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Analysis of Erosion Rate Based on Geographic Information System (GIS) in Enrekang District

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ABSTRACT

Rapid population growth and land-use change in tropical mountainous areas can accelerate land degradation by reducing infiltration and increasing erosion, sedimentation, and threats to agricultural productivity and downstream water infrastructure. This study estimated and mapped spatial patterns of soil loss and erosion hazard in Enrekang District (Enrekang Regency, South Sulawesi) to support sustainable land management planning by integrating the Universal Soil Loss Equation (USLE) and Geographic Information Systems (GIS). A quantitative survey from October–December 2025 covered 27,975.57 ha in 66 land units. Field surveys collected soil samples for texture, structure, organic matter, and permeability to derive soil erodibility (K) using the Wischmeier and Smith equation; LS came from DEM/SRTM processing; and land-use classes informed C and P factors based on Arsyad's references. Rainfall erosivity (R) was computed from 10-year monthly rainfall data (2015–2024) using the Lenvain approach. GIS overlay of R, K, LS, C, and P produced erosion rates (A) and hazard classes following RTL-RLKT. Rainfall erosivity ranged from 1,158–3,044 annually, with monthly values of 22–781, lowest in August and highest in December. K was highest in Dystropepts (0.32) and lowest in Tropaquepts (0.26), but high erosion also occurred where moderate K coincided with steep slopes and inadequate conservation. Soil loss was higher in slope classes III–IV. Highest erosion occurred on dryland agriculture (up to 1,537.28 t ha^{-1} yr^{-1}), mixed dryland agriculture (up to 1,563.71 t ha^{-1} yr^{-1}), and open land, while settlements were lowest.

INTRODUCTION

Rapid population growth has a direct impact on the soaring demand for space for residential areas, the agricultural sector, and infrastructure expansion (Borrelli et al., 2017; Hu et al., 2021). Meanwhile, the carrying capacity and availability of land resources are static and increasingly limited (Menghis et al., 2025). This imbalance triggers pressure on space, driving massive land-use changes including deforestation, conversion of natural vegetation, and the development of built-up areas without consideration for soil conservation principles (Borrelli et al., 2017; Suripin, 2004). Such land conversion with minimal mitigation efforts makes a tangible contribution to the acceleration of environmental degradation, as indicated by declining rainwater infiltration capacity and surging erosion and sedimentation intensity (Hu et al., 2021; Suripin, 2004).

Soil is an environmental component that plays a vital role in supporting plant growth and maintaining water balance in a given area (Arsyad, 2010). A common form of land degradation is erosion (Utomo et al., 2016). Erosion is the phenomenon in which soil particles detach from the main mass due to the force of water or wind, and are subsequently transported and deposited downstream (Suripin, 2004). Its impacts include not only the stripping of nutrient-rich topsoil and a decrease in agricultural productivity (Aslam, 2020), but also the silting of rivers due to sedimentation and the damage of water infrastructure (Asdak, 2010).

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The threat of erosion indicates higher vulnerability in mountainous regions with a tropical climate due to the dynamic interaction between high-intensity rainfall and soil susceptibility to erosion (Asdak, 2010). Slope gradient is the main determining factor. Soil mass loss increases dramatically on steep topography with minimal vegetation cover (Gilani et al., 2021). Therefore, calculating the rate of soil loss becomes a crucial instrument in formulating strategies for land degradation control and soil conservation (Arsyad, 2010).

Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith is the most widely used empirical model to predict average annual soil loss (Arsyad, 2010). This model estimates the rate of erosion through five main parameters, including the rainfall erosivity factor, soil erodibility factor, slope length and steepness factor, crop cover factor, and land conservation practices factor.

Enrekang Subdistrict features varied topography dominated by undulating to steep slopes and high land use dynamics. Given its wide area, soil loss analysis requires spatial modeling to estimate erosion accurately and efficiently (Kharismanda, 2024). The integration of Geographic Information Systems (GIS) serves as a computational tool for processing and mapping USLE parameters in raster format. This GIS-based approach enables the spatial visualization of erosion hazard levels across each land unit. Based on this urgency, this study was conducted with a focus on GIS-Based Erosion Rate Analysis in Enrekang Subdistrict as a foundation for sustainable land management planning.

MATERIALS AND METHODS

This study uses a quantitative descriptive survey method to estimate the rate of erosion in Enrekang District, Enrekang Regency, South Sulawesi Province, with a study area covering 27,975.57 hectares divided into 66 land units. The research was conducted from October 2025 to December 2025. The survey approach was chosen because this study collects spatial and physical land data (slope gradient, soil type, land use) directly in the field to then be analyzed spatially using a Geographic Information System (GIS).

