Estimation of Erosion and Sediment Delivery Ratio in the Pepe River Sub-Watershed Area, Boyolali Regency using the USLE Method at BPDAS Solo

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Abstract

Watersheds integrate hydrological, soil, topographic, and land-use processes that determine erosion and sediment delivery. This study estimated annual soil loss, erosion hazard level, and Sediment Delivery Ratio (SDR) in the Pepe Sub-watershed, a tropical catchment within the Upper Bengawan Solo watershed system, using ArcGIS-based spatial analysis, the Universal Soil Loss Equation (USLE), and Boyce SDR estimation. Secondary spatial data from BPDAS Solo, rainfall records for 2015-2024, and thematic maps of soil type, slope, and land use/land cover were analyzed. The mean erosion rate was 57.32 t ha-1 yr-1, while the moderate, severe, and very severe erosion classes exceeded the tolerable soil loss threshold (EDP = 40 t ha-1 yr-1). The severe and very severe classes had class erosion rates of 288.39 and 634.63 t ha-1 yr-1, respectively; however, their mapped area should be quantified from the final TBE raster attribute table before publication. The SDR value of 0.0187 indicates that approximately 1.87% of gross erosion is delivered to the outlet, resulting in an estimated sediment yield of 33,936.18 t yr-1. These findings inform SDG 6.6, SDG 11.5, SDG 13.1, and SDG 15.3 by supporting erosion control, sediment reduction, and land-degradation mitigation in tropical watershed planning.

Keywords: watershed, erosion, sedimentation, soil conservation, land management

Introduction

A Watershed (Drainage Basin) is an integrated ecosystem consisting of upstream, middle, and downstream sections. Within a watershed, every input can be assessed through the processes reflected in the outputs at the watershed outlet. The primary input in a watershed is rainfall, while the outputs include water discharge, sediment load, and nutrients. As an ecosystem, a watershed is composed of various components such as human activities and technologies, vegetation, soil, and the river system. Rainfall within the watershed interacts with all these components, producing outputs such as streamflow and sediment load.

The Pepe Sub-watershed is part of the Upper Bengawan Solo watershed network and contributes to the river-flow system affecting Surakarta and surrounding areas. The catchment is characterized by a combination of settlement expansion, agricultural activity, heterogeneous land cover, and terrain ranging from flat areas to very steep slopes. These anthropogenic and geomorphological gradients distinguish the Pepe Sub-watershed from other USLE-modeled catchments in Java because erosion risk is controlled not only by rainfall and soil type, but also by the spatial interaction between built-up areas, cultivated land, and steep volcanic terrain. In addition, increased erosion can raise the sediment load entering river bodies, which may reduce river capacity and trigger flooding. Land-use changes can also increase runoff discharge and sediment yield entering the river system, ultimately accelerating river or reservoir sedimentation and affecting hydrological functions (Daramola et al., 2022).

Erosion is a natural process involving the detachment and transport of soil particles by agents such as water or wind. This process can occur throughout the watershed, from upstream to downstream areas. Factors influencing erosion include rainfall, soil type, vegetation, and slope. High rainfall or poor vegetation cover makes soil more susceptible to erosion. Detached soil particles are then carried by surface runoff into rivers or other water channels. This process not only alters land surface morphology but also affects water quality in rivers and lakes (Nahib et al., 2024).

The Sediment Delivery Ratio (SDR) is an important parameter in erosion and sedimentation studies, representing the ratio between the amount of sediment produced in an area and the amount that reaches the outlet or measurement point. SDR reflects the efficiency of the flow system in transporting sediment from its source to the deposition site. SDR values are influenced by factors such as topography, vegetation, land use, and rainfall characteristics. Areas with steep slopes and low vegetation cover generally have higher SDR values because sediment is more easily transported by runoff (Thomas et al., 2020). Previous GIS-based erosion studies in Java commonly quantify gross soil loss using USLE or RUSLE, but fewer studies explicitly connect source-area erosion estimates with SDR-based sediment delivery and management implications for sub-watershed planning. In the Pepe Sub-watershed, such integration is important because sediment generated from vulnerable land units may reduce river capacity, increase sedimentation, and affect downstream hydrological function (Firdaust et al., 2023). Therefore, this study aimed to estimate the spatial distribution of soil erosion, classify erosion hazard levels, and quantify the Sediment Delivery Ratio in the Pepe Sub-watershed using GIS-based USLE analysis. The results are expected to support conservation prioritization, land-use planning, and sediment-control policy within the Upper Bengawan Solo watershed system.

