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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

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Soil erosion is widely recognized as one of the most severe environmental problems affecting terrestrial ecosystems, especially in highland regions that are subject to intense rainfall and rapid land-use changes (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Globally, anthropogenic activities have accelerated the rate of erosion, with annual soil losses estimated to reach approximately 75 billion tons (Singh et al. 2023). This scale of degradation highlights both ecological and socio-economic consequences, considering that soil is effectively a non-renewable resource within a human time frame. The impacts of soil erosion extend far beyond the immediate degradation of land and natural ecosystems. They directly affect agricultural productivity, rural livelihoods, and food security (Antronico et al. 2020; Hishamunda et al. 2024).

Steep slopes magnify these processes by increasing runoff velocity and shear stress, thereby intensifying soil detachment and transport (Zhu et al. 2024). However, beyond these natural drivers, human activities significantly exacerbate erosion risks. Unsustainable land use, poor agricultural practices, deforestation, and limited awareness of conservation all contribute to accelerating land degradation (Panagos et al. 2016). These combined pressures also produce downstream consequences such as sediment accumulation in rivers, reduced water storage capacity, and increased flood risks (Kardhana et al. 2024).

The economic costs associated with soil erosion are equally daunting. Globally, remediation and rehabilitation expenses covering agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually (Carollo et al. 2023, 2024; Panagos et al. 2015). Developing countries are disproportionately affected, as limited financial and institutional resources make it difficult to implement comprehensive soil conservation programs (Molla & Sisheber 2017). This makes targeted and cost-effective erosion management strategies an urgent priority.

Efforts to assess, map, and model soil erosion have therefore become increasingly important at multiple spatial scales. Reliable estimation of soil loss is critical for spatial planning, watershed management, and the formulation of effective conservation policies (Alewell et al. 2019). Among the various approaches, the Universal Soil Loss

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Equation (USLE) is one of the most widely adopted empirical models for predicting long-term soil erosion. The model integrates five principal factors rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) to estimate annual soil loss (Ferro 2010; Li et al. 2024). Despite its empirical basis, the USLE remains relevant because of its adaptability, simplicity, and proven effectiveness across diverse landscapes.

Advancements in Geographic Information Systems (GIS) have further enhanced the applicability of USLE by providing powerful tools for integrating spatial datasets, performing terrain analysis, and mapping erosion risk across heterogeneous environments (Brychta et al. 2022). The integration of USLE and GIS allows researchers and policymakers to identify erosion hotspots, quantify soil loss potential, and prioritize areas for conservation interventions in a cost-efficient and spatially explicit manner.

These issues are particularly evident in the Tirtomoyo sub-watershed (Wonogiri–Pacitan), which features varied topography from gentle to steep slopes. Intensive land use agriculture, deforestation, and settlements has increased erosion risk by over 50% (Tian & Lan, 2023). Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

A key research gap remains, as most erosion studies in Indonesia focus on larger watersheds or reservoir sedimentation, overlooking spatial variability in smaller sub-watersheds like Tirtomoyo. Existing studies are often descriptive and rarely quantify soil loss across land units. Additionally, limited use of GIS-based USLE modeling at this scale hinders the development of targeted conservation strategies.

This study applies a GIS-based USLE model in the Tirtomoyo sub-watershed to: (1) estimate potential soil loss, (2) map erosion risk, and (3) identify conservation priority areas. The results support integrated watershed management, sustainable land use, sedimentation control, and mitigation of land degradation.

MATERIALS AND METHODS

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Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km². The area forms part of the Bengawan Solo River Basin and serves as an important agricultural and residential zone. The sub-watershed is characterized by a highland landscape with elevation ranging from 150 to 900 m a.s.l. and slope gradients varying from 0–45%.

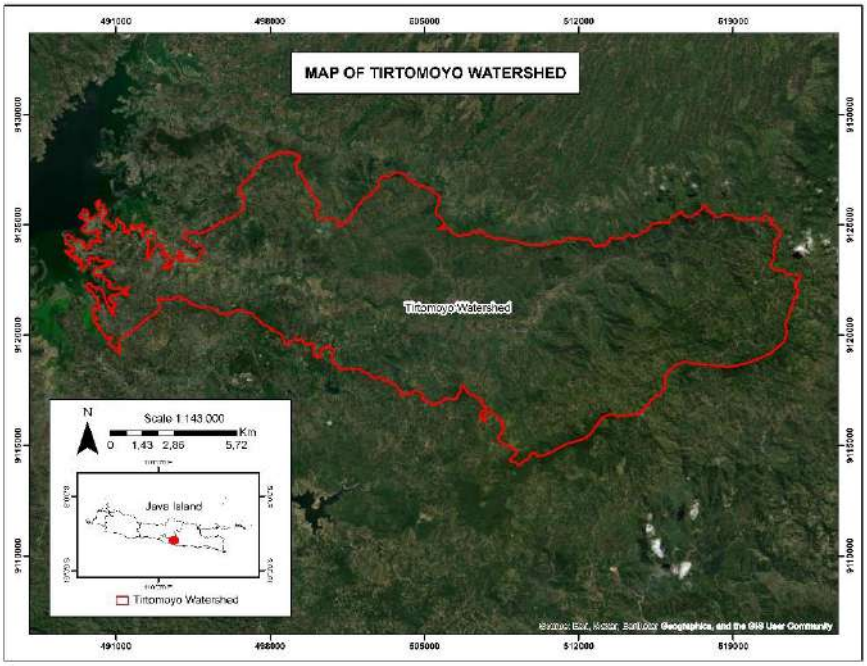

Figure 1. Location of Tirtomoyo Watershed

Data Collection

This study applied a GIS-based USLE to estimate spatial soil loss and identify conservation priority areas. USLE was chosen over RUSLE due to limited rainfall intensity and temporal data, and remains suitable for medium-scale, long-term erosion analysis. The model integrates five factors as follows:

A: R x K x LS x C x P

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at

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four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical equation:

$$IR: 2.21 \times P^{1.36}$$

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following equation:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate

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Erossion Classs	Erossion (ton/ha/tahun)	Class
IV	180-480	Severe
V	>480	Very severe

Source : USDA

Soil erosion is classified into five categories based on annual soil loss (tons/ha/year) following USDA standards. Class I (very light, <15) is tolerable with minimal impact; Class II (light, 16–60) shows early degradation but can be controlled with simple measures; Class III (moderate, 60–180) indicates significant fertility loss without conservation; Class IV (severe, 180–480) reflects serious degradation with rapid topsoil loss; and Class V (very severe, >480) represents extreme degradation requiring intensive and sustained conservation efforts.

Data analysis

Data analysis in this study used Land Mapping Units (LMUs) as the primary unit, each defined by a combination of geomorphology, soil type, slope, and land use. A total of 33 distinct LMUs were identified in the Tirtomoyo watershed (Figure 2). This spatial approach allows for more representative analysis than administrative boundaries, as it better captures biophysical variability.

A land unit is an area with relatively uniform characteristics that can be delineated on a map (FAO, 1976), typically based on landform, soil, slope, and land use. The number of land units reflects the diversity of land characteristics in a region. Previous studies have applied similar approaches with varying parameters, such as landform, soil, slope, land use, and geology (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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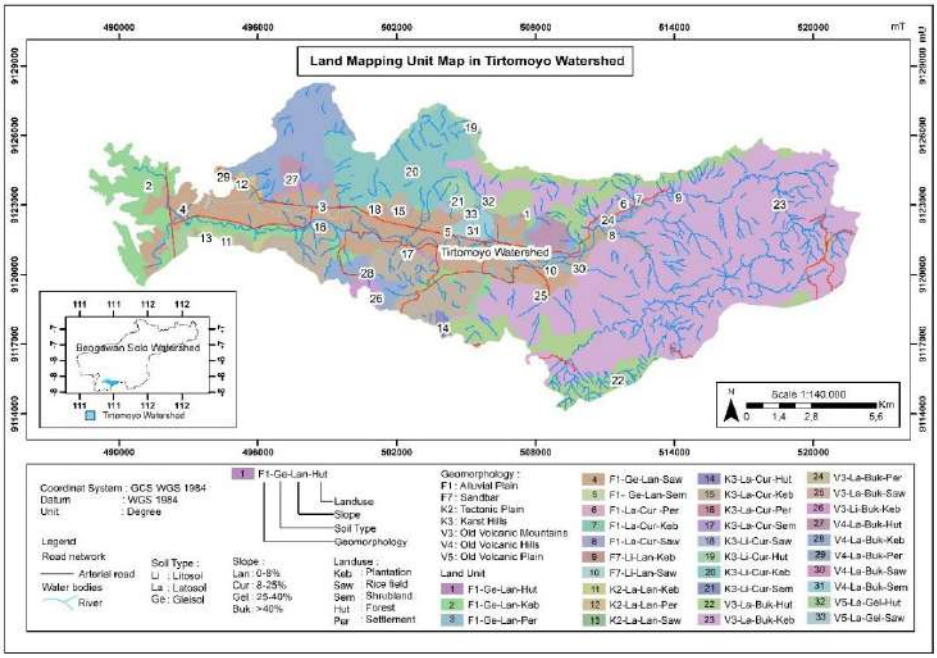

Figure 2. Land Mapping Units of the Tirtomoyo watershed

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor (R) in the Tirtomoyo watershed was conducted based on precipitation data from four main stations: Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan.

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The collected data indicate that the average annual rainfall in the area reaches 2,676.42 mm/year (Figure 3). The spatial variability of rainfall across the sub-watershed shows that rainfall intensity and distribution are uneven, resulting in differences in erosion risk among locations.

The annual rainfall of 2,676.42 mm has the potential to generate a high rainfall erosivity factor (R). Land units in the Tirtomoyo Sub-watershed that lack adequate vegetation cover or soil conservation practices tend to fall into the severe to very severe erosion classes (e.g., units F7-Li-Lan-Keb and F7-Li-Lan-Saw). Conversely, in land units with good conservation measures such as bench terraces or strip cropping, despite receiving the same rainfall, erosion levels are controlled within the very light to light classes (e.g., F1-Ge-Lan-Keb and V3-La-Buk-Saw). Land units managed under agroforestry generally show light to moderate erosion; however, on steep slopes and hilly landforms (such as V3-La-Buk-Hut and V3-La-Buk-Per), erosion still falls into the severe category, indicating that vegetation alone is insufficient to control surface runoff under high rainfall conditions.

High rainfall, particularly when it exceeds the soil's infiltration capacity, increases surface runoff volume. When rainwater cannot infiltrate the soil due to shallow or saturated conditions, it flows over the surface at high velocity. This flow transports detached soil particles, causing surface erosion (Liang et al. 2025). Therefore, the high rainfall in the Tirtomoyo watershed is a dominant factor contributing to soil loss potential and should be a primary consideration in land conservation efforts in the region.

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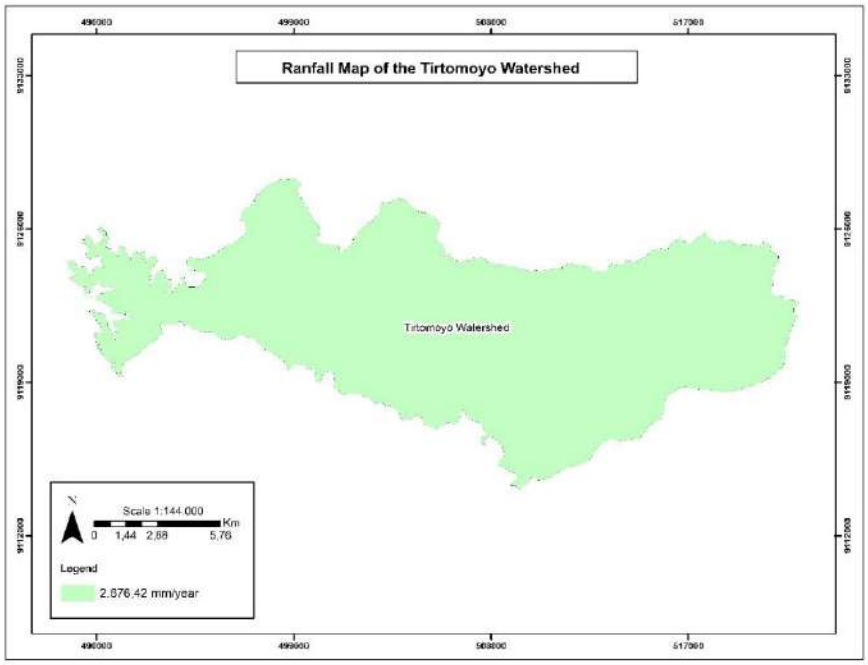

Figure 3. Rainfall Map of Tirtomoyo watershed

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 4). Based on Table 3, the land unit characteristics, there are variations in the values of M, organic matter content (BO), soil structure, and permeability that influence the degree of erosion susceptibility. The M values range from 162.03 to 2,233.41, where land with low M values (such as F1-Ge-Lan) tends to have finer textures and is relatively more resistant to erosion, while land with high M values (such as F1-La-Cur-Saw and F7-Li-Lan) indicates coarser textures that are more prone to erosion. Soil organic matter content also varies, ranging from 4.82% to 8.91%. Land with higher BO values, such as F7-Li-Lan and V3-Li-Buk, tends to be more fertile with more stable soil aggregates, thereby reducing erosion risk. In contrast, land with lower BO values (~4.82%), such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, has less stable aggregates that are more easily dispersed, thus increasing erosion susceptibility.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

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Source : data processing, 2025

In terms of soil structure, some land units have a value of 1 (poor/laminar structure), which raises the risk of degradation, whereas units with a value of 3 (good granular structure) are more stable. Soil permeability ranges from 4 (moderate–somewhat rapid) to 5 (rapid), where land with higher permeability (e.g., F7-Li-Lan and V3-Li-Buk) has better water infiltration capacity, thereby reducing surface runoff. Overall, the most erosion-prone land units are those with a combination of high M values, low BO, poor soil structure, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel. Conversely, land units with medium to high M values but supported by high BO, good soil structure, and rapid permeability, such as F7-Li-Lan and V3-Li-Buk, tend to be more resistant to erosion. However, despite the influence of organic matter, structure, and permeability, these areas remain in the severe category, showing that vegetation cover alone is insufficient to withstand high rainfall conditions. In particular, zones with dense clay soils and low permeability, such as point 2 and Litosol-dominated areas, have been identified as having high K-factor values and thus require conservation priority, since clay soils exacerbate erosion on steeper slopes (Luquin et al. 2025).

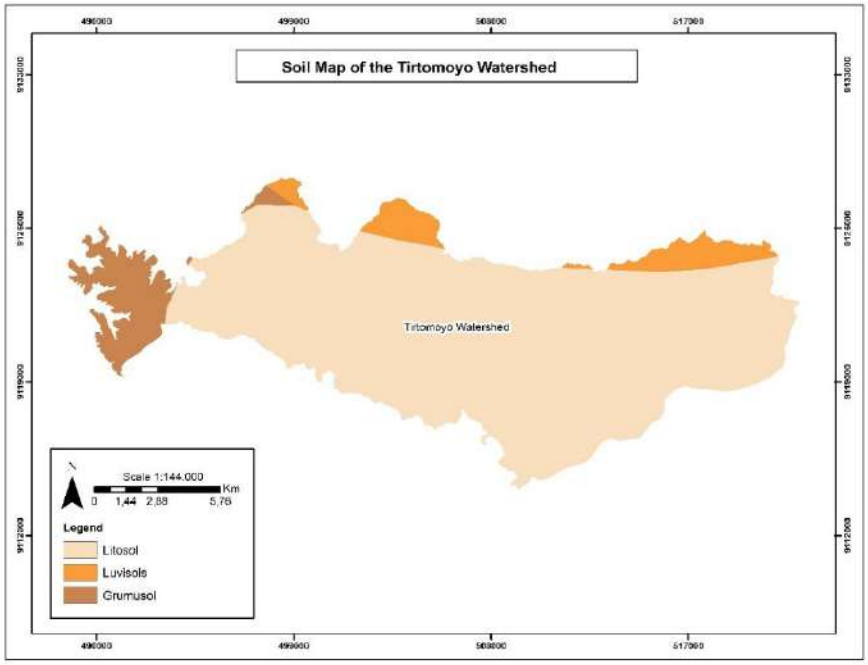

Figure 4. Soil Type Map of Tirtomoyo watershed

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Topographic Factor (LS)

Slope data in the Tirtomoyo Sub-watershed, derived from DEM analysis, show slope classes ranging from 0–8% to >45% (Figure 5), and these variations are directly reflected in the erosion classes of the 33 land units. Units located on steep to very steep slopes, especially in the eastern, central, and western sections, generally correspond to severe to very severe erosion classes, as seen in F7-Li-Lan-Keb and F7-Li-Lan-Saw, where slope gradients exceed 25% and generate high LS values that accelerate runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). By contrast, land units situated on gentle slopes (0–8%) in the central watershed tend to fall into very light or light erosion classes, such as F1-Ge-Lan-Keb and V3-La-Buk-Saw, where limited slope length and low gradients reduce erosive energy.

Areas with moderate slopes (10–35°) often show moderate erosion severity, particularly when conservation measures are absent or insufficient, as in some K3-La-Cur units, which aligns with observations that slopes in this range face elevated erosion risks (Pan et al. 2025). These findings confirm that slope gradient and length are decisive factors in shaping erosion severity, with high LS values amplifying soil loss in unmanaged steep terrain, while low LS values in flatter areas reduce erosion potential even under high rainfall. Identifying slope-driven hotspots using DEM data is therefore essential for prioritizing conservation in the Tirtomoyo Sub-watershed, as the steepest areas are consistently the main contributors to soil loss.

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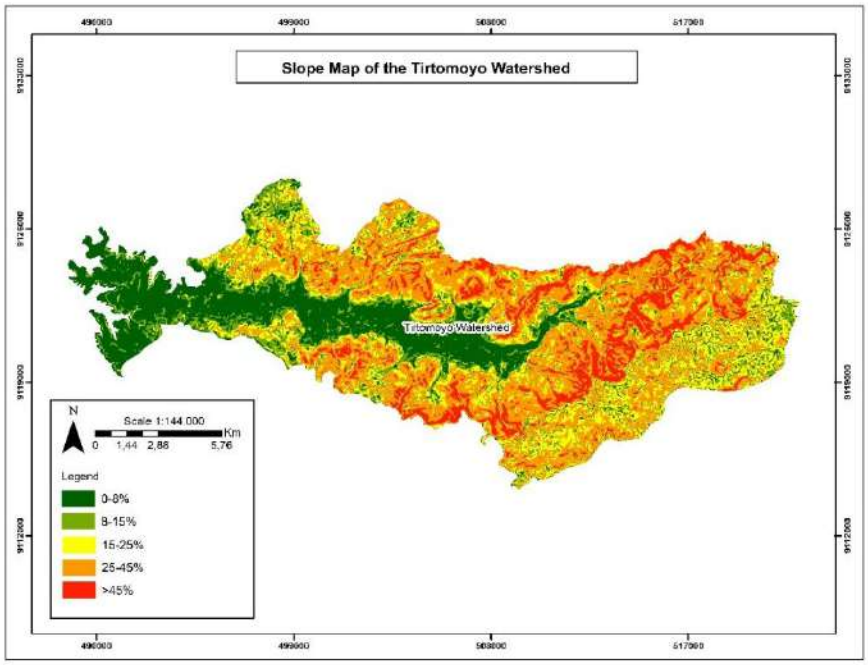

Figure 5. Slope Map of Tirtomoyo watershed

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak stands (*Tectona grandis*). Other crops such as rice, maize, banana, bamboo, elephant grass, and mango indicate that the area is largely utilized for forestry and agriculture (Figure 6). Teak provides relatively effective soil cover due to its deep roots and dense canopy, resulting in low C-factor values. In contrast, paddy fields and seasonal crops such as maize exhibit higher C values, particularly during the early planting season or when the land is left bare.

The C factor is determined by the capacity of a plant species or land cover to protect soil from the direct impact of raindrops and surface runoff. Dense vegetation cover, as in teak or bamboo, reduces the direct impact of rainfall on the soil surface and slows down surface flow. Well-developed root systems can control runoff and erosion in the short term (Mas et al., 2024).

Seasonal changes in vegetation, especially in agricultural land, lead to significant fluctuations in C-factor values. When the land is tilled or left fallow, the soil surface becomes more susceptible to erosion due to minimal protection. Areas with seasonal crops and crop rotations require special

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attention in soil conservation management, which can include mulching, cover crops, or agroforestry systems.

a

b

Figure 6. (a) *Zea mays L.* and (b) *Bambusoideae*

Conservation Practice Factor (P)

Various soil and water conservation practices, such as agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo sub-watershed; however, many areas remain without conservation measures. The presence of these techniques significantly influences the P factor in the USLE method. Practices such as bench terracing and strip cropping reduce surface flow velocity and enhance water infiltration into the soil, resulting in lower P values, which indicate higher erosion control efficiency. The sub-watershed is dominated by terracing on sloped land, forming stepped levels to reduce runoff velocity (Figure 7).

Areas lacking conservation measures have P values approaching 1, indicating no reduction in erosion risk through land management. This is a particular concern, as without conservation interventions especially in steep and high-rainfall areas soil erosion potential increases sharply. Mapping and classifying P values is therefore essential for informed decision-making in land conservation planning, particularly in priority areas with high erosion risk.

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Figure 7. Terracing Conservation Technique

Erosion Susceptibility of Tirtomoyo Sub-watershed

The table 4, shows that conservation methods significantly influence erosion outcomes: bench terraces and strip cropping are most effective on cultivated land, while agroforestry provides moderate protection but may require reinforcement on steep terrain. Units without conservation show the highest vulnerability, underscoring the importance of expanding soil and water conservation practices to reduce land degradation risks in the watershed.

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light

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Land Unit	C	Conservation Method	Class
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 8 illustrates the spatial distribution of erosion severity in the Tirtomoyo watershed, measured in hectares. The data indicate that moderate erosion dominates the area, covering approximately 10,386 ha, followed by mild erosion at 6,670 ha and very mild erosion at 2,953 ha. More severe erosion categories occupy smaller areas, with severe erosion covering 1,772 ha and very severe erosion being the least extensive at only 52 ha.

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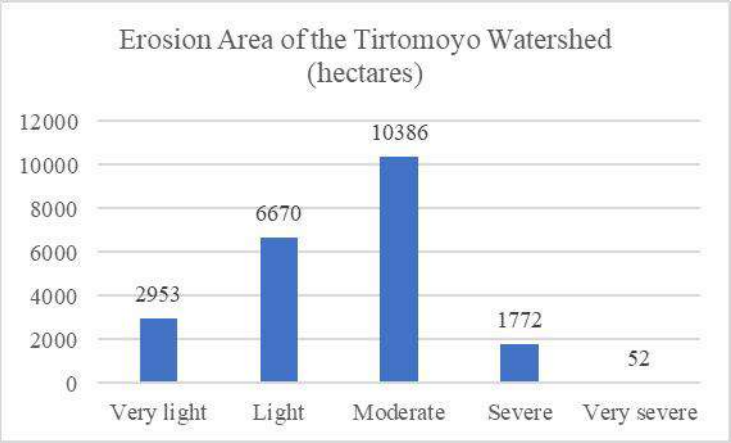

Figure 8. Erosion Susceptibility of Tirtomoyo watershed

Although very severe erosion is relatively rare in the Tirtomoyo watershed, the cumulative extent of moderate and mild erosion represents a significant concern for land and water resource management. The predominance of moderate erosion indicates ongoing surface soil loss, which, if unmanaged, has the potential to develop into more severe degradation. Therefore, soil conservation measures should be prioritized in areas experiencing moderate to mild erosion, while protection interventions should also be maintained in zones of severe erosion to prevent further expansion of damage.

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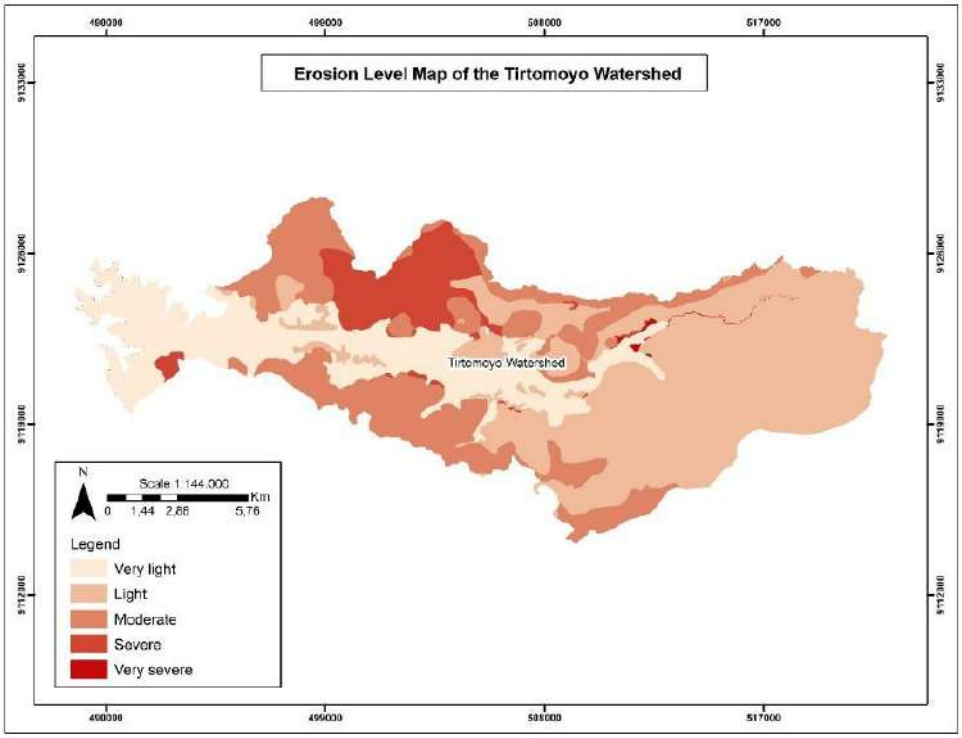

Figure 9. Erosion Map of Tirtomoyo watershed

The Tirtomoyo watershed exhibits diverse biophysical characteristics that influence its susceptibility to erosion. The area comprises various landforms, including alluvial plains, karst hills, old volcanic mountains, and old volcanic plains, with soil types such as Litosols, Latosols, and Gleysols. Major land cover includes forests, plantations, paddy fields, settlements, and shrublands.

Moderate erosion predominates, particularly in undulating to steep areas (8–40%) that are largely used as plantations or croplands with mixed vegetation cover, including teak, bamboo, banana, and seasonal crops. Areas experiencing severe to very severe erosion are generally located on steep slopes (>40%) with sparse vegetation or exposed land, such as the V3-La-Buk and V4-La-Buk land units, which are planted with maize, cassava, or elephant grass and often lack adequate conservation practices.

The combination of perennial crops such as teak with agroforestry conservation systems results in relatively low CP values, effectively reducing erosion rates, whereas lands without conservation or with seasonal crops on steep slopes exhibit high CP values, contributing to severe erosion categories. Conservation

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methods applied in the sub-watershed vary, including terracing, strip cropping, and agroforestry, but their distribution remains uneven in critical areas.

Figure 10. Gully Erosion in Tirtomoyo watershed

Figure 4 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (X. Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Y. Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices,

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areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully

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erosion, or landslides, which frequently occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo sub-watershed is mainly driven by high rainfall, steep slopes, clay-rich low-permeability soils, and limited conservation practices. Of the 33 land units analyzed, the most critical hotspots occur on steep litosols, classified as severe to very severe. Units without conservation measures experience the highest soil loss, while bench terraces and strip cropping significantly reduce erosion, confirming their effectiveness. Agroforestry offers moderate control but remains insufficient on steep slopes. Priority actions include: implementing structural measures (bench terraces, slope stabilization, check dams) in very severe areas; expanding strip cropping and agroforestry with improved ground cover in moderate-risk zones; rehabilitating degraded lands through reforestation and vegetative buffers on slopes >25%; and strengthening monitoring and maintenance of conservation structures to ensure long-term effectiveness.

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2. Bukti Konfirmasi Review Dan Hasil Review Pertama
(10 Juni 2026)

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

[GE] Editor Decision

1 message

Chatarina Muryani <jurnal@mail.uns.ac.id> Wed, Jun 10, 2026 at 10:48 AM
Reply-To: Hendra Hendra <hendra@ung.ac.id>
To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

The following message is being delivered on behalf of GeoEco.

MS Khabibur Rahman:

We have reached a decision regarding your submission to GeoEco, "SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED".

