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Integrative Application of USLE and GIS for Modeling Soil Erosion Dynamics and Conservation Prioritization in the Poboya Watershed, Indonesia

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ABSTRACT

Land-cover change driven by agricultural expansion, mining activities, and forest conversion is a major cause of declining hydrological function in watershed ecosystems. The loss of vegetation accelerates soil erosion, sedimentation, and ecological instability. This study aims to model and quantify soil erosion rates across land units in the Poboya Watershed by integrating the Universal Soil Loss Equation (USLE) with Geographic Information Systems (GIS). Analytical units were generated through an overlay of slope, soil type, and land-use maps, and subsequently validated through field surveys. The USLE factors (R, K, LS, C, and P) were derived from climate data, laboratory soil analyses, a Digital Elevation Model (DEM), vegetation indices, and observations of conservation practices. The results indicate that 56% of the Poboya Watershed area falls within the very low to low erosion classes; however, 33% of the area exhibits moderate to very severe erosion, particularly in zones with steep slopes, highly erodible soils, and areas affected by mining and dryland agriculture. These conditions highlight the presence of erosion hotspots that may accelerate downstream sedimentation and intensify land degradation. The findings underscore the need for critical-land rehabilitation, enhanced vegetative and mechanical conservation measures on steep slopes, and forest protection to sustain the watershed's ecological functions.

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INTRODUCTION

Soil erosion is a natural geomorphic process influenced by rainfall intensity, soil properties, slope gradient, and land-cover conditions. However, accelerated erosion is predominantly driven by human activities such as forest conversion, land clearing without appropriate conservation measures, and unsustainable mining practices (Ahmad et al., 2020; Panagos et al., 2021). Uncontrolled erosion results in the loss of topsoil, reduced land productivity, increased river sedimentation, and widespread environmental degradation at the watershed scale.

The Poboya Watershed, which forms part of the Palu Watershed, is characterized by a relatively high level of land degradation due to extensive land conversion for dryland agriculture and traditional gold mining. Data from the Palu–Poso Watershed Management Agency indicate that approximately 1,338.14 ha (18.31%) of the total watershed area has been classified as critical land. This condition is further exacerbated by pronounced seasonal rainfall and steep slopes that intensify erosion processes and surface runoff.

Modeling soil erosion potential at the watershed scale is essential for formulating effective management strategies. The Universal Soil Loss Equation (USLE; Wischmeier & Smith, 1978) and its subsequent advancements, including the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997; Panagos et al., 2015), are widely used worldwide due to their reliability in quantifying soil-loss estimates. The integration of USLE with Geographic Information Systems (GIS) enhances model accuracy through improved spatial computation and visualization of erosion-risk distribution (Bekele & Gemi, 2021; Negese et al., 2021; Luvai et al., 2022). Recent studies also highlight the importance of combining USLE–GIS approaches with field-based validation to better capture local biophysical conditions and anthropogenic pressures (Abdo et al., 2020; Sharma et al., 2023).

Given these concerns, this study aims to analyze soil-erosion dynamics in the Poboya Watershed through the integration of USLE and GIS and to identify priority conservation areas to support hydrometeorological disaster mitigation and sustainable land-resource management.

MATERIALS AND METHODS

Study Area

This study was centered in the Poboya Watershed, Palu City, Central Sulawesi, with the primary data acquisition period extending from April to November 2025. A multi-stage hybrid methodology was implemented, encompassing structured field surveys, soil sampling for physicochemical characterization, and climate data acquisition, all intended for the accurate parameterization of USLE model inputs.

Research Procedures

1. Delineation and Generation of Land Unit Maps

Land units were established as the main analytical framework by overlaying slope, soil-type, and land-use maps. Geographic Information Systems (GIS) were used to process these spatial layers, resulting in land-unit polygons that represent unique combinations of the three biophysical parameters.

