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Spatial Integration of Rainfall and Runoff Kinetic Energy for Soil Erosion Prediction in the Pandanduri Reservoir Catchment Area, Indonesia

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ABSTRACT:
The main problem that occurs in the Water Catchment Area is soil erosion. The results of soil erosion can cause increased sedimentation, which ultimately reduces the capacity of the reservoir. Several erosion approach models, such as USLE, generally emphasize rainfall as a factor of soil detachment, while surface runoff as a sediment carrier has not been explicitly integrated into spatial analysis. This study aims to integrate rain kinetic energy and runoff kinetic energy in predicting soil erosion in the Pandanduri Reservoir Catchment Area by incorporating both energies based on runoff occurrence land units (SLKL). The data needed in this study include rainfall data, DEM, soil type maps, and land cover maps. Rain kinetic energy is calculated as a temporal controlling factor, and runoff kinetic energy is derived from slope and flow accumulation factors. The analysis results identified 30 land units, 84 runoff units, and 235 runoff occurrence land units. The calculation results show that the erosion rate ranges from 0.02–8.90 tons/ha/year. Runoff kinetic energy exhibits significant spatial variation and strongly influences the rate of soil erosion. The integration of rainfall kinetic energy and runoff kinetic energy provides a more realistic erosion prediction and can be used as a basis for determining conservation priorities in the Pandanduri Reservoir Catchment Area.

Keywords: Soil erosion; rain kinetic energy; runoff kinetic energy; runoff occurrence land units; geographic information systems

INTRODUCTION

Several studies have examined soil erosion prediction models using various approaches. Wischmeier and Smith (1978) developed the Universal Soil Loss Equation (USLE), which places rainfall as the primary controlling factor for erosion through the concept of rainfall erosivity. Renard et al. (1997) refined this model with the Revised Universal Soil Loss Equation (RUSLE), which considers more detailed factors. Nearing (1997) developed the Water Erosion Prediction Project (WEPP) model, which is more comprehensive in predicting erosion. Gezichi et al. (2025) assessed soil erosion risk in the mountainous region of northeastern Turkey using the RUSLE model and CMIP6 climate projections. Achu and Thomas (2023) modeled soil erosion and sediment yield in a tropical mountain river basin in the Southern Western Ghats, India, using RUSLE and geospatial tools. Ren et al. (2021) examined sedimentation and its response to management strategies in the Three Gorges Reservoir, Yangtze River, China. Zhang et al. (2025) analyzed the impact of rainfall and slope on slope runoff and erosion. However, these studies generally considered rainfall as a factor in soil detachment, while surface runoff as a sediment transporter was not explicitly considered in spatial analyses. The theory proposed by Mendekati et al. (2004) supports the importance of integrating physical factors affecting soil detachment and transport in more realistic erosion prediction models; however, the spatial implementation of integrating rainfall kinetic energy and runoff kinetic energy remains rare.

The most important environmental problem occurring in the reservoir water catchment area is erosion (Achu & Thomas, 2023; Gezichi et al., 2025), because it plays a significant role in increasing the sedimentation rate, which ultimately reduces the reservoir capacity (Mete & Bayram, 2024; Ren et al., 2021; Shrestha et al., 2022). Various erosion models have been developed, such as the USLE (Universal Soil Loss Equation) method (Van et al., 2022), RUSLE (Demirel et al., 2019), and the Water Erosion Prediction Project (WEPP) model, which basically place rainfall as the main factor controlling erosion through the concept of rainfall erosivity (Luo et al., 2025). However, runoff factors as carriers of soil particles—in the form of sheet erosion, rill erosion, gully erosion, and cliff erosion—have not been adequately taken into account (Guo et al., 2026). Theoretical studies by Nearing Admas et al., (2022); Yan & Chang, (2025) support the importance of integrating physical factors that influence soil detachment and transport in a more realistic erosion prediction model (Bronstert et al., 2023).

Naturally, some of the rain that falls in a watershed area is used by plants (Arsyad, 2010; Ikhwan et al., 2022)., some is absorbed into the soil (Li et al., 2020), and some runs off the surface of the soil in the form of runoff (Hamizak et al., 2025; Nicosia et al., 2024). The surface runoff then flows into river channels downstream and eventually enters the sea. The movement of water that flows over the land surface can occur directly from a spatial unit into a river, or from one spatial unit through another before entering a tributary and subsequently the main river (Cai et al., 2024; Firoozi & Firoozi, 2024).

Surface runoff that accumulates along slopes and flow channels ultimately increases flow velocity (Ma & Zheng, 2022; Sun et al., 2018; Tapas et al., 2024; Yan et al., 2024) and kinetic energy, thereby enhancing the flow's ability to transport soil material (Ibanez et al., 2025; Mineo et al., 2019; Peraturan Menteri PUPR, 2015). However, the role and position of runoff kinetic energy are still rarely explicitly integrated into spatial erosion analysis (Mikoš et al., 2010).

