

Designing the Post-Mining Future: Hydrological Modeling as a Foundation for Sustainable Pit Lake Management

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Abstract

Sustainable post-mining management is essential to mitigate environmental impacts and ensure that disturbed landscapes transition into safe and productive land uses. Coal extraction often leaves deep mining voids that evolve into pit lakes, requiring careful hydrological assessment. This study applies a water-balance model to predict water-level dynamics and filling scenarios for ex-mining voids at a coal mine in East Kalimantan, Indonesia. Results show that filling a 290 m deep pit lake through direct precipitation takes 37.5 years, but river diversion could reduce it to 10.3 years. The study highlights the importance of hydrological modelling in supporting sustainable post-mining land-use planning.

Keywords: Post-mining, hydrology, water balance model, pit lake, sustainability

Introduction

Post-mining landscapes, particularly pit lakes, have been widely studied due to their long-term environmental and hydrological implications. Pit lakes are commonly formed in deep mining voids and function as terminal water bodies within modified catchment systems, where hydrological inputs largely determine water balance, stratification, and water quality evolution (Castendyk & Webster-Brown, 2007; McCullough & Lund, 2006). Their sustainability depends on the interaction between catchment processes, groundwater exchange, and climatic conditions, making hydrological assessment a critical component of post-mining management. Moreover, in this case, technical sustainability also could be done by hydrological engineering design related to river diversions during pit lakes' filling period until a stable post-mining landscape is achieved.

Previous studies emphasize that water balance modeling is essential for predicting pit lake filling rates and long-term stability. Conceptual rainfall-runoff models have been

widely applied in data-limited regions due to their ability to estimate streamflow using limited input data (Smakhtin, 2001). In tropical environments, where hydrological data are often scarce, such models provide a practical approach to simulate inflow conditions and evaluate management scenarios. Additionally, environmental flow frameworks highlight the importance of maintaining downstream ecological integrity when implementing water diversion strategies (Bunn & Arthington, 2002; Richter *et al.*, 1996).

International experiences further demonstrate the potential for integrated pit lake management. In Germany, large-scale post-mining lake systems have been successfully developed through controlled flooding strategies, improving water quality while enabling socio-economic utilization such as tourism and regional water management (Schultze *et al.*, 2010). Similar approaches have been explored in Australia, where pit lakes are increasingly recognized as potential assets rather than liabilities (McCullough & Lund, 2006).

Despite these advancements, limited studies explicitly integrate hydrological modeling with decision-making for pit lake filling strategies under data-constrained conditions, particularly in tropical regions such as Indonesia. This gap highlights the need for applied modeling approaches that link hydrological prediction with sustainable post-mining land-use planning.

The post-mining plans are designed to be constructed primarily once the pit lake has filled to capacity to ensure the physical and chemical stability of the pit lake is maintained. The chemical stability is supported by minimizing contact between factors that trigger AMD: water isolation that limits contact between oxygen and material containing sulfide mineral (Gautama et al., 2013). These plans also incorporate environmental, hydrological, geochemical, socio-economic, and regulatory dimensions within a unified planning framework. Decree of Ministry of Energy and Mineral Resources No. 1827 of 2018 on Guidelines for the Implementation of Good Mining Practices and No. 344 of 2025 on Technical Guidelines for the Implementation of Land Reclamation and Post-Mining Activities in Mineral and Coal Mining Operations require every mining industry in Indonesia to develop comprehensive reclamation and post-mining plans which emphasizes the importance of incorporating socially and economically sustainable programs to support long-term community development. In this study, a few land-use recommendations were

developed to become mine closure success criteria, allowing the mining company to be responsible to the government and the community. The recommendations applied SMART (Specific, Measurable, Achievable, Relevant, and Time-bound) principle to create the master plan. This master plan will be discussed in a Focus Group Discussion (FGD) with local stakeholders.