2. Field Data Collection and Laboratory Analysis

Field investigations were conducted to obtain data on effective soil depth, texture, structure, and permeability. Soil samples were analyzed in the laboratory to determine the soil erodibility factor (K). Rainfall data were acquired from the Indonesian Agency for Meteorology, Climatology, and Geophysics (BMKG) and relevant institutions to calculate the rainfall erosivity factor (R). Land-use and vegetation conditions were derived from recent satellite imagery such as Landsat 8 OLI/TIRS or Sentinel-2 MSI using vegetation-index analysis to determine the cover-management factor (C). Conservation practices (e.g., terracing, strip cropping, contour ridges, and other soil- and water-conservation measures) were documented through field observations and community interviews to determine the support-practice factor (P).

Data Processing and Analysis

Soil erosion rates were estimated using the Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978; updated in Renard et al., 1997; Panagos et al., 2015; Naharuddin et al., 2019; Luvai et al., 2022):

$$A = R * K * LS * CP$$

Where: A: annual soil loss (tons·ha^{-1}·$year^{-1}$), R**:** rainfall erosivity factor (MJ·mm·ha^{-1}·h^{-1}·$year^{-1}$), K**:** soil erodibility factor derived from soil texture, organic matter, structure, and permeability, LS: slope length and steepness factor calculated from a 30-m Digital Elevation Model (DEM), C: cover-management factor obtained from vegetation indices (e.g., NDVI) derived from satellite imagery, P: support-practice factor determined from field observations and local conservation practices.

The estimated soil-loss values for each land unit were classified according to the Erosion Hazard Level (EHL) following criteria from the Indonesian Ministry of Forestry (2009) and FAO guidelines (2015). Spatial distribution maps of erosion severity were then generated using GIS to identify erosion hotspots and priority areas for conservation within the Poboya Watershed.

RESULTS AND DISCUSSION

Rainfall Erosivity (R)

The spatial analysis of the Poboya Watershed reveals a dominant presence of the low rainfall class (2,000–2,200 mm/year), which covers 74.5% of the watershed, whereas the medium rainfall class (2,200–2,400 mm/year) accounts for 25.5%. Notably, despite its smaller area, the medium rainfall class exhibits a substantially higher R-factor (1,683.96) compared to the low rainfall class (1,230.02). This disparity suggests that areas with more intense rainfall particularly those in the upper watershed with steeper slopes are critical sources of erosive energy and potential sediment yield.

Such patterns are consistent with studies showing that rainfall erosivity in tropical and humid environments is strongly linked to precipitation intensity, frequency, and kinetic energy (Das et al., 2025). Seasonal and topographic variability in erosivity can significantly influence the spatial distribution of soil erosion risk (Das et al., 2025). In line with this, our results highlight that medium rainfall concentrated in steep terrain amplifies runoff energy, promoting soil detachment and transport.

Given this spatial heterogeneity, a zone-based conservation strategy is imperative: conservation efforts should prioritize upper, steep, medium-rainfall zones because of their disproportionately high erosivity potential. This is in line with watershed management practices that target “hotspots” of erosivity for mitigation (Adeyeri et al., 2024).

Soil Erodibility Index (K)

The soil erodibility (K) index across Poboya ranges between 0.20 and 0.30**,** indicating moderate to high susceptibility to erosion. Distric Cambisol, which dominates 61.4% of the watershed, exhibits a high K value of 0.28. This is indicative of cohesive yet structurally unstable soils on steep slopes, which are easily detached under high energy rainfall.

In contrast, Ustic Arenosols (18.3%) have the lowest K (0.20), yet they remain vulnerable to splash erosion, especially when vegetation cover is removed. Other soils, such as Eutric and Ustic Cambisols (approximately 20% of area), show moderate to high erodibility (K = 0.25–0.27), reinforcing the overall sensitivity of land cover to erosion.

The highest K value (0.30) is found in settlement areas (0.4% of area), likely reflecting anthropogenic degradation, compaction, and reduced organic matter. Such human-impacted soils are more vulnerable because of altered structure and permeability an observation supported by recent studies in tropical mining and disturbed landscapes (Rehman et al., 2024).

