Mine Closure Strategy for Pit Lakes Formation in Indonesia: Initial Framework for Open Pit Coal Mine

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Abstract

The formation of pit lakes during coal mine closure poses complex environmental, hydrological, geological, and socio-economic challenges that require integrated and proactive planning. This study develops a strategic framework for pit lake formation in Indonesia by combining hydrological modelling, geochemical assessment, and regulatory analysis. A key focus is the use of nearby river water for controlled pit filling to mitigate acid mine drainage (AMD) and enhance long-term landscape sustainability. The framework is applied to Pit D2 in the Binungan River watershed, evaluating two scenarios: precipitation-only and river-supplemented filling. Hydrological modelling using HEC-RAS identifies an optimal diversion channel elevation of +4 masl to manage flood risks. Water quality modelling with PHREEQC demonstrates that river supplementation significantly improves water chemistry, reducing Fe concentrations from 211.57 to 0.94 mg/L, sulfate from 459.46 to 28.83 mg/L, and increasing pH from 5.64 to 6.07—approaching regulatory standards. Beyond improving water quality, the study highlights the potential of pit lakes as flood retention systems in high-rainfall areas such as Kalimantan. Given limited regulatory guidance on river use for pit lake filling, this research underscores the importance of considering such approaches within mine closure planning. Future efforts should further integrate pit lake development into early-stage mine design to support sustainable, multi-functional post-mining land use.

Keywords: Pit-lake, mine closure, coal mine, flood retention

Introduction

Open-pit coal mining in Indonesia commonly results in residual mine voids due to high overburden-to-coal stripping ratios. According to the Ministry of Energy and Mineral Resources (ESDM, 2020), there were 1,164 coal mining permit areas (WIUP) nationwide, many of which are expected to convert mine voids into pit lakes as part of mine closure. However, Indonesia's coal is geochemically prone to generating acid mine drainage (AMD), primarily due to the exposure of potentially acid-forming (PAF) material and its imbalance with non-acid-forming (NAF) material during mining operations.

To guide pit lake development, the government has established regulatory frameworks such as ESDM Regulation No. 7 of 2014, mandating reclamation, water quality monitoring, and mine void water management, and Government Regulation No. 22 of 2021, which sets water quality standards based on intended water use. The formation of pit lakes requires integrated planning of both water quantity and quality. While precipitation, runoff, and groundwater recharge are typical filling sources, these are often insufficient and slow, especially for large voids. Additionally, PAF exposure on pit walls can worsen water quality over time. Thus, engineered solutions such as controlled catchments and surface water supplementation must be considered.

This study evaluates the feasibility of using nearby rivers to fill a coal mine void in Berau Regency, primarily to prevent the formation of acidic pit lakes caused by the exposure of PAF materials. River water supplementation is explored as a geochemical mitigation strategy to reduce AMD risk while also supporting more sustainable post-mining land use.

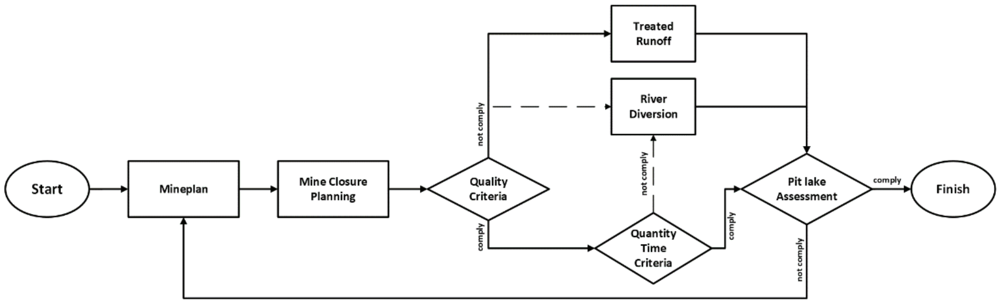

Figure 1 Flowchart Pit Lake Formation Decision Making Tree.

Methods

The methodology used in this study is based on the implementation of a decision-making tree strategy for pit lake formation, as illustrated in Fig. 1.

