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Spatiotemporal Water Quality Assessment of Lake Mahalona via Google Earth Engine

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Freshwater lake ecosystems are increasingly recognized as sensitive indicators of environmental health, where shifts in physicochemical water quality parameters reflect broader ecological pressures from anthropogenic activities and climate variability This study aims to map the spatial distribution, analyze temporal trends, and evaluate the water quality status of Lake Mahalona in Towuti Subdistrict, East Luwu Regency, South Sulawesi, based on pH, TSS, BOD, COD, and ammonia parameters. The analysis was conducted using the GEE platform with Sentinel 2 Level-2A imagery data for pH, TSS, BOD, and COD parameters, as well as GEOS-CF data for ammonia, covering the period from January to November 2025. The methods applied included creating an Area of Interest (AOI), using the JRC Global Surface Water Mapping Layers, v1.4, utilizing Harmonized Sentinel-2 MSI Level-2A (SR), atmospheric correction, cloud and water body masking, outlier removal using the inter-quantile range, deriving functional equations for water quality parameters, and exporting the data. Satellite-derived estimates yielded pH values ranging from 6.587 to 7.154; TSS from 17.55 to 19.821 mg/L; BOD from 3.215 to 7.266 mg/L; COD from 2.857 to 6.116 mg/L; and atmospheric ammonia pressure indicators at 0.001 mg/L. Time-series analysis revealed fluctuations in all parameters, with increases in TSS, BOD, and COD from August to October, while ammonia remained stable at very low concentrations. Based on Government Regulation No. 22 of 2021, the pH, TSS, COD, and ammonia parameters still meet Class II and III water quality standards; however, the BOD value has exceeded the 2 mg/L threshold, indicating organic pollution pressure from anthropogenic activities in the watershed. The GEE-based approach demonstrates considerable potential for efficient spatial and temporal monitoring of lake water quality, providing important baseline information for the sustainable management and conservation of Lake Mahalona.

Keywords: Google Earth Engine, Lake mahalona, Remote sensing, Water quality,

INTRODUCTION

Water is the most widely consumed resource globally and vital for human survival. Freshwater resources support food production, household needs, and the industrial sector; however, anthropogenic activities, land-use changes, and climate variability continue to threaten the sustainability of water resources worldwide (Jahangeer et al., 2025). As one of the terrestrial aquatic ecosystems, lakes play a strategic role from ecological, social, and economic perspectives. In Indonesia, lakes in the Wallacea region including the Malili Lake Complex in South Sulawesi harbor high biodiversity with unique limnological conditions.

The Malili Lake Complex, comprising Lake Matano, Lake Mahalona, and Lake Towuti, is an ancient lake system of international conservation value. Anthropogenic activities around this lake complex have led to a decline in water quality, affecting the water's fertility (Suryono & Lukman, 2018). As part of this system, Lake Mahalona faces environmental pressures from activities within its watershed, including land-use changes, settlements, and potential mining activities in Towuti Subdistrict, East Luwu Regency. Water quality parameters such as Potential of Hydrogen (pH), Total Suspended Solids (TSS), Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), and Ammonia (NH_3) serve as key indicators for assessing the health status and pollution levels of water bodies, with COD levels in the Malili Lake Complex showing a trend of increase over time, underscoring the need for continuous monitoring (Suryono & Lukman, 2018).

Conventional water quality monitoring relies on in-situ sampling and laboratory analysis, which, while accurate, entail significant costs and limited spatial and temporal coverage (Jaywant & Arif, 2024). This pointbased approach often fails to detect local events such as pollutant plumes or algal blooms, and low sampling frequency can miss short-term changes triggered by runoff or storms (Jaywant & Arif, 2024). Advances in remote sensing and geographic information systems (GIS) open new opportunities for more efficient monitoring. Google Earth Engine (GEE) serves as a cloud computing platform enabling rapid and scalable spatiotemporal analysis, providing access to petabyte-scale data, server-side computing, and integrated cloud storage through concise JavaScript-based scripts (Jahangeer et al., 2025). GEE has seen widespread adoption in water resource monitoring, assessment, and management (Hasan et al., 2024), including for active optical parameters such as chlorophyll-a, turbidity, and TSS using multispectral data from Landsat and Sentinel-2 satellites (ARSET, 2023; Men, 2025). Its application has been successfully demonstrated across various regions worldwide, ranging from long-term chlorophyll-a mapping in Lake Balaton, Hungary (Li et al., 2025), to a 40-year hydrological dynamics analysis of Lake Ilgın, Turkey (Atiz & Durduran, 2025). However, application of this method to lakes in Indonesia, particularly Lake Mahalona in South Sulawesi, remains very limited.

