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Research Article

Application of QUAL2K for Water Quality Impact Assessment of Mining-Impacted River: A Case Study of Sungai Rui, Perak

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Abstract

Tin mining activities pose significant environmental risks, particularly to adjacent water bodies, by releasing pollutants that degrade water quality and disrupt aquatic ecosystems. This study investigates the water quality impacts of tin mining in the upstream region of Sungai Rui, Perak, a tropical river system that supports the endemic *Thynnichthys thynnoides*. Using the QUAL2K water quality model, five scenarios were simulated to assess the effects of mining phases and management practices on key water quality parameters, with a focus on total suspended solids (TSS), biochemical oxygen demand (BOD), pH, and ammoniacal nitrogen (NH_3-N). Results revealed that during construction without mitigation, TSS levels at the project site (WQ9) increased from a baseline of 49.84 mg/L (NWQS Class II) to 3,979.86 mg/L (Class V). Under tailing pond outburst conditions, BOD at WQ3 (Sg. Rui–Perak confluence) rose from 3.19 mg/L (Class II) to 23.73 mg/L (Class V), and NH_3-N spiked from 0.155 mg/L to 11.39 mg/L (Class V). pH levels also dropped from 7.65 to 6.08, indicating increased acidity. The application of best management practices (BMPs) during construction significantly reduced TSS to 47.97 mg/L, showing near-baseline recovery. These findings underscore the severe impact of unmitigated mining activities on river water quality and highlight the importance of BMPs and regulatory enforcement. The model also illustrates the limited dilution capacity of downstream rivers under high pollution loads, reinforcing the need for preventive measures at the source.

Keywords: environmental impact assessment, TSS, mining, pollution, water quality modelling

1. INTRODUCTION

Mining activities, especially tin mining, have long been recognized as a significant source of water pollution in river ecosystems. These activities introduce various pollutants such as heavy metals, suspended solids, and acidic runoff that degrade water quality and threaten aquatic biodiversity [1]-[4]. Production of severe mineral-contaminated discharge waters is observed worldwide at active and abandoned mine site. In many regions, including Malaysia, historical and ongoing mining operations have disrupted ecological balance, particularly in upstream river stretches where mitigation measures are often lacking or poorly enforced Sungai Rui in Perak, Malaysia, is one such river under stress due to mining-induced pollution [5][6]. In 2014, the river experienced a significant fish kill incident linked to mining activities upstream, raising public health and ecological concerns. The species *Thynnichthys thynnoides*, endemic to this river, has been particularly affected, jeopardizing both biodiversity and local livelihoods [7]. Additionally, arsenic levels in Sungai Rui have exceeded safe thresholds, forcing the closure of the Air Ganda Water Treatment Plant since 2019 [8].

To better understand and mitigate these impacts, water quality modelling tools are essential. The QUAL2K model, developed by the US EPA, has been widely used to simulate pollutant behavior in streams and rivers, offering critical insights into the influence of human activities on water bodies using analytical and statistical techniques during various scenarios [9]-[11]. Changes in river flow due to human activities can impact water quality parameters, necessitating scenario-based modelling tools like QUAL2K to assess and predict these effects [12]-[14]. In tropical rivers of Malaysia, a well-documented research study was conducted across the country using the QUAL2K model [15]-[17]. Among available free modelling tools, QUAL2K is particularly advantageous due to its simplicity, low data requirements, and suitability for one-dimensional river systems. Unlike more complex free models such as SWAT or HEC-RAS, QUAL2K allows straightforward simulation of point and non-point source pollution with user-

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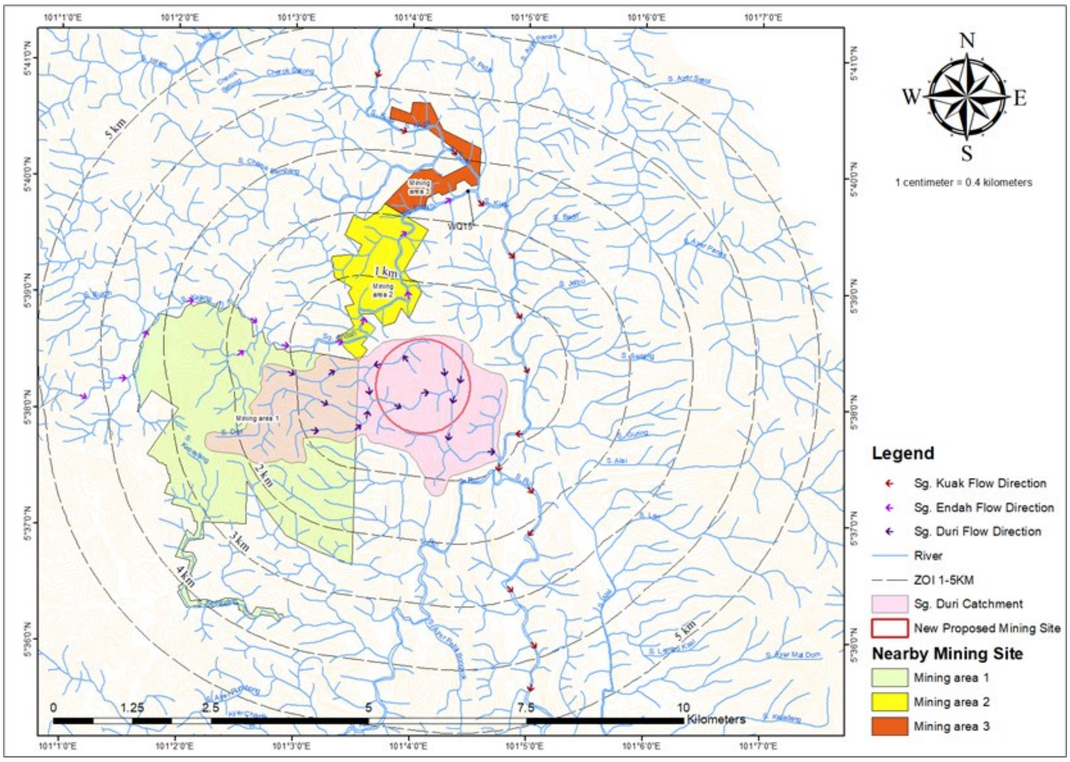


