Analysis of Soil Erosion on Mine Area

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Abstract. Mining activities disturbing large areas of land may increase erosion rate up to several hundred times greater than from undisturbed areas. The erosion process occurs in stripping overburden, excavation of rocks and minerals, dumping in stockpile and waste dump, and mine reclamation. Since the eroded material/sediment becomes a big problem to the environment and for mining operations, estimation of soil erosion need to be carried out to create a good mine planning. For the early stage, a study of soil erosion was performed to classify erosion hazard level and to estimate soil erosion size. This study uses the Revised Unified Soil Loss Equation (RUSLE) method supported with Geographic Information System application for study area in the Block D1-D3 of Petea Mine Area. The study result showed that the research area can be classified into four erosion hazard level namely; low, medium, heavy, and very heavy with estimated material losses is 116,146.43 tons/year.

1. Introduction
Mining activities may produce environmental impacts such as erosion, sinkholes, loss of biodiversity or the contamination of soil, groundwater, and surface water. This paper discusses the erosion in mining area. The erosion of exposed hillsides, mine dumps, tailing dams, and resultant siltation of drainages, creeks and rivers may significantly impact the surrounding areas. The soil erosion depends on: climatic conditions, soil erodibility, overland slope and slope length, ground cover, soil conservation control practices, and catchment drainage characteristics. Mining activities tend to change radically several of these factors and severe sediment production could occur in the following locations: topsoil stockpiles, spoil piles, waste dumps, bare topsoil areas, steep out slopes, ramps, and haul roads [1]. Most methods for determining soil erosion and sediment transport have been developed based on studies with agricultural lands. Although relatively little work has been done with surface mined lands, they will in general have similar sedimentation characteristics to agricultural areas.

The most widely accepted and utilized soil erosion estimation is Unified Soil Loss Equation (USLE) developed by ARS scientists W. Wischmeier and D. Smith. The Universal Soil Loss Equation [2]:

\[ A = R \cdot K \cdot LS \cdot C \cdot P \]  

where A is the soil loss per unit area, R is a rainfall factor usually expressed as the product of rainfall energy times the maximum 30 minutes intensity for a given rainstorm, K is soil erodibility, LS is a dimensionless length slope factor, C is a dimensionless soil cover factor and P is a dimensionless conservation practice factor. Equation (1) should only be used to determine gross erosion from an area. To determine the sediment yield at a downstream point the gross erosion needs to be multiplied
by a sediment delivery ratio term (sediment yield/gross erosion). Numerous methodologies have been developed to predict sediment delivery ratios. A method known as the Modified Universal Soil Loss Equation (MUSLE) overcomes the problem of determining a delivery ratio and has seen widespread application. The method is defined by the following equation:

\[ Y = 11.8( Q \cdot q) - 0.56 \cdot KLSCP \]  

(2)

where \( Y \) is a single storm sediment yield (ton), \( Q \) is the storm runoff volume (m\(^3\)), \( q \) is the peak storm discharge (m\(^3\)/sec), and \( K \), \( L \), \( S \), \( C \), and \( P \) are the standard USLE terms used in equation (1).

However, the USLE was modified by incorporating the features that make its application suitable to mining lands, construction sites and other land applications and the same is popularly known as the revised universal soil loss equation (RUSLE). The RUSLE is an exceptionally well-validated empirical soil erosion prediction model which estimates average annual soil loss and sediment yield resulting from inter-rill and rill erosion. It computes the average annual soil erosion rate caused by rainfall and its associated overland flow. Galetovic et al. maintained that the RUSLE included several modifications that have specific importance to mined lands, construction sites, and reclaimed land applications. For example, ‘K-factor’ was modified to account for the variability of soil erodibility during the year. Now, both K and C factors take into account the multivariate influences of rock fragments covered within soil profiles and fragments resting upon hill slope surfaces. Also, the equations used to estimate the LS factor were reconstituted to improve their accuracy and extended to include steeper hill slope gradients than the equations contained in the USLE [3].

The main objective of this paper is to quantify the soil erosion from the mining area by using the RUSLE method and to determine the erosion hazard level. The RUSLE method is used to estimate erosion rate, and all parameter is represented with map using Geographic Information System (GIS) Application software. The overlay is then used to determine erosion hazard level. The study area is in the Block D1-D3 of Petea area of PT Vale Indonesia Tbk, covering an area of 1,071.83 hectares with elevation about 1,075 meters above sea level.

