; Ferynandari et al., 2026; Zahrani et al., 2026). Conservation-based land management, such as agroforestry and reduced soil disturbance, has been reported to reduce sediment loss in hilly landscapes (El Harche et al., 2023).

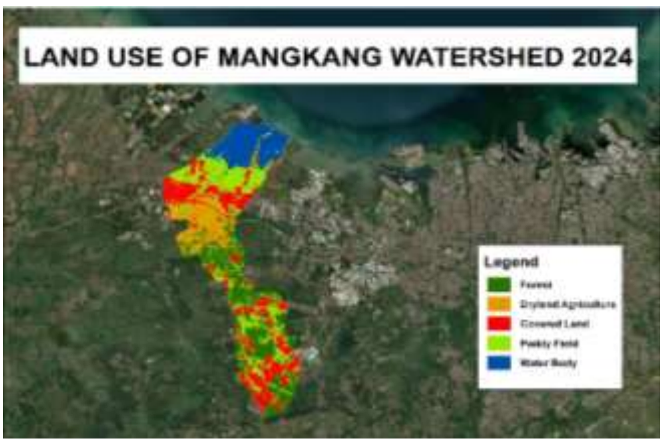

Figure 3. Land use 2024

The highest CP value was assigned to bare land or open soil because this land-use type has minimal vegetation protection and is highly exposed to rainfall impact and surface runoff. The term "covered land" was replaced with "bare land or open soil" to avoid conceptual misunderstanding, since a CP value of 1.00 represents land with very limited or no protective cover. Forest areas have lower CP values because vegetation can reduce raindrop energy, increase infiltration, and minimize soil detachment. These findings indicate that land-cover conditions and conservation practices strongly influence erosion risk in the Mangkang Watershed.

Estimation Erosion Rate

Soil loss in the Mangkang Watershed was estimated using the Universal Soil Loss Equation (USLE) integrated within a GIS environment. The estimation was carried out by combining several erosion parameters, including rainfall erosivity, soil erodibility, slope length and steepness, land cover management, and conservation practice factors. This approach enables the spatial estimation of annual soil loss per unit area and supports the identification of erosion-prone zones within the watershed (Ali et al., 2016; El Harche et al., 2023; Pham et al., 2018).

In this study, erosion rate and total soil loss were distinguished to avoid unit misinterpretation. The annual erosion rate was expressed in ton/ha/year, representing soil loss per unit area, whereas total soil loss was expressed in ton/year, representing the accumulated soil loss across the entire watershed. Total soil loss was calculated by multiplying the average annual erosion rate by the watershed area, as shown in Equation (3).

$$TE = A \times WA \tag{3}$$

In Equation (3), TE represents total soil loss expressed in ton/year, A refers to the average annual erosion rate expressed in ton/ha/year, and WA indicates the watershed area expressed in hectares.

The estimated thickness of eroded soil was calculated by converting the average erosion rate into soil loss depth using soil bulk density, as shown in Equation (4).

$$D = \frac{A}{\rho_b \times 10} \tag{4}$$

In Equation (4), D represents the estimated soil loss thickness expressed in mm/year, A is the average annual erosion rate expressed in ton/ha/year, and ρ_b is the soil bulk density expressed in g/cm³. In this study, a standard soil bulk density value of 1.20 g/cm³, equivalent to 1.20×10^3 kg/m³, was used to convert erosion rate into soil loss thickness.

Based on the corrected unit conversion, the average erosion rate in the Mangkang Watershed in 2024 was estimated at 46.42 ton/ha/year. With a standardized watershed area of 4,374 ha, the estimated total soil loss reached 203,029.08 ton/year. This value is equivalent to an average soil loss thickness of 3.87 mm/year. The result indicates that soil erosion in the study area remains above the tolerable soil loss threshold of 2.50 mm/year. Therefore, further conservation measures are required, particularly in areas classified as high and very high erosion hazard zones. Table 5 presents the estimated erosion rate, total soil loss, and soil loss thickness in the Mangkang Watershed in 2024.