Figure 1. Rivers in proximity to project site.

friendly scenario testing. This makes it ideal for assessing localized impact such as those from mining without requiring extensive spatial datasets or specialized modelling expertise. However, few studies in Malaysia have applied QUAL2K specifically for mining-impacted tropical rivers, and fewer still have focused on modelling multiple environmental management scenarios.

This study aims to fill that gap by using the QUAL2K framework to assess the water quality impacts of tin mining in the Sungai Rui catchment. It models five different scenarios ranging from baseline conditions to worst-case tailing pond failures focusing on parameters such as total suspended solids (TSS), pH, biological oxygen demand (BOD), and ammoniacal nitrogen (NH_3-N). This work provides much-needed data to inform best management practices (BMPs), supports environmental planning, and contributes to safeguarding water resources in mining-impacted regions.

2. MATERIALS AND METHODS

2.1. Study Area

This proposed mining area is located 2 km from one of the oldest tin mining sites in Malaysia (Fig. 1), situated in Klian Intan, which also lies within the Baling Formation. The Klian Intan area in Upper Perak has a long history and is considered one of the largest mining sites, with activities first starting in 1850, making it operational for approximately 170 years [18].The study area lies between the latitudes 5° 38' 36.81"N and 5° 37' 56.28"N and longitudes 101° 3' 34.62"E and 101° 4' 47.94"E of district Pengkalan Hulu, Perak, Peninsular Malaysia. The elevation is dominated by hilly areas that are undulated between 180 and 360 m above mean sea level. The slopes are gradual with localized steep gradients from 25° to 34°.

A 88% of the total project site is located within the Sg. Duri catchment, which spans an extensive area of over 671 ha. The river's headwater emerges from the active mining site. It flows into the project site and continues for 1.4 km beyond the project boundary, passing through a secondary forest before eventually discharging into Sg. Kuak at their confluence. The climate is tropical and humid, with an average temperature ranging from 25.4 and 27.2 °C. The monthly rainfall recorded at Hospital Lenggong Meteorological Station from 2021 to 2022 ranged between 15.3 to 470.9 mm. The highest monthly rainfall was recorded in October 2021 (470.9 mm) while the lowest monthly rainfall was recorded in January 2022 (15.3 mm). The simulation exercise will focus on modeling stretches of Sg. Duri, Sg. Kuak, Sg. Rui and Sg. Perak to assess the impacts on waterways within the catchment area of the proposed project site, as well as the receiving waterways and sensitive areas affected by the project's commencement.

2.2. Data Collection and Processing

The sampling activities for water quality monitoring were conducted twice, from February 1st to 2nd, 2023, and from March 20th to 22nd, 2023. On-site testing of pH, temperature, and dissolved oxygen (DO) was conducted. In the laboratory, physical and chemical parameters were measured, such as turbidity, BOD, NH3-N and TSS. A streamflow gauge station was located at Sungai Rui near Jambatan Jalan. Discharge data spanning 30 years were collected from the Department of Irrigation and Drainage, Malaysia.

2.3. Model Formulation

The QUAL2K framework simulates the migration and transformation of selected pollutants which focus on TSS, BOD, NH_3N and pH, treating the stream as a one-dimensional channel with non-uniform steady flow and accounting for both point source (PS) and non-point source (NPS) pollution loads. Additionally, the model can simulate changes at user-defined time steps within 1 h throughout the daily cycle [19]. This model is capable of simulating several water quality parameters, including temperature, pH, DO, BOD, TSS, nutrients (e.g., NH_3-N, NO_3-N), and algae dynamics [20]. In this study, the selected parameters which are TSS, BOD, pH, and NH_3N were chosen due to their direct relevance to mining-related pollution and their impact on water quality. TSS is a key indicator because it reflects sediment transport and the presence of heavy metals. NH_3-N and BOD were included for their sensitivity to organic and nitrogen pollution commonly found in mine runoff. Although DO was measured during field sampling, it was not modeled due to its complex behavior and dependence on many fluctuating factors like algae activity and temperature. Including it would have made the model more complicated. Therefore, the chosen parameters provided a practical and focused approach for assessing mining impacts on river water quality.

QUAL2K assumes discharge (Q) either in rectangular or trapezoidal-shaped channels. A trapezoidal-shaped channel was used in this study. Channel side slopes (S) were assessed based on the

Table 1. Descriptions and assumptions of scenarios.

