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Research Paper

Study on the Mine Drainage System of The Pit Nusa in Lhoknga, Aceh Besar, Aceh

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Abstract

Mine drainage management is a crucial aspect of mining operations, ensuring safety, efficiency, and sustainability. Poor water control may lead to operational disturbances, slope instability, and long-term environmental risks. Although studies on mine drainage exist, research focusing on integrated hydrological and hydrogeological analysis for both operational and post-mining conditions in the Lhoknga mining area, Aceh, remains limited. This study aims to design an effective mine drainage system that supports mining safety and minimizes environmental impacts. The research employed a combination of primary and secondary data, including rainfall records, groundwater measurements, hydraulic conductivity tests, infiltration rates, and topographic data. Hydrological analysis was conducted to calculate design rainfall, rainfall intensity, and runoff using the Gumbel distribution, Mononobe equation, and Rational method. Hydrogeological modeling applied Darcy's Law, utilizing finite-difference numerical simulation, to evaluate groundwater flow and pit inflow. Water balance components were also analyzed, encompassing rainfall, evapotranspiration (using the Thornthwaite method), infiltration, runoff, and groundwater contribution. The results established a 30-year return period design rainfall of 57.5 mm/day, yielding an intensity of 7.91 mm/hour. The water balance analysis revealed that surface runoff is the dominant component, accounting for 70.33% of total precipitation. The hydrogeological model (R2=0.8) accurately predicted the formation of a cone of depression post-mining, with an estimated groundwater table drawdown of 5-15 meters. The primary contribution is a detailed technical drainage plan specifying designs for open channels and sumps for the mine drainage system. The plan necessitates a combination of open-channel drainage and a pumping system for the Northern Pit, while the Southern Pit can initially rely on gravity drainage.

Keywords *hydrology, hydrogeology, mining, mine drainage system, water resources management*

INTRODUCTION

The research area in Lhoknga District, Aceh Besar Regency, is approximately 15 km from Banda Aceh City, with good accessibility via land routes (Figure 1). Morphologically, it consists of rolling hills and gentle plains within the Barisan Range physiographic zone, with a topography that trends downward from northeast to southwest. As the site is planned for mining and post-mining activities, Minister of Energy and Mineral Resources Decree No. 1827 K/30/MEM/2018 (Ministry of Energy and Mineral Resources, 2018) guides the implementation of Good Mining Practices, where hydrological and hydrogeological aspects are crucial for designing technical drainage systems to protect environmental resources, ensure safety, and mitigate hazards (Islamiaty et al., 2021; Syarifuddin et al., 2017). Effective water management is essential to prevent operational disruptions, equipment corrosion, and safety risks (Khusairi, 2015; Sepniko et al., 2018), and to minimize impacts on regional river flows and groundwater resources used by local communities (Gautama, 2019). There is a growing concern to minimize long-term environmental impacts on regional water resources, a challenge posed by increasing climate variability (Bonacci, 2019; Lopes et al., 2022). Global precedents underscore that failures in mine drainage design can lead to severe

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environmental contamination and safety disasters, highlighting that a proactive, site-specific, and forward-looking approach is a fundamental necessity (Younger et al., 2002; Wolkersdorfer, 2008; Bainton et al., 2021). The critical importance of this study is underscored by global precedents, where failures in mine drainage design have led to severe environmental contamination and safety disasters, highlighting that a proactive and site-specific approach is not just a regulatory requirement but a fundamental necessity for sustainable and safe operations. This study aims to develop an effective technical drainage plan for both mining and post-mining water management through a hydrological and hydrogeological analysis approach.

Figure 1. Research Area Location and Land Route Access From Kota Banda Aceh (Basemap: Google maps, 2025).

