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RESEARCH ARTICLE

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# RELATIONSHIP BETWEEN RECLAMATION LAND COVER BASED ON THE NORMALIZED DIFFERENCE VEGETATION INDEX AND VOID WATER CHARACTERISTICS AT MELAWAN PANEL 2

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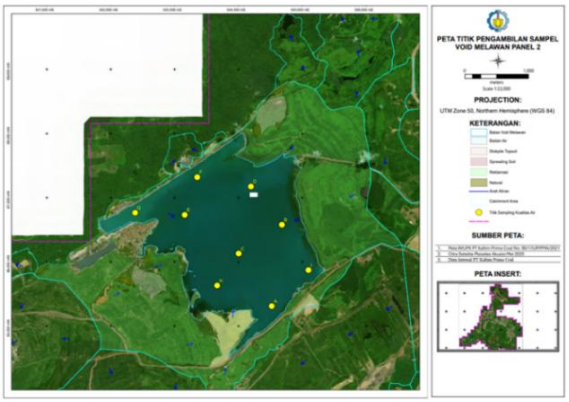
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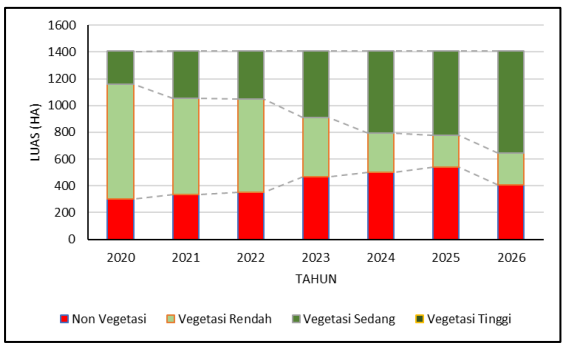
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**Graphical abstract**




**ABSTRACT**
The dynamics of reclamation land cover were assessed using multitemporal Sentinel-2 satellite imagery from 2020 to 2026 and classified into four NDVI categories: non-vegetation, low vegetation, moderate vegetation, and high vegetation. Water quality was evaluated based on pH, Total Suspended Solids (TSS), iron (Fe), and manganese (Mn) through purposive sampling at nine monitoring points across three depth zones (surface, middle, and bottom) during both dry and rainy seasons from 2024 to 2026. Spatial analysis was conducted using QGIS, trend analysis was performed using Kendall's tau-b, and relationships among variables were assessed using Spearman correlation. The results showed that the proportion of moderate vegetation increased significantly from 18% to 54%, while the mean NDVI increased from 0.17 to 0.27 ($\tau$ = 0.851; $p < 0.05$). Void water quality characteristics remained relatively stable and complied with the standards stipulated in the Indonesian Ministerial Decree of Environment No. 113 of 2003. Spearman correlation analysis revealed a strong positive relationship between NDVI and pH ($r = 0.690$; $p < 0.001$) and a strong negative relationship between NDVI and Mn ($r = -0.628$; $p < 0.001$), whereas the relationships between NDVI and TSS and between NDVI and Fe were not statistically significant. These findings indicate that the development of reclamation vegetation within the catchment area is associated with the environmental stability of the void aquatic system.

**Keywords:** Mine void, Reclamation land cover, NDVI, Catchment area, Void water quality.

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## 1. INTRODUCTION

Open-pit coal mining causes significant landscape transformation, one of which is the formation of post-mining excavation basins known as voids. Voids filled with rainwater and surface runoff develop into artificial water bodies whose physicochemical characteristics are governed by complex hydrological and geochemical processes. When sulfide minerals, particularly pyrite ($FeS_2$), exposed during excavation come into contact with oxygen and water, an oxidation reaction occurs, producing ferrous iron ($Fe^{2+}$), sulfate ($SO_4^{2-}$), and hydrogen ions ($H^+$) through the reaction: $FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$. The accumulation of $H^+$ ions lowers water pH and leads to the formation of Acid Mine Drainage (AMD), which subsequently affects water quality parameters such as pH, Total Suspended Solids (TSS), iron (Fe), and manganese (Mn) (Younger *et al.*, 2002; Sánchez-España & Yusta, 2015).

This study was conducted at Void Melawan Panel 2, located within the operational area of PT Kaltim Prima Coal, East Kutai Regency, East Kalimantan Province. The Melawan Panel 2 pit is a post-open-pit coal mining excavation that was fully decommissioned around 2019. Since then, the basin has been filled with rainwater, surface runoff from its surrounding catchment area, and pumped water from adjacent mining areas, forming a permanent void water body with a surface area of approximately ±400 ha. The void depth is estimated to reach tens of meters, making it one of the largest voids within PT KPC's concession area. The catchment area surrounding the void consists of post-mining land that has been progressively reclaimed from 2011 to 2025, with reclamation vegetation dominated by fast-growing pioneer species such as *Paraserianthes falcarataria*, *Senna siamea*, and *Albizia saman*, supplemented by local species including *Vitex pinnata, Shorea spp, Dryobalanops lanceolata* and among others.

The condition of the catchment area plays a critical role in determining water quality in post-mining aquatic systems (Sánchez-España & Yusta, 2015). Catchment areas govern surface runoff, erosion, and sediment transport toward water bodies. Areas with adequate vegetation cover generally exhibit lower runoff and erosion rates compared to exposed land (Asdak, 2023). In the context of post-mining management, reclamation activities are conducted to restore degraded environments. The development of reclamation vegetation may affect surface hydrological conditions through increased infiltration and reduced erosion. Evaluation of reclamation vegetation conditions is therefore important for understanding its association with water quality in void aquatic systems.