Lake Mahalona, characterized by oligotrophic water conditions with low biological productivity (Suryono & Lukman, 2018), requires a sensitive monitoring approach to detect changes in water quality. The pH parameter reflects acidity conditions influencing aquatic biochemical processes; TSS relates to turbidity and sediment transport; BOD and COD indicate organic pollution levels; while ammonia signals contamination from domestic wastewater and agricultural activities. Simultaneous monitoring of these five parameters through a spatial approach will provide a comprehensive picture of Lake Mahalona's water quality status.

This study is designed to address three interconnected research objectives. The first objective is to identify and map the spatial distribution of water quality parameter concentrations, encompassing pH, TSS, BOD, COD, and ammonia, in the waters of Lake Mahalona through the GEE platform during the period January to November 2025. Building upon this spatial baseline, the second objective seeks to analyze temporal trends in the concentration values of those parameters across the same observation period, with particular attention to seasonal dynamics and potential anthropogenic influences. The third objective aims to evaluate the overall water quality status of Lake Mahalona based on the GEE-derived monitoring results, assessed against the water quality standards stipulated in Government Regulation No. 22 of 2021. Collectively, these objectives are intended to generate a comprehensive, spatially explicit understanding of water quality dynamics in an ecologically significant ancient lake system that has thus far received limited attention in the remote sensing literature.

Based on the above description, research on "Spatially-Based Water Quality Monitoring Analysis (pH, TSS, BOD, COD, and Ammonia) Using Google Earth Engine at Lake Mahalona, Towuti Subdistrict, East Luwu Regency, South Sulawesi Province" is important to conduct. This study is expected to produce accurate, periodic, and efficient spatial information on lake water quality as a basis for sustainable lake management.

METHODS

Research Location and Time

This study was conducted at Lake Mahalona, which is administratively located in Towuti Subdistrict, East Luwu Regency, South Sulawesi Province. Lake Mahalona covers an area of 25 km² and is situated at an elevation of 300 meters above sea level; it is part of the Malili Lake Complex, an ancient lake system with unique ecological characteristics and high conservation value. Geographically, this area is located at the following coordinates: Latitude:02° 33′ 44″ –02° 37′ 16″ S and Longitude:121° 27′ 53″ – 1210 31′ 02′′ E (Suryono & Lukman, 2018; South Sulawesi Natural Resources Conservation Agency, 2024). The spatial resolution detail reaches 19 meters per pixel at zoom level 13. The study location was identified using Sentinel-2 satellite imagery (Figure 1). This location was selected based on the importance of Lake Mahalona as a water resource supporting the livelihoods of the surrounding communities and its role in maintaining the balance of the regional ecosystem. The study was conducted during the period from January 1, 2025, to November 1, 2025.

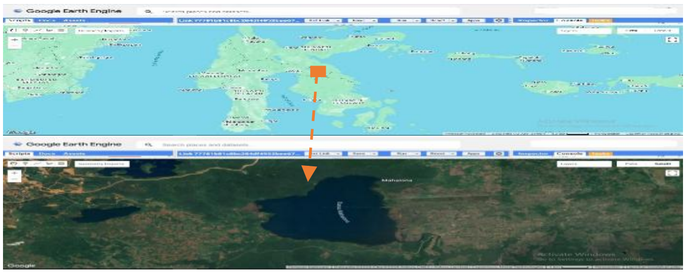

Figure 1 Visualization of the Sentinel-2 Image Map at the Study Location (Lake Mahalona Area) in 2025

Data Types and Sources

Remote sensing is the art and science of obtaining information about objects, areas, or phenomena through the analysis of data acquired using instruments without direct contact with the studied objects (Lillesand & Kiefer, 1979). In this study, data were obtained from medium-resolution optical satellite imagery, specifically Sentinel-2 Level-2A (Surface Reflectance), accessed and processed online via the GEE platform. This imagery was selected based on its spatial, temporal, and spectral characteristics, which are suitable for estimating water quality parameters including pH, TSS, BOD, and COD. For the Ammonia parameter, data were sourced from the GEOS-CF (Goddard Earth Observing System Composition Forecast) dataset by selecting the NH_3 band, available for a maximum date range of one week. The GEE platform, which is JavaScript-based, enables in-depth analysis through both spatial visualizations and statistical functional equations, allowing the resulting water quality data to be directly compared against applicable quality standards.