Methods

The hydrological water-balance model used in this study was an Excel-based modelling, conducted by calculating the balance between inputs and outputs from a pit lake. From the hydrological model, pit lake filling duration and pit lake final volume was generated and was used as a basis of analysis in determining water infrastructure requirements and post-mining land-use planning. Water recovery in a pit lake should have a greater inputs than outputs to ensure a surplus and the pit lake will be filled eventually. A water quality model was also developed using PHREEQC to analyse annual pit lake water quality until the end of the filling period, which includes the geochemical impact of the exposed mining seam. The model was supported by exposed lithological data combined with rainwater and groundwater quality, generating stratified water quality in the pit lake.

Two scenarios were conducted as an alternative for pit lake filling method. The first scenario relied on direct precipitation only. Rainfall data series of 16 years were collected from a local ground station. Around

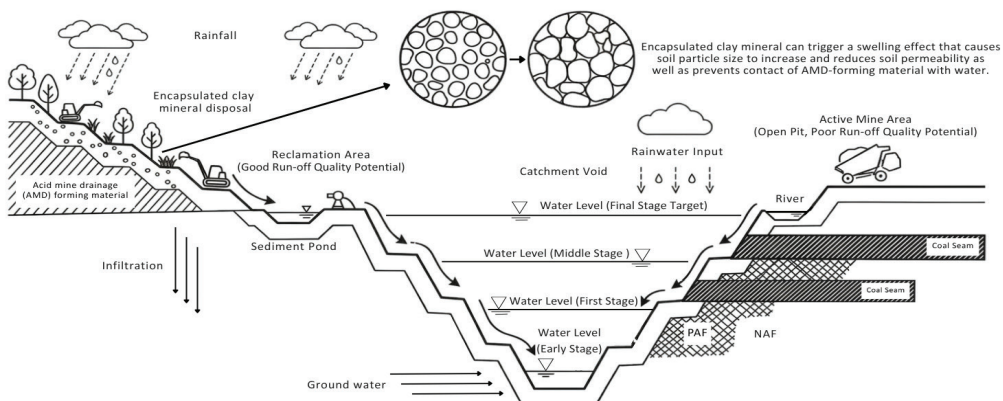


Figure 1 Pit lake modelling concept illustration.



East Kalimantan, Indonesia, the climate type based on Schmidt-Ferguson classification was considered as type A, which is a tropical rainforest area with a really wet character with annual rainfall around 1.935 to 3.733 mm/year. The second scenario of pit lake filling method included river diversion as an additional inflow that allows faster pit lake filling duration which is favorable by the company since backfilling is impractical to reclaim a large void and complete backfilling is not feasible because coal mining creates a material deficit. Evapotranspiration rate using Penman method was also accounted as an output for the water-balance model. The climatology data from Sultan Aji Muhammad Sulaiman Sepinggan International Airport meteorological station was used, resulting in a monthly evapotranspiration rate ranged between 4.49 to 6.79 mm/day.

Results and Discussion

This study focuses on one of two mining blocks at a coal mine company in East Kalimantan, Indonesia, and mainly on one examined void. The assessed void was the biggest

one, reaching the depth of 292 m, with a partial backfilling conducted on the northern side of the void. There was a nearby river that had the potential to be an additional input in filling the void, allowing the increase in water inflow that could shorten the pit lake filling period. This strategy could be considered as controlled flooding management, as applied in other international mining practices.

Based on hydrological analysis using the NRECA method in Figure 2, monthly runoff discharge and reliable river discharge (Q_{80}) were estimated to represent dependable water availability throughout the year using the same rainfall data from a nearby airport. The Q_{80} discharge was selected as it reflects flow conditions that can be maintained with 80% reliability and is widely used in water resource planning to ensure supply sustainability without compromising environmental requirements (McMahon & Adeloye, 2005; Smakhtin, 2001). To maintain the hydrological balance, only 30% of the river discharge was allocated for pit lake filling, while the remaining flow was preserved within the natural river. This approach aligns