Our decision is: Revisions Required

The reviewers consider your research valuable and relevant; however, there are several issues that need to be reviewed before the manuscript can be considered for publication. Please carefully review the comments provided by the reviewers and make any necessary revisions. The review results can be found at https://jurnal.uns.ac.id/geoeco. When submitting a revised version, please include:

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2. A clearly marked version highlighting the changes, and
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Thank you for your cooperation.
Regards
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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is widely recognized as one of the most severe environmental problems affecting terrestrial ecosystems, especially in highland regions that are subject to intense rainfall and rapid land-use changes (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Globally, anthropogenic activities have accelerated the rate of erosion, with annual soil losses estimated to reach approximately 75 billion tons (Singh et al. 2023). This scale of degradation

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highlights both ecological and socio-economic consequences, considering that soil is effectively a non-renewable resource within a human time frame. The impacts of soil erosion extend far beyond the immediate degradation of land and natural ecosystems. They directly affect agricultural productivity, rural livelihoods, and food security (Antronico et al. 2020; Hishamunda et al. 2024).

Steep slopes magnify these processes by increasing runoff velocity and shear stress, thereby intensifying soil detachment and transport (Zhu et al. 2024). However, beyond these natural drivers, human activities significantly exacerbate erosion risks. Unsustainable land use, poor agricultural practices, deforestation, and limited awareness of conservation all contribute to accelerating land degradation (Panagos et al. 2016). These combined pressures also produce downstream consequences such as sediment accumulation in rivers, reduced water storage capacity, and increased flood risks (Kardhana et al. 2024).

The economic costs associated with soil erosion are equally daunting. Globally, remediation and rehabilitation expenses covering agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually (Carollo et al. 2023, 2024; Panagos et al. 2015). Developing countries are disproportionately affected, as limited financial and institutional resources make it difficult to implement comprehensive soil conservation programs (Molla & Sisheber 2017). This makes targeted and cost-effective erosion management strategies an urgent priority.

Efforts to assess, map, and model soil erosion have therefore become increasingly important at multiple spatial scales. Reliable estimation of soil loss is critical for spatial planning, watershed management, and the formulation of effective conservation policies (Alewell et al. 2019). Among the various approaches, the Universal Soil Loss Equation (USLE) is one of the most widely adopted empirical models for predicting long-term soil erosion. The model integrates five principal factors rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) to estimate annual soil loss (Ferro 2010; Li et al. 2024). Despite its empirical basis, the USLE remains relevant because of its adaptability,

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simplicity, and proven effectiveness across diverse landscapes.

Advancements in Geographic Information Systems (GIS) have further enhanced the applicability of USLE by providing powerful tools for integrating spatial datasets, performing terrain analysis, and mapping erosion risk across heterogeneous environments (Brychta et al. 2022). The integration of USLE and GIS allows researchers and policymakers to identify erosion hotspots, quantify soil loss potential, and prioritize areas for conservation interventions in a cost-efficient and spatially explicit manner.

These issues are particularly evident in the Tirtomoyo sub-watershed (Wonogiri–Pacitan), which features varied topography from gentle to steep slopes. Intensive land use agriculture, deforestation, and settlements has increased erosion risk by over 50% (Tian & Lan, 2023). Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

A key research gap remains, as most erosion studies in Indonesia focus on larger watersheds or reservoir sedimentation, overlooking spatial variability in smaller sub-watersheds like Tirtomoyo. Existing studies are often descriptive and rarely quantify soil loss across land units. Additionally, limited use of GIS-based USLE modeling at this scale hinders the development of targeted conservation strategies.

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2. There is no mention of previous studies conducted in watersheds around Wonogiri, Central Java, or on Java in general.
3. This gap is still an assumption, not a synthesis of the literature.

This study applies a GIS-based USLE model in the Tirtomoyo sub-watershed to: (1) estimate potential soil loss, (2) map erosion risk, and (3) identify conservation priority areas. The results support integrated watershed management, sustainable land use, sedimentation control, and mitigation of land degradation.

MATERIALS AND METHODS

Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km². The area forms part of the Bengawan Solo River Basin and serves as an important agricultural and residential zone. The sub-watershed is characterized by a highland landscape with elevation

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ranging from 150 to 900 m a.s.l. and slope gradients varying from 0–45%.

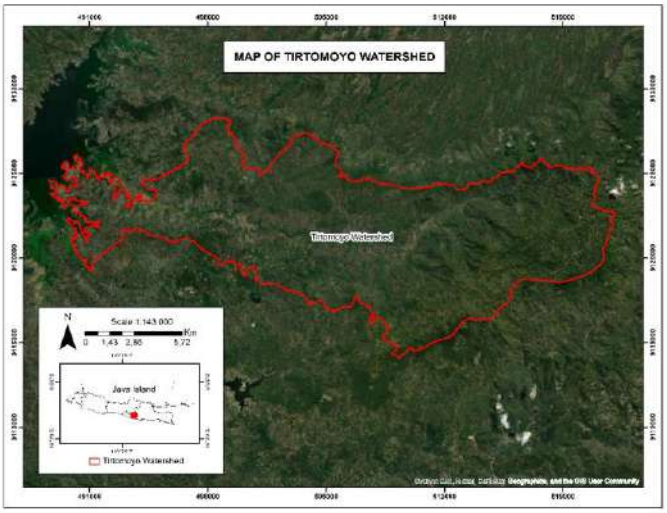

Figure 1. Location of Tirtomoyo Watershed

Data Collection

This study applied a GIS-based USLE to estimate spatial soil loss and identify conservation priority areas. USLE was chosen over RUSLE due to limited rainfall intensity and temporal data, and remains suitable for medium-scale, long-term erosion analysis. This model integrates five factors shown in equation 1.

A: R x K x LS x C x P (1)

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical equation:

$IR: 2.21 \times P^{1.36}$

IR : Indeks erosivitas

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P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following equation:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100$$

K : soil erodibility

oM : percentage of organic matter (C-organic × 1.724)

s : soil structure code

p : soil profile permeability class code

M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source : USDA

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Soil erosion is classified into five categories based on annual soil loss (tons/ha/year) following USDA standards. Class I (very light, <15) is tolerable with minimal impact; Class II (light, 16–60) shows early degradation but can be controlled with simple measures; Class III (moderate, 60–180) indicates significant fertility loss without conservation; Class IV (severe, 180–480) reflects serious degradation with rapid topsoil loss; and Class V (very severe, >480) represents extreme degradation requiring intensive and sustained conservation efforts.

Data analysis

Data analysis in this study used Land Mapping Units (LMUs) as the primary unit, each defined by a combination of geomorphology, soil type, slope, and land use. A total of 33 distinct LMUs were identified in the Tirtomoyo watershed (Figure 2). This spatial approach allows for more representative analysis than administrative boundaries, as it better captures biophysical variability.

A land unit is an area with relatively uniform characteristics that can be delineated on a map (FAO, 1976), typically based on landform, soil, slope, and land use. The number of land units reflects the diversity of land characteristics in a region. Previous studies have applied similar approaches with varying parameters, such as landform, soil, slope, land use, and geology (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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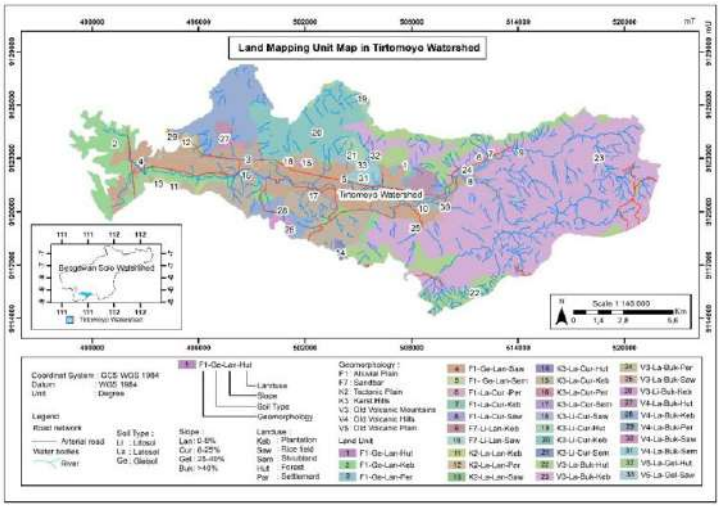

Figure 2. Land Mapping Units of the Tirtomoyo watershed

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

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The analysis of the rainfall erosivity factor (R) in the Tirtomoyo watershed was conducted based on precipitation data from four main stations: Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan.

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The collected data indicate that the average annual rainfall in the area reaches 2,676.42 mm/year (Figure 3). The spatial variability of rainfall across the sub-watershed shows that rainfall intensity and distribution are uneven, resulting in differences in erosion risk among locations.

The annual rainfall of 2,676.42 mm has the potential to generate a high rainfall erosivity factor (R). Land units in the Tirtomoyo Sub-watershed that lack adequate vegetation cover or soil conservation practices tend to fall into the severe to very severe erosion classes (e.g., units F7-Li-Lan-Keb and F7-Li-Lan-Saw). Conversely, in land units with good conservation measures such as bench terraces or strip cropping, despite receiving the same rainfall, erosion levels are controlled within the very light to light classes (e.g., F1-Ge-Lan-Keb and V3-La-Buk-Saw). Land units managed under agroforestry generally show light to moderate erosion; however, on steep slopes and hilly landforms (such as V3-La-Buk-Hut and V3-La-Buk-Per), erosion still falls into the severe category, indicating that vegetation alone is insufficient to control surface runoff under high rainfall conditions.

High rainfall, particularly when it exceeds the soil's infiltration capacity, increases surface runoff volume. When rainwater cannot infiltrate the soil due to shallow or saturated conditions, it flows over the surface at high velocity. This flow transports detached soil particles, causing surface erosion (Liang et al. 2025). Therefore, the high rainfall in the Tirtomoyo watershed is a dominant factor contributing to soil loss potential and should be a primary consideration in land conservation efforts in the region.

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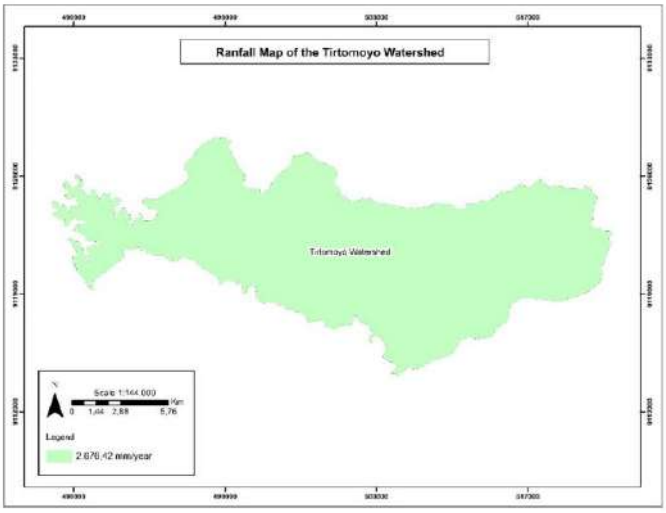

Figure 3. Rainfall Map of Tirtomoyo watershed

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 4). Based on Table 3, the land unit characteristics, there are variations in the values of M, organic matter content (BO), soil structure, and permeability that influence the degree of erosion susceptibility. The M values range from 162.03 to 2,233.41, where land with low M values (such as F1-Ge-Lan) tends to have finer textures and is relatively more resistant to erosion, while land with high M values (such as F1-La-Cur-Saw and F7-Li-Lan) indicates coarser textures that are more prone to erosion. Soil organic matter content also varies, ranging from 4.82% to 8.91%. Land with higher BO values, such as F7-Li-Lan and V3-Li-Buk, tends to be more fertile with more stable soil aggregates, thereby reducing erosion risk. In contrast, land with lower BO values (~4.82%), such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, has less stable aggregates that are more easily dispersed, thus increasing erosion susceptibility.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

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Source : data processing, 2025

In terms of soil structure, some land units have a value of 1 (poor/laminar structure), which raises the risk of degradation, whereas units with a value of 3 (good granular structure) are more stable. Soil permeability ranges from 4 (moderate–somewhat rapid) to 5 (rapid), where land with higher permeability (e.g., F7-Li-Lan and V3-Li-Buk) has better water infiltration capacity, thereby reducing surface runoff. Overall, the most erosion-prone land units are those with a combination of high M values, low BO, poor soil structure, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel. Conversely, land units with medium to high M values but supported by high BO, good soil structure, and rapid permeability, such as F7-Li-Lan and V3-Li-Buk, tend to be more resistant to erosion. However, despite the influence of organic matter, structure, and permeability, these areas remain in the severe category, showing that vegetation cover alone is insufficient to withstand high rainfall conditions. In particular, zones with dense clay soils and low permeability, such as point 2 and Litosol-dominated areas, have been identified as having high K-factor values and thus require conservation priority, since clay soils exacerbate erosion on steeper slopes (Luquin et al. 2025).

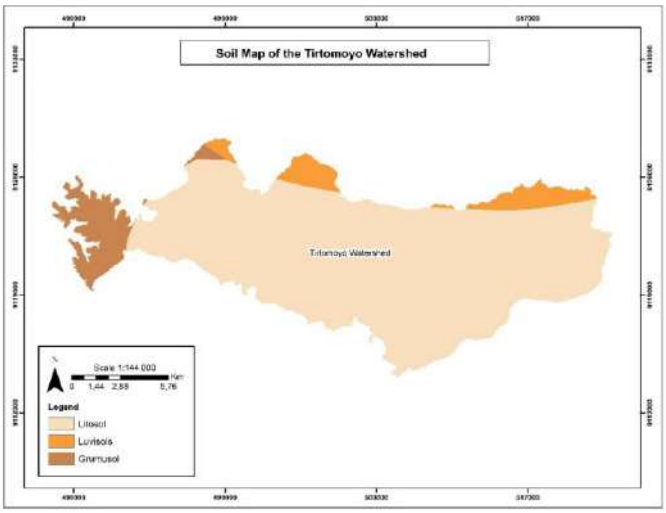

Figure 4. Soil Type Map of Tirtomoyo watershed

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Topographic Factor (LS)

Slope data in the Tirtomoyo Sub-watershed, derived from DEM analysis, show slope classes ranging from 0–8% to >45% (Figure 5), and these variations are directly reflected in the erosion classes of the 33 land units. Units located on steep to very steep slopes, especially in the eastern, central, and western sections, generally correspond to severe to very severe erosion classes, as seen in F7-Li-Lan-Keb and F7-Li-Lan-Saw, where slope gradients exceed 25% and generate high LS values that accelerate runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). By contrast, land units situated on gentle slopes (0–8%) in the central watershed tend to fall into very light or light erosion classes, such as F1-Ge-Lan-Keb and V3-La-Buk-Saw, where limited slope length and low gradients reduce erosive energy.

Areas with moderate slopes (10–35°) often show moderate erosion severity, particularly when conservation measures are absent or insufficient, as in some K3-La-Cur units, which aligns with observations that slopes in this range face elevated erosion risks (Pan et al. 2025). These findings confirm that slope gradient and length are decisive factors in shaping erosion severity, with high LS values amplifying soil loss in unmanaged steep terrain, while low LS values in flatter areas reduce erosion potential even under high rainfall. Identifying slope-driven hotspots using DEM data is therefore essential for prioritizing conservation in the Tirtomoyo Sub-watershed, as the steepest areas are consistently the main contributors to soil loss.

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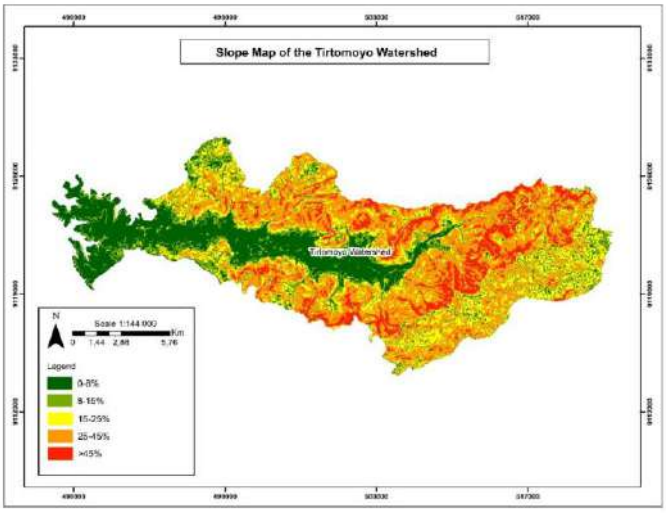

Figure 5. Slope Map of Tirtomoyo watershed

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak stands (*Tectona grandis*). Other crops such as rice, maize, banana, bamboo, elephant grass, and mango indicate that the area is largely utilized for forestry and agriculture (Figure 6). Teak provides relatively effective soil cover due to its deep roots and dense canopy, resulting in low C-factor values. In contrast, paddy fields and seasonal crops such as maize exhibit higher C values, particularly during the early planting season or when the land is left bare.

The C factor is determined by the capacity of a plant species or land cover to protect soil from the direct impact of raindrops and surface runoff. Dense vegetation cover, as in teak or bamboo, reduces the direct impact of rainfall on the soil surface and slows down surface flow. Well-developed root systems can control runoff and erosion in the short term (Mas et al., 2024).

Seasonal changes in vegetation, especially in agricultural land, lead to significant fluctuations in C-factor values. When the land is tilled or left fallow, the soil surface becomes more susceptible to erosion due to minimal protection. Areas with seasonal crops and crop rotations require special

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attention in soil conservation management, which can include mulching, cover crops, or agroforestry systems.

a

b

Figure 6. (a) *Zea mays L.* and (b) *Bambusoideae*

Conservation Practice Factor (P)

Various soil and water conservation practices, such as agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo sub-watershed; however, many areas remain without conservation measures. The presence of these techniques significantly influences the P factor in the USLE method. Practices such as bench terracing and strip cropping reduce surface flow velocity and enhance water infiltration into the soil, resulting in lower P values, which indicate higher erosion control efficiency. The sub-watershed is dominated by terracing on sloped land, forming stepped levels to reduce runoff velocity (Figure 7).

Areas lacking conservation measures have P values approaching 1, indicating no reduction in erosion risk through land management. This is a particular concern, as without conservation interventions especially in steep and high-rainfall areas soil erosion potential increases sharply. Mapping and classifying P values is therefore essential for informed decision-making in land conservation planning, particularly in priority areas with high erosion risk.

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Figure 7. Terracing Conservation Technique

Erosion Susceptibility of Tirtomoyo Sub-watershed

The table 4, shows that conservation methods significantly influence erosion outcomes: bench terraces and strip cropping are most effective on cultivated land, while agroforestry provides moderate protection but may require reinforcement on steep terrain. Units without conservation show the highest vulnerability, underscoring the importance of expanding soil and water conservation practices to reduce land degradation risks in the watershed.

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Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light

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Land Unit	C	Conservation Method	Class
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 8 illustrates the spatial distribution of erosion severity in the Tirtomoyo watershed, measured in hectares. The data indicate that moderate erosion dominates the area, covering approximately 10,386 ha, followed by mild erosion at 6,670 ha and very mild erosion at 2,953 ha. More severe erosion categories occupy smaller areas, with severe erosion covering 1,772 ha and very severe erosion being the least extensive at only 52 ha.

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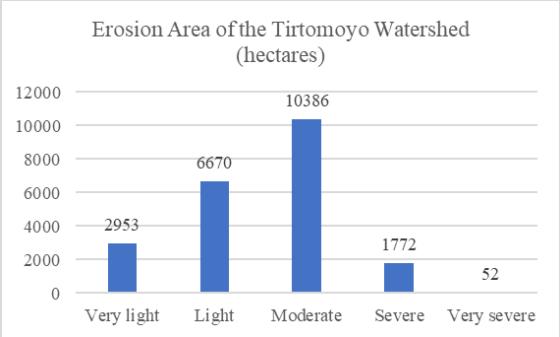

Figure 8. Erosion Susceptibility of Tirtomoyo watershed

Although very severe erosion is relatively rare in the Tirtomoyo watershed, the cumulative extent of moderate and mild erosion represents a significant concern for land and water resource management. The predominance of moderate erosion indicates ongoing surface soil loss, which, if unmanaged, has the potential to develop into more severe degradation. Therefore, soil conservation measures should be prioritized in areas experiencing moderate to mild erosion, while protection interventions should also be maintained in zones of severe erosion to prevent further expansion of damage.

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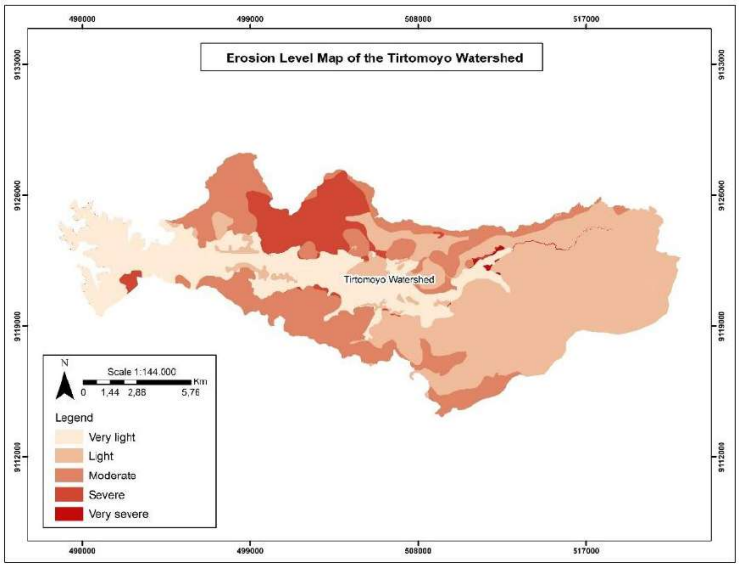

Figure 9. Erosion Map of Tirtomoyo watershed

The Tirtomoyo watershed exhibits diverse biophysical characteristics that influence its susceptibility to erosion. The area comprises various landforms, including alluvial plains, karst hills, old volcanic mountains, and old volcanic plains, with soil types such as Litosols, Latosols, and Gleysols. Major land cover includes forests, plantations, paddy fields, settlements, and shrublands.

Moderate erosion predominates, particularly in undulating to steep areas (8–40%) that are largely used as plantations or croplands with mixed vegetation cover, including teak, bamboo, banana, and seasonal crops. Areas experiencing severe to very severe erosion are generally located on steep slopes (>40%) with sparse vegetation or exposed land, such as the V3-La-Buk and V4-La-Buk land units, which are planted with maize, cassava, or elephant grass and often lack adequate conservation practices.

The combination of perennial crops such as teak with agroforestry conservation systems results in relatively low CP values, effectively reducing erosion rates, whereas lands without conservation or with seasonal crops on steep slopes exhibit high CP values, contributing to severe erosion categories.

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Conservation methods applied in the sub-watershed vary, including terracing, strip cropping, and agroforestry, but their distribution remains uneven in critical areas.

Figure 10. Gully Erosion in Tirtomoyo watershed

Figure 4 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (X. Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Y. Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

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Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

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A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo sub-watershed is mainly driven by high rainfall, steep slopes, clay-rich low-permeability soils, and limited conservation practices. Of the 33 land units analyzed, the most critical hotspots occur on steep litosols, classified as severe to very severe. Units without conservation measures experience the highest soil loss, while bench terraces and strip cropping significantly reduce erosion, confirming their effectiveness. Agroforestry offers moderate control but remains insufficient on steep slopes. Priority actions include: implementing structural measures (bench terraces, slope stabilization, check dams) in very severe areas; expanding strip cropping and agroforestry with improved ground cover in moderate-risk zones; rehabilitating degraded lands through reforestation and vegetative buffers on slopes >25%; and strengthening monitoring and maintenance of conservation structures to ensure long-term effectiveness.

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2. The limitations of the study have not been explained.
3. The conclusion does not provide direction for further research.

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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is widely recognized as one of the most severe environmental problems affecting terrestrial ecosystems, especially in highland regions that are subject to intense rainfall and rapid land-use changes (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Globally, anthropogenic activities have accelerated the rate of erosion, with annual soil losses estimated to reach approximately 75 billion tons (Singh et al. 2023). This scale of degradation

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highlights both ecological and socio-economic consequences, considering that soil is effectively a non-renewable resource within a human time frame. The impacts of soil erosion extend far beyond the immediate degradation of land and natural ecosystems. They directly affect agricultural productivity, rural livelihoods, and food security (Antronico et al. 2020; Hishamunda et al. 2024).

Steep slopes magnify these processes by increasing runoff velocity and shear stress, thereby intensifying soil detachment and transport (Zhu et al. 2024). However, beyond these natural drivers, human activities significantly exacerbate erosion risks. Unsustainable land use, poor agricultural practices, deforestation, and limited awareness of conservation all contribute to accelerating land degradation (Panagos et al. 2016). These combined pressures also produce downstream consequences such as sediment accumulation in rivers, reduced water storage capacity, and increased flood risks (Kardhana et al. 2024).

The economic costs associated with soil erosion are equally daunting. Globally, remediation and rehabilitation expenses covering agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually (Carollo et al. 2023, 2024; Panagos et al. 2015). Developing countries are disproportionately affected, as limited financial and institutional resources make it difficult to implement comprehensive soil conservation programs (Molla & Sisheber 2017). This makes targeted and cost-effective erosion management strategies an urgent priority.

Efforts to assess, map, and model soil erosion have therefore become increasingly important at multiple spatial scales. Reliable estimation of soil loss is critical for spatial planning, watershed management, and the formulation of effective conservation policies (Alewell et al. 2019). Among the various approaches, the Universal Soil Loss Equation (USLE) is one of the most widely adopted empirical models for predicting long-term soil erosion. The model integrates five principal factors rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) to estimate annual soil loss (Ferro 2010; Li et al. 2024). Despite its empirical basis, the USLE remains relevant because of its adaptability,

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simplicity, and proven effectiveness across diverse landscapes.

Advancements in Geographic Information Systems (GIS) have further enhanced the applicability of USLE by providing powerful tools for integrating spatial datasets, performing terrain analysis, and mapping erosion risk across heterogeneous environments (Brychta et al. 2022). The integration of USLE and GIS allows researchers and policymakers to identify erosion hotspots, quantify soil loss potential, and prioritize areas for conservation interventions in a cost-efficient and spatially explicit manner.

These issues are particularly evident in the Tirtomoyo sub-watershed (Wonogiri–Pacitan), which features varied topography from gentle to steep slopes. Intensive land use agriculture, deforestation, and settlements has increased erosion risk by over 50% (Tian & Lan, 2023). Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

A key research gap remains, as most erosion studies in Indonesia focus on larger watersheds or reservoir sedimentation, overlooking spatial variability in smaller sub-watersheds like Tirtomoyo. Existing studies are often descriptive and rarely quantify soil loss across land units. Additionally, limited use of GIS-based USLE modeling at this scale hinders the development of targeted conservation strategies.

This study applies a GIS-based USLE model in the Tirtomoyo sub-watershed to: (1) estimate potential soil loss, (2) map erosion risk, and (3) identify conservation priority areas. The results support integrated watershed management, sustainable land use, sedimentation control, and mitigation of land degradation.

MATERIALS AND METHODS

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Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km². The area forms part of the Bengawan Solo River Basin and serves as an important agricultural and residential zone. The sub-watershed is characterized by a highland landscape with elevation

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ranging from 150 to 900 m a.s.l. and slope gradients varying from 0–45%.

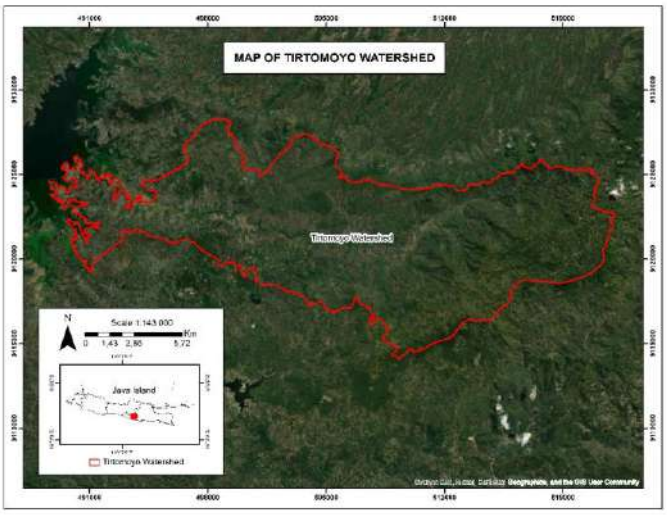

Figure 1. Location of Tirtomoyo Watershed

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Data Collection

This study applied a GIS-based USLE to estimate spatial soil loss and identify conservation priority areas. USLE was chosen over RUSLE due to limited rainfall intensity and temporal data, and remains suitable for medium-scale, long-term erosion analysis. The model integrates five factors as follows:

A: R x K x LS x C x P

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical equation:

IR: 2.21 x $P^{1.36}$

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IR : Indeks erosivitas

P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following equation:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100$$

K : soil erodibility

oM : percentage of organic matter (C-organic × 1.724)

s : soil structure code

p : soil profile permeability class code

M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

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Source : USDA

Soil erosion is classified into five categories based on annual soil loss (tons/ha/year) following USDA standards. Class I (very light, <15) is tolerable with minimal impact; Class II (light, 16–60) shows early degradation but can be controlled with simple measures; Class III (moderate, 60–180) indicates significant fertility loss without conservation; Class IV (severe, 180–480) reflects serious degradation with rapid topsoil loss; and Class V (very severe, >480) represents extreme degradation requiring intensive and sustained conservation efforts.

