

Spatio-Temporal Analysis of Water Quality in the PT Perkebunan Nusantara IV Regional 5 Reservoir Using Sentinel-2 Satellite Imagery (2023–2025)

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ABSTRACT

Reservoir water quality is a critical factor in supporting the functions of raw water supply, irrigation, and the sustainability of aquatic ecosystems. This study analyzes the spatiotemporal dynamics of water quality in the PTPN XII Pelaihari Reservoir during 2023–2025 with Sentinel-2 satellite imagery. The main parameters observed include Total Suspended Solids (TSS), turbidity, chlorophyll-a, and Colored Dissolved Organic Matter (CDOM) as indicators of physical and biological conditions. Using a quantitative, descriptive remote sensing approach, Level-2A Sentinel-2 imagery was processed in Google Earth Engine. Analysis was conducted for both dry and rainy seasons to assess hydrological impacts. Results show significant seasonal dynamics: TSS decreased from 97 mg/L in 2023 to 65 mg/L in 2025, while turbidity rose to 0.78. Chlorophyll-a increased in the 2024 dry season, indicating higher phytoplankton productivity, but declined in 2025 due to turbidity. CDOM rose in 2025, suggesting more dissolved organic matter. Spatially, the dry season showed stable, homogeneous parameter distribution, while the rainy season was more heterogeneous due to runoff. The PTPN XII Pelaihari Reservoir has potential as a raw water source, though quality fluctuates seasonally. Sentinel-2 remote sensing enables effective, sustainable water quality monitoring and supports adaptive management.

Keywords: Remote sensing; Reservoir; Sentinel-2; Spatio-temporal; Water quality

INTRODUCTION

Dams are artificial aquatic ecosystems that play a strategic role in supplying raw water, irrigation, and flood control. In addition, they support fisheries and the socio-economic activities of local communities. The sustainability of these functions is significantly influenced by water quality conditions that are spatially and temporally dynamic. Deterioration in water quality can

lead to increased sedimentation, eutrophication, and disruption of aquatic ecosystems; therefore, continuous water quality monitoring is a critical requirement in dam management (Putri et al., 2025; Saguling & Barat, 2025)

Overall water quality can be assessed using several indicators that reflect the water's physical, chemical, and biological characteristics. These indicators include Total Suspended Solids (TSS), turbidity, chlorophyll-a, and Coloured Dissolved Organic Matter (CDOM) (Neale et al., 2024). The TSS indicator helps determine turbidity levels and light penetration, which directly affect photosynthesis and dissolved oxygen levels. Research at the Porong River Estuary indicates that TSS values range from 48–366 mg/L (in situ) and 50–250 mg/L from satellite imagery, demonstrating that remote sensing can capture variations in water quality, albeit with a certain degree of accuracy (Muzdalifah et al., 2025)

In addition to TSS, chlorophyll-a is also used as an indicator of water fertility and phytoplankton biomass. An increase in chlorophyll-a may indicate high nutrient input, which could trigger eutrophication. A study at the Bodri River Estuary showed that chlorophyll-a estimates from satellite imagery have a very strong correlation with field data ($r = 0.935$; $R^2 = 0.875$) within a range of 1.78–5.3 mg/m³, making this parameter effective for use in remote sensing-based water quality analysis (Alqadri et al., 2022).

Water quality monitoring can be conducted using conventional field sampling methods. This method has limitations in terms of spatial coverage and observation frequency, as well as high costs. Therefore, remote sensing methods are needed that can integrate spatial and temporal dimensions to understand the distribution and dynamics of changes in water quality. This technology can monitor large areas periodically with greater efficiency at a reasonable cost (Agustin et al., 2025; Nurhayati et al., 2020)

Sentinel-2 satellite imagery is a widely used remote sensing method for water quality monitoring. Sentinel-2 provides high spatial resolution (10–20 m) and multispectral capabilities, enabling the extraction of water optical properties through reflectance analysis. Its Multispectral Instrument (MSI), which consists of multiple spectral bands, is particularly suitable for estimating various water quality parameters (e.g., turbidity and suspended solids) (Seth et al., 2026). Furthermore, Sentinel-2 has been widely applied to map Total Suspended Solids (TSS) and other water quality parameters, demonstrating strong capability for spatial and temporal monitoring (Chowdhury et al., 2025).