Remote sensing approaches based on the Normalized Difference Vegetation Index (NDVI) have been widely employed to evaluate reclamation vegetation development in a spatially and temporally explicit manner, as they can represent vegetation density through multispectral imagery analysis (Blachowski *et al.,* 2023). Nevertheless, studies specifically integrating NDVI-based reclamation land cover dynamics with void water quality characteristics remain relatively limited

Based on these conditions, this study aims to: (1) analyze the dynamics of NDVI-based reclamation land cover within the catchment area of Void Melawan Panel 2 for the period 2020–2026; (2) evaluate void water quality characteristics based on pH, TSS, Fe, and Mn parameters for

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the period 2024–2026; and (3) examine the relationship between reclamation vegetation conditions and void water quality characteristics.

## 2. METHODS

### Study Area

The study was conducted at Void Melawan Panel 2, located within the operational area of PT Kaltim Prima Coal, East Kutai Regency, East Kalimantan Province. The study area encompasses the void water body and its catchment area, which directly contributes to surface runoff flowing into the void. The research location map and water quality sampling points are presented in Figure 1.

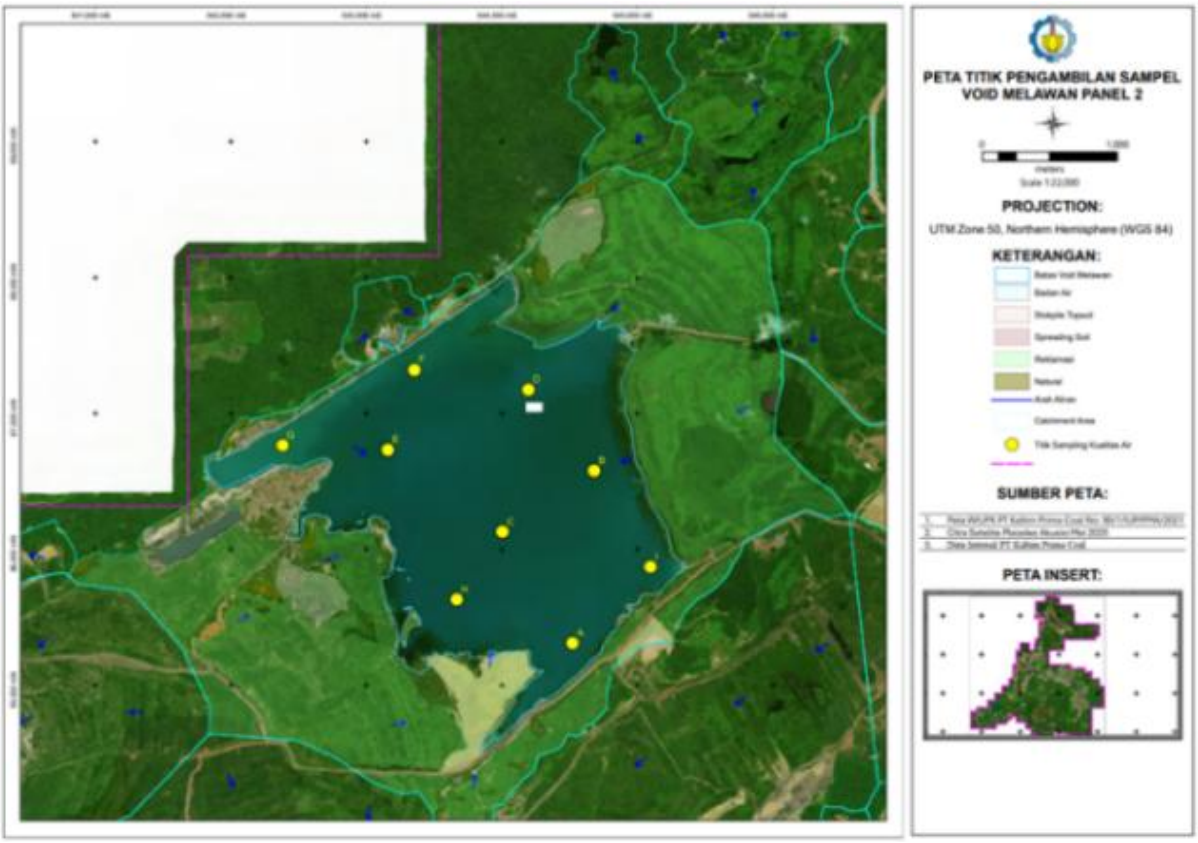



**Figure 1** Location Map and Water Quality Sampling Points of Void Melawan Panel 2

### Data Collection

#### a. Land Cover Data (NDVI)

Land cover data were acquired from Sentinel-2 Level-2A (surface reflectance) cloud-free satellite imagery at seven annual time points for the period 2020–2026. Imagery processing was conducted using QGIS software, utilizing the Near Infrared (NIR, Band 8) and Red (Band 4) channels. NDVI values were calculated using the standard formula (Rouse *et al.,* 1974):

$$NDVI = (NIR - Red) / (NIR + Red) \quad (1)$$

NDVI values were subsequently classified into four categories based on thresholds adapted from the Circular of the Director General of Mineral and Coal, Ministry of Energy and Mineral Resources No. 9.E/MB.07/DBT.PL/2023, as presented in Table 1.

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**Tabel 1** Vegetation Cover Classification Based on NDVI Values (Source: Adapted from Circular of the Director General of ESDM No. 9.E/MB.07/DBT.PL/2023)

| No | Vegetation Category | NDVI Range | Description |
|---|---|---|---|
| 1 | Non-vegetasi | NDVI < 0 | Includes water bodies, exposed land, and tailing material with no vegetation response |
| 2 | Low Vegetation | 0,01 – 0,33 | Sparse vegetation cover, seedlings, or low-density grassland |
| 3 | Moderate vegetation | 0,33 – 0,66 | Moderately dense vegetation cover, including reclamation plants with canopy beginning to close |
| 4 | High vegetation | NDVI ≥ 0,66 | Dense forest or vegetation with high density and fully closed canopy |

**b. Void Water Quality Data**

Water quality data were obtained through primary sampling over the period 2024–2026 (six sampling periods: three years × two seasons). Sampling was conducted at nine observation points selected using purposive sampling to represent overall void water body conditions. At each point, sampling was carried out at three depth zones: surface (0–0.5 m), middle (½ of total depth), and bottom (−0.5 m from the bottom). The total number of samples analyzed was 162 observations (9 points × 3 depth zones × 6 periods).