Table 5 . Erosion Rate Estimation

Parameter	Value	Unit
Average erosion rate	46.42	ton/ha/year
Watershed area	4,374.00	ha
Total soil loss	203,029.08	ton/year
Estimated soil loss thickness	3.87	mm/year
Tolerable soil loss threshold	2.50	mm/year

The corrected erosion rate indicates that soil loss in the Mangkang Watershed remains environmentally significant, although it is no longer presented as an unrealistic extreme value. Similar GIS-USLE studies have shown that erosion rates vary spatially depending on rainfall erosivity, slope characteristics, soil erodibility, and land-cover conditions (Ali et al., 2016; Pham et al., 2018; Yustika et al., 2019). Recent USLE-based assessment in Indonesia also confirms that basin-wide erosion risk can be effectively evaluated using spatial modelling approaches (Kardhana et al., 2024). At a broader scale, land-use change has been identified as a major factor accelerating soil erosion, supporting the need for land-cover control in erosion-prone watersheds (Borrelli et al., 2017; Ebabu et al., 2022; Panagos et al., 2017).

The corrected erosion value shows that the previous value of 46,419.56 ton/ha/year was not appropriate as an average erosion rate because it would imply an unrealistic magnitude of soil loss at the watershed scale. By distinguishing erosion rate from total soil loss, the revised calculation provides a more reasonable interpretation of soil degradation in the Mangkang Watershed. Although the corrected erosion rate is lower than the previous value, it remains environmentally significant because the estimated soil loss thickness still exceeds the tolerable threshold.

To ensure consistency among parameter maps, the final watershed area used in erosion rate estimation and Erosion Hazard Index classification was standardized at 43.74 km², equivalent to 4,374 ha. All spatial layers were projected into the same coordinate system, clipped using the same watershed boundary, and adjusted to the same spatial extent before overlay analysis. This step was conducted to minimize topological inconsistencies among rainfall, soil, slope, land-use, and conservation practice layers.

Erosion Hazard Index

Spatial analysis using GIS provides a comprehensive basis for identifying and classifying erosion-prone areas within the Mangkang Watershed. The Erosion Hazard Index (EHI) was determined by comparing the estimated erosion rate with the tolerable soil loss value (Li et al., 2025; Liu et al., 2026). A higher EHI value indicates that estimated soil loss exceeds the tolerable threshold and that the land requires greater conservation attention. Referring to the classification system proposed by Hammer (1981), erosion hazard levels were categorized into four classes: low, moderate, high, and very high. Areas classified as high and very high should be prioritized for rehabilitation, soil conservation, land-use control, and sustainable land management interventions (Issaka et al., 2017).

The analysis shows that the very high erosion hazard class covered 15.74 km² or 36.00% of the total watershed area. This indicates that more than one-third of the Mangkang Watershed requires priority conservation attention. This condition may be influenced by land-use change, steep terrain, high rainfall intensity, erodible soil characteristics, and limited conservation practices. Table 6 presents the Erosion Hazard Index classification for the Mangkang Watershed in 2024. Meanwhile, the red-shaded areas in Figure 4 represent critical zones with very high erosion risk. These zones require special attention because of their high vulnerability to soil degradation and their potential contribution to downstream environmental pressure.

Table 6. Erosion Hazard Index Classification

Erosion hazard index	Area (km²)	Percentage (%)
Low	8.89	20.32
Moderate	9.61	21.97
High	9.50	21.71
Very high	15.74	36.00
Total	43.74	100.00

The EHI classification provides a spatial basis for identifying priority conservation areas. Geospatial prioritization has been shown to improve the identification of critical erosion risk zones and support more targeted conservation planning (Ahmad, 2017; Campos et al., 2025). Similar GIS-based studies on flood vulnerability and environmental risk mapping also demonstrate that spatial classification can support decision-making in watershed management (A. D. Purwanto et al., 2023; A. Purwanto et al., 2023; Virgota et al., 2024). In addition, watershed carrying capacity assessment can help evaluate whether land-use pressure exceeds the environmental support capacity of a catchment (Amini et al., 2025). Since soil erosion and degradation can also affect water quality, priority management in high-risk areas is essential for maintaining long-term watershed health (Issaka et al., 2017).