No	Scenarios	Treatment
1	Existing condition	Represents baseline conditions for model calibration
2	Construction phase, without mitigation measure	Simulates worst-case conditions during land preparation without BMPs. TSS levels in uncontrolled runoff range from 2,000–4,200 mg/L [25].
3	Construction phase, with mitigation measure	Assumes BMPs are properly implemented, following MSMA (2012) guidelines. Peak discharge events are considered, with sediment basins designed to retain 90% of TSS for rainfall up to 50mm. Expected TSS in runoff and treatment systems is ≤ 50 mg/L (NWQS standard). Parameter: TSS
4	Operation phase with tailing pond outburst condition	Models a sudden tailing pond failure during peak discharge events, releasing pollutants at an estimated 416.0 m^3/s. The tailing input was based on non-compliance towards Mineral Development (Effluent) Regulations 2016*. Parameters: TSS, BOD, and pH
5	Operation phase with tailing pond overflow condition	Simulates tailing pond overflow due to excessive water inflow, with an estimated discharge of 16.0 m^3/s. The tailing input was based on non-compliance towards Mineral Development (Effluent) Regulations 2016*. Parameters: TSS, BOD, and pH

*The input used based on non-compliance towards Mineral Development (Effluent) Regulations 2016, column 3; TSS>50 mg/l, BOD_5>20, pH=3.5

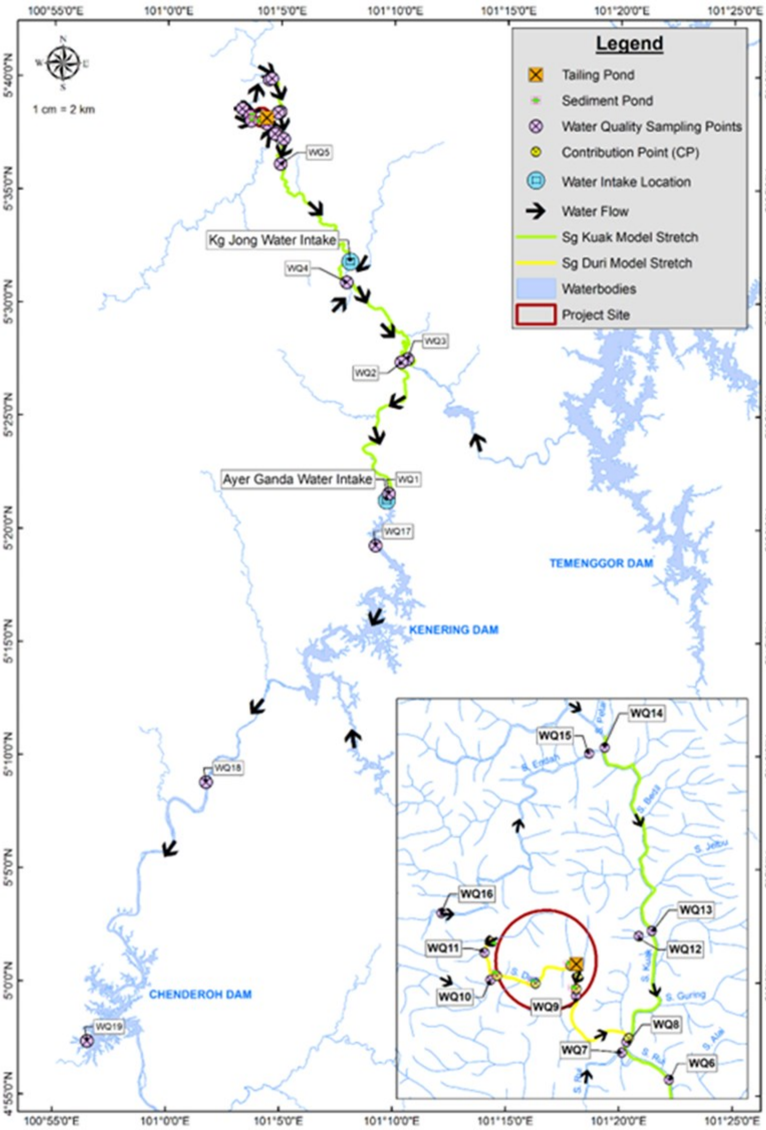


Figure 2. The point sources and water quality stations of the modelling stretch.

field survey. The channel bottom width (B_o) was estimated based on the top width and measured from the field survey. Reach depth (H) was measured from field survey. Using side slopes, bottom width, and reach depth, the cross-sectional area (Ac) was calculated by Eq. 1.

$$A_c = [B_o + 0.5 (S_1 + S_2) H]H \quad (1)$$

Velocity (v) of reach was calculated by Eq. 2.

$$v = \frac{Q}{A_c} \quad (2)$$

2.4. Scenario Selection Criteria

The model has the capability of simulating multiple scenarios, but only 5 scenarios have been tested to predict water quality impacts at the proposed site. The model assumes that non-point sources from groundwater diffusion are insignificant and therefore ignored due to the Baling Formation in the Gerik area of Perak, Malaysia, which is primarily composed of the Grik Siltstone, dating from the Upper Ordovician to Lower Silurian periods [21]. The presence of interbedded pyroclastic rocks further reduces hydraulic conductivity, restricting groundwater flow into the river system [22][23]. Consequently, due to the predominance of low-permeability siltstone and associated rock formations, the contribution of groundwater to surface water in this area is expected to be minimal [21][24]. Water quality impacts were modeled based on 5 different pollutant-treatment scenarios as mentioned in Table 1.

2.5. Peak Discharge

In order to assess the increase in runoff as a result of the proposed development, peak discharge value for each development phase was estimated by using rational method, which is recommended in Urban Stormwater Management Manual for Malaysia 2012 (MSMA), for catchment less than 80 ha. Peak discharge estimation was carried out on the storm event for 10 and 100 years return period for 3 different conditions, namely; pre-development stage (entirely covered by forest); mining stage; and post-development stage (entirely covered with crops). These estimates were important for modeling NPS pollution. For Scenario 2, 4 and 5, a higher runoff coefficient (C ≈ 0.7–0.9) was applied to represent exposed and compacted surfaces during active construction and mining activity, which generate more runoff. In Scenario 3, a lower coefficient (C ≈ 0.3) was used to reflect the effect of BMPs such as sediment basins and vegetated buffer zones. The resulting discharge values were used in the QUAL2K model to simulate runoff volume and TSS loading during rainfall events, allowing the study to assess the water quality impacts of land clearing with and without mitigation. The formula for the rational method shown in Eq. 3.

$$Q_y = \frac{C \cdot yI_t \cdot A}{360} \qquad (3)$$

where, Q_y y year average recurrence interval (ARI) peak flow (m^3/s), C is dimensionless runoff coefficient, yI_t is y year ARI average rainfall intensity over time of concentration (mm/h), and A is drainage area (ha).