Water samples were collected using a Kemmerer Water Sampler at all three depth zones. Samples were stored in 500 mL polyethylene bottles and cooled to 4°C during transport to the laboratory. Parameters analyzed included pH (measured in situ using a calibrated digital pH meter), TSS (gravimetric method, SNI 06-6989.3-2004), total Fe (Atomic Absorption Spectrophotometry, AAS method), and total Mn (AAS method). Results were compared against coal mining wastewater quality standards stipulated in Kepmen LH No. 113 of 2003, with threshold values: pH 6–9; TSS ≤ 400 mg/L; Fe ≤ 7 mg/L; Mn ≤ 4 mg/L.

**Data Analysis**

Data analysis in this study was conducted in three stages: (1) analysis of reclaimed land cover using the Normalized Difference Vegetation Index (NDVI), (2) analysis of void water quality characteristics, and (3) analysis of the relationship between these two variables.

**a. Reclamation Land Cover Analysis (NDVI)**

Sentinel-2 satellite imagery data for the period 2020–2026 were processed using QGIS to obtain NDVI values within the catchment area of Void Melawan Panel 2. Spatial analysis was

conducted to characterize the distribution of NDVI values and their year-to-year changes. Annual NDVI values were analyzed using a mean NDVI approach based on vegetation class proportions to describe reclamation vegetation development within the catchment area.

Trend analysis was performed using Kendall's tau-b, selected because the data are non-parametric and time-series in nature, to identify the statistical significance of NDVI trend changes (Ott & Longnecker, 2015).

**b. Void Water Quality Characteristics Analysis**

Water quality data comprising pH, TSS, Fe, and Mn were analyzed descriptively to characterize variation across seasons and depth zones during the observation period. To assess differences between the rainy and dry seasons, statistical tests were applied: (1) paired t-test for normally distributed data (pH, TSS, Mn), and (2) Wilcoxon signed-rank test for non-normally distributed data (Fe). Data normality was first assessed using the Shapiro-Wilk test, as the number of samples per group was ≤ 30 (Ott & Longnecker, 2015). Results were compared against applicable standards under Kepmen LH No. 113 of 2003.

**c. Analysis of the Relationship Between Land Cover and Void Water Quality**

The relationship between reclamation land cover conditions and void water quality was analysed using Spearman correlation. The NDVI values used in the correlation analysis represent the annual mean NDVI of the catchment area of Void Melawan Panel 2. Each water quality observation was paired with the corresponding annual NDVI value based on the year of sampling. Accordingly, all 2024 water quality observations were paired with the 2024 NDVI value, 2025 observations with the 2025 NDVI value, and 2026 observations with the 2026 NDVI value. This approach was adopted to represent reclamation land cover conditions at the catchment scale, which collectively influences the void aquatic system.

Spearman correlation was selected because the environmental data used is non-parametric and do not fully satisfy normality assumptions. Correlation strength was interpreted using the following criteria: $r < 0.20$ (very weak), 0.20–0.39 (weak), 0.40–0.59 (moderate), 0.60–0.79 (strong), and $\geq 0.80$ (very strong) (Ott & Longnecker, 2015). All statistical analyses were performed using SPSS version 26 at a significance level of $\alpha = 0.05$

## 3. RESULT AND DISCUSSION

### Reclamation Land Cover Dynamics

Analysis of Sentinel-2 imagery revealed that reclamation land cover conditions within the catchment area improved significantly during the period 2020–2026. The proportion of moderate vegetation increased from 18% to 54%, while low vegetation decreased from 61% to 17%. This compositional shift was not a natural process, but rather the result of a planned reclamation program implemented progressively by PT Kaltim Prima Coal in accordance with the Reclamation Plan (Rencana Reklamasi/RR) and Post-Mining Plan (Rencana Pascatambang/RPT) as mandated under Government Regulation No. 78 of 2010. The program involved land filling and grading, top-soil spreading, cover crop planting, and reclamation planting. Vegetation was dominated by fast-growing pioneer species including *Parserianthes falcataria* and *Cassia siamea*, combined with local

species such as *Shorea spp*. and *Dipterocarpus spp*. as a long-term succession strategy toward mature vegetation.

Figure 2 illustrates the increase in mean NDVI from 0.17 in 2020 to 0.27 in 2026, reflecting increasing canopy density as reclamation plants matured. This is consistent with Triwibowo *et al.,* (2024), who reported that NDVI values in coal mine reclamation areas in South Kalimantan reached 0.6–0.7 after 8–20 years of planting. The mean NDVI range of 0.17–0.27 (low to moderate vegetation) observed here indicates that the Melawan Panel 2 reclamation area is still in an early-to-intermediate growth phase.

The Kendall's tau-b test confirmed a statistically significant increasing trend with $\tau = 0.851$ and $p = 0.009$ (Table 2). Increased vegetation cover on reclaimed land has been shown to reduce surface runoff and erosion (Lv *et al.,* 2020). Increased vegetation cover in catchment areas can influence hydrological conditions through the control of surface flow and sedimentation (Asdak, 2023; Zhao *et al.,* 2022). This finding is consistent with Triwibowo *et al*., (2024), who demonstrated that NDVI time-series analysis is effective in distinguishing between stable and declining reclamation areas.

