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Sustainable Water Infrastructure Assessment of Raw Water Availability and Demand in a Nickel Mining-Impacted Watershed: A Case Study of the Pali River, East Halmahera, Indonesia

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Abstract

Rapid regional development, population growth, and land-use conversion associated with nickel mining have intensified pressure on raw water resources in many tropical watersheds. In mining-affected regions, the sustainability of water infrastructure depends not only on projected demand but also on the long-term reliability of raw water availability under low-flow conditions. This study assesses raw water availability, future clean water demand, and watershed protection requirements for the Pali River, the main gravity-fed raw water source for Maba City, East Halmahera, Indonesia. A quantitative hydrological approach was applied by integrating population projection, water demand estimation, watershed delineation, rainfall–runoff analysis using the F.J. Mock water balance model, and mining-induced catchment reduction scenarios. Water demand was projected to 2045, while dependable discharge was evaluated using Q90 low-flow reliability. The results show that the projected average clean water demand for Maba City reaches 36.19 L/s in 2045. Under the baseline non-mining condition, the Pali River watershed has an effective catchment area of 1.75 km^2 and a Q90 dependable discharge of 17.19 L/s. This value is already insufficient to meet the projected average demand under critical dry-season conditions. Mining-related catchment contraction further reduces the effective watershed area to 0.733 km^2 under Scenario 1 and 0.2973 km^2 under Scenario 2, decreasing dependable discharge to 7.20 L/s and 2.92 L/s, respectively. These findings indicate that the Pali River alone cannot provide a reliable long-term raw water supply for Maba City. Protection of the entire contributing watershed, development of alternative raw water sources, additional storage infrastructure, and continuous water quality monitoring are therefore essential to support sustainable water infrastructure planning in this nickel mining-impacted watershed.

Keywords: raw water reliability, dependable flow, water demand projection, nickel mining, watershed protection, Pali river

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INTRODUCTION

As regional development progresses, the demand for clean water continues to increase. In watersheds affected by mining activities, maintaining a reliable raw water supply becomes an important challenge due to potential changes in hydrological conditions. Therefore, assessing raw water availability and future water demand is essential to ensure sustainable water infrastructure planning and long-term water security (Harmiyati & Fuaji, 2023; Darmawan et al., 2022). Consequently, the concept of smart water management has emerged as a subcategory within the broader framework of smart cities (Soares Ascenção et al., 2023). While global challenges such as climate change, population growth, and water scarcity continue to affect water resource management, ensuring the reliability of raw water supply at the watershed scale remains a critical local concern. This issue is particularly important in watersheds affected by mining activities, where land-use changes may alter hydrological processes, reduce infiltration capacity, increase surface runoff, and potentially affect long-term water availability. Therefore, assessing the balance between raw water availability and future water demand is essential to support sustainable water infrastructure planning and water security in mining-impacted regions.

Mining areas represent regions that require particular attention in the provision of clean water. In addition to experiencing rapid population growth, these areas face a continuous decline in raw water availability due to mining activities that reduce water catchment areas (Sinyo et al., 2025). Furthermore, beyond issues of quantity, water quality is also progressively deteriorating as a result of intensified mining activities (Amelia et al., 2025). Problems related to shallow groundwater and river water in different countries arise from various factors, including natural causes such as disasters, as well as human activities such as waste pollution and other anthropogenic influences (Palupi et al., 2024). Nickel mining activities (soil stripping, waste disposal, and tailings) often pollute rivers and springs used by residents for drinking water and daily needs (Lo et al., 2024). Heavy metal levels such as nickel, chromium, and manganese can exceed water quality standards, rendering the water unfit for consumption (Yanti et al., 2019; Onuma, 2024). Mining causes significant soil erosion, clouding rivers with silt and fine material (Wibowo et al., 2020). This disrupts clean water treatment and shortens the lifespan of reservoirs and water installations due to silting (Herawati et al., 2025). Mining-induced land-use changes may alter watershed hydrological processes by increasing surface runoff, reducing infiltration and groundwater recharge, and decreasing baseflow during dry periods. These changes can affect dependable discharge and the long-term reliability of raw water availability. Therefore, hydrological assessment is essential to support sustainable water resource management in mining-impacted watersheds. Deforestation and disruption of catchment areas have led to a reduction in groundwater and surface water reserves (Febriany & Akbar, 2024). Several residents in East Halmahera have complained that wells are drying up or river levels are dropping drastically during the dry season. Mining companies often divert water for operational needs (such as ore washing, dust control, and power generation), leaving residents with water shortages. In some villages, residents are forced to purchase clean water or rely on rainwater (Palupi et al., 2024).

Maba City is the capital of East Halmahera Regency, North Maluku Province, Indonesia. Maba City has an area of 991.29 km^2. The population of Maba City in 2024 was 11,143 people. Along with the development of all aspects of life, the need for water will also increase. Increasing population growth in an area will have an impact on clean water supply facilities, which will also experience an increase. Some problems arising from meeting clean water needs are the uneven availability of raw water for clean water. Therefore, efforts are required to meet the demand for clean water production. One of these efforts is to improve the service of a good distribution network system and be able to serve the clean water needs of residents in the area by utilizing the discharge capacity of existing water sources around the population (Herawati et al., 2025). Maba City is one of the central government areas and also a nickel mining area that has serious problems in providing clean water. Currently, the existing raw water sources that have been utilized are surface water sources. The Pali River is the primary source of clean water in this area. However, the Pali River is currently located within a mining area, making the reliability of its raw water capacity a serious concern. The Pali River's catchment area also includes a nickel mining area, which, if protected and restricted, will disrupt the supply of clean water for drinking. The Pali River is strategically important as the primary gravity-fed raw water source for Maba City. Its natural flow enables a reliable water supply with

minimal energy and operational requirements. Therefore, maintaining the long-term availability of the river is essential for regional water security and sustainable water infrastructure development.