2.6. Model Calibration and Validation

For calibration purposes (Table S1), the water quality data obtained in March 2023 was used. Multiple baseline water monitoring points were strategically positioned at different sections of the river, specifically where it receives discharge from nearby active mining activities. All parameters were calibrated and validated before QUAL2K modeling. The model parameters were calibrated through an iterative trial and error process until the simulated

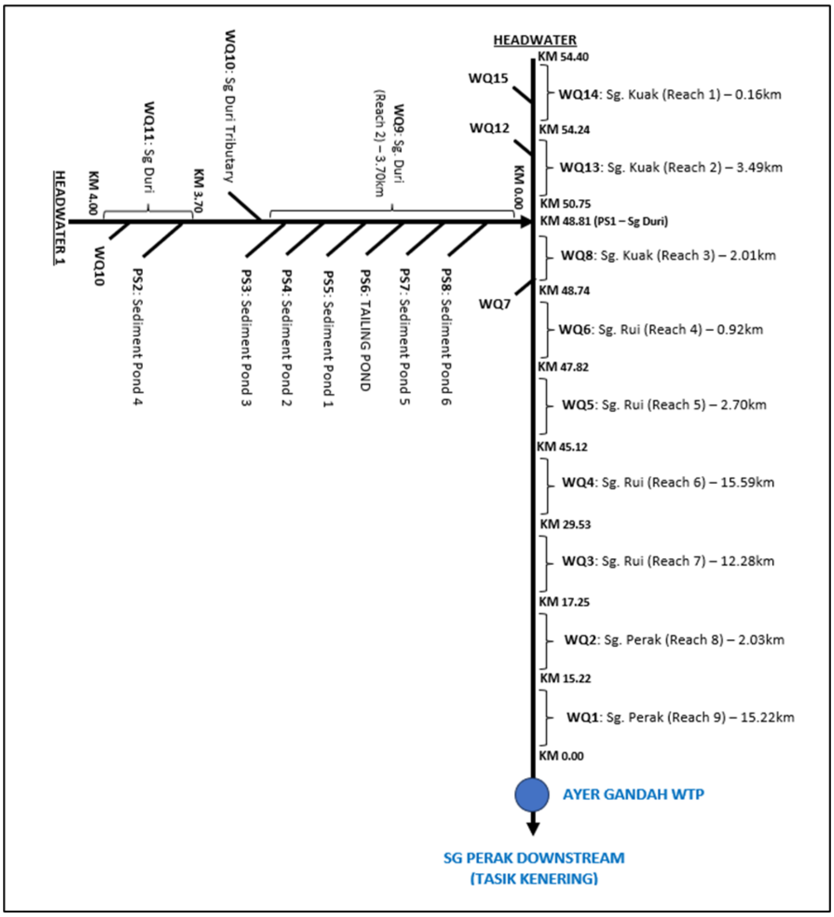


Figure 3. Schematic diagram of modelling stretch.

Table 2. Summary of the data obtained from in-situ and laboratory measurements.

Parameter	Min	Max	Avg	Standard Deviation	Method	Detection Limit	Class IIA Limit*
pH	3.15	7.75	7.04	1.09	YSI Professional Plus	-	6.0-9.0
Conductivity (µS/cm)	50.2	1799	371	495.38	YSI Professional Plus	-	1000
NH_3N (mg/l)	0.131	0.547	0.282	0.12	APHA 4500 NH_3 – B	0.005	0.3
Temp (°C)	25.1	33.2	29	2.32	YSI Professional Plus	-	Normal +2°C
DO (mg/l)	4.09	7.79	6.59	1.06	APHA 4500 O-G (2005)	-	5.0–7.0
Turbidity (mg/l)	3.5	139.95	34.53	33.98	APHA 2130 B	0.01	50
BOD_5 (mg/l)	2	3	2.68	0.47	APHA 5210 B (2005)	2	3
COD (mg/l)	12	24	17.63	3.35	APHA 5220 C (2005)	1	25
TSS (mg/l)	10	129	42.63	35.06	APHA 2540 D (2005)	0.5	50
TDS (mg/l)	22	736	184.1	208.72	APHA 2540 C	0.5	1000

** National Water Quality Standards, Department of Environment (DOE) Malaysia; *ND is not detected*

results closely matched the observed data.

2.7. Model Setup

A schematic, or schematic diagram, is a representation of the elements of a system using abstract, graphic symbols rather than realistic pictures. The map showing the point sources and water quality stations of the modelling stretch are shown in Figure 2 while the simplified form in schematic diagram version is shown in Figure 3.

3. RESULTS AND DISCUSSIONS

3.1. Baseline Water Quality Results

Chemical parameters were analyzed according to the standard methods [26]. The accuracy and precision of the data were above 95%. A summary of the data is given in Table 2.

3.2. River Hydraulic Data

The average surveyed hydraulic data for each station are presented in Table 3. The channel slope was measured using a digital elevation model (30 m resolution) and Google Earth. Sixteen cross-section stations were surveyed using current-meter measurements by wading, from bridges, and from a stationary boat [27].

3.3. River Discharge

River discharge (Q), is a key parameter that influences water quality and pollutant transport in river systems. For this study, the discharge values used in the QUAL2K simulations were based on different development scenarios to reflect potential changes in flow conditions. Figure 4 present the discharge patterns for Sg. Duri and Sg. Rui-Perak, respectively, under various modeled scenarios.