Based on the above explanation, this study proposes an approach to analyzing erosion by integrating rainfall kinetic energy and runoff kinetic energy based on runoff occurrence land units (SLKL). This approach is expected to provide a more realistic understanding of the primary drivers of erosion.

The novelty of this study lies in its innovative spatial integration of rainfall kinetic energy and runoff kinetic energy to predict soil erosion in the Pandanduri Reservoir catchment area, Indonesia. Unlike conventional erosion models such as USLE and RUSLE, which only consider rainfall kinetic energy as the controlling factor, this study explicitly integrates the contribution of runoff kinetic energy derived from slope factors and flow accumulation based on runoff occurrence land units (SLKL). This approach allows for a more realistic analysis because it considers the movement of runoff water across the land surface, including the accumulation of energy from upstream units flowing to downstream units. The analysis identified 30 land units, 84 runoff units, and 235 runoff occurrence land units throughout the Pandanduri Reservoir catchment area. This integration provides a more accurate spatial representation of runoff kinetic energy variations, which are strongly influenced by topographic characteristics and interactions between land units, thus resulting in erosion predictions that are closer to actual field conditions.

The purpose of this study is to integrate rainfall kinetic energy and runoff kinetic energy in predicting soil erosion in the Pandanduri Reservoir Catchment Area based on runoff occurrence land units (SLKL), and to analyze the spatial variation in the contribution of both forms of energy to the erosion rate. This study also aims to examine the relationship between runoff kinetic energy and soil erosion rate through Pearson correlation tests and simple linear regression. The theoretical benefit of this study is to enrich the development of erosion prediction models by integrating surface runoff factors that have thus far received limited attention in spatial erosion analysis. Practically, the results of this study can serve as a basis for policymakers, watershed managers, and related agencies such as the Ministry of Public Works and Public Housing and BWS Nusa Tenggara I in determining land conservation priorities in the Pandanduri Reservoir catchment area. The resulting maps of erosion rate distribution and erosion pressure can be used to identify land units that require immediate conservation intervention, particularly units with high runoff kinetic energy accumulation that contribute significantly to the total sediment load in the reservoir.

This research has important implications in various fields. In hydrology and soil conservation, the findings confirm that runoff kinetic energy has significant spatial variation and strongly influences soil erosion rates, with a correlation value of $r = 0.681$ ($p = 0.000$), indicating a strong and statistically significant relationship. This implies the need to consider runoff accumulation between land units in conservation planning, rather than focusing solely on the local characteristics of individual land areas. In the field of watershed (DAS) and reservoir management, this study shows that land units with locally low erosion rates can still contribute significantly to the total sediment load at the watershed outlet due to their catchment area and the accumulation of runoff from upstream areas. Therefore, watershed management strategies should prioritize not only land units with locally high erosion rates but also land units that act as pathways for energy concentration and transfer, particularly runoff. In public policy, the results of this study can serve as a reference for central and regional governments in formulating more targeted land conservation policies, for example by prioritizing interventions in land units with high runoff energy accumulation. For future researchers, this study opens opportunities to develop models by incorporating additional factors such as dynamic land cover changes, more detailed soil characteristics, and testing similar approaches in watersheds with different characteristics to examine the generalizability of these findings.

METHOD

The research was conducted in the Pandanduri Reservoir Catchment Area. Based on PUPR Ministerial Regulation No. 4 of 2015 concerning River Basin Criteria and Determination in Appendix V.71 of the Lombok River Basin, the Pandanduri Reservoir is located in the Palung River Basin with DAS number 094 with WS Code 03.02.A3, with the Pandanduri Reservoir catchment area being 67.42 km^2 (Sanchez et al., 2012).

This study used five years of rainfall data across the Pandanduri Reservoir catchment area, DEM data, soil type maps, and land cover maps. All spatial data were processed using a geographic information system (GIS), specifically ArcGIS 10.8, to support land unit-based analysis of runoff events (SLKL).

Data analysis in this study was carried out in several ways, such as calculating the kinetic energy of rain using an empirical equation in the form of a power-law between kinetic energy and rain intensity which is presented in equation 1.

$$KE = 0.119.I^{0.87} \tag{1}$$

where is KE = Kinetic energy of rain (MJ/ha.mm), and I= Rain intensity (mm/hour). The form of this equation refers to the concept of the relationship between rainfall and rainfall intensity which has been widely used in research related to rainfall erosivity (Chen et al., 2025; Eslami et al., 2025; Gezici et al., 2025; Wang et al., 2025). In this study, the kinetic energy of rainfall is treated as a temporal controlling factor, not a spatial differentiating factor for erosion.

