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WORD COUNT

5791 Words

CHARACTER COUNT

31083 Characters

PAGE COUNT

12 Pages

FILE SIZE

164.0KB

SUBMISSION DATE

Nov 4, 2022 4:22 PM GMT+7

REPORT DATE

Nov 4, 2022 4:24 PM GMT+7

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Research Article

Please be careful in tenses; when describing methods and results, you should use the **past tense**. The **present tense** is appropriate for accepted facts, such as the background information presented in the Introduction. In addition, you may use the **present tense** when you discuss your results and conclusions

- Some methods are mixed with the Introduction and Results
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Mercury pollution in the soil and river water of the Ratai watershed by artisanal and small-scale gold mining activities in Pesawaran District, Lampung, Indonesia

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Article history:
Received Day Month 20xx
Accepted Day Month 20xx
Published Day Month 20xx

Keywords:
ASGM
Erosion
Mercury
USLE
Way Ratai watershed

Abstract

The high risk of mercury pollution in the Ratai watershed due to artisanal and small-scale gold mine activities in Pesawaran District, Lampung, Indonesia, was evaluated. Studies are needed to improve the understanding of the effect of heavy metal pollution, especially mercury (Hg), in soil and river water along the watershed because of erosion. ~~The high risk of mercury pollution in the Ratai watershed due to Artisanal artisanal and SmallSmall Scale scale Gold gold Mine mine activities in Pesawaran District, Lampung, Indonesia, was evaluated.~~ The Universal Soil Loss Equation (USLE) integrated with Geographic Information Systems (GIS) model wa~~i~~s used to analyze the transport of mercury (Hg) from nonpoint source pollution loads to the Way Ratai River using rainfall-based erosion. Soils and river water samplings were conducted in 2020. Biophysical conditions, the land cover, and the rainfall data of the Ratai watershed were also taken into account. The results indicated that Hg concentration in the soil and the river water were high ranged from 0.26 – 28.[illegible] mg L^{-1} and from 0.08 – 14.1 mg L^{-1}, respectively. ~~The Hg contents are high and above the quality standard for mercury in soils and water based on Indonesian Government Regulation Number 82 of the year 2001, which should not exceed 0.005 mg L^{-1}.~~ The reason for the high Hg contents in the soils and the river waters was ~~due to~~ the high erosion rate in the watershed. As the study area was characterized by high rainfall erosivity and low to high soil ~~erodability~~ erodibility, the erosion-caused Hg contamination in soil and water can~~an~~ be significant if no conservation strategies are developed.

To cite this article: Author, F., Author, S. and Author, T. 2022. Paper title; the title should be a brief phrase describing the contents of the paper. Journal of Degraded and Mining Lands Management 9(0):0000-0000, doi:10.15243/jdmlm. 2022.000.0000.

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Introduction

Processing of rocks containing gold (ore) is gold that has very high economic value generally uses the mercury (Hg) amalgamation method, especially for artisanal and small-scale gold mining (ASGM). This type of mining occurs in most nations in the tropics (Villas-Boas et al., 2001), including Indonesia (Damayanti and Lutfie, 2009; Arifin et al., 2020)~~, because it is becoming a vital source of income for the communities (ILO, 1999)~~.. However, handling Hg in the field is not optimal due to ~~limited~~ lacking of knowledge, capital, and equipment owned by small-scale miners. On the other hand, the miners generally process ore into gold without using a wastewater treatment plant so that the processing waste (tailings) will be dumped into the ground and carried~~d~~ by rainfall, erosion, and surface run-off, which will eventually enter the river. Esdaile and Chalker (2018) stated that Mercury-dependent ASGM ~~is the largest~~ can be source of mercury pollution ~~on Earth and causes more mercury pollution than any other human activities~~. According to Fernández-Martínez et al. (2005), from mining activities, ~~-~~surface run-off or infiltrated water brings the metallurgical wastes or Hg ~~from mining activities,~~ pollutants ~~from mining activities can reach into the mine water system and ultimately~~ into the environment. So that, ~~when the mine/metallurgical wastes enter contact with surface run-off or infiltrated water. Donkor et al. (2005) stated that~~ ASGM by Hg amalgamation ~~is the primary source of~~causes water resource contamination ~~with~~ by heavy metals (Donkor et al., 2005).

