p-ISSN 2460-0768 e-ISSN 2597-6044 GeoEco, Vol. 12, No 2. July 2026 Page. 655 - 677
https://doi.org/10.20961/ge.v12i2.118320 https://jurnal.uns.ac.id/GeoEco/article/view/118320

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

MS Khabibur Rahman[1*], Anggun Deristani[2], Pranichayudha Rohsulina[1], Célestin Havyarimana[3]
[1]Geography Education Study Program, Faculty of Teacher Training and Education, Veteran Bangun Nusantara University, Sukoharjo, Indonesia
[2]Graduate Program of Environmental Science, School of Graduates, Universitas Sebelas Maret, Surakarta, Indonesia
[3]Biology Department, Faculty of Sciences, University of Burundi, P.O. Box 2700 Bujumbura, Burundi

*E-mail: khabib.ynwa@gmail.com

ARTICLE INFO

Article History
Received : 04/05/2026
Revised : 12/05/2026
Accepted : 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.

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 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

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**).

p-ISSN 2460-0768 e-ISSN 2597-6044
https://doi.org/10.20961/ge.v12i2.118320

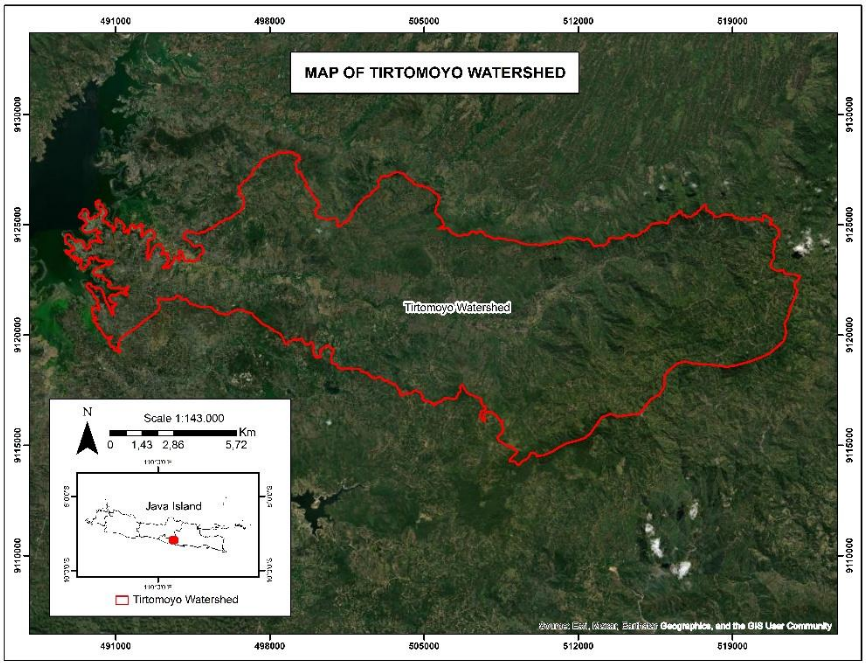

Figure 1. Location of Tirtomoyo Watershed

Source: Author, 2025

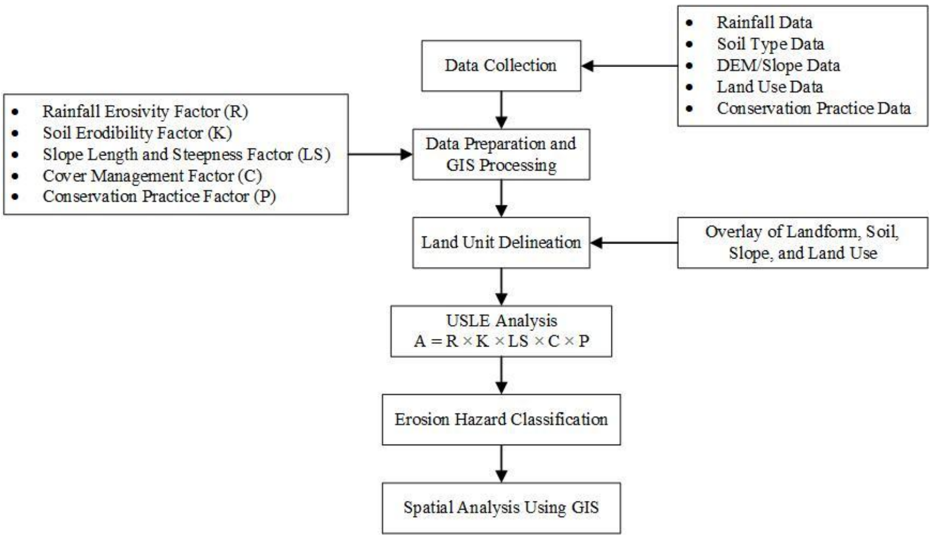

Figure 2. Research Flowchat

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.

