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Impact of Open Pit Coal Mine on Groundwater Recharge: Alternative Method for Environmental Assessment

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ABSTRACT

Coal mines are widespread in Indonesia. It is the primary energy source for Indonesian electricity, which also contributes to the national revenues even during the Corona Virus Disease (COVID-19) pandemic. On the other hand, groundwater is also one of the important resources in Indonesia. It is commonly utilized for domestic water supply including drinking water, irrigation, municipalities, and industries. Mining with an open-pit system or surface mining is regarded as an activity that affects environmental deterioration. The impact on groundwater including a decrease in the quantity of groundwater is a common and significant issue concerned. According to environmental regulations in Indonesia, each mining company is obliged to submit Environmental Impact Assessment (EIA) documents before starting the mining production to protect and manage the groundwater in mine areas. The objective of this study is to analyze the impact of coal mining on groundwater recharge using a water balance approach as a part of EIA. Water balances, before and during the mining operation, should be evaluated based on natural hydrological conditions in the land around open pit coal mine areas. Hydrologic data, such as precipitation (P) and temperature, combined with topographic data, were collected to calculate the evaporation-transpiration (ET) and run-off (Ro) values. Then, groundwater recharge (U) was determined by a water balance equation (U=P–ET-Ro). The estimation of runoff coefficient before and during mining operation were used to predict the value of runoff, controlling the estimation of recharge before and during mining operation by water balance equation. The results of this study showed that the groundwater recharge before mining operation was 659 mm. Meanwhile, during mining operation, the recharges were 321 mm/year at land clearing stage, 152 mm/year at open pit mining, 321 mm/year after backfilling stage, and 557 mm/year after re-vegetation stage. Decreasing the recharge value during mining operation would influence the total amount of groundwater in the aquifer storage around the mine area. Based on this study, it can be concluded that runoff coefficient determination before and during mining operations could be an alternative to assess the impact of open pit coal mines on groundwater quantity.

INTRODUCTION

Coal is recognized as the primary energy resource for electricity in Indonesia as about 80% of domestic coal is used for power generation. In addition, with specific low ash and low sulfur, Indonesian coal become a favorite in China and India as the dominant export target of the Indonesian coal industry. Around 80% of Non-Tax State Revenue of the Indonesian mining sub-sector comes from the coal industry. This factor is positive leading to constant global market demand for Indonesian coal despite the price being volatile, especially during Corona Virus Disease (COVID-19) pandemic. Indonesian coal reserves are 38.84 billion tons with average coal production of 600 million tons per year (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2021). As one of the largest coal producers and exporters in the world, coal mining companies are widespread in Indonesia. One area where many coal mines are located in Kalimantan Island, in which 62.1% of the Indonesian coal reserves (25.84 billion tons) and resources (88.31 billion tons) are located.

Mining, both with the open pit system (surface mining) and underground system, has been regarded as activities that impact the surrounding environment (Haq et al, 2016). Direct impact on groundwater, including a decrease in the quantity of groundwater, is the particular issue concerned in this study. Mining activities, such as land clearing and soil removal, are considered to reduce the recharge in the vicinity of mine area.

Naturally, water balance is closely related to the hydrologic cycle. According to Freeze & Cherry (1976), Schwartz & Zhang (2002), Todd & Mays (2005), the hydrologic cycle is a continuous process of water circulation on the Earth. Water evaporates from the ocean and land surfaces and becomes water vapor in the atmosphere. The water vapor condenses and precipitates as rainfall or snow on the land and ocean. On the land, some portion of precipitated water may be absorbed by vegetation, infiltrate into the ground and percolate to recharge groundwater. Some other portions of precipitated water may flow into streams as a run-off and then back to the ocean. Due to elevated temperatures, evapotranspiration will increase in the land area. Evapotranspiration is the term for both the direct return of surface water to the atmosphere by evaporation and its indirect return through the leaves of plants (Pipkin et al., 2005).

Thus, based on environmental regulations in Indonesia, each mining company is obliged to submit Environmental Impact Assessment (EIA) documents to the government, before operation. The purpose of this study is to estimate the impact of coal mining on groundwater recharge using a water balance approach as a part of the EIA. The study of groundwater is a complex process related to natural systems and processes involved. Therefore, natural hydrological conditions around open pit coal mine areas should be understood to determine the water balance in mine areas.