Further, mining ore and placer gold deposits have been identified as one of the most ecologically damaging aspects of the gold mining industry (Tarras-Wahlberg et al., 2001; Tarras-Wahlberg et al., 2002). Fernández-Martínez et al. (2005) ~~stated~~ reported that mercury pollution in soils, surface waters, and sediments in areas affected by Hg mining operations in Asturias, Spain is vast. ~~However, data about the mercury pollution-dependent ASGM in soils and surface waters due to erosion in Indonesia are still lacking.~~Testing the Hg contents due to ASGM activities in Indonesia, especially Hg in soils (Damayanti and Lutfie 2009; Mirdat et al., 2013) and in water (Yulis, 2018; Arifin et al., 2020) have been carried out. Most of the results show that ASGM causes the mercury content in the soil and water to exceed the mercury quality standard that has been set. However, researchs on the effect of erosion using USLE models on mercury pollution-dependent ASGM in soils and surface waters ~~However, data about the mercury pollution-dependent ASGM in soils and surface waters due to erosion in Indonesia~~ are still lacking.

The ASGM activities in Pesawaran District, Lampung, Indonesia**,** are estimated to have been running for more than ten years, so it is estimated that the lands and river waters around the processing site of ore to gold using the amalgamation method have experienced Hg pollution. As we know, Hg pollution is hazardous to human health (Jarup, 2003; Björkman et al., 2007; WHO, 2007; Saturday, 2018) and the environment (Donkor et al., 2005; Ignatavičius et al., 2022). Therefore, ~~the~~ Hg contaminations ~~o~~ in~~f~~ soils, water, sediments, ~~water,~~ and biota ~~by Hg has become a primary~~are needed to be concerned because ~~of their~~it causes toxicity, persistencye, and accumulation in food chains.

Accumulation of Hg in soil and water can occur due to erosion. ~~Erosion is moving or transporting soil or parts of soil from one place to another by natural media.~~ In nature, two leading causess ~~are active in this process~~of erosion are~~:~~ wind and water. In wet tropical climates such as Indonesia, water is the leading cause of erosion, while the wind does not have a significant effect ~~(Arsyad, 20)~~. ~~The erosion process occurs through crushing, transportation, and deposition Weil and Brady, 2017).~~ In the event of erosion, soil or parts from one place/location are eroded and transported, and then deposited in another. Soil erosion by water occurs through three main processes: the detachment of soil (as particles or aggregates) from the soil mass, the movement of loose material, and the deposition (Weil and Brady, 2017; FAO, 2019; Gachene et al., 2019). A considerable surface run-off will increase the amount of erosion so that it will carry Hg to a distant stream, deposit in the soil, the river water, and even reach the sea so that it will affect the life of biota in the ocean.

Soil erosion processes occur due to rain ~~(rain)~~ and run-off, which are influenced by various factors, including rainfall (intensity, diameter, duration, and amount of rain), soil characteristics (physical properties), land cover, slope steepness, slope length (~~Wischmeier and Smith, 1978~~FAO, 2019). These factors work simultaneously in influencing erosion. Loss of soil will only occur if the two processes above are carried out. Without a destructive process and soil particles, erosion will not occur; erosion will be minimal without the transportation process.

The quantity of Hg that enters soils and water because of erosion is uncertain due to lack of sufficient data (Panagos et al., 2021). USLE-based soil erosion modelling has been widely used elsewhere (Pandey et al., 2007; Kinnel, 2010; Mahapatra et al., 2018; Borrelli et al., 2021). Soil erosion models can estimate the level of erosion and predict the occurrence of heavy metal pollution due to erosion which can affect health and the environment.

~~The amount of erosion can be measured directly in the field using small plots or predicted using models. Erosion prediction models that are commonly used today are parametric. A parametric model to predict the erosion~~

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~~of a plot of land has been developed by Weischmeier and Smith (1978), known as The Universal Soil Loss Equation (USLE). USLE allows planners to estimate the average erosion rate of a given soil on a steep slope with a specific rainfall pattern for each type of cropping and management action (soil conservation action) that may be taken or is being used. The equations used to classify the various physical and management parameters that affect the rate of erosion into six main variables whose values for each site can be expressed numerically. To predict the erosion in the research area, The USLE is integrated with Geographic Information System (GIS).~~

The research aimed to study the direct impact of ASGM activities on Hg accumulation in soil and river water based on the estimation of the soil erosion ~~with associated nonpoint source pollution loads~~ using USLE and GIS, especially in the case of Ratai Watershed Pesawaran District, Lampung, Indonesia.

Materials and Methods

Mapping the research location and the drainage system

The research was conducted in Bunut Seberang Village, Teluk Ratai District, Pesawaran Regency, Lampung Province, Indonesia, from September to December 2020 (Figure 1).

Figure 1. Research ~~Site~~ location

The research implementation was begun by mapping the location of the excavation of gold rock and the location of processing ore into gold. Followed by mapping the drainage system (map of the river network) to estimate the direction of the surface flow to the nearest river from the excavation location and the processing ore into gold location.

Soil sampling

Soil samples were taken at six locations that were not expected to be affected by mining activities and were suspected of being affected by the upstream, middle, and downstream of the Ratai watershed (the coordinates of sampling locations are shown in Table 3). Samplings of river water were in the upstream part that was not affected by mining activities and in the downstream part that was suspected of being affected by mining activities.