The kinetic energy of runoff is calculated by considering the slope gradient, flow direction, and flow accumulation factors derived from the DEM. The equation used is presented in equation 2 below:

$$E = I.\ LS \tag{2}$$

where E = Runoff energy on a land unit, KE = Kinetic energy of rain, and LS = Index of length and slope of slope. The equation is used based on previous research (Abeje et al., 2025; Ghosh et al., 2023; Todisco et al., 2025), where rainfall intensity is converted into rain energy parameters used in conjunction with the LS factor map. Although the equation is not stated explicitly, the approach taken is based on a combination of rainfall strength and the effect of slope on runoff.

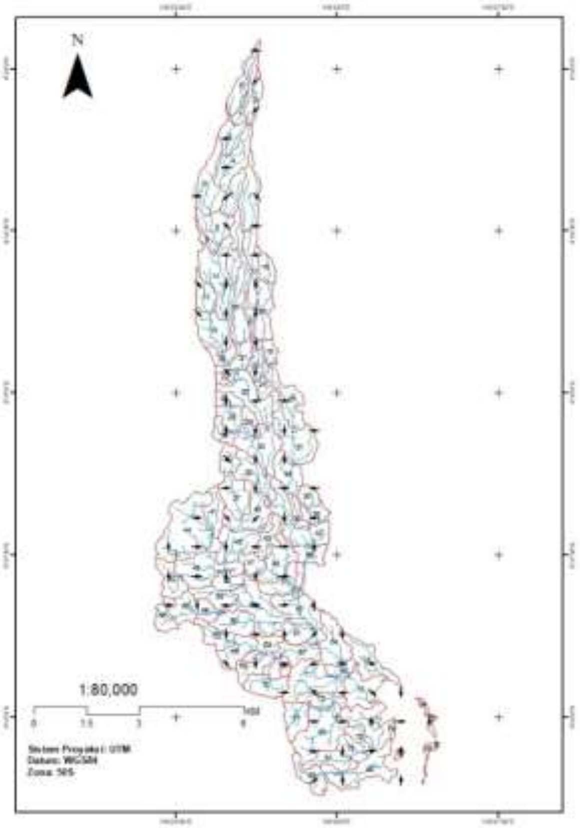
The analysis is then carried out by integrating the kinetic energy of rainfall and runoff with other supporting factors, namely slope length and steepness, soil erodibility, and land cover. Equation 3 shows a modified version of the classic USLE equation.

$$A = (I+E)KLSCP \tag{3}$$

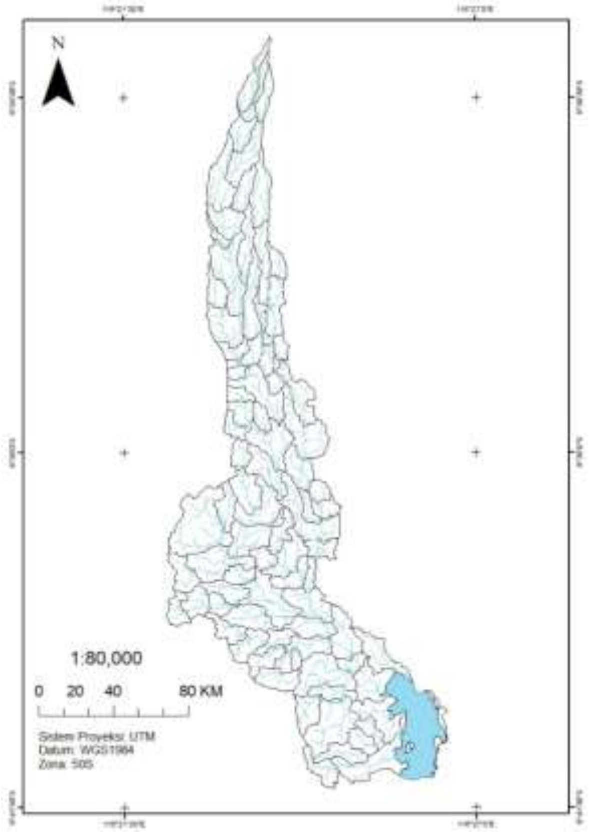
where A = Amount of erosion (ton/ha/year), K = Soil erodibility index, LS = Slope gradient factor, and CP = Soil management factor. The use of this formula is based on the basic principle that the total energy that triggers erosion comes from two main components, the energy from raindrops hitting the soil surface and the energy from surface flow (runoff) that erodes and carries soil particles. Combining KE and E values in one formula is a conceptual approach based on fluid mechanics, in which both forms of energy are considered as simultaneous contributors to the erosion process.