LITERATURE REVIEW

The design of a mine drainage system requires a comprehensive hydrological analysis and a firm understanding of subsurface water flow principles (Asdak, 2004; Syarifuddin et al., 2017; Yusran et al., 2015). The process begins with rainfall as the primary water source, where a design rainfall for a specific return period is determined using methods like the Gumbel distribution to estimate extreme events. This design rainfall is used to calculate time-variable rainfall intensity, often with the Mononobe formula, where the selection of the return period is critical for assessing hydrological risk over the mine's lifetime (Syarifuddin et al., 2017). The resulting surface runoff is then quantified using the Rational Method, which incorporates rainfall intensity, catchment area, and a runoff coefficient influenced by land cover and slope (Todd & Mays, 2005).

A significant component of water inflow is groundwater, governed by Darcy's Law (Fetter & Kreamer, 2022), which states that flow is proportional to the hydraulic gradient and the hydraulic conductivity of the geological material. A practical analysis is achieved through a water balance calculation that accounts for all incoming and outgoing components. This includes precipitation (P), partitioned into evapotranspiration (estimated by the Thornthwaite (1948) formula), infiltration, and surface runoff (Bear, 1979; Younger et al., 2002; Asdak, 2004), with groundwater inflow estimated using a steady-state application of Darcy's equation (Davis, 1984). For an open pit mine like Pit Nusa, the technical implementation to control these water inflows—from rain, runoff, and seepage typically involves an integrated system of open channels, sumps, dewatering pumps, and settling ponds to ensure operational safety and efficiency (Prabowo et al., 2023; Rosada et al., 2024). Ultimately, the entire planning process synthesizes long-term rainfall data, calculated surface runoff, and estimated groundwater contributions (Binolombangan et al., 2023).

While traditional design relies on these conventional methods, recent advances have shifted towards advanced numerical modeling with software like MODFLOW for dynamic groundwater simulations, climate-resilient design using projected rainfall data, and integrated life-cycle water management that plans for post-mining impacts (Scanlon et al., 2002; Bai et al., 2021; Bonacci, 2019; Younger et al., 2002). Positioning itself against studies in the Indonesian context that often lack this integrated perspective (e.g., Khusairi, 2015; Prabowo et al., 2023), this research builds on established methods but advances the state-of-practice by employing a MODFLOW model to simulate pre- and post-mining groundwater dynamics, conducting a detailed quantitative water balance, and explicitly incorporating climate resilience through a 30-year return period design rainfall.

RESEARCH METHOD

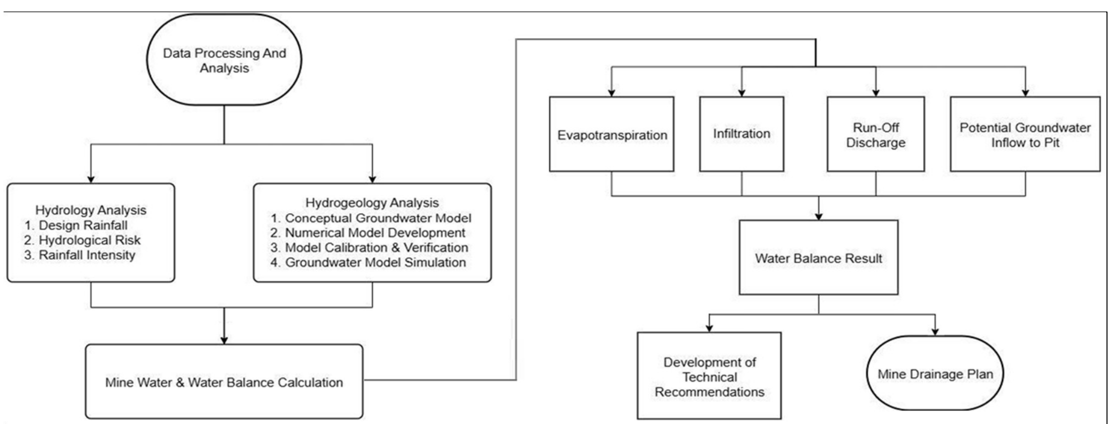


Figure 2. Research Flowchart

This study utilizes both primary data (directly collected measurements) and secondary data (from literature and existing sources) for its analysis. Figure 2 summarizes the research flowchart. The data processing involves three main stages: Hydrology Analysis, Hydrogeology Analysis, and Mine Water and Water Balance Calculation. The hydrology analysis stage calculates design rainfall using the Gumbel equation, assesses hydrological risk, and determines rainfall intensity with the

Mononobe formula. Hydrogeology Analysis implements a numerical groundwater model developed using a finite difference approach with specific assumptions, including treating the flow as a homogeneous, isotropic porous medium and calibrating it under steady-state conditions.