Furthermore, clean water in areas with limited water resources requires a modern approach such as a Smart Water Management System (SWMS). This system is capable of detecting leaks, controlling water pressure, and monitoring water quality in real time, supported by IoT technology (Tjendani et al., 2022). The SWMS concept helps water utilities optimize limited water resources, improve operational efficiency, and minimize water loss. This finding is particularly relevant for Maba City, which faces the threat of a raw water deficit and high pressure from mining activities. Although mining impacts on water quality and land cover have been widely discussed, limited studies have quantitatively assessed how nickel mining-induced catchment reduction affects dependable raw water discharge and long-term clean water demand in East Halmahera.

METHOD

This quantitative research measured river discharge to determine water availability. Topographic data, rainfall data, and soil infiltration values were collected. These data were used to conduct hydrological analysis to determine the reliability of raw water sources and water catchment areas that must be protected from destructive activities and nickel mining. This research was conducted in the Pali River and its catchment area, which is a nickel mining area in Maba City District, the capital of East Halmahera Regency.

Data Requirements and Sources

This study utilized both primary and secondary data. The primary data consisted of river discharge measurements, topographic data, watershed characteristics, and raw water quality data collected from the study area. Secondary data included population statistics, rainfall records, climatological data, and spatial data obtained from relevant government agencies.

The data used in each analytical stage are summarized as follows: (1) Population projection analysis: historical population data of Maba City obtained from the Central Statistics Agency (BPS) and local government records. (2) Water demand calculation: population projection data and water consumption standards issued by the Directorate General of Human Settlements, Ministry of Public Works and Housing, Indonesia. (3). Rainfall and climatological analysis: monthly rainfall data and climatological data, including temperature and evapotranspiration-related parameters, obtained from the Meteorology, Climatology, and Geophysics Agency for the period 2014–2024. (4). Watershed delineation: topographic maps, DEM data, GPS survey data, and GIS-based spatial analysis. (5). Dependable discharge calculation: rainfall and climatological data for 2014–2024, watershed area, and hydrological parameters required by the F.J. Mock model. Monthly rainfall and climatological data from 2014–2024 were used as input for the F.J. Mock water balance model. Climatological parameters, including evapotranspiration data, were obtained from the Meteorology, Climatology, and Geophysics Agency records for the study area. (6). Mining scenario analysis: watershed delineation results and GIS-based assessment of watershed area reduction under different mining scenarios. (7). Water quality assessment: laboratory test results of raw water samples collected from the Pali River water source.

Population Projection

After calculating the three projection methods, the standard deviation for each method was determined. The projection method with the lowest standard deviation was selected as the most appropriate method for estimating future population growth. To account for the potential increase in population associated with mining activities, an additional population scenario was considered by assuming that non-local mining workers contribute approximately 35% of the projected local population. This assumption was used solely for scenario analysis and does not represent an official demographic estimate.

Water Demand Calculation

Water demand was estimated based on projected population growth and water demand standards. Domestic water demand was calculated using a consumption rate of 130 L/person/day.

Non-domestic water demand was assumed to be 20% of domestic demand, while water loss was estimated at 20% of total demand. The maximum day factor and peak hour factor were assumed to be 1.1 and 1.5, respectively.

Domestic water demand was calculated as equation (1):

$$Q_d = (P \times C_d)/86{,}400 \quad (1)$$

where:

Q_d = domestic water demand (L/s);

P = projected population;

C_d = domestic water consumption (L/person/day).

Non-domestic water demand was calculated as equation (2):

$$Q_{nd} = 0.2 \times Q_d \quad (2)$$

where: Q_{nd} = non-domestic water demand (L/s).

Water loss was estimated as equation (3):

$$Q_l = 0.2 \times (Q_d + Q_{nd}) \quad (3)$$

where: Q_l = water loss (L/s).

Average water demand was calculated as equation (4):

$$Q_r = Q_d + Q_{nd} + Q_l \quad (4)$$

where: Q_r = average water demand (L/s).

Maximum daily demand was calculated as equation (5):

$$Q_{max} = F_{max} \times Q_r \quad (5)$$

where: F_{max} = maximum day factor

Peak hour demand was calculated as equation (6):

$$Q_{peak} = F_p \times Q_{max} \quad (6)$$

where: F_p = peak hour factor.

For raw water reliability assessment, dependable discharge was compared with average water demand because average demand represents the continuous supply requirement. Maximum daily and peak hour demands were used as design references for storage and distribution infrastructure.

Watershed Delineation

Watershed delineation was conducted using topographic data, digital elevation models, GPS survey data, and GIS-based spatial analysis. Global Mapper was used to identify the contributing catchment area of the Pali River and to calculate the effective watershed area under baseline and mining-affected conditions. The delineation results were also used to identify watershed protection boundaries and evaluate the extent of catchment contraction under mining scenarios.