A spatio-temporal approach is important because water quality is influenced by seasonal factors and anthropogenic activities. A study at the Selorejo Dam showed that water quality conditions declined significantly, with the percentage of sampling points meeting quality standards dropping from 66.67% in 2021 to 14.29% in 2024, while the “lightly polluted” category rose to 85.71% (Agustin et al., 2025). Additionally, the distribution of water hyacinth in Saguling Reservoir has exceeded 1,100 hectares at times. This situation indicates strong environmental pressure and significant spatial variation (Saguling & Barat, 2025)

Nevertheless, most previous studies still rely on field data for validation. This opens up opportunities for the development of research based entirely on satellite imagery, particularly for areas with limited in situ data. In this context, the PTPN XII Pelaihari Dam is a dam whose water is used as drinking water. Thus, this dam can serve as an important subject for analysis using a Sentinel-2-based spatio-temporal approach during the 2023–2025 period.

This study aims to conduct spatio-temporal monitoring of water quality in the PTPN XII Pelaihari Reservoir from 2023 to 2025 using Sentinel-2 satellite imagery, focusing on TSS, turbidity, chlorophyll-a, and CDOM. This approach is expected to provide a comprehensive

overview of the spatial distribution and temporal dynamics of water quality and to support the development of a more efficient and sustainable monitoring system.

METHODS

Research Design

The research design is an observational study based on secondary data. All data were obtained from Sentinel-2 satellite imagery as the primary source of information. This approach enables a broad, continuous, and multitemporal analysis of water quality conditions (Nurfadilah et al., 2026).

Instrument Research

The study was conducted at the PTPN XII Pelaihari Dam, located in Tanah Laut Regency, South Kalimantan Province (Figure 1). This dam is an artificial water body used for water supply, irrigation, and other supporting activities. Spatially, the study area is defined by the dam's inundation boundary, which was identified using satellite imagery.

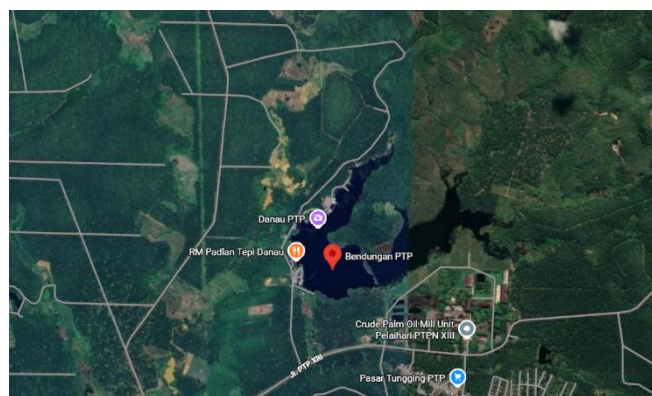


Figure 1. Location of the PTPN XII dam in Tanah Laut Regency

Water boundaries were determined using a water index approach, such as the Normalized Difference Water Index (NDWI), which utilizes a combination of the green band (Band 3) and near-infrared band (Band 8) in Sentinel-2 imagery. NDWI values > 0 are used to identify water areas, while values ≤ 0 indicate land (Agustin et al., 2025).

Image Data Sources and Acquisition

The primary data used in this study are Level-2A (Bottom of Atmosphere reflectance) images from the Sentinel-2 Multispectral Instrument (MSI). The data were obtained free of charge through the official Copernicus Open Access Hub platform (<https://scihub.copernicus.eu>) or Google Earth Engine (GEE). Image selection was based on the following criteria: (a) Cloud cover < 10 –20%, (b) Dam area not covered by clouds, (c) Acquisition dates representative of the season (Luca et al., 2022). The data used consists of multitemporal imagery from 2023 to 2025, with data collected at times representative of seasonal conditions, namely the rainy season: November–March and the dry season: April–October.