The model is built for both pre-mining and post-mining topographies. Mine water and Water Balance Calculation stage quantifies key water cycle components: evapotranspiration (using the Thornthwaite (1948) formula), infiltration (based on field-measured conductivity), runoff (using the Rational formula), and potential groundwater inflow into the mine pit (using Darcy's equation). The final output of this data processing is used to provide technical recommendations for the mine drainage plan, including the design of channels, sumps, and pumps.

FINDINGS AND DISCUSSION

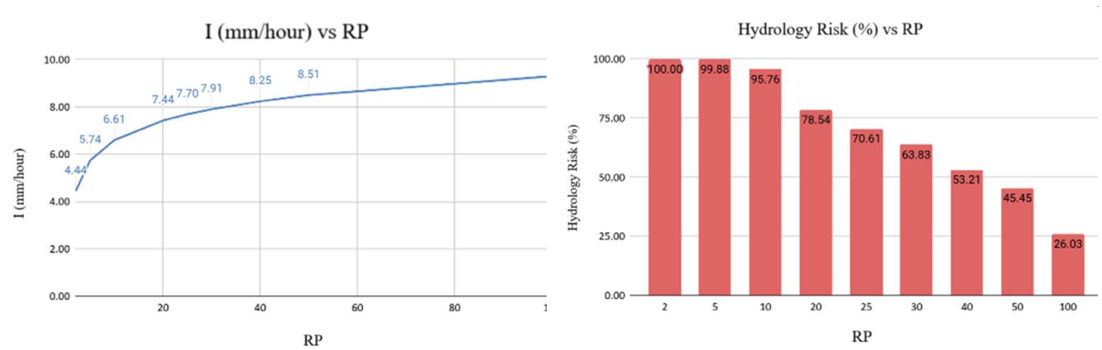
Rainfall Design, Rainfall Intensity and Hydrology Risk

Based on the average maximum rainfall data over 10 years (2014–2023), the average daily rainfall was 33.36 mm/day. This value was then used as the basis for calculating rainfall intensity using the Mononobe Formula at various Rainfall Return Periods (RP). For a 30-year RP, the design rainfall was 57.5 mm/day (Table 1). While the daily rainfall lasts for 4 hours (Rangkuti et al., 2020), the intensity is 7.91 mm/hour. Under these conditions, the calculated hydrological risk reached 63.83%.

Figure 3 (a) shows the relationship between rainfall intensity and Rainfall Return Periods at the research area. It can be seen that the longer the rainfall return used, the higher the rainfall intensity. This is because rainfall intensity is proportional to the design rainfall, the value of which is directly influenced by the selected rainfall return period. Meanwhile, Figure 3 (b) shows the relationship between hydrological risk and Rainfall Return Periods (RP). This graph shows that the longer the rainfall return period, the smaller the percentage chance of rainfall occurring at least once during that period.

Table 1. Calculation Results for Rainfall Design, Rainfall Intensity and Hydrology Risk

RP	Daily Rainfall Design(Xt - mm/days)	I (mm/hour)	Hydrology Risk(%)
2	32.29	4.44	100.00
5	41.76	5.74	99.88
10	48.03	6.61	95.76
20	54.04	7.44	78.54
25	55.95	7.70	70.61
30	57.50	7.91	63.83
40	59.94	8.25	53.21
50	61.83	8.51	45.45
100	67.66	9.31	26.03



(a) (b)

Figure 3. Correlation Between Rainfall Return Periods (RP) and (a) Rainfall Intensity (I) and (b) Hydrological Risk