Data analysis

Data analysis in this study used Land Mapping Units (LMUs) as the primary unit, each defined by a combination of geomorphology, soil type, slope, and land use. A total of 33 distinct LMUs were identified in the Tirtomoyo watershed (Figure 2). This spatial approach allows for more representative analysis than administrative boundaries, as it better captures biophysical variability.

A land unit is an area with relatively uniform characteristics that can be delineated on a map (FAO, 1976), typically based on landform, soil, slope, and land use. The number of land units reflects the diversity of land characteristics in a region. Previous studies have applied similar approaches with varying parameters, such as landform, soil, slope, land use, and geology (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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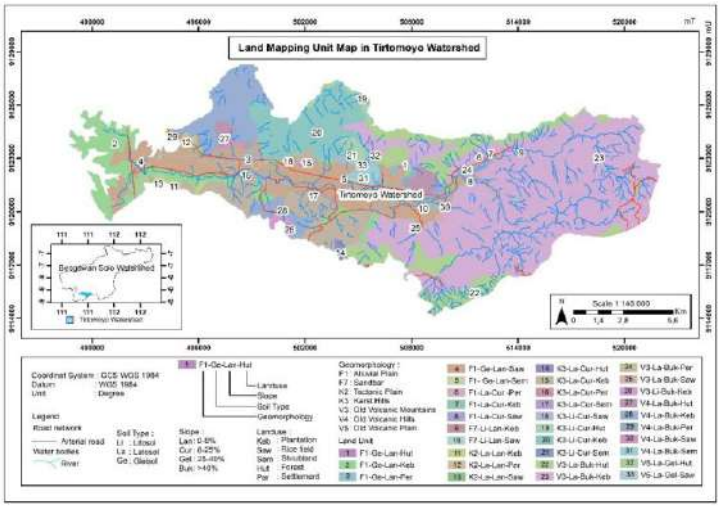

Figure 2. Land Mapping Units of the Tirtomoyo watershed

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor (R) in the Tirtomoyo watershed was conducted based on precipitation data from four main stations: Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan.

Table 2. Rainfall in Tirtomoyo Watershed

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The collected data indicate that the average annual rainfall in the area reaches 2,676.42 mm/year (Figure 3). The spatial variability of rainfall across the sub-watershed shows that rainfall intensity and distribution are uneven, resulting in differences in erosion risk among locations.

The annual rainfall of 2,676.42 mm has the potential to generate a high rainfall erosivity factor (R). Land units in the Tirtomoyo Sub-watershed that lack adequate vegetation cover or soil conservation practices tend to fall into the severe to very severe erosion classes (e.g., units F7-Li-Lan-Keb and F7-Li-Lan-Saw). Conversely, in land units with good conservation measures such as bench terraces or strip cropping, despite receiving the same rainfall, erosion levels are controlled within the very light to light classes (e.g., F1-Ge-Lan-Keb and V3-La-Buk-Saw). Land units managed under agroforestry generally show light to moderate erosion; however, on steep slopes and hilly landforms (such as V3-La-Buk-Hut and V3-La-Buk-Per), erosion still falls into the severe category, indicating that vegetation alone is insufficient to control surface runoff under high rainfall conditions.

High rainfall, particularly when it exceeds the soil's infiltration capacity, increases surface runoff volume. When rainwater cannot infiltrate the soil due to shallow or saturated conditions, it flows over the surface at high velocity. This flow transports detached soil particles, causing surface erosion (Liang et al. 2025). Therefore, the high rainfall in the Tirtomoyo watershed is a dominant factor contributing to soil loss potential and should be a primary consideration in land conservation efforts in the region.

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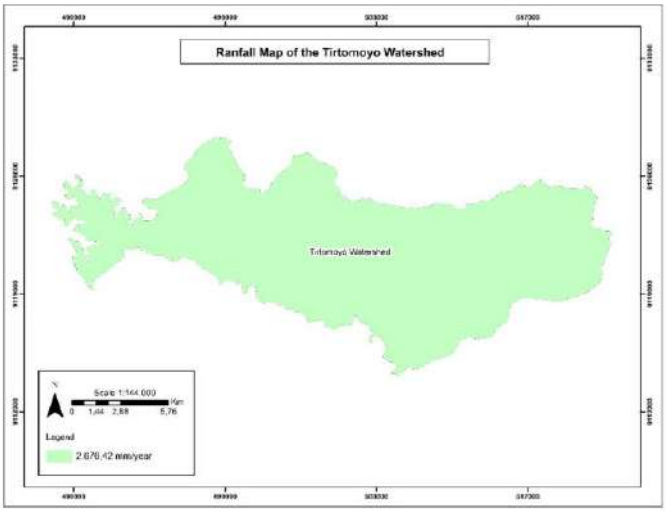

Figure 3. Rainfall Map of Tirtomoyo watershed

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 4). Based on Table 3, the land unit characteristics, there are variations in the values of M, organic matter content (BO), soil structure, and permeability that influence the degree of erosion susceptibility. The M values range from 162.03 to 2,233.41, where land with low M values (such as F1-Ge-Lan) tends to have finer textures and is relatively more resistant to erosion, while land with high M values (such as F1-La-Cur-Saw and F7-Li-Lan) indicates coarser textures that are more prone to erosion. Soil organic matter content also varies, ranging from 4.82% to 8.91%. Land with higher BO values, such as F7-Li-Lan and V3-Li-Buk, tends to be more fertile with more stable soil aggregates, thereby reducing erosion risk. In contrast, land with lower BO values (~4.82%), such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, has less stable aggregates that are more easily dispersed, thus increasing erosion susceptibility.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source : data processing, 2025

In terms of soil structure, some land units have a value of 1 (poor/laminar structure), which raises the risk of degradation, whereas units with a value of 3 (good granular structure) are more stable. Soil permeability ranges from 4 (moderate–somewhat rapid) to 5 (rapid), where land with higher permeability (e.g., F7-Li-Lan and V3-Li-Buk) has better water infiltration capacity, thereby reducing surface runoff. Overall, the most erosion-prone land units are those with a combination of high M values, low BO, poor soil structure, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel. Conversely, land units with medium to high M values but supported by high

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BO, good soil structure, and rapid permeability, such as F7-Li-Lan and V3-Li-Buk, tend to be more resistant to erosion. However, despite the influence of organic matter, structure, and permeability, these areas remain in the severe category, showing that vegetation cover alone is insufficient to withstand high rainfall conditions. In particular, zones with dense clay soils and low permeability, such as point 2 and Litosol-dominated areas, have been identified as having high K-factor values and thus require conservation priority, since clay soils exacerbate erosion on steeper slopes (Luquin et al. 2025).

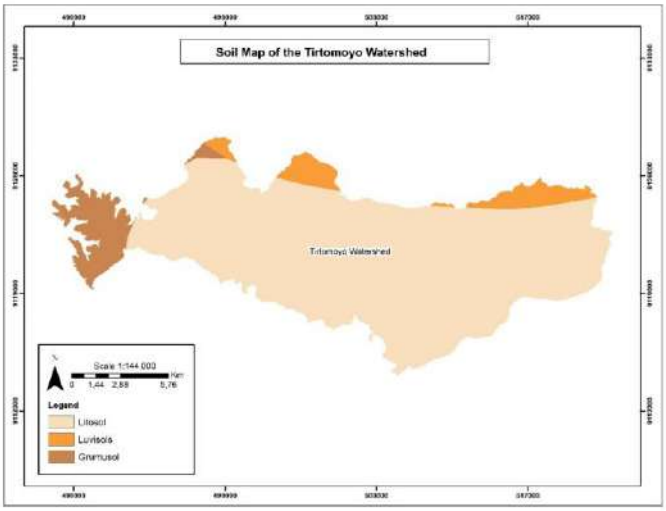

Figure 4. Soil Type Map of Tirtomoyo watershed

Topographic Factor (LS)

Slope data in the Tirtomoyo Sub-watershed, derived from DEM analysis, show slope classes ranging from 0–8% to >45% (Figure 5), and these variations are directly reflected in the erosion classes of the 33 land units. Units located on steep to very steep slopes, especially in the eastern, central, and western sections, generally correspond to severe to very severe erosion classes, as seen in F7-Li-Lan-Keb and F7-Li-Lan-Saw, where slope gradients exceed 25% and generate high LS values that accelerate runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). By contrast, land units situated on gentle slopes (0–8%) in the central watershed tend to fall into very light or light erosion classes, such as F1-Ge-Lan-Keb

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and V3-La-Buk-Saw, where limited slope length and low gradients reduce erosive energy.

Areas with moderate slopes (10–35°) often show moderate erosion severity, particularly when conservation measures are absent or insufficient, as in some K3-La-Cur units, which aligns with observations that slopes in this range face elevated erosion risks (Pan et al. 2025). These findings confirm that slope gradient and length are decisive factors in shaping erosion severity, with high LS values amplifying soil loss in unmanaged steep terrain, while low LS values in flatter areas reduce erosion potential even under high rainfall. Identifying slope-driven hotspots using DEM data is therefore essential for prioritizing conservation in the Tirtomoyo Sub-watershed, as the steepest areas are consistently the main contributors to soil loss.

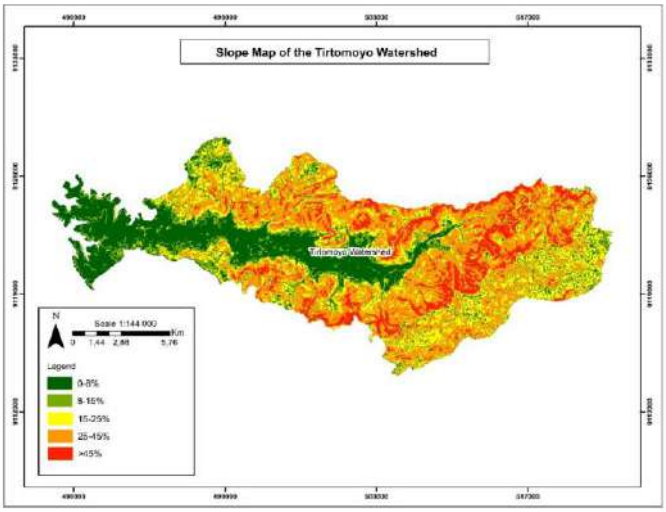

Figure 5. Slope Map of Tirtomoyo watershed

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak stands (*Tectona grandis*). Other crops such as rice, maize, banana, bamboo, elephant grass, and mango indicate that the area is largely utilized for forestry and agriculture (Figure 6). Teak provides relatively effective soil cover due to its deep roots and dense canopy, resulting in

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low C-factor values. In contrast, paddy fields and seasonal crops such as maize exhibit higher C values, particularly during the early planting season or when the land is left bare.

The C factor is determined by the capacity of a plant species or land cover to protect soil from the direct impact of raindrops and surface runoff. Dense vegetation cover, as in teak or bamboo, reduces the direct impact of rainfall on the soil surface and slows down surface flow. Well-developed root systems can control runoff and erosion in the short term (Mas et al., 2024).

Seasonal changes in vegetation, especially in agricultural land, lead to significant fluctuations in C-factor values. When the land is tilled or left fallow, the soil surface becomes more susceptible to erosion due to minimal protection. Areas with seasonal crops and crop rotations require special attention in soil conservation management, which can include mulching, cover crops, or agroforestry systems.

a b

Figure 6. (a) *Zea mays L.* and (b) *Bambusoideae*

Conservation Practice Factor (P)

Various soil and water conservation practices, such as agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo sub-watershed; however, many areas remain without conservation measures. The presence of these techniques significantly influences the P factor in the USLE method. Practices such as bench terracing and strip cropping reduce surface flow velocity and enhance water infiltration into the soil, resulting in lower P values, which indicate higher erosion control efficiency. The sub-watershed is

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dominated by terracing on sloped land, forming stepped levels to reduce runoff velocity (Figure 7).

Areas lacking conservation measures have P values approaching 1, indicating no reduction in erosion risk through land management. This is a particular concern, as without conservation interventions especially in steep and high-rainfall areas soil erosion potential increases sharply. Mapping and classifying P values is therefore essential for informed decision-making in land conservation planning, particularly in priority areas with high erosion risk.

Figure 7. Terracing Conservation Technique

Erosion Susceptibility of Tirtomoyo Sub-watershed

The table 4, shows that conservation methods significantly influence erosion outcomes: bench terraces and strip cropping are most effective on cultivated land, while agroforestry provides moderate protection but may require reinforcement on steep terrain. Units without conservation show the highest vulnerability, underscoring the importance of expanding soil and water conservation practices to reduce land degradation risks in the watershed.

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light

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Land Unit	C	Conservation Method	Class
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 8 illustrates the spatial distribution of erosion severity in the Tirtomoyo watershed, measured in hectares. The data indicate that moderate erosion dominates the area, covering approximately 10,386 ha, followed by mild erosion at 6,670 ha and very mild erosion at 2,953 ha. More severe erosion categories occupy smaller areas, with severe erosion covering 1,772 ha and very severe erosion being the least extensive at only 52 ha.

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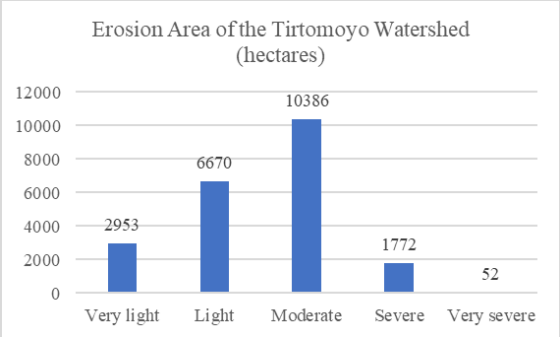

Figure 8. Erosion Susceptibility of Tirtomoyo watershed

Although very severe erosion is relatively rare in the Tirtomoyo watershed, the cumulative extent of moderate and mild erosion represents a significant concern for land and water resource management. The predominance of moderate erosion indicates ongoing surface soil loss, which, if unmanaged, has the potential to develop into more severe degradation. Therefore, soil conservation measures should be prioritized in areas experiencing moderate to mild erosion, while protection interventions should also be maintained in zones of severe erosion to prevent further expansion of damage.

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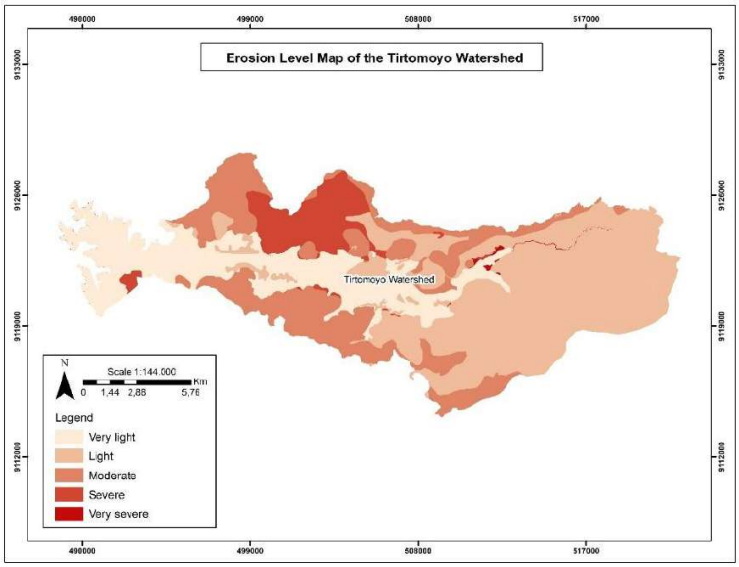

Figure 9. Erosion Map of Tirtomoyo watershed

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The Tirtomoyo watershed exhibits diverse biophysical characteristics that influence its susceptibility to erosion. The area comprises various landforms, including alluvial plains, karst hills, old volcanic mountains, and old volcanic plains, with soil types such as Litosols, Latosols, and Gleysols. Major land cover includes forests, plantations, paddy fields, settlements, and shrublands.

Moderate erosion predominates, particularly in undulating to steep areas (8–40%) that are largely used as plantations or croplands with mixed vegetation cover, including teak, bamboo, banana, and seasonal crops. Areas experiencing severe to very severe erosion are generally located on steep slopes (>40%) with sparse vegetation or exposed land, such as the V3-La-Buk and V4-La-Buk land units, which are planted with maize, cassava, or elephant grass and often lack adequate conservation practices.

The combination of perennial crops such as teak with agroforestry conservation systems results in relatively low CP values, effectively reducing erosion rates, whereas lands without conservation or with seasonal crops on steep slopes exhibit high CP values, contributing to severe erosion categories.

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Conservation methods applied in the sub-watershed vary, including terracing, strip cropping, and agroforestry, but their distribution remains uneven in critical areas.

Figure 10. Gully Erosion in Tirtomoyo watershed

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Figure 4 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (X. Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Y. Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

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Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

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A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo sub-watershed is mainly driven by high rainfall, steep slopes, clay-rich low-permeability soils, and limited conservation practices. Of the 33 land units analyzed, the most critical hotspots occur on steep litosols, classified as severe to very severe. Units without conservation measures experience the highest soil loss, while bench terraces and strip cropping significantly reduce erosion, confirming their effectiveness. Agroforestry offers moderate control but remains insufficient on steep slopes. Priority actions include: implementing structural measures (bench terraces, slope stabilization, check dams) in very severe areas; expanding strip cropping and agroforestry with improved ground cover in moderate-risk zones; rehabilitating degraded lands through reforestation and vegetative buffers on slopes >25%; and strengthening monitoring and maintenance of conservation structures to ensure long-term effectiveness.

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3. Bukti konfirmasi submit revisi pertama, respon kepada reviewer, dan artikel yang diresubmit
(18 Juni 2026)

Table of Question and Answer

Question	Answer
The justification for the research location is weak, such as not explaining the watershed area, not explaining the watershed's strategic position within the regional hydrological system, and not explaining why Tirtomoyo is more important than other sub-watersheds. Ideally, it would be necessary to explain the hydrological function of the sub-watershed; its position relative to the Wonogiri Reservoir; the level of land degradation; and historical landslide or erosion events.	Thank you for your comment. These issues are particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary within the upper Bengawan Solo watershed system that directly contributes sediment and surface runoff to the Wonogiri Reservoir, one of Indonesia's most important multipurpose reservoirs for irrigation, flood control, hydropower generation, and water supply. The sub-watershed is characterized by highly variable topography, ranging from gentle to steep slopes, with extensive agricultural land use, forest conversion, and expanding settlements. These conditions have accelerated land degradation processes and increased erosion susceptibility by more than 50%. Historical records and field observations also indicate recurring soil erosion, sediment transport, and localized landslide events, particularly on steep cultivated slopes. Due to its significant hydrological role, high erosion potential, and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area for assessing land degradation and watershed management strategies.
1. There is no literature evidence to suggest that previous research has predominantly focused on large watersheds. 2. There is no mention of previous studies conducted in watersheds around Wonogiri, Central Java, or on Java in general. 3. This gap is still an assumption, not a synthesis of the literature.	Thank you for your comment. Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have extensively investigated soil erosion and sedimentation using USLE- and MUSLE-based approaches. Research conducted in the Keduang Sub-watershed, Krisak Reservoir watershed, Parangjoho Reservoir watershed, and Nawangan Reservoir watershed primarily focused on estimating erosion rates, sediment yield, erosion hazard levels, and their impacts on reservoir sedimentation and storage capacity (Sutrisno et al., 2011; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). Similarly, studies on the Wonogiri Reservoir have emphasized sedimentation dynamics and reservoir performance degradation resulting from upstream land degradation (Santosa, 2016; Murdhianti, 2021). While these studies have provided valuable insights into watershed degradation and sedimentation processes, they generally focus on watershed-scale assessments and reservoir management issues. Consequently, detailed information regarding the spatial variability of soil loss across land units within smaller sub-watersheds remains limited. In particular, the Tirtomoyo Sub-watershed, despite its strategic role as part of the Upper Bengawan Solo catchment and its contribution to sediment transport toward the Wonogiri Reservoir system, has received relatively little attention.
All equations must be numbered, and there must be a sentence that refers to them	Thank you for your comment. We have revised it.

Question	Answer
The discussion is too normative; it would be better to add more information on why R is high in Tirtomoyo; how it compares to other watersheds; and whether it is considered high for Central Java	Thank you for your comment. The average annual rainfall in the Tirtomoyo Sub-watershed reaches 2,676.42 mm $year^{-1}$, indicating a humid tropical environment with substantial rainfall erosivity potential. This relatively high rainfall is influenced by the watershed's location within the southern part of Central Java, which is strongly affected by monsoonal circulation and orographic rainfall processes associated with the hilly terrain of the Southern Java Mountains. As moist air masses from the Indian Ocean are forced to rise over the mountainous landscape, rainfall intensity and duration increase, contributing to elevated rainfall erosivity (R-factor). Compared with several watersheds in Central Java, the annual rainfall recorded in the Tirtomoyo Sub-watershed is relatively high. Previous studies in parts of the Bengawan Solo watershed, Serayu watershed, and Progo watershed generally reported annual rainfall ranging from approximately 1,800 to 2,500 mm $year^{-1}$, whereas the Tirtomoyo Sub-watershed exceeds 2,600 mm $year^{-1}$. Such conditions suggest that the rainfall erosivity in Tirtomoyo is among the higher categories for Central Java and can significantly accelerate soil detachment and transport processes, particularly on steep slopes and poorly protected land surfaces. The influence of rainfall on erosion is evident in several land units where severe to very severe erosion occurs despite similar soil characteristics. High-intensity rainfall generates runoff when rainfall rates exceed soil infiltration capacity, increasing the kinetic energy available for soil particle detachment and transport. However, the results also demonstrate that the impact of high rainfall can be substantially reduced through effective conservation practices. Land units equipped with bench terraces and strip cropping generally exhibit very light to light erosion rates, whereas cultivated land on steep slopes without adequate conservation measures remains highly susceptible to erosion. These findings indicate that although rainfall erosivity constitutes a dominant natural driver of erosion in the Tirtomoyo Sub-watershed, land management practices play a critical role in determining the magnitude of soil loss.
Is there no map and results?	Thank you for your comment. A land cover map was not included in this study because land cover information was obtained through field sampling based on land units rather than through a wall-to-wall land cover classification approach. Therefore, the analysis was conducted at the land-unit level, where each sampling unit represents specific combinations of landform, soil type, slope, and land use characteristics
No Comparison with Previous Research	Thank you for your comment. We have revised it.

Question	Answer
1. The conclusion does not detail the location or extent of priority conservation areas, so the results of the priority area identification remain unclear. 2. The limitations of the study have not been explained. 3. The conclusion does not provide direction for further research.	Thank you for your comment. Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas. This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

Table of Question and Answer

Question	Answer
There is no research novelty. Novelty can include: a location that has never been studied; integration of recent data; and so on.	Thank you for your comment, we have revised it. Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Murdhianti, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales. The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited. The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.
Add a research flowchart to systematically understand the research design, from the research stages; data input; processing; and the resulting output.	Thank you for your comment, we have revised it.
There are no sentences that refer to figure numbers.	Thank you for your comment, we have revised it.
All images and tables must have a source	Thank you for your comment, we have revised it.
There are no sentences that refer to table numbers.	Thank you for your comment, we have revised it.
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Make sure all references have been cited	Thank you for your comment, we have revised it.

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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is one of the most severe environmental problems affecting terrestrial ecosystems, particularly in highland areas experiencing intense rainfall and rapid land-use change (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Human activities have accelerated global soil degradation, with annual soil losses estimated at approximately 75 billion tons (Singh et al. 2023). Beyond degrading land resources, soil erosion reduces

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agricultural productivity, threatens rural livelihoods and food security, and generates significant ecological and socio-economic impacts (Antronico et al. 2020; Hishamunda et al. 2024).

Erosion is intensified by steep slopes, which increase runoff velocity and soil detachment, as well as by unsustainable land use, deforestation, poor agricultural practices, and inadequate conservation measures (Panagos et al. 2016; Zhu et al. 2024). These processes also contribute to river sedimentation, declining water storage capacity, and increased flood risk (Kardhana et al. 2024). Globally, the costs of erosion-related agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually, with developing countries facing the greatest challenges due to limited conservation resources (Carollo et al. 2023, 2024; Molla & Sisheber 2017; Panagos et al. 2015).

Assessing and mapping soil erosion is essential for spatial planning, watershed management, and the development of effective conservation policies (Alewell et al. 2019). Among the available approaches, the Universal Soil Loss Equation (USLE) remains one of the most widely used models for estimating long-term soil loss by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) (Ferro 2010; Li et al. 2024). Its integration with Geographic Information Systems (GIS) has enhanced erosion assessment through spatial analysis, hotspot identification, and conservation prioritization across heterogeneous landscapes (Brychta et al. 2022).

The need for such assessments is particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed that contributes runoff and sediment to the Wonogiri Reservoir. Characterized by steep terrain, agricultural expansion, forest conversion, and growing settlements, the sub-watershed faces high erosion susceptibility and recurring land degradation problems, including soil erosion, sediment transport, and localized landslides. Given its important hydrological role and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area for erosion assessment and conservation planning.

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Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Murdhianti, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales.

The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited.

The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.

MATERIALS AND METHODS

Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km² (Figure 1).

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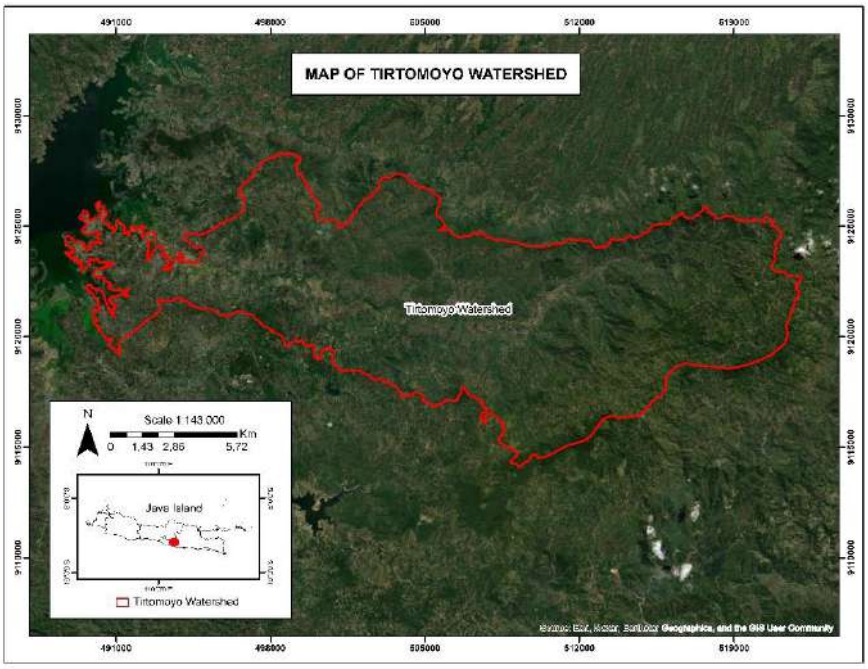

Figure 1. Location of Tirtomoyo Watershed

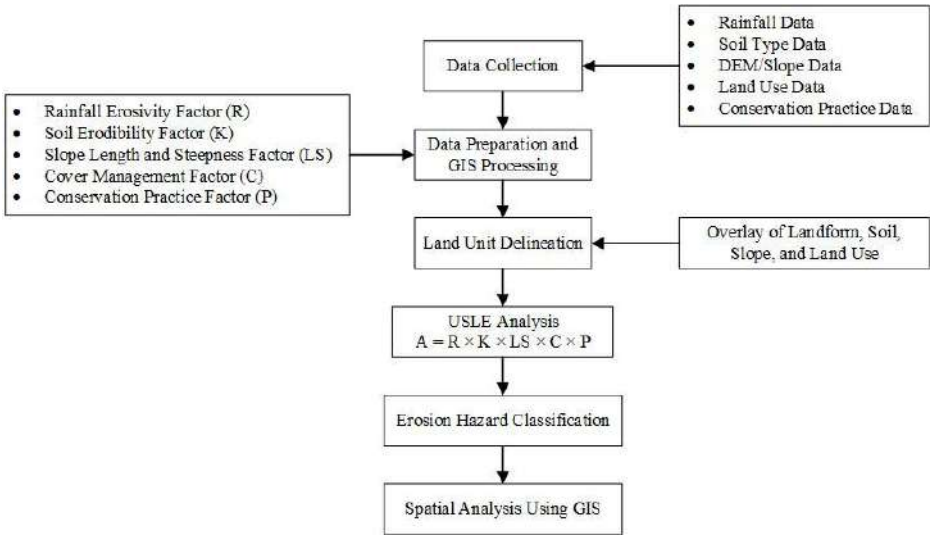

Figure 2. Research Flowchat

Data Collection

This study applied GIS-based USLE to estimate soil loss and identify conservation priority areas. USLE was selected because it remains suitable for long-term erosion assessment under limited rainfall data availability. This model integrates five factors shown in equation 1.