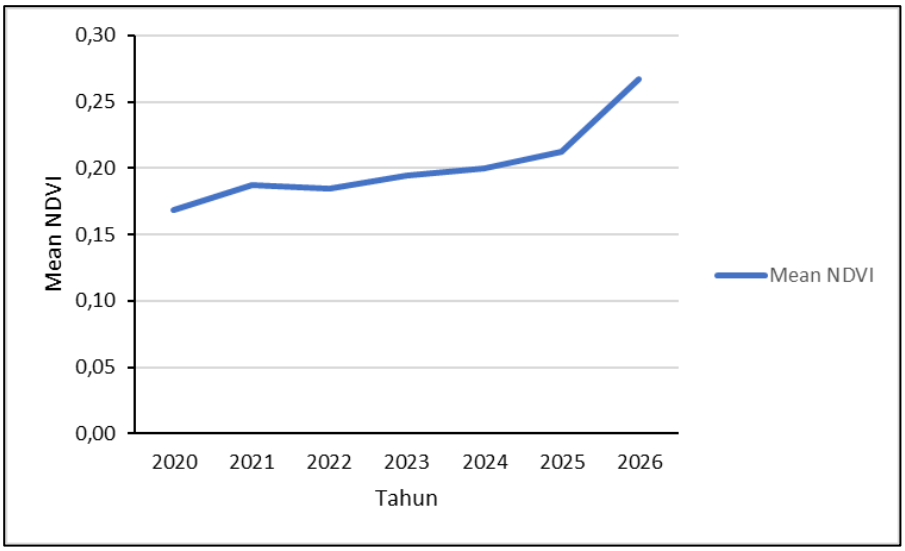



**Figure 2** Changes in Mean NDVI Values at the Catchment Area of Void Melawan Panel 2 (2020–2026).

**Table 2** Results of Kendall's tau-b Trend Test for Mean NDVI

| Variable | Kendall's Tau (τ) | p-value | Remarks |
|---|---|---|---|
| Mean NDVI | 0.851 | 0.009 | Significant increasing trend |

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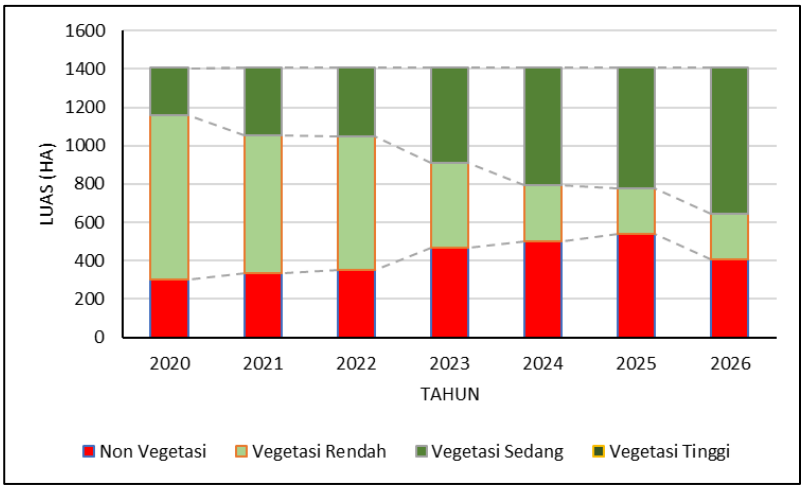



**Figure 0** Changes in Vegetation Category Area Based on NDVI Classification (2020–2026)

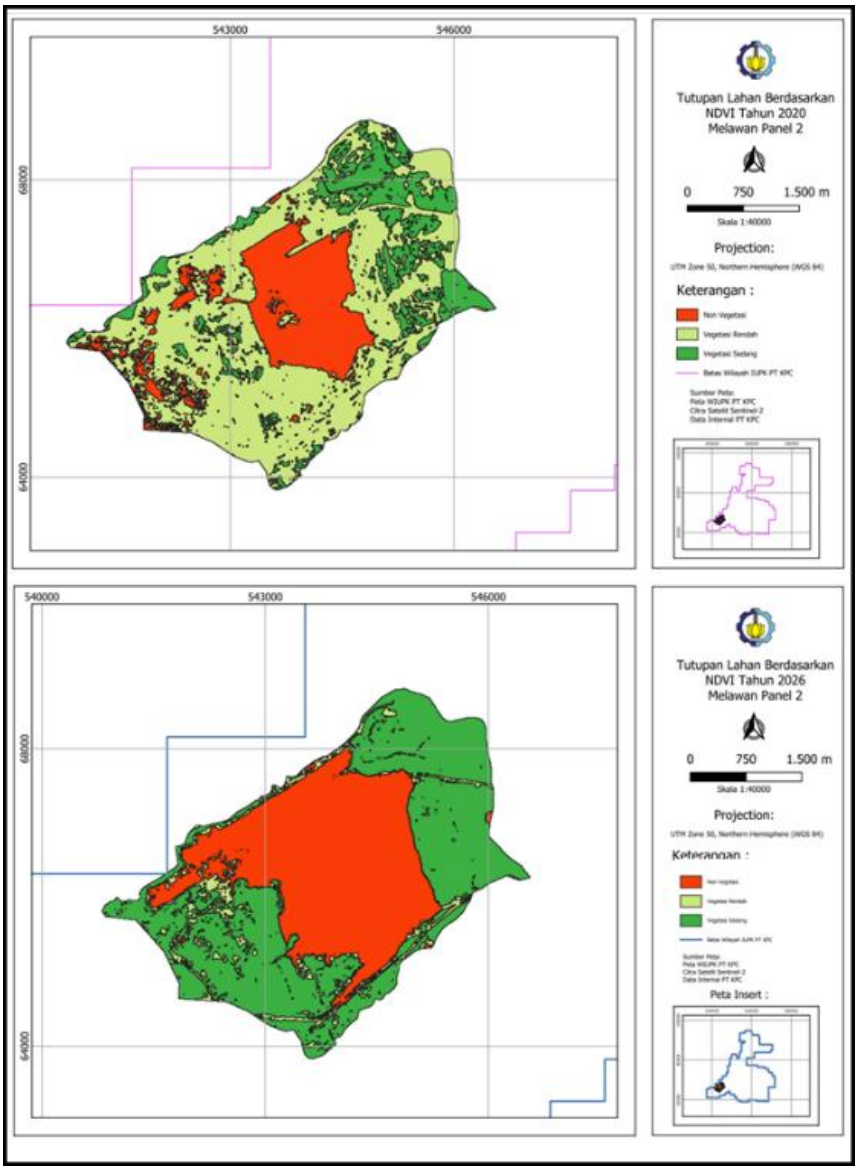



**Figure 4** Comparison of NDVI-Based Land Cover Conditions in 2020 and 2026

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### Catchment Area Hydrological Conditions

Catchment area hydrological conditions serve as the linking factor between reclamation land cover dynamics and void water quality characteristics. Monthly rainfall data for the period 2024–2026 from the nearest station are presented in Table 3 and Figure 5.