Materials and Methods

Data processing and analysis were conducted from June 30 to August 8, 2025 at the Balai Pengelolaan Daerah Aliran Sungai (BPDAS) Solo, located at Jl. Tentara Pelajar, Plempungan, Bolon, Colomadu, Karanganyar Regency, Central Java. The study area was the Pepe Sub-watershed, which belongs to the Upper Bengawan Solo watershed system. The tools used included stationery, a smartphone for field documentation, and a laptop for data processing. Google Earth was used for visual interpretation, while ArcGIS 10.7 was used for spatial processing and thematic-map preparation. The spatial datasets included erosion-hazard data and supporting watershed physical-condition data from BPDAS Solo. Rainfall data used for the erosivity calculation covered the 2015-2024 period; 2025 was treated only as the period of data processing and was not included in the rainfall time series.

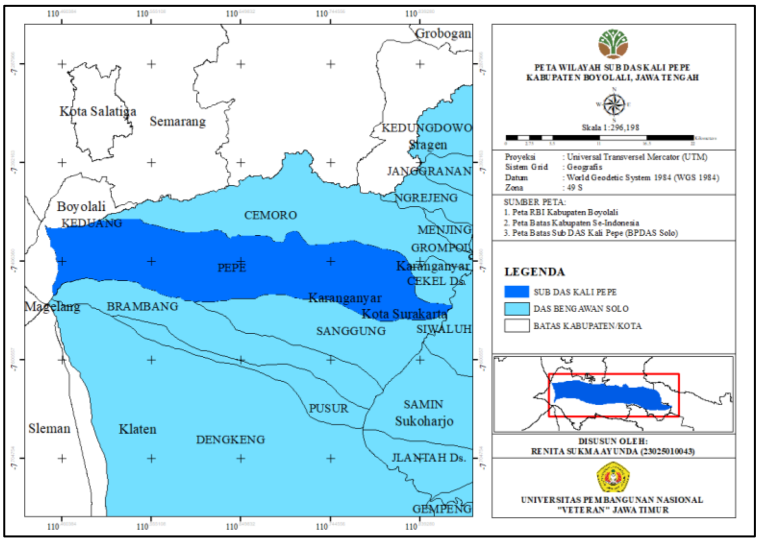

Figure 1. Map of the Kali Pepe Sub-watershed Area

Data collection was carried out using both primary and secondary data. Primary data were obtained through observation, recording, and documentation of the research objects. Meanwhile, secondary data were collected from official documents, government publications, archives of the BPDAS Solo agency, as well as previous research journals. The secondary data used included the Google Earth layer of the Kali Pepe Sub-watershed, the Indonesian Topographic Map (Rupa Bumi Indonesia) of Boyolali Regency at a scale of 1:25,000, slope data, soil type data, rainfall data of Boyolali Regency from 2015–2024, and data on land use and land management in the Pepe Sub-watershed.

Rainfall erosivity can be calculated using the Lenvain (1975) formula (Sari et al., 2020), as follows:

R_m = 2, 21 $(Rain)_m^{1,36}$

With :

R_m = Average rainfall erosivity index (mm/month)

$(Rain)_m^{1,36}$ = Average monthly rainfall (cm/month)

A commonly used method to predict erosion rates is the USLE (Universal Soil Loss Equation), developed by Wischmeier and Smith in 1978 (Aprilio et al., 2023). The equation is as follows:

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

With :

A = Erosion rate (tons/ha/year)

R = Rainfall erosivity index

K = Soil erodibility index

LS = Slope length and steepness index

CP = Land use and soil management index

The formula used to calculate tolerable soil loss employs the Hammer (1981) method (Stefano & Ferro, 2016), with the equation as follows:

$$Edp = \frac{de \times fd}{w} \times BD \times 10$$

With :

Edp = Tolerable soil loss (tons/ha/year)

de = Effective soil depth (mm)

fd = Soil depth factor = 1

W = Resource life / land use lifespan (300 years)

BD = Bulk density (gr/cm^3)

However, since no direct field observations were conducted, an average-value approach based on literature was used, namely: de = 1000 mm, fd = 1, BD = 1.2 g/cm^3, and W = 300 years.