Data Collection and Analysis Techniques

All data collection and analysis processes were performed automatically through scripting on the GEE platform. The workflow began with the creation of an Area of Interest (AOI) using the draw a rectangle tool to delineate the waters of Lake Mahalona, followed by water body extraction using the JRC Global Surface Water Mapping Layers v1.4. Sentinel-2 imagery was accessed through the Harmonized Sentinel-2 MSI: MultiSpectral Instrument, Level-2A (SR) dataset, with cloud removal applied via cloud masking methods, spatial filtering using filterBounds() and updateMask(), and temporal filtering using filterDate().

Pre-processing included atmospheric correction to convert digital values into surface reflectance values using the Sen2Cor algorithm for Sentinel-2, as well as masking processes to remove pixels obscured by clouds, cloud shadows, and non-water land cover based on QA band algorithms and the JRC Global Surface Water classification dataset (Atiz & Durduran, 2025; Dabhadkar, 2025). Outlier removal was subsequently performed using the inter-quartile range (IQR) method to prevent biased data values.

Empirical functional equations for estimating pH, TSS, BOD, and COD were applied to atmospherically corrected Sentinel-2 Level-2A surface reflectance data within the GEE platform, utilizing spectral band combinations derived from satellite-based water quality monitoring principles (Atiz & Durduran, 2025). It is acknowledged that BOD and COD estimation from multispectral data is inherently indirect and relies on empirical relationships not independently validated against in-situ measurements at Lake Mahalona. Results were visualized as time-series trend charts and spatial distribution maps. For the ammonia parameter, the GEOS-CF (Goddard Earth Observing System Composition Forecast, fcst tavg1hr v1) NH_3 band was utilized to characterize atmospheric ammonia loading pressure above the lake surface as an indicator of potential external nitrogen input through atmospheric deposition, rather than to estimate dissolved ammonia directly within the water column. This approach is grounded in the established role of atmospheric NH_3 deposition as a quantitatively significant nitrogen input pathway to oligotrophic freshwater lakes where point-source loading is minimal (Ellis et al., 2015; Hayashi et al., 2020). Retrieved NH_3 values were converted from molar mixing ratios to mg/L using a conversion factor of 55.5 mol/L × 17 g/mol × 1,000, followed by outlier removal using the IQR method. The resulting values represent atmospheric ammonia pressure indicators above Lake Mahalona rather than direct water column measurements, and should be interpreted alongside the limitations noted in the corresponding section. All processed data were subsequently exported using the Export.image.toDrive() command for further analysis and comparison against applicable water quality standards.

The data analysis steps in this study are designed to convert digital satellite image values into graphical data and spatial distribution maps of water quality parameters through a series of cloud-based computational processes on the GEE platform. The analysis begins with pre-processing, which includes atmospheric correction to convert digital values into surface reflectance values using algorithms such as Sen2Cor for Sentinel-2, as well as masking processes to remove pixels obscured by clouds, cloud shadows, and non-water land cover based on QA band algorithms and water classification datasets such as JRC Global Surface Water (Atiz & Durduran, 2025; Dabhadkar, 2025).

RESULTS AND DISCUSSION

Visualization of Sentinel-2 Image Maps for pH Parameters in Lake Mahalona Waters During the Period (January 1, 2025 – November 1, 2025)

Based on Figure 2, which is the processed result from the GEE platform, a spatial analysis was conducted to monitor water quality in Lake Mahalona using a remote sensing and Geographic Information System (GIS) approach at a zoom level of 13 with a spatial resolution of approximately 19 meters per pixel. The use of platforms like GEE with Sentinel-2 satellite data for water quality parameter analysis is an increasingly common scientific approach due to its ability to process satellite data efficiently over large areas, particularly in hard-to-reach regions (Ting et al., 2025).

