

Soil Erosion Analysis in Reclamation and Land Clearing Areas Using the USLE and RUSLE Approaches

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Soil erosion is one of the major environmental problems that leads to land degradation and sedimentation in water bodies. The Universal Soil Loss Equation (USLE) and the Revised Universal Soil Loss Equation (RUSLE) are models commonly used to estimate soil erosion rates in a given area. This study aims to analyze the erosion rate in the study site using the USLE and RUSLE approaches and to evaluate the contributing factors that influence the observed erosion levels. The results indicate that the estimated erosion rates in various land areas are as follows: stockpile area at 122.42 tons/ha/year (USLE) and 206.15 tons/ha/year (RUSLE), with a difference of 83.73 tons/ha/year; topsoil stock area at 40.88 tons/ha/year (USLE) and 68.83 tons/ha/year (RUSLE), with a difference of 27.95 tons/ha/year; land clearing area at 33.08 tons/ha/year (USLE) and 55.71 tons/ha/year (RUSLE), with a difference of 22.63 tons/ha/year; and revegetation area at 29.62 tons/ha/year (USLE) and 49.87 tons/ha/year (RUSLE), with a difference of 20.25 tons/ha/year. Based on field data verification, the erosion estimates generated using the USLE method (Utomo equation) were found to be more accurate. The main factors influencing erosion rates are slope gradient, soil type, land use, and rainfall intensity. The difference in results between USLE and RUSLE is attributed to modifications in the rainfall erosivity factor and the soil conservation factor in the RUSLE model. This study provides recommendations for conservation strategies that can be applied to reduce erosion risks in the study area.

Keywords: soil erosion, USLE, RUSLE, soil conservation.

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Introduction

Erosion is the process by which soil or parts of the soil are displaced or removed from one location to another, caused by the movement of water, wind, and/or ice. Erosion consists of three main processes: detachment (the dislodging of soil particles), transportation (the movement of soil particles), and deposition (the settling of transported soil particles). Detachment occurs as a result of raindrop impact on the soil surface. Climate, soil characteristics, topography, time, and human land use are the primary factors influencing erosion (Firmansyah et al., 2023).

Predicting erosion rates in overburden stockpile areas of coal mining sites is essential due to the environmental impacts associated with mining activities. Soil erosion can be influenced by various factors, including soil type, vegetation cover, rainfall intensity, and slope gradient. One of the most commonly used methods to estimate soil erosion is the Universal Soil Loss Equation (USLE) (Iashania, 2025), which has been proven effective in multiple studies across Indonesia.

The erosion model applied in this study is the Universal Soil Loss Equation (USLE), which is designed to estimate the long-term average annual rate of soil loss in a given area. However, the limitation of the USLE method is that it only predicts the amount of erosion and does not account for the transport and deposition processes, nor the resulting sedimentation (Iashania, 2018).

The application of the USLE method in mining areas involves collecting data on rainfall, soil erodibility, and land use. For instance, a study by Ndun et al. demonstrated that USLE-based analysis provides clear insight into erosion potential in agricultural lands, which is also relevant for mining areas (Ndun et al., 2021; Muhammad et al., 2024). Additionally, research by Halim indicated that conservation measures such as bench terracing can significantly reduce erosion rates in affected areas (Akbar, 2021).

Furthermore, the study by Yusuf et al. (2020) highlights the importance of mapping soil erosion distribution using Geographic Information Systems (GIS) to obtain a more accurate representation of erosion potential in a given area.

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By utilizing spatial data, researchers can identify zones with high erosion risk and plan appropriate mitigation measures.

Predicting erosion rates in overburden stockpile areas of coal mining operations is essential due to the environmental impacts associated with mining activities. One of the widely used methods for erosion prediction is the Universal Soil Loss Equation (USLE), which has proven effective in various studies conducted in Indonesia (Putri & Rahman, 2024).