3.4. Simulation Results

The simulation results presented in Figure 5 to Figure 8 illustrate the spatial variation of key water quality parameters—TSS, pH, BOD, and NH_3-N under various modeled scenarios. These scenarios include baseline (existing) conditions, construction with and without mitigation, and operational-stage incidents such as tailing pond overflow or failure. The results are shown separately for the Sg. Duri sub-catchment and the downstream reaches of Sg. Kuak, Sg. Rui, and Sg. Perak to highlight both localized and cumulative impacts. Each parameter is evaluated in reference to the National Water Quality Standards (NWQS) to assess compliance levels and the potential severity of mining-related disturbances on water quality along the river.

3.5. Discussion

3.5.1. Impacts During Construction Stage

3.5.1.1. TSS

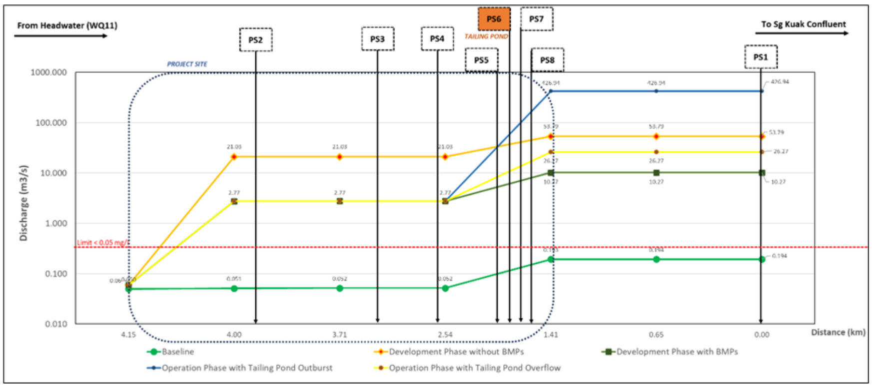
Based on the field survey results, Sg. Duri generally has higher levels of TSS with a class II-averaged condition compared to the Sg. Rui-Perak stretches, which is generally within the class I condition. Specifically, during the wetter season, the TSS value exceeds 240 mg/L at one of Sg. Duri's tributaries, WQ 11, may be attributed to runoff water from active mining sites, with a notable impact in the upper region. However, as the water flows downstream into the mainstream of Sg. Duri, the TSS levels quickly recover and remain within Class II limits before discharging into Sg. Kuak.

On the other hand, the ambient concentration of TSS in the Sg. Rui-Perak stretch recorded a commendable level, averaging to stay below the NWQS class II limit. This indicates that the water quality in the Sg. Rui-Perak stretch demonstrates favorable environmental conditions in comparison to Sg. Duri, which experiences higher TSS levels. In the context of this project, TSS loading may potentially be released into the waterways during mining construction activities. The predominant factors contributing to TSS loading are the clearing activities from the project site, including grubbing and total removal of vegetation using excavators and heavy equipment. If the land is left exposed, rapid particle displacement during high rainfall via runoff will be exacerbated.

The TSS simulated events showed varying results (Figure 5). When simulating BMP failure during construction, it became evident that the absence of functioning BMPs caused a significant

Table 3. River hydraulic data.

Station	Average				River
	Width (m)	Depth (m)	Velocity (m/s)	Q (m^3/s)	
WQ1	120.00	4.60	0.10	55.20	Sg. Perak
WQ2	70.00	2.49	0.76	132.99	Sg. Perak
WQ3	46.00	0.78	0.31	11.00	Sg. Rui
WQ4	24.00	0.49	0.83	9.65	Sg. Rui
WQ5	13.50	1.04	0.65	9.10	Sg. Rui
WQ6	25.50	0.69	0.45	7.89	Sg. Rui
WQ7	18.00	0.47	0.83	7.00	Sg. Rui
WQ8	10.50	0.58	0.85	5.13	Sg. Kuak
WQ9	2.00	0.12	0.80	0.192	Sg. Duri
WQ10	1.25	0.11	0.80	0.11	Sg. Duri
WQ11	3.10	0.13	0.13	0.05	Tributary Sg. Duri
WQ12	0.65	0.03	0.30	0.006	Tributary Sg. Kuak
WQ13	8.70	0.46	0.58	2.34	Sg. Kuak
WQ14	18.70	0.32	0.37	2.22	Sg. Kuak
WQ15	4.70	0.24	0.67	0.76	Sg. Endah
WQ16	3.80	0.25	0.47	0.44	Sg. Endah
WQ17	-	-	-	-	Kenering Dam
WQ18	180.00	1.54	0.60	166.80	Sg. Perak
WQ19	-	-	-	-	Chenderoh Dam