Groundwater Simulation

The results of hydrogeological modeling indicate that the groundwater table and flow direction are influenced by local geological conditions, surface color, and mining activities. Initial modeling was carried out under pre-mining conditions (steady state), then compared with the post-mining scenario (transient) using the Life of Mine (LOM) design. Groundwater modeling was conducted under the initial conditions, assuming that the surface color was still natural or had not been altered by mining activities. Model calibration results using groundwater level data from 20 boreholes yielded a correlation coefficient of 0.8, an NRMS of 17.4%, and an average error of 2.22 m. This correlation value indicates that the model can accurately represent field conditions. The direction of groundwater flow generally moves from east to west, following the topographic gradient and flowing into a river system that serves as the primary boundary for the main flow. The river then flows into the sea in the western part of the research area. These findings suggest that regional hydrogeological conditions are significantly influenced by morphology and the presence of rivers, which are the primary controllers of flow.

In the post-mining scenario, modeling was carried out by incorporating topographical changes in accordance with the Life of Mine (LOM) design. Mining is planned up to an elevation of 6 meters above sea level at the pit bottom. This change disrupts the aquifer conditions due to the cutting of the water-bearing layer. Simulation results show the formation of a cone of depression around the mine pit area. Groundwater level drawdown is estimated to occur in the range of 5 to 15 meters during the mine's life. In addition, changes in the hydraulic gradient were also identified, around 5% on the eastern slope and 2% on the western slope. These conditions have the potential to affect slope stability and groundwater availability around the mine area. The modeling results show that mining activities have a significant impact on local hydrogeological conditions. The cone of depression phenomenon not only lowers the local groundwater level around the pit but can also affect the balance of the regional groundwater system, especially in relation to river flow.

Water Balance

The water balance condition in the research area has already been studied by Riyadi (2025). Analysis results indicate that the monthly evapotranspiration (ET) values range from 15.51 to 18.23 cm, with an average of 16.58 cm/month. This ET value is then multiplied by the latitude correction factor, which is based on the Earth's latitude and 12 hours of sunshine. The calculation results gave an average corrected ET value of 16.93 cm/month. When converted to a daily basis, assuming 30 days per month, the daily evapotranspiration (ETh) was 0.56 cm/day or equivalent to

0.0056 m/day. The daily evapotranspiration volume (VETh) is calculated by multiplying the ETh value by the catchment area (CA). This calculation determines the daily amount of water lost through evapotranspiration. This means that the larger the catchment area, the greater the volume of water that undergoes evapotranspiration. At the research site, with a catchment area of 1.25 km^2, the daily evapotranspiration volume obtained was 7,053.13 m^3. Water balance calculations were conducted in the research area for rainfall catchment areas ranging from 0.25 km^2 to 2.25 km^2. Rainfall volume was calculated using a rational equation as the basis for calculating total water (100%). Referring to the results of the water balance study in the research area by Riyadi (2025), it was found that evapotranspiration (Et) contributed 17.82%, infiltration (Inf.) contributed 11.86%, while surface runoff (R) contributed contributed 70.33%. This figure of 70.33% was then used as the runoff coefficient (C = 0.703) in calculating the runoff discharge.

The potential runoff water calculations for the Northern and Southern pits, with a catchment area (CA) simulation ranging from 0.25 to 2.25 km^2, are 5,542.22 m^3/day to 49,880.01 m^3/day (Table 2). This runoff discharge is calculated based on a surface runoff coefficient of 0.703,, a rainfall intensity of 7.91 mm/hour, and an average annual rainfall of 138 days (an average of 11 days per month). The daily runoff water potential for the Northern pit and Southern pit,, respectively, is, is 27,711.12 m^3/day (for a a 1.25 km^2 catchment area) and 11,084.45 m^3/day (for a a 0.5 km^2 catchment area). The assessment of groundwater inflow into the mining pits was based on Darcy's Law (Riyadi, 2025). While surface infiltration tests indicated a high hydraulic conductivity of 2.330 × 10^ (-3) m/s for the 1-meter-thick soil layer, the underlying rock, with a much lower conductivity of 2.608 × 10^ (-7) m/s, was identified as the governing factor for groundwater flow. Using this rock conductivity value (K), a range of potential inflows was calculated. The hydraulic gradient (i) in the area was estimated between 1.75% and 8.75% (equivalent to 1-5°). The Northern pit, with an opening width of 2.0 km, has an estimated average potential groundwater inflow of 1.18 × 10^3103 m^3/day. The Southern pit,, with an opening width of 1.5 km, has an, hasan estimated average potential groundwater inflow of 8.86 × 10^2 m^3/day.

