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INTEGRATING USLE AND GIS TECHNIQUES FOR SOIL EROSION HAZARD MAPPING IN IJO WATERSHED

Afrilia Nur Fajriyah; Gangsar Edi Laksono; Eko Ahmad Riyanto; Arianti Mutia Ningrum; Fajar Firmansyah

Environmental Science, Department of Science and Technology, Universitas Islam Negeri Profesor Kiai Haji Saifuddin Zuhri Purwokerto, Indonesia

Author Correspondence: eko.ahmad.r@uinsaizu.ac.id

ABSTRACT

Soil erosion is a critical form of land degradation, particularly in tropical watersheds characterized by high rainfall intensity and steep topography. This study aims to assess erosion hazard levels in the Ijo Watershed, Central Java, Indonesia, by integrating the Universal Soil Loss Equation (USLE) with Geographic Information System (GIS) techniques. Five USLE factors—rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover (C), and conservation practice (P)—were analyzed using multi-source data, including rainfall records, soil maps, Digital Elevation Model (DEM), land cover maps, and field surveys. Results show that erosion hazard ranges from very low to very high, with the largest proportion in the very low category (35.09%) and the smallest in the very high category (8.74%). Areas with steep slopes and minimal conservation practices were identified as priority zones for intervention. The novelty of this study lies in applying the USLE–GIS approach to a small tropical watershed, which remains understudied despite its ecological and socio-economic importance. The findings not only fill knowledge gaps on erosion dynamics in small-scale watersheds but also provide scientific evidence for spatially explicit land management and conservation strategies. This contributes directly to Sustainable Development Goals (SDG 15) and Indonesia's Land Degradation Neutrality (LDN) targets.

KEYWORDS

soil erosion; watershed management; USLE; GIS; land conservation planning

ARTICLE HISTORY

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INTRODUCTION

Soil erosion is one of the most severe forms of land degradation, with profound implications for environmental sustainability and human well-being. Globally, about 75 billion tons of soil are lost annually due to erosion, with nearly 80% occurring in developing countries in tropical and subtropical regions (FAO, 2019). Soil erosion significantly impacts agriculture, leading to various environmental, economic, and social consequences: loss of top soils (Seitz et al., 2020; Weslati & Serbaji, 2024; Yustika et al., 2021), water pollution (Assouline et al., 2017; Boardman, 2021; Rashmi et al., 2022), carbon emissions (Kumar, 2020), reduced agriculture productivity (Bhandari & Darnsawasdi, 2013), food security and increased production cost (Quinton & Fiener, 2024; Seitz et al., 2020; Shaw Reid, 2015).

In Indonesia, high rainfall intensity and complex topography make soil erosion one of the most critical environmental challenges. The Ministry of Environment and Forestry reported that more than 14 million hectares of land are classified as critical, primarily due to erosion (Decree of the Minister of Environment & Forestry No. 306 Concerning the Determination of National Critical Land, 2018). Central Java, including the Ijo Watershed, is highly vulnerable due to the combination of steep slopes, intensive rainfall, and unsustainable land-use practices. Such conditions directly threaten local agricultural productivity and watershed ecosystem balance.

The Universal Soil Loss Equation (USLE), developed by Wischmeier and Smith (1978), remains widely applied for soil erosion assessment worldwide. Its simplicity and adaptability, especially when combined with GIS and remote sensing, make it an effective tool for spatial erosion hazard mapping (Ganasri & Ramesh, 2016). Recent global studies highlight the increasing significance of soil erosion under climate and land-use change (Borrelli et al., 2020; Panagos et al., 2017)

Previous studies in large Indonesian watersheds, such as Brantas, Citarum, and Solo, confirm that rainfall, soil type, slope, and land cover strongly influence erosion dynamics (Indarto, 2019; Kardhana et al., 2024; Karina, 2017). However, research on small-scale watersheds such as Ijo remains limited, even though they play critical ecological roles as buffers for local communities and are often more vulnerable to anthropogenic pressures. Moreover, most studies emphasize quantification of erosion without adequately linking results to conservation policy and long-term watershed management.