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

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:

$$IR: 2.21 \times P1.36 \quad (2)$$

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.

p-ISSN 2460-0768 e-ISSN 2597-6044 *GeoEco, Vol. 12, No 2. July 2026 Page. 655 - 677*
https://doi.org/10.20961/ge.v12i2.118320 https://jurnal.uns.ac.id/GeoEco/article/view/118320

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.

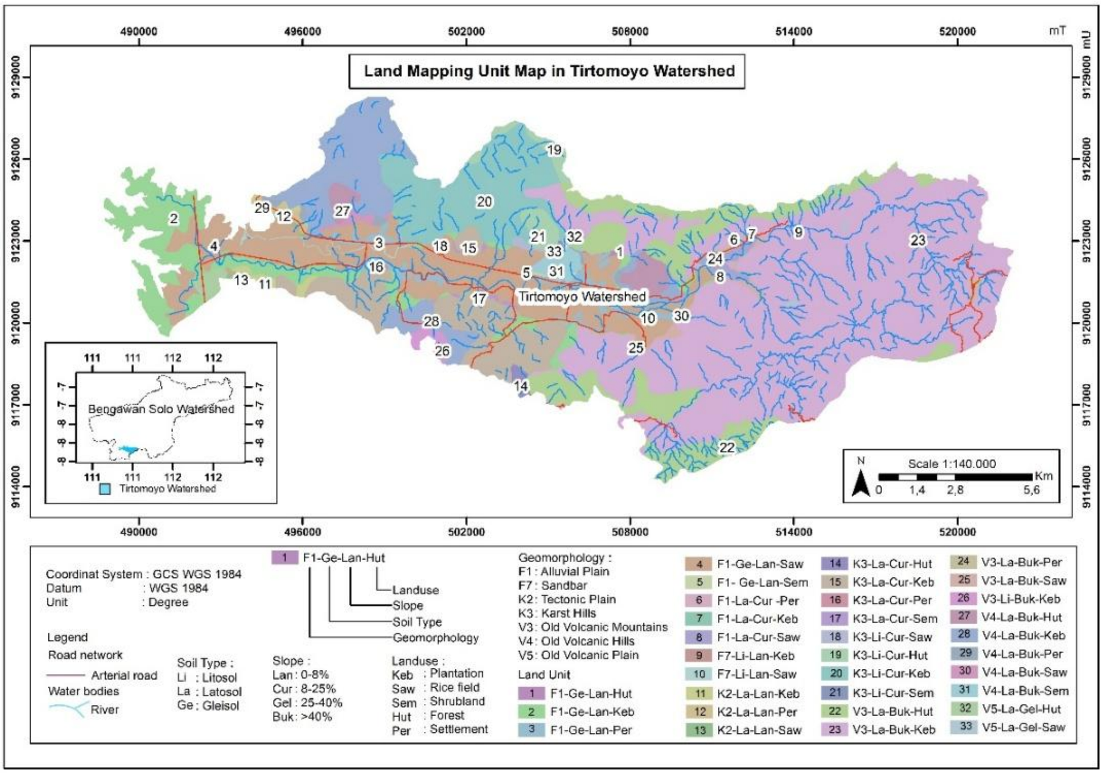

Figure 3. Land Mapping Units of the Tirtomoyo watershed

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, 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

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.