RESULTS AND DISCUSSION

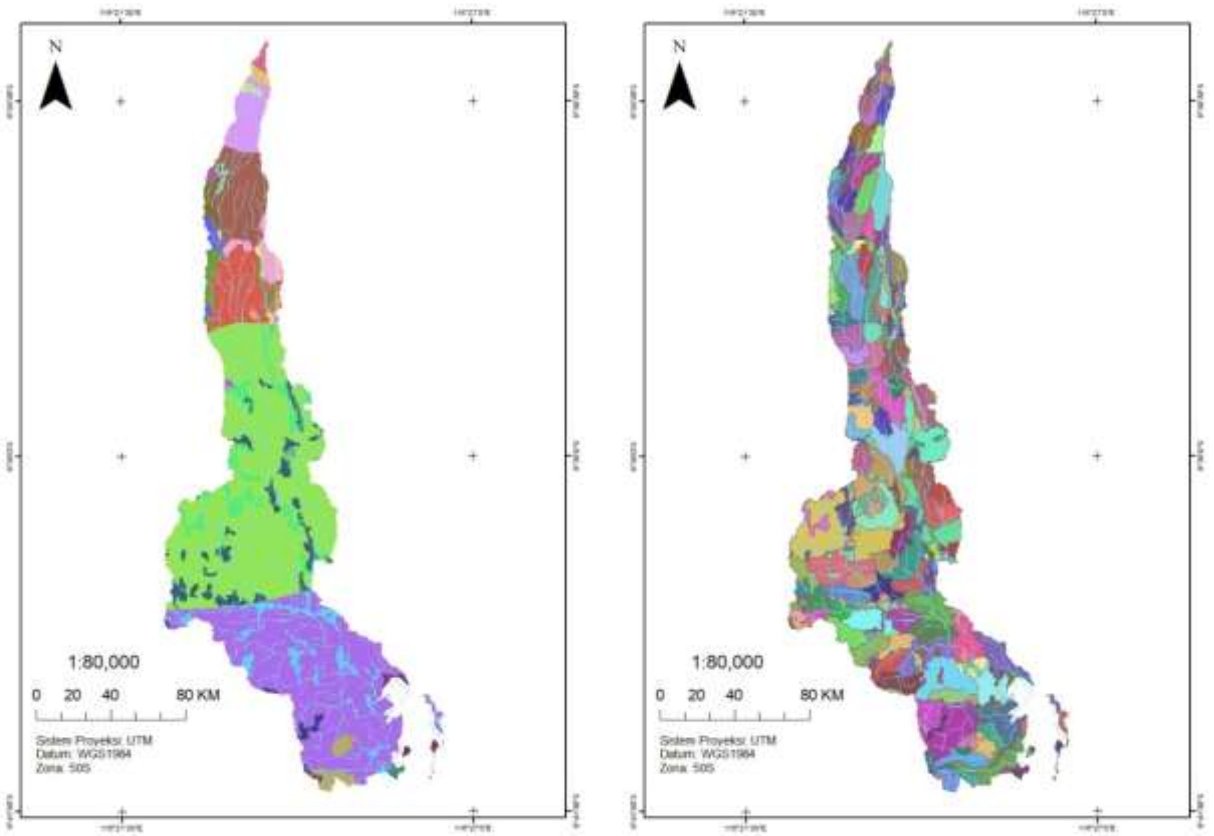
Based on the analysis results in ArcGIS software, four main maps were obtained in this study: a land unit map, a runoff boundary map, a runoff direction map, and a land unit map of runoff events. These maps can be seen in Picture 1, Picture 2, Picture 3, Picture 4 following. From the analysis results, 30 land units were obtained based on the resultsoverlaysoil type map, slope gradient map, and land use map, 84 runoff units, and there are 235 land units of runoff events that have been successfully identified throughout the Pandanduri Reservoir catchment area.



a. Flow Direction Map
Source: Processed Primary Data (2025)



b. Runoff Boundary Map
Source: Processed Primary Data (2025)



c. Land Unit Map
Source: Processed Primary Data (2025)

d. Land Unit Map of Runoff Events (SLKL)
Source: Processed Primary Data (2025)

Kinetic Energy of Rain

Rainfall data was obtained from BWS Nusa Tenggara I for the period 2020-2024 which was processed using the method*Polygon Thiessen*and the Mononobe Equation in finding the rainfall intensity value at the research location.Table 1 And Table 2 The following presents data on rainfall and rainfall intensity.

Once the rainfall intensity is known, the next step is to calculate the kinetic energy of the rain. The average KE value over five years was 1,281 MJ/ha·mm,and this value is used as a representative value of the annual rainfall kinetic energy in each land unit of runoff occurrence (SLKL) in spatial analysis. The rainfall kinetic energy (KE) can be seen inTable 3 and Figure 5.