METHODOLOGY

Research Area

One of the coal mining concessions located in Barito Timur, Central Kalimantan was selected for this study. The company has a concession covering an area of 2,000 – 3,000 ha. The coal target is about 400,000 – 700,000 tons per month with the open pit system. Geologically, the mining site is located in the Warukin Formation, lithologically dominated by silt and clay material (see Fig. 1). According to Asminco (1996), Warukin Formation consists of three parts, namely upper Warukin, middle Warukin, and lower Warukin. Upper Warukin is dominated by a coal layer of 30 – 40 m in thickness and a clay layer. Middle Warukin is classified into upper sandstone and lower sandstone. Meanwhile, lower Warukin is relatively dominated by claystone.

Data Collection

Primary data were collected from field investigations, such as groundwater tables and river water level measurements. Water levels in dug wells and boreholes were measured to estimate the direction of the groundwater flow pattern. Primary data also include a detailed investigation of geological conditions in the study area. Secondary data were also collected from various information sources, such as a topographic map from the National Land Affairs Department of Indonesia, regional geological maps from the Research and Development Center of Geology in Bandung, meteorological data from the Department of Meteorological Climatological and Geophysics in Buntok collected between 2010 to 2019, and mining plan design from a mining company in the study area.

Estimation of Water Balance Before and During Mining Operation

Water balance in the natural condition was estimated based on hydrological conditions. Meanwhile, meteorological data, including rainfall and temperature, were interpreted to understand the hydrological conditions such as evapotranspiration, run-off, and recharge. Evapotranspiration was estimated from an empirical equation from Turc (1954, in Putra 2013)

$$ET_r = \frac{P}{\sqrt{0.9 + \frac{P^2}{\left(300 + 25 \cdot T_m + 0.05 \cdot T_m{}^3\right)^2}}} \tag{1}$$

Where,

ETr : Annual Evapo-transpiration (mm/year)

P : Annual Precipitation (mm/year)

Tm : Annual temperature (^{O}C)

Surface run off is part of the rainfall that flows over the land surface to rivers, lakes, and the sea. The flow occurs because the rainwater that reaches the ground surface is not infiltrated due to the intensity of the rain exceeding the infiltration capacity or other factors, such as the slope, the shape and compactness of the soil surface and vegetation. In addition, rainwater that has entered the ground then comes out again to the ground surface and flows to the lower part. Sharma method (in Putra, 2013) was used to obtain the run-off value. This method requires annual temperature (Tm), annual rainfall (P), and area of watershed (A).

$$Ro = \frac{1.511 x P^{1.44}}{T_m^{1.34} x A^{0.0613}} \tag{2}$$

Where,

Ro : Run-off (cm/year)

P : Precipitation (cm/year)

Tm : Annual temperature (^{O}C)

A : Area of watershed (km^2)

Recharge values were calculated by water balance concept, described by this equation:

$$U = P - ET - Ro \tag{3}$$

Where,

P : Annual Precipitation (mm/year)

Ro : Annual Run-off (mm/year)

ET : Annual Evapo-transpiration (mm/year)

U : Annual Recharge (mm/year)

Land clearing and natural landscape degradation due to mining operation were regarded to increase the run-off value. Increasing the run-off value would impact the decrease in the recharge value. Therefore, prediction of the recharge value during mine operation could be made by comparing run-off value on the natural condition and during mining operation. In this study, run-off coefficients from the Sivanappan classification (1992) were applied (Table 1). The runoff coefficient is the ratio between the peak velocity of runoff to the rainfall intensity which is influenced by the rate of soil infiltration, vegetation cover, and rainfall intensity.

Table 1. Run-off coefficients from Sivanappan Classification (1992)

Vegetation and Topography	Material		
	Sandy clay	Dusty silt and clay	Dusty Silt
1. Forest			
Flat (slope <5%)	0.1	0.30	0.40
Bumpy (5-10%)	0.25	0.35	0.50
Hilly-montainous (>25%)	0.30	0.50	0.60
2. Reed			
Flat (slope <5%)	0.1	0.30	0.40
Bumpy (5-10%)	0.16	0.36	0.55
Hilly-montainous (>25%)	0.22	0.42	0.60
3. Agriculture			
Flat (slope <5%)	0.30	0.50	0.60
Bumpy (5-10%)	0.40	0.60	0.70
Hilly-montainous (>25%)	0.52	0.72	0.82

RESULTS AND DISCUSSION

Hydrologic Setting of Study Area

Based on rainfall data obtained from the Meteorological and Geophysics Station of Buntok (2021), annual precipitation in 2010-2019 varies between 1,499 mm/year and 3,350 mm/year, with an average of 2,798 mm/year. The highest precipitation occurred in 2010 with an amount of 3,350 mm, while the lowest precipitation was in 2019 with an amount 1,499 mm/year (Tabel 2).