**Table 3** Monthly Rainfall Data at the Catchment Area of Void Melawan Panel 2 (mm/month)

| Month | 2024 | 2025 | 2026 |
|---|---|---|---|
| January | 328 | 327 | 291 |
| February | 210 | 71 | 313 |
| March | 200 | 208 | 355 |
| April | 103 | 240 | 198 |
| May | 231 | 296 | 11 |
| June | 114 | 128 | - |
| July | 196 | 110 | - |
| August | 189 | 171 | - |
| September | 155 | 245 | - |
| October | 250 | 81 | - |
| November | 226 | 207 | - |
| December | 183 | 358 | - |

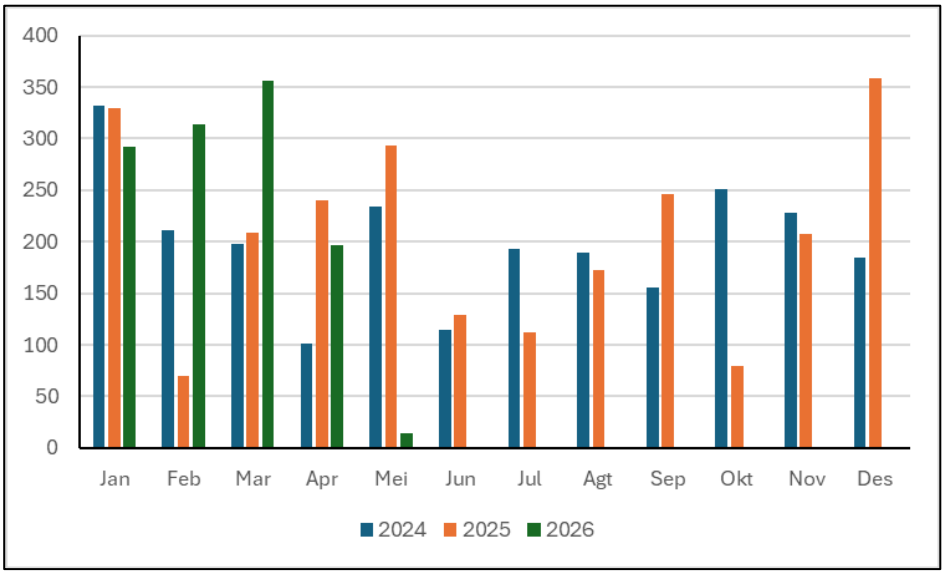



**Figure 5** Monthly Rainfall Graph (2024–2026) at the Catchment Area of Void Melawan Panel 2

Rainfall patterns exhibited clear seasonal variation, with peak rainfall occurring from October to April (rainy season) and a decline from May to September (dry season). Annual mean rainfall ranged from 2,385 to 2,642 mm/year, characteristic of the high-rainfall environment typical of East Kalimantan. High rainfall intensity during the rainy season has the potential to increase surface runoff volume from the catchment area toward the void, particularly in areas with suboptimal vegetation cover.

**Void Water Quality Characteristics**

Water quality characteristics of Void Melawan Panel 2 during the period 2024–2026 showed relatively stable conditions across all observed parameters. pH values ranged from 6.0 to 6.9, indicating a relatively neutral condition with no significant formation of Acid Mine Drainage (AMD). TSS ranged from 2 to 9.67 mg/L, Fe concentrations from 0.05 to 0.09 mg/L, and Mn from 0.22 to 1.60 mg/L. All water quality parameters remained below the applicable standards under the Decree of the Minister of Environment No. 113 of 2003 on Wastewater Quality Standards for Coal Mining Activities, as presented in Table 4.

**Table 4** Range of Void Water Quality Parameters (2024–2026) Compared to Applicable Standards (Kepmen LH No. 113 of 2003)

| Parameter | Observed Range | Standard (Kepmen LH 113/2003) | Status |
|---|---|---|---|
| pH | 6,0-6,9 | 6-9 | Compliant |
| TSS (mg/L) | 2-9,67 | 400 | Compliant |
| Fe (mg/L) | 0,05-0,09 | 7 | Compliant |
| Mn (mg/L) | 0,22-1,60 | 4 | Compliant |

The annual mean pH trend is presented in Figure 6. pH values in 2024 ranged from 6.0 to 6.3, followed by a slight decline toward 6.0 during the 2025 dry season, before increasing consistently in 2026 to the range of 6.7–6.9. Dry season pH was generally lower than rainy season pH. This is related to differences in dilution volume: during the rainy season, rainfall input dilutes $H^+$ ions, resulting in higher pH, while reduced dilution during the dry season can slightly lower pH. The upward pH trend from 2024 to 2026 indicates a stabilization of void water chemical conditions, concurrent with the development of reclamation vegetation in the catchment area.