Table 1. Results of Calculation of Average Annual Daily Rainfall for the Pandanduri Reservoir Watershed

No	Year	Rainfall (mm)			P Average(mm)
		Kopang (22.72 Km^2)	Perian (19.89 Km^2)	Loang Make (12.25 Km^2)	
1	2020	125	81	52	92.75
2	2021	89	121	71	96.58
3	2022	91	135	49.37	97.66

4	2023	76	77	133	89.09
5	2024	124	146	111	129.07

Source: Processed Primary Data (2025)

Table 2. Rainfall Intensity (I)

No	Year	R_{24}(mm)	Tc (hour)	I (mm/hour)
1	2020	92.75	3.44	14.11
2	2021	96.58	3.44	14.69
3	2022	97.66	3.44	14.86
4	2023	89.09	3.44	13.55
5	2024	129.07	3.44	19.64

Source: Processed Primary Data (2025)

Once the annual rainfall intensity value is obtained, the next step is to calculate the kinetic energy of the rain as it falls on the ground surface. This energy significantly influences the rate of soil particle detachment and the onset of erosion. The following is a calculation of the kinetic energy of rain (KE).

Rain intensity (I) = 14.11 mm/hour

$KE = 0.119.I^{0.87}$

$KE = 0.119.(14,11)^{0.87}$

KE = 1,190 MJ/ha.mm

After carrying out the calculations, the KE values for 2020 to 2024 were obtained as follows.

Table 3. Rain Kinetic Energy Value (KE)

No	Year	I (mm/jam)	KE (MJ/ha.mm)
1	2020	14.11	1.190
2	2021	14.69	1.233
3	2022	14.86	1.245
4	2023	13.55	1.149
5	2024	19.64	1.587
Average			1.281

Source: Processed Primary Data (2025)

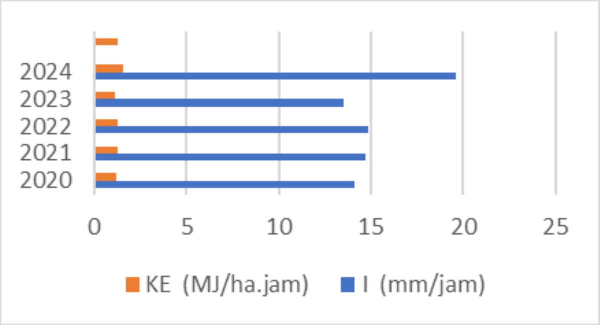


Figure 5. Graph of Rain Intensity Against Rain Kinetic Energy (KE).
Source: Processed Primary Data (2025)

The analysis results show that rainfall kinetic energy varies between years but is spatially uniform throughout the catchment area. The average rainfall kinetic energy value of 1,281 MJ/ha.mm was used as a temporal controlling factor in the erosion analysis.

Kinetic Energy of Runoff

Based on calculations taking into account slope factors, flow direction and flow accumulation, as well as the relationship between land units, it was found that the kinetic energy of runoff shows significant spatial variations between land units where runoff occurs. In general, high runoff energy values are found in downstream land units and areas with large flow accumulation Dibaba & Ebsa, (2022); Fenta et al., (2024) so that the influence of topography and interactions between land units can be clearly seen.

Based on the calculation of the kinetic energy of runoff from equation 2, the value of E per unit of land for runoff occurrence is obtained before approaching the relationship between runoff per unit.Number 6The following graph presents the influence of slope factors on the value of the kinetic energy of runoff from each land unit of runoff events in the Pandanduri Reservoir Catchment Area.

Figure 6. The Effect of Slope Factors on Runoff Kinetic Energy Values
Source: Processed Primary Data (2025)

Based on the graph above, it is known that the slope factor has a large contribution to the value of the kinetic energy of runoff. This can be seen from each slope with a steep and very steep category having a value of 8.7-12 MJ/ha·mm, while on a slope with a flat class it is only 0.5 MJ/ha·mm. This shows the relationship between slope factors and runoff kinetic energy, indicating that increasing slope and slope length are directly proportional to the increase in runoff energy value at the land unit level (Karakoyun & Kaya, 2022; Raza et al., 2021).

After knowing the value of the local runoff kinetic energy in each land unit of the runoff event, the next step is to consider the accumulation of kinetic energy from the upstream unit flowing to the downstream unit. The flow direction between units is obtained from the results of processing the flow direction (*flow direction*) and flow network using DEM data. In determining the total runoff kinetic energy acting on a land unit, the kinetic energy from all upstream units flowing into the unit is summed to obtain the total E value for each land unit. Figure 7 and Table 4. shows the influence of slope factors on the kinetic energy value of runoff that occurs in the Pandanduri Reservoir Catchment Area.