In addition, the study by Yusuf and Santoso (2022) also emphasizes the critical role of GIS-based erosion mapping in providing detailed spatial insights into erosion potential. This spatial approach allows for the identification of high-risk zones and the formulation of targeted mitigation strategies.

This research aims to identify the factors influencing erosion in overburden stockpile areas under various conditions and to evaluate erosion predictions to support effective planning and management efforts.

Methods

Study Area

This study was conducted at PT Adaro Indonesia, focusing on several operational zones within the Pit Wara site. The selected areas included land clearing zones, overburden dumps, topsoil stockpiles, and revegetated land. In total, ten (10) monitoring points were established across these distinct land-use types to capture spatial variability in erosion potential. Figure 1 presents an aerial view of the research site, illustrating the spatial distribution of these operational zones.

Soil Sampling

At each monitoring point, two types of soil samples were collected: disturbed and undisturbed samples. Disturbed samples were obtained using a soil auger at a depth of 0–30 cm from the surface. These samples were analyzed to determine soil texture, organic carbon content (C-organic), and particle density. Undisturbed samples were collected using a ring sampler. These were used to determine bulk density and soil permeability, which are essential input parameters for erosion modeling. Detailed laboratory procedures and measurements are summarized in Table 1.

Figure 2 illustrates the condition of the overburden disposal area where several soil samples were collected during field observation.



Figure 1 Aerial Photograph of the Mining Site at PT Adaro Indonesia

Erosion Prediction Approach

To estimate the potential rate of soil erosion in the study area, the Universal Soil Loss Equation (USLE) was applied. This empirical model has been widely validated and utilized in various erosion studies, particularly in disturbed and post-mining environments (Susanto & Wahyudi, 2022).

The USLE model requires input parameters representing five key erosion factors: rainfall erosivity (R), soil erodibility (K), slope length and steepness (LS), land cover management (C), and conservation practice (P). In this study, field observations were conducted at each monitoring point to measure slope length (in meters) and slope steepness (in percent), which are critical for calculating the LS factor. Additional site-specific data were collected to support the estimation of other USLE components.

Table 1 Parameters, Methods, and Instruments for Soil Observation

| Parameter | Unit | Method | Instruments |
|----------------------------|---------------------|-------------------------------|------------------------------|
| Texture | % fraction | Pipette method | Pipette and balance |
| Bulk density | g cm ⁻³ | Gravimetric | Ring sampler and balance |
| Particle density | g cm ⁻³ | Gravimetric | Volumetric flask and balance |
| Soil permeability | cm hr ⁻¹ | Measurement with ring sampler | Stopwatch |
| Soil structure | – | Direct field observation | – |
| Organic carbon (C-organic) | % | Walkley & Black method | Titration apparatus |



Figure 2 Location of Overburden Disposal Site

Estimation of soil erosion at each monitoring point or location was carried out using the mathematical model Universal Soil Loss Equation (USLE) (Wischmeier & Smith, 1978; Rianto, 2023; Yellishetty et al., 2013). The procedure for calculating erosion values is based on several variables integrated into the Equation 1.

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

where:

A = estimated annual soil loss (tons/hectare/year)

R = rainfall erosivity factor

K = soil erodibility factor

LS = slope length and steepness factor

C = cover management factor

P = support practice (conservation) factor

Rainfall erosivity refers to the ability of rainfall to detach and transport soil particles. To analyze this component, the equation developed by Utomo and Mahmud (1983) was applied as follows:

$$EI = 10.8 + 4.15 \times PM \quad (2)$$

where EI is the rainfall erosivity index and PM is the monthly rainfall (mm).

In this equation, EI represents the monthly erosivity index, and PM denotes the monthly rainfall amount (in cm).