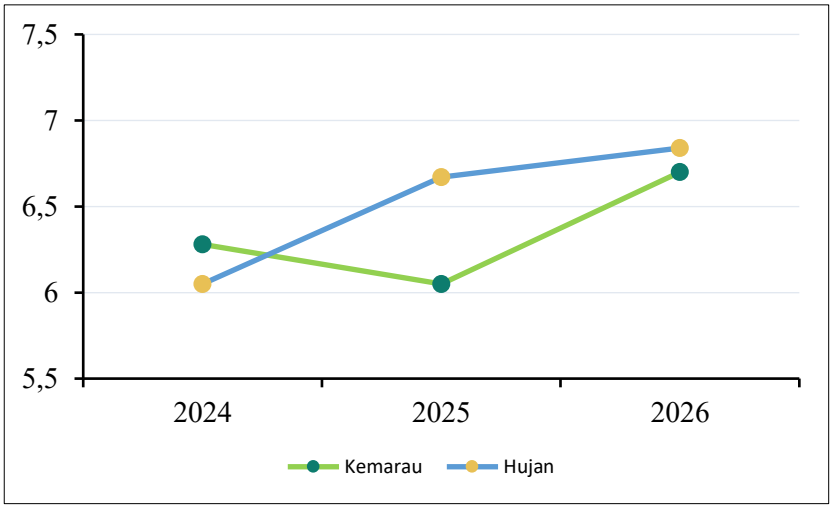



**Figure 6** Annual Mean pH Trend at Void Melawan Panel 2

The annual mean TSS trend is presented in Figure 7. TSS exhibited more dynamic variation than other parameters. In 2024, TSS ranged from 3 to 5 mg/L with rainy season values slightly higher than the dry season. In 2025, rainy season TSS in the bottom layer increased to nearly 7 mg/L, indicating increased sediment transport from the catchment area. In 2026, a pattern reversal occurred in which dry season TSS was higher than rainy season values, likely related to sediment resuspension processes resulting from reduced thermal stratification during the dry season (Effendi, 2016).

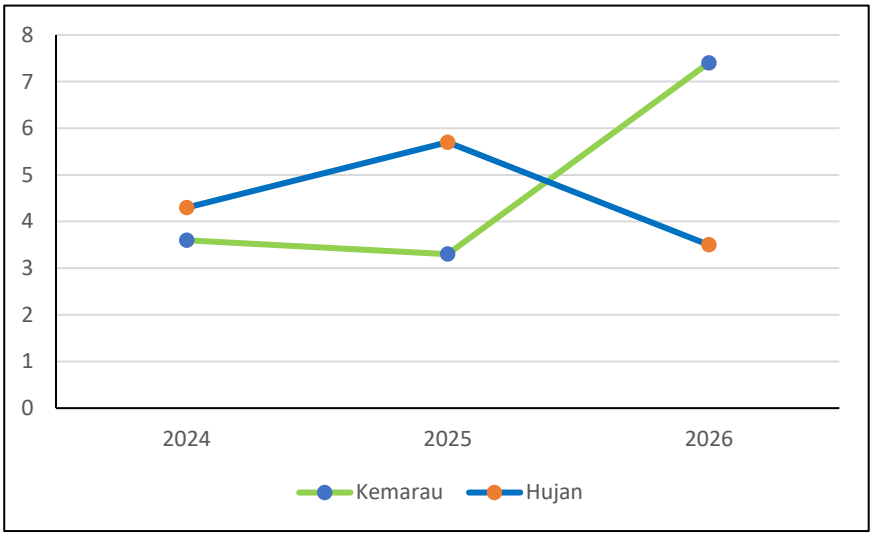



**Figure 7** Annual Mean TSS Trend at Void Melawan Panel 2

This non-uniform TSS dynamics indicate that TSS concentrations are influenced by a combination of external factors (catchment runoff) and internal factors (bottom sediment resuspension), consistent with the findings of Brontowiyono *et al.,* (2022) but with additional complexity from internal water body dynamics

The annual Fe concentration trend is presented in Figure 8. Fe concentrations exhibited the most consistent stability among all parameters, remaining narrowly within 0.05–0.09 mg/L throughout the entire observation period with no meaningful variation between seasons or depth zones. This stability is attributed to the efficient precipitation of $Fe^{3+}$ as $Fe(OH)_3$ within the neutral

pH range through the reaction: $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+$ (Sánchez-España & Yusta, 2015). As long as pH remains within the range of 6.0–6.9, dissolved Fe consistently precipitates, maintaining low and stable concentrations regardless of seasonal hydrological variation.

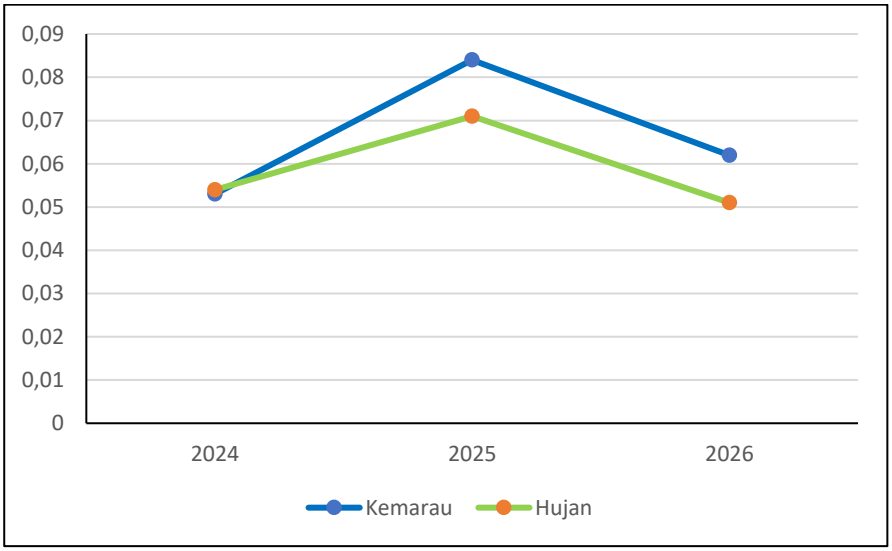



**Figure 8** Annual Mean Fe Trend at Void Melawan Panel 2

The annual Mn concentration trend is presented in Figure 9. Unlike Fe, Mn exhibited greater variation: Mn concentrations in 2024 and 2025 ranged from 1.2 to 1.6 mg/L, with dry season values consistently higher than rainy season values. However, in 2026, a sharp decline occurred to the range of 0.22–0.27 mg/L. This seasonal pattern reflects Mn's sensitivity to redox conditions: during the dry season, reduced dilution and potential anoxic conditions in the lower water column promote the reduction and dissolution of $Mn^{2+}$ through the reaction: $MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{2+} + 2H_2O$ (Stumm & Morgan, 1996). The sharp decline in Mn in 2026, coinciding with increases in both pH and NDVI, suggests an association between reclamation vegetation development and the redox conditions of the void water body, discussed further in the following section.