Water Availability and Dependable Flow Analysis

Water availability was evaluated using the F.J. Mock rainfall–runoff model, which is widely applied in Indonesia for estimating river discharge in watersheds with limited streamflow records. The model converts rainfall into streamflow through a monthly water balance approach. The input data consisted of monthly rainfall, climatological data, and watershed characteristics. Rainfall data covering the period [YEAR–YEAR] were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG). Potential evapotranspiration was calculated using climatological data from the nearest meteorological station. The model incorporates soil moisture storage, infiltration, groundwater storage, and baseflow components to estimate monthly river discharge.

The infiltration coefficient and groundwater recession coefficient were selected based on watershed characteristics and land-cover conditions within the Pali River watershed. Monthly runoff was calculated from effective rainfall after accounting for evapotranspiration losses and soil moisture changes. The simulated monthly discharges were arranged from the highest to the lowest value, and the probability of exceedance was calculated using the Weibull formula. The dependable discharge (Q90) was defined as the discharge that exceeded 90% of the time and was used to assess the reliability of raw water availability. Where discharge observations were available, the simulated

results were compared with observed discharge data to evaluate the reasonableness of model performance.

Potential evapotranspiration data were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG). The monthly evapotranspiration values were used directly as input to the F.J. Mock model for the water balance analysis. These data represent the climatic conditions of the study area and were incorporated into the estimation of soil moisture, groundwater storage, and streamflow generation. Monthly rainfall data covering the period 2014–2024 were obtained from the Meteorology, Climatology, and Geophysics Agency (BMKG). These data were used as the primary hydrological input for the F.J. Mock model to estimate monthly streamflow and dependable discharge in the Pali River watershed. Monthly reference evapotranspiration (ETo) data for the same period were also obtained from BMKG and incorporated into the water balance analysis.

Standard F.J. Mock parameter values were adopted because detailed field measurements required for model calibration were not available. The model was applied to generate monthly streamflow estimates for the Pali River watershed throughout the analysis period. Dependable discharge was determined from the simulated monthly discharge series. The minimum monthly discharge value was used to represent the dependable flow condition and to evaluate the reliability of raw water availability for future water supply planning. The dependable discharge was determined from the monthly discharge series generated by the F.J. Mock model. The minimum monthly discharge value during the analysis period was used as the dependable discharge, representing the most critical condition for evaluating the reliability of raw water availability in the Pali River watershed.

Analytical Stages of the Study

The analysis stages are designed to sequence the steps to be carried out, simplify the analysis process, and achieve the research objectives. The stages are as follows: Calculating Water Requirements: Water requirements are calculated to ensure that the community surrounding the study area has sufficient water for the projected year. The amount of water required depends on the population in the study area. The steps for calculating water requirements are as follows: Population projection calculations are performed using three projection methods: the arithmetic method, the geometric method, and the least squares method. After calculating the three methods, the standard deviation for each method is determined. The projection method used is the one with the smallest standard deviation.

Water requirements are divided into two categories: domestic and non-domestic water requirements (Chen et al., 2022). The water requirements calculation refers to the standard water requirements based on water requirement standards issued by the Directorate General of Cipta Karya, Ministry of Public Works and Public Housing Indonesia. The amount of water requirements is calculated based on the projected population for 20 years (Abu-Bakar et al., 2021). To calculate domestic water requirements, assume a water consumption of 100 liters per person per day. Meanwhile, non-domestic needs are allocated at 30% of domestic needs. Consumption at public hydrant units is 30 liters/person/day. Water loss is assumed to be 20%. The target service coverage is 90%.

Water availability analysis is conducted to determine the adequacy of water discharge to meet water needs in the study area. To determine water needs, the potential evapotranspiration rate is calculated in the study area. The parameters and data used to calculate potential evapotranspiration are meteorological, climatological, and geophysical data at the study site (Wang et al., 2024).

Mining Scenario Analysis

Mining impact scenarios were evaluated using a simplified watershed area reduction approach. The analysis assumed that reductions in effective catchment area due to mining activities would result in proportional reductions in dependable discharge. Under this assumption, discharge values for each mining scenario were estimated by scaling the baseline dependable discharge according to the remaining watershed area. This approach was intended to provide a first-order assessment of potential impacts on raw water availability. Changes in hydrological parameters such as infiltration capacity, runoff characteristics, evapotranspiration, groundwater recharge, soil

moisture storage, and sedimentation were not explicitly simulated. Therefore, the results should be interpreted as indicative estimates rather than detailed hydrological predictions.

A limitation of this study is that mining impacts were assessed using proportional watershed area reduction rather than a fully distributed hydrological model. Consequently, the analysis does not explicitly represent changes in infiltration, runoff generation, groundwater processes, sediment transport, or water quality that may occur following land-cover alteration caused by mining activities. Future studies should incorporate dynamic watershed modeling to evaluate these processes in greater detail. The mining impact scenarios were evaluated using a proportional watershed area scaling approach. This approach assumes that reductions in the effective watershed area due to mining activities result in proportional reductions in dependable discharge. The dependable discharge under each mining scenario was estimated using equation (7):

$$Q_s = Q_b \times \frac{A_s}{A_b} \qquad (7)$$

where:
Q_s = dependable discharge under the mining scenario (L/s);
Q_b = baseline dependable discharge (L/s);
A_s = remaining watershed area under the mining scenario (km^2);
A_b = baseline watershed area (km^2).