The estimation of erosion

The analysis approach was based on the watershed, where in this approach, the biophysical conditions, the land cover of the watershed, and the rainfall data would significantly affect the soil erosion that would affect the amount of Hg in the soil and river water.

Erosion estimation for each land unit was calculated using the Universal of Soil Loss Equation (USLE) model (Wischmeier and Smith, 1978) ~~. The determination of the value of the factors in the USLE model can be calculated using~~with the existing formula~~s~~:

$$A = R.K.L.S.C.P$$

~~Where:~~ In SI units, the ~~A (Mg ha^{-1} yr^{-1}) is the annual~~ average annual soil erosion rate (A) in t ha^{-1} yr^{-1}, ~~R (MJ mm h^{-1} ha^{-1} yr^{-1}) is~~ the rainfall-runoff erosivity factor (R) in MJ mm h^{-1} ha^{-1} yr^{-1}, ~~, K (Mg h MJ^{-1} mm^{-1}) is~~ the soil erodibility factor (K) in t ha h ha^{-1} MJ^{-1} mm^{-1}~~,~~; while ~~L (dimensionless) is~~ the slope length ~~factor, S (dimensionless) is the slope~~ and steepness factor (LS), ~~C (dimensionless) is~~ the land cover and management factor (C), ~~P (dimensionless) is~~ the soil conservation or prevention practices factor (P)~~.~~ are dimensionless. The impact of the factors R capture~~ing~~ the energy and amount of sediment yield. USLE-type models ~~are designed to predict long-term average annual soil loss; they~~ have successfully predicted long-term average annual soil loss ~~event soil losses~~ reasonably well at some geographic locations (Kinnell, 2010; Borrelli et al., 2021). ~~The choice of a soil erosion prediction tool depends on the spatial and temporal scale of the intended model application, as the question of scale is crucial in choosing the right modelling approach.~~ Process-oriented models required an application of the used equations at a given spatial scale, ranging from plot to basin, and at the event temporal scale (Alewell et al., 2019). ~~Integrating~~ USLE and GIS ~~is an effective tool~~could be integrated for mapping the spatial distribution of soil erosion from the entire watershed (Bekele and Gemi, 2021).

Rain erosivity factor (R). ~~Rain erosion is the number of rain erosion index units which is the multiplication of total rain energy (E) with a maximum rainfall intensity of 30 minutes (I30) annually.~~ Wischmeier and Smith (1978) used EI30 as an index of rain erosivity; because ~~the product of~~ total rain energy (E) and maximum intensity for 30 minutes (I30) annually showed~~s~~ a very close relationship with the amount of eroded soil. The formula calculates

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the kinetic energy of rain in USLE: E = 210 + 89 log I. In Indonesia, the daily rainfall data for calculating EI are not widely available, so scientists ally use the EI formula developed by Bols (1978).

According to Bols (1978), ~~th in erosivity factor (~~R factor~~)~~ is the sum of ~~the~~ monthly rainfall erosion index values ~~and is calculated~~ based on the equation:

$$R = \sum_{i=1}^{12} (EI30)i$$

~~The value of EI30 is calculated using the following formula proposed by~~ Lenvain (1975 in Bols, 1978) proposed the formula to calculate EI30 value~~:~~ as follows:

$$EI30 = 2.34\, R^{1.98}$$

The total rainfall at the study location was 1699.5 mm yr^{-1}.

oil erodibility factor (K). Soil erodibili the rate of erosion per rai osion index for ~~a~~ soil that is~~is~~ allowed from standard small plot 22 m long, i cated on a 9% slope without plants. Soil erosion sensitivity i~~i~~s strongly influenced by ~~soil texture,~~ il organic matter ~~content~~, soil texture, permeability, and stability of soil structure. Soil erodibility is~~is~~ calculated using the formula (Wischmeier and Smith ~~formula, (~~1978):

$$100K = \{1.292\,(2.1\,M^{1.4}\,(10^{-4})(12 - a) + 3.25\,(b - 2) + 2.5\,(c - 3)\}$$

Where:

K = ~~E~~ Soil erodibility ~~of soil~~ (dimensionless)
M = Soil texture class (% fine sand + % dust) (100 - % clayey)
A = Organic material (%)
B = Soil structure code
C = Soil profile permeability code

ope length and ~~slope~~ steepness (LS). Slope length factor (L)~~, namely~~ the ratio between the amount of erosion o particular slope length and soil erosion with a slope length of 22 m ~~and~~ in identical conditions. Meanwhile, t ope steepness factor (S) is the ratio between the amount of soil erosion at a particular slope and soil erosion a slope of 9% with identical conditions. LS f~~F~~actors ~~for the slope length and slope~~ can also be calculated directly (combined) according to the formula (Wischmeier and Smith, 1978):

$$LS = \sqrt{X(0{,}0138 + 0{,}00965S + 0{,}00138S^{2}})$$

LS = Slope length and s~~lope~~teepness factor
X = Length of slope (m)
S = slope steepness (%)

The topographical conditions of the research site were mostly 61% in the steep category, 19% wavy, and 20% flat.