To further assess rainfall erosivity using the RUSLE method, the Bols equation was employed to capture the impact of rainfall intensity and to reflect both the amount and velocity of surface runoff. The equation is as follows:

$$EI = 6.119 \times R^{1.21} \times D^{-0.47} \times M^{0.53} \quad (3)$$

where:

R = monthly rainfall (cm)

D = number of rainy days

M = maximum daily rainfall in the month (cm)

This formulation enables a more detailed estimation of erosivity by considering not only total rainfall but also its temporal distribution and intensity.

Results and Discussion

Estimation of the R Factor (Rainfall Erosivity Index)

The rainfall erosivity (R) factor was estimated using rainfall data provided by PT Adaro Indonesia. Based on the average annual rainfall at each monitoring location, the estimated R values were calculated using both USLE and RUSLE methods. The average R value derived from the USLE method was 1,158, while the R value obtained using the RUSLE method was 1,950. The higher R value calculated using Equation (3) is attributed to the inclusion of maximum monthly rainfall, which increases the magnitude of the erosivity estimate compared to Equation (2), which is based solely on average monthly rainfall.

Estimation of the K Factor (Soil Erodibility Index)

The K factor was estimated using laboratory analysis data of the physical and chemical properties of the soil, provided by the PT Adaro Indonesia laboratory. The detailed results used for this estimation are presented in Table 2.

Estimation of the LS Factor (Slope Length and Steepness Index)

The LS factor was calculated by combining slope length (L, in meters) and slope gradient data at each observation site. The LS values for different locations are Topsoil stockpile area: 1.06, Pit area: 1.07, Overburden disposal area: 1.23, and Revegetation area: 0.96. These values reflect variations in topographic conditions that influence erosion potential across the study area.

Table 2 K Factor Calculation (Soil Erodibility Index)

| Sample Code | % Silt | % Sand | % Clay | C-Organic (%) | Soil Structure | Permeability (cm/hr) | K Factor |
|---------------|--------|--------|--------|---------------|----------------|----------------------|----------|
| Topsoil | 21.36 | 12.71 | 44.09 | 0.84 | Massive blocky | 6.54 | 0.222 |
| Land Clearing | 11.32 | 8.96 | 47.32 | 0.32 | Massive blocky | 2.12 | 0.178 |
| Overburden | 15.32 | 9.02 | 41.54 | 1.45 | Massive blocky | 2.23 | 0.191 |
| Revegetation | 30.96 | 9.19 | 44.97 | 1.02 | Massive blocky | 0.92 | 0.296 |

Rainfall Erosivity Factor (R)

The estimation of the rainfall erosivity factor (R) was conducted using rainfall data collected by PT Adaro Indonesia. Based on calculations of the average annual rainfall at each monitoring location, the R value estimated using the USLE method was 1,158, while the RUSLE method produced a higher value of 1,950. The greater R value obtained using Equation (3) compared to Equation (2) is due to its inclusion of the maximum monthly rainfall, which significantly increases the erosivity estimate during peak rainfall events.

Estimation of the C Factor (Cover Management Factor)

The C factor represents the influence of vegetative cover on the magnitude of soil erosion. This value was determined based on several reference studies involving erosion plots, which provide relative benchmark values for land cover conditions in comparable regions. In this study, the assigned C values were 0.30 for the topsoil, land clearing, and revegetation areas, and 0.60 for the overburden disposal area. Figure 3 shows a representative monitoring plot in the revegetation area, where dense ground cover was observed, contributing to reduced erosion rates.

Estimation of the P Factor (Support Practice Factor)

The P factor represents the impact of land management practices related to soil conservation efforts. A value of 1.00 is assigned when no conservation measures are implemented.

Soil erosion prediction was carried out using the Universal Soil Loss Equation (USLE), where soil loss is calculated based on the values of R, K, LS, C, and P factors. The estimated soil erosion values for each monitoring location based on the USLE method are presented in Table 3, while those based on the RUSLE method are shown in Table 4.



Figure 3 Revegetated monitoring plot at PT Adaro Indonesia, characterized by dense ground cover that supports erosion control.