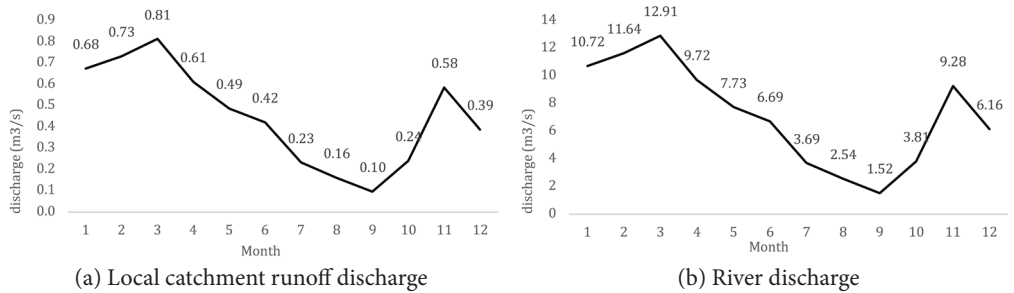


Figure 2 Comparison of Flow Discharge Calculations Using NRECA Method.

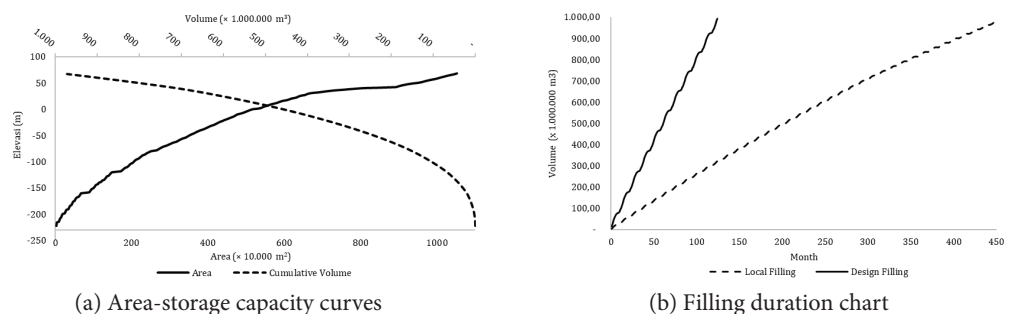


Figure 3 Area-storage capacity curves and Filling duration chart.



with environmental flow principles, which emphasize the need to maintain sufficient natural flow to sustain aquatic ecosystems and downstream water users (Acreman & Dunbar, 2004; Poff *et al.*, 2009).

The void has a surface area of 10.56 km², with a base elevation of -222 m and a crest elevation of 68 m, resulting in a total storage capacity of approximately 982,602,164 m³. Based on modelling results, two filling scenarios were evaluated. Under the first scenario, relying solely on local catchment runoff, the pit lake would require approximately 450 months (37.5 years) to reach full capacity. In contrast, the second scenario, the local catchment inflow was supplemented by water diversion from the nearby river, significantly reduces the filling duration to approximately 124 months (10.3 years). The storage capacity curve of the void can be seen in Figure 2a and the filling curves for each scenario are presented in Figure 2b.

In Indonesia, mining companies are required to hold a specific legal document known as a mining business permit, which includes mining exploration business permits and mining production operation business permits. The maximum duration for both types of permits is stipulated in Government Regulation of the Republic of Indonesia No. 96 of 2021, which is also determined based on a feasibility study previously approved by the minister. For a coal mining company, mining exploration business permits is limited up to 7 years and mining production operation business permits is limited up to 20 years. On the other hand, mining

companies are also required to prepare a post-mining plan document. This document must be approved by the national authorities, such as the Ministry of Energy and Mineral Resources, and companies must already have it approved no later than 2 years before the end of the mining operation period. In this document, the maximum duration of the post-mining period is not explicitly specified but is aligned with the company's post-mining plan. However, this duration is tied to the company's responsibilities. The sooner the post-mining period ends—provided the success criteria have been met—the company's responsibilities regarding that area are considered fulfilled. The Ministry of Energy and Mineral Resources will verify whether the reclamation has been completed. Once the reclamation is confirmed to meet the required criteria, the reclamation guarantee will be paid back.