2. Research Methodology
The research was conducted by collecting data from PT. Vale Indonesia Tbk, Environmental Office of South Sulawesi, and relevant published data on website. The collected data from PT. Vale Indonesia Tbk is topographic data/map and recorded rainfall data of the Block D1-D3 of Petea Mine Area (Hydrological Department), and pit design of the Block D1-D3 of Petea Mine Area (Department of Long Term Planning). The collected data from South Sulawesi Environmental Office is land use map, and the data from website are Geological Map of Bungku Quadrangle Sulawesi with scale 1: 250.000 developed by the Geological Resource Center, and Map of World Soil Type.

The collected data were used to generate five parameters of the RUSLE equation, which include; rainfall-runoff erosivity factor (R), soil erodibility factor (K), slope length and steepness factor (LS), land cover (C) and land support practice (P). The rainfall-runoff erosivity factor (R) was generated predicted rainfall using Gumbel Method and was defined unity for the study area. The soil erodibility factor (K) were estimated by using composition of clay, silt, and sand, and was also assumed unity. For the study area. The slope length (L) and steepness factor (S), the land cover and management factor (C), and the land support practices factor (P) were drawn in the GIS environmental software. Furthermore, by using overlay maps system for the RUSLE parameter, the erosion hazard level was defined, and the erosion rate for each erosion hazard area was counted.

3. Soil Erosion from Mining Area
3.1. Geological Setting
The Block D1-D3 Petea mining area is in the mountains with an altitude of 150 – 1,075 meters above sea level. This area is dominated with a steep slope in the center to the north area, and moderate slope in the south. A complex tectonic shown in this region is indicated by number of geological structures; folds, joint, and fault. The main fault is Matano Fault in northwest-southeast direction. The Matano
Fault is a sinistral fault that is considered to be connected with the Sorong Fault. The Block D1-D3 of Petea area is composed by the Ultramafic Complex (Ku).

The Ultramafic Complex (Ku) consists of harzburgite, lherzolite, wehrlite, websterite, serpentinite, dunite, diabase and gabro [4]. Harzburgite is green to black, massive, locally refined minerals, composed of fine to coarse minerals, consisting of olivine, pyroxene and serpentinite. The latest mineral is alteration product from pyroxene and olivine. Lherzolite is blackish green, massive and medium to coarse grained. Wehrlite is black, massive, and fine-grained to coarse grained. The rock is composed of olivine, sometimes pyroxene. These minerals are converted into serpentine, talc and idingsit. Websterite is solid black and massive composed of olivine and pyroxene minerals, finely grained to moderate. Serpentine replaced olivine and pyroxene fills the modified crystal fracture. Serpentinite is gray to blackish green, massive composed of antigoritic minerals, clay and fine grained magnetite. These rocks are generally often found sturdy structures and there is a cesarean mirror (solid, fine-grained to moderate, composed of plagioclase minerals, orthoclase, pyroxene and ore minerals, these rocks are strongly altered in several places. Fine to moderate-grained dunite, greenish, grayish-green to blackish, composed of olivine minerals, pyroxene, plagioclase and ore minerals, olivine and pyroxene minerals are transformed into serpentine minerals, talc and chlorite, these rocks are found to be strongly altered, showing the structure of the nest of the ore. Black-spotted gabro, medium to coarse, massive, this rock-forming mineral consists of plagioclase and olivine. These rocks are found in the form of cracks that break through ultramafic rocks.

Figure 1. Geological map of study area and its surrounding (Geological Research and Development Center, Bandung, 1993)

3.2. Parameter of the RUSLE Model
The RUSLE model is an empirical model that is the most widely used for erosion modelling in mining [3]. The RUSLE equation computes the average annual erosion or average soil loss (A). The A is usually expressed in ton/ha/year. Several factors related to the A need to be generated are; the R is the rainfall-runoff erosivity factor (J/ha); the K is the soil erodibility factor (t/J); the LS is the hill slope length and steepness factor (dimensionless); the C is the cropping management factor (dimensionless); and the P is the supporting conservation practice factor (dimensionless). To estimate the soil loss in this mine area, the RUSLE model was used in a GIS environment.
The rainfall-runoff erosivity factor (R) is computed using Equation (3) proposed by Singh et al. [3]:

$$R = 79 + 0.363 \times (X) \ (J/h)$$  \hspace{1cm} (3)

where X is the average annual rainfall (mm). Estimation of the R factor uses a daily rainfall data for five years (2012-2017) were collected from the study area. The rainfall data was analyzed using Gumbel Method to estimate rainfall for a desired 5 years return period. The estimated rainfall-runoff factor for the Block D1-D3 Petea mine area is 100.2 J/h. Since the rainfall intensity recorded on this area only at one gauge station, the rainfall/runoff erosivity factor are similar for the study area.