1. The primary output of mine planning and operations is an open residual void, which is typically documented in the mine closure plan. This plan includes dimensions and the proposed utilization of the remaining pit.
2. The conversion of the residual void into a pit lake requires consideration of several critical factors, particularly the water quality that will develop. The selection of an appropriate filling method is based on water quality modelling, assuming precipitation and surface runoff as the default inflow conditions.
3. If the modelled water quality of the pit lake does not comply with environmental standards as regulated by Government Regulation No. 22 of 2021, alternative runoff management strategies must be considered. These may include enhancing alkalinity to neutralize pit wall leachate or utilizing nearby water bodies with suitable quality.
4. Additionally, the timeframe for pit lake filling, which is generally proportional to the pit dimensions, must be considered. The use of nearby water bodies can be considered as an option to accelerate the filling process.
5. Once the pit lake filling model has been developed, a final evaluation against pit lake criteria must be conducted. If the established criteria are not met, the mine planning process must be reassessed iteratively to ensure the feasibility of pit lake formation.

Study Area

The Binungan Coal Mine site, which has been in production since 1996, is located in Pegat Bukur Village, Sambaliung District. This study focuses on Binungan Mine Operation - 01, specifically Pit D2, which is projected for conversion into a pit lake. Pit D2 commenced operations in 2012 and was ceased production by September 2022. It serves as the study location for implementing the pit lake formation strategy framework outlined previously. Pit D2 covers a surface area of 122.1 hectares, with a depth of 90 meters and an approximate volume of 41 million cubic meters. The pit is situated between two rivers—Kelai River and the downstream section of Binungan River—both of which are part of the Kalimantan V River Basin (Berau-Kelai). The location and longitudinal profile of Pit D2 are illustrated in Fig. 2.

According to data from the Berau-Kelai River Basin Authority, the Kelai River does not meet the Class 2 raw water quality standard based on East Kalimantan Regional Regulation No. 02 of 2011 (PUPR, 2019), primarily due to land-use pressures from settlements, agriculture, plantations, and mining in the upstream catchment. Interestingly, the elevated sulfate levels in the Kelai River could potentially stimulate sulfate-reducing bacteria (SRB) activity, which may help mitigate acidification within pit lakes. However, due to concerns over other contaminants, variable flow conditions,

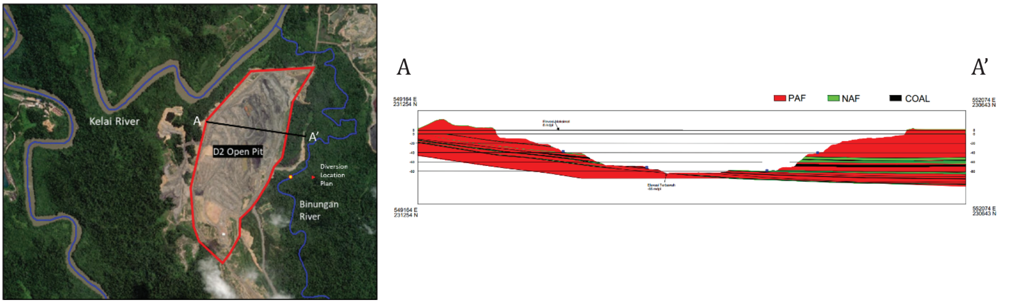

Figure 2 Location of Pit D2 Relative to Surrounding Water Bodies and PAF-NAF Distribution.

and long-term ecological risks, the Binungan River was selected as a more stable and environmentally suitable water source for controlled pit lake filling.

Data

The data used in this study include the geochemical model of Pit D2, the leachate conditions of PAF and NAF rocks in Pit D2, the catchment area conditions of the Binungan Watershed (DAS Binungan), and the current state of the Binungan River.

Geochemical Model and Leachate Water Quality of Pit D2

The PAF and NAF rock mapping for Pit D2, previously conducted by the company, has been validated using rock samples to develop a geochemical model. The geochemical modelling and leachate water quality assessment were conducted using kinetic testing on four rock samples through the Free Draining Column Leach Test (FDCLT) using AMIRA standards. These results serve as the basis for predicting the water quality of the future pit lake.