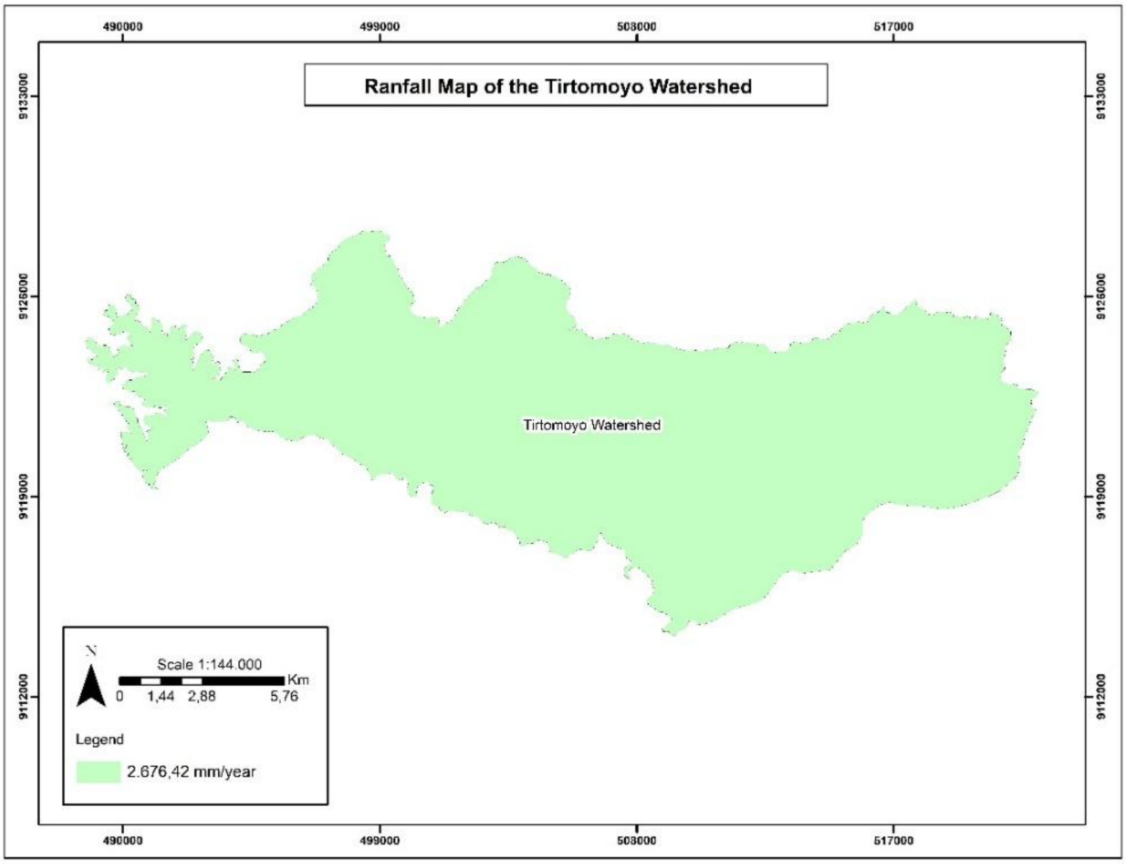

Figure 4. Rainfall Map of Tirtomoyo watershed
Source: Author, 2025

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

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).