This study addresses this knowledge gap by applying the USLE–GIS approach to the Ijo Watershed, aiming to quantify erosion hazard, map its spatial distribution, and provide policy-relevant recommendations for soil and water conservation.

RESEARCH METHODS

1. Research Design and Study Area

A spatially based quantitative approach was employed, integrating the USLE model with GIS. The USLE estimates annual average soil loss using rainfall, soil, slope, land cover, and conservation practice factors. GIS facilitated spatial data integration, overlay analysis, and erosion hazard mapping.

The study was conducted in the Ijo Watershed, located in Central Java, Indonesia, an area characterized by high rainfall, diverse land use, and steep topography that makes it particularly vulnerable to erosion. Administratively, the watershed spans several sub-districts and plays a critical role in supporting local agriculture and water resources.

Watershed boundaries were delineated using the official Watershed Map issued by the Ministry of Environment and Forestry (KLHK), which provides nationally standardized delineation of watershed units. The Ijo Watershed exhibits diverse land uses, ranging from forest and shrubland in upper catchments to plantations and intensive agriculture on mid- and lower-slopes. Steep slope gradients (>25%) are concentrated in the upper watershed, while lowland areas are dominated by settlements and irrigated paddy fields. This combination of steep slopes, high rainfall intensity, and agricultural pressure makes the watershed highly susceptible to soil erosion.

The spatial extent and boundary of the study area are shown in Figure 1, which also illustrates administrative units and the river network that drains the watershed.