Using this approach, the baseline dependable discharge of 17.19 L/s was reduced to 7.20 L/s when the watershed area decreased from 1.75 km^2 to 0.733 km^2, and to 2.92 L/s when the watershed area decreased to 0.2973 km^2. This scenario-based approach provides a preliminary estimate of the potential impact of watershed reduction on raw water availability. However, it does not explicitly consider changes in infiltration capacity, runoff coefficient, soil moisture storage, groundwater recharge, baseflow contribution, erosion, sedimentation, or other hydrological changes that may occur due to mining activities. Therefore, the results should be interpreted as simplified estimates of the impact of watershed contraction on dependable discharge.

Watershed delineation is carried out to determine watershed boundaries that influence raw water sources. Watershed delineation is also used to determine watershed area. Computer programs such as ArcGIS or Global Mapper are used to determine watershed boundaries and calculate watershed area (Patel et al., 2026; Swain et al., 2022). In addition to determining the watershed area for calculating water availability, watershed delineation is also used to determine the area affected by mining activities within the watershed area. The results of this watershed delineation analysis serve as a reference in determining the boundaries of areas that must be protected and free from mining activities (Li et al., 2025).

RESULTS AND DISCUSSION

Population Projection Analysis

Population projection for Maba City was conducted using three methods: the least-squares, arithmetic, and geometric projection methods. The projected population values for the period 2025–2045 are presented in Figure 1. The projections indicate a continuous increase in population throughout the planning period. At the beginning of the projection period, the three methods produced relatively similar estimates. However, the differences among the methods became more apparent toward the end of the projection period.

As shown in **Figure 1**, the geometric method produced the highest population estimate by 2045, while the arithmetic method produced the lowest estimate. The projected population in 2045 was 24,408 people using the geometric method and 23,162 people using the arithmetic method. This difference reflects the sensitivity of long-term population projection to the selected growth model. The geometric method assumes compound growth, resulting in a higher projected population over time, whereas the arithmetic method assumes a constant absolute increase.

To determine the most appropriate projection method for subsequent water demand analysis, the standard deviation of each method was calculated based on its deviation from the historical population trend. The arithmetic method produced the lowest standard deviation, indicating the closest agreement with the observed population pattern. Therefore, the arithmetic projection was selected as the basis for estimating future clean water demand in Maba City.

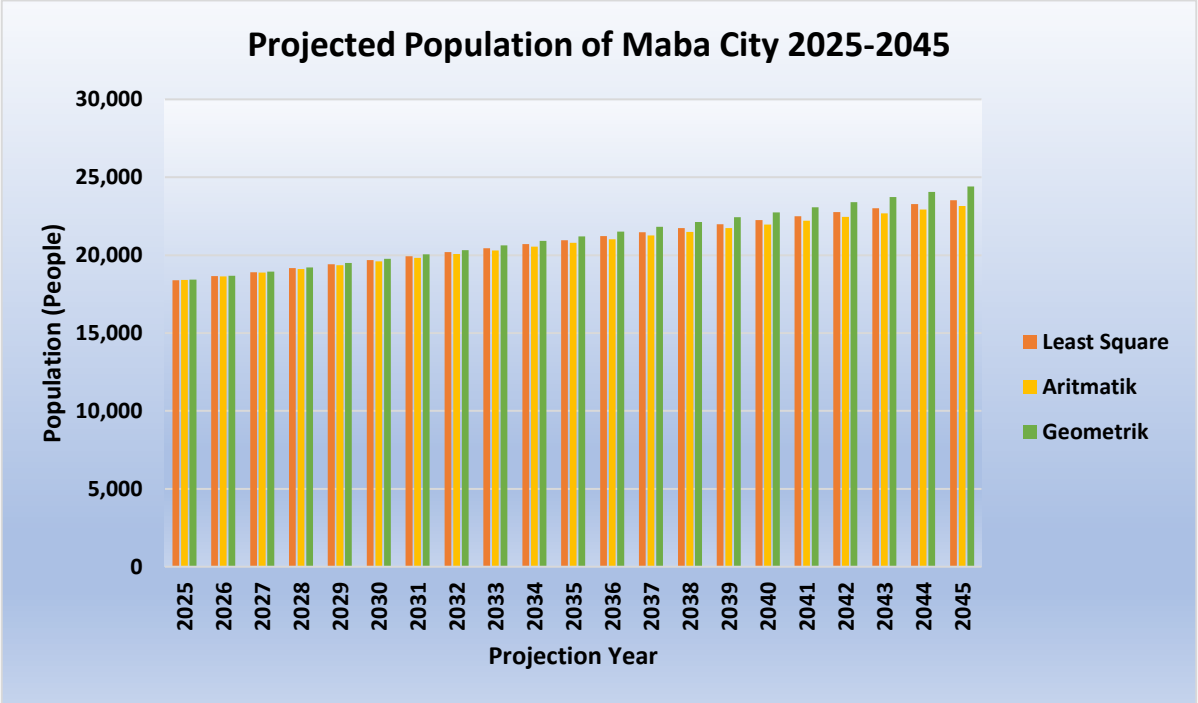


Figure 1. Comparison of projected population growth in Maba City for the 2025–2045 planning period using the least-squares, arithmetic, and geometric projection methods. The projection results were used as the basis for estimating future clean water demand

At the beginning of the year, the projections from the three methods produced relatively similar population numbers. However, by the end of the year, the projections showed significant differences. The largest population was obtained using the geometric method, at 24,408 people, and the smallest population was obtained using the arithmetic method, at 23,162 people.