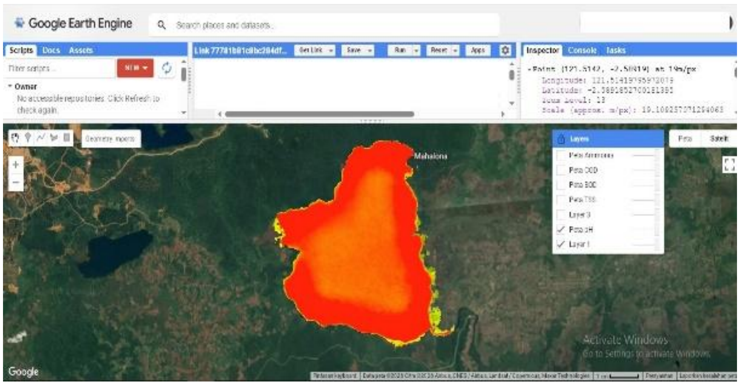

Figure 2 Visualization of Sentinel-2 Image Map for pH Parameters in the Waters of Lake Mahalona during the Period (January 1, 2025 – November 1, 2025)

The presence of thematic layers such as the "pH Map" indicates a comprehensive effort to map water quality parameters. The aim is to map the spatial distribution of acidity levels (pH) or pollutant concentrations in lake waters. The use of a spatial resolution of approximately 19 meters per pixel allows for a more detailed identification of the distribution of water quality variables, so this approach reflects the application of remote sensing technology and geographic information systems in aquatic environmental studies, which aim to support water resource management based on accurate and up-to-date scientific data. Scientifically, cloud computing platforms like GEE enable efficient temporal and spatial analysis to monitor the health status of Lake Mahalona. The use of platforms like GEE for analyzing water quality parameters is an increasingly common scientific approach due to its ability to process satellite data (such as Sentinel-2) for efficient environmental monitoring over vast areas, particularly in hard-to-reach regions (Ting et al., 2025).

Figure 3 a spatial distribution map of satellite-derived pH estimates in Lake Mahalona's waters has been created, with estimated values ranging from 6.587 to 7.154, where values in the 6 range are represented by green to yellow, and values in the 7 range by orange to red. This range indicates that the water body of Lake Mahalona is in a neutral condition that still meets general water quality standards and, from a limnological perspective, remains suitable for supporting aquatic life (News, 2018). These mapping results are consistent with previous limnological research in the Malili Lake Complex, which confirmed that the waters of Lake Mahalona still reflect oligotrophic conditions despite potential threats from anthropogenic activities in the surrounding watershed (Suryono & Lukman, 2018). Such spatial visualizations are crucial for detecting horizontal variations in pH that may indicate pollutant input points, enabling more targeted and effective environmental management interventions (Pereira et al., 2020).

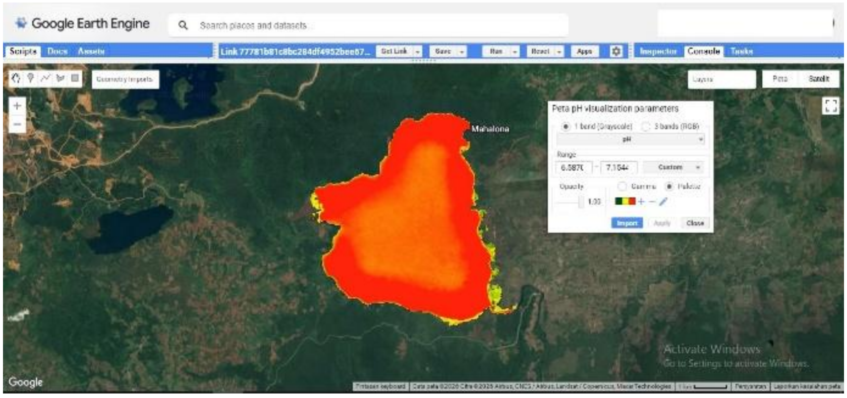

Figure 3 Visualization of the Spatial Distribution Map of pH Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Analysis of Monitoring Results from Sentinel-2 Imagery for pH Parameters in Lake Mahalona Waters during the Period (January 1, 2025 – November 1, 2025)

Based on the data in Figure 4, fluctuations in pH values of Lake Mahalona's water were observed throughout January to November 2025. In March 2025, the lowest pH value recorded was 6.656, indicating water conditions that remained within the permissible normal range for lake water quality standards, although tending to be slightly acidic. This value remains within the thresholds established in Government Regulation No. 22 of 2021 for all water classes (6–9) and falls within the range commonly found in tropical lake waters that support aquatic life (Siahaan et al., 2021).