Tolerable soil erosion refers to the maximum allowable erosion rate (expressed in mm/year or tons/ha/year) that still permits the maintenance of a sufficient topsoil depth to sustain long-term plant growth and high productivity (Arsyad, 1989). According to Kartasapoetra (2000), Soil Loss Tolerance is the level of soil erosion that can be balanced by natural soil formation processes, assisted by human conservation efforts, such that the rate of erosion remains below the rate of soil formation.

In determining the tolerable erosion threshold, several key soil characteristics must be considered, including

1. Thickness of the topsoil layer
2. Physical properties of the soil
3. Prevention of gully erosion
4. Decline in organic matter content
5. Loss of plant nutrients

Table 3 Estimated Soil Erosion Using the USLE Method

| Location | R | K | LS | C | P | Erosion (tons/ha/year) |
|---------------------|------|-------|------|------|------|------------------------|
| Topsoil Stockpile | 1158 | 0.222 | 1.06 | 0.30 | 0.50 | 40.88 |
| Land Clearing | 1158 | 0.178 | 1.07 | 0.30 | 0.50 | 33.08 |
| Overburden Disposal | 1158 | 0.191 | 1.23 | 0.60 | 0.75 | 122.42 |
| Revegetation Area | 1158 | 0.296 | 0.96 | 0.30 | 0.30 | 29.62 |

Table 4 Predicted Soil Erosion at PT Adaro Using the RUSLE Method (tons/hectare/year)

| Location | R | K | LS | C | P | Erosion (tons/ha/year) |
|---------------------|------|-------|------|-----|------|------------------------|
| Topsoil Stockpile | 1950 | 0.222 | 1.06 | 0.3 | 0.5 | 68.83 |
| Land Clearing | 1950 | 0.178 | 1.07 | 0.3 | 0.5 | 55.71 |
| Overburden Disposal | 1950 | 0.191 | 1.23 | 0.6 | 0.75 | 206.15 |
| Revegetation Area | 1950 | 0.296 | 0.96 | 0.3 | 0.3 | 49.87 |

Figure 4 illustrates the predicted soil erosion rates across four distinct land-use types at PT Adaro Indonesia, based on the Universal Soil Loss Equation (USLE). The overburden disposal area shows the highest erosion rate, reaching approximately 122.42 tons/ha/year, indicating its vulnerability due to steep slopes and limited vegetation cover. In contrast, the revegetation area exhibits the lowest erosion rate at 29.62 tons/ha/year, demonstrating the effectiveness of vegetation in mitigating erosion. The topsoil stockpile and land clearing areas show moderate erosion levels at 40.88 and 33.08 tons/ha/year, respectively. These results highlight the critical role of land management practices and vegetative cover in controlling erosion intensity in mining environments.

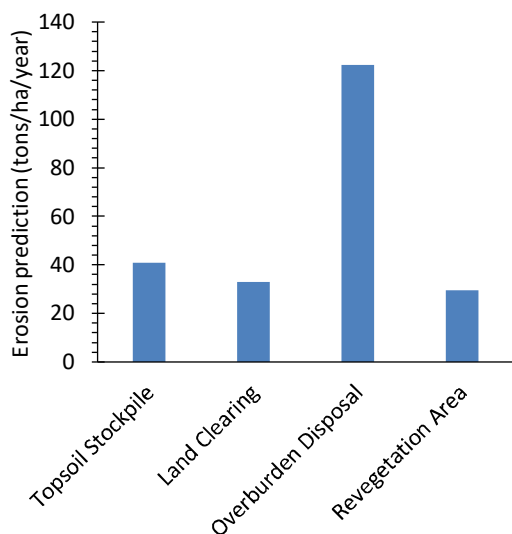


Figure 4 Comparison of Soil Erosion at Monitoring Locations Using the USLE Equation