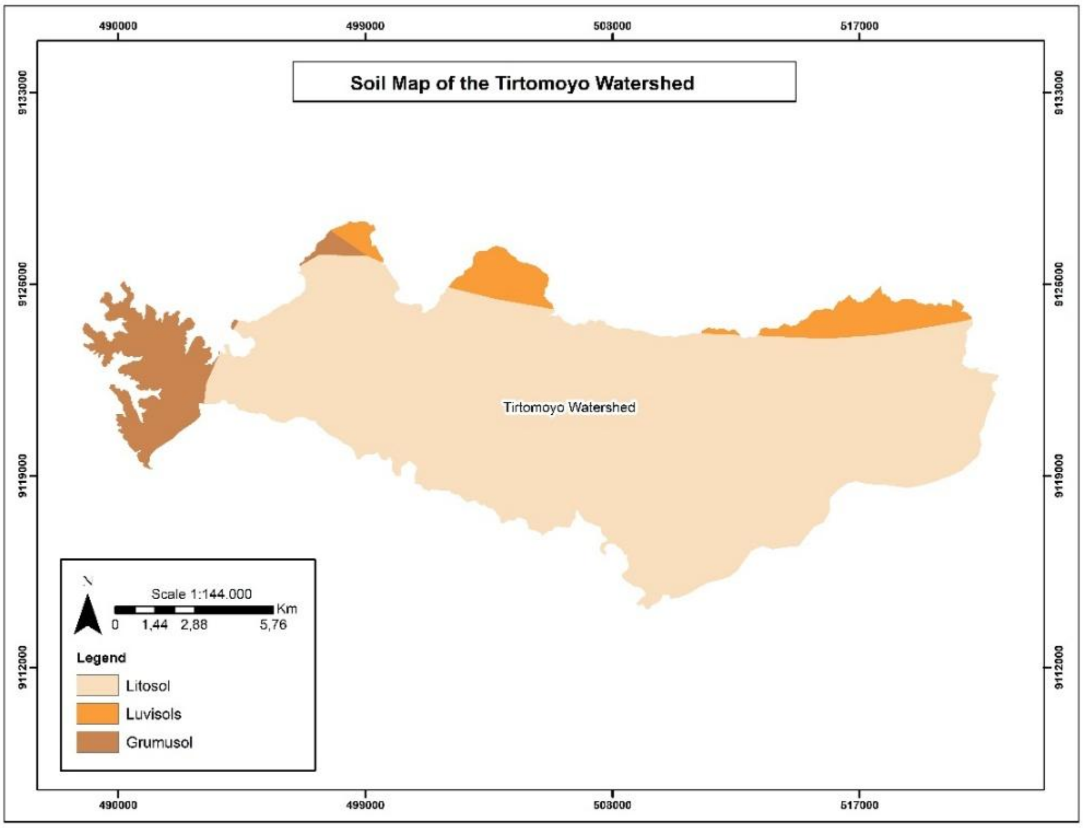

Figure 5. Soil Type Map of Tirtomoyo watershed
Source: Author, 2025

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.

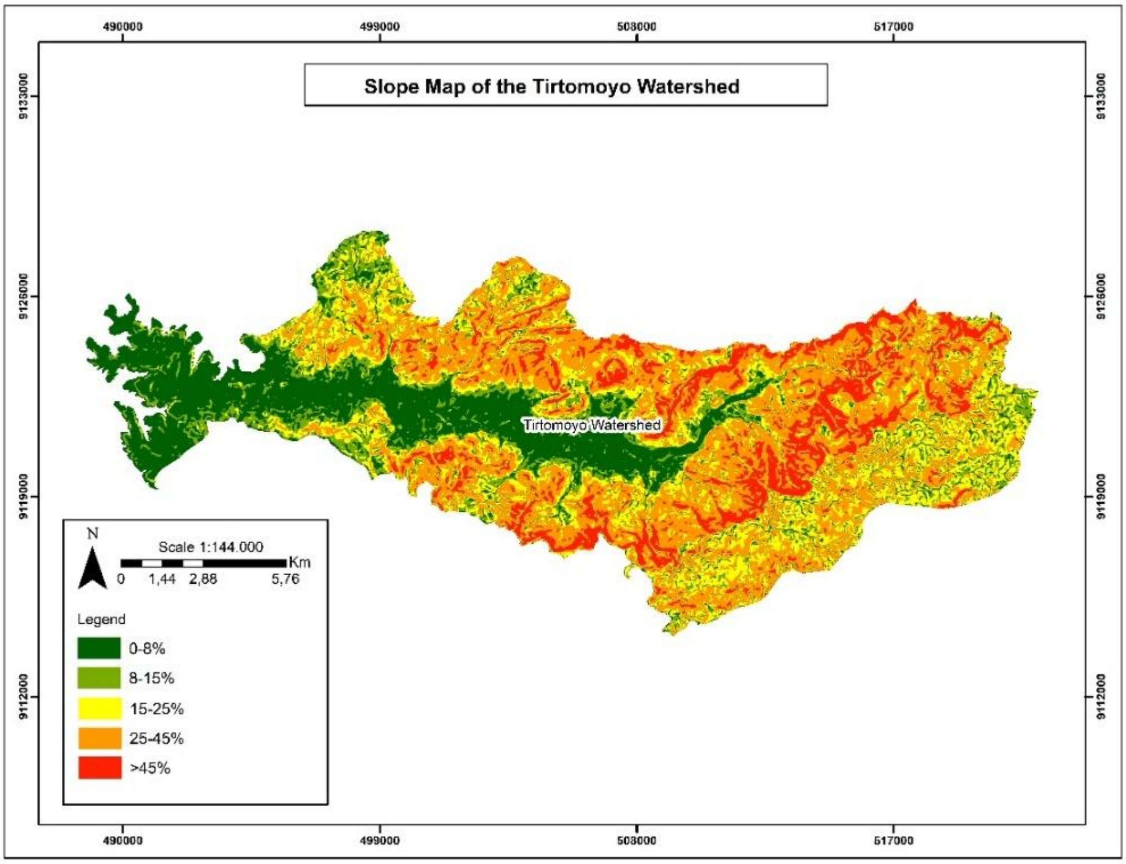

Figure 6. Slope Map of Tirtomoyo watershed

Source: Author, 2025

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 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.