The instruments used include GPS, compass, sample ring, hammer, soil auger, measuring tape, and a set of computers with GIS software (ArcView, ArcGIS, and SRTM data). The materials used consist of the 1:50,000 scale Indonesian Topographic Map, administrative map, soil type map, land use map, and 1:10,000 scale slope class map of Enrekang Regency, as well as 10-year rainfall data (2015–2024) obtained from the Enrekang Regency Central Statistics Agency.

1. **Data Collection**

   Data were collected through two main techniques, namely field surveys and secondary data retrieval. Field surveys were conducted to collect soil samples from each land unit for laboratory analysis of texture, structure, organic matter content, and soil permeability, which serve as the basis for determining the soil erodibility (K) value. Slope gradient and slope length data were obtained from processing Digital Elevation Model (DEM) data. Secondary data in the form of monthly rainfall data for 10 years (2015–2024) were collected from BPS to calculate the rainfall erosivity (R) value.

2. **Data Processing and Analysis**

   Prediction of erosion rate is calculated using the Universal Soil Loss Equation (USLE) method from Wischmeier and Smith (1978), with the following equation:

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

   with A being the erosion rate (ton ha^{-1} yr^{-1}), R the rainfall erosivity factor (kJ ha^{-1}), K the soil erodibility factor (ton kJ^{-1}), LS the slope length and steepness factor, C the crop management factor, and P the soil conservation practice factor.

   a) The R value is calculated using the Lenvain (1975) equation in Bols (1978) in Hadjowigeno(2007):

   $$RM = 2{,}34\ R^{1{,}36}$$

   Where RM is monthly erosivity, R is monthly rainfall (cm). The annual value of R (rainfall erosivity) is obtained by totaling RM for a year.

   b) The K value was calculated using the Wischmeier and Smith (1978) equation based on soil texture, structure, permeability, and organic matter content as determined by laboratory testing.

   $$100\ K = 1{,}292[2{,}1\ M^{1{,}14}\ (10)\ (12\text{-}a) + 3{,}25(b\text{-}2) + 2{,}5\ (c\text{-}3)]$$

   Where:

   M : Percentage of very fine sand and dust (diameter 0.1–0.05 and 0.05–0.02 mm) x (100%clay)

   a : Organic Matter Percentage

b : Soil structure value code used in soil classification
c : Soil permeability class

c) The LS value is calculated using the formula
$LS = \sqrt{L}\,(0{,}0138 + 0{,}00965\,S + 0{,}00138\,S^2)$,
with L being the slope length (m) and S being the slope gradient (%)
d) The C and P values are determined based on the reference table by Arsyad (2010) according to the type of land use and conservation measures applied.
e) All spatial data (soil type map, land use, and slope class) were processed and overlaid using GIS software to produce land unit maps and erosion hazard level maps. The calculated erosion rates (ton ha^{-1} $year^{-1}$) were then classified into erosion hazard classes (light, moderate, severe, and very severe) based on the RTL-RLKT criteria of the Department of Forestry (1995), then analyzed descriptively to examine the relationship between land use types and the distribution of erosion hazard levels in the study area.

RESULTS AND DISCUSSION

The erosion rate in Enrekang District was analyzed using the Universal Soil Loss Equation (USLE), integrated with Geographic Information Systems (GIS). This approach is commonly used because it allows the combination of rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover/management (C), and conservation practices (P) factors into raster-based spatial analysis, enabling the distribution of soil loss to be mapped more clearly for each land unit (Bekele & Gemi, 2020; Fajriyah et al., 2025; Seika et al., 2021)

Land use in the study area includes, among others, secondary dryland forest, residential areas, dryland agriculture, mixed dryland agriculture, savanna, shrubland, rice fields, open land, and bodies of water. The diversity of land use types also leads to variations in erosion characteristics, given that each land cover type provides a different level of protection to the soil surface against the erosive force of falling raindrops. The mapped spatial pattern shows that the rate of erosion in this area is not uniform across all locations. Areas with steep slopes utilized for agriculture or as open land tend to experience much higher erosion compared to areas still covered by dense vegetation or rice fields. These findings indicate that, aside from natural conditions, human land use patterns also play a significant role in accelerating the rate of erosion.

Rainfall erosivity is one of the key variables in the USLE equation, as it represents the capacity of rainwater to detach soil particles from the land surface. Based on rainfall data, the annual rainfall erosivity ranges from 1,158 to 3,044, while monthly erosivity falls within the range of 22–781. The lowest value is recorded in August, while the peak occurs in December. The magnitude of the R value is primarily influenced by the intensity and kinetic energy of raindrops. The rainy season periods with high intensity increase the likelihood of soil aggregate detachment and surface runoff formation, especially when rainfall exceeds infiltration capacity (Ke & Zhang, 2022). Areas with high rainfall require stricter conservation measures. This underscores that climatic factors, particularly rainfall intensity, make a significant contribution to erosion rates. Therefore, areas with high rainfall require stricter implementation of conservation measures compared to areas with lower rainfall.