The equation used to calculate the Erosion Hazard Level (Arif et al., 2025) is as follows:

$$TBE = \frac{A}{T}$$

With:

TBE = Erosion hazard level

A = Erosion rate (tons/ha/year)

T (Edp) = Tolerable soil loss (tons/ha/year)

The Sediment Delivery Ratio (SDR) relates the rate of erosion to sediment yield. In this study, the SDR value was calculated using the equation proposed by Boyce (1975) formula (Arif et al., 2025):

$SDR = 0.419 \times Ws^{-0.3}$

The estimated sediment yield per unit area according to Asdak (2004) (Aprilio et al., 2023) can be calculated using the following equation:

$Y = A \times SDR \times Ws$

With :

Y = Sediment yield per unit area

A = Erosion rate (tons/ha/year)

Ws = Watershed area

SDR = Sediment Delivery Ratio

Result and Discussion

R Factor (Rainfall Erosivity)

Rainfall erosivity is closely related to erosion because rainfall controls the detachment of soil particles and the formation of surface runoff. In this study, rainfall classes derived from CHIRPS data for 2015-2024 were used to represent the spatial variation of erosive rainfall in the Pepe Sub-watershed. The reported R-factor values ranged from 259.12 to 334.27, increasing consistently with annual rainfall from 2,686 to 3,465 mm year-1.

Table 1. Regression Analysis Results: N and Vegetation Index

Annual Rainfall (mm/year)	Erosivity Index (R)	Criteria
2686	259,12	Moderate
2895	279,28	Moderate
3097	298,77	High
3279	316,33	High
3465	334,27	High

Source: CHIRPS data (2015–2024) and calculation results

Based on annual rainfall data processing for 2015-2024, five rainfall erosivity classes were identified in the Pepe Sub-watershed, ranging from 259.12 to 334.27. These five classes correspond to rainfall values between 2,686 and 3,465 mm year-1 and represent the dominant raster groups generated through spatial reclassification. Therefore, both Table 1 and Figure 2 should consistently be interpreted as five rainfall-erosivity classes. The eastern part of the sub-watershed had the highest reported R value of 334.27, whereas the southeastern part had the lowest value of 259.12.