Table 2. Estimated Runoff Water Discharge Calculation

Runoff Coeff (C)				0.703
I (mm/hour)				7.91
Daily Rain hours				4
Average Anual Raindays (days)				138
Average Monthly Raindays (days)				11
CA (km^2)	**Q (m^3/s)**	**Q Daily (m^3/day)**	**Q Monthly (m^3/mth)**	**Q Anual (m^3/yr)**
0.25	0.38	5,542.22	63,643.20	763,718.36
0.50	0.77	11,084.45	127,286.39	1,527,436.72
0.75	1.15	16,626.67	190,929.59	2,291,155.08
1.00	1.54	22,168.89	254,572.79	3,054,873.44
1.25	1.92	27,711.12	318,215.98	3,818,591.80
1.50	2.31	33,253.34	381,859.18	4,582,310.17
1.75	2.69	38,795.56	445,502.38	5,346,028.53
2.00	3.08	44,337.79	509,145.57	6,109,746.89
2.25	3.46	49,880.01	572,788.77	6,873,465.25

Source: Riyadi, (2025)

Mine Drainage Plan

The mine dewatering system for the Nusa-Lam Ateuk-Lambaro Kueh open pit mine is designed to control water inflow through a network of open channels, sumps, and settling ponds, as illustrated in the overall mine drainage system map (Figure 4). While the general site hydrology directs water flow westward toward the pit, the specific drainage design differs significantly between the Northern and Southern pits. The Northern pit, which forms a depression due to mining activity, requires a sump to collect water that is then pumped to a settling pond. Conversely, the Southern pit's elevation parallels the surrounding contours, meaning it does not form a depression; consequently, no sump or pumping is required, as open channels drain runoff directly to the settling pond. The open channels drain is trapezoidal in shape and designed to accommodate the runoff water (Table 3), then direct it into a sump. In both designs, the settling pond would serve to settle suspended materials before the cleaned water is released back into the environment, with additional embankments constructed to prevent external runoff from entering the mine site.

The water supply volume in the Northern pit area consists of groundwater and runoff, amounting to 1,181 m^3/day on non-rainy days and 28,892.12 m^3/day on rainy days, which includes an additional 6,927.78 m3/hour of rainwater within four rain hours (Table 4). The sump is crucial for storage, with a minimum required capacity of 7,000 m^3 and a recommended capacity of 10,500 m^3 to prevent flooding. The contained water is then pumped to a settling pond using a Multiflo MF420 pump with a capacity of 936 m^3/hour. Pumping the entire rainy-day volume takes 30.87 hours with a single pump, or 15.43 hours with two pumps operating simultaneously. To ensure effectiveness and provide a contingency, it is recommended to deploy two pumping units in a 2:1 work hours ratio configuration. Analysis of pumping operational capacity and daily leftover water in the sump (Figure 5) supports the use of a 1.5-unit configuration. In this setup, the main pump operates for 16 hours and the backup pump for 8 hours daily during rain, providing the necessary capacity while allowing time for maintenance. This strategy efficiently manages the daily inflow, with the flexibility to extend operating hours to handle any residual water.