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$$A: R \times K \times LS \times C \times P \quad (1)$$

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical shown in equation 2:

$$IR: 2.21 \times P^{1.36} \quad (2)$$

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following shown in equation 3:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100 \quad (3)$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

Table 1. Erossion Class

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Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source : USDA

Based on USDA standards, soil erosion was classified as very light (<15 t ha^{-1} yr^{-1}), light (15–60), moderate (60–180), severe (180–480), and very severe (>480), representing increasing levels of land degradation and conservation urgency.

Data analysis

Data analysis was conducted using Land Mapping Units (LMUs), defined by combinations of geomorphology, soil type, slope, and land use. A total of 33 LMUs were identified in the Tirtomoyo watershed (Figure 2), providing a more representative basis for analysis than administrative boundaries by capturing biophysical variability. Land units represent areas with relatively homogeneous characteristics (FAO, 1976), and similar approaches have been widely applied using combinations of landform, soil, slope, land use, and geological parameters (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

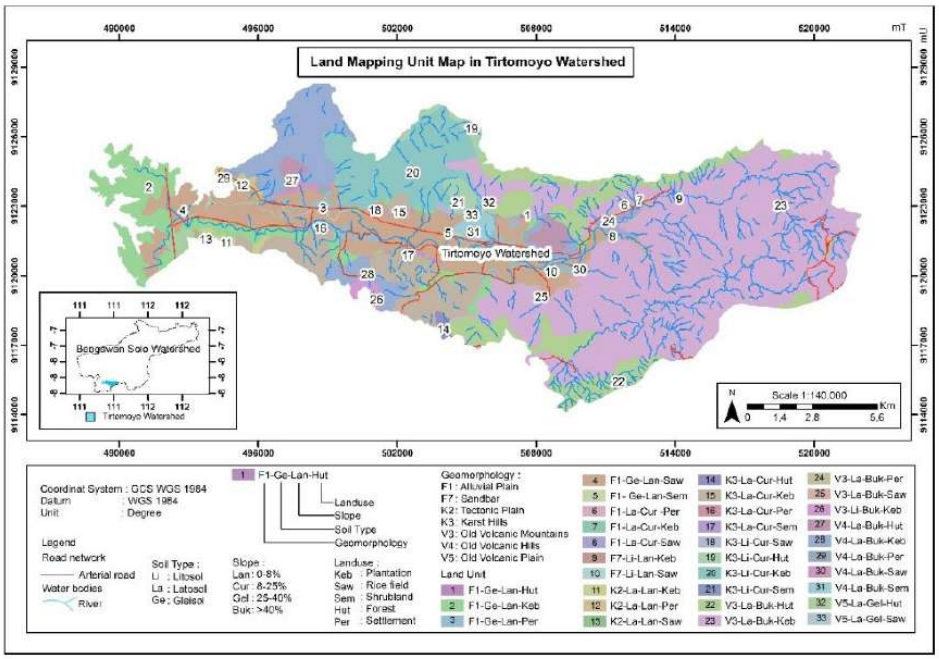

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Figure 2. Land Mapping Units of the Tirtomoyo watershed

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor in the Tirtomoyo watershed was conducted based on precipitation data (Figure 3).

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The average annual rainfall in the Tirtomoyo Sub-watershed is 2,676.42 mm year^{-1}, reflecting a humid tropical climate with high rainfall erosivity potential. This condition is influenced by monsoonal circulation and orographic effects associated with the hilly terrain of southern Central Java, which enhance rainfall intensity and duration. Compared with several watersheds in Central Java, where annual rainfall generally ranges from 1,800 to 2,500 mm year^{-1}, Tirtomoyo receives relatively higher rainfall, indicating elevated erosion risk.

The effect of rainfall is evident in several land units classified as severe to very severe erosion. High-intensity rainfall increases surface runoff when infiltration capacity is exceeded, thereby accelerating soil detachment and transport. However, erosion rates are substantially lower in areas

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implementing bench terraces and strip cropping, whereas steep cultivated lands without conservation measures remain highly vulnerable. These findings indicate that while rainfall erosivity is a major driver of soil loss, effective land management plays a crucial role in reducing erosion in the Tirtomoyo Sub-watershed.

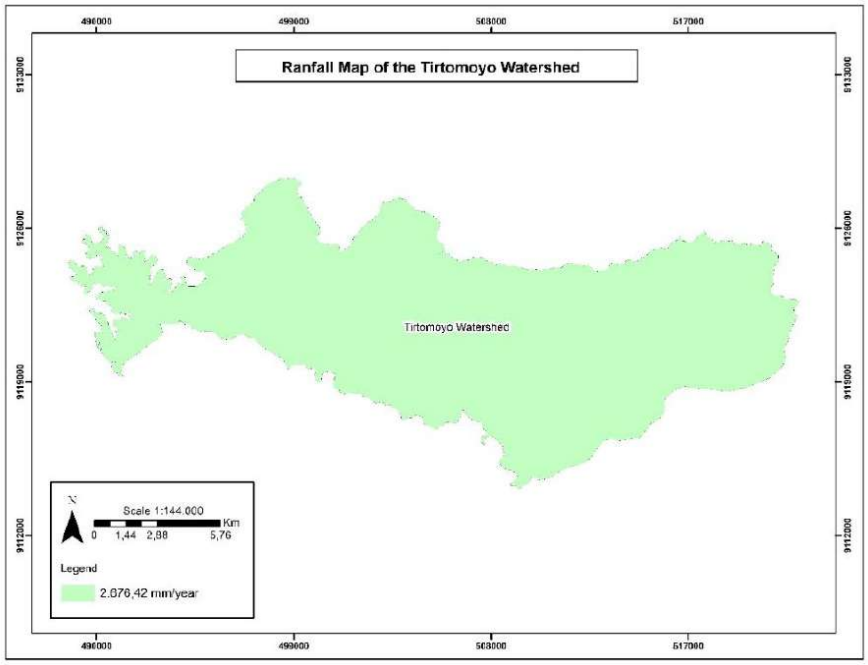

Figure 3. Rainfall Map of Tirtomoyo watershed

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 4). As shown in Table 3, land units exhibit considerable variation in texture, organic matter content, soil structure, and permeability, which influence erosion susceptibility. The M factor ranges from 162.03 to 2,233.41, with higher values generally indicating greater erodibility. Organic matter content varies from 4.82% to 8.91%; land units with higher organic matter, such as F7-Li-Lan and V3-Li-Buk, tend to have more stable aggregates and lower erosion risk, whereas units with lower organic matter, including K3-La-Cur, V4-La-Buk, and V5-La-Gel, are more susceptible to erosion due to reduced aggregate stability.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source : data processing, 2025

Soil structure varies from poor (value 1) to good granular structure (value 3), while permeability ranges from moderate–rapid (4) to rapid (5). Land units with poor structure, low organic matter, high M values, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, exhibit the highest erosion susceptibility. In contrast, units with higher organic matter, better structure, and rapid permeability, including F7-Li-Lan and

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V3-Li-Buk, are relatively more resistant to erosion due to improved aggregate stability and infiltration capacity. However, these areas still fall within the severe erosion category, indicating that favorable soil properties alone cannot offset the effects of high rainfall and steep slopes. Areas dominated by clay-rich Litosols, particularly at Point 2, show high K-factor values and therefore require conservation priority, as clay soils can intensify erosion on sloping terrain (Luquin et al., 2025).

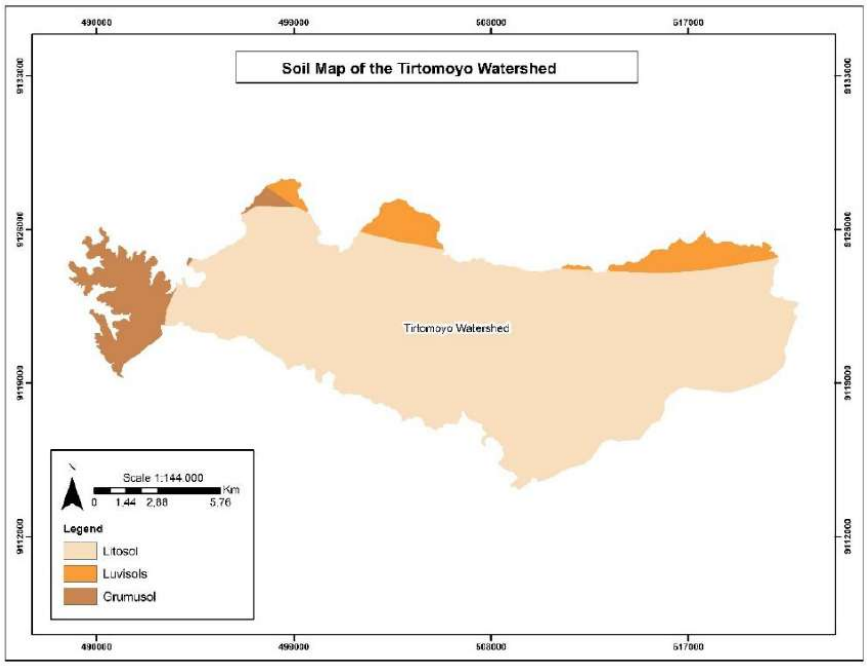

Figure 4. Soil Type Map of Tirtomoyo watershed

Topographic Factor (LS)

Slope analysis derived from the DEM indicates gradients ranging from 0–8% to >45% across the Tirtomoyo Sub-watershed (Figure 5). Land units on steep to very steep slopes, particularly in the eastern, central, and western areas, are generally classified as severe to very severe erosion zones, such as F7-Li-Lan-Keb and F7-Li-Lan-Saw, due to high LS values that increase runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). Conversely, units on gentle slopes (0–8%), including F1-Ge-Lan-Keb and V3-La-Buk-Saw, exhibit very light to light erosion because of lower erosive energy. Moderate slopes (10–35°) commonly show moderate erosion, especially where conservation measures are limited, as observed in several K3-La-Cur units (Pan et al. 2025). These findings confirm that slope gradient and

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length are key controls of erosion severity, highlighting steep-slope areas as priority targets for conservation.

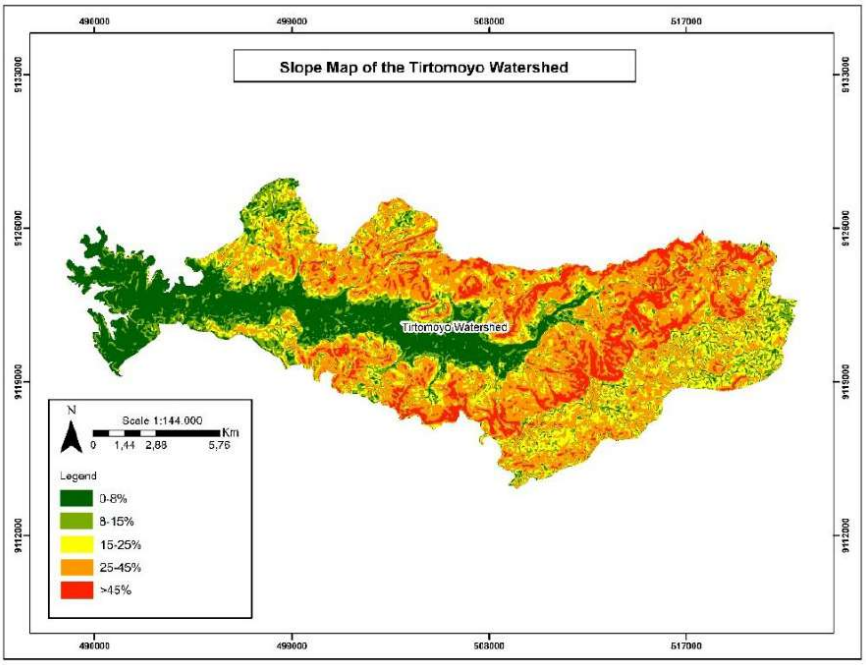

Figure 5. Slope Map of Tirtomoyo watershed

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak (*Tectona grandis*), alongside rice, maize, banana, bamboo, elephant grass, and mango, reflecting the predominance of forestry and agricultural activities (Figure 6). Teak and bamboo provide effective soil protection through dense canopy cover and extensive root systems, resulting in lower C-factor values, whereas paddy fields and seasonal crops generally exhibit higher C values, particularly during planting or fallow periods. The C factor reflects the ability of vegetation to reduce raindrop impact and surface runoff, thereby minimizing erosion (Mas et al., 2024). Consequently, agricultural areas with seasonal vegetation are more vulnerable to erosion and require conservation measures such as mulching, cover crops, or agroforestry systems.

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a b

Figure 6. (a) *Zea mays L.* and (b) *Bambusoideae*

Conservation Practice Factor (P)

Various soil and water conservation practices, including agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo Sub-watershed, although many areas remain unmanaged. These practices influence the USLE P factor by reducing runoff velocity and increasing infiltration, thereby lowering erosion risk. Bench terraces are the dominant conservation measure on sloping land (Figure 7). In contrast, areas without conservation have P values close to 1, indicating minimal erosion control and greater vulnerability, particularly on steep slopes under high rainfall. Therefore, mapping P-factor distribution is important for identifying conservation priorities and supporting effective land management.

Figure 7. Terracing Conservation Technique

Erosion Susceptibility of Tirtomoyo Sub-watershed

Table 4 shows that conservation practices strongly influence erosion

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rates. Bench terraces and strip cropping are the most effective measures on cultivated land, while agroforestry provides moderate protection, although its effectiveness may decline on steep slopes under high rainfall conditions (Jose et al., 2022). Areas without conservation exhibit the highest erosion vulnerability, highlighting the importance of expanding soil and water conservation measures. Bench terraces reduce runoff velocity and soil loss, whereas strip cropping limits runoff and sediment transport by interrupting surface flow pathways (FAO, 1986; El Jazouli et al., 2023).

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate

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Land Unit	C	Conservation Method	Class
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 8 shows that moderate erosion is the dominant class in the Tirtomoyo watershed, covering approximately 10,386 ha, followed by mild erosion (6,670 ha) and very mild erosion (2,953 ha). Severe and very severe erosion occupy smaller areas, covering 1,772 ha and 52 ha, respectively.

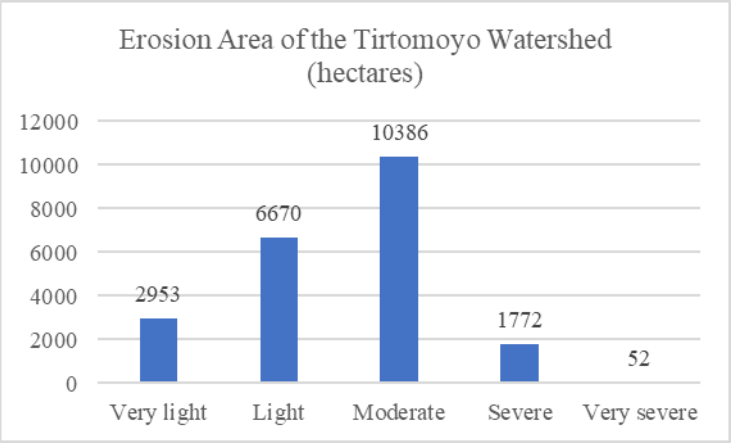

Figure 8. Erosion Susceptibility of Tirtomoyo watershed

Although very severe erosion is limited, the dominance of moderate and mild erosion poses a significant management concern (Figure 9). These areas require priority conservation measures to prevent further degradation, while severe erosion zones need continued protection to limit the expansion of damage.

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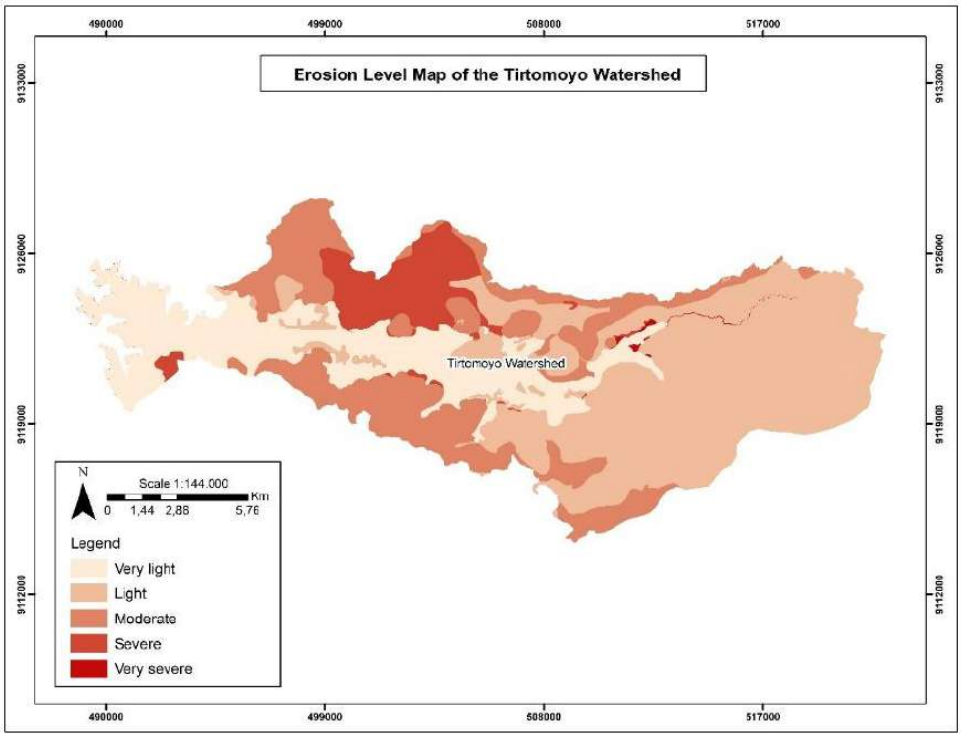

Figure 9. Erosion Map of Tirtomoyo watershed

The Tirtomoyo watershed consists of diverse landforms and soil types, including alluvial plains, karst hills, old volcanic landscapes, and soils such as Litosols, Latosols, and Gleysols, with land cover dominated by forests, plantations, paddy fields, settlements, and shrublands. Moderate erosion is the dominant class, particularly in undulating to steep areas (8–40%) used for plantations and mixed agriculture. Severe to very severe erosion occurs mainly on steep slopes (>40%) with sparse vegetation and limited conservation practices, such as in the V3-La-Buk and V4-La-Buk land units. Areas with teak-based agroforestry generally exhibit lower CP values and reduced erosion, whereas seasonal crops on steep slopes without conservation measures show higher CP values and greater erosion risk. Although conservation practices such as terracing, strip cropping, and agroforestry are present, their implementation remains uneven across critical areas.

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Figure 10. Gully Erosion in Tirtomoyo watershed

Figure 10 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-

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La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently occur in steep, high-rainfall areas like

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the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas.

This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

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4. Bukti konfirmasi review dan hasil review kedua Bukti konfirmasi submit revisi pertama, respon kepada reviewer, dan artikel yang diresubmit
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[GE] Editor Decision

1 message

Chatarina Muryani <jurnal@mail.uns.ac.id> Tue, Jun 23, 2026 at 1:07 PM
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To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

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Thank you for the article you have submitted to us.

After reviewing your manuscript, we have identified several minor revisions that require correction. These revisions do not affect the main substance of the article, but are necessary to improve the clarity and quality of the presentation.

We kindly request that you make corrections according to the attached notes and resubmit the revised manuscript.

Thank you for your attention and cooperation.
Regards
Hendra Hendra
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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is one of the most severe environmental problems affecting terrestrial ecosystems, particularly in highland areas experiencing intense rainfall and rapid land-use change (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Human activities have accelerated global soil degradation, with annual soil losses estimated at approximately 75 billion tons (Singh et al. 2023). Beyond degrading land resources, soil erosion reduces

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agricultural productivity, threatens rural livelihoods and food security, and generates significant ecological and socio-economic impacts (Antronico et al. 2020; Hishamunda et al. 2024).

Erosion is intensified by steep slopes, which increase runoff velocity and soil detachment, as well as by unsustainable land use, deforestation, poor agricultural practices, and inadequate conservation measures (Panagos et al. 2016; Zhu et al. 2024). These processes also contribute to river sedimentation, declining water storage capacity, and increased flood risk (Kardhana et al. 2024). Globally, the costs of erosion-related agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually, with developing countries facing the greatest challenges due to limited conservation resources (Carollo et al. 2023, 2024; Molla & Sisheber 2017; Panagos et al. 2015).

Assessing and mapping soil erosion is essential for spatial planning, watershed management, and the development of effective conservation policies (Alewell et al. 2019). Among the available approaches, the Universal Soil Loss Equation (USLE) remains one of the most widely used models for estimating long-term soil loss by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) (Ferro 2010; Li et al. 2024). Its integration with Geographic Information Systems (GIS) has enhanced erosion assessment through spatial analysis, hotspot identification, and conservation prioritization across heterogeneous landscapes (Brychta et al. 2022).

The need for such assessments is particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed that contributes runoff and sediment to the Wonogiri Reservoir. Characterized by steep terrain, agricultural expansion, forest conversion, and growing settlements, the sub-watershed faces high erosion susceptibility and recurring land degradation problems, including soil erosion, sediment transport, and localized landslides. Given its important hydrological role and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area for erosion assessment and conservation planning.

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Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Murdhianti, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales.

The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited.

The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.

MATERIALS AND METHODS

Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km² (Figure 1).

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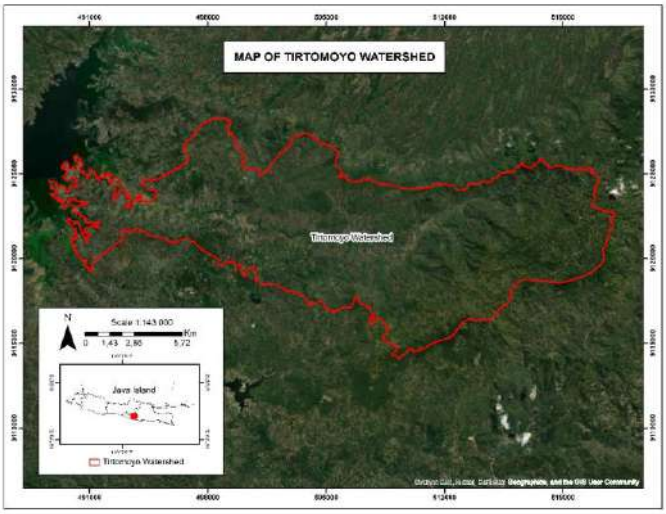

Figure 1. Location of Tirtomoyo Watershed

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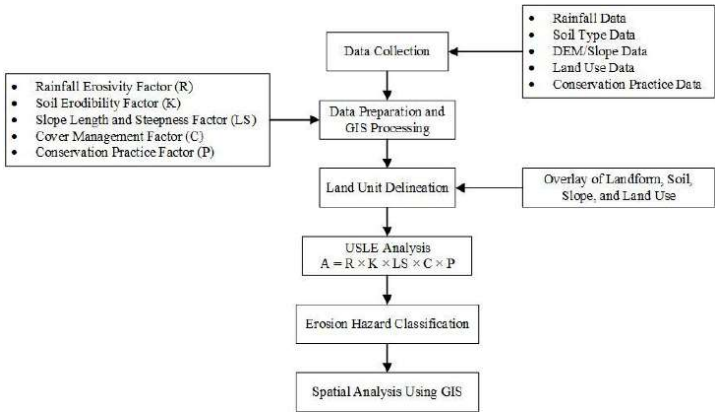

Figure 2. Research Flowchat

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Data Collection

This study applied GIS-based USLE to estimate soil loss and identify conservation priority areas. USLE was selected because it remains suitable for long-term erosion assessment under limited rainfall data availability. This model integrates five factors shown in equation 1.

$$A: R \times K \times LS \times C \times P \quad (1)$$

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical shown in equation 2:

$$IR: 2.21 \times P^{1.36} \quad (2)$$

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following shown in equation 3:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100 \quad (3)$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P

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factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source : USDA

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Based on USDA standards, soil erosion was classified as very light (<15 t ha^{-1} yr^{-1}), light (15–60), moderate (60–180), severe (180–480), and very severe (>480), representing increasing levels of land degradation and conservation urgency.

Data analysis

Data analysis was conducted using Land Mapping Units (LMUs), defined by combinations of geomorphology, soil type, slope, and land use. A total of 33 LMUs were identified in the Tirtomoyo watershed (Figure 2), providing a more representative basis for analysis than administrative boundaries by capturing biophysical variability. Land units represent areas with relatively homogeneous characteristics (FAO, 1976), and similar approaches have been widely applied using combinations of landform, soil, slope, land use, and geological parameters (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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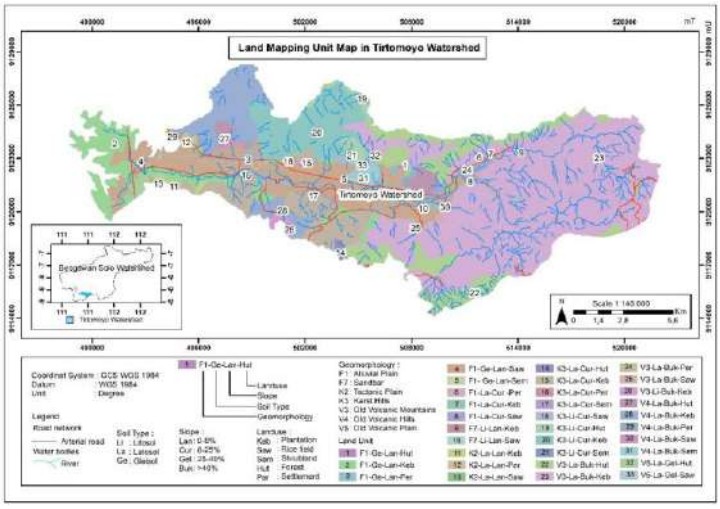

Figure 2. Land Mapping Units of the Tirtomoyo watershed

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Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor in the Tirtomoyo watershed was conducted based on precipitation data (Figure 3).

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The average annual rainfall in the Tirtomoyo Sub-watershed is 2,676.42 mm year^{-1}, reflecting a humid tropical climate with high rainfall erosivity potential. This condition is influenced by monsoonal circulation and orographic effects associated with the hilly terrain of southern Central Java, which enhance rainfall intensity and duration. Compared with several watersheds in Central Java, where annual rainfall generally ranges from 1,800 to 2,500 mm year^{-1}, Tirtomoyo receives relatively higher rainfall, indicating elevated erosion risk.

The effect of rainfall is evident in several land units classified as severe to very severe erosion. High-intensity rainfall increases surface runoff when infiltration capacity is exceeded, thereby accelerating soil detachment and transport. However, erosion rates are substantially lower in areas implementing bench terraces and strip cropping, whereas steep cultivated lands without conservation measures remain highly vulnerable. These findings indicate that while rainfall erosivity is a major driver of soil loss, effective land management plays a crucial role in reducing erosion in the Tirtomoyo Sub-watershed.