Vegetations factors and management (C). The determin n of the C factor for various plants, such as mixed cropping, coffee, etc., is based on various previous studies ischmeier and Smith, 1978).

Conservation action factor (P). The conservation action factor is also determined based on various previous studies (Wischmeier and Smith, 1978).

Surface run-off volume

Estimating surface run-off volume in a watershed can use a rainfall-runoff relationship model, namely the USDA-~~.S. method~~ Soil Conservation Services (SCS)~~.~~ method. The amount of run-off volume (Q) depends on the rainfall (P) and the volume of storage available to hold water (S).

The equation used is:

$$Q = \frac{(P - 0.2S)^{2}}{P + 0.8S}$$

Q = Total surface flow (mm)

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P = Rainfall (mm)
S = Maximum potential water retention (mm)
Based on the empirical equation, the value of S is estimated using the equation:

$$S = \frac{25400}{CN} - 254$$

S = Maximum potential water retention (mm)
CN = Curve number (run-off curve number)

The run-off curve number depends on the soil properties~~ of the soil~~, soil use, hydrological conditions, and previous water conditions. CN values are determined based on soil type, land use, infiltration, and soil hydrological conditions (previous groundwater conditions).

The Erosion Index

The erosion index is the ratio between actual erosion and tolerable soil loss. Based on data on land cover, soil type, topography, and rainfall, using the USLE method, the amount of erosion can be estimated. The magnitude of the erosion index describes the erosion hazard level.

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$$\text{Surface run coeffcicient (SRC)} = \frac{\text{Total DRO a year (764.81 mm)}}{\text{Total rainfall a year (1699.5 mm)}} \times 100\% = 45\%$$

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The estimation of the surface run-off volume at the research location using the SCS (Soil Conservation Services-USDA) method was 45%, called the Surface Run-off Coefficient (SRC). From the total rainfall that falls, 45% of rainfall would become surface run-off and enter the river flow.

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According to the Menteri Kehutanan Republik Indonesia (2014), the surface run-off coefficient of 45% is categorized as high. Excessive run-off volume could potentially cause flooding downstream. Indonesian climate is generally divided into wet and dry climates. From the research data, November till March was wet months, while July till October was dry months. Oldeman's climate classification is to make climate types based on the number of wet months and dry months. The wet month category is the month with rainfall>200mm and the dry month with rainfall <100 mm. The annual rainfall that accumulates in a short period (December-February) causes the soil to be unable to accommodate all the volume of rainwater. As a result, most of the rainwater becomes surface run-off; this is exacerbated by the increasing conversion of forest functions to other uses such as agriculture, housing, industry, and rice fields, which can cause considerable flooding in the downstream area. Furthermore, it is said that the significant surface run-off will also cause excessive erosion, which will directly reduce soil fertility. Decreasing soil fertility will cause less vegetation to grow properly, so the land cover will decrease. Therefore, recharging water reserves in the upstream area will reduce and result in drought during the dry season.

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~~The run-off curve number depends on the properties of the soil, soil use, hydrological conditions, and previous water conditions. CN values are determined based on soil type, land use, infiltration, and soil hydrological conditions (previous groundwater conditions).~~

Mercury (Hg) analysis method

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Mercury (Hg) contents in the soils and river water were analyzed using Cold Vapor Atomic Absorption Spectroscopy (CV-AAS) or Mercury analyzer. The analysis used US EPA SW-846-7470A method. In principle, Hg^{2+} ions were reduced by Sn^{2+} to Hg atoms and then these atoms were analyzed quantitatively with a cold vapor-atomic absorption spectrophotometer at a wavelength of 253.7 nm. Preparation of a calibration curve in the range of 1 g Hg/L – 20 g Hg/L by inserting 100 ml of a working standard Hg solution at levels (1, 2, 4, 8, 10, 15 and 20) g Hg/L into each 250 ml Erlenmeyer each then add 5 mL of concentrated H_2SO_4 and 2.5 mL of concentrated HNO_3 into each Erlenmeyer, then add 15 mL of $KMnO_4$ solution and wait up to 15 minutes. If the purple color disappears, add more $KMnO_4$ until the purple color does not disappear. After that, add 8 mL of $K_2S_2O_8$ and heat it in a water bath for 2 hours at 95°C, then cool to room temperature. If the temperature of the solution has cooled, then add enough NaCl hydroxylamine solution to reduce the excess $KMnO_4$ and add 5 mL of $SnCl_2$. Immediately measure the level of Hg in the solution using a cold steam AAS that has been optimized according to the instructions of the tool (Hadi and Aisah, 2015).