The projection method used for subsequent analysis was selected based on the lowest standard deviation value. A lower standard deviation indicates that the projected population values are more consistent with the historical population trend and therefore provide a more representative basis for future population estimation. The results of the standard deviation calculations for each projection method can be seen in **Table 1**.

Table 1. Standard deviation

No	Projection Method	Standard Deviation
1	Least Square	738
2	Arithmetic	683
3	Geometric	689

The standard deviation values shown in **Table 1** represent the variation between the projected population and the historical population trend. These values are expressed in persons. A lower standard deviation indicates that the projection method better represents the observed population growth pattern. Therefore, the arithmetic method, which produced the lowest standard deviation value of 683 persons, was selected for further analysis.

Estimation of Water Demand

The calculation of domestic and non-domestic water needs is based on population categories. The calculation is based on the following provisions: (1) Household connection unit consumption is

130 L/person/day; (2) Public hydrant unit consumption is 30 L/person/day; (3) Water supply unit consumption is 30 L/person/day; (4) Non domestic consumption is 20% of domestic consumption; (5) The maximum day factor is 1.1; (6) Peak hour factor is 1.5; (7) Number of people per unit: 5 people; (8) Number of people per unit: 100 people; (9) Service coverage: 90%; (10) Assumption of 20% water loss. With the above provisions, the water requirement calculation results are shown in **Table 2**.

Table 2. Water Demand Calculation Results for Maba City (2025–2045)

Year	Population (people)	Domestic Water Demand (L/s)	Non Domestic Water Demand (L/s)	Total (L/s)	Water Loss (%)	Water Loss (L/s)	AVG Water Demand (L/s)	Max. Daily Demand (L/s)	Peak Hour Demand (L/s)
2025	18,404	19.17	3.83	23.00	20	5.75	28.76	33.07	43.13
2026	18,641	19.42	3.88	23.30	20	5.83	29.13	33.60	43.69
2027	18,879	19.67	3.93	23.60	20	5.90	29.50	34.12	44.25
.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
2043	22,686	23.63	4.73	28.36	20	7.09	35.45	40.97	53.17
2044	22,924	23.88	4.78	28.65	20	7.16	35.82	41.19	53.73
2045	23,162	24.13	4.83	28.95	20	7.24	36.19	41.62	54.29

Note: Only selected years are presented in the table for brevity. Intermediate years were omitted but included in the complete calculation.

For the assessment of raw water availability, the dependable discharge was compared with the average water demand. The average demand represents the long-term water requirement that must be continuously supplied by the raw water source. Meanwhile, the maximum daily demand and peak hour demand were calculated primarily for water supply infrastructure planning, including reservoir sizing and distribution system design.

The results of the water demand projections from 2025 to 2045 can be seen in **Table 2**. The calculation results are based on the population calculated from the previous population projection. The amount of water demand depends on the population. The larger the population, the greater the water demand. As can be seen in the table, the total water demand at the beginning of the year, the projection is 23 L/s until 2045 reaches 28.95 L/s. By taking into account the water loss factor of 20%, the water demand increases. The average water demand at the beginning of the projection year is 28.76 L/s and at the end of the projection year it becomes 36.19 L/s. The calculation of the maximum daily demand is used to determine the reservoir capacity. The maximum daily demand at the beginning of the projection year is 33.07 L/s and at the end of the projection year it is 41.62 L/s. The peak hour demand at the beginning of the projection year is 43.13 L/s and at the end of the projection year it is 54.29 L/s.

Water Availability Analysis Based on Dependable Flow

The availability of raw water for clean water in the Pali River was analyzed based on 3 conditions, namely conditions before mining activities, after initial mining activities, and when the condition of the water catchment area only left the river channel.

Dependable Discharge Calculation Before Nickel Mining Activities

This calculation, conducted in the absence of mining activity, aims to determine the reliability of the Pali River water source as a raw water source for Maba City's clean water supply. This reliable discharge calculation uses a 90% probability of the existing discharge. The dependable discharge calculation was conducted using the F.J. Mock water balance approach, which has been widely applied for discharge estimation in Indonesian watersheds with limited streamflow records (Tunas & Lesmana, 2011). The calculation is performed using climatological data and the latitude of the study area. The calculation focuses on the balance between rainfall and evaporation. The calculation of water availability involves several steps. The calculation steps are as follows: Input Meteorological Data; Calculate Potential Evapotranspiration; Calculate Actual Evapotranspiration; Calculate Water Balance; Calculate Runoff and Groundwater Storage; Calculate Watershed Area. The Pali river watershed area is 1.75 km^2. The watershed area was obtained through geospatial data and processed

using the GIS-based Global Mapper computer program. The watershed area in the study area can be seen in **Figure 2**.