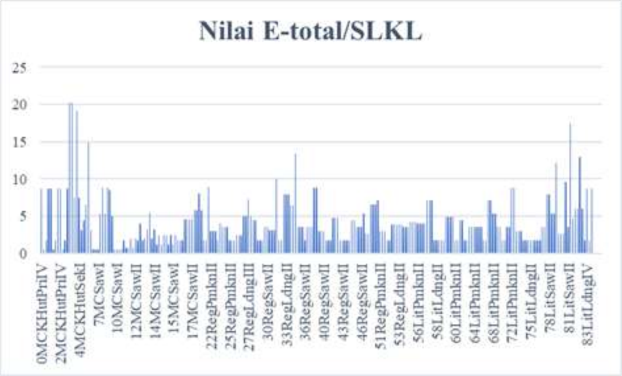


Figure 7. Graph of the Influence of Slope Factors on Runoff Kinetic Energy Values

Source: Processed Primary Data (2025)

The fluctuating pattern of E-total values on the graph also reflects that the kinetic energy of runoff does not increase linearly from upstream to downstream, but is strongly influenced by a combination of slope factors and runoff accumulation. From this, certain land units can have high E-total values even though the slope is relatively gentler because they receive accumulated runoff from land units located in the upstream area.

Integration of Rain and Runoff Kinetic Energy on Erosion

The integration of rain and runoff kinetic energy produces higher erosion predictions in certain areas compared to the classical approach. This shows that the contribution of surface runoff as a carrier of soil particles has a dominant role after the detachment process by rain.

After the value of the kinetic energy of rain and the kinetic energy of runoff are known as in Figure 8, plus the value of the soil erodibility factor, slope, and land use, then the amount of erosion in the Pandanduri Reservoir Catchment Area can be calculated using a modified equation, which can be seen in Figure 9 and Table 5. Based on the calculation results, the highest erosion rate is in the runoff land unit with the code 4MChutSekV with a total erosion rate of 8,900772 tons/ha/year, namely the runoff land unit with brown Mediterranean soil type, secondary forest land use, and steep slopes. The following is a graph of the erosion rate in each runoff land unit.

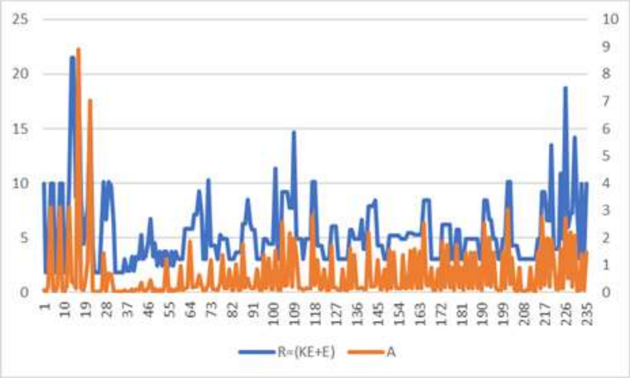


Figure 8. Graph of the Effect of Erosion Based on the Value of Rain and Runoff Kinetic Energy

Source: Processed Primary Data (2025)

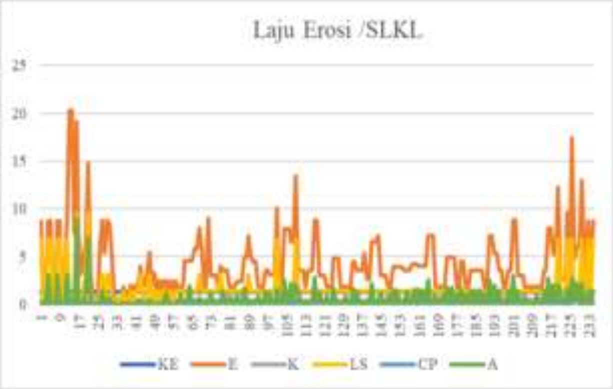


Figure 9. Erosion Rate Graph for Each Land Unit of Pandanduri Reservoir Watershed Runoff Event

Source: Processed Primary Data (2025)

Along with the graph and Table above, the following is a map of the distribution of potential land degradation which has been compiled based on the erosion rate in each land unit where runoff occurs in the Pandanduri Reservoir Catchment Area.

Based on Figure 10,It can be seen that the surface erosion value in land units subject to runoff events is relatively low, ranging from 0.02–8.90 tons/ha/year. This condition indicates that erosion in the Pandanduri watershed is spatially distributed without showing a dominant erosion concentration in any particular location.