Table 4. Total Daily Mine Water in Northern Pit

No.	Mine Water Supply Parmeters	Values
1	Hourly Runoff (m^3/hour)	6,927.78
2	Daily rain hours (hours)	4
3	(a) Daily Runoff (m^3/day), 4 rain hours	27,711.12
4	(b) Northern Pit Groundwater inflow (m^3/day), 24 hours	1,181.00
5	**(c = a+b) Total Daily Mine Water in Northern Pit (m^3/day)**	**28,892.12**

Table 3. Open Channel Dimensions

	Open Channel										
No	**A (km^2)**	**Q (m^3/s)**	**m**	**n**	**S**	**d**	**h (X%)**	**b (m)**	**a (m)**	A(m)	B(m)
	CA	**Manning**	**cotα**	**Mannings Roughness Coefficient**	**ΔH/ΔL**	**((nQ)/(As(0.5^(2/3)(S^(1/2))))^(3/8))**	**d*(1+%)**	**d*(b/d)**	**h/sinα**	As*d	b+2md
1	0.25	0.39	0.577	0.03	0.02	0.38	0.45	0.437	0.437	0.248	0.874
2	0.50	**0.77**	0.577	0.03	0.02	0.49	0.59	0.566	0.566	0.417	1.133
3	0.75	1.16	0.577	0.03	0.02	0.57	0.69	0.66	0.66	0.56	1.32
4	1.00	1.54	0.577	0.03	0.02	0.64	0.76	0.73	0.73	0.70	1.47
5	1.25	**1.92**	0.577	0.03	0.02	0.69	0.83	0.80	0.80	0.83	1.60
6	1.50	2.31	0.577	0.03	0.02	0.74	0.89	0.86	0.86	0.95	1.71
7	1.75	2.69	0.577	0.03	0.02	0.78	0.94	0.91	0.91	1.07	1.81
8	2.00	3.08	0.577	0.03	0.02	0.82	0.99	0.95	0.95	1.18	1.91
9	2.25	3.46	0.577	0.03	0.02	0.86	1.03	1.00	1.00	1.29	1.99

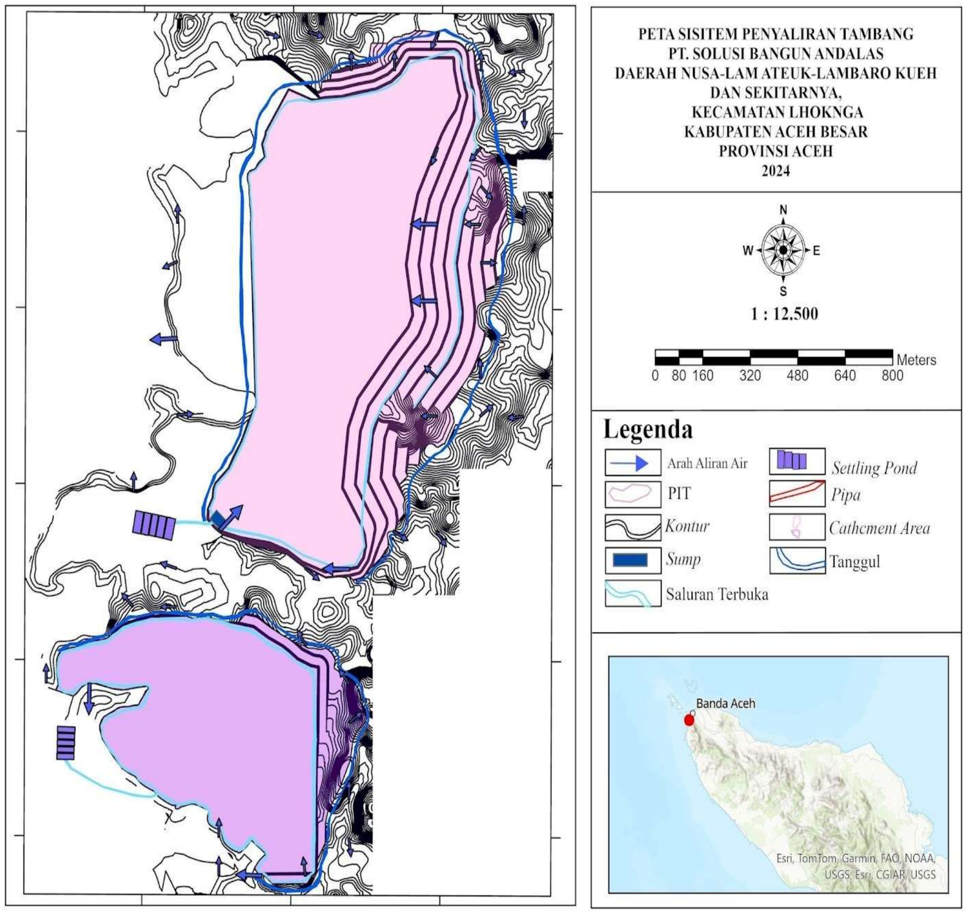
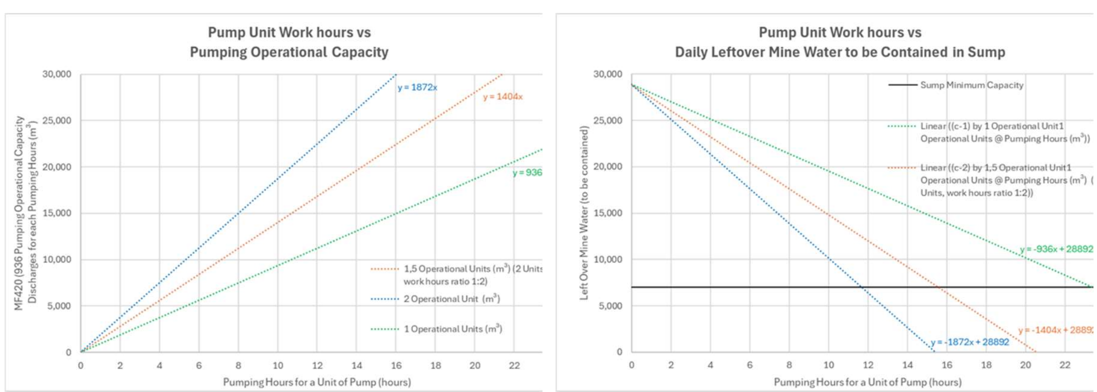