Hydrological engineering, as the primary aspect analyzed in this study, also plays a role in the development of the company's strategy for complying with regulations regarding these post-mining obligations. Based on the hydrological analysis described above regarding the reduced duration of void filling, the post-mining period for which the company is responsible will automatically be shortened as well. This provides benefits such as reduced daily operational costs, reduced potential AMD generation through limiting the presence of oxygen to an exposed sulfide material (Younger, 2002), and also accelerates the utilization of water bodies for the local community.

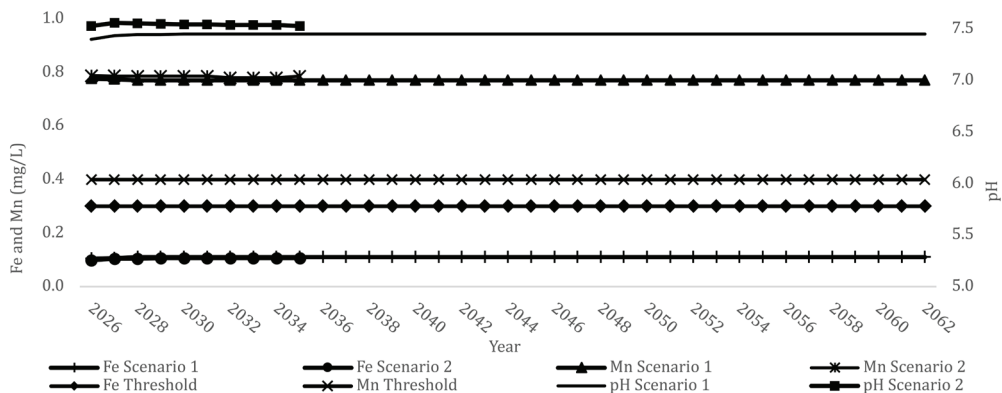


Figure 4 Water quality prediction for scenario 1 and 2.



The results of the pit lake water quality model generated from PHREEQC are shown in Figure 3, showing the model for two scenarios on pH, iron (Fe), and manganese (Mn) concentration. These parameters were selected according to Minister of Environment Decree No. 113 of 2003 concerning Wastewater Quality Standards for Coal Mining Businesses and/or Activities. Meanwhile each of the thresholds were selected according to Republic of Indonesia Government Regulation Number 22 of 2021 concerning lake water quality standards for Class I water quality standard, which can be utilized as raw water for drinking water, and/or other uses. The threshold for pH is 6 – 9, Fe concentration is 0.3 mg/L, and Mn concentration is 0.4 mg/L. Based on the model, pH and Fe concentration during the filling period complied within the threshold, meanwhile Mn concentration remained above the quality standard, averaged in 0.77 mg/L. Therefore, water treatment is needed to make sure the pit lake could be utilized properly in the future.

Beyond hydrological recovery and water quality model, the study evaluates potential post-mining land uses, including industrial zones, agroforestry, renewable energy development, and urban expansion. These opportunities highlight the need to integrate hydrological modeling with long-term spatial, social, and economic planning. Although deep mining voids present serious technical and environmental challenges, they

also offer opportunities to reimagine post-mining landscapes as multifunctional assets that contribute to a regional development that is environmentally and economically sustainable.