The leachate water quality data were obtained from four rock samples, which were analyzed using the FDCLT kinetic test method. These results form the basis for modelling the water quality of the post-mining lake and are presented in Table 1.

Binungan Watershed Conditions

The Binungan Watershed covers an area of 136 km^2, predominantly consisting of secondary dryland forest with a slope range of 0-5%. Within this watershed, the Binungan River extends approximately 35 km in length. The river has a slope gradient of approximately 0.04%, with a riverbed elevation of +2.5

Table 1 Leachate Water Quality Results of Pit D2 Rock Samples Using FDCLT.

No	Parameter	Unit	PAF-A	NAF-B	NAF-C	PAF-D
1	Aluminium	mg/L	27.87	2.84	1.27	15.79
2	Iron	mg/L	771.15	<0.1	1.57	308.31
3	Manganese	mg/L	7.85	<0.1	<0.1	1.03
4	Calcium	mg/L	13.64	182.93	57.35	7.87
5	Magnesium	mg/L	13.12	362.67	96.36	6.27
6	Natrium	mg/L	5.94	<0.01	3.22	1.13
7	Potassium	mg/L	1.70	<0.01	5.22	10.13
8	Sulfate	mg/L	684.32	7,428.22	1,409.64	1,730.59
9	Alkalinity as $CaCO_3$	mg/L	-	516.00	117.00	-
10	Chlorine	mg/L	2.35	<0.01	2.44	2.29
11	pH		5.65	8.20	8.06	2.87

Table 2 Binungan Rainfall and River Water Quality.

No	Parameter	Unit	Rainfall	Binungan River	No	Parameter	Unit	Rainfall	Binungan River
1	Aluminium	mg/L	0.001	3	7	Potassium	mg/L	0.2	0.98
2	Iron	mg/L	0.01	0.001	8	Sulfate	mg/L	2.1	2.32
3	Manganese	mg/L	0.01	0.04	9	Alkalinity as $CaCO_3$	mg/L	6.7	26.7
4	Calcium	mg/L	1.2	12.5					
5	Magnesium	mg/L	1.3	11	10	Chlorine	mg/L	0.1	41.8
6	Natrium	mg/L	0.6	3.67	11	pH		5.8	7.01

masl at the planned diversion point. The river's maximum width reaches 48 meters, while its baseflow discharge is approximately 10 m^3/ second, resulting in a water column height of about 1.5 meters. Binungan river and rainfall water quality that will be used for pit lake filling model are presented in Table 2.

Pit Lake Filling Model

The filling model was developed based on the geochemical classification, as outlined in Table 1, and follows the decision-making framework presented in Fig. 1. Based on these considerations, the pit lake filling scenarios are divided into two approaches: filling through precipitation and filling through a combination of precipitation and river diversion. The Binungan River's baseflow discharge of 10 m^3/second provides sufficient flow capacity to support controlled filling without significantly altering regional hydrology. However, recognizing that watersheds support diverse life forms and that population growth and land-use changes may increase future reliance on this ecosystem, post-mining lake development must prioritize long-term ecological sustainability, ensuring minimal impacts on aquatic habitats and surrounding biodiversity.

The water quality modelling expected to develop in Pit D2 as a post-mining lake based on geochemical characteristics follows the process illustrated in Fig. 3 and Fig. 4.

A hydrograph analysis of the Binungan River was conducted using HEC-RAS software, utilizing the SCS hydrograph method to determine the optimal elevation for the diversion channel. This was done to effectively capture flood discharge and volume flow passing through the Binungan River segment near Pit D2 (A-A'), as shown in Fig. 5. Using a 10-year return period rainfall, the maximum water level in the Binungan River was determined to be +6 masl. Additionally, baseflow data at the diversion cross-section indicated a water surface elevation of +3.5 masl. Based on this information, the optimal diversion channel level for the Binungan River was determined to be +4 masl.

Result and Discussion

Following the two previously designed scenarios as mentioned in methodology section, the water quality modelling for Pit D2 was carried out using PHREEQC software through Inverse Modelling, Forward Modelling, and Mixing Simulations. The results of the modelling are presented in Table 3.