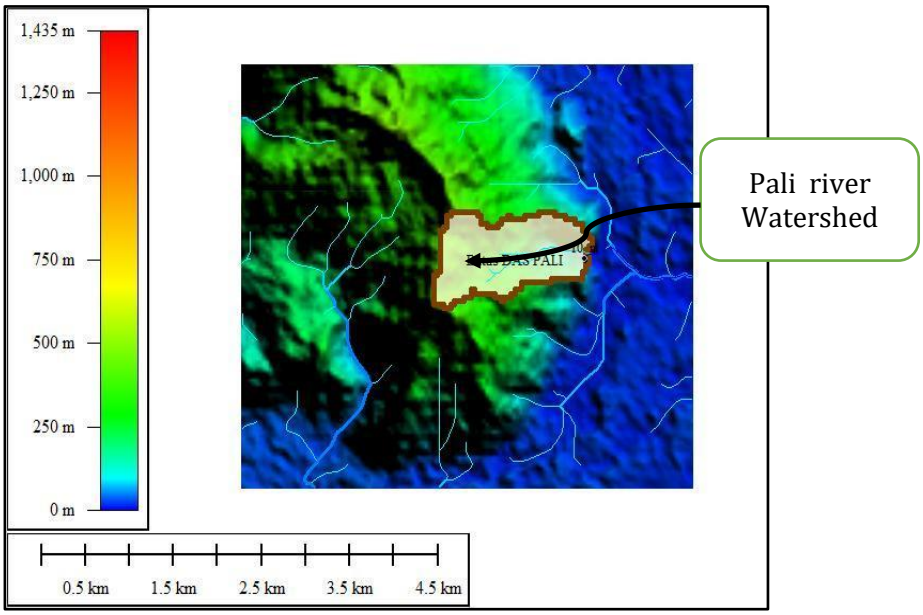


Figure 2. The Pali river watershed

Water surpluses occur eight months a year, while deficits occur in July and August. The maximum discharge calculated is 91.155 L/s, and the minimum is 14.59 L/s. The predicted discharge is based on a 90% probability, or Q90. The raw water availability of the Pali River was evaluated under baseline conditions prior to mining disturbance using the F.J. Mock water balance model. The watershed area under this condition is 1.75 km^2, as determined through GIS-based watershed delineation. The simulated monthly discharge pattern is presented in **Figure 3**.

As shown in Figure 3, river discharge exhibits clear seasonal variation throughout the year. Higher discharge values occur during the wetter months, with peaks in January (91.53 L/s), May (100.63 L/s), and December (89.25 L/s). In contrast, substantially lower discharge values are observed during the dry-season period, particularly in July (14.61 L/s), September (23.28 L/s), and October (21.88 L/s). This seasonal fluctuation indicates that the Pali River is strongly influenced by rainfall variability and has limited low-flow reliability during dry months.

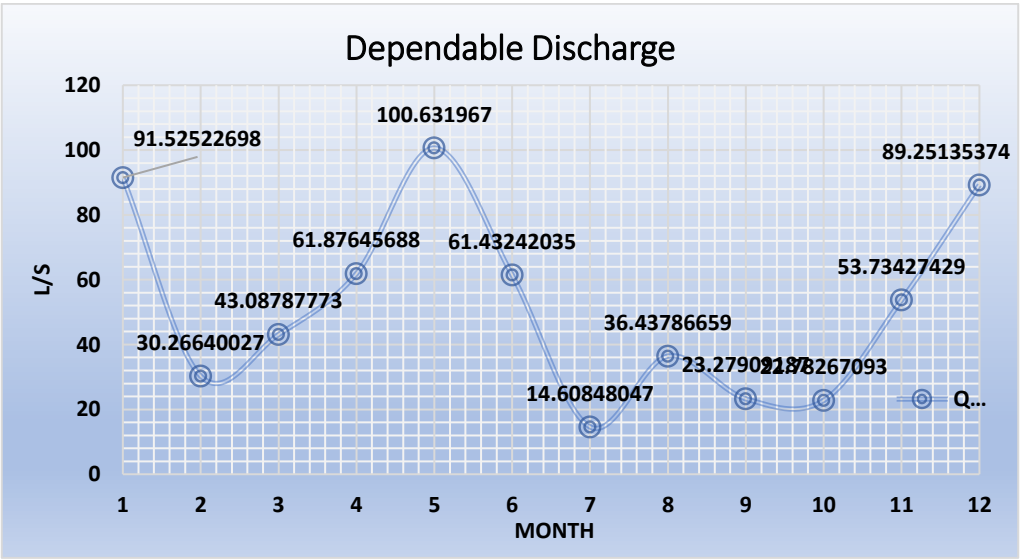


Figure 3. Monthly simulated discharge of the Pali River under baseline conditions before mining disturbance. The discharge series was used to derive the Q90 dependable discharge for raw water reliability assessment.

The monthly simulated discharge series was subsequently ranked and analyzed using exceedance probability to determine the dependable discharge. Based on the Q90 criterion, the dependable discharge of the Pali River under baseline non-mining conditions was estimated at 17.19 L/s. This value represents the discharge that can be expected to be equaled or exceeded 90% of the time and is therefore used as the basis for assessing the reliability of the river as a raw water source.