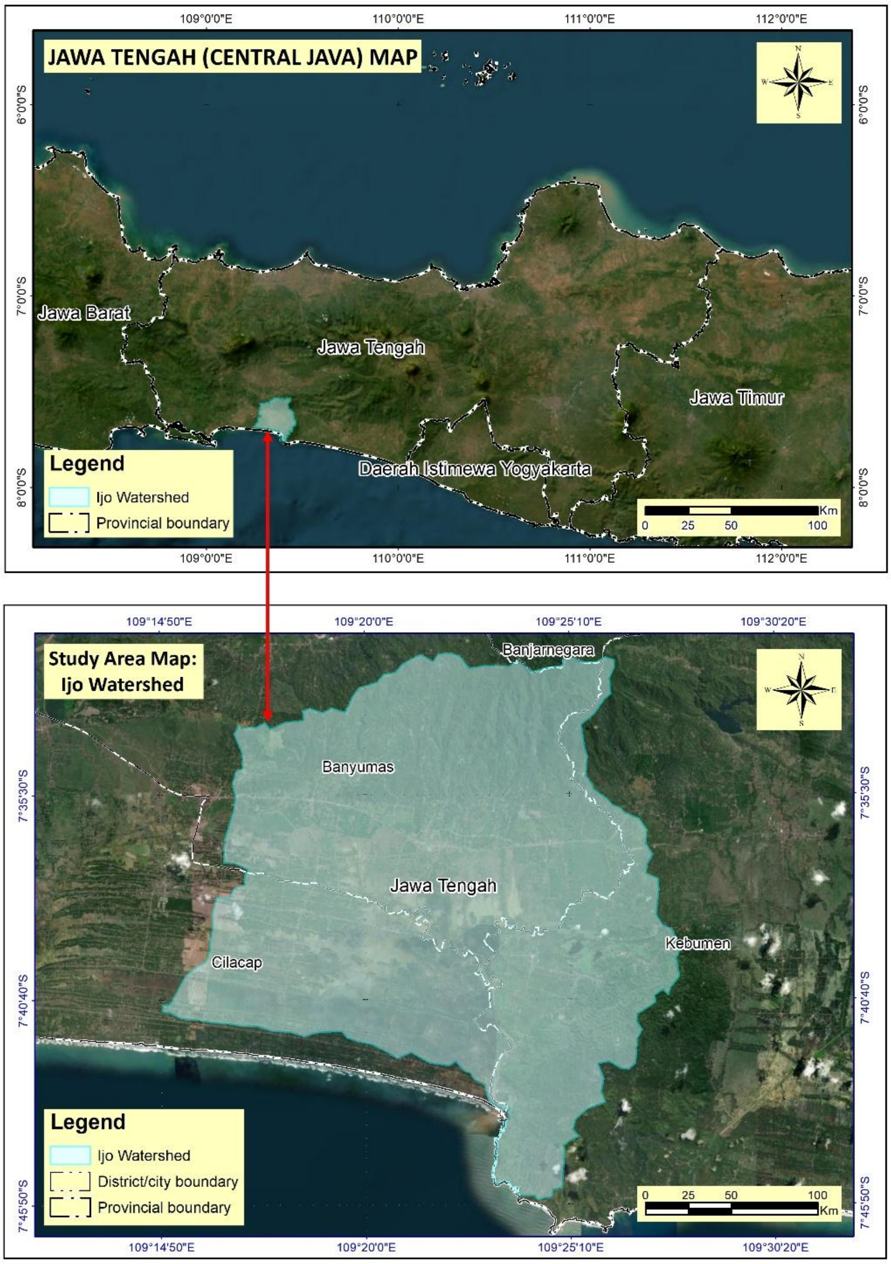

Figure 1. Location map of the Ijo Watershed (boundary delineated based on KLHK Watershed Map)

2. Data Collection

a. Rainfall erosivity (R): Derived from Rainfall data for the Ijo and Serayu watersheds the Serayu-Opak-Progo Watershed Management Agency in 2023

b. Soil erodibility (K): Obtained from the Central Java soil map from Geospatial Information Agency

c. Slope length and steepness (LS): Derived from SRTM DEM (30 m).

d. Land cover and conservation practice (CP): Based on 2019 land cover maps from Geospatial Information Agency.

The DEM resolution (30 m) may not capture micro-topographic details. Land cover data (2019) may not fully represent 2024 conditions; however, field survey verification was conducted. Future research should employ higher-resolution DEMs (e.g., DEMNAS, LiDAR) and incorporate land-use dynamics.

3. Data Analysis

Erosion rate was estimated using the USLE formula:

$$A = R \times K \times LS \times CP \qquad 1$$

Where A is annual soil loss (t/ha/yr). Spatial processing used ArcGIS 10.8. Erosion hazard was classified following the Ministry of Forestry (1988) shown Table 1.

Table 2. Soil Erosion Hazard Class

Class	Erosion Rate (t/ha/year)	Erosion Hazard Class
I	< 15	Very slight
II	15 – 60	Slight
III	60 – 180	Moderate
IV	180 – 480	Severe
V	> 480	Very severe

Source: Ministry of Forestry (1988)

RESULTS AND DISCUSSION

1. Spatial Distribution of Erosion Hazard

The spatial analysis of soil erosion hazard in the Ijo Watershed, derived from the integration of USLE factors in a GIS environment, reveals a wide variation ranging from *very slight* to *very severe* erosion classes. The classification follows the Ministry of Forestry (1988) standards and is presented in **Table 2,** while the spatial distribution across the watershed is illustrated in **Figure 2.**

Table 2. Distribution of Soil Erosion Hazard in the Ijo Watershed

Erosion Hazard Class	Erosion Rate (t/ha/year)	Area Proportion (%)	Characteristics
Very slight	< 15	35,09	Forest and shrubland areas with dense vegetation cover.
Slight	15 – 60	24,21	Moderately covered land, e.g., plantations.
Moderate	60 – 180	16,30	Agricultural land with limited vegetation.
Severe	180 – 480	15,63	Steep slopes with minimal conservation practices
Very severe	> 480	8,74	Bare land and steep terrain without conservation; highly critical areas.