Figure 4. Erosion hazard index in 2024

The use of GIS in this study strengthens the spatial interpretation of erosion hazard because it enables the integration of rainfall, soil, slope, land-use, and conservation practice data within a single analytical framework. Previous studies have shown that GIS and remote sensing can support flood risk mapping, watershed vulnerability assessment, and land-use change monitoring in different catchment systems (A. Purwanto et al., 2023; Virgota et al., 2024). Therefore, the EHI map generated in this study can be used not only as an erosion risk map, but also as a planning tool for identifying priority areas for conservation intervention.

The spatial distribution of EHI indicates that erosion hazard is not uniform across the watershed. Areas with high and very high erosion hazard are mainly associated with steep slopes, exposed soil surfaces, agricultural areas on sloping terrain, and land-use transition zones with limited vegetation protection. Therefore, the EHI map can be used as a spatial basis for determining priority areas for soil conservation planning.

Discussion

The findings of this study indicate that soil erosion in the Mangkang Watershed is controlled by the interaction of rainfall characteristics, soil erodibility, slope morphology, land-cover conditions, and conservation practices. Areas classified as high and very high erosion hazard are generally associated with steep terrain, exposed soil surfaces, land-use conversion, and limited vegetation protection. This pattern confirms the conceptual basis of the USLE model, in which rainfall erosivity, slope length and steepness, cover management, and conservation practices strongly influence the magnitude of soil loss. Similar patterns have also been reported in previous erosion studies, where erosion-prone areas commonly occur in steep terrain, areas with reduced vegetation cover, intensive land-use pressure, and insufficient soil conservation measures (Ali et al., 2016; Gia et al., 2018; Kardhana et al., 2024; Yustika et al., 2019).

This result is also consistent with broader studies showing that soil erosion risk is strongly controlled by the interaction between rainfall erosivity, topography, land-use change, and vegetation cover. Land-use change has been identified as a major driver of accelerated soil erosion at the global scale, while rainfall erosivity remains one of the most important factors determining soil detachment and transport (Borrelli et al., 2017; Ebabu et al., 2022; Panagos et al., 2017). In Indonesian watershed studies, land-cover change and urban expansion have also been shown to influence hydrological response, runoff generation, and environmental pressure (Fajri et al., 2025; Ferynandari et al., 2026; Zahrani et al., 2026).

The revised erosion calculation shows that the average erosion rate in the Mangkang Watershed reached 46.42 ton/ha/year in 2024. This value is equivalent to an estimated soil loss thickness of 3.87 mm/year, which exceeds the tolerable soil loss threshold of 2.50 mm/year. These results indicate that soil degradation in the watershed remains a significant environmental concern and that existing land management practices are not yet sufficient to reduce erosion risk in vulnerable zones. The relatively large proportion of very high erosion hazard areas further suggests that conservation planning should focus on locations where steep slopes, bare or poorly protected soil surfaces, and inadequate vegetation cover occur together. This interpretation is consistent with (Ebabu et al., 2022; Kwin Hariyanto et al., 2024; Yustika et al., 2019), who emphasized the importance of vegetation cover, conservation practices, and spatially based watershed management in reducing erosion risk.

The spatial distribution of the Erosion Hazard Index shows that erosion risk is not evenly distributed across the watershed. Low and moderate hazard classes represent areas where erosion risk remains relatively controlled, while high and very high hazard classes indicate priority zones that require immediate intervention. This spatial variation demonstrates the usefulness of GIS-based modelling for identifying critical erosion areas more specifically than general watershed-scale assessments. In this context, the EHI map provides practical information for local governments, watershed managers, and spatial planners in determining where conservation measures should be implemented first. GIS-based erosion mapping has also been recognized as an effective approach for producing erosion risk maps and supporting conservation planning (Ali et al., 2016; Anley et al., 2024; Gia et al., 2018; Herbanu et al., 2024).