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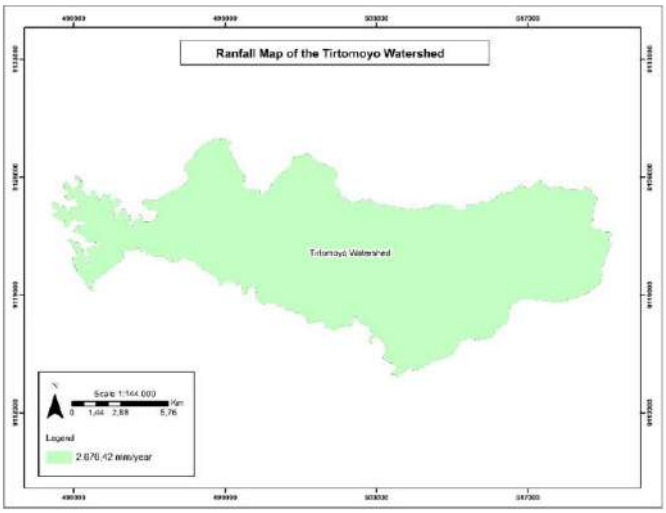

Figure 3. Rainfall Map of Tirtomoyo watershed

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Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 4). As shown in Table 3, land units exhibit considerable variation in texture, organic matter content, soil structure, and permeability, which influence erosion susceptibility. The M factor ranges from 162.03 to 2,233.41, with higher values generally indicating greater erodibility. Organic matter content varies from 4.82% to 8.91%; land units with higher organic matter, such as F7-Li-Lan and V3-Li-Buk, tend to have more stable aggregates and lower erosion risk, whereas units with lower organic matter, including K3-La-Cur, V4-La-Buk, and V5-La-Gel, are more susceptible to erosion due to reduced aggregate stability.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source : data processing, 2025

Soil structure varies from poor (value 1) to good granular structure (value 3), while permeability ranges from moderate–rapid (4) to rapid (5). Land units with poor structure, low organic matter, high M values, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, exhibit the highest erosion susceptibility. In contrast, units with higher organic matter, better structure, and rapid permeability, including F7-Li-Lan and V3-Li-Buk, are relatively more resistant to erosion due to improved aggregate stability and infiltration capacity. However, these areas still fall within the severe erosion category, indicating that favorable soil properties alone cannot offset the effects of high rainfall and steep slopes. Areas dominated by clay-rich Litosols, particularly at Point 2, show high K-factor values and therefore

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require conservation priority, as clay soils can intensify erosion on sloping terrain (Luquin et al., 2025).

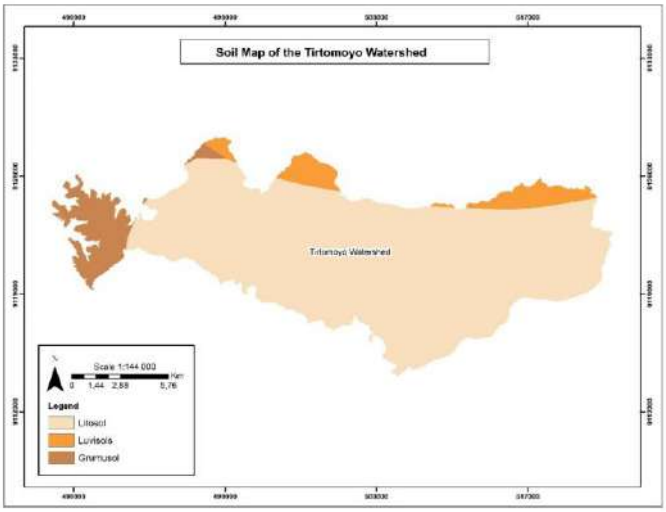

Figure 4. Soil Type Map of Tirtomoyo watershed

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Topographic Factor (LS)

Slope analysis derived from the DEM indicates gradients ranging from 0–8% to >45% across the Tirtomoyo Sub-watershed (Figure 5). Land units on steep to very steep slopes, particularly in the eastern, central, and western areas, are generally classified as severe to very severe erosion zones, such as F7-Li-Lan-Keb and F7-Li-Lan-Saw, due to high LS values that increase runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). Conversely, units on gentle slopes (0–8%), including F1-Ge-Lan-Keb and V3-La-Buk-Saw, exhibit very light to light erosion because of lower erosive energy. Moderate slopes (10–35°) commonly show moderate erosion, especially where conservation measures are limited, as observed in several K3-La-Cur units (Pan et al. 2025). These findings confirm that slope gradient and length are key controls of erosion severity, highlighting steep-slope areas as priority targets for conservation.

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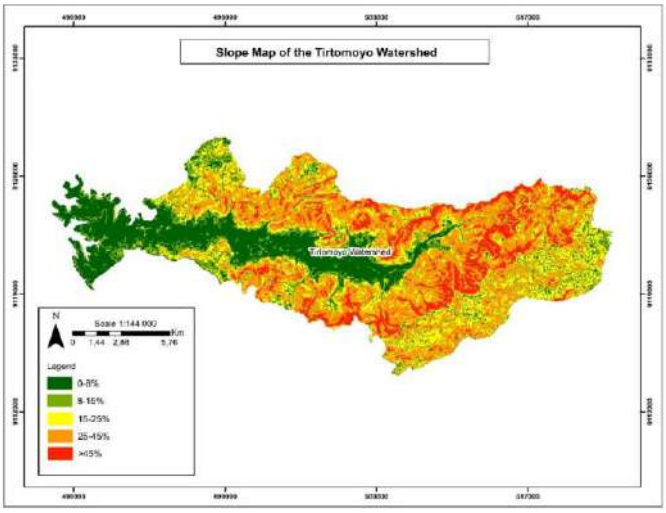

Figure 5. Slope Map of Tirtomoyo watershed

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Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak (*Tectona grandis*), alongside rice, maize, banana, bamboo, elephant grass, and mango, reflecting the predominance of forestry and agricultural activities (Figure 6). Teak and bamboo provide effective soil protection through dense canopy cover and extensive root systems, resulting in lower C-factor values, whereas paddy fields and seasonal crops generally exhibit higher C values, particularly during planting or fallow periods. The C factor reflects the ability of vegetation to reduce raindrop impact and surface runoff, thereby minimizing erosion (Mas et al., 2024). Consequently, agricultural areas with seasonal vegetation are more vulnerable to erosion and require conservation measures such as mulching, cover crops, or agroforestry systems.

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a

b

Figure 6. (a) *Zea mays L.* and (b) *Bambusoideae*

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Conservation Practice Factor (P)

Various soil and water conservation practices, including agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo Sub-watershed, although many areas remain unmanaged. These practices influence the USLE P factor by reducing runoff velocity and increasing infiltration, thereby lowering erosion risk. Bench terraces are the dominant conservation measure on sloping land (Figure 7). In contrast, areas without conservation have P values close to 1, indicating minimal erosion control and greater vulnerability, particularly on steep slopes under high rainfall. Therefore, mapping P-factor distribution is important for identifying conservation priorities and supporting effective land management.

Figure 7. Terracing Conservation Technique

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Erosion Susceptibility of Tirtomoyo Sub-watershed

Table 4 shows that conservation practices strongly influence erosion

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rates. Bench terraces and strip cropping are the most effective measures on cultivated land, while agroforestry provides moderate protection, although its effectiveness may decline on steep slopes under high rainfall conditions (Jose et al., 2022). Areas without conservation exhibit the highest erosion vulnerability, highlighting the importance of expanding soil and water conservation measures. Bench terraces reduce runoff velocity and soil loss, whereas strip cropping limits runoff and sediment transport by interrupting surface flow pathways (FAO, 1986; El Jazouli et al., 2023).

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate

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Land Unit	C	Conservation Method	Class
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 8 shows that moderate erosion is the dominant class in the Tirtomoyo watershed, covering approximately 10,386 ha, followed by mild erosion (6,670 ha) and very mild erosion (2,953 ha). Severe and very severe erosion occupy smaller areas, covering 1,772 ha and 52 ha, respectively.

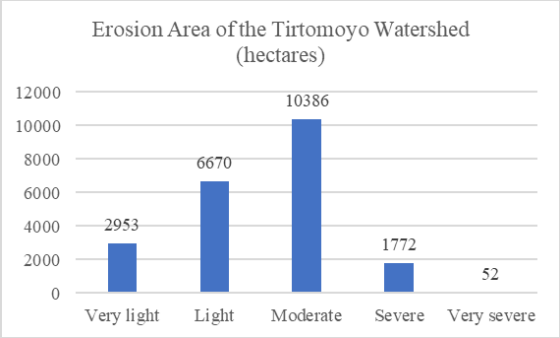

Figure 8. Erosion Susceptibility of Tirtomoyo watershed

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Although very severe erosion is limited, the dominance of moderate and mild erosion poses a significant management concern (Figure 9). These areas require priority conservation measures to prevent further degradation, while severe erosion zones need continued protection to limit the expansion of damage.

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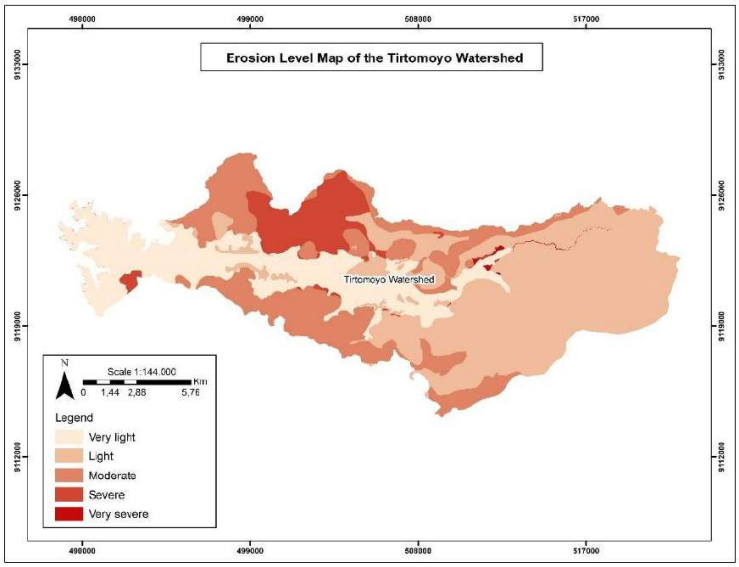

Figure 9. Erosion Map of Tirtomoyo watershed

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The Tirtomoyo watershed consists of diverse landforms and soil types, including alluvial plains, karst hills, old volcanic landscapes, and soils such as Litosols, Latosols, and Gleysols, with land cover dominated by forests, plantations, paddy fields, settlements, and shrublands. Moderate erosion is the dominant class, particularly in undulating to steep areas (8–40%) used for plantations and mixed agriculture. Severe to very severe erosion occurs mainly on steep slopes (>40%) with sparse vegetation and limited conservation practices, such as in the V3-La-Buk and V4-La-Buk land units. Areas with teak-based agroforestry generally exhibit lower CP values and reduced erosion, whereas seasonal crops on steep slopes without conservation measures show higher CP values and greater erosion risk. Although conservation practices such as terracing, strip cropping, and agroforestry are present, their implementation remains uneven across critical areas.

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Figure 10. Gully Erosion in Tirtomoyo watershed

Figure 10 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-

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La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently occur in steep, high-rainfall areas like

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the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas.

This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

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5. Bukti konfirmasi submit revisi kedua, respon kepada reviewer, dan artikel yang diresubmit **Bukti konfirmasi submit revisi pertama, respon kepada reviewer, dan artikel yang diresubmit (23 Juni 2026)**

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

Revised II

1 message

MS Khabibur Rahman <khabib.ynwa@gmail.com> Tue, Jun 23, 2026 at 2:59 PM
To: geoeco@fkip.uns.ac.id

Dear Editor,

We would like to express our sincere gratitude to you and the reviewers for the valuable comments and constructive suggestions provided on our manuscript.

In response to the reviewers' comments, we have carefully revised the manuscript and addressed all issues raised during the review process. We believe that these revisions have significantly improved the quality, clarity, and scientific contribution of our work.

Please find attached the following documents for your consideration:

1. Revised manuscript.
2. Response to reviewers document detailing how each comment has been addressed.

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Yours sincerely,

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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is one of the most severe environmental problems affecting terrestrial ecosystems, particularly in highland areas experiencing intense rainfall and rapid land-use change (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Human activities have accelerated global soil degradation, with annual soil losses estimated at approximately 75 billion tons (Singh et al. 2023). Beyond degrading land resources, soil erosion reduces

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agricultural productivity, threatens rural livelihoods and food security, and generates significant ecological and socio-economic impacts (Antronico et al. 2020; Hishamunda et al. 2024).

Erosion is intensified by steep slopes, which increase runoff velocity and soil detachment, as well as by unsustainable land use, deforestation, poor agricultural practices, and inadequate conservation measures (Panagos et al. 2016; Zhu et al. 2024). These processes also contribute to river sedimentation, declining water storage capacity, and increased flood risk (Kardhana et al. 2024). Globally, the costs of erosion-related agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually, with developing countries facing the greatest challenges due to limited conservation resources (Carollo et al. 2023, 2024; Molla & Sisheber 2017; Panagos et al. 2015).

Assessing and mapping soil erosion is essential for spatial planning, watershed management, and the development of effective conservation policies (Alewell et al. 2019). Among the available approaches, the Universal Soil Loss Equation (USLE) remains one of the most widely used models for estimating long-term soil loss by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) (Ferro 2010; Li et al. 2024). Its integration with Geographic Information Systems (GIS) has enhanced erosion assessment through spatial analysis, hotspot identification, and conservation prioritization across heterogeneous landscapes (Brychta et al. 2022).

The need for such assessments is particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed that contributes runoff and sediment to the Wonogiri Reservoir. Characterized by steep terrain, agricultural expansion, forest conversion, and growing settlements, the sub-watershed faces high erosion susceptibility and recurring land degradation problems, including soil erosion, sediment transport, and localized landslides. Given its important hydrological role and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area for erosion assessment and conservation planning.

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Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Murdhianti, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales.

The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited.

The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.

MATERIALS AND METHODS

Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km² (Figure 1).

The erosion hazard assessment was conducted using the USLE model integrated with GIS, involving data collection, spatial data processing, land unit delineation through overlay analysis, estimation of soil loss using the factors R, K, LS, C, and P, followed by erosion hazard classification and spatial analysis (Figure2).

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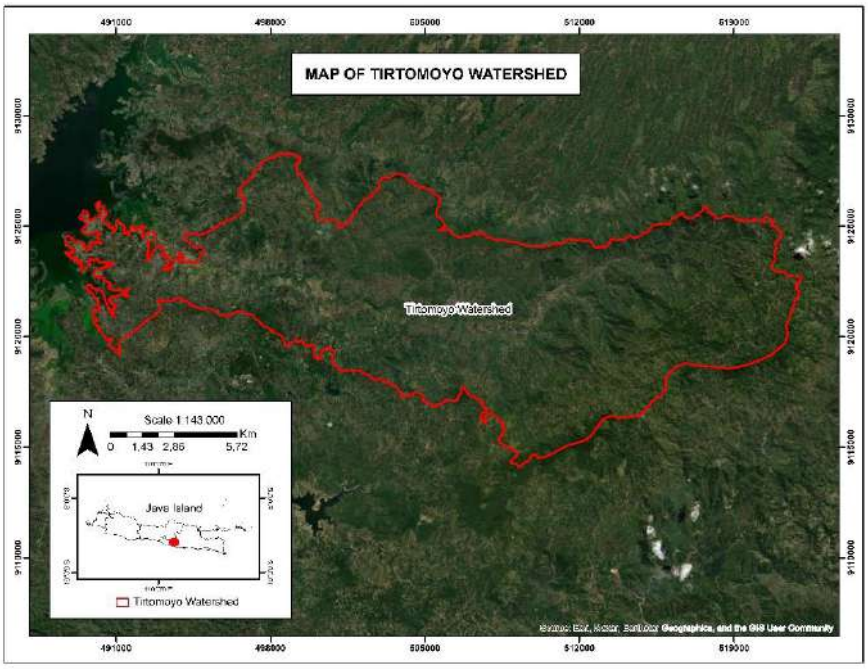

Figure 1. Location of Tirtomoyo Watershed

Source: Author, 2025

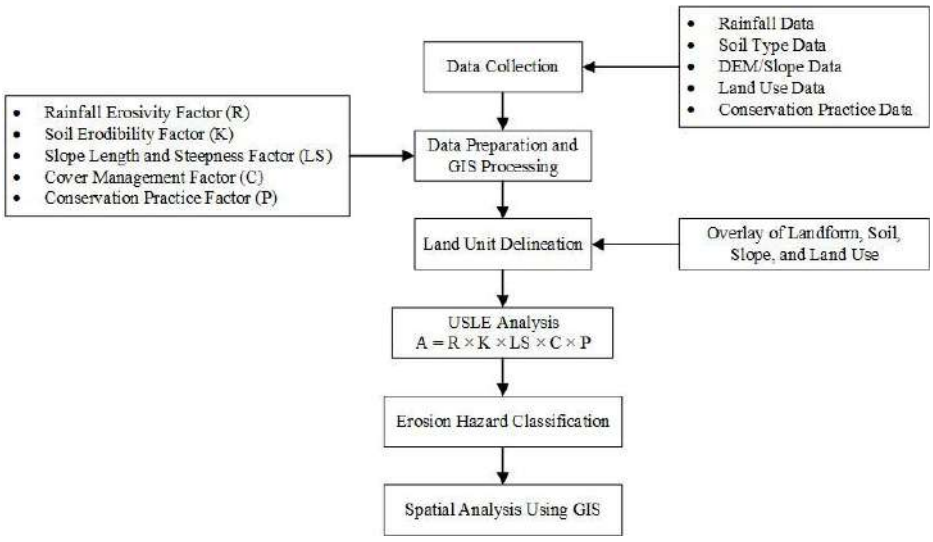

Figure 2. Research Flowchat

Source : Author, 2025

Data Collection

This study applied GIS-based USLE to estimate soil loss and identify conservation priority areas. USLE was selected because it remains suitable for long-term erosion assessment under

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limited rainfall data availability. This model integrates five factors shown in equation 1.

$$A: R \times K \times LS \times C \times P \quad (1)$$

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (1989) empirical shown in equation 2:

$$IR: 2.21 \times P^{1.36} \quad (2)$$

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following shown in equation 3:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100 \quad (3)$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

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Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source : USDA, 1999

Based on USDA standards, soil erosion was classified as very light (<15 t ha^{-1} yr^{-1}), light (15–60), moderate (60–180), severe (180–480), and very severe (>480), representing increasing levels of land degradation and conservation urgency.

Data analysis

Data analysis was conducted using Land Mapping Units (LMUs), defined by combinations of geomorphology, soil type, slope, and land use. A total of 33 LMUs were identified in the Tirtomoyo watershed (Figure 3), providing a more representative basis for analysis than administrative boundaries by capturing biophysical variability. Land units represent areas with relatively homogeneous characteristics (FAO, 1976), and similar approaches have been widely applied using combinations of landform, soil, slope, land use, and geological parameters (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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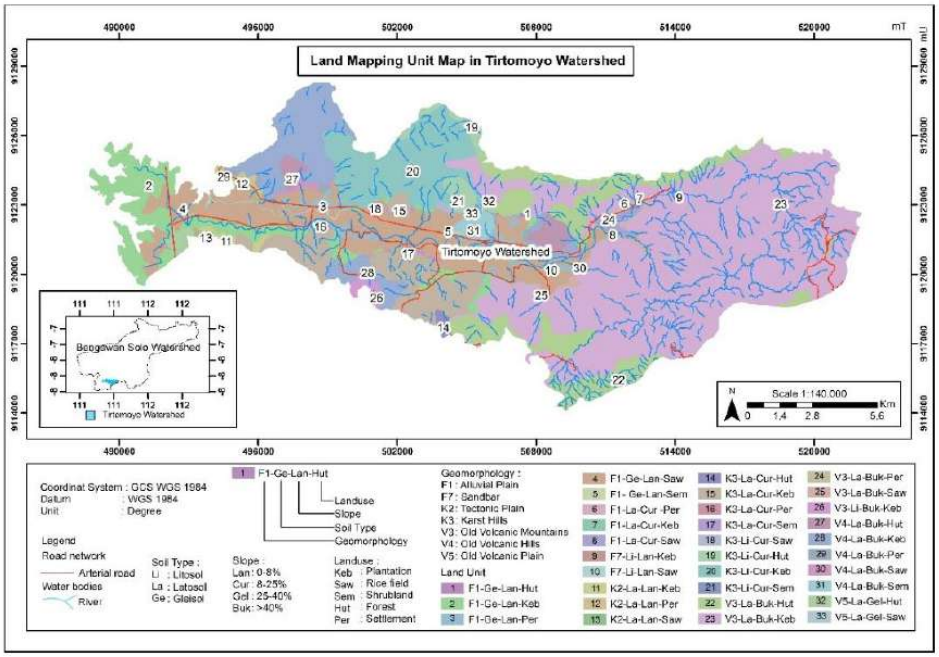

Figure 3. Land Mapping Units of the Tirtomoyo watershed

Source : Author, 2025

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor in the Tirtomoyo watershed was conducted based on precipitation data (Figure 4).

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The average annual rainfall in the Tirtomoyo Sub-watershed is 2,676.42 mm year^{-1}, reflecting a humid tropical climate with high rainfall erosivity potential. This condition is influenced by monsoonal circulation and orographic effects associated with the hilly terrain of southern Central Java, which enhance rainfall intensity and duration. Compared with several watersheds in Central Java, where annual rainfall generally ranges from 1,800 to 2,500 mm year^{-1}, Tirtomoyo receives relatively higher rainfall, indicating elevated erosion risk.

The effect of rainfall is evident in several land units classified as severe to very severe erosion. High-intensity rainfall increases surface runoff when infiltration capacity is exceeded, thereby accelerating soil detachment and transport. However, erosion rates are substantially lower in areas implementing bench terraces and strip cropping, whereas steep cultivated lands without conservation measures remain highly vulnerable. These findings indicate that while rainfall erosivity is a major driver of soil loss, effective land management plays a crucial role in reducing erosion in the Tirtomoyo Sub-watershed.

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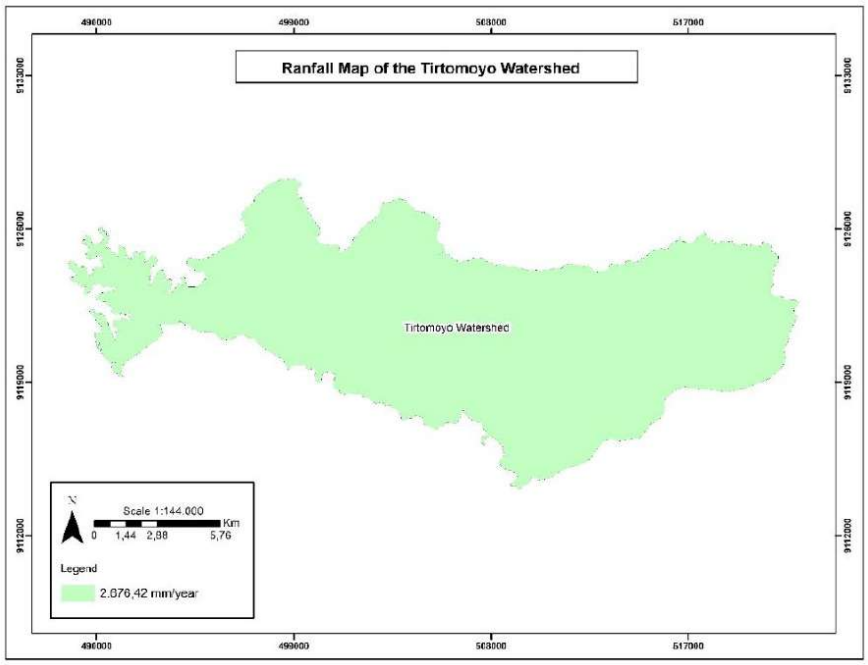

Figure 4. Rainfall Map of Tirtomoyo watershed

Source : Author, 2025

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 5). As shown in Table 3, land units exhibit considerable variation in texture, organic matter content, soil structure, and permeability, which influence erosion susceptibility. The M factor ranges from 162.03 to 2,233.41, with higher values generally indicating greater erodibility. Organic matter content varies from 4.82% to 8.91%; land units with higher organic matter, such as F7-Li-Lan and V3-Li-Buk, tend to have more stable aggregates and lower erosion risk, whereas units with lower organic matter, including K3-La-Cur, V4-La-Buk, and V5-La-Gel, are more susceptible to erosion due to reduced aggregate stability.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source : data processing, 2025

Soil structure varies from poor (value 1) to good granular structure (value 3), while permeability ranges from moderate–rapid (4) to rapid (5). Land units with poor structure, low organic matter, high M values, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, exhibit the highest erosion susceptibility. In contrast, units with higher organic matter, better structure, and rapid permeability, including F7-Li-Lan and V3-Li-Buk, are relatively more resistant to erosion due to improved aggregate stability and infiltration capacity. However, these areas still fall within the severe erosion category, indicating that favorable soil properties alone cannot offset the effects of high rainfall and steep slopes. Areas dominated by clay-rich Litosols, particularly at Point 2, show high K-factor values and therefore

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require conservation priority, as clay soils can intensify erosion on sloping terrain (Luquin et al., 2025).

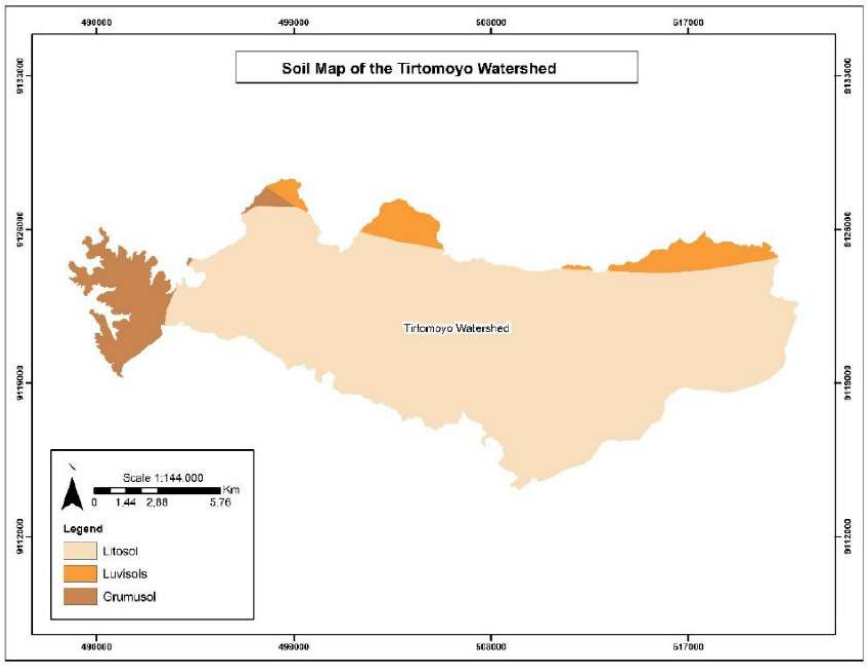

Figure 5. Soil Type Map of Tirtomoyo watershed
Source : Author, 2025

Topographic Factor (LS)

Slope analysis derived from the DEM indicates gradients ranging from 0–8% to >45% across the Tirtomoyo Sub-watershed (Figure 6). Land units on steep to very steep slopes, particularly in the eastern, central, and western areas, are generally classified as severe to very severe erosion zones, such as F7-Li-Lan-Keb and F7-Li-Lan-Saw, due to high LS values that increase runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). Conversely, units on gentle slopes (0–8%), including F1-Ge-Lan-Keb and V3-La-Buk-Saw, exhibit very light to light erosion because of lower erosive energy. Moderate slopes (10–35°) commonly show moderate erosion, especially where conservation measures are limited, as observed in several K3-La-Cur units (Pan et al. 2025). These findings confirm that slope gradient and length are key controls of erosion severity, highlighting steep-slope areas as priority targets for conservation.