Estimated Total Suspended Solids (TSS)

Total Suspended Solids (TSS) were estimated using an empirical algorithm based on the spectral reflectance of Sentinel-2 imagery. TSS parameters are closely related to light scattering at red and near-infrared (NIR) wavelengths, so these bands are commonly used in TSS modelling. In this study, TSS estimation was performed using a red-band-based algorithm (Band 4, $\lambda \approx 665$ nm) that has been widely applied to inland waters (Jiang et al., 2023):

$$TSS = a \cdot e^{(b \cdot R_{rs}(B4))}$$

or another option is to use the band ratio:

$$TSS = a + b \left(\frac{R_{rs}(B4)}{R_{rs}(B3)} \right)$$

where TSS = Total Suspended Solids concentration (mg/L); $R_{rs}(Bn)$ = reflectance in the nth band; and a, b = empirical constants. This approach is based on the relationship between an increase in suspended particles and an increase in reflectance in the red band due to the backscattering effect (Sabila et al., 2024).

Turbidity Estimation

Turbidity is a parameter that is optically highly correlated with TSS, but is more sensitive to changes in light scattering in the visible spectrum. Turbidity estimation is performed using a reflectance approach in the red band or a combination of the red and NIR bands (Stephen et al., 2023). The model used in this study is based on a simple linear relationship:

$$Turbidity = a \cdot R_{rs}(B4) + b$$

or non-linear models:

$$Turbidity = a \cdot e^{(b \cdot R_{rs}(B4))}$$

Turbidity is expressed in NTU units, and the red band (B4) was selected because it is sensitive to suspended particles.

The selection of the red band is based on the optical characteristics of turbid water. Increased turbidity causes an increase in reflectance at that wavelength due to scattering by suspended particles (Matos et al., 2024).

Chlorophyll-a Estimation

Chlorophyll-a is a key indicator of primary productivity and water fertility. Chlorophyll-a estimation is performed using a spectral band ratio approach that is sensitive to chlorophyll absorption in the blue and red spectra and reflectance in the green spectrum. The model used in this study is the green-red band ratio (Falcioni et al., 2023).

$$Chl-a = a \left(\frac{R_{rs}(B3)}{R_{rs}(B4)} \right)^b$$

or an alternative logarithmic-based model:

$$Chl-a = a + b \ln \left(\frac{R_{rs}(B3)}{R_{rs}(B2)} \right)$$

where Chl-a = chlorophyll-a concentration (mg/m³); Band 2 (blue), Band 3 (green), and Band 4 (red) are used due to their sensitivity to phytoplankton pigments.

This approach has proven effective in various studies, with a high correlation between image estimates and field data (r up to 0.935)(Bertone et al., 2024).

Estimated of Coloured Dissolved Organic Matter (CDOM)

CDOM is a component of dissolved organic matter that affects light absorption, particularly at blue wavelengths. Therefore, CDOM estimates typically use the ratio of blue and green bands (Zeng et al., 2023). The model used in this study is

$$CDOM = a \cdot \ln \left(\frac{R_{rs}(B2)}{R_{rs}(B3)} \right) + b$$

or

$$CDOM = a \left(\frac{R_{rs}(B2)}{R_{rs}(B3)} \right)^b$$

where:

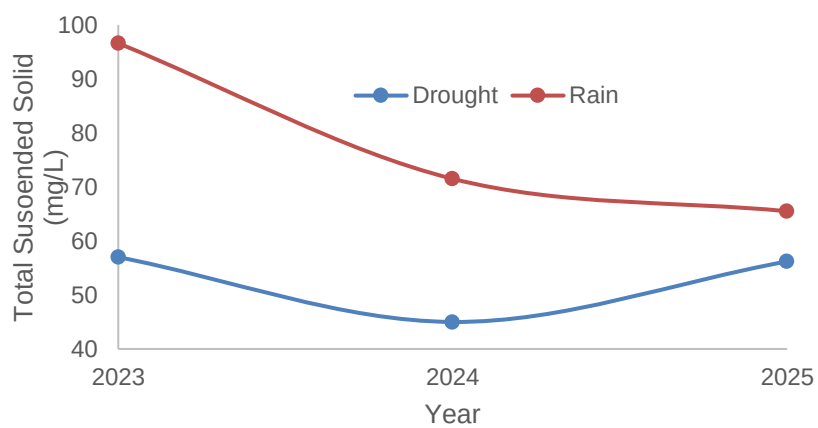
CDOM = concentration of dissolved organic matter