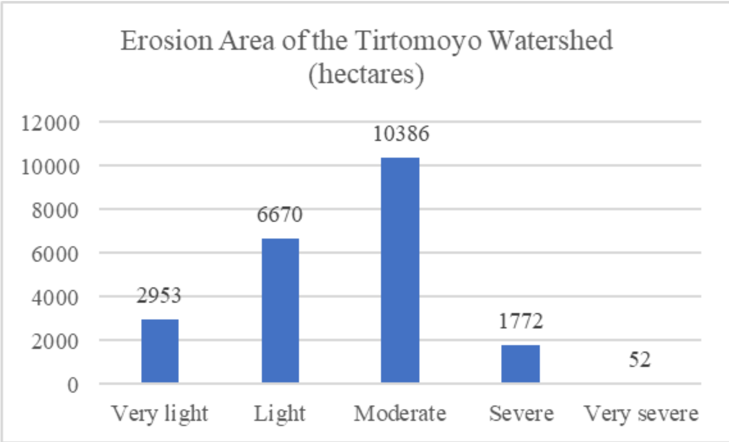

Figure 9. Erosion Susceptibility of Tirtomoyo watershed
Source: Author, 2025

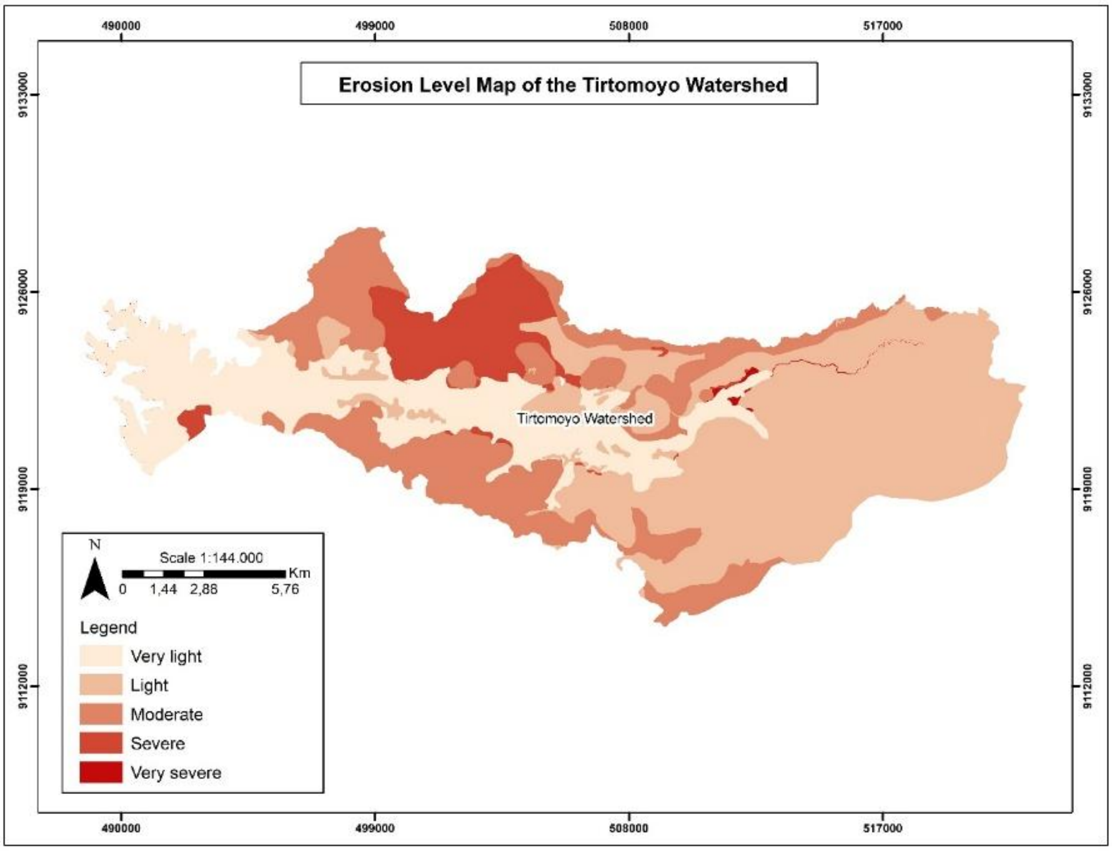

Figure 10. Erosion Map of Tirtomoyo watershed
Source: data processing, 2025

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.