Soil erodibility indicates the inherent vulnerability of soil to destruction by raindrop impact and surface runoff. This value is generally influenced by soil texture, aggregate stability, organic matter, shear strength, as well as the infiltration and permeability capacity of the soil (Bekele & Gemi, 2020; Seika et al., 2021). Test results show that Dystropepts have a K value of 0.32, followed by Rendolls at 0.30, Eutropepts at 0.30, while Tropaquepts have the lowest value, at 0.26. This variation in values confirms that the resistance of each soil type to aggregate destruction by rainfall is not the same. The higher the K value of a soil, the more susceptible it is to erosion compared to soils with lower K values. Nevertheless, soil erodibility is not the sole determinant of the magnitude of the erosion rate. Several locations were found with a moderate K value but still exhibited a high rate of erosion, which was more influenced by slope steepness and land use patterns that did not adhere to soil conservation principles. This explains why differences in soil types within a single area can result in significant variations in erosion rates, even though other factors such as slope and land cover still play a major role (Nazarlu et al., 2026).

The LS factor represents the influence of slope length and steepness on the magnitude of erosion. The longer and steeper the slope, the greater the potential acceleration of surface runoff and the transport energy of soil particles (Panagos et al., 2015; Alebachew et al., 2025). DEM processing produces four slope classes: 0–8%, 8–15%, 15–25%, and 25–40%. Areas with slope classes III and IV show much greater soil loss compared to flat regions due to rainwater flowing over steep slopes having a shorter infiltration time, so that most of the water instead becomes surface runoff.

The type of land use has a significant effect on the magnitude of the erosion rate. Agricultural expansion, forest conversion, and reduced vegetation cover increase the risk of erosion and sedimentation (Malik et al., 2025; Wondim et al., 2023; Kardhana et al., 2024). Conversely, dense vegetation cover suppresses erosion by protecting the soil surface from the impact of rainfall and reducing runoff (Wu et al., 2024). Differences in land use types have a significant impact on the rate of erosion. Based on USLE calculations, the highest erosion rates are found in dryland agriculture, mixed dryland agriculture, and open land, while the lowest erosion rates are recorded in residential areas, savanna, and portions of irrigated rice fields.

In secondary dryland forests, erosion rates are in the range of 44.73–671.29 tons ha^{-1} $year^{-1}$. Although this area still retains vegetation cover, the steep slope gradient causes parts of the forest to continue experiencing erosion in considerable amounts. In contrast, on dry agricultural land, the recorded erosion rate is much higher, reaching 1,537.28 tons ha^{-1} $year^{-1}$, while mixed dryland agriculture reaches 1,563.71 tons ha^{-1} $year^{-1}$. These high figures are influenced by a combination of steep slopes, limited vegetation cover during certain periods, and suboptimal implementation of soil conservation measures. Conversely, residential areas recorded an erosion rate of only about 0.02 tons ha^{-1} $year^{-1}$, while savanna areas were around 0.34 tons ha^{-1} $year^{-1}$. The low rates indicate that land surface conditions in these two types are relatively stable and therefore not easily eroded by surface runoff.

Table 1. Average Erosion Rates for Various Land Uses in Enrekang District

No.	Land Use	Erosion	Erosion class	Dangers of Erosion	Area (Ha)
1	Secondary Dryland Forest	44.73	II	Light	89.80
		124.50	III	Medium	704.18
		319.25	IV	Weight	1,015.49
		671.29	V	Very Weight	693.65
2	Settlement	0.020	I	Light	99.77
3	Dryland Agriculture	56.389	II	Light	16.63
		100.673	III	Medium	536.16
		352.002	IV	Weight	715.41
		1,537.279	V	Very Weight	9,929.40
4	Mixed Dryland Farming	130.327	III	Medium	300.16
		307.768	IV	Weight	577.42
		1,563.709	V	Very Weight	2,989.81
5	Savana	0.339	I	Light	918.36
6	Rice field	3.463568901	I	Light	384.37
		35.66771662	II	Medium	108.94
		68.78608304	III	Weight	27.15
7	Thicket/Shrubland	7.991710476	I	Light	2,270.28
		31.36580652	II	Light	4,592.84
		92.34235332	III	Medium	1,174.63
		189.4299085	IV	Weight	2.49
8	Open Land	104.357964	III	Medium	10.59
		380.2854796	IV	Weight	17.21
			V	Very Weight	477.84

Source: Primary data after processing, 2026

The results of the erosion hazard classification indicate that Enrekang District exhibits a range of hazard classes, from light, moderate, heavy, up to very heavy. Most forest, rice field, and savanna areas fall into the light to moderate categories, while dryland agriculture, mixed farming, and open land are dominated by the heavy to very heavy classes. Land conversion from natural vegetation to cultivated land without the application of conservation techniques significantly increases the risk of erosion (Arsyad, 2010). In addition, land located on steep slopes tends to have a higher erosion hazard level compared to lowland areas (Osok, et al, 2018).