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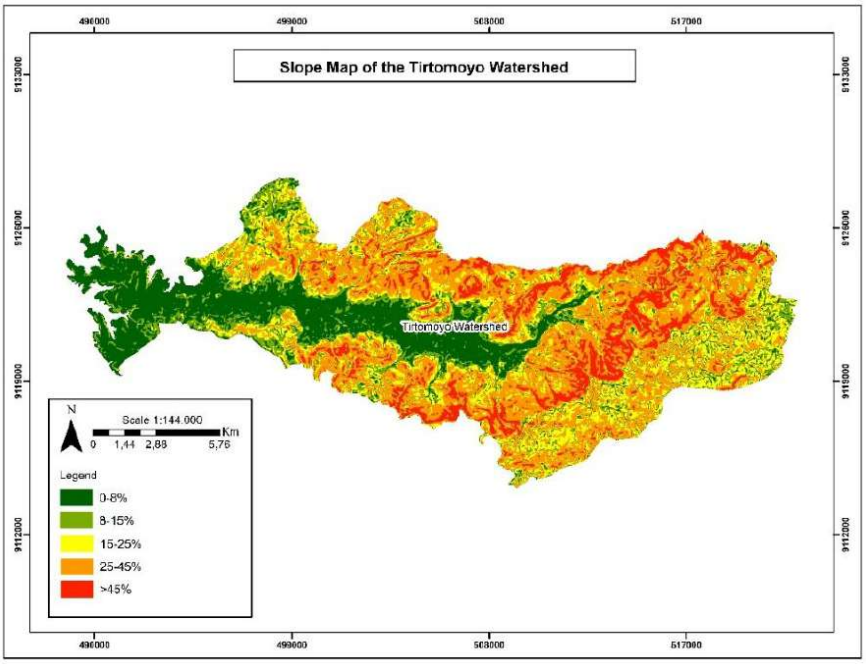

Figure 6. Slope Map of Tirtomoyo watershed
Source : Author, 2025

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak (*Tectona grandis*), alongside rice, maize, banana, bamboo, elephant grass, and mango, reflecting the predominance of forestry and agricultural activities (Figure 7). Teak and bamboo provide effective soil protection through dense canopy cover and extensive root systems, resulting in lower C-factor values, whereas paddy fields and seasonal crops generally exhibit higher C values, particularly during planting or fallow periods. The C factor reflects the ability of vegetation to reduce raindrop impact and surface runoff, thereby minimizing erosion (Mas et al., 2024). Consequently, agricultural areas with seasonal vegetation are more vulnerable to erosion and require conservation measures such as mulching, cover crops, or agroforestry systems.

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a b

Figure 7. (a) *Zea mays L.* and (b) *Bambusoideae*

Source : Author, 2025

Conservation Practice Factor (P)

Various soil and water conservation practices, including agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo Sub-watershed, although many areas remain unmanaged. These practices influence the USLE P factor by reducing runoff velocity and increasing infiltration, thereby lowering erosion risk. Bench terraces are the dominant conservation measure on sloping land (Figure 8). In contrast, areas without conservation have P values close to 1, indicating minimal erosion control and greater vulnerability, particularly on steep slopes under high rainfall. Therefore, mapping P-factor distribution is important for identifying conservation priorities and supporting effective land management.

Figure 8. Terracing Conservation Technique

Source : Author, 2025

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Erosion Susceptibility of Tirtomoyo Sub-watershed

Table 4 shows that conservation practices strongly influence erosion rates. Bench terraces and strip cropping are the most effective measures on cultivated land, while agroforestry provides moderate protection, although its effectiveness may decline on steep slopes under high rainfall conditions (Jose et al., 2022). Areas without conservation exhibit the highest erosion vulnerability, highlighting the importance of expanding soil and water conservation measures. Bench terraces reduce runoff velocity and soil loss, whereas strip cropping limits runoff and sediment transport by interrupting surface flow pathways (FAO, 1986; El Jazouli et al., 2023).

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate

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Land Unit	C	Conservation Method	Class
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 9 shows that moderate erosion is the dominant class in the Tirtomoyo watershed, covering approximately 10,386 ha, followed by mild erosion (6,670 ha) and very mild erosion (2,953 ha). Severe and very severe erosion occupy smaller areas, covering 1,772 ha and 52 ha, respectively.

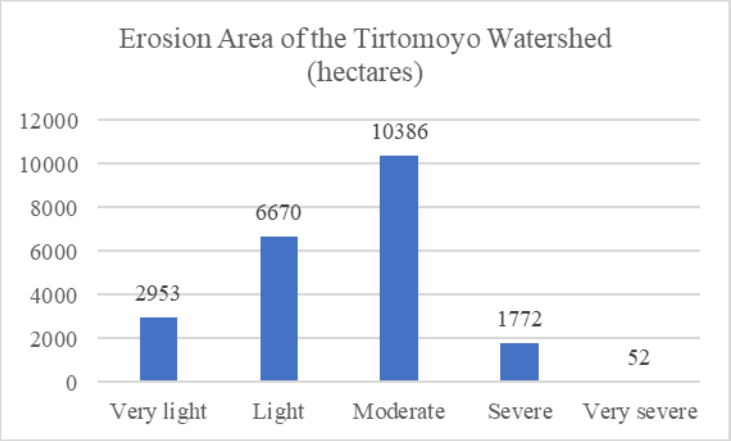

Figure 9. Erosion Susceptibility of Tirtomoyo watershed

Source : Author, 2025

Although very severe erosion is limited, the dominance of moderate and mild erosion poses a significant management concern (Figure 10). These areas require priority conservation measures to prevent further degradation, while severe erosion zones need continued protection to limit the expansion of damage.

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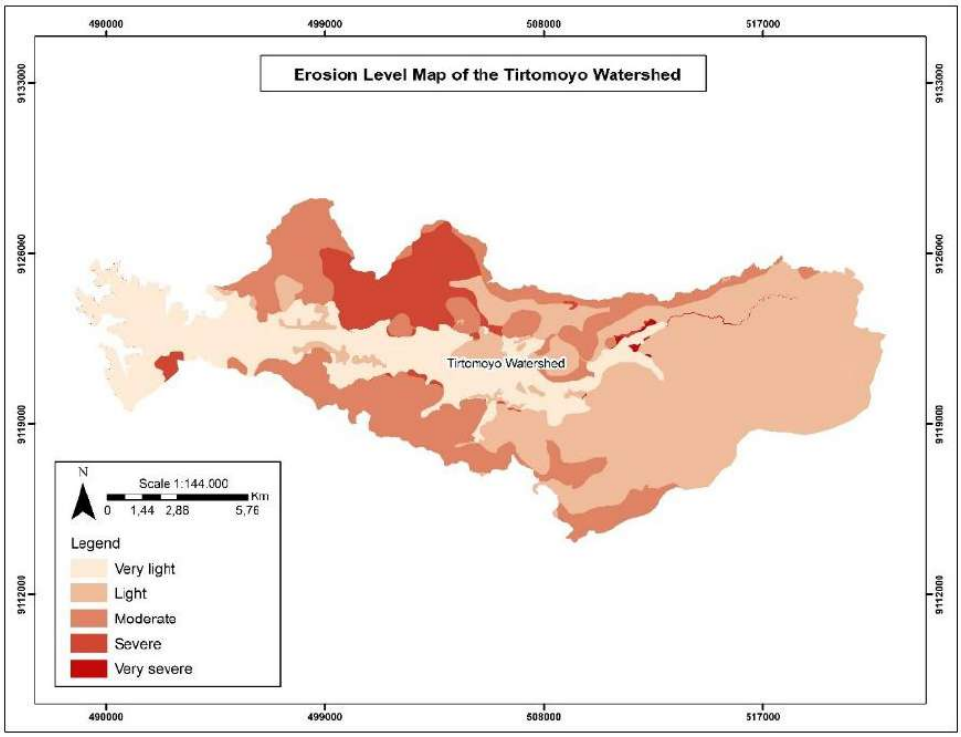

Figure 10. Erosion Map of Tirtomoyo watershed

Source : data processing, 2025

The Tirtomoyo watershed consists of diverse landforms and soil types, including alluvial plains, karst hills, old volcanic landscapes, and soils such as Litosols, Latosols, and Gleysols, with land cover dominated by forests, plantations, paddy fields, settlements, and shrublands. Moderate erosion is the dominant class, particularly in undulating to steep areas (8–40%) used for plantations and mixed agriculture. Severe to very severe erosion occurs mainly on steep slopes (>40%) with sparse vegetation and limited conservation practices, such as in the V3-La-Buk and V4-La-Buk land units. Areas with teak-based agroforestry generally exhibit lower CP values and reduced erosion, whereas seasonal crops on steep slopes without conservation measures show higher CP values and greater erosion risk. Although conservation practices such as terracing, strip cropping, and agroforestry are present, their implementation remains uneven across critical areas.

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Figure 11. Gully Erosion in Tirtomoyo watershed
Source : Author, 2025

Figure 11 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes

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(>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently

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occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas.

This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

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6. Bukti konfirmasi review **dan hasil review ketiga (24 Juni 2026)**

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

[GE] Editor Decision

1 message

Chatarina Muryani <jurnal@mail.uns.ac.id> Wed, Jun 24, 2026 at 11:53 AM
Reply-To: Hendra Hendra <hendra@ung.ac.id>
To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

The following message is being delivered on behalf of GeoEco.

MS Khabibur Rahman:

Thank you for the article you have submitted to us.

After reviewing your manuscript, we have identified several minor revisions that require correction. These revisions do not affect the main substance of the article, but are necessary to improve the clarity and quality of the presentation.

We kindly request that you make corrections according to the attached notes and resubmit the revised manuscript.

Thank you for your attention and cooperation.
Regards
Hendra Hendra
Scopus ID : 57200752912, Department of Geography Education, Universitas Negeri Gorontalo

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7. Bukti konfirmasi submit **revisi** kedua, respon kepada reviewer, dan artikel yang diresubmit
(28 Juni 2026)

Table of Question and Answer

Question	Answer
Not in the reference list	Thank you for your comment. We have revised it. • JICA, 2007. Penanganan sedimentasi Waduk Wonogiri, Surakarta. • Felani, G. F., Sholichin, M., & Sayekti, R. W. (2023). Perencanaan pengendalian erosi dan sedimentasi di DAS Waduk Nawangan Kabupaten Wonogiri Jawa Tengah. Jurnal Teknologi dan Rekayasa Sumber Daya Air, 3(1), 146–160. • Asdak, C., (2007). Hidrologi dan Pengelolaan Daerah Aliran Sungai, Gadjah Mada University Press, Yogyakarta. • Maharani, B. V., Wahyuni, S., & Harisuseno, D. (2021). Analisis evaporasi Waduk Wonorejo Kabupaten Tulungagung menggunakan pendekatan empiris. Jurnal Teknologi dan Rekayasa Sumber Daya Air, 1(2), 917–928. • Palupi, G. A., Sholichin, M., & Sisinggih, D. (2023). Analisa erosi dan sedimentasi Waduk Parangjoho Kabupaten Wonogiri menggunakan metode MUSLE dan peningkatan kapasitas tampungan waduk. Jurnal Teknologi dan Rekayasa Sumber Daya Air, 3(1), 110–123. • Juwono, P. T., Asmaranto, R., & Murdhianti, A. (2020). Useful life of Ngancar Reservoir due to erosion and sedimentation. International Journal of Recent Technology and Engineering (IJRTE), 9(2), 661–667. https://doi.org/10.35940/ijrte.B3825.079220

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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS, Environmental, Soil, USLE*

INTRODUCTION

Soil erosion is one of the most severe environmental problems affecting terrestrial ecosystems, particularly in highland areas experiencing intense rainfall and rapid land-use change (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Human activities have accelerated global soil degradation, with annual soil losses estimated at approximately 75 billion tons (Singh et al. 2023). Beyond degrading land resources, soil erosion reduces

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agricultural productivity, threatens rural livelihoods and food security, and generates significant ecological and socio-economic impacts (Antronico et al. 2020; Hishamunda et al. 2024).

Erosion is intensified by steep slopes, which increase runoff velocity and soil detachment, as well as by unsustainable land use, deforestation, poor agricultural practices, and inadequate conservation measures (Panagos et al. 2016; Zhu et al. 2024). These processes also contribute to river sedimentation, declining water storage capacity, and increased flood risk (Kardhana et al. 2024). Globally, the costs of erosion-related agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually, with developing countries facing the greatest challenges due to limited conservation resources (Carollo et al. 2024; Molla & Sisheber 2017; Panagos et al. 2015).

Assessing and mapping soil erosion is essential for spatial planning, watershed management, and the development of effective conservation policies (Alewell et al. 2019). Among the available approaches, the Universal Soil Loss Equation (USLE) remains one of the most widely used models for estimating long-term soil loss by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) (Ferro 2010; Li et al. 2024). Its integration with Geographic Information Systems (GIS) has enhanced erosion assessment through spatial analysis, hotspot identification, and conservation prioritization across heterogeneous landscapes (Brychta et al. 2022).

The need for such assessments is particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed that contributes runoff and sediment to the Wonogiri Reservoir. Characterized by steep terrain, agricultural expansion, forest conversion, and growing settlements, the sub-watershed faces high erosion susceptibility and recurring land degradation problems, including soil erosion, sediment transport, and localized landslides. Given its important hydrological role and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area for erosion assessment and conservation planning.

Field evidence shows gully erosion and riverbank instability, while JICA

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(2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Juwono, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales.

The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited.

The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.

MATERIALS AND METHODS

Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km² (Figure 1).

The erosion hazard assessment was conducted using the USLE model integrated with GIS, involving data collection, spatial data processing, land unit delineation through overlay analysis, estimation of soil loss using the factors R, K, LS, C, and P, followed by erosion hazard classification and spatial analysis (Figure2).

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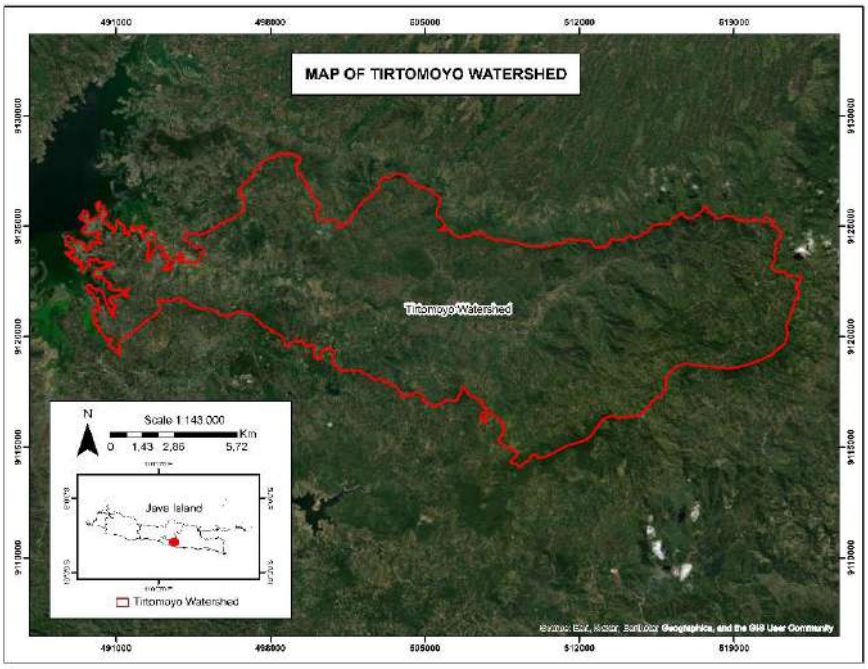

Figure 1. Location of Tirtomoyo Watershed

Source: Author, 2025

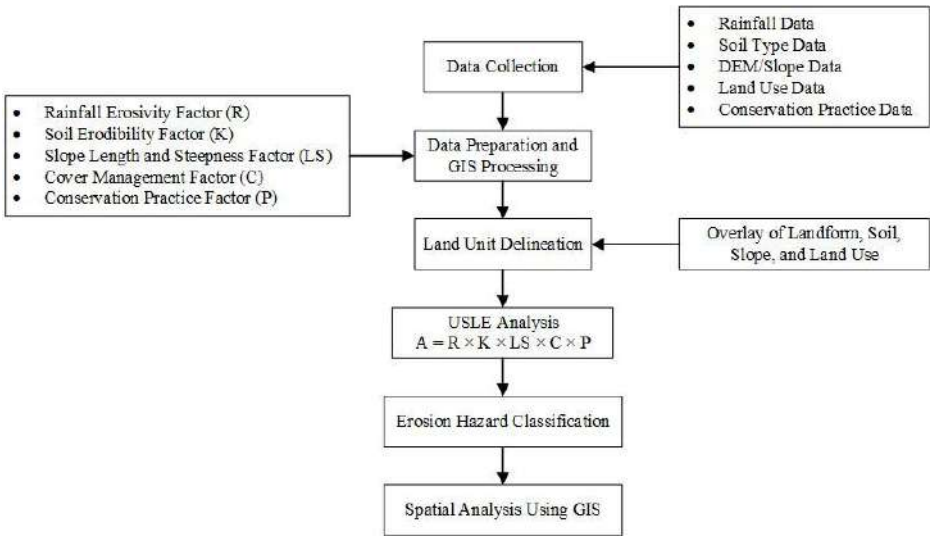

Figure 2. Research Flowchat

Source : Author, 2025

Data Collection

This study applied GIS-based USLE to estimate soil loss and identify conservation priority areas. USLE was selected because it remains suitable for long-term erosion assessment under

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limited rainfall data availability. This model integrates five factors shown in equation 1.

$$A: R \times K \times LS \times C \times P \quad (1)$$

A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (DHV, 1989 in Asdak, 2007) empirical shown in equation 2:

$$IR: 2.21 \times P^{1.36} \quad (2)$$

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following shown in equation 3:

$$K=100\{2.71\times M1.14(10-4)(12-oM)+4.20(s-2)+3.23(p-3)\}/100 \quad (3)$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

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Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source : USDA, 1999

Based on USDA standards, soil erosion was classified as very light (<15 t ha^{-1} yr^{-1}), light (15–60), moderate (60–180), severe (180–480), and very severe (>480), representing increasing levels of land degradation and conservation urgency.

Data analysis

Data analysis was conducted using Land Mapping Units (LMUs), defined by combinations of geomorphology, soil type, slope, and land use. A total of 33 LMUs were identified in the Tirtomoyo watershed (Figure 3), providing a more representative basis for analysis than administrative boundaries by capturing biophysical variability. Land units represent areas with relatively homogeneous characteristics (FAO, 1976), and similar approaches have been widely applied using combinations of landform, soil, slope, land use, and geological parameters (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

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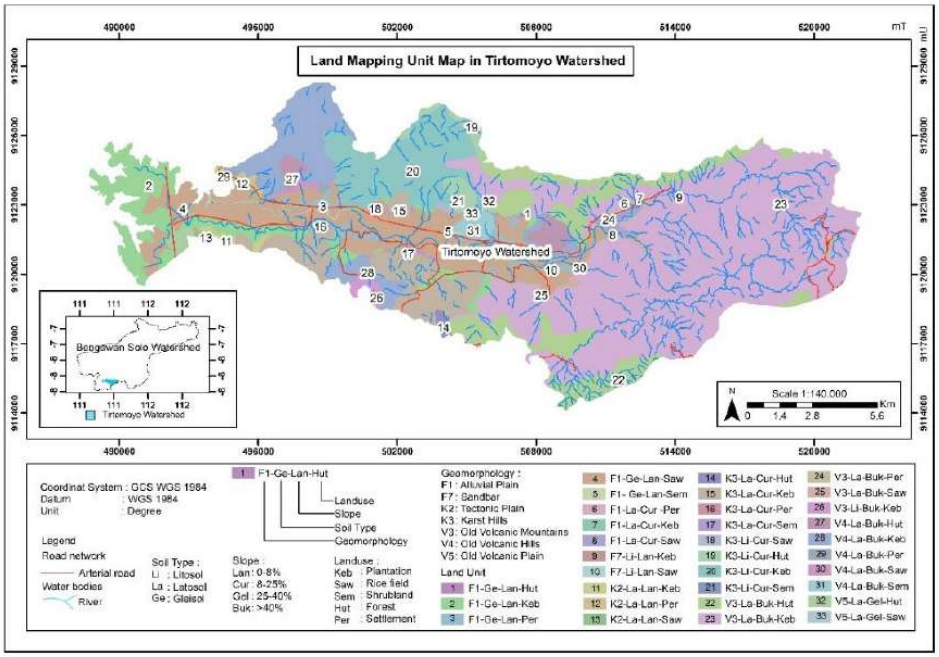

Figure 3. Land Mapping Units of the Tirtomoyo watershed

Source : Author, 2025

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor in the Tirtomoyo watershed was conducted based on precipitation data (Figure 4).

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5

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Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source : River Basin Development Authority of Bengawan Solo

The average annual rainfall in the Tirtomoyo Sub-watershed is 2,676.42 mm year^{-1}, reflecting a humid tropical climate with high rainfall erosivity potential. This condition is influenced by monsoonal circulation and orographic effects associated with the hilly terrain of southern Central Java, which enhance rainfall intensity and duration. Compared with several watersheds in Central Java, where annual rainfall generally ranges from 1,800 to 2,500 mm year^{-1}, Tirtomoyo receives relatively higher rainfall, indicating elevated erosion risk.

The effect of rainfall is evident in several land units classified as severe to very severe erosion. High-intensity rainfall increases surface runoff when infiltration capacity is exceeded, thereby accelerating soil detachment and transport. However, erosion rates are substantially lower in areas implementing bench terraces and strip cropping, whereas steep cultivated lands without conservation measures remain highly vulnerable. These findings indicate that while rainfall erosivity is a major driver of soil loss, effective land management plays a crucial role in reducing erosion in the Tirtomoyo Sub-watershed.

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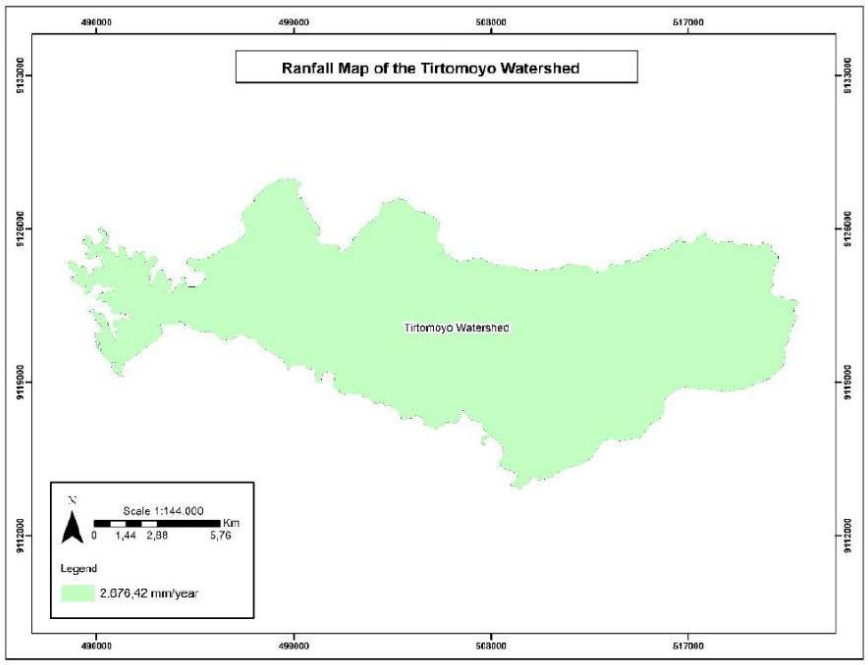

Figure 4. Rainfall Map of Tirtomoyo watershed

Source : Author, 2025

Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (Figure 5). As shown in Table 3, land units exhibit considerable variation in texture, organic matter content, soil structure, and permeability, which influence erosion susceptibility. The M factor ranges from 162.03 to 2,233.41, with higher values generally indicating greater erodibility. Organic matter content varies from 4.82% to 8.91%; land units with higher organic matter, such as F7-Li-Lan and V3-Li-Buk, tend to have more stable aggregates and lower erosion risk, whereas units with lower organic matter, including K3-La-Cur, V4-La-Buk, and V5-La-Gel, are more susceptible to erosion due to reduced aggregate stability.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4

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Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source : data processing, 2025

Soil structure varies from poor (value 1) to good granular structure (value 3), while permeability ranges from moderate–rapid (4) to rapid (5). Land units with poor structure, low organic matter, high M values, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, exhibit the highest erosion susceptibility. In contrast, units with higher organic matter, better structure, and rapid permeability, including F7-Li-Lan and V3-Li-Buk, are relatively more resistant to erosion due to improved aggregate stability and infiltration capacity. However, these areas still fall within the severe erosion category, indicating that favorable soil properties alone cannot offset the effects of high rainfall and steep slopes. Areas dominated by clay-rich Litosols, particularly at Point 2, show high K-factor values and therefore

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require conservation priority, as clay soils can intensify erosion on sloping terrain (Luquin et al., 2025).

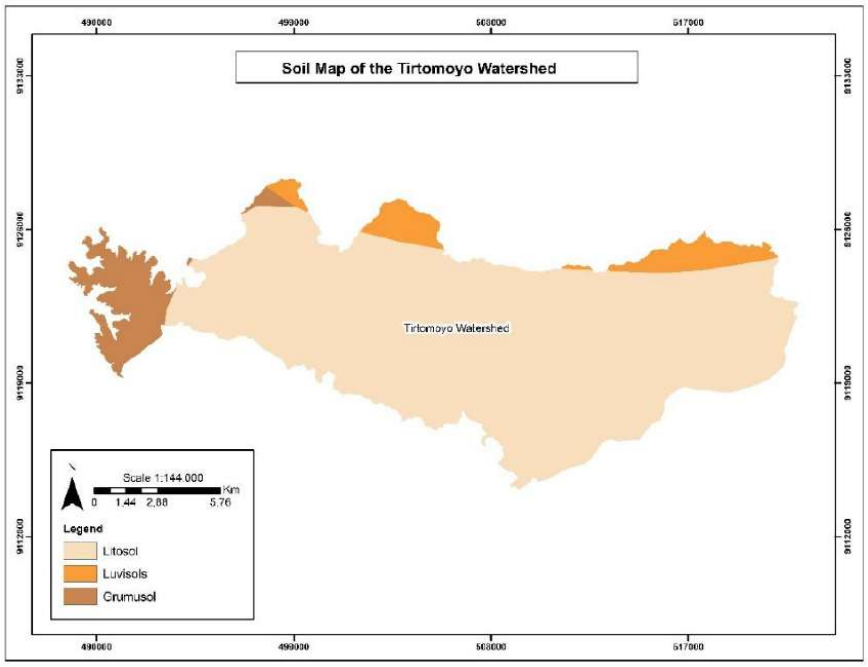

Figure 5. Soil Type Map of Tirtomoyo watershed
Source : Author, 2025

Topographic Factor (LS)

Slope analysis derived from the DEM indicates gradients ranging from 0–8% to >45% across the Tirtomoyo Sub-watershed (Figure 6). Land units on steep to very steep slopes, particularly in the eastern, central, and western areas, are generally classified as severe to very severe erosion zones, such as F7-Li-Lan-Keb and F7-Li-Lan-Saw, due to high LS values that increase runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). Conversely, units on gentle slopes (0–8%), including F1-Ge-Lan-Keb and V3-La-Buk-Saw, exhibit very light to light erosion because of lower erosive energy. Moderate slopes (10–35°) commonly show moderate erosion, especially where conservation measures are limited, as observed in several K3-La-Cur units (Pan et al. 2025). These findings confirm that slope gradient and length are key controls of erosion severity, highlighting steep-slope areas as priority targets for conservation.

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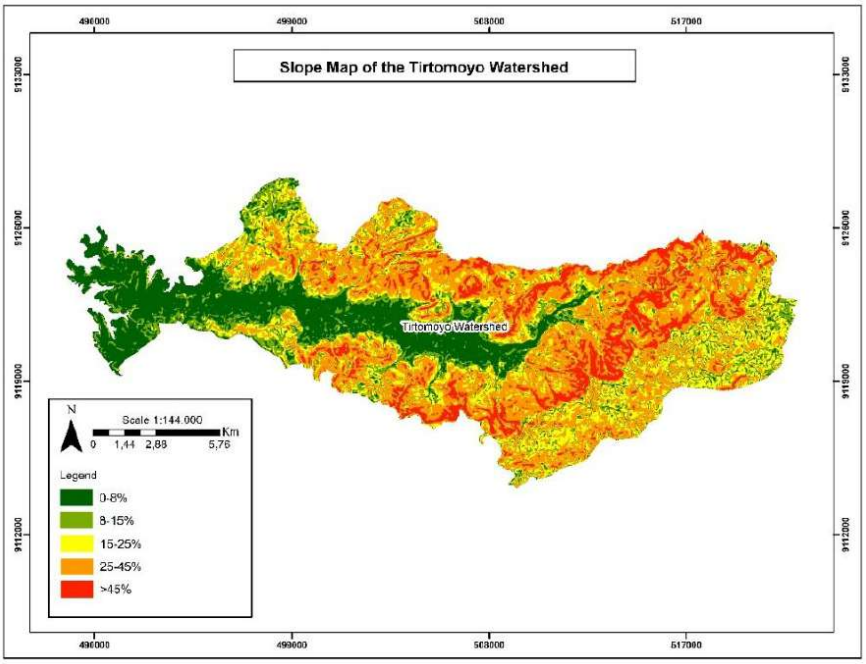

Figure 6. Slope Map of Tirtomoyo watershed
Source : Author, 2025

Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak (*Tectona grandis*), alongside rice, maize, banana, bamboo, elephant grass, and mango, reflecting the predominance of forestry and agricultural activities (Figure 7). Teak and bamboo provide effective soil protection through dense canopy cover and extensive root systems, resulting in lower C-factor values, whereas paddy fields and seasonal crops generally exhibit higher C values, particularly during planting or fallow periods. The C factor reflects the ability of vegetation to reduce raindrop impact and surface runoff, thereby minimizing erosion (Mas et al., 2024). Consequently, agricultural areas with seasonal vegetation are more vulnerable to erosion and require conservation measures such as mulching, cover crops, or agroforestry systems.