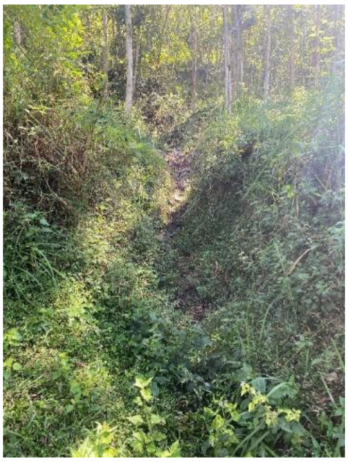

Figure 11. Gully Erosion in Tirtomoyo watershed
Source: Author, 2025

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.

REFERENCES

Alewell, C. Borrelli, P. Meusburger, K., and Panagos, P. 2019. Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research* (Vol. 7, Issue 3, pp. 203–225). International Research and Training Center on Erosion and Sedimentation and China Water and Power Press. https://doi.org/10.1016/j.iswcr.2019.05.004

Antronico, L. De Pascale, F. Coscarelli, R., and Gullà, G. 2020. Landslide risk perception, social vulnerability and community resilience: The case study of Maierato (Calabria, southern Italy). *International Journal of Disaster Risk Reduction*, *46*. https://doi.org/10.1016/j.ijdrr.2020.101529

Asdak, C., (2007). Hidrologi dan Pengelolaan Daerah Aliran Sungai, Gadjah Mada University Press, Yogyakarta.

Ashiagbor, G. Forkuo, E.K. Aabeyir, R., and Forkuo, E.K. 2013. Modeling soil erosion using RUSLE and GIS tools. *International Journal of Remote Sensing & Geoscience (IJRSG)*, *2*(4).

Brychta, J. Podhrázská, J., and Šťastná, M. 2022. Review of methods of spatio-temporal evaluation of rainfall erosivity and their correct application. *Catena* (Vol. 217). https://doi.org/10.1016/j.catena.2022.106454

Carollo, F.G. Serio, M.A. Pampalone, V., and Ferro, V. 2024. The unit plot of the Universal soil loss equation (USLE): Myth or reality? In *Journal of Hydrology* (Vol. 632). Elsevier B.V. https://doi.org/10.1016/j.jhydrol.2024.130880

El Jazouli, A. Barakat, A. Ghafiri, A. El Moutaki, S. Ettaqy, A., and Khellouk R. 2017. Soil erosion modeled with USLE, GIS, and remote sensing: a case study of Ikkour watershed in Middle Atlas (Morocco). In *Geoscience Letters* (Vol. 4, Issue 1). SpringerOpen. https://doi.org/10.1186/s40562-017-0091-6

El Jazouli, A., et al. 2023. Quantification of the effects of conservation practices on surface runoff and soil erosion in croplands and their trade-off: A meta-analysis. *Science of the Total Environment*, 864, 161015. https://doi.org/10.1016/j.scitotenv.2022.161015

FAO. 1986. *Watershed Management Field Manual: Conservation Bench Terraces*. Food and Agriculture Organization.

FAO. 1976. A Framework for Land Evaluation. FAO Soil Bulletin 52. Soil Resources Management and Conservation Service Land and Water Development Division.

Ferro, V. 2010. Deducing the USLE mathematical structure by dimensional analysis and self-similarity theory. *Biosystems Engineering*, *106*(2), 216–220. https://doi.org/10.1016/j.biosystemseng.2010.03.006

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. https://doi.org/10.21776/ub.jtresda.2023.003.01.14

Hishamunda, S. Fashaho, A. Uwihirwe, J. Bugenimana, E.D. Mpambara Musinga, C., and Munyandamutsa, P. 2024. Controlling soil erosion and landslides through ecosystem-based adaptation interventions in the hilly landscape of western Rwanda. *Soil Advances*, *2*, 100020. https://doi.org/10.1016/j.soilad.2024.100020

JICA, 2007. Penanganan sedimentasi Waduk Wonogiri, Surakarta.

