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APPLICATION OF THE MODIFIED UNIVERSAL SOIL LOSS EQUATION (MUSLE) FOR SOIL EROSION PREDICTION AND EROSION HAZARD CLASSIFICATION IN NICKEL MINING

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Abstract:
Nickel mining activities in the North Morowali area cause changes in the surface structure of the land and increase the risk of erosion, especially around the settling pond area. The erosion that occurs affects the shallowing of the pond, reduces its sediment storage capacity, and creates a potential for turbid water runoff to overflow into the surrounding environment. This study aims to predict the erosion rate and classify the level of erosion hazard (TBE) using the Modified Universal Soil Loss Equation (MUSLE) method, which is more representative of mining conditions with extreme rainfall and dynamic morphology. Data collection was conducted through literature studies, field observations, and the processing of primary and secondary data, including rainfall, soil type, topography, and land use. Data analysis was carried out using ArcGIS 10.8 software for mapping rain catchment areas, slope gradients, and soil classification. The calculation results show that the annual sedimentation rate reaches 7256.073 m^3/year, with a sedimentation rate of 62.806 tons/ha/year, and is included in the class III category (moderate erosion). Conservation recommendations are directed at a combination of vegetative methods, such as planting cover crops and local vegetation, and mechanical methods, such as terracing and drainage channels, according to slope contours.
Keywords: Soil Erosion, MUSLE, Nickel Mining, Erosion Hazard Level

INTRODUCTION

Nickel mining activities, carried out using open-pit mining methods, cause significant changes to the surface structure of the land and alter land use patterns. Activities such as overburden removal, land clearing, and material disposal result in unstable exposed soil surfaces that are highly susceptible to erosion (Funay, 2024). The direct impacts of these activities can disrupt hydrological balance and increase surface runoff, especially during heavy rainfall. In such conditions, loose soil on the surface that is not protected by vegetation is easily eroded and carried by surface runoff to downstream areas. Additionally, changes in land use often neglect soil conservation measures, especially on sloping land (Sari et al., 2020).

Erosion is the process of soil or soil particles being lost or eroded from one location to another due to the action of water or wind (Pasaribu et al., 2018). Soil erosion is also a primary cause of land degradation (Brevik et al., 2017). Erosion can occur through three sequential processes, namely detachment, transportation, and deposition of soil materials, causing erosion (Pistocchi et al., 2002). Surface erosion can occur as a result of water flow and slope angle, which are one of the main factors influencing water erosion. Steeper slopes cause greater erosion as a result of higher runoff and faster flow velocity (Nigam et al., 2017). Surface runoff carrying eroded material often ends up in settling ponds designed to collect runoff and sediment particles before releasing them into the external environment.

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The higher the rainfall intensity, the greater the surface runoff, resulting in less water being absorbed by the soil and causing high erosion rates (Ferijal, 2012). In addition, this also affects the production of more sediment and the effectiveness of sedimentation ponds. It is consistent with the observed issues, indicating that sedimentation ponds often experience rapid sedimentation, exceeding their estimated capacity and planned maintenance frequency. This sedimentation not only reduces the pond's effectiveness in retaining sediment but also increases the risk of turbid water overflowing into surrounding areas, thereby increasing operational costs for periodic sediment excavation. Based on field observations, it can be concluded that sedimentation indicates erosion occurring in the upstream part of the sedimentation pond, particularly from hillsides, active mining zones, and disposal areas located higher than the sedimentation pond. According to research (Surahmad et al., 2021), eroded material will undergo sedimentation in the sedimentation pond. If the material entering the pond exceeds the pond's capacity, this will cause sedimentation in the pond, preventing it from accommodating water flow.