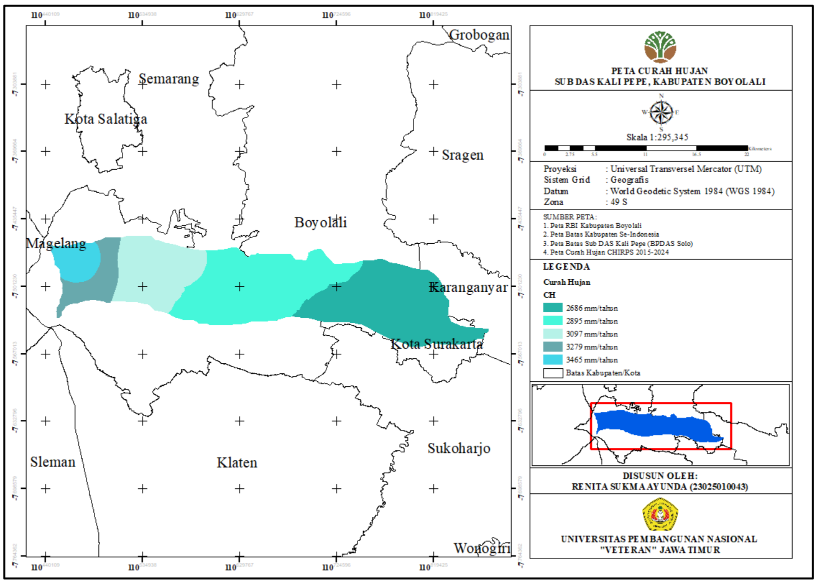

Figure 2. Rainfall Map of the Kali Pepe Sub-watershed

Rainfall erosivity is a key driver of soil erosion because it represents the energy of rainfall to break soil aggregates and initiate runoff. However, the R-factor requires careful unit verification. Using the Lenvain equation with annual rainfall converted into average monthly rainfall in centimeters produces diagnostic annual R values in a substantially higher range than those reported in Table 1. The erosivity value is influenced by rainfall amount, intensity, and distribution, which play important roles in runoff formation and erosion processes (Andriyani et al., 2024). A rainfall erosivity map is used to identify the spatial variation of erosion potential within a region. In this study, rainfall erosivity in the Kali Pepe Sub-watershed was calculated using the R-factor in the USLE method, utilizing CHIRPS rainfall data from the 2015–2024 period, which provides wide coverage and consistent data (Tong et al., 2025). Physically, erosivity represents the kinetic energy of rainfall capable of breaking down soil aggregates and triggering surface runoff. Therefore, higher erosivity values indicate a greater potential for erosion (Chen et al., 2025).

K Factor (Soil Erodibility)

Soil erodibility represents the susceptibility of soil to erosion processes; the higher the erodibility value, the more easily the soil is detached and transported. The level of erodibility is influenced by several factors, including soil texture, structure, organic matter content, and permeability. Soil type is one of the key factors determining the degree of erodibility or the vulnerability of an area to erosion. Based on the classification and interpretation of soil maps using the USDA Soil Taxonomy system, the Kali Pepe Sub-watershed is dominated by three soil types: Alfisols, Vertisols, and Andisols. Each of these soil types has different physical and chemical characteristics, resulting in varying K-factor values according to their natural properties.

Table 2. Regression Analysis Results: N and Vegetation Index

Soil Type	K Value
Alfisols	0,188
Vertisols	0,187
Andisols	0,302

Source: USDA Soil Taxonomy; PUSLITTANAK

Soil type is a primary factor influencing erodibility, represented by the K factor in USLE. Three dominant soil orders were identified in the Pepe Sub-watershed: Alfisols, Vertisols, and Andisols. Andisols showed the highest K value (0.302), indicating greater susceptibility to detachment than Alfisols (0.188) and Vertisols (0.187). This vulnerability is commonly associated with volcanic-derived soils that may contain high proportions of silt and fine sand, low bulk density, and aggregate structures that become unstable when vegetation cover is removed or soil organic matter declines. Consequently, deforested or poorly covered Andisols should be treated as high-priority conservation targets because rainfall impact and runoff can rapidly detach fine particles and accelerate land degradation.

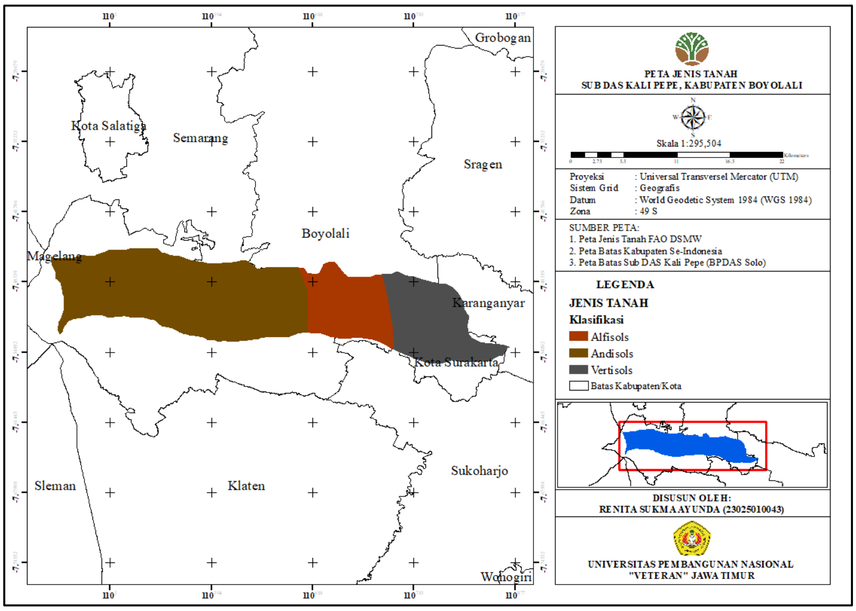

Figure 3. Soil Type Map of the Kali Pepe Sub-watershed

LS Factor (Slope Length and Steepness)