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a b

Figure 7. (a) *Zea mays L.* and (b) *Bambusoideae*

Source : Author, 2025

Conservation Practice Factor (P)

Various soil and water conservation practices, including agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo Sub-watershed, although many areas remain unmanaged. These practices influence the USLE P factor by reducing runoff velocity and increasing infiltration, thereby lowering erosion risk. Bench terraces are the dominant conservation measure on sloping land (Figure 8). In contrast, areas without conservation have P values close to 1, indicating minimal erosion control and greater vulnerability, particularly on steep slopes under high rainfall. Therefore, mapping P-factor distribution is important for identifying conservation priorities and supporting effective land management.

Figure 8. Terracing Conservation Technique

Source : Author, 2025

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Erosion Susceptibility of Tirtomoyo Sub-watershed

Table 4 shows that conservation practices strongly influence erosion rates. Bench terraces and strip cropping are the most effective measures on cultivated land, while agroforestry provides moderate protection, although its effectiveness may decline on steep slopes under high rainfall conditions (Jose et al., 2022). Areas without conservation exhibit the highest erosion vulnerability, highlighting the importance of expanding soil and water conservation measures. Bench terraces reduce runoff velocity and soil loss, whereas strip cropping limits runoff and sediment transport by interrupting surface flow pathways (FAO, 1986; El Jazouli et al., 2023).

Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate

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Land Unit	C	Conservation Method	Class
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source : data processing, 2025

Figure 9 shows that moderate erosion is the dominant class in the Tirtomoyo watershed, covering approximately 10,386 ha, followed by mild erosion (6,670 ha) and very mild erosion (2,953 ha). Severe and very severe erosion occupy smaller areas, covering 1,772 ha and 52 ha, respectively.

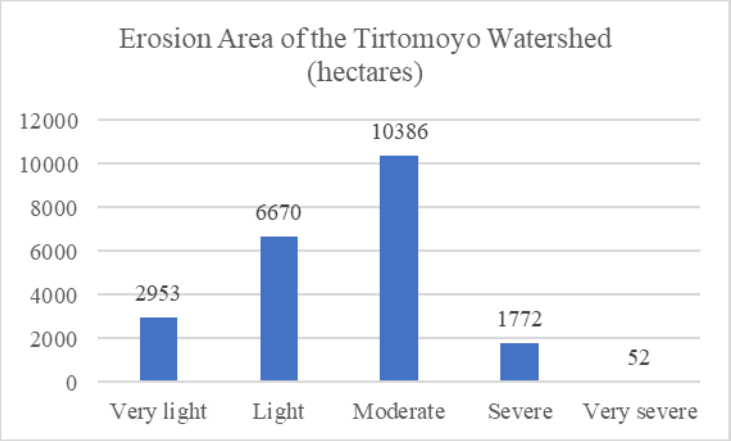

Figure 9. Erosion Susceptibility of Tirtomoyo watershed

Source : Author, 2025

Although very severe erosion is limited, the dominance of moderate and mild erosion poses a significant management concern (Figure 10). These areas require priority conservation measures to prevent further degradation, while severe erosion zones need continued protection to limit the expansion of damage.

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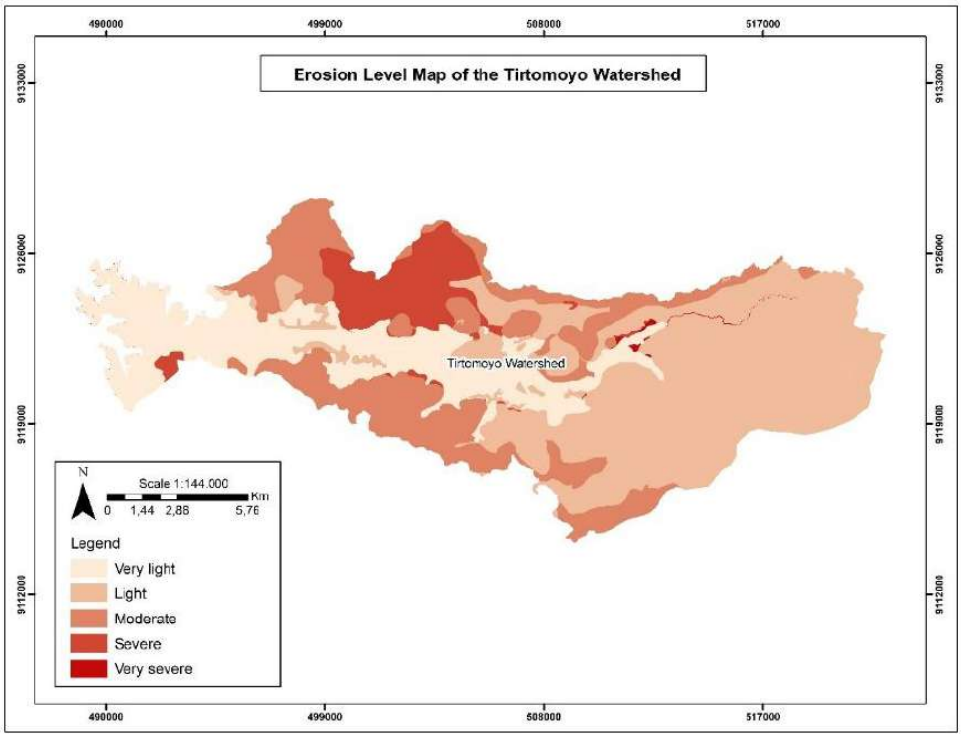

Figure 10. Erosion Map of Tirtomoyo watershed

Source : data processing, 2025

The Tirtomoyo watershed consists of diverse landforms and soil types, including alluvial plains, karst hills, old volcanic landscapes, and soils such as Litosols, Latosols, and Gleysols, with land cover dominated by forests, plantations, paddy fields, settlements, and shrublands. Moderate erosion is the dominant class, particularly in undulating to steep areas (8–40%) used for plantations and mixed agriculture. Severe to very severe erosion occurs mainly on steep slopes (>40%) with sparse vegetation and limited conservation practices, such as in the V3-La-Buk and V4-La-Buk land units. Areas with teak-based agroforestry generally exhibit lower CP values and reduced erosion, whereas seasonal crops on steep slopes without conservation measures show higher CP values and greater erosion risk. Although conservation practices such as terracing, strip cropping, and agroforestry are present, their implementation remains uneven across critical areas.

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Figure 11. Gully Erosion in Tirtomoyo watershed
Source : Author, 2025

Figure 11 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes

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(>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently

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occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas.

This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

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8. Bukti konfirmasi artikel accepted
(20 Juni 2026)

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

[GE] Editor Decision

1 message

Chatarina Muryani <jurnal@mail.uns.ac.id> Mon, Jun 29, 2026 at 2:12 PM
Reply-To: Hendra Hendra <hendra@ung.ac.id>
To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

The following message is being delivered on behalf of GeoEco.

MS Khabibur Rahman:

We are delighted to inform you that your manuscript entitled “SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED” has been officially accepted for publication in GeoEco following a thorough and rigorous peer-review process.

The reviewers and the editorial committee highly appreciate the clarity of your writing, the quality of your analysis, and the significant scholarly contribution your study offers to the field. Your manuscript meets the scientific and ethical standards of our journal, and we believe it will be a valuable addition to the current body of knowledge.

Furthermore, should you be willing to proceed with the publication fee, your article will be scheduled for publication in the upcoming issue, specifically Volume Vol 12 No 2 in July 2026. Based on the provisions contained in the Author Guidelines (https://jurnal.uns.ac.id/GeoEco/about/submissions#authorGuidelines), the publication fee of IDR 1,500,000 can be made via bank transfer to the following account:

Bank: BCA
Account Number: 3271135031
Account Holder: Chatarina Muryani

Please send your payment proof to: geoeco@fkip.uns.ac.id
and also upload it via the following link:
https://bit.ly/PaymentProofGeoEco

Thank you for choosing GeoEco as the platform to disseminate your research findings. We truly appreciate your dedication and look forward to the possibility of receiving your future submissions.

Best Regards
Hendra Hendra
Scopus ID : 57200752912, Department of Geography Education, Universitas Negeri Gorontalo

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9. Bukti LoA **(30 Juni 2026)**

GeoEco

Editorial Office: Department of Geography Education, Universitas Sebelas Maret, Jalan Ir. Sutami 36 A, Surakarta, 57126, Indonesia, Tel. +62-89510320291, E-mail: geoeco@fkip.uns.ac.id

LETTER OF ACCEPTANCE

30 June 2026

Dear MS Khabibur Rahman, et al

Based on the results of the review process and the decision of the editorial board, we hereby declare that your scientific article:

Article Title	: Soil Erosion Modeling and Conservation Priority Mapping in The Tirtomoyo Sub-Watershed
Authors	: MS Khabibur Rahman, et al
Journal	: GeoEco (Sinta 2 Accreditation)
Volume and Issue	: Volume 12 No 2 July 2026

ACCEPTED for publication in GeoEco after going through an assessment process according to applicable academic standards and publication ethics.

We congratulate you on the acceptance of your article and thank you for your contribution to the development of science through scientific publication.

If necessary, please contact us for further information.

Thank you.

Geoeco Journal

Prof. Dr. Chatarina Muryani, M.Si
Editor in Chief GeoEco

10. Bukti Copyediting Review Request
(13 Juli 2026)

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

[GE] Copyediting Review Request

2 messages

Chatarina Muryani <jurnal@mail.uns.ac.id> Mon, Jul 13, 2026 at 4:13 PM
Reply-To: Hendra Hendra <hendra@ung.ac.id>
To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

The following message is being delivered on behalf of GeoEco.

MS Khabibur Rahman:

Your submission "SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED" for GeoEco has been through the first step of copyediting, and is available for you to review by following these steps.

1. Click on the Submission URL below.
2. Log into the journal and click on the File that appears in Step 1.
3. Open the downloaded submission.
4. Review the text, including copyediting proposals and Author Queries.
5. Make any copyediting changes that would further improve the text.
6. When completed, upload the file in Step 2.
7. Click on METADATA to check indexing information for completeness and accuracy.
8. Send the COMPLETE email to the editor and copyeditor.

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Username: ms_kr

This is the last opportunity to make substantial copyediting changes to the submission. The proofreading stage, that follows the preparation of the galleys, is restricted to correcting typographical and layout errors.

If you are unable to undertake this work at this time or have any questions, please contact me. Thank you for your contribution to this journal.

Hendra Hendra
Scopus ID : 57200752912, Department of Geography Education, Universitas Negeri Gorontalo

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MS Khabibur Rahman <khabib.ynwa@gmail.com> Mon, Jul 13, 2026 at 7:16 PM
To: Hendra Hendra <hendra@ung.ac.id>

Lengkap
[Quoted text hidden]

11. Bukti konfirmasi artikel published
(14 Juli 2026)

Gmail **MS Khabibur Rahman <khabib.ynwa@gmail.com>**

[GE] Copyediting Review Acknowledgement

1 message

Chatarina Muryani <jurnal@mail.uns.ac.id> Wed, Jul 15, 2026 at 10:42 AM
Reply-To: Hendra Hendra <hendra@ung.ac.id>
To: MS Khabibur Rahman <khabib.ynwa@gmail.com>

The following message is being delivered on behalf of GeoEco.

_____

MS Khabibur Rahman:

Thank you for reviewing the copyediting of your manuscript, "SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED," for GeoEco. We look forward to publishing this work.

Hendra Hendra
Scopus ID : 57200752912, Department of Geography Education, Universitas Negeri Gorontalo
hendra@ung.ac.id

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SOIL EROSION MODELING AND CONSERVATION PRIORITY MAPPING IN THE TIRTOMOYO SUB-WATERSHED

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ABSTRACT

The Tirtomoyo sub-watershed is characterized by highland topography and is currently under considerable pressure from anthropogenic activities. Such conditions have contributed to significant soil erosion, which poses a major threat to land productivity and environmental sustainability in the area. The main objective of this research is to analyze the potential soil loss within the sub-watershed. The Universal Soil Loss Equation (USLE) method was applied, as it provides a systematic approach to understanding the relationship between soil loss and the contributing factors of erosion. These factors include soil erodibility (K), slope length and steepness (LS), land use (C), land management practices (P), and rainfall erosivity (R). The unit of analysis was based on land mapping units, allowing for spatially detailed assessment of erosion vulnerability. The results of the study indicate that the Tirtomoyo sub-watershed exhibits varying degrees of erosion susceptibility, with moderate erosion being the most dominant class. The physical condition of the area, consisting of rolling to steep terrain, combined with insufficient vegetation cover and limited conservation practices, has exacerbated soil loss. Field observations also identified the presence of gully erosion, where concentrated surface runoff has carved deep and wide channels, highlighting the severity of land degradation in certain locations. These findings emphasize the urgency of implementing appropriate land management strategies to reduce the erosion rate. Measures such as vegetation restoration, terracing, and improved soil conservation practices are essential to maintain land productivity and minimize environmental impacts.

Keywords: *ArcGIS; environmental; soil; USLE*

INTRODUCTION

Soil erosion is one of the most severe environmental problems affecting terrestrial ecosystems, particularly in highland areas experiencing intense rainfall and rapid land-use change (Ashiagbor et al. 2013; Pham et al. 2018; Ristić et al. 2012). Human activities have accelerated global soil degradation,

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with annual soil losses estimated at approximately 75 billion tons (Singh et al. 2023). Beyond degrading land resources, soil erosion reduces agricultural productivity, threatens rural livelihoods and food security, and generates significant ecological and socio-economic impacts (Antronico et al. 2020; Hishamunda et al. 2024).

Erosion is intensified by steep slopes, which increase runoff velocity and soil detachment, as well as by unsustainable land use, deforestation, poor agricultural practices, and inadequate conservation measures (Panagos et al. 2016; Zhu et al. 2024). These processes also contribute to river sedimentation, declining water storage capacity, and increased flood risk (Kardhana et al. 2024). Globally, the costs of erosion-related agricultural losses, infrastructure damage, and sediment management are estimated at around USD 20 billion annually, with developing countries facing the greatest challenges due to limited conservation resources (Carollo et al. 2024; Molla & Sisheber 2017; Panagos et al. 2015).

Assessing and mapping soil erosion is essential for spatial planning, watershed management, and the development of effective conservation policies (Alewell et al. 2019). Among the available approaches, the Universal Soil Loss Equation (USLE) remains one of the most widely used models for estimating long-term soil loss by integrating rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), cover management (C), and conservation practices (P) (Ferro 2010; Li et al. 2024). Its integration with Geographic Information Systems (GIS) has enhanced erosion assessment through spatial analysis, hotspot identification, and conservation prioritization across heterogeneous landscapes (Brychta et al. 2022).

The need for such assessments is particularly evident in the Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed that contributes runoff and sediment to the Wonogiri Reservoir. Characterized by steep terrain, agricultural expansion, forest conversion, and growing settlements, the sub-watershed faces high erosion susceptibility and recurring land degradation problems, including soil erosion, sediment transport, and localized landslides. Given its important hydrological role and contribution to reservoir sedimentation, the Tirtomoyo Sub-watershed represents a critical area

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for erosion assessment and conservation planning.

Field evidence shows gully erosion and riverbank instability, while JICA (2007) identified the area as a major sediment source for the Wonogiri Reservoir, producing millions of tons annually. Landslides further indicate significant slope instability.

Previous studies in the Wonogiri region and the Upper Bengawan Solo watershed have assessed soil erosion and sedimentation using USLE- and MUSLE-based approaches, particularly in the Keduang, Krisak, Parangjoho, and Nawangan watersheds, as well as the Wonogiri Reservoir (Sutrisno et al., 2011; Santosa, 2016; Juwono, 2021; Putri et al., 2023; Palupi et al., 2023; Felani et al., 2023). These studies mainly focused on erosion rates, sediment yield, erosion hazards, and reservoir sedimentation impacts at watershed and reservoir scales.

The Tirtomoyo Sub-watershed (Wonogiri–Pacitan), a strategic tributary of the Upper Bengawan Solo watershed, contributes significant runoff and sediment to the Wonogiri Reservoir. Despite its high erosion susceptibility resulting from steep terrain, intensive agriculture, land-use change, and recurrent landslide events, spatial assessments of soil-loss variability at the land-unit scale remain limited.

The novelty of this study lies in applying a GIS-based USLE approach with recent spatial datasets to quantify soil loss, map erosion risk, and identify conservation priority areas at the land-unit level in the Tirtomoyo Sub-watershed. By providing a more spatially explicit evaluation of erosion hotspots than previous watershed-scale studies, this research supports targeted conservation planning and sustainable watershed management.

MATERIALS AND METHODS

1. Study area

This study was conducted in the Tirtomoyo Sub-watershed, located in Wonogiri Regency, Central Java, Indonesia, covering an area of approximately 213.88 km² (**Figure 1**).

The erosion hazard assessment was conducted using the USLE model integrated with GIS, involving data collection, spatial data processing, land unit delineation through overlay analysis, estimation of soil loss using the factors R, K, LS, C, and P, followed by erosion hazard classification and spatial analysis (**Figure 2**).

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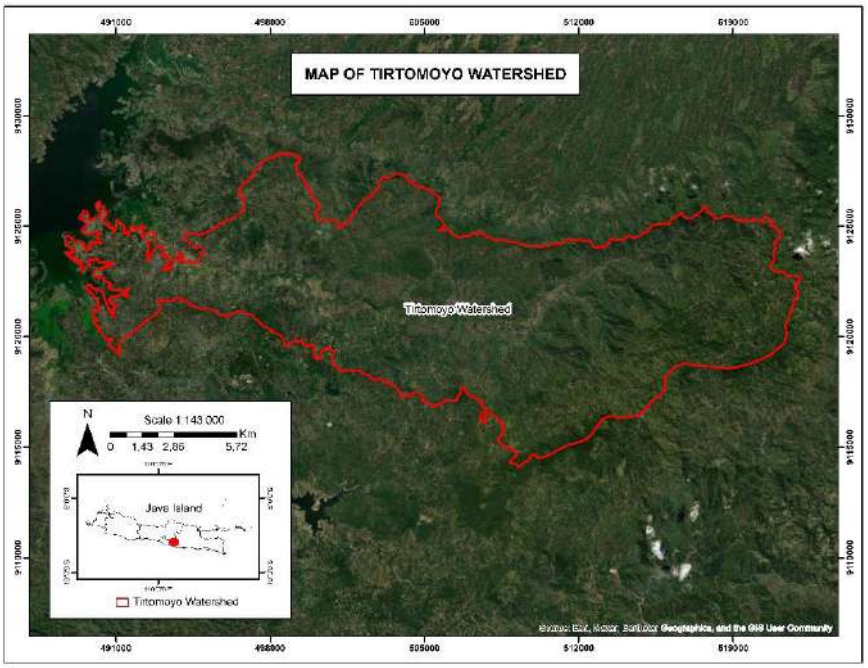

Figure 1. Location of Tirtomoyo Watershed

Source: Author, 2025

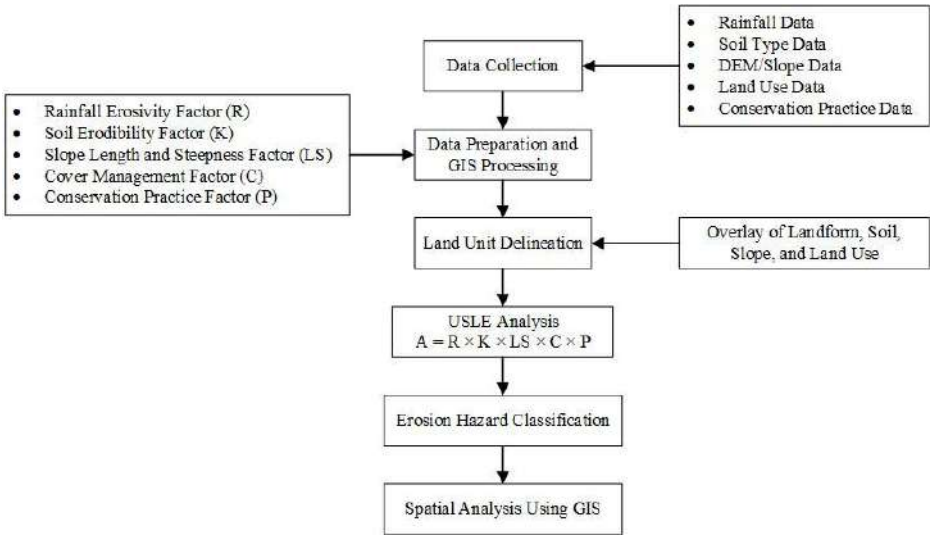

Figure 2. Research Flowchat

Source : Author, 2025

2. Data Collection

This study applied GIS-based USLE to estimate soil loss and identify conservation priority areas. USLE was selected because it remains suitable for long-term erosion assessment under limited rainfall data availability. This model integrates five factors shown in equation 1.

$$A: R \times K \times LS \times C \times P \quad (1)$$

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A : Soil loss rate (ton/ha/year)
R : Rainfall erosivity factor
K : Soil erodibility factor
LS : Slope length and steepness factor
C : Land cover factor
P : Conservation practice factor

The R factor was calculated from monthly rainfall data (2015–2024) at four stations Batuwarno, Giriwoyo, Jatisrono, and Waduk Nawangan sourced from the Bengawan Solo River Basin Authority. Due to limited kinetic energy data, erosivity was estimated using the Lenvain (Asdak, 2007) empirical shown in equation 2:

IR: 2.21 x P1.36 (2)

IR : Indeks erosivitas
P : Monthly rainfall

P represents mean monthly rainfall (mm). R maps were generated using IDW interpolation and classified into erosivity levels (low to very high) based on quantiles. R values ranged from 1,890 to 3,210, with an average of 2,670.

The K factor was estimated from soil samples taken at representative points based on a 1:25,000 soil map. Values were determined using soil texture, structure, and organic matter content (Santarsiero et al., 2023), and calculated using the following shown in equation 3:

$$K = 100 \{2.71 \times M1.14 (10-4) (12-oM) + 4.20 (s-2) + 3.23 (p-3)\} /100 \quad (3)$$

K : soil erodibility
oM : percentage of organic matter (C-organic × 1.724)
s : soil structure code
p : soil profile permeability class code
M : the M value can also be estimated if only the soil texture class is known

The LS factor was derived from DEM processing in GIS and validated through field measurements using a clinometer and measuring tape (El Jazouli et al., 2017). Topographic data were obtained from 30 m resolution DEMNAS, with samples taken from 33 accessible land units to represent site conditions and support erosion analysis.

The C factor was derived from supervised classification of Sentinel-2 imagery and validated through ground checks to match actual land cover types (Kijowska-Strugała et al., 2025). The P factor was determined for agricultural areas through field observations and farmer interviews to identify conservation practices (Kardhana et al., 2024). All data were then used for spatial analysis.

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Table 1. Erossion Class

Erossion Classs	Erossion (ton/ha/tahun)	Class
I	<15	Very light
II	16-60	Light
III	60-180	Moderate
IV	180-480	Severe
V	>480	Very severe

Source: USDA, 1999

Based on USDA standards in **Table 1**, soil erosion was classified as very light (<15 t ha^{-1} yr^{-1}), light (15–60), moderate (60–180), severe (180–480), and very severe (>480), representing increasing levels of land degradation and conservation urgency.

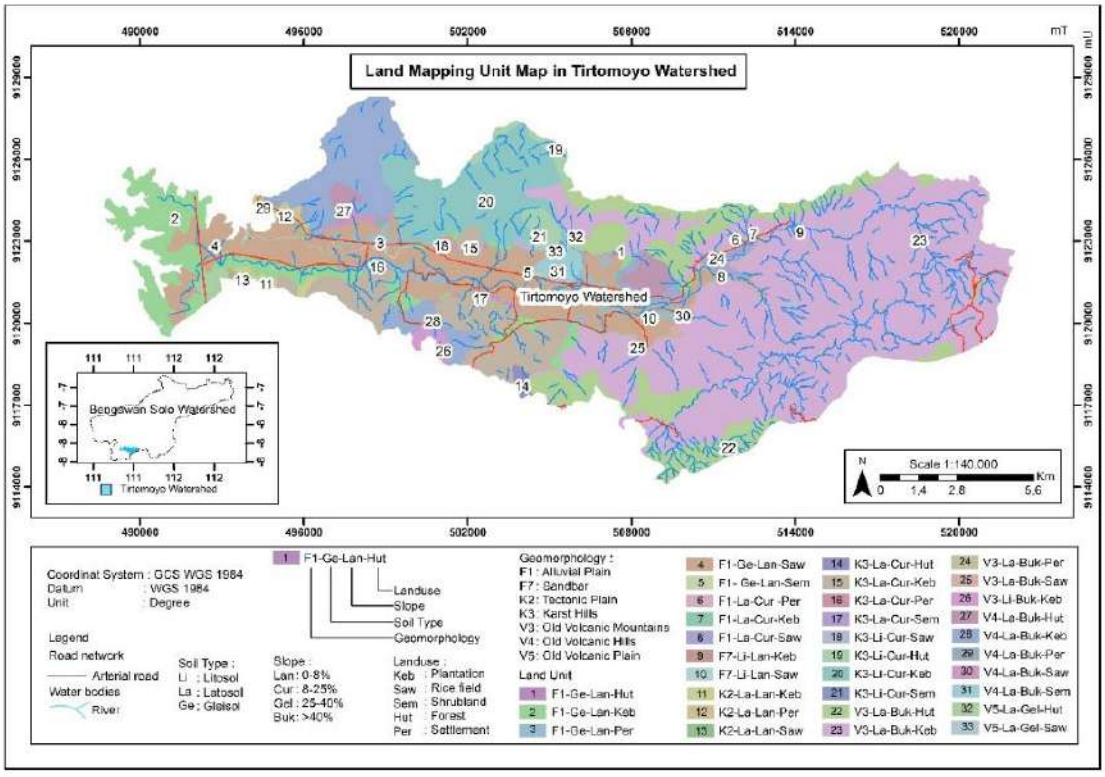

Figure 3. Land Mapping Units of the Tirtomoyo watershed

Source: Author, 2025

3. Data analysis

Data analysis was conducted using Land Mapping Units (LMUs), defined by combinations of geomorphology, soil type, slope, and land use. A total of 33 LMUs were identified in the Tirtomoyo watershed (**Figure 3**), providing a more representative basis for analysis than administrative boundaries by capturing biophysical variability. Land units represent areas with relatively homogeneous characteristics (FAO,

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1976), and similar approaches have been widely applied using combinations of landform, soil, slope, land use, and geological parameters (Taryono et al., 2001; Simanungkalit, 2011; Purnomo et al., 2013; Umar et al., 2017).

Each USLE parameter was processed in raster format using ArcGIS and combined to estimate soil loss (ton/ha/year). The results were mapped to show erosion risk levels, and validated through field observations and brief community interviews in high-erosion areas.

RESULTS AND DISCUSSION

1. Rainfall Erosivity Factor (R)

The analysis of the rainfall erosivity factor in the Tirtomoyo watershed was conducted based on precipitation data (**Figure 4**). The average annual rainfall in the Tirtomoyo Sub-watershed is 2,676.42 mm year^{-1}, reflecting a humid tropical climate with high rainfall erosivity potential. This condition is influenced by monsoonal circulation and orographic effects associated with the hilly terrain of southern Central Java, which enhance rainfall intensity and duration. Compared with several watersheds in Central Java, where annual rainfall generally ranges from 1,800 to 2,500 mm year^{-1}, Tirtomoyo receives relatively higher rainfall, indicating elevated erosion risk.