To estimate the erosion rate, several methods can be used. Generally, methods based on an annual approach are used to estimate the average annual erosion rate, such as the USLE (Universal Soil Loss Equation) developed by Wischmeier and Smith (1971). However, this method is less accurate in calculating the actual volume of water flow. According to previous research, the erosion rate calculated using the MUSLE method was found to be higher than that calculated using the USLE method. Additionally, the MUSLE method is more suitable for calculating sedimentation rates (Saputra & Abdurrosyid, 2022). At the study site, event-based approaches have not been applied, so an appropriate erosion rate estimate is required. Based on this, the MUSLE (Modified Universal Soil Loss Equation) method can be used as a more relevant alternative because it is a modification of the USLE equation that estimates erosion and sedimentation rates by changing the rainfall erosivity factor to a surface runoff factor (Belo, 2019). This model provides a systematic framework for measuring soil erosion and sediment production in response to various factors, including land use changes, slope characteristics, rainfall, and soil management (Edike & Camara, 2024). Erosion rate predictions using the MUSLE method are more representative of mining conditions with extreme rainfall and rapid landform changes.

Based on previous studies related to erosion rate estimates using the MUSLE model in several regions, the values vary significantly. As shown in the results of studies (Sujatmoko et al., 2022; Salviya et al., 2023) in sub-river basins, the highest erosion rates are caused by a lack of conservation efforts in these areas, which results in increased erosion rates. Erosion rate estimates are also used as a consideration in predicting erosion hazard classification (EHC). In a study (Belo, 2019), five classes of soil erosion hazard levels were identified, ranging from very severe erosion to very mild erosion, with the main factor being the erosion rate value. Land conservation priorities are determined based on the existing erosion hazard level, ranging from very severe to moderate classes. According to research (Meylina, 2015; Sari et al., 2020), soil erosion can be addressed through revegetation at each erosion-prone location to normalize the erosion hazard level in areas with land degradation.

This study aims to estimate soil erosion and classify erosion hazard levels in nickel mines by applying the MUSLE method. It can be directly linked to sedimentation issues in settling ponds and used as a consideration in land conservation guidelines based on erosion hazard class values.

METHODS

This study was conducted in the nickel mine settling pond area located in Molino Village, North Morowali Regency. The study area can be reached from Kupang by plane or boat, followed

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by a two-day road trip by car or motorcycle. The settling pond area consists of 10 compartments, namely 9 settling ponds and 1 control point.

Data Collection Methods. The scope of this study includes literature review, field observation, data collection, and data processing. The required data consists of primary and secondary data. Primary data includes documentation of the research area and settling pond area, while secondary data includes rainfall data for the last 10 years (2015–2024), topography data, soil type maps, and water catchment area interpretation maps.

Data Analysis Method. The data obtained will be used to calculate rainfall data, combine maps with shapefile (shp) data using ArcGIS 10.0 software to produce soil type maps to determine soil erodibility values, process DEM data for slope length and gradient, and land cover maps. Next, the erosion rate will be predicted using the MUSLE (Modified Universal Soil Loss Equation) method (Shi et al., 2022) with the following equation:

$$\mathbf{SY = R \times K \times LS \times C \times P}$$

Explanation:
SY = Total soil erosion (tons/year)
R = Surface runoff
K = Soil erodibility factor
LS = Slope factor
C = Land use factor
P = Soil conservation measures

1. Surface Runoff. It refers to water that always flows on the ground surface, both before and after reaching the channel. The R value can be calculated using the following equation (Shi et al., 2022):

$$\boldsymbol{R = a(VQ \times Q_p)b}$$

Explanation:
VQ = Surface flow volume (m^3)
Qp = Peak flow (m^3/s)
a = 11,8 (constant)
b = 0,56 (constant)

The value of VQ (surface flow volume) is calculated using the following equation (Shi et al., 2022):

$$\boldsymbol{VQ = D \times A \times C \times P}$$

Explanation:
D = Average rainfall (mm/year)
A = Watershed area (km^2)

Peak discharge is the peak surface flow rate. If it rains hard during this time, water from the whole catchment will flow to the outlet all at once. The surface runoff rate will then peak. The magnitude of peak discharge can be calculated using the following equation (Shi et al., 2022):

$$\boldsymbol{Q_p = 0,278 \times C \times I \times A}$$

Explanation:
C = Runoff coefficient
I = Rainfall intensity (mm/hour)

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2. Soil Erodibility Index (K). Zhang et al. (2018) define soil erodibility as the ease with which soil is broken down by the force of falling raindrops and/or the force of surface runoff. Soil properties that affect erodibility are texture, structure, organic matter, and permeability (Isdianti et al., 2022). Soil erodibility is divided into six classes. This is based on guidelines from the United States Department of Agriculture, Soil Conservation Service (1973) (Kumar et al., 2021).