The slope map in this KKP activity was developed using SRTM DEM data with a resolution of 30 × 30 meters, which was then classified into several classes and assigned scores according to each class, as presented in Table 3.

Table 3. Recapitulation of LS Values in the Kali Pepe Sub-watershed

Slope Length	Class	LS Value
< 8 %	Flat	0,4
8 - 15 %	Gently sloping	1,4
15 - 25 %	Moderately steep	3,1
25 - 45 %	Steep	6,8
> 45 %	Very steep	9,5

Source: Calculation results, 2025; Lesmana et al., 2021

The Pepe Sub-watershed exhibits varied topographic conditions, with slope classes ranging from flat to very steep. Areas with slopes less than 8% dominate the recorded slope area, covering approximately 26,795.06 ha, while areas with slopes greater than 45% cover only 27.21 ha. Land with slopes of 8-15%, 15-25%, and 25-45% covers 3,023.76 ha, 952.68 ha, and 475.05 ha, respectively. Although steep classes occupy smaller areas, their LS values are much higher; therefore, they have disproportionate influence on potential erosion where erosive rainfall, erodible soil, and exposed land cover coincide.

Slope length and steepness determine runoff volume, flow velocity, and the capacity of surface water to transport detached particles. Increasing slope steepness increases runoff velocity and reduces residence time for infiltration, thereby increasing erosion potential. For this reason, slope classes above 15% require greater attention in conservation planning, particularly where they overlap with dryland farming, plantation/garden land, shrubland, or built-up expansion (Salma et al., 2024). An increase in slope steepness leads to higher surface runoff velocity and reduced soil infiltration capacity, making steeper areas more susceptible to erosion (Fiantika et al., 2018).

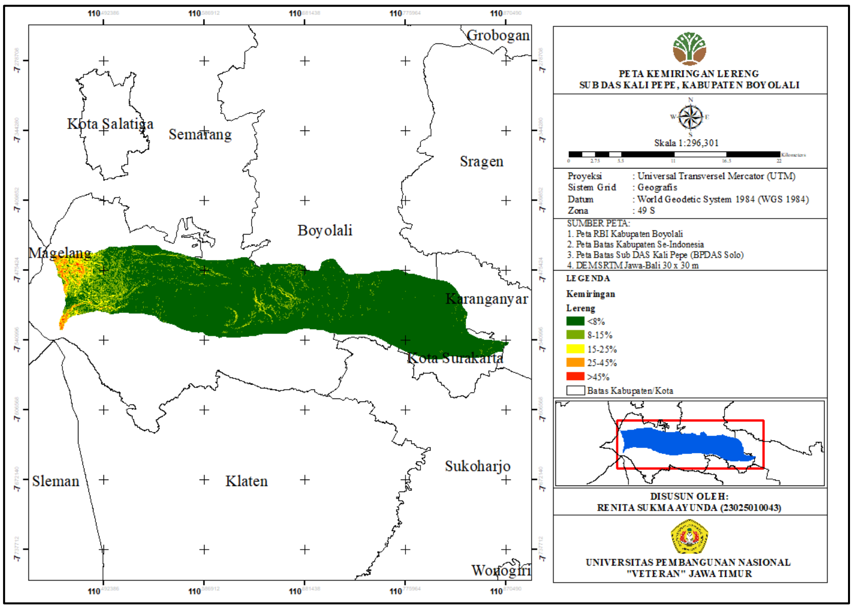

Figure 4. Slope Map of the Kali Pepe Sub-watershed

CP Factor (Land Use and Land Cover)