Band 2 (blue, ~490 nm) and Band 3 (green, ~560 nm) are used because CDOM strongly absorbs in the blue spectrum

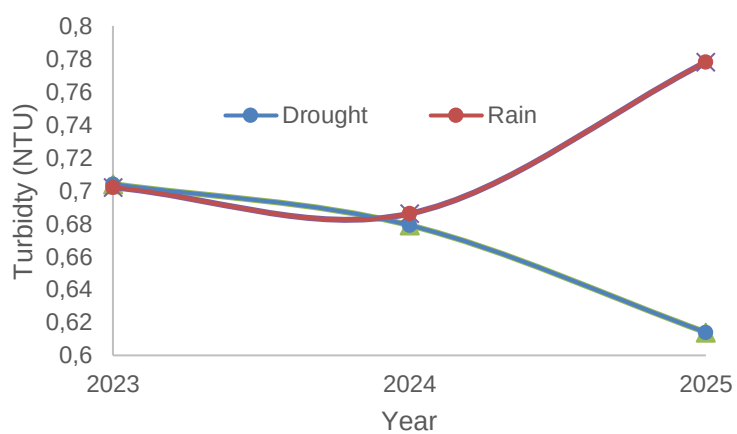
This approach is based on the optical properties of CDOM, which cause a decrease in reflectance at short wavelengths, making the blue-to-green ratio a sensitive indicator of CDOM concentration (Zeng et al., 2023).

RESULTS AND DISCUSSION

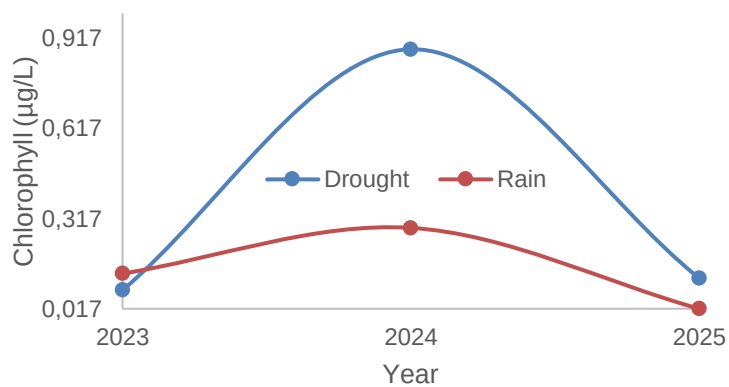
The PTPN XII Pelaihari Dam is an artificial reservoir located in Tanah Laut Regency, South Kalimantan. The dam serves as a source of raw water, provides irrigation, and controls flooding, while also supporting fisheries and the surrounding environment. Water quality is influenced by hydrological dynamics and activities within the watershed. The results of water quality analysis of the PTPN XII Pelaihari Reservoir based on Sentinel-2 imagery indicate significant spatio-temporal dynamics during the 2023–2025 period. These variations are clearly evident in the parameters of turbidity, Total Suspended Solids (TSS), chlorophyll-a, and Colored Dissolved Organic Matter (CDOM). The hydrological dynamics during the dry and rainy seasons can be seen in Figure 1.