Compared with the projected average clean water demand of 36.19 L/s in 2045, the baseline dependable discharge is insufficient to meet future demand under critical low-flow conditions. This result indicates that even before considering mining-induced watershed reduction, the Pali River alone may not be able to provide a reliable long-term raw water supply for Maba City. Therefore, watershed protection, additional storage, and alternative raw water source development are required to improve future water security.

Mining Scenario 1 (Left-Side Mining)

This scenario assumes that nickel mining activities occur on the left side of the Pali River watershed. Under this condition, the effective watershed area is reduced from 1.75 km^2 to 0.733 km^2, as determined using geospatial analysis and GIS-based processing with Global Mapper **(Figure 4)**. To provide an initial assessment of mining impacts on raw water availability, the analysis assumes that dependable discharge decreases proportionally with the reduction in effective watershed area. Based on this assumption, the dependable discharge is estimated to decrease from 17.195 L/s under the baseline condition to 7.20 L/s under Mining Scenario 1.

This estimate should be interpreted as a scenario-based approximation rather than the result of a physically distributed hydrological simulation. Potential changes in infiltration, runoff generation, groundwater recharge, sedimentation, and water quality were not explicitly modeled and therefore introduce uncertainty into the estimate.

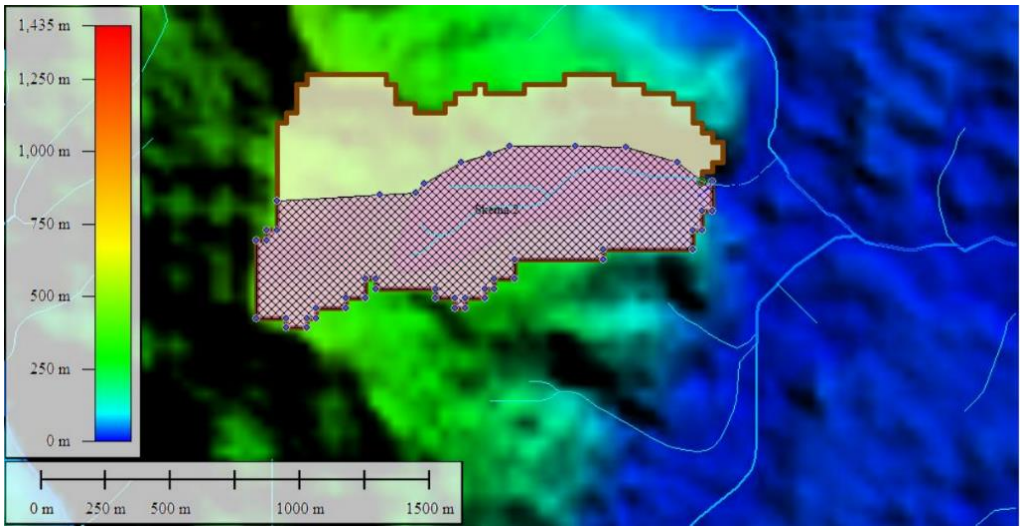


Figure 4. Watershed Contraction due to Nickel Mining Scenario 1

Mining Scenario 2 (Worst-Case Mining)

Figure 5 presents the worst-case mining scenario, in which nickel mining activities substantially reduce the effective watershed area contributing to the Pali River. Under this scenario, the remaining catchment area is only 0.297 km^2, representing an 83.00% reduction from the baseline watershed area of 1.750 km^2. This condition indicates that most of the natural catchment area that supports runoff generation and dry-season baseflow would be lost or disturbed if mining activities are allowed to expand within the watershed boundary.

Using the proportional watershed-area scaling approach, the dependable discharge decreases from 17.19 L/s under baseline conditions to only 2.92 L/s under Mining Scenario 2. This sharp reduction demonstrates the high sensitivity of the Pali River to catchment contraction. Because the Pali River is a small watershed, even partial loss of the contributing area can significantly reduce its ability to provide reliable raw water during low-flow periods.

The comparison of all scenarios is summarized in **Table 3**. Under the baseline condition, the Pali River has a watershed area of 1.750 km^2 and a dependable discharge of 17.19 L/s. Although this represents the highest discharge among the assessed scenarios, it remains lower than the projected average water demand of 36.19 L/s in 2045. Therefore, the Pali River alone is not sufficient to meet future water demand even under non-mining conditions. The situation becomes more critical under the mining scenarios. In Mining Scenario 1, the watershed area decreases by 58.10%, reducing dependable discharge to 7.20 L/s. In Mining Scenario 2, the watershed area decreases by 83.00%, and dependable discharge declines further to 2.92 L/s. These results confirm that mining-induced watershed reduction would substantially worsen the raw water deficit in Maba City.