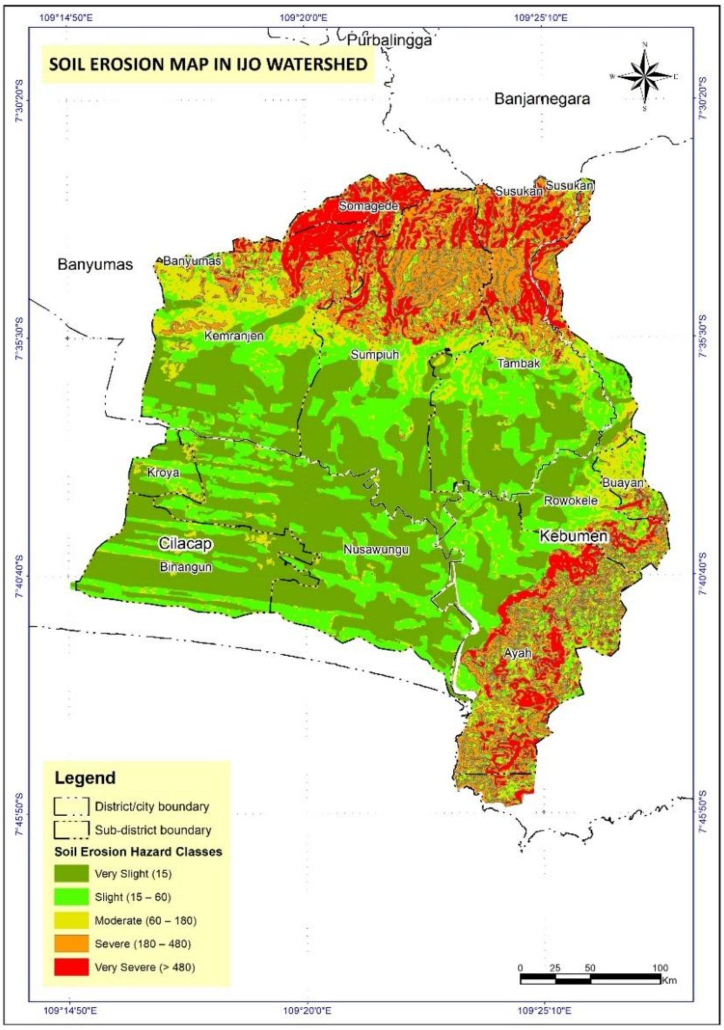

Figure 2. Soil erosion hazard map of the Ijo Watershed derived from USLE–GIS integration, classified into five hazard categories (very slight to very severe). The map highlights high-priority conservation zones, particularly in the northern and southeastern parts of the watershed.

The results indicate that the largest share of the watershed area, 35.09%, falls under the very slight erosion class (<15 t/ha/year). These zones are predominantly located in forested and shrubland areas, where dense vegetation provides effective soil protection. The slight erosion class (15–60 t/ha/year) accounts for 24.21% of the watershed, commonly observed in plantation areas with moderate canopy cover.

In contrast, moderate erosion (60–180 t/ha/year) covers 16.30%, mainly distributed in open agricultural lands with minimal ground cover. The severe erosion class (180–480 t/ha/year), representing 15.63%, is concentrated in steeply sloping areas with limited or poorly maintained conservation measures. Most concerning is the very severe erosion category (>480 t/ha/year), which accounts for 8.74% of the watershed and is concentrated in the northern sub-districts (Somagede, Susukan) and southeastern slopes (Ayah, Buayan). These zones are characterized by steep topography, erodible soils, and intensive land use without conservation practices, making them highly vulnerable to land degradation.

The spatial distribution presented in Figure 3 clearly demonstrates the contrast between the central and western parts of the watershed, which are relatively stable (dominated by very slight and slight classes), and the northern and southeastern areas, which are critical hotspots of erosion (severe to very severe classes). This pattern mirrors findings in other tropical watersheds, such as the Brantas Upper Watershed (Nugroho et al., 2019) and global assessments by Borrelli et al. (2021), both of which highlight the synergistic role of steep slopes, fragile soils, and intensive land use in accelerating soil erosion.

Overall, the combined extent of the severe and very severe classes amounts to more than 24% of the watershed, representing thousands of hectares of productive agricultural land at high risk of degradation. This proportion underscores the urgent need for targeted soil and water conservation interventions, particularly in highland farming areas and critical slope zones, to safeguard agricultural productivity and reduce downstream impacts such as sedimentation, flooding, and reservoir siltation.