From a process-based perspective, soil texture, organic matter content, and structure are key controls of K (Han et al., 2023). In tropical contexts, K variability can be strongly influenced by spatial differences in clay, silt, and organic carbon content, as well as by slope and land management (Nahib et al., 2024; Teku et al., 2025). Moreover, feedback mechanisms between erosion and soil thinning (truncation) can alter erodibility over time, as subsoil horizons with different physical properties become exposed (Batista et al., 2023).

Therefore, the prevalence of high-K soils across multiple soil types in Poboya underscores the compounded risk posed by land-cover change (e.g., mining, settlement) and topographic factors. It emphasizes the urgent need for conservation measures such as re-vegetation, soil structure stabilization, and controlled land use especially in steeper, highly erodible zones.

Slope Length and Steepness Index (LS)

The LS analysis reveals that the Poboya Watershed is predominantly composed of steep (25–45%) and very steep (>45%) slopes, covering approximately 91% of the total area. These slope categories exhibit LS values ranging from 6.8 to 9.5, significantly higher than those observed in flat or gently sloping terrains (0.4–1.3). Such topographic dominance indicates a strong gravitational and hydrological force, which greatly enhances runoff velocity and sediment transport capacity (Wischmeier & Smith, 1978; Renard et al., 1997).

High LS values have been widely demonstrated as one of the most influential contributors to soil erosion, especially in mountainous tropical watersheds. Studies in Ethiopia and India show that steep slopes with LS > 7 consistently generate disproportionately high erosion rates due to the combined effect of slope gradient, slope length, and flow accumulation (Gashaw et al., 2017; Karamage et al., 2020). Similar findings were also reported in Southeast Asia, where steep forested and mined landscapes experienced accelerated soil loss when vegetation cover was disturbed (Phuong et al., 2019).

Although the majority of these very steep lands in Poboya are unsuitable for agriculture, many have been converted for small-scale gold mining and land clearing. Such disturbances remove protective vegetative cover, reduce soil cohesion, and expose highly erodible surfaces, thereby amplifying soil detachment and mass movement risks (Borrelli et al., 2017; Panagos et al., 2020). The interaction between high LS, erodible soil, and declining vegetation creates a cumulative effect that severely increases erosion hazards, sediment yield, and landslide susceptibility across the watershed.

Given this condition, slope-specific conservation strategies such as terracing, controlled drainage, bioengineering, and slope stabilization are urgently required. Prioritizing these high-LS zones is essential to reduce downstream sedimentation and maintain ecological stability in the Poboya landscape.

Cover-Management Factor (C)

The C factor in the Poboya Watershed shows a high degree of spatial variability, ranging from 0.001 to 1.00**,** indicating substantial contrasts in vegetation structure, canopy density, and ground cover conditions. Primary forest dominates the landscape (52.73%) and is associated with an extremely low C = 0.001**,** emphasizing the protective role of intact forest cover in reducing raindrop impact, enhancing infiltration, and maintaining soil stability. Recent studies confirm that dense forest ecosystems significantly suppress soil erosion by improving organic matter accumulation and root reinforcement (Karamage et al., 2020; Li et al., 2023).

Shrubland, which occupies 43.22% of the watershed, has a moderate C = 0.05, reflecting partial protection but increased susceptibility when subjected to biomass removal or fire. Meanwhile, dryland agriculture (2.01%; C = 0.20) shows elevated erosion vulnerability due to periodic tillage and limited canopy cover during planting cycles. Similar patterns of high C values in cultivated uplands have been widely reported across Southeast Asia, particularly in smallholder systems where soil conservation measures are inconsistently implemented (Phinzi & Ngetar, 2019; Wijayanto et al., 2022).

Mining areas (0.19%) exhibit the highest C = 1.00**,** indicating total exposure of soil surfaces. The removal of vegetation and continuous disturbance create conditions conducive to splash erosion, gully initiation, and mass wasting processes. Evidence from recent tropical mining studies shows that landscapes with C values close to 1.00 contribute disproportionately to sediment yield and downstream siltation (Simatele et al., 2021).