Discussion

Several key water quality parameters of the proposed pit lake, as presented in the Table 3, meet the applicable environmental standards. However, dissolved iron (Fe) concentrations exceed the regulatory limits. Previous studies have demonstrated that this issue can be mitigated through various treatment approaches (Berg et al., 2019; Fan et al., 2018). Additionally, Government Regulation No. 22 of 2021 outlines specific chemical and biological parameters that must be met, some of which are beyond the scope of this study.

Based on the decision-making framework for pit lake filling (Fig. 1), the utilization of river water as a supplementary filling method can be considered, particularly in cases where geochemical constraints in the

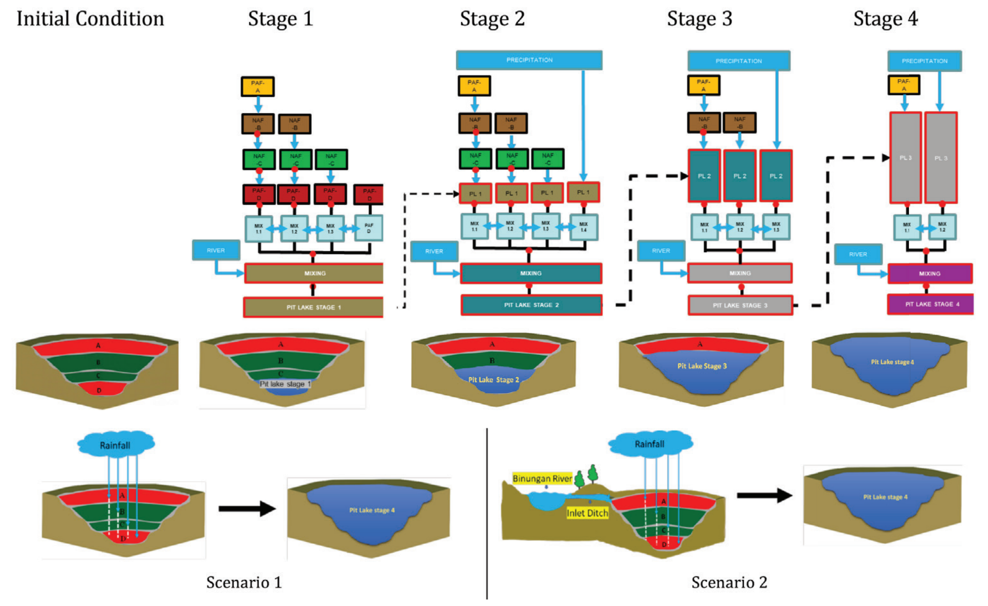

Figure 3 Pit Lake Filling Scenario.

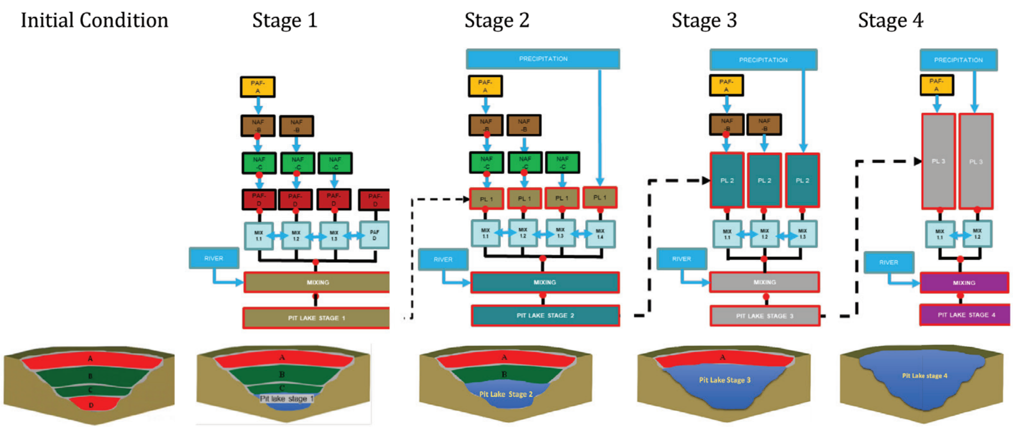

Figure 4 Pit Lake Water Quality Formation Model.