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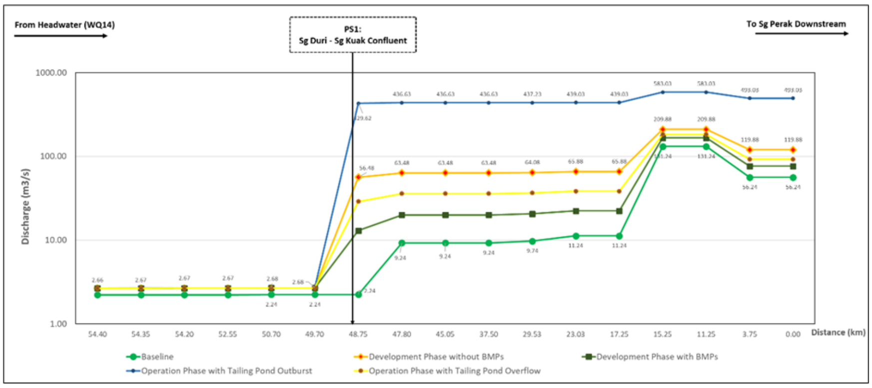
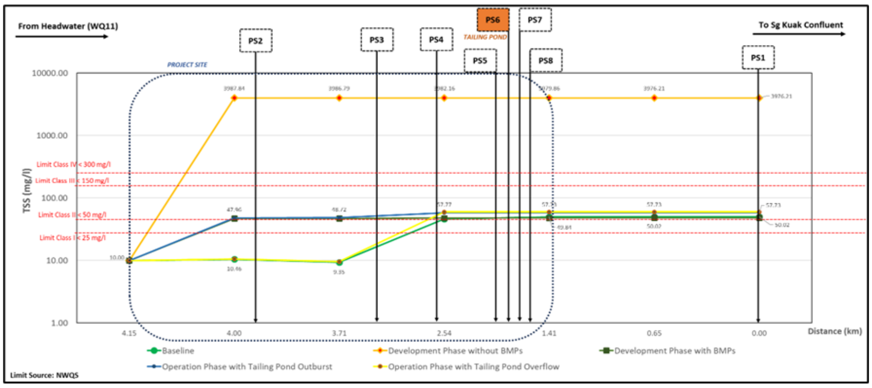


(b)

Figure 4. Discharge at different scenarios (a) , Q of Sg. Duri; (b) Q of Sg. Rui-Perak.



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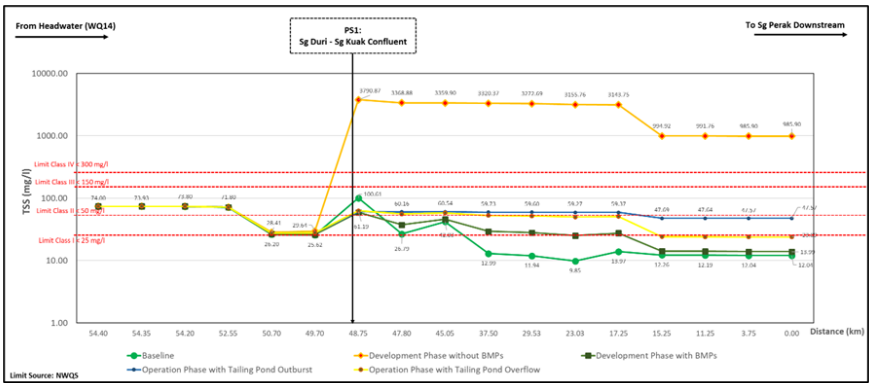
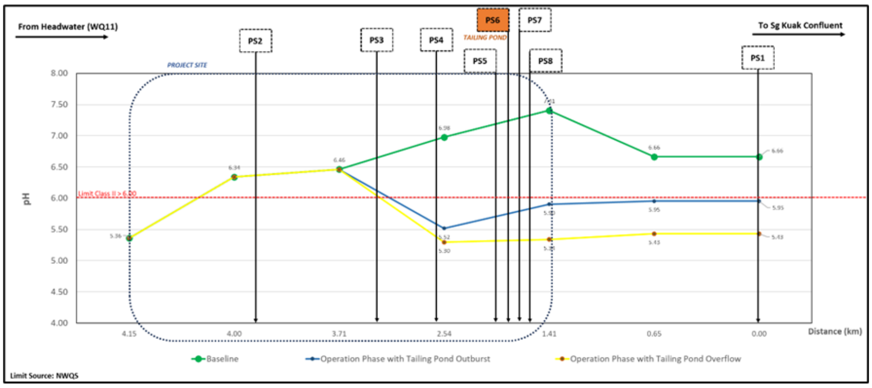


(b)

Figure 5. TSS simulations (a) Sg. Duri; (b) Sg. Kuak/Rui/Perak.



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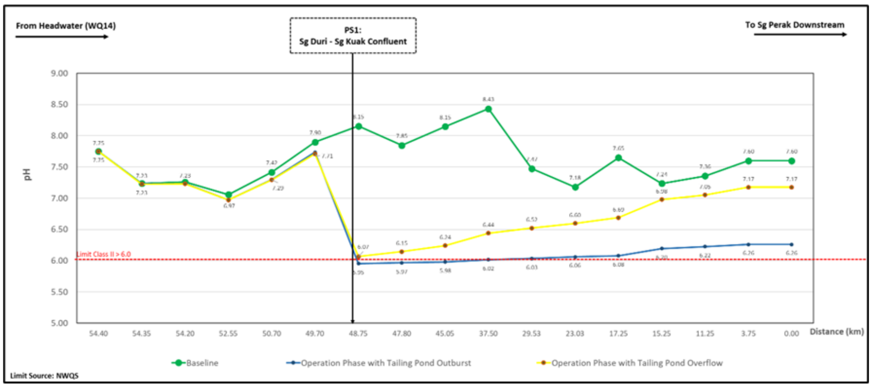

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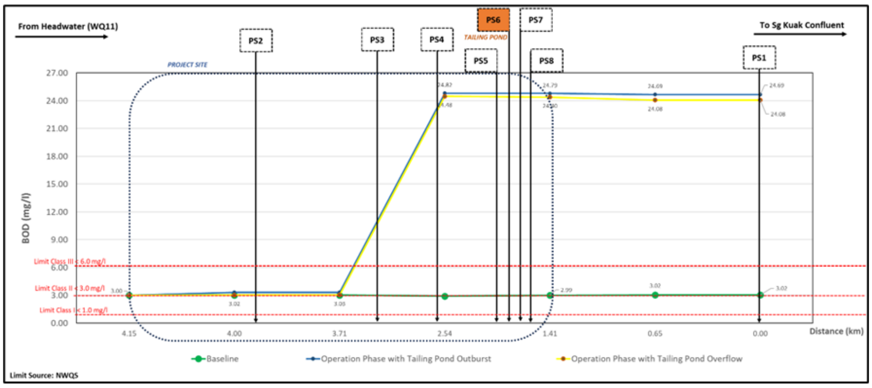
Figure 6. pH simulations (a) Sg. Duri; (b) Sg. Kuak/Rui/Perak.