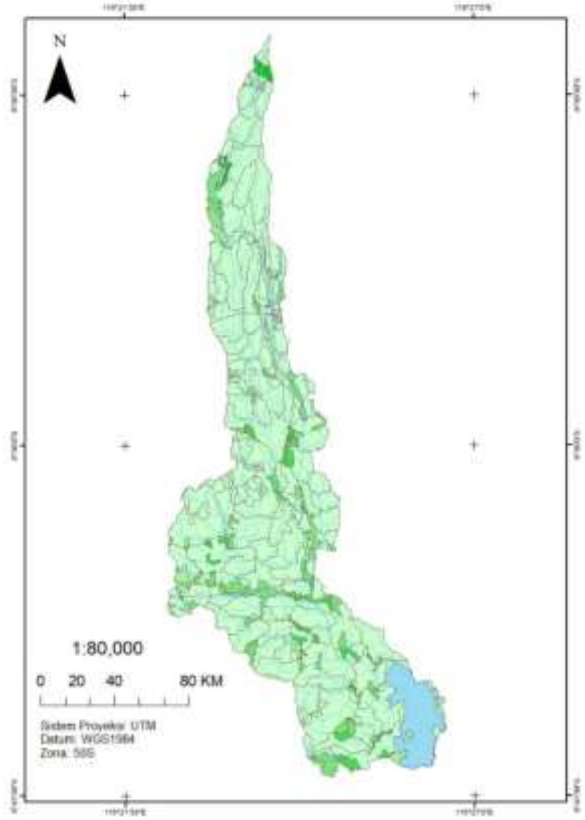


Figure 10. Map of Erosion Rate Distribution of Pandanduri Reservoir Catchment Area

Source: Processed Primary Data (2025)

Once the erosion rate of each runoff-prone land unit is known, the erosion pressure at each runoff boundary in the Pandanduri Reservoir Catchment Area can be determined. This value is based on the sum of the erosion values for each runoff-prone land unit within the runoff boundary unit. The distribution of erosion pressure at each runoff boundary is presented in Fig.Figure 11.

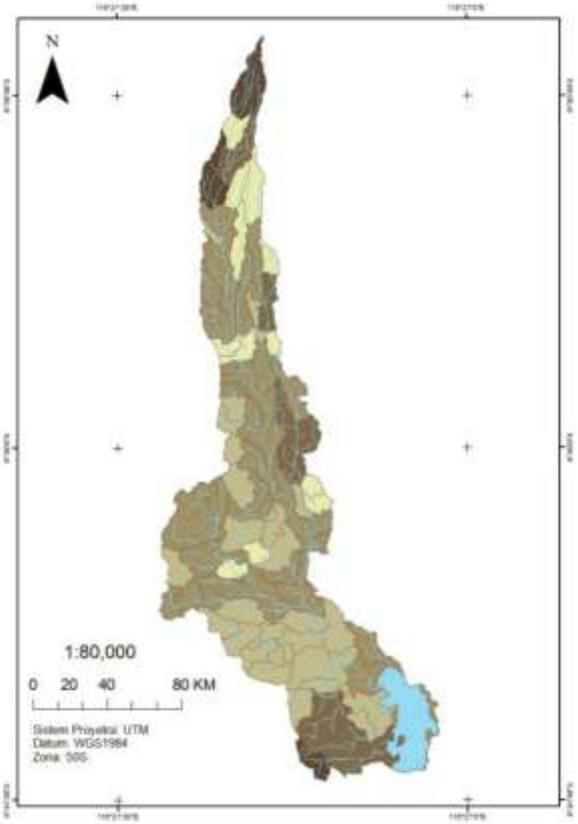


Figure 11. Map of Erosion Pressure Distribution at Each Runoff Boundary of the Pandanduri Reservoir Catchment Area

Source: Processed Primary Data (2025)

The above map of erosion pressure within the catchment area complements the map of erosion rate distribution, where relatively low erosion rates at the land unit scale still result in significant erosion accumulation at the catchment scale due to the large catchment area. This ultimately contributes to the total sediment load in the catchment.

The map also shows that land degradation is not only influenced by the local characteristics of a land unit, but is also very much determined by the relationship between runoff between land units and runoff events (SLKL) and the accumulation of kinetic energy of rain and runoff in the water catchment system.

Correlation and Regression Test Calculation Results

To strengthen the analysis, this study also examined the relationship between runoff kinetic energy and soil erosion rates in each land unit where the runoff occurred. The tests used were Pearson correlation and simple linear regression.

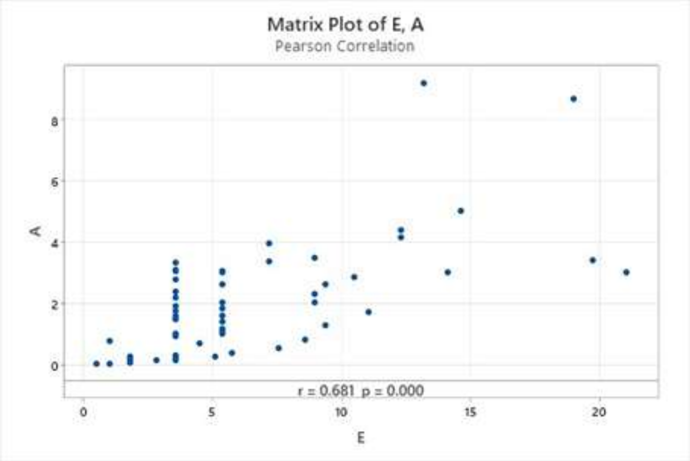


Figure 12. Pearson Correlation Test Method

Source: Processed Primary Data (2025)

Based on the results of the Pearson correlation test between the kinetic energy of runoff (E) and the rate of soil erosion (A) as in Figure 12, a correlation coefficient value of r = 0.681 was obtained with a significance level of p = 0.000. This value indicates a strong and statistically significant positive relationship between runoff kinetic energy and soil erosion rate in land units where runoff occurs in the Pandanduri Reservoir Catchment Area.