~~Mercury (Hg) contents in the soils and river water were analyzed using EPA's method, which is Method 7470a Mercury in Liquid Waste (Manual Cold-Vapor Technique) (U.S. EPA 1994). Method 7470 is a cold-vapour atomic absorption procedure approved for determining mercury concentration in mobility-procedure extracts, aqueous wastes, and ground waters. (Method 7470 can also be used for analyzing particular solid and sludge-type wastes; however, Method 7471 is usually the method of choice for these waste types). All samples must be subjected to an appropriate dissolution step prior to~~ before ~~analysis. The Hg concentration was measured using Atomic Absorption Spectroscopy (AAS).~~

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Data analysis

A Geographic Information System (GIS) was integrated with the USLE (Universal Soil Loss Equation) model in the identification of rainfall-based erosion and the transport of mercury (Hg) from nonpoint source pollution loads to the Way Ratai river. ArcGIS version 10.3 was used.

Data on soil types, land cover conditions, and topography were analyzed descriptively to the extent that mining impacts would pollute soils and river water. ~~Further, data on Hg contents in soil and river water were also correlated with the distance of Hg pollutants from the nearest purification (nonpoint source pollution).~~

~~The amount of erosion can be measured directly in the field using small plots or predicted using models. Erosion prediction models that are commonly used today are parametric. A parametric model to predict the erosion of a plot of land has been developed by Weischmeier and Smith (1978), known as The Universal Soil Loss Equation (USLE). USLE allows planners to estimate the average erosion rate of a given soil on a steep slope with a specific rainfall pattern for each type of cropping and management action (soil conservation action) that may be taken or is being used. The equations used to classify the various physical and management parameters that affect the rate of erosion into six main variables whose values for each site can be expressed numerically. To predict the erosion in the research area, The USLE is integrated with Geographic Information System (GIS).~~

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Results and Discussion

Soil type and land coverage

The total area of the watershed as the basis for analysis was 2,667.01 ha. The soil type in the research location was divided into two parts, namely, Inceptisols and Ultisols. Inceptisols soil dominated the watershed area as much as 85.07% (2,268.8 ha) and Ultisols soil covered an area of 14.93% (398.17 ha); the soil type map is presented in Figure 2. Inceptisol soil is a young soil with a high level of fertility. Meanwhile, ultisol soils are old soils that have undergone advanced leaching levels so that they have low base saturation and low pH with argillic or candic horizons (Subardja et al., 2014).
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Figure 2. The Soil Type at Research Location

Soil chemical and physical properties data are presented in Table 1. Soil conditions were described by the mineral and soil chemical content, based on the criteria for soil nutrient status ~~by Soil Research Institute (1983).~~ by Pusat Penelitian Tanah (1995). Generally, soil pH ranged from 5.28 to 6.64, including the slightly acidic category. The total soil nitrogen (N) content ranged from 0.01-0.15%, including the very low to low category. The available soil phosphorus (P) content ranged from 3.54-15.48 mg L^{-1}, including the very low to low category. At the same time, the soil exchangeable potassium content ranged from 0.24 to 1.05 me ~~—~~100 g^{-1}, including medium to very high category. The soils in the study area had low soil fertility, primarily N and P, due to the leaching of nutrients by surface run-off. According to FAO (2019), the loss of surface material causes ~~leads to~~ a decrease in the soil nutrients ~~supplying power of the soil~~. ~~Yustika et al. (2019) stated that nutrient~~ Nutrient loss could be prevented by implementing effective land management policies (Yus~~a~~tika et al., 2019).

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~~The physical condition of the soil related to the erosion process is the soil texture~~ (reference?). ~~In general, the soil texture in the research location included~~ is ~~sandy soil sensitive to erosion. The loss of surface material leads to decreased nutrient-holding power, most pronounced in sandy soils (FAO, 2019).~~

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Table 1. Soil chemical and physical properties of site location*

Location	pH	Total N (%)	Available P (ppm)	Exchangeable~~.~~ K (me 100g^{-1})	Soil Texture		
					Sand (%)	~~Loam~~ Silt (%)	Clay (%)
1	6.46	0.01	7.30	0.47	68.13	17.83	14.04
2	6.04	0.03	18.48	0.89	67.64	16.01	16.35
3	5.64	0.02	4.55	0.39	82.77	7.43	9.80
4	5.85	0.15	3.54	1.05	36.99	42.72	20.29
5	5.86	0.01	5.06	0.24	82.7	7.46	9.84
6	5.28	0.03	6.57	0.50	70.05	11.70	18.25