Based on the recapitulation of CP values, land use in the Kali Pepe Sub-watershed shows varying levels of protection against erosion. Land uses such as natural forest and paddy fields, including rainfed paddy fields, have low CP values of 0.01, indicating very high soil protection against erosion. This condition is due to dense vegetation cover or standing water in paddy fields, which can reduce rainfall impact and slow down surface runoff. Grasslands, as well as herbaceous and grass vegetation, also have relatively low CP values of 0.02, indicating a fairly good ability to reduce erosion. In contrast, land uses such as buildings, settlements, and activity areas have the highest CP value of 0.95. The land use map of the Kali Pepe Sub-watershed was derived from the Boyolali RBI Map data and subsequently classified based on CP factor values, as presented in Table 4.

Table 4. Recapitulation of LS Values in the Kali Pepe Sub-watershed

Land Use	CP Value
Buildings	0,950
Herbs and Grass	0,020
Natural Forest	0,010
Grassland	0,020
Plantation/Garden	0,500
Settlements and Activity Areas	0,950
Paddy Fields	0,010
Rainfed Paddy Fields	0,010
Shrubland	0,300
River	0,001
Dryland Farming	0,190
Other Non-Cultivated Vegetation	0,050
Reservoir	0,001

Source: Purnama, 2022; Sadewo et al., 2023

Plantation or garden land use has a CP value of 0.50, indicating moderate protection, whereas shrubland and dryland farming have CP values of 0.30 and 0.19, respectively. Other non-cultivated vegetation has a low CP value of 0.05, while rivers and reservoirs have the lowest values (0.001). Overall, higher CP values indicate lower surface protection and greater erosion susceptibility, whereas lower values indicate better capacity to reduce raindrop impact, runoff velocity, and sediment transport.