The allocation of water during the void/pit lake filling process is closely linked to the dynamic evolution of land use, which develops progressively in line with increasing water volume and water level, as illustrated in Figure 4. In the early stage, when water volume and elevation remain relatively low and unstable, water utilization is primarily focused on basic functions that support land conservation and ecosystem recovery, such as vegetation irrigation (agroforestry) and dust control. This approach aligns with the principle that the initial post-mining phase should prioritize biophysical stabilization and the control of environmental degradation (McCullough & Lund, 2006). As the system progresses into the first stage, with increasing water volume and the emergence of initial hydrological input, water allocation is gradually expanded to support biodiversity enhancement and the early development of land-based tourism, providing ecological water usage and begins to accommodate socio-economic needs, albeit at a limited scale. In the middle stage, as storage capacity and water levels increase significantly and become more stable, water utilization evolves toward productive, water-based activities such as freshwater aquaculture, as well as environmental education and food security

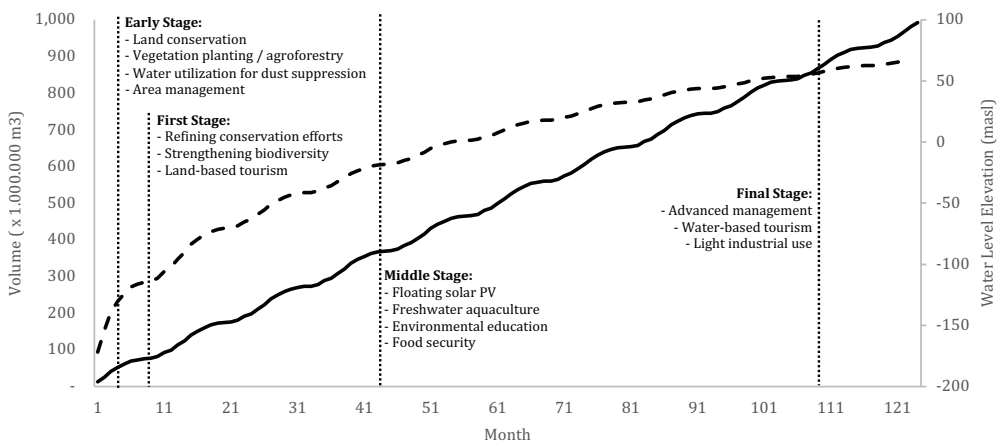


Figure 5 Land-use recommendations based on water level, volume, and filling duration design.



functions. This stage represents a transition from rehabilitative functions to sustainable productive uses, where the water body begins to serve as an economic resource without neglecting ecological considerations (Schultze *et al.*, 2010).

Finally, in the final stage, when long-term hydrological stability is achieved and water levels approach their maximum elevation, water allocation is optimized for higher-value activities such as floating solar photovoltaic (PV) systems and water-based tourism and light industrial use. At this stage, the integration of environmental, economic, and social functions becomes more pronounced, reflecting a multifunctional landscape approach in post-mining pit lake management (McCullough *et al.*, 2009). Through this staged framework, pit lake utilization can be progressively optimized from the initial filling phase to full capacity, ensuring sustained and evolving benefits ranging from fundamental ecological functions to more complex socio-economic applications.

Conclusion

This study demonstrates that the integration of hydrological analysis, water quality modeling, and post-mining land-use planning is an effective approach for optimizing the management of voids into sustainable pit lakes. Analysis results using the NRECA method indicate that utilizing 30% of the river's 80th percentile flow (Q_{80}) can significantly reduce the void filling duration from 37.5 years to 10.3 years without disrupting the downstream ecosystem balance. Moreover, water quality modeling shows that pH and Fe parameters met the national quality standards, while Mn concentrations still require further treatment. This hydrological approach is also expected to showcase a need in either passive or active treatment of pit lake water.

This hydrological engineering strategies also helped the company for complying with regulations regarding post-mining obligations. Through this approach, the responsibility of the company to realize the post-mining phase will be shortened in time, also providing benefits such as reduced operational costs and achieving stable, safe,

and self-sustaining mine conditions more quickly. Furthermore, a phased approach to water allocation enables the progressive optimization of pit lake functions, ranging from ecological conservation to more complex economic and social uses. This study initiates the idea that post-mining voids have the potential to be developed into multifunctional landscapes that not only support environmental restoration, but also provide sustainable benefits for regional development. This study confirms that pit lake filling duration can be accelerated when additional input, such as river diversion, is used.

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