Source: ~~*~~Soil Science Laboratory, University of Lampung (2020)*

Based on the research data (Table 1), the soil pH at the study site ranged from 5.28 to 6.46, including the slightly acidic category. Ignatavičius et al. (2022) stated that pH is one of the factors that affect the release of Hg in the environment. Hg uptake is affected by soil pH and decreases with acid pH. On the other hand, the contents of N, P, and K in the soil are in the very low category; total N ranged from 0.01% – 0.15%, available P ranged from 3.54 ppm – 18.48 ppm, and K-exc ranged from 0.24 me/100 g – 1.05 me/100 g. Low nutrients indicated low soil fertility due to the high level of leaching that occurs. Nutrients of N, P, and K are utilized by plants, microbes, and some are lost because they are leached into the soil and carried away by surface runoff.

Table 1 also shows that the sand content in the study area ranged from about 37% to 70%, silt about 7% to 43%, clay about 10% to 20%. The high sand content indicates that the study area has undergone further washing. The higher the sand content, the lower the ability of the soil to bind ions and the higher the leaching which will bring Hg to be eroded and contaminate the environment. The low clay content at the study site causes Hg not to be adsorbed by the soil. Ignatavičius et al. (2022) stated that Hg sorption capacity is influenced by the amount and quality of clay.

The land cover conditions are presented in Figure 3. The research location was dominated by forest cover of 81.78%, followed by dry land agriculture of 15.30%, settlement of 1.8%, and rice fields of 1.17%. It can be seen that the research areas are mostly covered by forest. According to Torri and Poesen (2014), with ~~, mentioned that with~~ increasing vegetation density, ~~there is an increase in~~ resistance by the soil to concentrated flow erosion increase ~~and a decrease in~~ run-off discharge during a rainfall event decrease. Generally, sheet and rill erosion wa~~i~~s reduced by 50% ~~percent~~ at about 20%~~vegetation covers of about 20% percent~~, 75% ~~percent~~ at ~~covers of~~ about 30 to 35% ~~percent~~, and 90% ~~percent~~ at ~~covers of~~ about 60% vegetation covers ~~percent~~ (Gyssels et al., 2005).

Figure 3. Land coverage of research location

~~The amount of erosion that occurs in the area is strongly influenced by the land cover conditions (please show the data?).~~ In addition, the soil's physical properties, the topographic soil conditions, and the rainfall will also affect the amount of erosion. For this reason, the topography and rainfall conditions of the research location must be considered. Topographic conditions and rainfall of the research location are presented in Figures 4 and ~~5~~Table 2, respectively. ~~The total rainfall at the study location was 1699.5 mm yr^{-1}, while the topographical conditions were mostly 61% in the steep category, 19% wavy, and 20% flat.~~

Figure 4. Topographic condition of research location

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~~Figure 5. Monthly Rainfall condition in the year 2018.~~

~~The erosion index is the ratio between actual erosion and tolerable soil loss. Based on data on land cover, soil type, topography, and rainfall, using the USLE method, the amount of erosion can be estimated. The magnitude of the erosion index describes the erosion hazard level.~~ In general, the erosion index in the research location wa~~i~~s in the very low to ~~a~~ low category, as much as 86%, while in the medium to ~~a~~ very high category wa~~i~~s only 14%. The erosion index is presented in Figure 5~~6~~.

Figure 5~~6~~. Erosion index of site location.

while in the medium to ~~a~~ very high category wa~~i~~s only 14%. The erosion index is presented in Figure 5~~6~~.

The surface run-off is determined mainly by the surface run-off coefficient, where surface run-off results from the response of forest cover, topography, and soil type to falling rainfall. Soil erosion is affected by wind, rainfall, and associated run-off processes, the vulnerability of soil to erosion, and the characteristics of land cover and management (~~David, 1988;~~ Aksoy and Kavvas, 2005; Panagos et al., 2015).

Table 2. The surface ~~volume of~~ run-off volume from the research area ~~by the U.S. method Soil Conservation Services method (SCS method).~~

Month	Rainfall (mm)	Direct Run Off (DRO) (mm)
Jan	124	143.54
Feb	202	74.19
Mar	205	115.53
Apr	167	85.77
May	150	119.18
Jun	105	59.96
Jul	0	0
Aug	15	23.26
Sep	139	13.46
Oct	65	30.18
Nov	286	64.4
Dec	255	35.35
Total	1699.5	764.81