Table 1. Classification of Soil Erodibility

Class	K Value	Class description
1	0 – 0,10	Very low
2	0,11 – 0,20	Low
3	0,21 – 0,32	Moderate
4	0,33 – 0,43	Fairly high
5	0,44 – 0,55	High
6	0,56 – 0,64	Very high

Source: Kumar et al., 2021

3. Slope Length and Slope Gradient (LS). Slope length measures the distance from the start of water flow to where sediment settles. It usually happens when the slope becomes less steep or when surface water flows into a channel. The effect of slope length on erosion varies, depending on soil type and rainfall intensity (Sukartaatmadja et al., 2003; He et al., 2022). Slope gradient is shown in degrees or percentages. It follows the RLKT guidelines from the Ministry of Forestry for Land Rehabilitation and Soil Conservation.

Table 2. Slope Class Assessment

Class	Slope (%)	Classification
I	0-8	Plain
II	9-15	Sloping
III	16-25	Moderately Step
IV	26-40	Steep
V	>40	Very Steep

Source: RLKT Ministry of Forestry, (1995)

4. Crop Management (C). Factor C shows how vegetation, soil surface, and land management affect soil loss from erosion. This vegetation cover factor can be calculated using the erosion factor index value for each land type, based on available land use maps (Panagos et al., 2015).

Table 3. C Factor Value

No	Land use	C Value
1	Open land without vegetation	1
2	Natural forest (lots of litter)	0,001
3	Natural forest (little litter)	0,005
4	Production forest (total land clearing)	0,5
5	Production forest (selective land clearing)	0,2

5. Soil Conservation (P). Soil conservation techniques (P) are defined as the ratio between the rate of soil erosion on land where conservation practices are implemented, such as the creation of terraces and hills, and the rate of soil erosion on land where conservation practices are not

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implemented. The effectiveness of conservation efforts in controlling erosion depends on the length and slope of the hillside (Anau et al., 2023).

Table 4. P Factor Value

No	Land use	*P* Value
1	Bench terrace	
	- Good construction	0,04
	- Average construction	0,15
	- Poor construction	0,35
	- Traditional terrace	0,40
2	Bahia grass strip	0,40
3	Soil preparation and planting along contour lines	
	Slope 0-8%	0,50
	Slope 9-20%	0,75
	Slope > 20%	0,90
4	Without conservation measures	1

Source: Nurhawaidah et al., 2019

Estimates of erosion rates and soil depth are used to predict the Erosion Hazard Level (EHL) for each land unit.

Table 5. Classification of Erosion Hazard Levels

No	Erosion Hazard Level (tons/ha/year)	Category
1	< 15	Normal
2	15 - 60	0,001
3	61 - 180	0,005
4	181 - 480	0,5
5	> 480	0,2

Source: Arsyad, 1989

RESULT AND DISCUSSION

The rate of erosion on a piece of land or in a region is affected by various factors, including rainfall, land use, crop type, slope angle, and slope length. In the mining process, water management is a critical aspect of preventing flooding and negative environmental impacts. Runoff water is one of the main sources of water entering mining sites, originating from rainfall that flows over the ground surface and carries soil particles with it.

The catchment area in this study was determined based on differences in elevation that indicate the direction of water flow. The catchment area was determined using topographic maps. To calculate the catchment area, mapping was carried out around the settling pond. The settling pond is at the lowest elevation. Water from the river enters the mining area and gathers in the pond. After that, it gets discharged back into the river or the outside environment. The catchment area was then calculated using ArcGIS 10.8 software, and its area was found to be 115.53 hectares, as shown in Figure 1.