However, the relationship between E and A is not entirely linear, as indicated by the relatively scattered distribution of points around the trend line. This condition indicates that in addition to runoff kinetic energy, erosion rates are also influenced by other factors such as soil erodibility and land cover.

Regression Equation

$$A = 0.297 + 0.2419 E \qquad (4)$$

Table 6. Linear Regression Test of the Effect of Runoff Kinetic Energy on Erosion Rate

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	0,297	0,221	1,34	0,183	
E	0,2419	0,0287	8,43	0,000	1,00

Source: Processed Primary Data (2025)

Simple linear regression analysis as in equation 4 and Table 5,was conducted to quantify the effect of runoff kinetic energy (E) on the rate of soil erosion (A) in the land unit of runoff event. The results of the parameter significance test showed that the runoff kinetic energy variable (E) had a t value = 8.43 with a p-value = 0.000, which means that the effect of runoff kinetic energy on the rate of soil erosion was very statistically significant.

From the normal probability plot of residuals on Figure 13 also shows that most of the data points follow the diagonal line well, indicating that the model residuals are approximately normally distributed. Although there are some extreme points in the upper tail of the distribution, the overall pattern is still acceptable for linear regression analysis on erosion spatial data which is naturally heterogeneous.

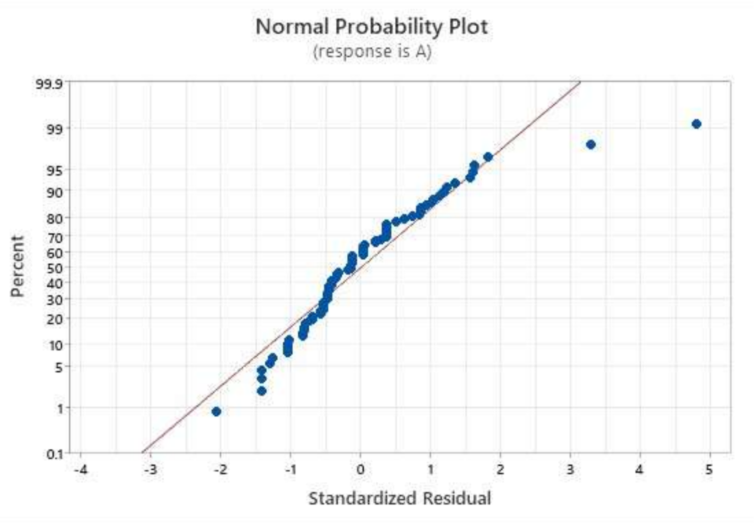


Figure 13. Normal Probability Plot of Simple Linear Regression Test Between Runoff Kinetic Energy and Erosion Rate of Pandanduri Reservoir Catchment Area

Source: Processed Primary Data (2025)

The normal probability plot of the residuals also shows that most data points follow the diagonal line well, indicating that the model residuals are approximately normally distributed. Although there are some extreme points in the upper tail of the distribution, the overall pattern is still acceptable for linear regression analysis on naturally heterogeneous erosion spatial data.

This condition indicates that the regression model used has met the general assumption of residual normality, so the results of the coefficient estimates and significance tests can be considered valid. The presence of small deviations in high residual values indicates the possible influence of certain local factors, such as land cover conditions or specific soil characteristics, which are not explicitly included in this simple regression model.

Implications for Watershed Management

The distribution map of erosion rates and erosion pressures in the Pandanduri Reservoir Catchment Area produced from this study shows that land units with low erosion rates can still contribute significantly to the total sediment load in the watershed due to the catchment area and accumulation of runoff from upstream areas. Therefore, it is important in watershed management strategies not only to focus on land units with high erosion locally, but also on land units that act as energy concentration and transfer pathways, especially runoff, must also be considered.

CONCLUSION

The results of this study indicate that the spatial variation of soil erosion in the Pandanduri Reservoir Catchment Area is more influenced by runoff kinetic energy than rainfall kinetic energy. Although rainfall energy is spatially uniform, differences in topographic characteristics and flow accumulation cause significant variations in runoff energy between land units. The integration of runoff kinetic energy in erosion analysis provides a more realistic spatial representation and can be a strong basis for determining conservation priorities in the Pandanduri Reservoir Catchment Area. It is recommended that future research incorporate additional dynamic factors such as seasonal land cover changes, soil moisture variability, and climate change scenarios to further refine erosion predictions. Furthermore, the methodology developed in this study should be tested in other watersheds with different geographical characteristics to validate its applicability and support the development of more comprehensive and adaptive watershed management strategies.

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