Jose, S., Dollinger, J., & colleagues. 2022. Agroforestry Systems for Soil Health Improvement and Maintenance. *Sustainability*, 14(22), 14877. https://doi.org/10.3390/su142214877

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

Kardhana, H. Solehudin. Wijayasari, W., and Rohmat, F.I.W. 2024. Assessing basin-wide soil erosion in the Citarum watershed using USLE method. *Results in Engineering*, *22*. https://doi.org/10.1016/j.rineng.2024.102130

Kijowska-Strugała, M. Demczuk, P., and Bucała-Hrabia, A. 2025. What are the impacts of land use change and cover-management factors on soil erosion modelling studies? *Catena*, *258*. https://doi.org/10.1016/j.catena.2025.109240

Lee, S. Chu, M.L. Guzman, J.A., and Botero-Acosta, A. 2021. A comprehensive modeling framework to evaluate soil erosion by water and tillage. *Journal of Environmental Management*, *279*. https://doi.org/10.1016/j.jenvman.2020.111631

Li, N. Zhao, H. Luo, Z. Wang, T. Yang, J. Li, L., and Que, S. 2024. Soil erosion prediction in multiple scenarios based on climate change and land use regulation policies in context of sustainable agriculture. *Catena*, *247*. https://doi.org/10.1016/j.catena.2024.108525

Liang, Y. Gao, G. Liu, J. Dunkerley, D., and Fu, B. 2023. Runoff and soil loss responses of restoration vegetation under natural rainfall patterns in the Loess Plateau of China: The role of rainfall intensity fluctuation. *Catena*, *225*. https://doi.org/10.1016/j.catena.2023.107013

Liu, C. Fan, H. Jiang, Y. Ma, R., and Song, S. 2023. Gully erosion susceptibility assessment based on machine learning-A case study of watersheds in Tuquan County in the black soil region of Northeast China. *Catena*, *222*. https://doi.org/10.1016/j.catena.2022.106798

Liu, X. Wang, D. Guo, M. Zhang, X. Chen, Z. Wan, Z., and Liu, J. 2025. Determination of future gully erosion risk and its spatially quantitative interpretability of driving factors in regional scale using machine learning algorithms. *Geoderma*, *459*. https://doi.org/10.1016/j.geoderma.2025.117396

Luquin, E. Herzmann, D. Gelder, B., and Cruse, R. 2025. Assessing the impact of residue cover on hillslope soil loss in the Midwest US: insights from the Daily Erosion Project modeling framework. *International Soil and Water Conservation Research*. https://doi.org/10.1016/j.iswcr.2025.08.006

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. https://doi.org/10.21776/ub.jtresda.2021.001.02.47

Mas, M.T. Verdú, A.M.C. Pardo, G. Pueyo, J. Claramunt, J., and Cirujeda, A. 2024. Shoot and biomass reduction of perennial weeds using hydromulches and physical changes in the mulches. *Journal of Plant Diseases and Protection*, *131*(2), 433–443. https://doi.org/10.1007/s41348-023-00833-6

Molla, T., and Sisheber, B. 2017. Estimating soil erosion risk and evaluating erosion control measures for soil conservation planning at Koga watershed in the highlands of Ethiopia. *Solid Earth*, *8*(1), 13–25. https://doi.org/10.5194/se-8-13-2017

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. https://doi.org/10.21776/ub.jtresda.2023.003.01.11

Pan, L. Chen, Y. Shi, D. Gao, J. Jiang, Y., and Liu, F. 2025. Spatio-temporal evolution of sloping farmland and identification of its erosion risk management and control zones in the Three Gorges Reservoir Area, China. *Resources, Environment and Sustainability*, *21*, 100255. https://doi.org/10.1016/j.resenv.2025.100255

Panagos, P. Borrelli, P. Poesen, J. Meusburger, K. Ballabio, C. Lugato, E. Montanarella, L., and Alewell, C. 2016. Reply to the comment on “The new assessment of soil loss by water erosion in Europe” by Fiener & Auerswald. *Environmental Science and Policy*, *57*, 143–150. https://doi.org/10.1016/j.envsci.2015.12.011

Panagos, P. Borrelli, P., and Meusburger, K. 2015. A new European slope length and steepness factor (LS-factor) for modeling soil erosion by water. *Geosciences (Switzerland)*, *5*(2), 117–126. https://doi.org/10.3390/geosciences5020117

Pham, T.G. Degener, J., and Kappas, M. 2018. Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam. *International Soil and Water Conservation Research*, *6*(2), 99–110. https://doi.org/10.1016/j.iswcr.2018.01.001

Purnomo, N.H. Sutikno. Sunarto., and Muta'ali, L, 2013. Risiko Longsorlahan Pada Lahan Pertanian Di Kompleks Gunungapi Kuarter Arjuno Jawa Timur. Forum Geografi, Vol. 27, No.1, Juli 2013, p.45-56. https://doi.org/10.23917/forgeo.v27i1.5081

Ristić, R. Kostadinov, S. Radić, B. Trivan, G., and Nikić, Z. 2012. *TORRENTIAL FLOODS IN SERBIA-MAN MADE AND NATURAL HAZARD*.