Figure 5 presents the predicted soil erosion rates at different monitoring locations using the Revised Universal Soil Loss Equation (RUSLE). The overburden disposal area exhibits the highest erosion rate at approximately 206.15 tons/ha/year, reflecting its steep slopes and limited vegetative cover, which contribute significantly to erosion intensity. The topsoil stockpile and land clearing areas show moderate erosion values of 68.83 and 55.71 tons/ha/year, respectively. Meanwhile, the revegetation area demonstrates the lowest erosion prediction, at 49.87 tons/ha/year, underscoring the positive impact of vegetation cover in reducing soil loss. Compared to the USLE results, the RUSLE method tends to produce higher erosion estimates due to its incorporation of rainfall intensity and improved conservation practice factors, offering a more sensitive reflection of erosivity and land management conditions.

Figure 6 illustrates a comparative analysis of predicted soil erosion using the USLE and RUSLE models alongside actual erosion data collected from the field. The overburden disposal area consistently exhibits the highest erosion across

all three data sets, with RUSLE predicting the greatest loss at 206.15 tons/ha/year, followed by USLE at 122.42 tons/ha/year, and actual field measurement at 90.33 tons/ha/year.

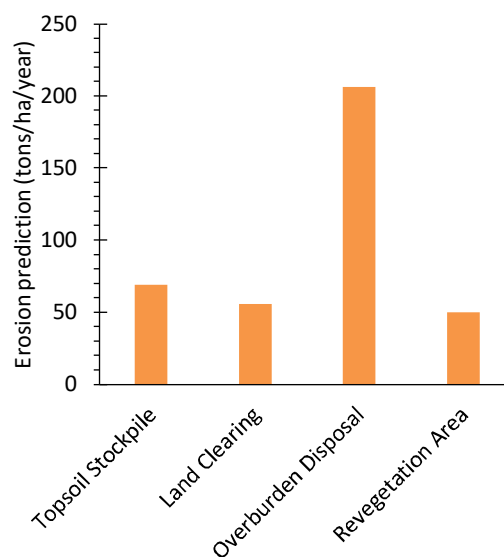


Figure 5 Comparison of Soil Erosion at Monitoring Locations Using the RUSLE Equation

Similar trends are observed in the topsoil stockpile and land clearing areas, where RUSLE estimates are significantly higher than those from USLE and field data. In the revegetation area, all three methods show the lowest erosion values, with actual erosion at 21.81 tons/ha/year, reinforcing the protective role of vegetation. Overall, the USLE model provides erosion estimates that more closely align with field data, suggesting its greater suitability for conditions in the study area. This comparison also highlights how model selection can influence erosion risk assessments and underscores the importance of field validation in erosion studies.

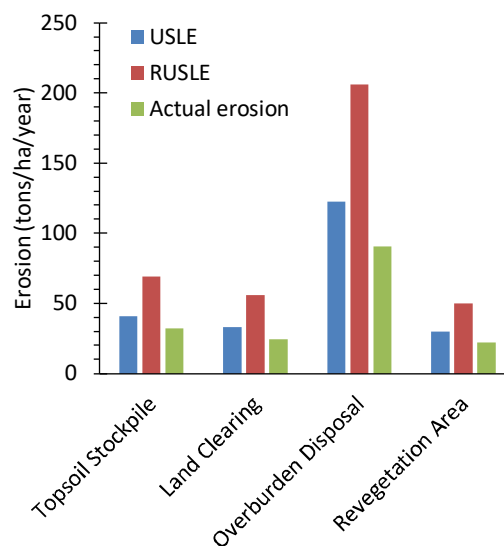


Figure 6 Comparison of Soil Erosion at Monitoring Locations Using USLE and RUSLE Equations Based on Field Data

This evaluation provides a reference for determining whether current erosion levels are within sustainable limits or if additional conservation interventions are needed. Based on calculations using the USLE method, the erosion rate in the overburden disposal area reached a significantly high value of 122.42 tons/ha/year (Equation 2), and even higher when calculated with the RUSLE method, at 206.15 tons/ha/year (Equation 3). These findings align with previous studies indicating that open mining areas tend to experience higher erosion rates compared to revegetated areas (Setiawan & Mulyani, 2023; Ren et al., 2023; Nugraha & Hariyanto, 2024). The high erosion rate in the disposal area is influenced by intense rainfall erosivity, the erodibility of the dumped material, and topographic conditions—consistent with observations made in mining reclamation contexts globally (Melese et al., 2021; Natarajan, 2023; Šarapatka & Bednář, 2022).