2. Factors Influencing Erosion

The spatial analysis indicates that erosion hazard in the Ijo Watershed is shaped by the interplay of several critical factors, namely rainfall intensity, slope characteristics, land cover types, and conservation practices. These factors interact multiplicatively in the USLE framework, producing distinct erosion patterns across the watershed.

The factor maps (Figure 3) provide insights into the spatial drivers of erosion in the Ijo Watershed. Rainfall erosivity (R) is highest in the northern part of the watershed, where annual rainfall intensity exceeds 1,900 MJ mm/ha/h/year, significantly increasing erosive power. Soil erodibility (K) varies across the watershed, with the southern section showing higher values (>0.3), indicating soils with lower aggregate stability and higher susceptibility to detachment. The slope length and steepness factor (LS) reaches maximum values (>9.0) in the upper and eastern catchments, where terrain is rugged and slopes exceed 25%. The CP factor reflects land cover and conservation practices: forested areas in the west and central watershed exhibit very low CP values (close to 0), whereas upland agriculture and settlements in the southeast and north show CP values near 1.0, indicating minimal conservation. These spatial patterns highlight the multiplicative effect of rainfall, slope, soil, and land cover on erosion processes.

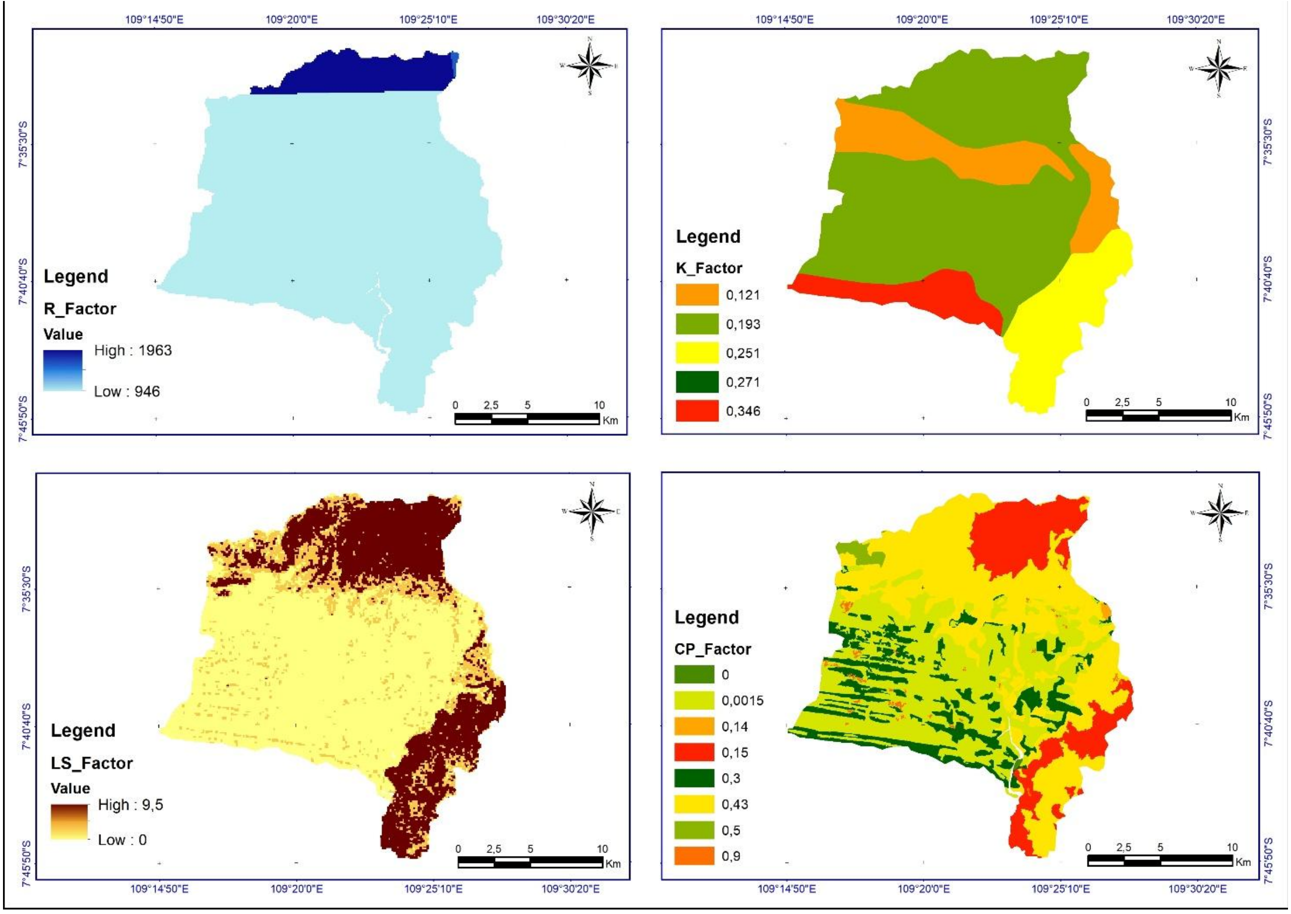

Figure 3. Spatial distribution of USLE factors in the Ijo Watershed: (a) rainfall erosivity (R factor), (b) soil erodibility (K factor), (c) slope length and steepness (LS factor), and (d) land cover and conservation practices (CP factor). These maps illustrate the spatial heterogeneity of erosion drivers across the watershed.

Rainfall is the primary driver of erosivity in tropical regions, where high-intensity storms can mobilize large volumes of soil. In the Ijo Watershed, the high annual rainfall contributes significantly to the erosivity index. Field observations confirmed that during peak rainy seasons, surface runoff increases dramatically on agricultural slopes, generating rill and sheet erosion. This finding aligns with global research by Panagos et al. (2017), which emphasized the growing contribution of extreme rainfall events to global erosivity. The implication is that climate change, with projections of more frequent heavy storms in Indonesia, may further intensify soil erosion in Ijo unless adaptive conservation practices are implemented.