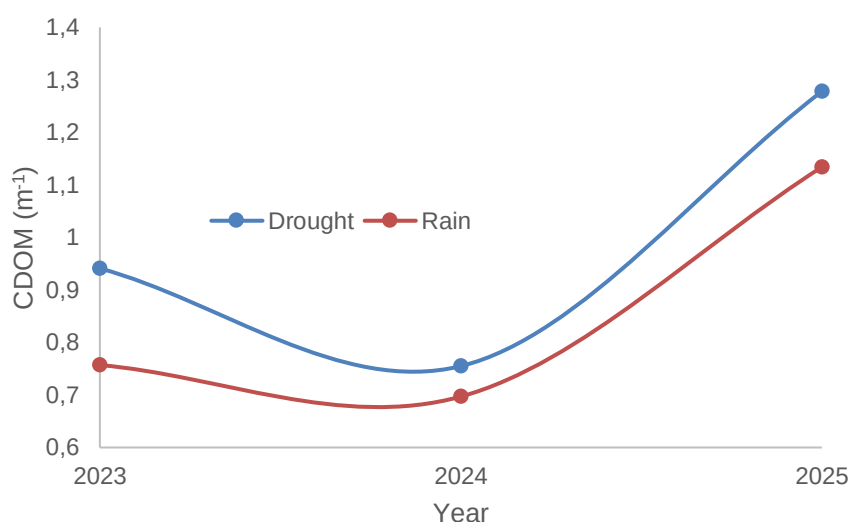
(a)



(b)



(c)



(d)

Figure 2. Hydrological dynamics during the dry and rainy seasons

The results of the analysis of water quality parameters in the PTPN XII Pelaihari Reservoir during the 2023–2025 period show clear variations between the dry season (drought) and the rainy season (rain), reflecting the strong influence of hydrological factors on water conditions. These variations are evident in four key parameters: Total Suspended Solids (TSS), turbidity, chlorophyll-a, and Coloured Dissolved Organic Matter (CDOM).

The TSS parameter (Figure 1a) shows a decreasing trend during the rainy season from 2023 to 2025, specifically from approximately 97 mg/L to approximately 65 mg/L. This decrease indicates a reduction in the sediment load entering the reservoir, which may be caused by changes in land-use conditions or reduced erosion in the watershed. Conversely, during the dry season, TSS values show a fluctuating pattern with a decrease in 2024 (~45 mg/L) and a subsequent increase in 2025 (~55 mg/L). This suggests that during the dry season, TSS dynamics are more influenced by internal reservoir processes such as sediment resuspension due to wind activity or changes in water level.

In contrast to TSS, the turbidity parameter (Figure 1b) shows a significant increase during the rainy season, particularly in 2025, when it reached approximately 0.78 NTU. This increase indicates rising turbidity due to the influx of suspended particles via surface runoff during periods of heavy rainfall. Meanwhile, during the dry season, turbidity shows a decreasing trend from around 0.70 in 2023 to around 0.61 in 2025, reflecting more stable water conditions and minimal external disturbances. The difference in patterns between TSS and turbidity suggests that turbidity is influenced not only by the amount of sediment but also by the size and optical properties of suspended particles (Abdullah et al., 2025)

Chlorophyll-a levels (Figure 1c) exhibit a different pattern compared to physical parameters. Chlorophyll-a levels increased significantly during the 2024 dry season, reaching approximately 0.9 µg/L, indicating an increase in phytoplankton biomass. These conditions typically occur in calmer waters with sufficient nutrient availability, thereby supporting photosynthesis. However, in 2025, chlorophyll-a values dropped sharply during both the rainy

and dry seasons. This decrease was likely caused by increased turbidity and CDOM, which reduced light penetration, thereby inhibiting phytoplankton growth (Patrick et al., 2025).

The CDOM parameter (Figure 1d) shows a fairly clear upward trend by 2025, during both the rainy and dry seasons. During the dry season, the CDOM value increases from approximately 0.95 in 2023 to approximately 1.30 in 2025, while during the rainy season it increases from approximately 0.75 to approximately 1.10. This increase indicates the accumulation of dissolved organic matter in the reservoir, likely originating from terrestrial runoff, vegetation decomposition, or anthropogenic activities. High CDOM levels can increase light absorption in the water column and lead to reduced water clarity and photosynthetic productivity (Patrick et al., 2025)

The dynamics of water quality parameters identified in the PTPN XII Pelaihari Reservoir indicate that this reservoir presents both potential and risks as a source of raw water for drinking water in the Pelaihari region. This study has shown that during the dry season, the reservoir is relatively more suitable for use with a lower level of treatment, whereas during the rainy season, more intensive treatment is required due to increased turbidity, TSS, and organic matter. The dynamics of Total Suspended Solids (TSS), chlorophyll-a, and Coloured Dissolved Organic Matter (CDOM) during the dry and rainy seasons are presented in Figure 3.

