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

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ARTICLE INFO

ABSTRACT

Article History

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.

Received

Revised

Accepted

: 04/05/2026

: 12/05/2026

: 29/06/2026

Citation:

Rahman, M.K., Deristani, A., Rohsulina, P., and Havyarimana, C. (2026) Soil Erosion Modeling and Conservation Priority Mapping In The Tirtomoyo Sub-Watershed. GeoEco. Vol. 12, No. 2.

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 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 (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 (Figure 2).

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 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 (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:

$$K = 100 \{2.71 \times M^{1.14} (10-4) (12-OM) + 4.20 (s-2) + 3.23 (p-3)\} / 100 \quad (3)$$

K

: soil erodibility

OM

: percentage of organic matter (C-organic $\times$ 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 Classes

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

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). 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). 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

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

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
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 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.

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.

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

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.

Figure 9. Erosion Susceptibility of Tirtomoyo watershed

Source: Author, 2025

Figure 10. Erosion Map of Tirtomoyo watershed

Source: data processing, 2025

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 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 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).

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.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support provided by the Research and Community Service Institute (LPPM) of Universitas Veteran Bangun Nusantara Sukoharjo through its research grant program. We also extend our sincere appreciation to all parties who contributed to this study, including field survey teams and local stakeholders, for their valuable assistance and support.

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