Field-verified data provided by the company, based on topographic surveys at each monitoring location, yielded the following actual erosion values: 32.17 tons/ha/year in the topsoil stockpile area, 24.47 tons/ha/year in the pit (land clearing area), 90.33 tons/ha/year in the overburden disposal area, and 21.81 tons/ha/year in the revegetated area. These actual values most closely match the estimates obtained using the USLE method with the Utomo equation, suggesting better accuracy compared to the RUSLE approach. Similar findings were confirmed by validation studies conducted by Silva et al. (2021) and Boakye et al. (2020), which emphasize the importance of model calibration with field data for accurate erosion prediction.

The erosivity factor plays a substantial role in determining erosion rates. As shown in Figure 5, the comparison between the two equations highlights that the Bols equation used in the RUSLE method tends to yield higher erosion loads than the Utomo equation. This is because the Bols equation incorporates rainfall kinetic energy and monthly maximum rainfall, leading to higher erosivity estimates (Cantik et al., 2023; Zhang et al., 2024). Furthermore, using high-resolution rainfall and digital elevation data has been shown to improve the reliability of the R-factor and LS-factor estimates, enhancing overall model performance (Li et al., 2023; Thapa, 2020).

These results also reinforce previous research findings, which indicate that soil erosion in mining areas can be mitigated through appropriate conservation techniques, such as the application of cover crops and effective land reclamation practices (Agustian & Pratama, 2023; Yellishetty et al., 2013; Reed & Kite, 2020). Additionally, a study by Fadillah & Ramadhan (2023) demonstrated that the application of dolomite lime can improve soil pH and facilitate the revegetation process in post-coal mining lands. The success of revegetation efforts is also supported by findings from Sitepu et al. (2023) and Setyaningsih et al. (2020), who noted the importance of appropriate species selection and biological amendments.

Conclusion

The erosion prediction results for the observed areas—including the overburden disposal, topsoil stockpile, and land clearing sites—demonstrate that erosion rates are highly influenced by the specific conditions of each location. This study confirms that the USLE model is a suitable tool for estimating erosion in mining environments, with significant influences from factors such as rainfall intensity, slope gradient, land use, and soil erodibility (Sutrisno & Wibowo, 2022).

Furthermore, mitigation strategies such as revegetation and soil conservation structures can effectively reduce the impact of mining-induced erosion (Putri & Rahman, 2024). The model analysis indicates erosion rates of 122.42 tons/ha/year (USLE) and 206.15 tons/ha/year (RUSLE) in the overburden disposal area, with a difference of 83.73 tons/ha/year. For the topsoil stockpile area, the rates were 40.88 tons/ha/year (USLE) and 68.83 tons/ha/year (RUSLE), differing by 27.95 tons/ha/year. The land clearing area showed 33.08 tons/ha/year (USLE) and 55.71 tons/ha/year (RUSLE), and the revegetation area had 29.62 tons/ha/year (USLE) and 49.87 tons/ha/year (RUSLE), respectively.

Among the two methods, the USLE approach yielded erosion values that more closely matched the actual field data. The discrepancies between the two models underscore the importance of considering land management and conservation practices in erosion control strategies. The dominant factors influencing erosion include slope steepness, rainfall erosivity, soil type, and land cover. Therefore, erosion prediction in open-pit mining areas depends significantly on land use conditions and the implementation of appropriate conservation measures. Proactive efforts are essential to minimize erosion and preserve land sustainability.

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