~~Total DRO a year (764.81 mm)~~

~~Surface run coeffcicient (SRC) = -- x 100% = 45%~~

~~Total rainfall a year (1699.5 mm)~~

~~The estimation of the surface run-off volume at the research location using the SCS (Soil Conservation Services-USDA) method is 45%, called the Surface Run-off Coefficient (SRO). The total rainfall that falls, 45% of rainfall would become surface run-off and enter the river flow.~~ The results of ~~calculating~~ the surface run-off in the location sites ~~using the SCS method~~ are presented in Table 2. During wet months (from January to June), rainfall ranged from 105 mm to 205 mm (with an average of 158.83 mm). While, direct run-off (DRO) ranged from 59.96 mm to 143.54 mm (with an average of 99.70 mm). DRO was calculated by US Soil Conservation Service (SCS) method as described previously. From these data, Surface Run-off Coefficient (SRC) a year which is ratio between total DRO and total rainfall a year was calculated and the value was 0.45. It means that from the total rainfalls a year, 45% of rainfalls would became surface run-off and flowed to the river. SRC 0.45 included as high category. FAO (2019) stated that rainfall and run-off affect the rate of water erosion at a site because both detach and transport the eroded soils.

~~The rate of water erosion occurring at a site depends on the rainfall itself (the source of rain splash detachment) and the run-off generated during the rainfall event, which both detaches and transports the eroded soil. Water added to the soil surface can either infiltrate the soil or flow along the soil surface as run-off (assuming a slight slope is present). The proportion of water that infiltrates the soil depends on the nature of the precipitation event (such as rainfall intensity, drop size, and snowmelt rates); the slope of the surface (generally, the higher the slope, the lower the percentage of water that infiltrates); and the infiltration rate of the soil (FAO, 2019).~~

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~~According to the Minister of Forestry of Republic Indonesia (2014), the surface run-off coefficient of 45 percent is categorized as high. Excessive run-off volume can potentially cause flooding downstream. Indonesian climate is generally divided into wet and dry climates. From the research data, November till March is wet months, while July till October is dry months. Oldeman's climate classification is to make climate types based on the number of wet months and dry months. The wet month category is the month with rainfall>200mm and the dry month with rainfall <100 mm. According to Irianto (2003), the annual rainfall that accumulates in a short period (December-February) causes the soil to be unable to accommodate all the volume of rainwater. As a result, most of the rainwater becomes surface run-off; this is exacerbated by the increasing conversion of forest functions to other uses such as agriculture, housing, industry, and rice fields, which can cause considerable flooding in the downstream area. Furthermore, it is said that the significant surface run-off will also cause excessive erosion, which will directly reduce soil fertility. Decreasing soil fertility will cause less vegetation to grow properly, so the land cover will decrease. Therefore, recharging water reserves in the upstream area will reduce and result in drought during the dry season.~~

Mercury (Hg) contents in the soils and river water

The ~~location of~~ water and soil sampling locations are ~~is~~ presented in Figure ~~7~~6, while ~~the analysis results of~~ the mercury contents in the soils and ~~the~~ river water are ~~presented~~ shown in Table 3. The results showed that the mercury contents in all samples from soil and river water is very high from the acceptable range. Hg content in soils ranged from 0.26 to 28.9 mg L^{-1}, and in the river water ranged from 0.08 to 14.1 mg L^{-1}. The mercury contents in the soils and water at all sampling points have exceeded the quality standard. Actually, the quality standard for mercury in soil and water should not exceeded 0.005 mg L^{-1} based on Indonesian Government Regulation No. 82 the year 2001 concerning water quality and pollution control (Presiden Republik Indonesia, 2001). The reasons why Hg contents in soils and river waters are ~~are~~ high; Because, firstly, there ~~i~~is~~s~~ no proper waste management; secondly, the distance from the ore-to gold refining or processing site i~~i~~s close to the river flow. In this study, the distances of the soil samples from ~~purification points~~processing site a~~a~~re between 30 m - 663 m, while the water samples ~~from the purification point~~ a~~a~~re between 30 m - 1161 m. Martin (2021) stated that most of the released Hg was deposited within 15 kilometers of the source.

~~the existence of pollution in soils and surface waters in the areas affected by Hg mining. M~~Mercury contents in the soils and the river water were strongly influenced by erosion and surface run-off at the study site ($p < 0.05$). Water erosion depends on the rainfall which the source of rain splash detachment, while run-off is generated during the rainfall event. Moreover, from the research data, it can be said that the study area was characterized by high rainfall erosivity. The erosion that occured at the study site was also high. The erosion index (EI) in the research area ranged from very low to high. Therefore, potential erosion ranged from weak to very strong. Although, more than 80% of the research area were covered by forest, which was in the outstanding category. However, the slope with the steepness more than 25% was about 42%, categorized as steeply, resulting in high surface flow and causing high erosion. The surface flow or run-off brought Hg particle into the soils and river water. Consequently, high erosion will be related to the polluted Hg in the environment. ~~Data Hg content in soils ranged from 0.26 to 28.9 mg L^{-1}, and in the river water ranged from 0.08 to 14.1 mg L^{-1}. Based on Indonesian Government Regulation No. 82 the year 2001 (President of Republic Indonesia, 2001) concerning water quality and pollution control, the quality standard for mercury in soil and water is not exceeded 0.005 mg L^{-1}. While~~ Therefore, ~~the mercury contents in the soils and water at all sampling points have exceeded the quality standard.~~ Small-scale gold mining activities without ~~a~~ permission have brought the soil and water bodies (rivers) ~~with~~ into the severely polluted category. Likely, ASGM activities in Pesawaran District caused Hg pollution in soils and surface waters of the Ratai watershed. Saturday (2018) reviewed that environmental pollution due to Hg contamination occured as shown by Hg concentration found in soils, sediments, and water samples.