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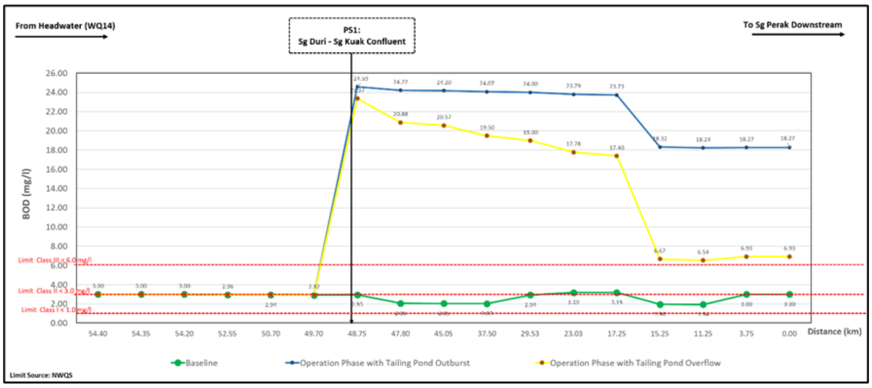
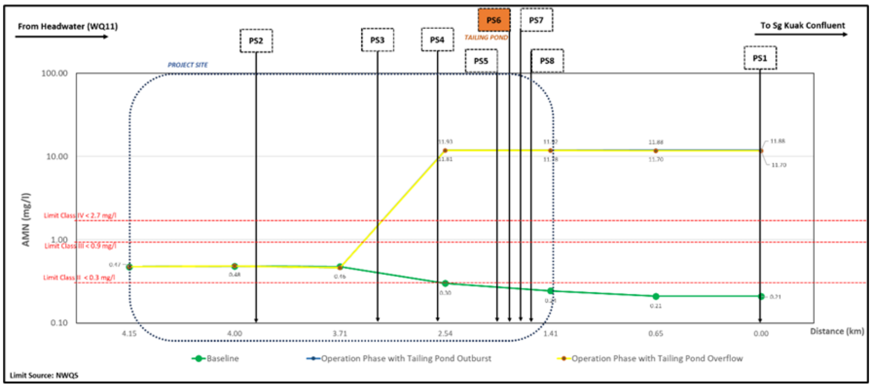


(b)

Figure 7. BOD simulations (a) Sg. Duri; (b) Sg. Kuak/Rui/Perak.



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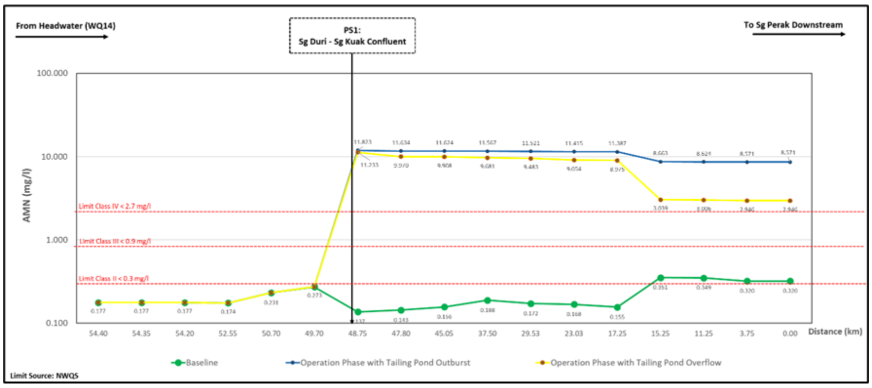

(b)

Figure 8. NH_3-N simulations (a) Sg. Duri; (b) Sg. Kuak/Rui/Perak.

increase in TSS concentration in water quality, particularly in Sg. Duri, where levels peaked at over 3900 mg/L. This TSS-laden water then flowed into Sg. Kuak and eventually flow into Sg. Rui and Sg. Perak. The dilution factor from Sg. Rui and Sg. Perak appeared to be insufficient to restore the original TSS class II of their respective downstream reaches if all recommended BMPs were not in place. A gradual decline in TSS concentration to over 900 mg/l was observed downstream at WQ 1. It is therefore recommended that a series of sediment basins and silt traps be constructed for each of the receiving water bodies to address this potential issue. The construction of sediment basins and buffer zones would result in a significant reduction of TSS levels (Scenario 3) and would allow the ambient values to return to their baseline condition. Buffer and riparian zones can be utilized as a method to manage non-point-source pollution. These areas play a crucial role in preventing pollutants from entering water bodies and preserving water quality by slowing down runoff, allowing pollutants to settle or be filtered, and transforming pollutants through biological or chemical processes [28][29]. Future implications include the need for stricter enforcement of BMP installation before site clearance begins, and the use of real-time turbidity sensors in sediment basins to ensure effectiveness during rainfall events. A predictive model like QUAL2K can also be used as a pre-assessment tool in environmental impact assessments (EIA) for future mining projects.

3.5.2. Impacts during Mining and Ore Processing Stage

In addition to the construction stage, the operational stage was also considered in scenarios 4 and 5. The main sources of pollution during this stage include overburden material transported by surface runoff and the failure of tailing pond operations.