Overall, the distribution of C values highlights the decline in ecological buffering capacity resulting from land-use change, particularly in disturbed or unmanaged areas. High-C zones represent priority targets for ecosystem-based interventions, including revegetation, agroforestry expansion, and erosion control through biological barriers.

Support Practice Factor (P)

The P factor across the watershed reflects the degree to which soil conservation practices are applied. The spatial pattern shows that primary forest, shrubland, and mining sites generally exhibit P = 1.0**,** indicating the absence of engineered soil conservation structures. This aligns with findings in other tropical watersheds where unmanaged slopes and unregulated mining intensify surface runoff and soil detachment (Vrieling et al., 2021).

In contrast, dryland agricultural areas demonstrate lower P values (P = 0.5–0.7), depending on the presence of contour farming or minimal soil conservation interventions. Although these measures reduce runoff velocity to some extent, their effectiveness remains limited when applied inconsistently or on steep slopes, as observed in numerous studies conducted in monsoonal and equatorial regions (Pham et al., 2020; Mandal et al., 2021).

The combination of high C and high P values in disturbed landscapes particularly mining zones and newly cleared lands creates erosion "hotspots" that require priority management. Strengthening conservation practices through terracing, mulching, vegetative contour strips, and check-dams is essential to reduce sediment yield from these high-risk areas.

Erosion Hazard Level (EHL)

Based on the analysis, the Poboya Watershed (7,376.65 ha) is classified into five EHL categories, ranging from very light to very severe. Spatial distribution shows that most of the watershed (56%) falls into the very light category, while only 0.7% is classified as very severe. The distribution is presented below:

Table 1. Erosion Hazard Levels in the Poboya Watershed

Class	**Area (ha)**	**Percentage (%)**	**Erosion Rate (ton/ha/year)**
Very Light	4,136.65	56%	< 15
Light	766.43	10%	15–60
Moderate	1,404.06	19%	60–180
Severe	1,017.67	14%	180–480
Very Severe	51.85	0.7%	> 480
Total	7,376.65	**100%**	

Overall, 75% of the Poboya Watershed is classified within the *very light to moderate* erosion hazard categories, indicating that the majority of the landscape still maintains a relatively stable ecological function due to the presence of primary/secondary forests and minimally disturbed land cover. This condition is consistent with erosion dynamics in tropical watersheds where forest-dominated catchments contribute to lower sediment detachment and runoff generation (Li et al., 2023; Karamage et al., 2020).

However, approximately 15% of the watershed, comprising the *severe and very severe* erosion classes, demonstrates a high vulnerability to soil loss. Although the proportion of very severe areas appears small, these zones exert disproportionate influence on watershed stability. Studies have repeatedly shown that severely eroded pockets—typically characterized by steep slopes, exposed soils, or mining-disturbed land—function as primary sediment sources, contributing up to 60–80% of total sediment yield despite occupying limited spatial extent (Borrelli et al., 2021; Mandal et al., 2021).

In the Poboya Watershed, these critical zones are generally associated with steep physiography, high LS values, and anthropogenic disturbances including artisanal gold mining and land clearing. Similar findings in tropical upland systems indicate that steep barren slopes accelerate mass wasting processes, rill–gully formation, and sediment connectivity, ultimately increasing downstream sedimentation and reducing river conveyance capacity (Simatele et al., 2021; Phinzi & Ngetar, 2019).

Therefore, the small but ecologically significant fraction of *very severe* erosion areas represents management priority hotspots. Immediate intervention—such as vegetative rehabilitation, erosion barriers, and post-mining ecological restoration—is crucial to prevent further degradation and mitigate the downstream impacts of excessive sediment transport. As emphasized in recent watershed management literature, targeted restoration of critical erosion hotspots yields the highest reduction in sediment loads relative to investment compared to blanket conservation measures (Pham et al., 2020; Vrieling et al., 2021).