Santarsiero, V. Lanorte, A. Nolè, G. Cillis, G. Tucci, B., and Murgante, B. 2023. Analysis of the Effect of Soil Erosion in Abandoned Agricultural Areas: The Case of NE Area of Basilicata Region (Southern Italy). *Land*, *12*(3). https://doi.org/10.3390/land12030645

Santosa, T. J. I. B. 2016. Analysis of sedimentation in Wonogiri Reservoir. *Journal of the Civil Engineering Forum*, 2(1), 27–32. https://doi.org/10.22146/jcef.24022

Shen, Y. Liu, G. Gu, J. Shu, C. Wang, K. Zhang, Q. Luo, H. Zhang, C., and Guo, Z. 2025. Predicting soil erosion rates of farmland with different slope shapes in Northeast China by using the improved RUSLE2 model. *Soil and Tillage Research*, *254*. https://doi.org/10.1016/j.still.2025.106760

Simanungkalit, N.M. 2011. Evaluasi Kemampuan Lahan dan Penggunaan Lahan Pertanian di Sub DAS Gotigoti Daerah Aliran Sungai Batangtoru Kabupaten Tapanuli Utara. Jurnal Geografi, Vol. 3, No.1. https://doi.org/10.24114/jg.v3i1.7284

Simelane, M.P.Z. Soundy, P., and Maboko, M.M. 2024. Effects of Rainfall Intensity and Slope on Infiltration Rate, Soil Losses, Runoff and Nitrogen Leaching from Different Nitrogen Sources with a Rainfall Simulator. *Sustainability (Switzerland)*, *16*(11). https://doi.org/10.3390/su16114477

Singh, M.C. Sur, K. Al-Ansari, N. Arya, P.K. Verma, V.K., and Malik. A. 2023. GIS integrated RUSLE model-based soil loss estimation and watershed prioritization for land and water conservation aspects. *Frontiers in Environmental Science*, *11*. https://doi.org/10.3389/fenvs.2023.1136243

Sutrisno, J., Sanim, B., Saefuddin, A., & Sitorus, S. R. P. 2011. Prediksi erosi dan sedimentasi di Sub Daerah Aliran Sungai Keduang Kabupaten Wonogiri. *Media Konservasi*, 16(2). https://doi.org/10.29244/medkon.16.2.%p

Taryono. Santoso, S.B., and Priyana, Y. 2001. Kajian Geomorfologi Untuk Evaluasi Lahan Kritis Di Kecamatan Cepogo Kabupaten Boyolali Provinsi Jawa Tengah. Forum Geografi, Vol.15, No.2, 2001:113-124. https://doi.org/10.23917/forgeo.v15i2.4576

Umar, I. Widiatmaka. Pramudya, B., and Barus, B. 2017. Evaluasi Kesesuaian Lahan Untuk Kawasan Pemukiman Dengan Metode Multi Criteria Evaluation Di Kota Padang. Jurnal Pengelolaan Sumberdaya Alam Dan Lingkungan, Vol.7, No.2 (Agustus 2017): 148-154. https://doi.org/10.29244/jpsl.7.2.148-154

USDA. (1999). *Soil quality test kit guide*. Washington, DC: Natural Resources Conservation Service, Soil Quality Institute.

Wang, Y. Hu, X. Yu, S. Wang, Z. Zhao, J. Fang, N. Xiao, H. Wang, L., and Shi, Z. 2024. Soil conservation of sloping farmland in China: History, present, and future. In *Earth-Science Reviews* (Vol. 249). Elsevier B.V. https://doi.org/10.1016/j.earscirev.2023.104655

Zhu, D. Dong, Y. Feng, R. Li, Y., and Zhai, C. 2024. Dynamic responses and cumulative damage of coastal bridges subjected to extreme sequential earthquake-tsunamis. *Soil Dynamics and Earthquake Engineering*, *187*. https://doi.org/10.1016/j.soildyn.2024.108975