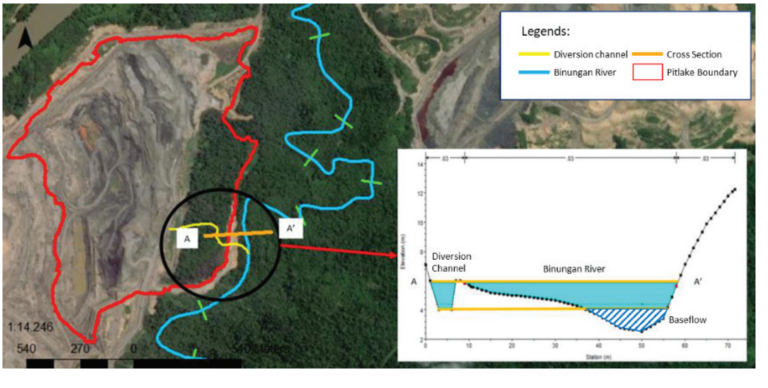

Figure 5 Diversion Channel Location from Binungan River to D2 Pit Lake.

Table 3 D2 Pit Lake Water Quality Model.

Parameter		Pit Lake Water Quality: Scenario 1 Precipitation Only	Pit Lake Water Quality: Scenario 2 (Precipitation + River Diversion)	Water Quality Standards*: Class 1	Class 2	Class 3	Class 4
pH		5.64	6.07	6-9	6-9	6-9	6-9
Sulfate	mg/L	459.46	28.83	300	300	300	400
Iron	mg/L	211.57	0.94	0.3	-	-	-
Manganese	mg/L	3.51	0.14	0.4	0.4	0.5	1

*The water quality classification according to Government Regulation No. 22 of 2021 is as follows:

- Class 1: Water suitable for drinking water sources and other uses requiring similar water quality.
- Class 2: Water suitable for water-based recreation facilities, freshwater aquaculture, livestock, irrigation, and other uses requiring similar quality.
- Class 3: Water suitable for freshwater aquaculture, livestock, irrigation, and other uses requiring similar quality.
- Class 4: Water suitable for irrigation and other uses requiring similar quality.

pit limit natural water quality improvement. This approach not only ensures that the resulting pit lake meets environmental carrying capacity standards as required by Government Regulation No. 22 of 2021 but also enhances the potential function of the lake as a flood retention system.

Currently, Indonesian regulations permit river diversions under specific conditions. Regulation of the Minister of Public Works and Public Housing Number 4 of 2024 on River Diversion stipulates that any modification to river flow must include a hydrological and hydraulic assessment, considering factors such as design flood discharge, flow profiles (including depth, velocity, and pattern), erosion, and sedimentation dynamics. Given these regulatory frameworks, the use of river water for pit lake filling, as outlined in the proposed strategy, presents a viable and potentially sustainable solution for post-mining land use.

Conclusions

Based on the analysis conducted, the utilization of rivers as an alternative for pit lake filling is feasible. This decision should be grounded on the pit lake model, particularly if precipitation-based filling alone results in water quality below environmental standards for pit lakes. Additionally, the use of pit lakes for flood retention should be considered. Currently, Indonesian regulations do not explicitly govern this aspect, leading to limited recognition by coal mining companies and the government. Given Indonesia's high rainfall, the prevalence of PAF rock formations, and the massive dimensions of former mining pits, the potential for pit lakes as flood retention systems remains largely untapped.

However, several key considerations must be addressed, including regional watershed water balance, accurate geochemical modelling, social and environmental impacts assessment of river diversion, both in terms of flood discharge and full river redirection, and criteria for pit lake feasibility, including dimensions, water quality, and filling duration.

Future research should focus on integrating pit lake formation models into mine planning as an iterative approach to minimize long-term management requirements. Additionally, studies should examine the long-term hydrological, hydrogeological, and ecological impacts of river utilization for pit lake filling and pit lake function as flood retention systems.

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