Analysis of Erosion Hazard Classes

a. Very Light Class

This class dominates the watershed, covering 4,136.65 ha (56%). The erosion rate (<15 ton/ha/year) is below the soil loss tolerance threshold for most Indonesian soils (typically 30 ton/ha/year). This condition indicates that areas in this category likely have good vegetation cover such as primary/secondary forests or well-managed land serving as essential buffers for watershed ecosystem integrity. Maintaining these areas is crucial for long-term sustainability.

b. Light Class

This class covers 766.43 ha (10%) with erosion rates of 15–60 ton/ha/year. Although still relatively controlled, the values exceed the tolerance threshold for shallow or fine-textured soils. Light erosion often occurs in dryland agricultural areas or sparse shrublands. Without proper management, these areas may transition into the moderate or severe categories.

c. Moderate Class

Moderate erosion covers 1,404.06 ha (19%) with rates of 60–180 ton/ha/year. Soil loss at this level is significant enough to reduce soil fertility, deplete nutrients, and increase river sedimentation. These areas are typically located on steep to very steep slopes with shrubland or dryland agriculture lacking conservation measures. Active soil conservation interventions are urgently needed.

d. Severe Class

The severe category occupies 1,017.67 ha (14%) with erosion rates of 180–480 ton/ha/year—far exceeding soil loss tolerance. These highly degraded areas are commonly found on steep slopes with erodible soils (e.g., Distric Cambisol) and regions undergoing forest conversion. Human activities, including mining, significantly contribute to elevated erosion in this class.

e. Very Severe Class

Although limited to 51.85 ha (0.7%), areas with erosion rates >480 ton/ha/year represent critical points within the Poboya Watershed. Such extremely high erosion suggests bare land on very steep slopes. These areas are generally unproductive for agriculture and highly prone to landslides and flash floods due to elevated sediment supply to river systems.

CONCLUSION

This study provides a comprehensive assessment of the spatial dynamics of erosion risk in the Poboya Watershed by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), and land-use management (CP). The results collectively demonstrate that erosion potential in the watershed is predominantly governed by the interaction between intense rainfall in upper catchment areas, highly erodible soils, steep physiography, and rapidly changing land cover. Although areas with low to moderate rainfall dominate the landscape, the medium-rainfall zones located mainly in upper and steeper terrain produce disproportionately high erosive energy, making them critical contributors to sediment yield.

Soil characteristics further amplify this vulnerability. The dominance of Distric Cambisol, with its inherently high erodibility (K = 0.28), combined with the presence of other moderately erodible soil groups, indicates that much of the watershed is naturally predisposed to degradation. Human disturbances, particularly settlement expansion and artisanal gold mining, exacerbate soil instability, reflected in the highest K values recorded in disturbed areas. These findings highlight the strong influence of anthropogenic pressures in accelerating land degradation, especially when vegetative cover is significantly reduced.

Topography plays a central role in shaping erosion patterns. With 91% of the watershed classified as steep to very steep, LS values are exceptionally high, intensifying surface runoff and sediment mobilization. Such terrain is intrinsically unsuitable for agriculture or settlements, yet land clearing and mining activities are widespread. This mismatch between land capability and land use creates a compounded erosion effect, reinforcing the urgency for landscape-level corrective measures.

The separation of C and P factors reveals a clear relationship between land-cover disturbance, absence of conservation practices, and increased erosion susceptibility. Mining sites and dryland agricultural zones represent critical erosion hotspots due to their high C and P values, while primary forests serve as the most effective natural erosion buffer. These findings underscore the need for spatially targeted erosion mitigation strategies, post-mining rehabilitation, and landscape-scale restoration to improve watershed resilience.

The Erosion Hazard Level (EHL) classification shows that although 75% of the watershed falls within very light to moderate erosion classes, approximately 15% of the area is categorized as highly vulnerable (severe to very severe). Despite its small spatial proportion, the very severe class represents ecological hotspots with extreme erosion rates (>480 ton/ha/year) and substantial downstream impacts.

Overall, this study underscores the urgent need for integrated watershed management focused on restoring vegetation cover, enforcing land-use regulations, rehabilitating mined areas, and implementing soil conservation practices—particularly in steep upper catchments. These interventions are essential to reduce sediment yield, protect downstream ecosystems, and enhance the long-term sustainability of the Poboya Watershed.

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