Table 2. Precipitation in study area period 2010 - 2019

Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
January	288.4	453	479.9	310.7	284.8	404.3	383.5	311.4	113.8	175
February	170.6	199.2	385.3	377.4	169.2	252.4	336.9	221.7	399	149
March	303.7	211.4	260.7	362.1	305.2	405.1	392.4	410.7	302.5	172
April	319.5	320.4	294.5	345.3	266.1	253.6	257.9	224.7	168.2	177
May	280.3	283.4	232.6	390.8	352.1	116.7	330.9	240.9	123.9	51
June	263.8	117	84.3	95.1	214.3	198.4	112.6	187.3	72.6	148

Continued from **Table 2.**

Month	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
July	290.5	132.2	179.8	341.9	129.8	66.8	342.7	133.1	111.6	48
August	134.9	106.8	114	81.9	229.1	13.9	112.9	209.6	44.7	128
September	243.8	79.8	155.6	184.5	63.9	-	186.1	84.8	107.7	20
October	409.6	171.8	157.8	202.9	57.3	-	386.7	128.3	244.8	66
November	334	316	292.2	247.8	315	433.6	585	294.4	492.9	106
December	310.2	423.1	281.7	340.9	363.7	204.2	319.1	337.8	310.3	259
Annual	3,349.3	2,814.1	2,918.4	3,281.3	2,750.5	2,349	3,746.7	2,784.7	2,492	1,499

Source: Meteorological Station Buntok, 2022

In addition, the average monthly temperature in the research area varied between 26.6 °C and 27.4 °C. The annual temperature is 27° C. By substituting precipitation and temperature values of Turc (Equation 1), the average annual evapotranspiration (ET) was 1,630 mm/year. According to annual temperature and annual precipitation, an area of 20 km^2, the run-off value was calculated by the Sharma method (Equation 2) at 50.7 cm/year (507 mm/year).

The rational method (US Soil Conservation Service, 1973) is also an approach to predict runoff through mathematical calculations through several assumptions to simplify the calculation, involving rainfall intensity and area of the watershed. Rainfall with intensity occurs continuously, then the direct runoff rate increases for some periods until when the watershed has contributed to the flow at the outlet. This method commonly obtains reasonable results and is considered accurate for estimating surface runoff in Indonesia. One of the substantial parameters of the rational method is the intensity of rain (mm/hour) in research area. It is characteristic of rain events that are expected to occur in the future. However, the analysis of rainfall intensity requires a series of detailed measurement data at rainfall stations over a certain period, for example, maximum rainfall in one day and duration of rainfall. Therefore, in some cases like this study, when the detailed rainfall data is not available, an alternative method (i.e., Sharma) was necessary. In addition, the runoff value of Sharma (507 mm/year) was acceptable because it is not higher than the precipitation in the research area. By substituting precipitation, run-off, and evapotranspiration values on water balance (Equation 3), the recharge value in the research area was 659 mm/year.

Impact of Coal Mining Activity on Groundwater Recharge

Most coal mining companies in Indonesia applied open-pit coal mining method, which includes in surface mining system. It is economically favorable when the coal seams are located near the surface (less than 200 m). The operations of open pit coal mine begin with land clearing to remove growing plants in the working area covering the mine area, disposal or dumping area, topsoil stockpile, mining road, settling pond, and other supporting facilities. The land clearing process is carried out using human power and/or heavy equipment. Wood plants with a diameter of more than 30 cm were cut using chainsaws, while the smaller plants were uprooted using bulldozers. The timbers are collected and stacked in a place that does not interfere with the further mining process and can be used for construction purposes.

After clearing the land, the main open pit activity is conducted by (i) stripping the overlying rock strata and (ii) excavating the coal seams. The former includes the removal of top soil and other material called overburden. Topsoil is material with high nutrients and is indispensable for restoring soil fertility. It is generally moved into some spaces for conservation as a planting medium during reclamation and post mining. Overburden is stripped by making slopes, in which the geometry of the slope is determined based on geotechnical analysis to estimate slope stability. Then after removing top soil and overburden, the exposed coal deposits are excavated and transported to the coal stockpile Raw of Material (ROM). Backfilling method is a mandatory practice within open-pit coal mines, though it is noticed as costly and time-consuming. This process consists of returning overburden material that was removed during excavation into the mined-out area (i.e., the area where coal reserves have been excavated).