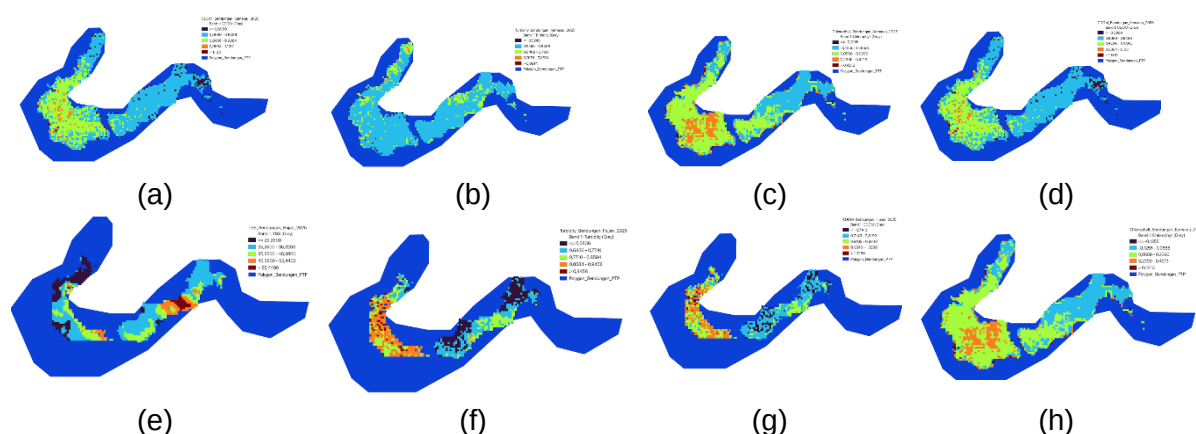


Figure 3. Water quality dynamics during the dry season (a–d) and the rainy season (e–h)

The spatial distribution of water quality in the PTPN XII Pelaihari Reservoir shows clear differences between the dry and rainy seasons. During the dry season (Figures a–d), water conditions are relatively more stable, with TSS and turbidity values that tend to be lower and are distributed more locally, particularly in the inlet area. This indicates that sediment input from external sources is relatively low, making internal processes such as sedimentation more dominant. Meanwhile, chlorophyll-a shows an increase in several zones, indicating higher phytoplankton activity due to calm water conditions and optimal light penetration. CDOM values during this season are relatively moderate and evenly distributed, reflecting low external organic matter input.

In contrast, during the rainy season (Figures e–h), water quality exhibits more complex dynamics. TSS and turbidity levels increase significantly and spread widely from the inlet area throughout the reservoir, due to surface runoff carrying sediment. These conditions lead to increased turbidity and decreased water clarity. At the same time, chlorophyll-a values tend to decrease, indicating inhibited photosynthetic activity due to limited light penetration.

Meanwhile, CDOM increases and spreads more widely, indicating high inputs of dissolved organic matter. Overall, the dry season is dominated by internal processes, while the rainy season is strongly influenced by external inputs.

CONCLUSION

This study shows that water quality in the PTPN XII Pelaihari Reservoir exhibits dynamics strongly influenced by seasonal factors and interannual variations. The rainy season tends to increase turbidity and CDOM due to surface runoff, whereas the dry season exhibits more stable water conditions with increased biological activity indicated by chlorophyll-a. The downward trend in TSS indicates a reduction in sediment load; however, the increase in turbidity and CDOM in 2025 suggests that significant environmental pressures still exist. Overall, the reservoir has potential as a source of raw water, but requires adaptive management due to the fluctuating nature of water quality. The use of Sentinel-2 satellite imagery has proven effective for spatio-temporal water quality monitoring, thereby serving as a basis for decision-making regarding sustainable water resource management.

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