3.5.2.1. TSS

In the operational phase of the mining project, the primary sources of pollution are the overburden materials carried by surface runoff and the potential failure of the tailing pond operation. During the overburden removal stage, a large amount of soil and other unwanted materials may be transported into nearby waterways if not properly managed. Regarding the TSS runoff impacts (Figure 5), while not as pronounced as during earthwork activities, still exhibited visibility, particularly in the rainy season. Based on simulated results, in the event of high surface runoff and a tailing pond burst or overflow, the TSS level in Sg. Duri increased and remained within the class III limit, in contrast to the average baseline class II condition. As water flowed into Sg. Perak, downstream TSS levels at WQ 1 transitioned from class I to class II during the tailing pond burst condition, with a recorded value of 47.47 mg/L. Conversely, under tailing overflow conditions, the TSS level rose from 12.04 to 23.89 mg/L. While the class II condition remained unchanged, the value experienced a slight increase compared to the baseline condition.

3.5.2.2. pH

Under baseline conditions, pH remains neutral to slightly alkaline (6.66–7.65) (Figure 6), falling within class II limits. Notably, pH increases slightly downstream (e.g., from 7.41 at WQ9 to 7.60 at WQ1), due to dilution and buffering effects from tributaries such as Sg. Kuak and Sg. Rui. However, in scenarios 4 and 5, acid drainage from tailing pond events introduces highly acidic water (pH < 6), dropping pH to class III–V levels. For example, WQ9 declines to 5.90 (Scenario 4) and 5.34 (Scenario 5), worsening as water reaches PS1 (5.43). Although the Sg. Perak shows some recovery through dilution (pH at WQ1 rises to 6.26 –7.17), the pH remains degraded compared to the baseline. This decline clearly illustrates how under baseline conditions, downstream recovery is possible via dilution. However, when pollutant loads exceed natural assimilative capacity, as in Scenarios 4–5, the buffering effect becomes insufficient. As for management implication, tailing pond pH buffering systems (e.g., lime dosing) should be considered as part of operational BMPs, and pH monitoring stations should be placed at the project's discharge point.

3.5.2.3. BOD

BOD levels under baseline are generally within Class II limits (< 3 mg/L), with WQ9 and WQ1 showing 2.99 and 3.00 mg/L respectively (Figure 7). In contrast, tailing pond outburst (scenario 4) raises BOD at WQ9 to 24.79 mg/L, indicating Class V conditions due to organic loading. Although slight recovery occurs downstream, BOD remains severely elevated at WQ3 (23.73 mg/L) and WQ1 (18.27 mg/L), confirming the impact extends far beyond the project site. In all impacted scenarios, no recovery to class II or even class III is observed downstream, underscoring the persistent nature of organic pollution and the importance of containment strategies upstream. As for mitigation measures it is recommended for the operator to install secondary containment for tailing ponds and prepare emergency response plans including oxygenation systems to mitigate acute BOD shocks.

3.5.2.4. Ammoniacal nitrogen (NH_3-N)

Baseline NH_3-N values range from 0.24 mg/L at WQ9 to 0.155 mg/L at WQ3 (Figure 8), indicating mostly Class II conditions. Under tailing scenarios, levels increase dramatically reaching 11.92 mg/L at WQ9 and 11.387 mg/L at WQ3, both well into class V territory. Hence, NH_3N monitoring should be prioritized in mining site, and proactive nutrient control measures such as vegetated filter strips and nitrogen-binding substrates should be included in BMP design. Interestingly, at WQ1 (KM 0.00), the value decreases to 8.571 (scenario 4) and 2.946 mg/L (scenario 5), suggesting some dilution effect downstream but not enough to bring values back into compliance with class II. Again, this reinforces the role of the confluence and cumulative loading, if pollutant sources upstream exceed a threshold, downstream dilution alone cannot mitigate the impacts. The simulated result summary at selected points are shown in Table S2–Table S4.

4. CONCLUSIONS

Simulation results demonstrated significant variation in pollutant levels along different stretches of the river system. Under baseline conditions, water quality remained within acceptable limits (class I–II) across most monitoring points. However, under stress scenarios particularly during tailing pond outburst or overflow, pollutants such as TSS, BOD, pH, and NH_3-N exhibited sharp increases, especially in upstream locations (WQ9 and PS1). These concentrations exceeded class III–

V thresholds, and the impact persisted downstream, showing that pollution loads travel long distances and degrade water quality beyond the immediate mining zone. The application of BMPs during the construction phase (Scenario 3) significantly reduced TSS to near-baseline levels, confirming the effectiveness of sediment control structures. In contrast, scenarios without BMPs or with tailing pond failures led to extensive degradation, proving that uncontrolled mining activities pose a major risk to river ecosystems. Even with dilution at the confluence (PS1) and downstream reaches (WQ3 and WQ1), the magnitude of pollution under worst-case scenarios exceeded the river's natural buffering capacity, especially for NH_3N and BOD. The simulations clearly show that while natural dilution and river confluences provide some recovery, they are not sufficient to prevent water quality degradation during high-pollution events. Uncontrolled mining scenarios push parameters like TSS, BOD, and NH_3-N into class IV–V levels, violating national standards and threatening downstream water supplies. Future planning must include mandatory simulation modelling during EIA approvals, tighter regulation of tailing pond infrastructure, and long-term water quality monitoring at key downstream points. Overall, the study confirms that without proper mitigation, mining activities can severely compromise water quality across entire catchments. However, effective implementation of BMPs and strict monitoring of tailing facilities can significantly reduce these risks. These insights are critical for informing regulatory decisions, environmental planning, and the protection of downstream water.

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Conflicts of Interest

The authors declare no conflict of interest.

SUPPORTING INFORMATION

Supplementary data associated with this article can be found in the online version at doi: 10.47352/jmans.2774-3047.294

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