The impact of mining activities on the quantity of groundwater could be in the form of a decrease in groundwater level to below the operational limits of the mining pit (Hamilton & Wilson, 1977; Libicki, 1982; Erbele & Razem, 1985; Morris et al, 2003). Coal mining activities may be located in the aquifer layer so that the decrease in groundwater level can be caused by the mining activity itself or the dewatering activities carried out (Morris et al, 2003). According to Libicki (1982), groundwater subsidence caused by mining activities is a function of several factors, among these factors are the depth of groundwater subsidence, geological structure, infiltration coefficient & specific yield, and time. The impact in the form of a decrease in the groundwater level can occur in residential areas around the mining area. This is because groundwater subsidence is not limited only by mining areas, but is limited by geological and hydrogeological conditions in an area (Haq, 2015).

The quantity of groundwater is influenced by the water supply from the surface infiltrating the subsurface. Open pit mine would lead to a disturbance on the natural land surface due to the removal of top soil and overburden, and excavation of coal. This directly increases the surface runoff, and subsequently, affects the hydrologic – budget in research area which was estimated based on the water balance equation stating that groundwater inflow minus outflow equals the change in storage. Therefore, a change in the value of recharge could be predicted by comparing the run-off value before and during mining operation.

Factors that affect runoff can be grouped into (i) factors related to climate such as rainfall, and (ii) factors related to watershed characteristics including topography, geology, and land use (e.g., vegetation type and density). Vegetation can slow the rate of runoff and increase the amount of infiltration water on the ground due to surface detention, while a high slope (>15%) could increase the velocity of runoff and decrease the infiltration (Fig 1). The increase and decrease in the rate and volume of runoff are related to changes in the value of the runoff coefficient (C) expressed with a value of 0 to 1, which is the ratio between the amount of runoff and rainfall. It is the comparison value between the input rate and the peak discharge rate.

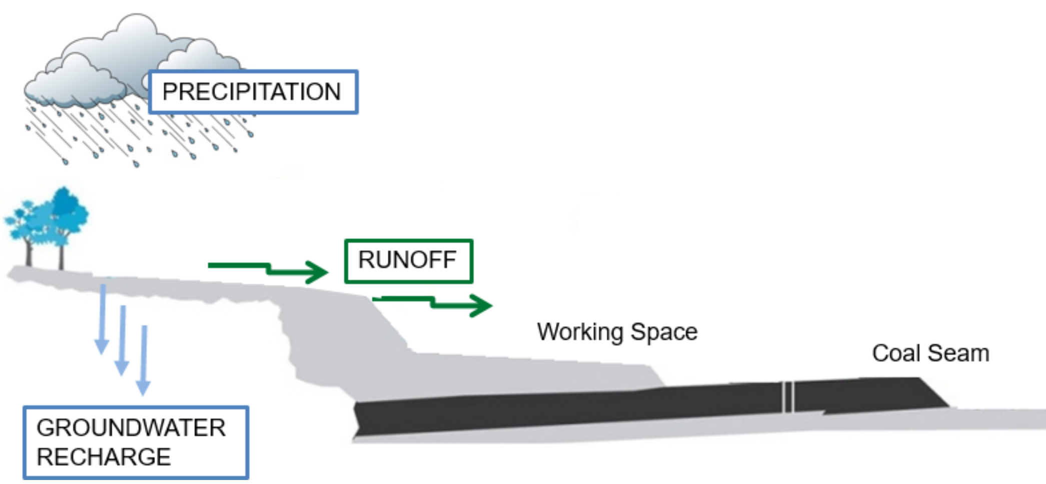

Figure 1. Hydrological setting during open pit coal mine. Land clearing and natural landscape degradation were regarded to increase the run-off. Increasing in the run-off would impact on decrease of the recharge

Although the runoff value in this study (507 mm/year) was estimated by the Sharma method which does not require run off coefficient for the calculation, change in the runoff coefficient before and during mining operation could be an alternative to predict the value of runoff before and during mining operation. For an instant, the natural condition of the research area is a flat forest with levels of slope <5%, and the dominant material are silt and clay. According to the classification of Sivanappan, (1992) (Table 1), the run-off coefficient before mining operation (i.e., natural condition) was 0.30. On the other hand, the condition during mining operation was a bumpy slope of 5-10%, and no forests and reeds. As a result, the run-off coefficient amounted to 0.60 or twice higher than the coefficient of natural run-off. The watershed characteristic and hydrological estimation before and during mining operation are resumed in Table 3.