Topography plays a decisive role in erosion hazard. The Ijo Watershed is characterized by extensive areas with slopes exceeding 25%, particularly in its upper catchments. These steep terrains were consistently classified within high to very high erosion categories. Long slope lengths also accelerate runoff velocity, reducing water infiltration and enhancing soil detachment. This pattern corresponds with Indarto (2019), who documented that slope steepness was the most dominant factor influencing erosion in the Brantas Upper Watershed. In the Ijo case, slope effects often override the protective role of moderate vegetation cover, meaning that even plantations with partial canopy can suffer from high erosion rates when located on steep terrain.

Land cover exerts strong control over erosion through canopy interception, root reinforcement, and surface protection. Forests and dense shrubs in Ijo are associated with very low erosion rates, confirming their role as natural buffers. Conversely, open agricultural land and upland farming areas show moderate to very high erosion hazards. Interestingly, plantation areas that are generally expected to have lower C-factor values still showed high erosion rates, particularly on steep slopes with sparse undergrowth. This suggests that monoculture plantations without ground cover vegetation provide insufficient erosion protection. Similar outcomes were reported by Borrelli et al. (2023), who noted that intensively managed croplands and poorly managed plantations are among the most erosion-prone land uses globally.

The absence or presence of soil conservation measures significantly modifies erosion risk. In the Ijo Watershed, many agricultural plots, particularly on steep slopes, lack adequate conservation structures such as terraces, bunds, or vegetative strips. This situation results in P-factor values approaching 1, amplifying the erosive potential of rainfall and slope conditions. Field surveys found only limited application of contour farming and terracing, often poorly maintained. Comparative studies in Southeast Asia (e.g., Ganasri & Ramesh, 2016) have shown that effective conservation practices can reduce erosion rates by more than 50%, underscoring the missed opportunity in Ijo for erosion control.

The results demonstrate that erosion cannot be attributed to a single variable but emerges from the combined influence of rainfall, slope, land cover, and conservation. For example, agricultural land on flat terrain with proper conservation showed only low erosion, despite high rainfall. In contrast, steep-slope agriculture without conservation was classified as very high hazard, even when rainfall was moderate. This interaction validates the multiplicative nature of the USLE equation and highlights the need for integrated watershed management.Anomalies, such as plantations classified as high erosion, suggest slope effects override vegetation cover when conservation measures are absent. This supports the multiplicative nature of USLE.