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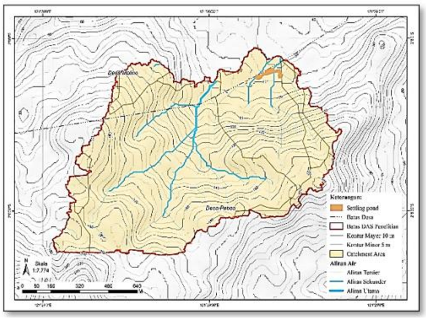

Source: Data Processed, 2025

Figure 1. Rainfall Catchment Area Map

The estimated erosion rate in the upstream settling pond of the nickel mining area is determined using the following values and factors, which are calculated using the MUSLE (Modified Universal Soil Loss Equation) method:

Surface Runoff. Surface runoff factors are calculated based on peak flow (Qp) and surface runoff volume (VQ). Qp is obtained from surface runoff discharge calculations with a 10-year return period. The area is on a slope with a gradient of 3%-5%. The land cover includes bare land and storage areas. Because of this, the surface runoff coefficient (C) value is 0.7. The rainfall intensity measured over 10 years is 7.54 mm/hour. The catchment area is 1.15 km^2. This results in a Qp value of 1.687 m^3/second. The surface runoff volume (VQ) is calculated by multiplying four things: the average rainfall height (mm/year), the river basin area (m^2), the surface runoff coefficient, and the land use and management factor. The average rainfall over 10 years was recorded at 75.278 mm/year, as shown in Table 6. The river basin covers 1,155,300 m^2. The crop management factor is 1.0, and the soil conservation factor is 0.04. It results in a surface runoff volume (VQ) of 3,478,746.93 m^3. Thus, the surface runoff volume is 72,822.10 m^3/s.

Table 6. Maximum Rainfall

No	Year	Maximum Daily Rainfall
1	2015	61,37
2	2016	45,25
3	2017	90,90
4	2018	45,69
5	2019	64,55
6	2020	116,69
7	2021	44,76
8	2022	50,51
9	2023	41,88
10	2024	191,99
Average rainfall ($\bar{X}$)		75,278

Source: Data Processed, 2025

Soil Erodibility. Soil erodibility factors are based on the dominant soil types in the watershed (DAS). The distribution of soil types in this watershed can be analyzed by combining shapefile (shp) data on soil types in Central Sulawesi Province, particularly in the study area. The average of the three soil types resulted in a soil erodibility value of 0.172, which is classified as very low. The soil types at the research location can be seen in Figure 2.

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Table 7. Soil Types and Soil Erodibility Values

No	Soil Type	K Value
1	Ochraquults	0,24
2	Paleborolls	0,15
3	Dystropepts	0,1

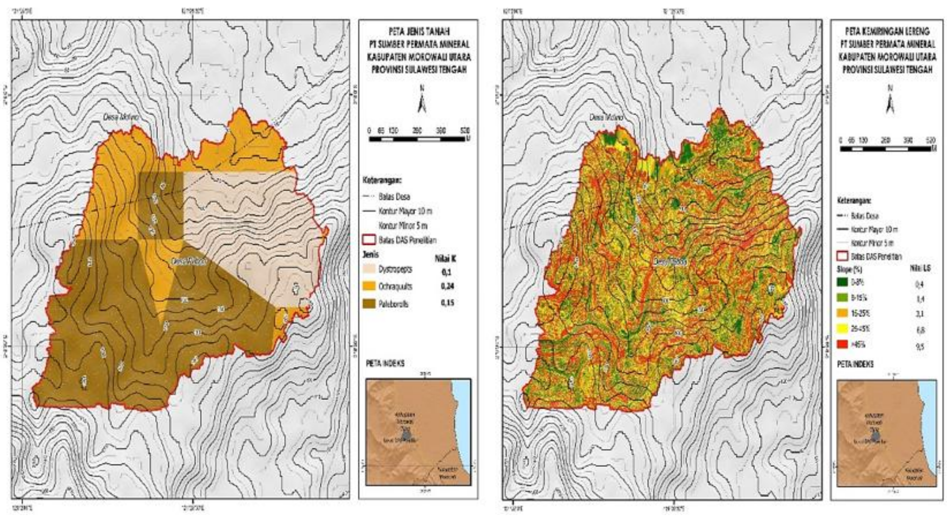
Source: Data Processed, 2025

Slope Length and Gradient. Erosion calculations rely on topographic measurements to determine slope length and gradient. The slope length and gradient factors are then determined based on the most dominant slope gradient in the river basin. This slope gradient can be determined by processing DEM data.