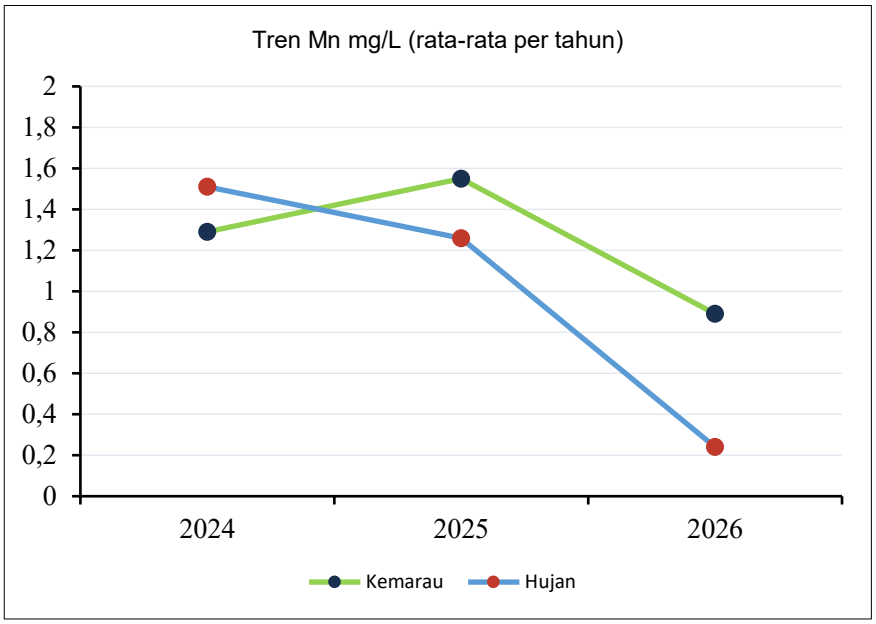



**Figure 9** Annual Mean Mn Trend at Void Melawan Panel 2

**Table 5** Results of Seasonal Difference Test (Dry Season vs. Rainy Season)

| Parameter | Statistical Test | p-value | Remark |
|---|---|---|---|
| pH | Paired t-test | 0,54 | Not significant (p > 0.05) |
| TSS | Paired t-test | 0,904 | Not significant (p > 0.05) |
| Fe | Wilcoxon | 0,317 | Not significant (p > 0.05) |
| Mn | Paired t-test | 0,437 | Not significant (p > 0.05) |

The results of the seasonal difference test indicate that most water quality parameters did not differ significantly between the dry and rainy seasons (p > 0.05), as presented in Table 5. This finding suggests that the Void Melawan Panel 2 aquatic system was relatively stable with respect to seasonal variation during the observation period.

**Relationship Between Reclamation Land Cover and Void Water** Quality

Spearman correlation analysis revealed that NDVI exhibited a strong positive and statistically significant relationship with pH (r = 0.690; p < 0.001), as presented in Table 6 and Figure 10. Improvements in reclamation vegetation quality tended to be accompanied by more stable, near-neutral pH conditions. From a mechanistic perspective, vegetation particularly *Parserianthes falcataria* and *Cassia siamea*, which dominate the reclamation area inhibits the kinetic energy of raindrops, reinforces soil aggregates through root systems, and enhances soil infiltration capacity.

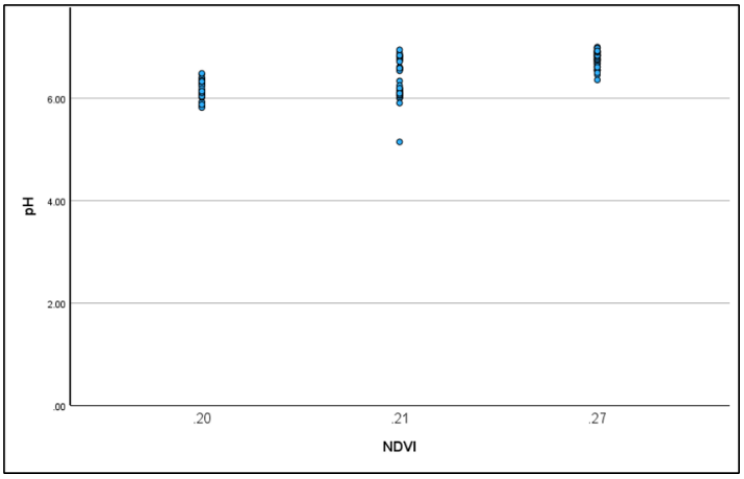



**Figure 10** Relationship Between NDVI and pH Values at Void Melawan Panel 2

These mechanisms directly reduce the volume of surface runoff and the transport of acidification-forming materials (particles containing sulfide minerals) from the overburden zone toward the void water body (Asdak, 2023; Lv *et al.,* 2020). The reduction in sulfide material input suppresses the rate of pyrite oxidation: $FeS_2 + 3.5O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+$, thereby reducing $H^+$ accumulation in the water body and maintaining pH stability. This finding is supported by *Zhao*

*et al.,* (2022), who demonstrated an association between NDVI dynamics, land cover change, and water resource quality conditions.