The soil erodibility factor (K) calculation was initiated Wischmeier et al., (1971) by representing susceptibility of soil to erosion and the rate of runoff, taking into account the % portion of silt, sand or organic matter, soil texture, soil structure and permeability as soil erodibility factor [2]. A simple method for indirectly estimating soil erodibility were applied by Bouyoucos equation based on soil physical properties (texture and organic matter content) as input data [5];

$$K = \frac{SAN + SIL}{CLA} \times \frac{1}{100}$$  \hspace{1cm} (4)

where: SAN, SIL and CLA are percent sand, silt and clay, respectively. The erodibility factor is calculated based on filter analysis of 27 soil samples taken from the mine site (Table 1) for the mine area and based on soil type data for areas outside the mine. Soil laterite is characterized with highly compacted and cemented soil can easily be cut into brick-shaped blocks. This material is quick stable or difficult to destroy by raindrops. Calculation the erodibility factor using equation 4 show a various value from 0.008 – 0.081 and average is 0.012 for the mining area and 0.032 for the area outside the mine. This erodibility value is also assumed to be similar within the study area.

The LS factor considers for two parameter slope length and slope steepness. The LS factor describes the combined effects of slope length (i.e., flow length) and slope gradient (i.e., grade or relief). Slope length is defined as the distance from the point of origin of overland flow to the point where the slope decreases sufficiently for deposition to occur or to the point where runoff enters a defined channel (wet or dry). The slope steepness is the segment or site slope. Slope length and slope steepness strongly influence the transport of soil particles once the soil particles are dislodged by raindrop impact or runoff. Soil loss increases more rapidly due to slope steepness than due to slope length.

Estimation of LS factor of Block D1-D3 of Petea Mine Area was performed by driven a slope map using topographical map. The topographical map is produced by Department of Geotechnics, Hydrology, Reclamation and Environment. The map represents surface relief with contour interval of 5 meters. Determination of the length and slope map is obtained based on the results of the raster calculator processing in Arcmap 10.3 Software, the value entered is the value of accumulated flow grid, grid slope percentage, and grid size.

The slope is one of the factors in determining the LS value. The results of the processed data on the processed raster calculator can be seen in Figure 2. Based on the equation entered into the raster calculator in Arcmap 10.3 Software, the LS value varies from 1 m to 16 m in length. Figure 1 shows that a high LS value is at a high level of steep steepness marked with a reddish orange color and a low LS value at a gentle steepness level marked with grays.
Figure 2. Map of estimated LS factor; Slope Steepness (left), and Slope Length (right)

Table 1. Slope steepness classification of the Blok D1-D3 of Petea Mine Area

| No | Slope (%) | Class      | Area (Ha) | Area (%) |
|----|-----------|------------|-----------|----------|
| 1  | 0 - 8     | Little or none | 76.78     | 7.16     |
| 2  | 8 - 15    | Gentle     | 13.83     | 1.29     |
| 3  | 15 - 25   | Moderate   | 219.48    | 20.48    |
| 4  | 25 - 45   | Steep      | 605.75    | 56.52    |
| 5  | > 45      | Extremely steep  | 102.54    | 14.55    |
|    |           | Total      | 1071.83   | 100.00   |

The C factor reflects the effect of cropping and management practices on soil erosion rates. Since the C factor represents the effect of plants, soil cover, soil biomass and soil disturbing activities to erosion, each land cover type can correspond to an estimated C value. Figure 3 shows the C-factor values for the different land use categories. The study area is classified into four types of land cover namely open land, shrubs, forests, and mining area. The C value of each land cover can be seen in Table 2.

Table 2. Cover factor value of the Blok D1-D3 Petea Mine Area

| No | Land use         | C value | Area (Ha) | Area (%) |
|----|------------------|---------|-----------|----------|
| 1  | Open (soil) area | 0.600   | 670.50    | 62.56    |
| 2  | Shrubs           | 0.001   | 45.46     | 4.24     |
| 3  | Forest           | 0.010   | 132.42    | 12.35    |
| 4  | Mining           | 0.034   | 223.45    | 20.85    |
|    | Total            |         | 1071.83   | 100.00   |

Based on the Table 2, it is shown that land use in the Block D1-D3 of Petea Mine Area is dominated with open (soil) area covering 683.21 ha with a value of C (0.6), mining land with an area of 223.06 ha and a value of C of (0.034), forest Land with an area of 135.37 ha and a C value of (0.01), and shrubs with an area of 53.15 ha and a C value of (0.001). Distribution of land cover in the Catchment Area can be seen in Figure 3.
Figure 3. Land use map

The P factor reflects the impact of support practices on the average annual erosion rate. As with the other factors, the P-factor differentiates between cropland and rangeland or permanent pasture. Since the Block D1-D3 of Petea Mine Area on going progress for mining activities, there is no soil treatment and conservation carried out, specifically for the D1 and D2 Block areas. Reclamation activity will be performed while the Block D3 is mined. Therefore, there is no processing activity and soil conservation for handling the deteriorated soil in this area. Therefore, estimation the P factor value is based on topographic values and slope values [6]. Table 3 shows the estimation of P factor value based slope and topographical condition. This shows that the handling of land conservation in the steep sloping area is greater than the area with the gentle slope.