The erosion hazard distribution map produced through GIS processing (Figure 1) provides spatial information that is very useful in determining priority points for soil and water conservation activities. This information can be utilized by local governments as a basis for formulating sustainable land management policies.

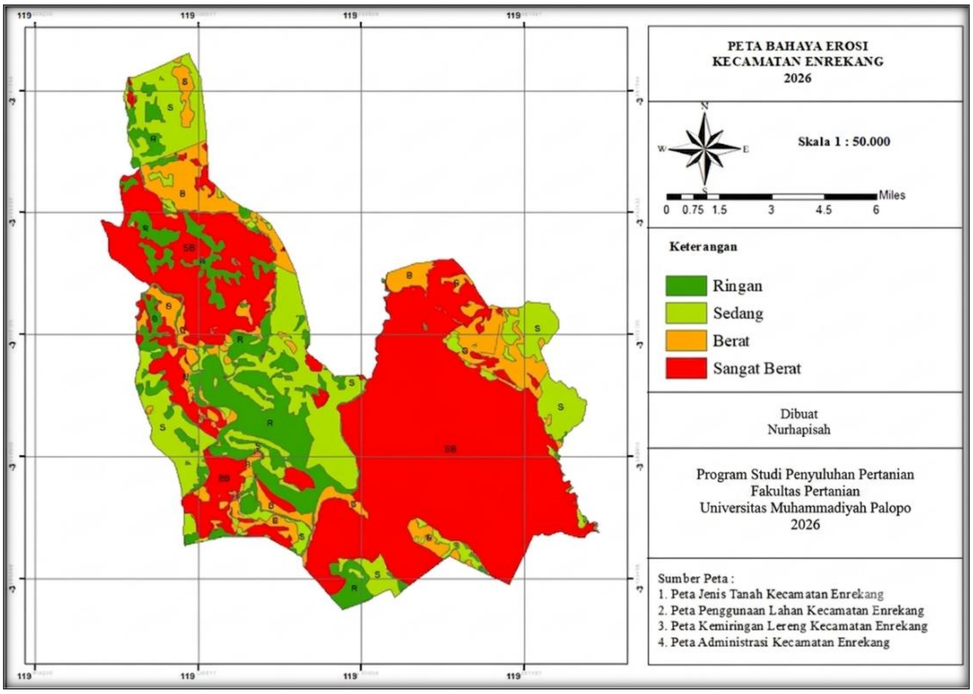

Figure 1. Erosion Hazard Map in Enrekang District

The rate of erosion in Enrekang District results from the interaction of various factors, including climate conditions, soil characteristics, regional topography, land use patterns, and the conservation efforts implemented. Among all USLE parameters, slope steepness (LS) and land use (C) are the two factors most decisive in determining the magnitude of soil loss (Rahim, 2026). Land on steep slopes with sparse vegetation generates high surface runoff, accelerating the detachment and transport of soil particles (erosion) (Rendra, 2025). Conversely, dense vegetation cover can dampen the impact energy of raindrops, promote increased infiltration, and slow the rate of surface runoff, thereby resulting in a lower level of erosion (Arsyad, 2010).

The utilization of Geographic Information Systems (GIS) can enhance the accuracy of identifying areas prone to high erosion risk, allowing conservation efforts to be focused on regions that genuinely require intervention (Ritung et al., 2007). Conservation techniques that can be recommended to reduce erosion rates in Enrekang District include the construction of terraces, contour planting, the use of cover crops, implementation of agroforestry systems, and rehabilitation of open lands. The application of these various techniques is expected to reduce surface runoff, promote increased water infiltration into the soil, and maintain long-term land productivity (Ashara et al., 2025)

The integration of the USLE method with Geographic Information Systems is a fairly reliable approach for mapping erosion hazard distribution patterns as well as supporting the formulation of soil and water conservation policies in Enrekang District. The information produced can serve as a foundation for more sustainable land use planning while also supporting efforts to preserve land resources in the study area.

CONCLUSIONS

The rate of erosion in Enrekang Subdistrict varies according to land use and is predominantly influenced by slope gradient and vegetation cover. Dryland agriculture and open land exhibit Very severe erosion, whereas savanna, rice fields, and settlements experience relatively low rates. The integration of USLE-GIS is effective in mapping the distribution of erosion hazards and supports priority conservation planning. The application of terraces, contouring, cover crops, and agroforestry is recommended on high-risk land to maintain the sustainability of land resources.

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