Table 3. Hydrological setting before (natural condition) and during mining operation

Parameters	Natural Conditions	Mining Operation
Vegetation	Forest	No Forest
Morphology	Average slope <5%	Average slope of 5-10%
Land Soil/Material	Silt and clay	Silt and clay
Runoff Coefficient	0.3	0.6

The runoff coefficient in Table 3 indicates that the run-off value during operation was predicted to be 1014 mm/year. The runoff in each stage during mining operation involving land clearing, open pit mining, after backfilling, and after re-vegetation could be predicted by using same methodology as shown in Table 4. During land clearing and after backfilling, the research area is predicted to be flat with no forest with levels of slope 5 – 10 %, and the runoff coefficient and value were 0.5 and 844 mm/year, respectively. Then after re-vegetation, the research area is predicted to be flat with reed and levels of slope <5%, and the runoff coefficient and value were 0.36 and 608 mm/year, respectively.

Based on the water balance equation, the recharge values during land clearing, open pit mining, after backfilling, and after re-vegetation stages were 321, 152, 321, and 557 mm/year, respectively. During land clearing and after backfilling, the recharge value decrease to 57.4% compared to natural condition. The most significant impact was during open pit mining with the lowest recharge value, about 36% compared to natural conditions. Afterwards, the recharge would recover after re-vegetation stage to 87.2% compared to natural conditions. Groundwater recharge estimation in each stage during open pit coal mine operation is illustrated in Fig 2.

Table 4. Run-off estimation before and during mining operation

Mining Stages	Vegetation and Topography	Runoff coefficient*	Runoff (mm/year)
Natural condition (before mining)	Flat Forest (slope <5%)	0.3	506
Land clearing	Flat with no forest (slope 5-10%)	0.5	845
Open pit mining	Bumpy area with no forest (slope 5-10%)	0.6	1014
Open pit mining after backfilling	Flat area with no forest (slope <5%)	0.5	845
Open pit mining after revegetation	Flat area with reed (slope <5%)	0.36	608

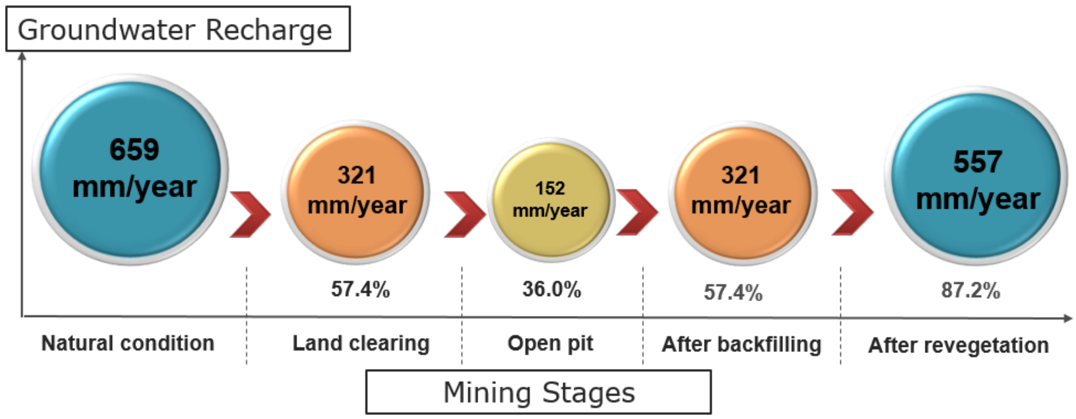

Figure 2. Groundwater recharge estimation in open pit coal mine operation

CONCLUSION

Estimation of the runoff coefficient before and during mining operation could be an alternative to predict the value of runoff before and during mining operation. Thus, the recharge value around the mine area could be estimated by the water budget concept. Land clearing and soil removal during mining operations would cause an increase in the run-off value, leading to a decrease in recharge value. The run-off value of 1,013 mm/year was predicted during open pit coal mine, twice higher than that of the natural condition (506 mm/year). The recharge value decreased from 659 mm/year before mining operation into152 mm/year during open pit mining. Therefore, the impact of coal mining activity may be significant. An understanding of natural hydrological systems is an important step in the groundwater modeling process. This is because a conceptual model of hydrogeology in coal mining areas can be developed to obtain accurate and under the actual situation in the field. This would result in an appropriate hydrogeological conceptual model, promoting the realistic prediction in the EIA document.

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