Table 8. Slope Length and Gradient

Class	Slope (%)	Classification	LS Value
I	0-8	Plain	0,4
II	9-15	Sloping	1,4
III	16-25	Moderately Step	3,1
IV	26-40	Steep	6,8
V	>40	Very Steep	9,5

Source: Data Processed 2025



Source: Data Processed, 2025

Figure 2. Soil Type Map at the Research Site and Slope Map

Land Use and Land Management Factors. Land use and management have a big impact on runoff and erosion, especially in mining zones. Mining activities change natural land into open areas, haul roads, or processing sites. This change lowers the soil's ability to take in rainfall. So, there is a higher risk of surface runoff and sediment transport. Identifying land use conditions is key to planning effective water control systems. It also helps with environmental management in mining operations. Based on the interpretation and analysis of satellite imagery, the land use map of the study area is presented in Figure 4. The study site has bare soil and lacks vegetation around the settling pond. Therefore, the C-factor value is assigned a value of 1.

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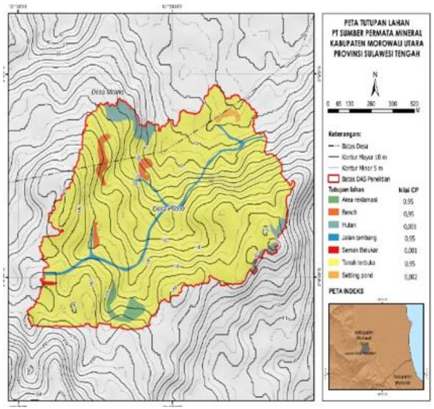

Source: Data Processed, 2025

Figure 3. Land Use Map

Soil Conservation Measures. Soil conservation measures are crucial for estimating erosion. They also greatly affect erosion rates. Land conservation measures in the study area include well-constructed bench terraces with a P-value of 0.04, and several areas without conservation measures, resulting in a value of 1. Land conservation practices will lower the erosion index. It also cuts down erosion vulnerability. If conservation measures are not taken or are done poorly, the risk of erosion will increase.

The erosion index, derived from the factors described above, serves as a parameter for determining the level of land sedimentation using the MUSLE method. The result is the product of the values of five factors: surface runoff (R), soil erodibility factor (K), slope length and steepness (LS), land use factor (C), and soil conservation measures (P). The resulting sedimentation rate at the study site is 7,256,073 m3/year.

Erosion Hazard Level. To estimate the erosion hazard level at the study site, the amount of sedimentation was divided by the area. The resulting sedimentation rate was 62,806 tons/ha/year. Based on Table 5, the classification of the study site is Class III, indicating a moderate erosion hazard level.

In the direction of land conservation, according to the value of erosion hazard class, namely moderate erosion, according to Baumgertel et al., (2018) vegetation plays an important role in controlling soil erosion, increasing the concentration and availability of organic c in the soil so that vegetative methods are the most effective action for soil protection on empty land such as disposal areas. Meanwhile, according to Sarminah et al. (2018), it is recommended to make terraces that suit field conditions, such as flat terraces, gulud terraces, credit terraces and bench terraces. In addition, it is necessary to continue with the creation of channels according to the direction of the slope to drain water to a safe place from erosion.

However, in its implementation, mechanical methods require greater costs compared to vegetative methods. So, the land conservation that can be done is a combination of vegetative and mechanical methods. Starting with planting ground cover plants to improve the physical-chemical properties of the soil, reduce the rate of erosion, and inhibit the transport of soil particles. Continued with planting local plants that can grow on nickel mining land. Research by Tuheteru et al. (2017) shows that 10 types of plants grow naturally on nickel revegetation land. These are Gymnostoma sumatrana, Sarcotheca celebica, Parinaria corymbosa, Timonius celebicus, Weinmannia fraxinea, and Alstonia macrophylla. Four plants are low accumulators: Nepenthes maxima, Cheilanthes tenuifolia, and Timonius celebicus. Mechanical methods involve making terraces that match the

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local conditions. You can also create drainage channels to direct water to sedimentation ponds. It helps in managing surface flow.

CONCLUSION

Based on the previous results and discussion, it can be concluded that the amount of sedimentation using the MUSLE method at the research site is 7,256,073 m^3/year. The research site is classified as class III for erosion hazards, which shows a moderate level of risk.

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