Table 2. Rainfall in Tirtomoyo Watershed

Month	Batuwarno	Giriwoyo	Jatisrono	Nawangan
January	397	378	337	327
February	4	0	61	388
March	247	271	335	278
April	123	73	91	146
May	313	241	288	197
June	59	90	7	69
July	18	51,5	2	30
August	0	0	2,3	0,5
September	23	39,5	26,1	12
October	45	83,5	6,6	69,5
November	349	592	225,4	535,6
December	535	571,5	465,3	473,6
Total (mm/month)	2113	2391	1846,7	2526,2

Source: River Basin Development Authority of Bengawan Solo

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The effect of rainfall is evident in several land units classified as severe to very severe erosion. High-intensity rainfall increases surface runoff when infiltration capacity is exceeded, thereby accelerating soil detachment and transport. However, erosion rates are substantially lower in areas implementing bench terraces and strip cropping, whereas steep cultivated lands without conservation measures remain highly vulnerable. These findings indicate that while rainfall erosivity is a major driver of soil loss, effective land management plays a crucial role in reducing erosion in the Tirtomoyo Sub-watershed.

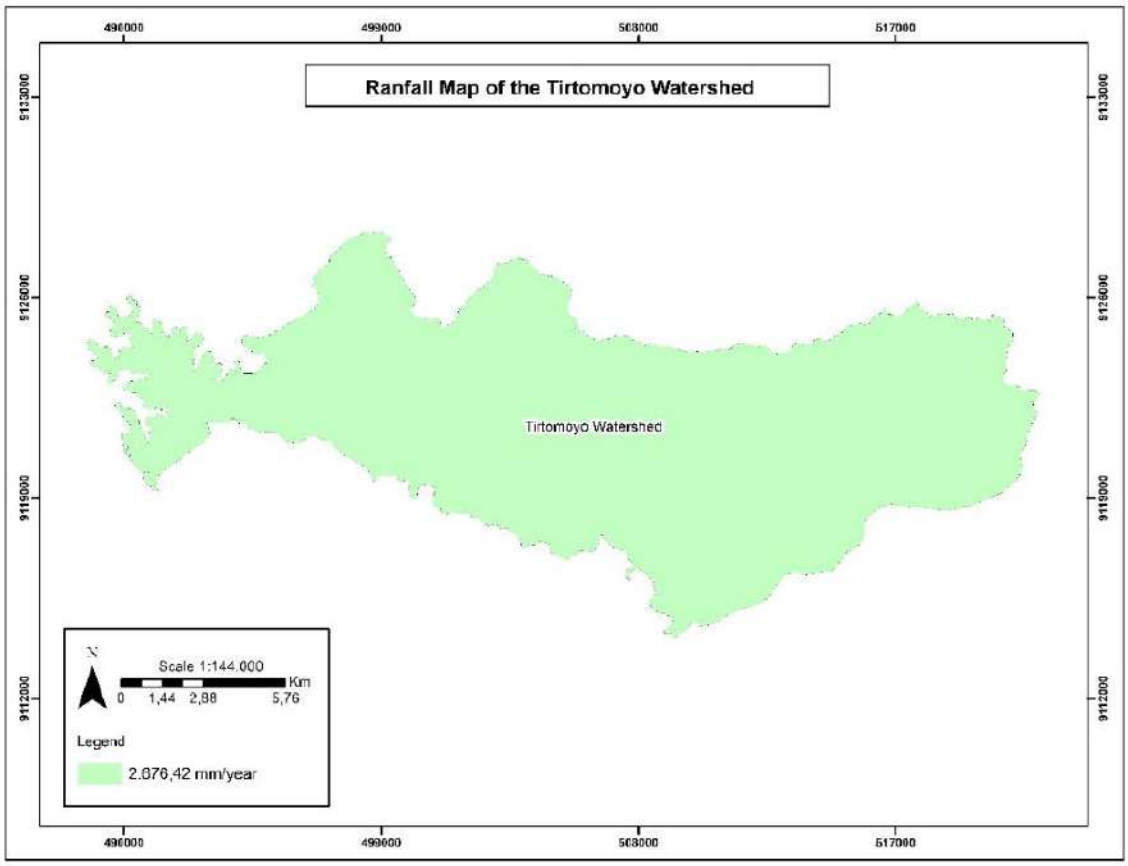

Figure 4. Rainfall Map of Tirtomoyo watershed
Source: Author, 2025

2. Soil Erodibility Factor (K)

The watershed is dominated by Luvisols, Grumusols, and Litosols (**Figure 5**). As shown in **Table 3**, land units exhibit considerable variation in texture, organic matter content, soil structure, and permeability, which influence erosion susceptibility. The M factor ranges from

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162.03 to 2,233.41, with higher values generally indicating greater erodibility. Organic matter content varies from 4.82% to 8.91%; land units with higher organic matter, such as F7-Li-Lan and V3-Li-Buk, tend to have more stable aggregates and lower erosion risk, whereas units with lower organic matter, including K3-La-Cur, V4-La-Buk, and V5-La-Gel, are more susceptible to erosion due to reduced aggregate stability.

Table 3. Soil Erodibility

Land Unit	M	Organic Matter (BO)	Soil Structure	Permeability
F1-Ge-Lan-Hut	162,03	7,76	3	4
F1-Ge-Lan-Keb	162,03	7,76	3	4
F1-Ge-Lan-Per	162,03	7,76	3	4
F1-Ge-Lan-Saw	162,03	7,76	3	4
F1-Ge-Lan-Sem	162,03	7,76	3	4
F1-La-Cur-Per	909,02	4,82	1	4
F1-La-Cur-Keb	909,02	4,82	1	4
F1-La-Cur-Saw	2233,41	4,82	1	4
F7-Li-Lan-Keb	2233,41	8,91	3	5
F7-Li-Lan-Saw	2233,41	8,91	3	5
K2-La-Lan-Keb	909,02	4,82	1	4
K2-La-Lan-Per	909,02	4,82	1	4
K2-La-Lan-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Per	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
K3-La-Cur-Saw	909,02	4,82	1	4
K3-La-Cur-Hut	909,02	4,82	1	4
K3-La-Cur-Keb	909,02	4,82	1	4
K3-La-Cur-Sem	909,02	4,82	1	4
V3-La-Buk-Hut	909,02	4,82	1	4
V3-La-Buk-Keb	909,02	4,82	1	4
V3-La-Buk-Per	909,02	4,82	1	4
V3-La-Buk-Saw	909,02	4,82	1	4
V3-Li-Buk-Keb	2233,41	8,91	3	5
V4-La-Buk-Hut	909,02	4,82	1	4
V4-La-Buk-Keb	909,02	4,82	1	4
V4-La-Buk-Per	909,02	4,82	1	4
V4-La-Buk-Saw	909,02	4,82	1	4
V4-La-Buk-Sem	909,02	4,82	1	4
V5-La-Gel-Hut	909,02	4,82	1	4
V5-La-Gel-Saw	909,02	4,82	1	4

Source: data processing, 2025

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Soil structure varies from poor (value 1) to good granular structure (value 3), while permeability ranges from moderate–rapid (4) to rapid (5). Land units with poor structure, low organic matter, high M values, and moderate permeability, such as K3-La-Cur, V4-La-Buk, and V5-La-Gel, exhibit the highest erosion susceptibility. In contrast, units with higher organic matter, better structure, and rapid permeability, including F7-Li-Lan and V3-Li-Buk, are relatively more resistant to erosion due to improved aggregate stability and infiltration capacity. However, these areas still fall within the severe erosion category, indicating that favorable soil properties alone cannot offset the effects of high rainfall and steep slopes. Areas dominated by clay-rich Litosols, particularly at Point 2, show high K-factor values and therefore require conservation priority, as clay soils can intensify erosion on sloping terrain (Luquin et al., 2025).

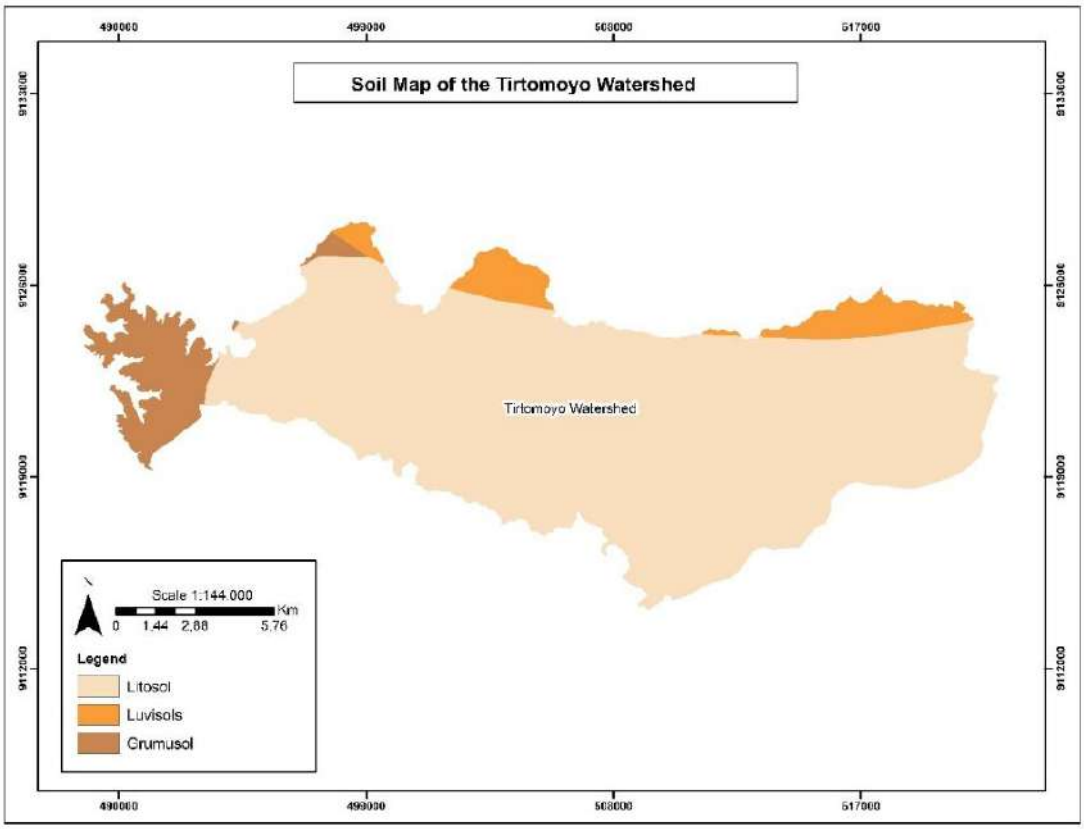

Figure 5. Soil Type Map of Tirtomoyo watershed
Source: Author, 2025

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3. Topographic Factor (LS)

Slope analysis derived from the DEM indicates gradients ranging from 0–8% to >45% across the Tirtomoyo Sub-watershed (**Figure 6**). Land units on steep to very steep slopes, particularly in the eastern, central, and western areas, are generally classified as severe to very severe erosion zones, such as F7-Li-Lan-Keb and F7-Li-Lan-Saw, due to high LS values that increase runoff and soil detachment (Simelane et al. 2024; Shen et al. 2025). Conversely, units on gentle slopes (0–8%), including F1-Ge-Lan-Keb and V3-La-Buk-Saw, exhibit very light to light erosion because of lower erosive energy. Moderate slopes (10–35°) commonly show moderate erosion, especially where conservation measures are limited, as observed in several K3-La-Cur units (Pan et al. 2025). These findings confirm that slope gradient and length are key controls of erosion severity, highlighting steep-slope areas as priority targets for conservation.

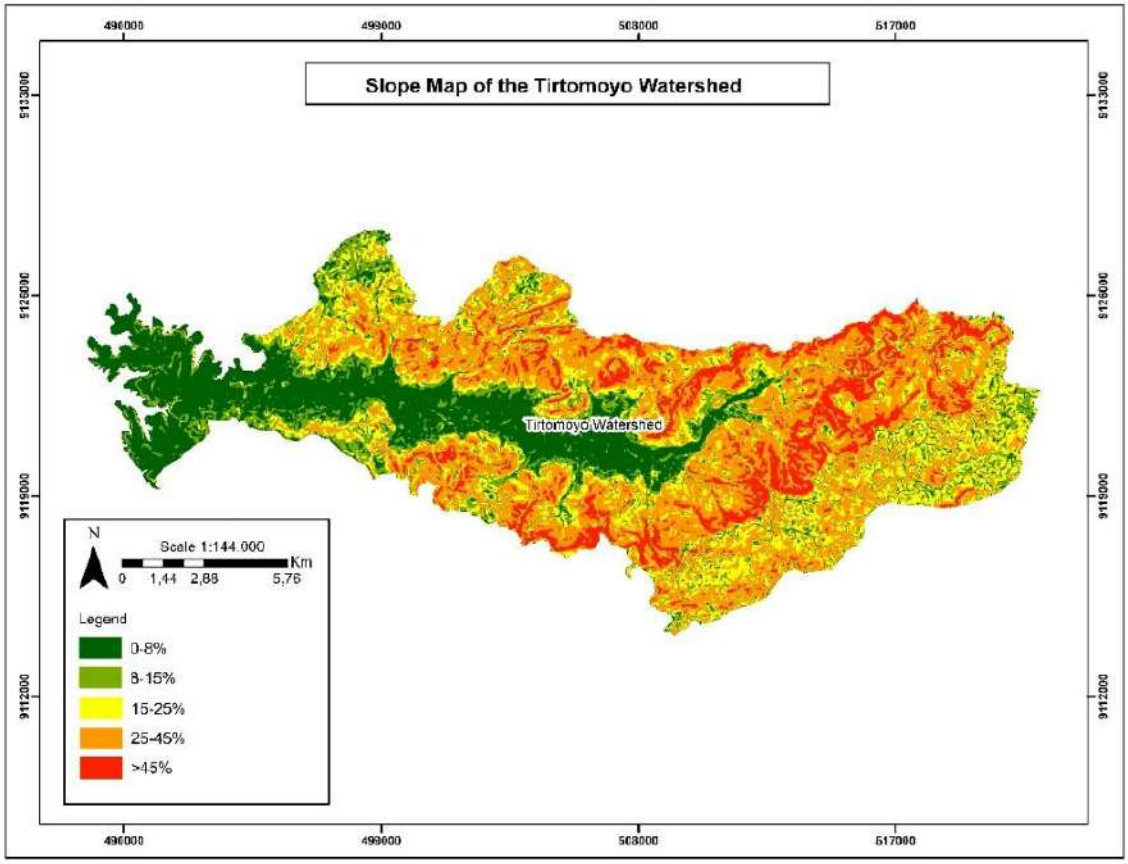

Figure 6. Slope Map of Tirtomoyo watershed

Source: Author, 2025

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4. Land Cover and Crop Management Factor (C)

Land use in the Tirtomoyo Sub-watershed is dominated by teak (*Tectona grandis*), alongside rice, maize, banana, bamboo, elephant grass, and mango, reflecting the predominance of forestry and agricultural activities (**Figure 7**). Teak and bamboo provide effective soil protection through dense canopy cover and extensive root systems, resulting in lower C-factor values, whereas paddy fields and seasonal crops generally exhibit higher C values, particularly during planting or fallow periods. The C factor reflects the ability of vegetation to reduce raindrop impact and surface runoff, thereby minimizing erosion (Mas et al., 2024). Consequently, agricultural areas with seasonal vegetation are more vulnerable to erosion and require conservation measures such as mulching, cover crops, or agroforestry systems.

a b

Figure 7. (a) *Zea mays L.* and (b) *Bambusoideae*

Source: Author, 2025

5. Conservation Practice Factor (P)

Various soil and water conservation practices, including agroforestry, bench terracing, and strip cropping, have been implemented in the Tirtomoyo Sub-watershed, although many areas remain unmanaged. These practices influence the USLE P factor by reducing runoff velocity and increasing infiltration, thereby lowering erosion risk. Bench terraces are the dominant conservation measure on sloping land (**Figure 8**). In contrast, areas without conservation have P values close to 1, indicating minimal erosion control and greater vulnerability, particularly on steep slopes under high rainfall. Therefore, mapping P-factor distribution is important for identifying

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conservation priorities and supporting effective land management.

Figure 8. Terracing Conservation Technique
Source: Author, 2025

6. Erosion Susceptibility of Tirtomoyo Sub-watershed

Table 4 shows that conservation practices strongly influence erosion rates. Bench terraces and strip cropping are the most effective measures on cultivated land, while agroforestry provides moderate protection, although its effectiveness may decline on steep slopes under high rainfall conditions (Jose et al., 2022). Areas without conservation exhibit the highest erosion vulnerability, highlighting the importance of expanding soil and water conservation measures. Bench terraces reduce runoff velocity and soil loss, whereas strip cropping limits runoff and sediment transport by interrupting surface flow pathways (FAO, 1986; El Jazouli et al., 2023).

Figure 9 shows that moderate erosion is the dominant class in the Tirtomoyo watershed, covering approximately 10,386 ha, followed by mild erosion (6,670 ha) and very mild erosion (2,953 ha). Severe and very severe erosion occupy smaller areas, covering 1,772 ha and 52 ha, respectively.

Although very severe erosion is limited, the dominance of moderate and mild erosion poses a significant management concern (**Figure 10**). These areas require priority conservation measures to prevent further degradation, while severe erosion zones need continued protection to limit the expansion of damage.

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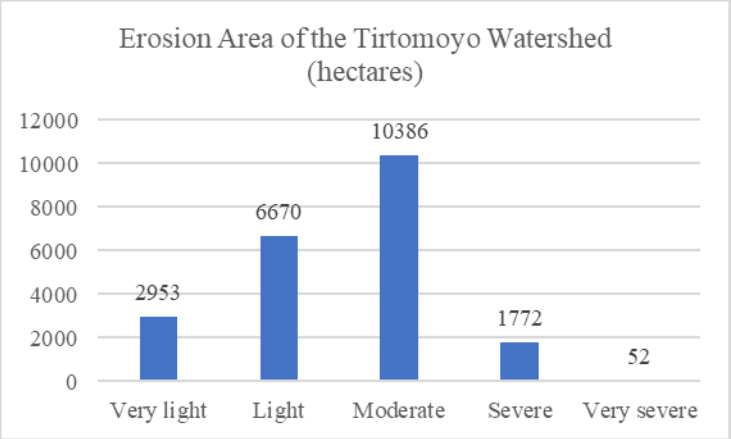

Figure 9. Erosion Susceptibility of Tirtomoyo watershed

Source: Author, 2025

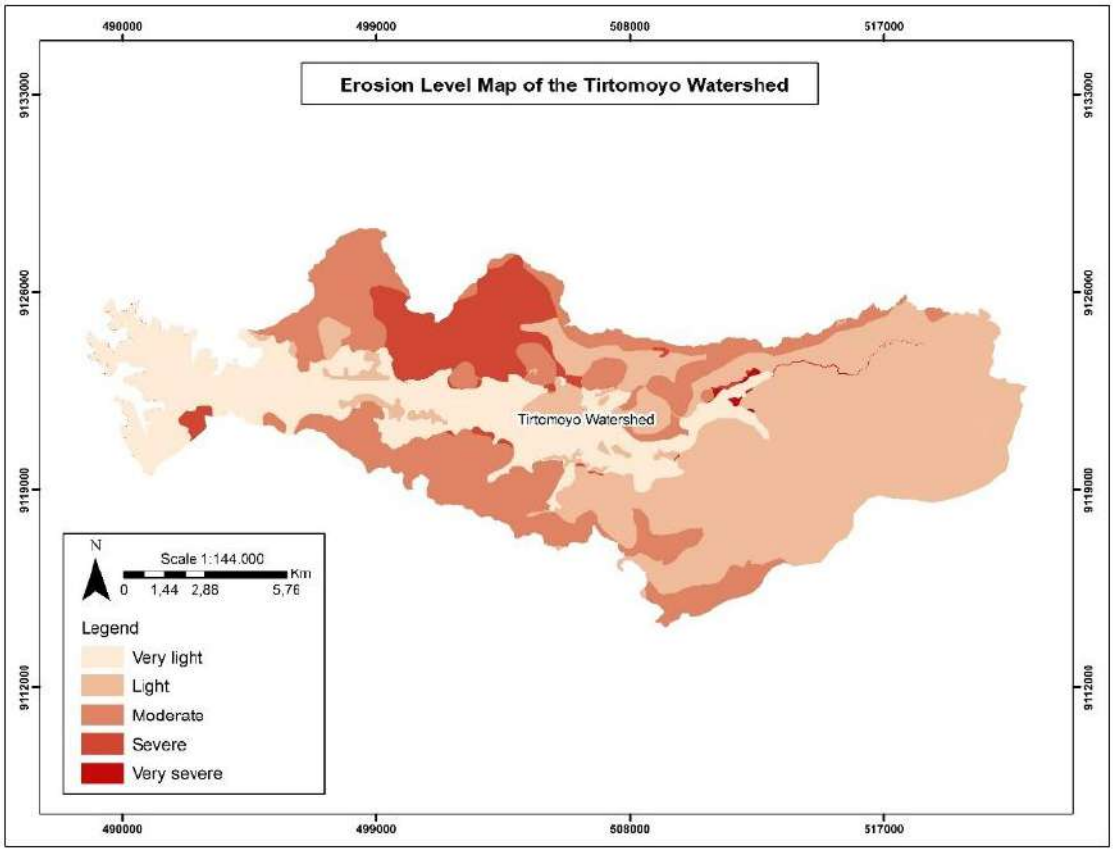

Figure 10. Erosion Map of Tirtomoyo watershed

Source: data processing, 2025

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Table 4. Conservation Method and Class Erosion

Land Unit	C	Conservation Method	Class
F1-Ge-Lan-Hut	*Tectona grandis*	Agroforestry	Very severe
F1-Ge-Lan-Keb	*Cenchrus purpureus*	Bench terrace	Very light
F1-Ge-Lan-Per	*Musa Paradisiaca*	Agroforestry	Very light
F1-Ge-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
F1-Ge-Lan-Sem	*Tectona grandis*	Agroforestry	Light
F1-La-Cur-Per	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
F1-La-Cur-Saw	*Oryza sativa*	Strip cropping	Very light
F7-Li-Lan-Keb	*Tectona grandis*	Without conservation	Very severe
F7-Li-Lan-Saw	*Oryza sativa*	Bench terrace	Very severe
K2-La-Lan-Keb	*Tectona grandis*	Agroforestry	Very light
K2-La-Lan-Per	*Musa Paradisiaca*	Bench terrace	Moderate
K2-La-Lan-Saw	*Oryza sativa*	Bench terrace	Very light
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Very light
K3-La-Cur-Keb	*Zea mays*	Without conservation	Very light
K3-La-Cur-Per	*Tectona grandis*	Agroforestry	Moderate
K3-La-Cur-Sem	*Bambusoideae*	Without conservation	Light
K3-La-Cur-Saw	*Oryza sativa*	Strip cropping	Moderate
K3-La-Cur-Hut	*Tectona grandis*	Without conservation	Severe
K3-La-Cur-Keb	*Tectona grandis*	Without conservation	Light
K3-La-Cur-Sem	*Bambusoideae*	Agroforestry	Moderate
V3-La-Buk-Hut	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Keb	*Zea mays*	Bench terrace	Very light
V3-La-Buk-Per	*Tectona grandis*	Agroforestry	Severe
V3-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V3-Li-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Hut	*Zea mays*	Strip cropping	Light
V4-La-Buk-Keb	*Tectona grandis*	Agroforestry	Light
V4-La-Buk-Per	*Mangifera indica*	Agroforestry	Moderate
V4-La-Buk-Saw	*Oryza sativa*	Strip cropping	Very light
V4-La-Buk-Sem	*Tectona grandis*	Agroforestry	Light
V5-La-Gel-Hut	*Tectona grandis*	Without conservation	Moderate
V5-La-Gel-Saw	*Oryza sativa*	Bench terrace	Severe

Source: data processing, 2025

The Tirtomoyo watershed consists of diverse landforms and soil types, including alluvial plains, karst hills, old volcanic landscapes, and soils such as Litosols, Latosols, and Gleysols, with land cover dominated by forests, plantations, paddy fields, settlements, and shrublands. Moderate erosion is the dominant class, particularly in undulating to steep areas (8–40%) used for plantations and mixed agriculture. Severe to very severe erosion occurs

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mainly on steep slopes (>40%) with sparse vegetation and limited conservation practices, such as in the V3-La-Buk and V4-La-Buk land units. Areas with teak-based agroforestry generally exhibit lower CP values and reduced erosion, whereas seasonal crops on steep slopes without conservation measures show higher CP values and greater erosion risk. Although conservation practices such as terracing, strip cropping, and agroforestry are present, their implementation remains uneven across critical areas.

Figure 11. Gully Erosion in Tirtomoyo watershed
Source: Author, 2025

Figure 11 illustrates gully erosion occurring in the Tirtomoyo watershed. This type of erosion is characterized by the formation of deep and wide channels due to concentrated surface flow, significantly scouring the soil and creating steep slopes on both sides of the gully. While some vegetation remains along the gully edges, the gully floor exhibits minimal cover, making it highly susceptible to further erosion during heavy rainfall. Vegetation affects soil erodibility by altering soil properties, thereby influencing gully development (Liu et al. 2023).

Indicates that gully erosion is influenced by topography, climate, and human activities (Liu et al. 2025). These conditions suggest that land degradation has progressed from sheet and rill erosion to gully erosion, resulting in reduced land productivity, disrupted surface water flow, and increased sediment contribution downstream.

Priority conservation actions are required in zones with high CP values and severe erosion, particularly through

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enhancing permanent vegetation cover, implementing mechanical conservation measures such as bench terracing, and managing ground cover vegetation. Soil and water conservation practices can be applied to sloping agricultural land (Wang et al. 2024). An integrated land unit–based management approach will help reduce erosion rates while maintaining land productivity in the Tirtomoyo sub-watershed.

Based on the analysis of erosion severity, land use, and conservation practices, areas experiencing severe to very severe erosion on steep slopes (>40%), such as the V3-La-Buk and V4-La-Buk land units dominated by seasonal crops (maize, cassava, elephant grass) without adequate conservation, should be prioritized for conservation and rehabilitation. Recommended measures include reforestation, agroforestry systems, bench terracing, and planting ground cover vegetation. Vegetation restoration acts to control surface runoff and soil erosion (Liang et al. 2023).

The findings of this study are strongly connected to sustainable agriculture, as soil erosion control plays a crucial role in maintaining long-term land productivity and ecological balance. Sustainable farming practices such as agroforestry, crop rotation, mulching, terracing, and the use of perennial plants with deep root systems can effectively reduce erosion rates, enhance soil fertility, and improve water retention. In the context of the Tirtomoyo watershed, integrating conservation techniques with agricultural land use not only preserves soil and water resources but also ensures that farming activities remain productive and resilient to environmental challenges. Therefore, the implementation of soil and water conservation strategies is essential for advancing sustainable agriculture that harmonizes farmers' livelihoods with the protection of natural ecosystems.

Sustainable land use planning should direct the utilization of steep slopes for deep-rooted perennial crops such as teak, bamboo, or fruit trees in mixed planting patterns, combined with mechanical and vegetative conservation measures. Areas with moderate erosion can be managed through conservation agriculture, crop rotation, and enhanced soil organic matter according to land suitability. Demonstrate that slope management practices, such as mulching or conventional methods, can reduce erosion (Lee et al. 2021).

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Controlling erosion in upstream areas is critical because high erosion rates can increase sediment loads downstream, causing channel siltation, reducing river capacity, increasing water turbidity, and disrupting aquatic ecosystems. Therefore, upstream interventions provide dual benefits for land sustainability and water resource protection in the Tirtomoyo watershed.

A primary limitation of the USLE model is that it only estimates sheet erosion and does not account for rill erosion, gully erosion, or landslides, which frequently occur in steep, high-rainfall areas like the Tirtomoyo watershed. The model is also static, as it does not consider seasonal variations such as changes in vegetation cover or rainfall intensity throughout the year.

It is recommended to integrate USLE with Geographic Information Systems (GIS) and high-resolution satellite imagery to more accurately map land-use dynamics and vegetation conditions. Routine field validation and long-term monitoring are essential to ensure that erosion estimates reflect actual conditions, while updating local parameters such as C and P factors to provide more targeted and effective conservation recommendations.

CONCLUSIONS

Soil erosion in the Tirtomoyo Sub-watershed is primarily driven by high rainfall, steep slopes, lithosol soils, and inadequate conservation practices. The highest erosion rates were identified in steep cultivated land units, particularly F7-Li-Lan-Keb and F7-Li-Lan-Saw, which should be prioritized for conservation interventions. Bench terraces and strip cropping effectively reduced erosion, whereas agroforestry alone was less effective on steep slopes. Priority conservation measures include terrace construction, slope stabilization, vegetative buffers, and reforestation in severe and very severe erosion areas.

This study is limited by the use of the USLE model, which estimates potential soil loss and does not account for gully erosion, landslides, or sediment transport processes. Future research should incorporate higher-resolution spatial data, field validation, and advanced erosion models to improve erosion assessment and conservation planning in the Tirtomoyo Sub-watershed.

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