Figure 4. Mine Dewatering System Schematic Plan



(a) (b)

Figure 5. Correlation graph of Pumping Unit Work Hours Related To (a) Pumping Operational Capacity And (b) Daily Leftover Mine Water To Be Contained in The Sump for 1, 1.5, and 2 units of Multiflo MF420 Configurations.

CONCLUSIONS

This study uses rainfall and rainy day data from the Sultan Iskandar Muda BMKG Station for the period 2014 to 2023, which represents the geographical conditions of the research area. The average daily rainfall was recorded at 33.36 mm/day, with a maximum value of 46.44 mm/day. For a 30-year rainfall recurrence period, the planned rainfall was obtained at 57.5 mm/day, and the rainfall intensity for a duration of 4 hours reached 7.91 mm/hour with a hydrological risk of 63.83%. The average number of rainy days per year is 138 days, or about 11 days per month. The water balance shows that of the total rainfall, 17.82% undergoes evapotranspiration, 11.86% infiltrates, and 70.33% becomes surface runoff. Groundwater flow in the research area generally moves from east to west towards the rivers and eventually to the sea. Numerical modeling using ModFlow software shows fairly accurate results with a correlation coefficient of 0.8 and an average groundwater level prediction error of 2.22 meters.

The potential for mine water entering comes from groundwater seepage that occurs continuously throughout the year, as well as from rainwater runoff that occurs during the rainy season. The mine water management strategy is site-specific: the Southern Pit, forming no depression, will use gravity-fed channels, while the Northern Pit requires active pumping. Here, water inflow reaches 28,892.12 m^3/day during rain, necessitating a sump with a recommended capacity of 10,500 m^3. To efficiently manage this volume, a two-pump system (Multiflo MF420, 936 m^3/hour each) in a 1.5-unit configuration is recommended, where a main pump operates for 16 hours and a backup for 8 hours. This plan enhances operational safety by preventing flooding, offers cost savings by minimizing pump reliance in the south, and protects the environment by controlling runoff. This practical plan ensures the mine can operate safely, affordably, and responsibly. However, the study is limited by its short-term data and simplified hydrogeological model, and it excludes the design of water treatment infrastructure. Further research is needed to develop a complete life-cycle water management strategy, including settling ponds and acid mine drainage treatment systems.

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