Land-use change is one of the main factors contributing to erosion risk in the Mangkang Watershed. The conversion of vegetated areas into agricultural land, residential zones, and other developed areas can reduce natural soil protection and increase surface runoff. When this condition occurs on sloping terrain, the soil surface becomes more vulnerable to rainfall impact and runoff-induced erosion. This finding supports previous research showing that the transformation of vegetated land into agricultural and built-up areas may increase runoff, soil detachment, and sediment input into drainage systems (Kucuker et al., 2022; Mendez, 2014; Tian et al., 2023). Therefore, land-use planning needs to be strengthened, particularly in upstream areas, steep-slope zones, and land-use transition areas where erosion susceptibility is higher.

Although the GIS-USLE approach provides useful spatial information for estimating potential soil loss and identifying erosion-prone areas, its methodological limitations must be clearly acknowledged. The USLE model primarily estimates sheet and rill erosion and does not directly simulate gully erosion, riverbank erosion, sediment routing, or sediment deposition. Therefore, the erosion hazard map produced in this study should be interpreted as an indication of potential soil loss source areas, not as a direct calculation of sediment movement within river channels. Future research should integrate USLE with more comprehensive hydrological or sediment transport models, such as SWAT, to better represent runoff generation, gully erosion, streambank erosion, and sediment dynamics (Ali et al., 2016; Chowdhury et al., 2023; Kucuker et al., 2022; Maurya et al., 2024).

Since the USLE model primarily estimates sheet and roll erosion, further studies should integrate hydrological or sediment transport models to represent runoff generation, sediment routing, and sediment yield more comprehensively. SWAT-based sediment modelling has been widely used to predict sediment concentrations and yields at basin scale, making it useful for complementing USLE-based erosion hazard mapping (Chowdhury et al., 2023; Kaffas et al., 2021; Kinnell, 2025; Maurya et al., 2024; Risal et al., 2018; Vigiak et al., 2015). This integration would improve the understanding of how erosion source areas contribute to sediment dynamics in river channels.

Based on the EHI classification, conservation measures should be prioritized in areas classified as very high and high erosion hazard zones. In degraded upstream areas and steep slopes, reforestation and slope stabilization are recommended to increase vegetation cover and reduce runoff velocity. In agricultural areas located on moderate to steep slopes, terracing, contour farming, and agroforestry systems should be applied to reduce soil detachment and maintain soil productivity. Along river corridors, riparian buffer development is needed to reduce erosion sources that may contribute to sediment input into drainage channels. In land-use transition zones, stricter spatial zoning and conservation-based land management are required to prevent further expansion of erosion-prone areas. These strategies are consistent with previous studies emphasizing the role of reforestation, agroforestry, riparian buffers, terracing, and soil conservation structures in reducing erosion risk (Kucuker et al., 2022; UNISDR, 2002; Wang et al., 2022).

Spatially targeted conservation is important because erosion risk is not distributed evenly across the watershed. Geospatial prioritization can help determine which areas should receive conservation intervention first, particularly where steep slopes, exposed soil, and high runoff potential overlap (Ahmad, 2017; Campos et al., 2025). In addition, conservation measures such as agroforestry, reforestation, terracing, and riparian buffer restoration can improve vegetation cover, reduce runoff velocity, and minimize soil detachment in erosion-prone areas (Ebabu et al., 2022; El Harche et al., 2023; Liu et al., 2026; Tian et al., 2023; Wang et al., 2022).

Field documentation is also important to support the interpretation of GIS-based modelling results. Photographs showing steep slopes, exposed soil surfaces, agricultural land on sloping terrain, and sediment accumulation along river channels can provide visual evidence of erosion-prone conditions in the study area. The addition of field photographs strengthens the discussion because it links spatial modelling outputs with actual environmental conditions observed in the Mangkang Watershed. This is important because erosion hazard maps should not only be interpreted as model outputs, but also as planning tools supported by field-based evidence.