NDVI also exhibited a strong negative and statistically significant relationship with Mn ($r = -0.628$; $p < 0.001$), as illustrated in Figure 11. Increased reclamation vegetation cover, which stabilizes pH within the range of 6.0–6.9, indirectly suppresses $Mn^{2+}$ mobility. Under neutral pH conditions, $Mn^{2+}$ tends to be oxidized and precipitated as $MnO_2$: $Mn^{2+} + ½O_2 + H_2O \rightarrow MnO_2 + 2H^+$, thereby reducing dissolved Mn concentrations (Freitas *et al.,* 2013). Furthermore, reduced sediment transport from the catchment area also directly decreases the input of particle-bound Mn into the void. This finding is consistent with Zhao *et al.* (2022), who showed an association between NDVI dynamics and water resource quality conditions.

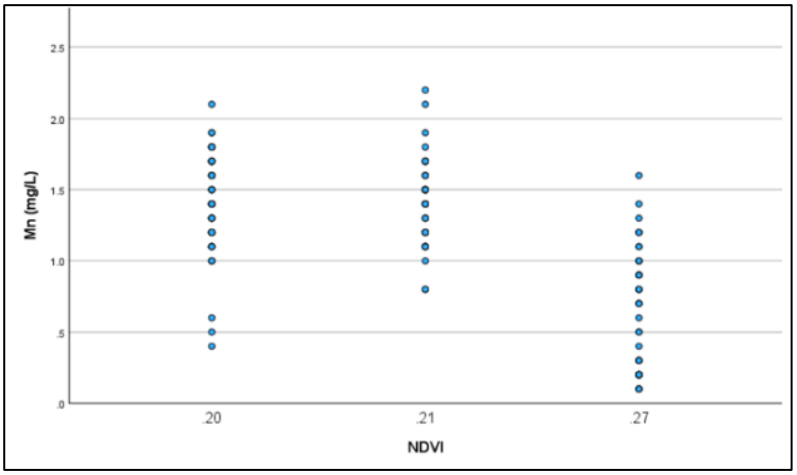



**Figure 11** Relationship Between NDVI and Mn Values at Void Melawan Panel 2

**Table 6** Spearman Correlation Results Between NDVI and Void Water Quality Parameters

| Variable | (r)* | p-value | Interpretation |
|---|---|---|---|
| NDVI vs pH | 0,690 | <0,001 | Strong positive, significant |
| NDVI vs TSS | 0,137 | 0,083 | Very weak positive, not significant |
| NDVI vs Fe | 0,092 | 0,244 | Very weak positive, not significant |
| NDVI vs Mn | −0,628 | <0,001 | Strong negative, significant |

* Correlation Coefficient

The relationship between NDVI and TSS ($r = 0.137$; $p = 0.083$) and between NDVI and Fe ($r = 0.092$; $p = 0.244$) was weak and not statistically significant. The non-significant NDVI–TSS relationship is attributable to the fact that TSS in void water bodies is not solely determined by sediment input from surface runoff but is also influenced by sediment resuspension processes and void morphology (Effendi, 2016). The large volume of the void also confers a high dilution capacity, such that annual NDVI variation is insufficiently sensitive to detect TSS changes occurring at a sub-annual scale. The stability of Fe concentrations is attributed to the efficient precipitation of $Fe(OH)_3$ within the observed pH range through the reaction: $Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3(s) + 3H^+$, maintaining low dissolved Fe concentrations regardless of land cover variation (Sánchez-España & Yusta, 2015).

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These findings demonstrate that the development of reclamation vegetation within the catchment area is associated with void water quality stability through the control of surface runoff, erosion, and material transport toward the water body. However, management of TSS and Fe quality requires additional technical approaches beyond revegetation alone, given the complexity of internal void water processes that also contribute to these parameters.

This study employed annual means NDVI values at the catchment scale, therefore the relationships obtained represent vegetation conditions at the landscape level. Spatial variation in vegetation cover around individual sampling points was not analyzed specifically. Additionally, the water quality parameters were limited to pH, TSS, Fe, and Mn in accordance with the research focus and data availability. Future research could integrate sub-catchment-based spatial analysis and additional parameters such as sulfate to obtain a more comprehensive understanding.

## 4. CONCLUSIONS

Based on the results of this study conducted to address three research objectives, the following conclusions are drawn:

a. Reclamation land cover within the catchment area of Void Melawan Panel 2 improved significantly during the period 2020–2026. The proportion of moderate vegetation increased by 36 percentage points (from 18% to 54%), while low vegetation decreased by 44 percentage points (from 61% to 17%). Mean NDVI increased from 0.17 to 0.27, with a statistically confirmed significant upward trend ($\tau = 0.851$; $p = 0.009$). Reclamation vegetation remained in the intermediate growth phase (moderate vegetation dominant), with no detection of high vegetation class (NDVI ≥ 0.66), indicating that the revegetation process is ongoing and has not reached climax stage. This improvement is the result of PT Kaltim Prima Coal's planned reclamation program combining fast-growing pioneer species *Parserianthes falcataria* and *Cassia siamea* with local species including *Shorea spp.*.and *Dipterocarpus spp.*

b. Void water quality characteristics during the period 2024–2026 were relatively stable and compliant with all applicable parameters under Kepmen LH No. 113 of 2003. pH ranged from 6.0 to 6.9 (neutral), TSS from 2 to 9.67 mg/L, Fe from 0.05 to 0.09 mg/L, and Mn from 0.22 to 1.60 mg/L. No significant indications of Acid Mine Drainage formation were detected during the observation period.

c. Spearman correlation analysis revealed a strong positive relationship between NDVI and pH ($r = 0.690$; $p < 0.001$) and a strong negative relationship between NDVI and Mn ($r = -0.628$; $p < 0.001$), indicating that the development of reclamation vegetation is associated with void water chemical stability through mechanisms of runoff control and reduction of reactive material transport. The relationships between NDVI and TSS and Fe were not significant, reflecting the complexity of internal void water processes that also influence these parameters.

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