~~The reasons why Hg contents in soils and river waters are high; Because, firstly, there is no proper waste management; secondly, the distance from the ore-to gold refining or processing site is close to the river flow. In this study, the distances of the soil sample from purification points are between 30 m - 663 m, while the water samples from the purification point are between 30 m - 1161 m.~~

Besides, a high Hg content in the soil and river water should be considered because it will be dangerous for health. Hg can be transformed by bacteria into methylmercury, and it then bioaccumulates in fish, shellfish, and other high-level predators, thus posing a human health risk (~~Turner and Southworth 1999~~Habiba et al., 2017). Mercury may have toxic effects on the nervous, digestive, immune systems, lungs, kidneys, skin, and eyes.

Figure ~~7~~6. The soil and water samples point location

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Table 3. The mercury (Hg) content in the soil and river water samples.

Sampling Point	Coord. soil location		Coord. water location		Hg Content (mg L^{-1})		Analysis Method
	X UTM	Y UTM	X UTM	Y UTM	Soil	Water	
1	510135	9379816	510131	9379803	3.84	9.6	US EPA SW-846-7470A
2	509845	9379768	509844	9379771	5.75	14.1	US EPA SW-846-7470A
3	510094	9379626	510092	9379626	21.8	0.08	US EPA SW-846-7470A
4	509330	9379319	509331	9379319	28.9	0.88	US EPA SW-846-7470A
5	510363	9378808	510363	9378809	0.26	0.08	US EPA SW-846-7470A
6	510886	9378609	510886	9378609	0.91	0.14	US EPA SW-846-7470A

~~Table 4. Correlation between distance to the nearest purification and Hg content in the soil and water. → what distance? The distance from what area? → this Table is confusing. What is this Table for?~~

	~~**r value***~~	
~~**Distance to the nearest purification**~~	~~**Hg content in the soil**~~	~~**Hg content in water**~~
~~Soil sample~~	~~-0.488ns~~	~~-0.572ns~~
~~Water sample~~	~~-0.545ns~~	~~-0.545ns~~

~~*ns: no significance~~

here ~~is~~ waswas no correlation between the sampling distance ~~of soil samples from the nearest purification~~ and Hg contents in the soils and river water. ~~Similarly, there is no correlation between the distance of water samples from the nearest purification and Hg contents in the soil and river water (Table 4). The correlation between the distances of purification points and the concentrations of Hg is not significant.~~ It is~~is~~ likely because the ~~purifications from~~ ore to gold processing are~~are~~ not carried out continuously over time, depending on the availability of ore material from the mining area. However, there is~~is~~ a tendency that the shorter the sampling distance ~~of soils and water samples~~ from ~~the nearest purification~~ore to gold processing site, the higher the Hg content in soils and water samples. Similarly, Odumo et al. (2014) stated the closer the distance from mining areas, the higher the mercury levels. ~~**Human-induced water erosion, like Hg mining-dependent ASGM could lead to higher sediment inputs into stream channels and increased sedimentation into reservoirs along the stream channels.**~~

Conclusion

Mercury (Hg) pollution in the soil and river water of the Ratai watershed by ASGM activities in Pesawaran District, Lampung, Indonesia, is~~was~~ high. The Hg contents in the soil and river water samples have~~ve~~ exceeded the quality standard for Indonesia's Hg pollution criteria.

Moreover, ~~The surface run-off coefficient is 45% percent, including the high category, which means the study area is characterized by high rainfall erosivity. The erosion that oc at the study site is also high. The erosion index in the research area ranged from very low to high. Therefore, otential erosion ranged from weak to very strong. Although, more than 80% percent of the research areas were covered by forest, which is in the outstanding category. However, the slope steepness was more than 40% percent, categorized as steeply, resulting in high surface flow and caused causing high erosion.~~

Hg pollution in the Ratai watershed by ASGM activities is related to high erosion because of high surface run-off and steepy slope in the research area.

Acknowledgements

The authors thank the Research Institute for Humanity and Nature (RHIN: a constituent member of NIHU) Japan for funding Project No. 14200102 and the University of Lampung for supporting this research.

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