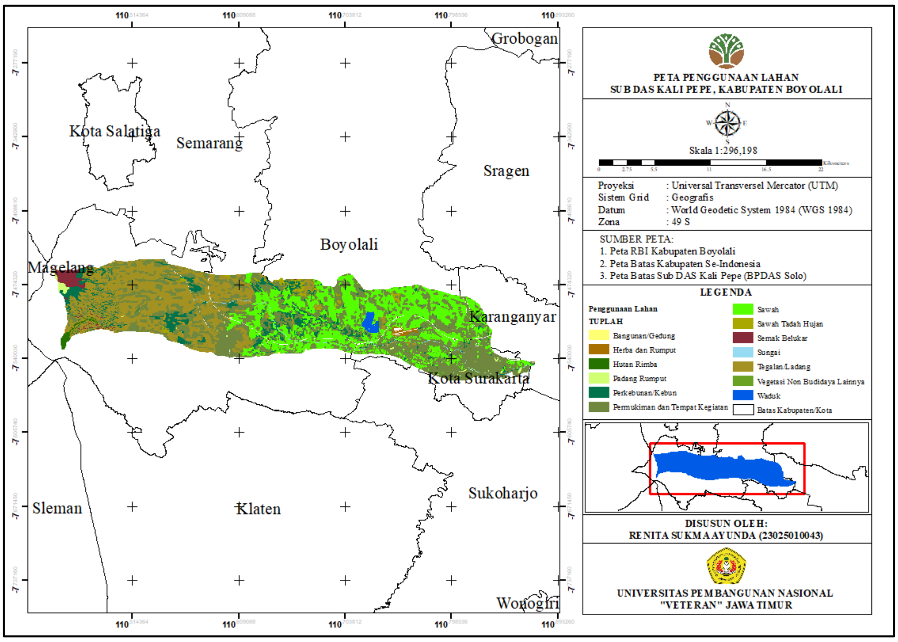

Figure 5. Recapitulation of CP Values in the Pepe Sub-watershed

Land use refers to the utilization of the Earth's surface by humans, such as forests, plantations, paddy fields, settlements, dryland farming areas, and water bodies. The vegetation factor in erosion analysis reflects the influence of land cover, litter, soil surface conditions, and land management on the amount of soil loss. Vegetation or land cover plays an important role in protecting the soil from direct raindrop impact and in reducing both the volume and velocity of surface runoff, thereby minimizing erosion potential. The P factor represents the ratio between the amount of soil loss from land with specific conservation practices and that from land without conservation measures. Vegetation also functions as a sediment trap before soil particles reach the watershed outlet. The presence of buffer strips or vegetative zones along riverbanks and drainage channels is effective in filtering sediment transported by surface runoff. These vegetative strips slow down water flow, allowing more time for sediment to settle before entering the main river channel (Paraya et al., 2025). The implementation of appropriate vegetation strategies can effectively control SDR values and contribute to reducing sedimentation in rivers and reservoirs. Land management that integrates vegetation planting according to regional characteristics is an important effort to reduce erosion and lower SDR, particularly in areas with high vulnerability to land degradation (Gulo & Lase, 2025).

Erosion Hazard Level (TBE)

Erosion Erosion in the Pepe Sub-watershed is controlled by the interaction of rainfall erosivity, soil erodibility, slope length-steepness, and land cover. The estimated erosion rates and erosion hazard levels were classified into five classes, as presented in Table 5 and Table 6.

Table 5. Classification of Erosion Rate (A) Classes

Erosion Rate (tons/ha/year)	Class
< 15	Very slight
15 - 60	Slight
60 - 180	Moderate
180 - 480	Severe
> 480	Very severe

Source: Sadewo et al., 2023

Table 6. Erosion Hazard Level (TBE) Results of the Kali Pepe Sub-watershed

A (ton/ha/year)	EDP	TBE	KBE	Categori
3,570	40	0,089	I	Very slight
30,722	40	0,7681	II	Slight
108,230	40	2,705	III	Moderate
288,394	40	7,209	IV	Severe
634,634	40	15,865	V	Very severe

A= annual soil loss or erosion rate; EDP = tolerable soil loss; TBE = A/EDP; KBE = erosion hazard class

The Erosion Hazard Level (TBE) was calculated as the ratio between actual erosion (A) and tolerable soil loss (EDP). The very slight and slight classes remained below the EDP threshold of 40 t ha-1 yr-1, with TBE values of 0.089 and 0.768, respectively. In contrast, the moderate, severe, and very severe classes exceeded the EDP threshold by approximately 2.71, 7.21, and 15.87 times. These exceedance ratios indicate that conservation planning should not rely only on class labels, but should prioritize areas where A exceeds EDP, especially the severe and very severe classes. The mapped area of each TBE class should be extracted from the final GIS raster attribute table to quantify how many hectares fall under the severe and very severe categories.

The tolerable soil erosion rate was calculated by considering several soil parameters, namely effective depth (de), soil depth factor (fd), bulk density (BD), and soil useful life (W). However, since no direct field observations were conducted, the calculation was carried out using average values derived from literature sources. The de value was set at 1000 mm, representing deep soil profiles commonly found in long-developed agricultural lands. The fd value of 1 was used to describe soil conditions with good to moderate drainage, which do not significantly accelerate or slow down water flow (Stefano & Ferro, 2016). A BD value of 1.2 g/cm³ was applied, reflecting the bulk density of medium- to fine-textured mineral soils, such as Alfisols and Vertisols, which are commonly found in tropical agricultural lands with relatively good porosity and organic matter content (Bakri et al., 2025). Furthermore, the soil useful life (W) was set at 300 years based on the estimated natural soil formation rate in tropical regions, which is relatively slow at around 0.3 mm per year. Therefore, the formation of a 1-meter soil layer is estimated to take approximately 300 years, a value that falls within the typical range of soil formation periods in tropical environments (Stefano & Ferro, 2016).