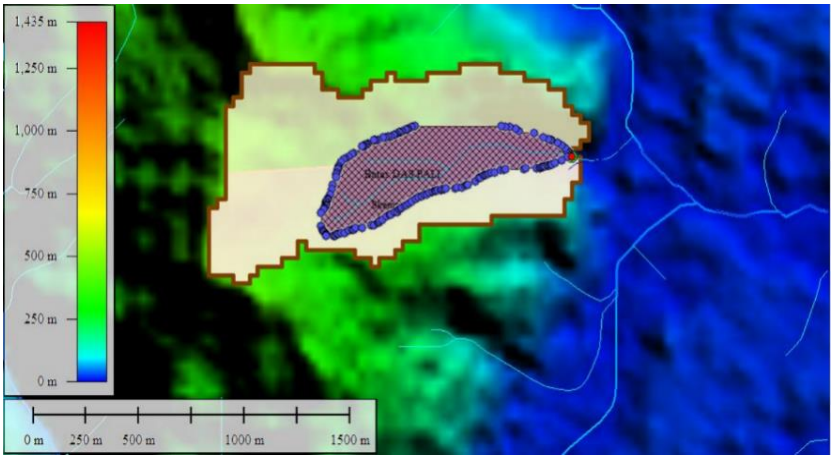


Figure 5. Worst-case nickel mining scenario showing substantial contraction of the effective Pali River watershed area. Under this condition, the remaining catchment area decreases to 0.297 km^2, resulting in a significant reduction in dependable discharge

Overall, **Table 3** indicates that none of the assessed watershed conditions can meet the projected average water demand in 2045. This finding highlights two important implications. First, the Pali River watershed must be protected from mining activities to prevent further reduction in dependable discharge. Second, watershed protection alone is not sufficient to ensure long-term water security; therefore, alternative raw water sources, storage facilities, and water demand management strategies should be developed to support sustainable water infrastructure planning in Maba City.

Table 3. Comparison of watershed area, area reduction, dependable discharge, and water supply adequacy under baseline and nickel mining-affected scenarios

Scenario	Watershed Area (km2)	Area Reduction (%)	Dependable Discharge (L/s)	Projected Average Water Demand in 2045 (L/s)	Ability to Meet 2045 Demand
Baseline Condition (No Mining)	1.750	0.00	17.19	36.19	Not Sufficient
Mining scenario 1 (Left - Side Mining)	0.733	58.10	7.20	36.19	Not Sufficient
Mining scenario 2 (Worst – Side Mining)	0.297	83.00	2.92	36.19	Not Sufficient

Recommendations for Future Alternative Raw Water Source Investigations

The dependable discharge analysis indicates that the Pali River alone may be insufficient to satisfy future water demand under critical hydrological conditions. Therefore, additional raw water sources should be investigated as part of long-term water supply planning for Maba City. Potential alternative sources include surface water from the Sangaji River and groundwater resources in the vicinity of the existing water treatment plant. However, this study did not assess the hydrological

capacity, water quality, pumping requirements, transmission distance, or hydrogeological feasibility of these alternatives. Consequently, these options should be regarded as preliminary recommendations that require further technical investigation before implementation.

Water Quality Analysis

Water quality is an important component of raw water suitability and should meet the requirements of quantity, continuity, quality, and affordability. Water quality testing conducted in this study indicated a manganese (Mn) concentration of 0.9 mg/L, which exceeds the applicable water quality standard of 0.5 mg/L. The elevated manganese concentration suggests that water treatment is required prior to distribution. Therefore, the use of manganese removal filter media is recommended, with treatment capacity adjusted to the planned production capacity of approximately 30–40 L/s. It should be noted that this study was limited to the available manganese data and did not include a comprehensive assessment of other physical and chemical parameters, such as pH, turbidity, TSS, TDS, iron (Fe), nickel (Ni), chromium (Cr), or other mining-related contaminants. Future studies should incorporate a broader water quality monitoring program to better evaluate the potential impacts of nickel mining on raw water quality.

CONCLUSION

This study assessed the reliability of the Pali River as a raw water source for Maba City, East Halmahera, under future demand and nickel mining-induced watershed reduction scenarios. The projected average clean water demand increases to 36.19 L/s by 2045. Under baseline non-mining conditions, the Pali River watershed has an area of 1.75 km^2 and a Q90 dependable discharge of 17.19 L/s. This value is lower than the projected demand, indicating that the Pali River alone is insufficient to meet future water requirements under dependable low-flow conditions. Mining-induced watershed contraction further reduces raw water reliability. Under Mining Scenario 1, the effective watershed area decreases to 0.733 km^2 and dependable discharge decreases to 7.20 L/s. Under the worst-case scenario, the watershed area decreases to 0.2973 km^2 and dependable discharge decreases to 2.92 L/s. These results highlight the high vulnerability of small tropical watersheds to mining-related catchment disturbance. Protection of the entire Pali River watershed is essential to preserve its function as a gravity-fed raw water source. However, watershed protection alone is insufficient to meet projected demand. Therefore, Maba City requires an integrated water security strategy that includes alternative raw water source development, storage infrastructure, demand management, leakage reduction, and continuous water quality monitoring. The elevated manganese concentration of 0.9 mg/L also indicates the need for appropriate treatment before distribution. Future studies should apply physically based hydrological modeling and comprehensive water quality assessment to better quantify the long-term impacts of nickel mining on raw water sustainability.

AUTHOR CONTRIBUTIONS

Conceptualization, HTT and BT; methodology, HTT, M, and S; software, S and BSG; validation, BT and BSG; formal analysis, HTT and M; investigation, HTT, M, and S; resources, HTT and BT; data curation, M and S; writing—original draft preparation, HTT; writing—review and editing, HTT, BT, and BSG; visualization, S and M; supervision, BT and BSG; project administration, HTT; funding acquisition, HTT.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest concerning the publication of this article. The authors also confirm that the data and the article are free of plagiarism.

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