Figure 4. Map of land conservation
### Table 3. Land conservation factor based on slope steepness

| Slope (%) | Elevation | Strip Cropping | Area (ha) | Area (%) |
|-----------|-----------|---------------|-----------|----------|
| 0.0 – 7.0 | 0.55      | 0.27          | 406.50    | 37.93    |
| 7.0 – 11.3| 0.60      | 0.30          | 125.20    | 11.68    |
| 11.3 – 17.6| 0.80    | 0.40          | 265.00    | 24.72    |
| 17.6 – 26.8| 0.90    | 0.45          | 97.78     | 9.12     |
| < 26.8    | 1.00      | 0.50          | 177.35    | 16.55    |
| **Total** |           |               | **1071.83**| **100**  |

3.3. **Mine Erosion Hazard Level**

The major causes of erosion problems at a surface mining operation are the extent of the disturbed areas, poor drainage plans and the lack of a sediment control strategy which is integrated with the mining operations. In developing a sediment control plan the following basic approach should be adopted: minimize the area which is disturbed at any one time; develop a drainage control system for the mine lease area; integrate drainage, erosion and sediment control into each stage of the mining operation; develop a mining and rehabilitation plan prior to initiating mining activities; construct drainage and erosion controls in advance of mining activities; divert storm runoff away from areas with high erosion potential; incorporate measures to reduce the flow velocity of storm runoff; limit the handling of spoil and topsoil materials; rehabilitate areas as soon as possible; maintain drainage and erosion control measures [1].

Estimation of erosion rate in this research was calculated based on map of mine erosion hazard level with support by GIS software. The erosion hazard level map was generated by overlaying maps developed with parameter of the RUSLE equation (R, K, LS, C, P). The overlay parameters produced four hazard levels, namely: low level, medium level, high level, and very high hazard level. The estimation of average erosion rate for each level from low to very high hazard are 100.42 ton/ha/year, 113.58 ton/ha/year, 158.85 ton/ha/year, and 201.93 ton/ha/year, respectively. Furthermore, the widest area distribution is the criteria of low hazard level, then highest hazard level, medium hazard level, and high hazard level with an area of 949.35 ha, 75.03 ha, 41.43 ha, and 6.02 ha, respectively.

### Table 4. Detail information for each erosion hazard level

| No. | Hazard Level | Erosion Rate (ton/ha/year) | Area (ha) | Material Losses (ton/year) |
|-----|--------------|----------------------------|-----------|---------------------------|
| 1   | Low          | 100.42                     | 949.35    | 95,333.73                 |
| 2   | Medium       | 113.58                     | 41.43     | 4,705.62                  |
| 3   | High         | 158.85                     | 6.02      | 956.28                    |
| 4   | Very High    | 201.93                     | 75.03     | 15,150.81                 |
| **Total erosion** |               | 1071.83                   | 116,146.43 |                             |

Based on data on the Table 4, in the total erosion from the Petea Watershed is 116,146.43 tons/year. This material loss volume was mainly caused by erosion from low hazard level area with area 949.35 ha to produce 95,333.73 ton/year. This due to wide of area is 88.57 % of the research area. The smallest material loss was caused by erosion from the high hazard level with area of 6.02 ha. Two other hazard level produced material loss volume of 4,705.62 tons/year for medium category, and 15,150.81 tons/year for the very high category. The analysis result show that the material loss volume depends on the wide area of each hazard level category. Therefore, the erosion hazard level represents the rate erosion but is not to indicate the volume of material loses or transported.
4. Conclusions
The study of soil erosion on mining area illustrates that without careful management and the development of a sediment control scheme, the erosion from a surface mine can be severe. By using overlay maps of the RUSLE equation parameter on geographic information system, it was generated the erosion hazard level in the Mine Block D1-D3 area. The erosion hazard map categorizes hazard level into four categories, namely: low, moderate, severe, and very heavy erosion hazard levels. In the mine area, it estimated that erosion rates various from 100.42 – 201.93 ton/ha/year, with total material losses is 116,146.43 tons/year.

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