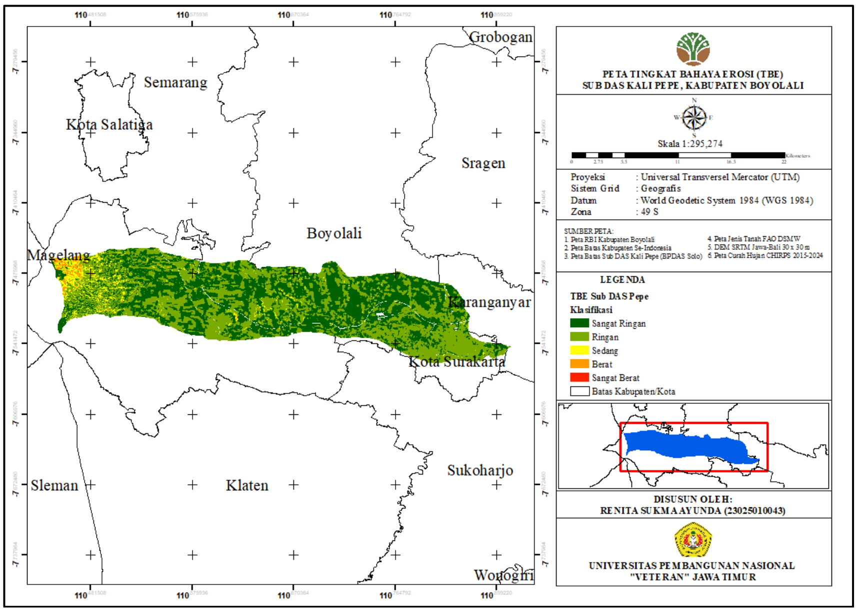

Figure 6. Erosion Hazard Level Map of the Kali Pepe Sub-watershed

Sediment Delivery Ratio (SDR)

The Pepe Sub-watershed covers 31,636.97 ha within the Bengawan Solo watershed system. The Sediment Delivery Ratio (SDR) was calculated as 0.0187 using the Boyce equation, indicating that approximately 1.87% of gross erosion is transported to the outlet. The remaining sediment is likely retained, redeposited, or stored within hillslopes, drainage channels, floodplains, paddy fields, and vegetated areas inside the sub-watershed.

Table 7. Sediment Delivery Ratio (SDR) Results and Sediment Load

Sub-Watershed	Ws (Area ha)	SDR	A (tons/ha/year)	Y (tons/year)
Kali Pepe	31.636,97	0,0187	57,32	33936,18

Source: Calculation results, 2025

The mean erosion rate (A) was 57.32 t ha-1 yr-1. When multiplied by watershed area and SDR, this value produced an estimated sediment yield of 33,936.18 t yr-1. The implied gross erosion is approximately 1.81 million t yr-1, showing that even a low SDR can still generate a substantial sediment load when the contributing area is large. This result highlights the need for upstream erosion control because reducing soil loss at source areas will reduce sediment pressure at the river outlet. Figure 12. demonstrates that sediment yield responds multiplicatively to changes in mean erosion rate and SDR. A simultaneous 20% increase in both parameters raises sediment yield by approximately 44% relative to the base scenario, whereas a simultaneous 20% decrease reduces sediment yield by approximately 36%.

SDR values are influenced by watershed area, topography, drainage density, land cover, and sediment-storage opportunities. A low SDR in this study suggests that the Pepe Sub-watershed has considerable internal sediment retention, but it does not eliminate downstream risk. Sediment retained within the catchment can be remobilized during high-intensity rainfall events, land clearing, channel disturbance, or extreme runoff. Therefore, erosion mitigation should combine source-area conservation with channel and riparian-zone management (Seeboonruang et al., 2025).

Conclusion

The GIS-based USLE-SDR assessment indicates that erosion control in the Pepe Sub-watershed should be treated as a spatial planning priority within the Upper Bengawan Solo watershed network. Management should prioritize land units where high rainfall erosivity, erodible Andisols, steep slopes, and high CP land-cover classes overlap. Conservation measures should include maintaining permanent vegetation cover, reinforcing riparian buffers, applying contour-based cultivation or terracing on sloping agricultural land, and controlling runoff from built-up and settlement expansion areas. The SDR result shows that only a small fraction of eroded material reaches the outlet, but the large gross erosion potential means that upstream soil loss remains a significant sediment-management issue. For policy implementation, BPDAS Solo and regional spatial-planning agencies should integrate erosion-hazard maps into land-use control, conservation zoning, and sediment-reduction programs for the Upper Bengawan Solo watershed system.

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