The integration of remote sensing and GIS-based modelling also provides opportunities for continuous monitoring of erosion-prone areas. Periodic spatial data can support early detection of land degradation and enable timely management responses before erosion becomes more severe. This approach strengthens adaptive and data-driven watershed management, especially in areas experiencing rapid land-use change. Future research should incorporate high-resolution spatial data and multi-temporal land-use analysis to improve model accuracy. LiDAR, drone imagery, and multi-sensor Landsat datasets can support more detailed terrain and land-cover mapping, especially in rapidly changing watersheds (Ferynandari et al., 2026; Zahrani et al., 2026). Long-term field measurements using sediment plots, runoff gauges, and monitoring stations are also needed to improve model calibration and validation. In addition, climate change projections and predictive geospatial approaches such as CA–Markov modelling should be incorporated to anticipate future land-use change and its potential environmental implications (Deska et al., 2026). These improvements would strengthen the development of adaptive, evidence-based, and sustainable watershed management strategies.

Overall, the results demonstrate that GIS-based USLE modelling can support sustainable watershed management by identifying erosion-prone areas and guiding spatially targeted conservation planning. The EHI map provides practical information for prioritizing conservation interventions, particularly in high and very high hazard zones. Therefore, the findings of this study can serve as a scientific basis for land-use control, soil conservation planning, and adaptive watershed management in the Mangkang Watershed and other rapidly developing catchments with similar environmental pressures.

Conclusion

This study assessed soil erosion hazard in the Mangkang Watershed using a GIS-based Universal Soil Loss Equation approach. The results show that the average erosion rate in 2024 was estimated at 46.42 ton/ha/year, equivalent to an average soil loss thickness of 3.87 mm/year. This value exceeds the tolerable soil loss threshold of 2.50 mm/year, indicating that soil degradation in the watershed remains a serious environmental concern. The Erosion Hazard Index was classified into low, moderate, high, and very high categories, with the very high hazard class covering 15.74 km² or 36.00% of the total watershed area. The findings indicate that erosion risk is mainly controlled by rainfall erosivity, slope conditions, land-cover characteristics, soil erodibility, and limited conservation practices. Spatially targeted conservation measures should be prioritized in high and very high erosion hazard zones. Reforestation and slope stabilization are recommended for degraded upstream and steep-slope areas, while terracing, contour farming, and agroforestry are more suitable for agricultural land located on moderate to steep slopes. Riparian buffer restoration is also needed along river corridors to reduce potential erosion sources that may contribute to downstream sediment input. The GIS-based erosion hazard map provides useful spatial evidence for watershed managers, local governments, and spatial planners in determining priority areas for soil conservation and land-use control. However, because the USLE model primarily estimates sheet and rill erosion, the results should be interpreted as potential soil loss information rather than direct sediment transport or deposition analysis. Future research should integrate higher-resolution spatial data, field-based erosion monitoring, time-series land-use analysis, climate change projections, and hydrological models such as SWAT to improve the accuracy and comprehensiveness of erosion and sediment dynamics assessment.

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Author Contributions

Each author played a crucial role in the development and completion of this study. RWA led the conceptual design, developed the methodological framework, carried out the GIS-based erosion modeling, and prepared the original draft of the manuscript along with data visualization. UA contributed to the research supervision, validation of analytical methods, and provided critical input during the review and editing phases of the manuscript. SMBP managed spatial data acquisition and processing, supported the erosion analysis, and contributed to the structure and clarity of the manuscript. A brought expertise in hydrodynamic and watershed systems, contributed to field data interpretation, and provided strategic insights into policy relevance and critical review.

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Conflicts of Interest

The authors declare that there are no competing interests or personal relationships that could have appeared to influence the work reported in this manuscript. All authors have contributed collaboratively and transparently, ensuring the integrity of the research.

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