3. Discussion

The erosion hazard assessment in the Ijo Watershed reveals a spatially heterogeneous pattern, with 35.09% of the area classified as very low erosion and 8.74% as very high erosion. This result is consistent with findings from other tropical watersheds, where forested areas are associated with lower erosion, while steep slopes with agricultural expansion and poor conservation practices exhibit higher erosion risk (Ganasri & Ramesh, 2016; Indarto, 2019). However, compared to Ethiopian highland studies (Kebede et al., 2021), where moderate erosion was dominant, the Ijo Watershed still maintains relatively large areas of very low erosion, highlighting the ecological function of remnant forest cover in buffering soil loss.

At the global scale, erosion dynamics are increasingly influenced by climate variability and anthropogenic land-use change (Yaswanth et al., 2022). Borrelli et al. (2020) projected that under business-as-usual land-use trajectories, global soil erosion could increase significantly by 2070. Similarly, Panagos et al. (2017) emphasized the role of extreme rainfall events in accelerating erosivity worldwide. The dominance of very high erosion hazard zones (24% of the watershed in high to very high categories) underscores the relevance of these global trends at the local scale of Ijo. It suggests that small tropical watersheds may act as "hotspots" of land degradation, particularly when conservation measures are

The erosion hazard map provides a spatial decision-support tool for watershed management. Zones classified as high and very high should be prioritized for soil and water conservation. Recommended interventions include mechanical measures such as terracing and check dams, vegetative measures such as reforestation and cover crops, and land-use zoning that restricts cultivation on steep slopes. Beyond technical measures, integration with policy frameworks is critical. The findings directly support Indonesia's National Action Plan for Land Degradation Neutrality (LDN) under UNCCD commitments and align with SDG 15.3, which calls for halting and reversing land degradation by 2030.

The strength of this study lies in integrating multi-source data (rainfall, soils, DEM, land cover, and field surveys) with GIS, producing spatially explicit erosion hazard maps. Such integration improves representativeness compared to studies relying solely on secondary data. However, limitations remain. The 30 m DEM resolution restricts micro-topographic detail essential for small-scale watershed analysis. Land cover data from 2019 may not capture recent dynamics, despite field verification in 2024. Moreover, no sensitivity analysis of USLE factors was conducted, which could have provided insight into the relative contribution of slope, rainfall, or conservation practices to total erosion.

Future studies on small tropical watersheds should move beyond static erosion assessments by employing higher-resolution DEMs (e.g., LiDAR or DEMNAS 8 m) to capture micro-topographic variations more accurately, while also incorporating temporal land-use dynamics and climate variability scenarios to reflect changing environmental conditions. In addition, factor sensitivity analysis is necessary to identify the most influential drivers of erosion and thereby prioritize conservation strategies more effectively. Integrating socio-economic assessments, particularly quantifying the impacts of erosion on agricultural productivity, food security, and rural livelihoods, will also enhance the policy relevance of erosion hazard studies. Finally, longitudinal monitoring to evaluate the effectiveness of implemented conservation practices would provide valuable insights for adaptive watershed management and strengthen the scientific basis for achieving Land Degradation Neutrality and related SDG targets.

CONCLUSION

This study demonstrates that soil erosion hazard in the Ijo Watershed ranges from very low to very high, with 24% of the area requiring priority conservation. Steep slopes, high rainfall, open land use, and limited conservation practices are the main drivers of erosion.

This research applies USLE–GIS to a small tropical watershed, filling gaps in erosion hazard studies at this scale in Indonesia. The spatial erosion hazard map provides a decision-making tool for land-use zoning, watershed conservation, and sustainable agricultural planning. Integration into local government planning and national LDN strategies is strongly recommended. Future research should adopt higher-resolution DEMs, dynamic land-use data, climate variability scenarios, and socio-economic assessments of erosion impacts.

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