However, the pH increased to 7.049 in August 2025, indicating a shift toward a more stable neutral condition tending toward slightly alkaline. This increase could be caused by inflow from the catchment area containing alkaline minerals, increased phytoplankton photosynthetic activity consuming carbon dioxide, or inflow of domestic wastewater containing detergents (Ismawati, 2025; World Health Organization, 2017). Although this increase remains within quality standards, fluctuating pH changes warrant attention as they can affect nutrient availability and heavy metal toxicity in the water.

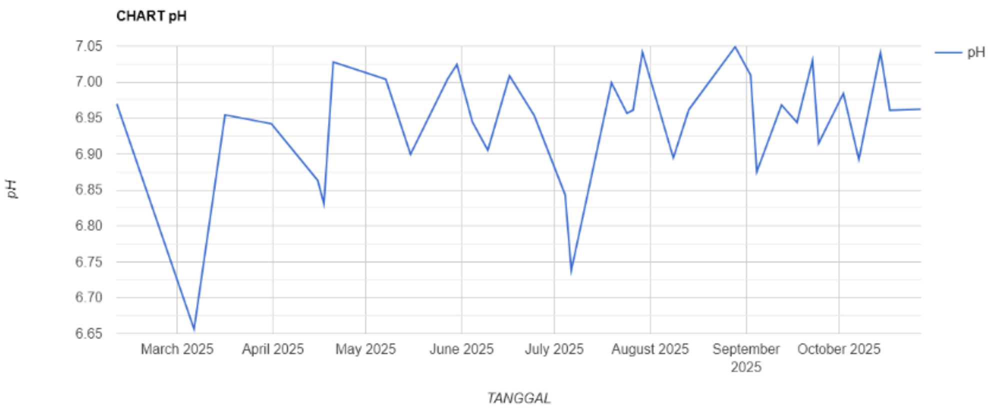

Figure 4 Trend Graph of pH Parameters in Lake Mahalona Waters for the Period (January 1, 2025 – November 1, 2025)

Visualization of Sentinel-2 Image Maps for TSS Parameters in Lake Mahalona Waters During the Period (January 1, 2025 – November 1, 2025)

Based on Figure 5, which shows the GEE-processed "TSS Map" layer for Lake Mahalona, spatial mapping has been conducted to analyze the distribution of total suspended solids concentrations in the lake's waters. The TSS parameter is a key indicator in limnological studies and water quality assessment as it represents the total amount of solid particles suspended in the water column, including both organic and inorganic materials, which can affect sunlight penetration, photosynthesis, and the life of aquatic organisms. Various TSS estimation algorithms have been developed from satellite imagery using red and near-infrared bands sensitive to water turbidity (Hariyanto et al., 2017), with recent machine learning approaches yielding even more accurate estimates than standard algorithms (Yuliara et al., 2025).

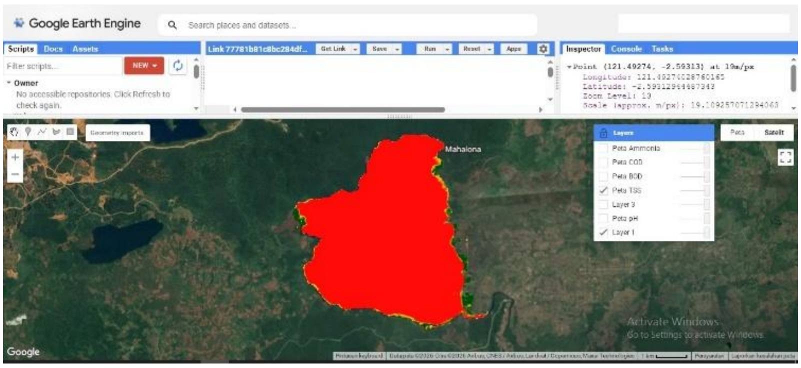

Figure 5 Visualization of Sentinel-2 Image Maps for the TSS Parameter in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Based on Figure 6, a spatial distribution map of TSS concentrations in Lake Mahalona's waters has been created, with satellite-derived estimated values ranging from 17.55 to 19.821 mg/L. This relatively low TSS concentration range indicates that the lake's turbidity level remains in the favorable category and supports aquatic life, with sunlight penetration into the water column remaining optimal to support phytoplankton photosynthesis and aquatic vegetation growth. According to Government Regulation No. 22 of 2021, the TSS quality standard for Class II water is 50 mg/L; thus, the TSS values for Lake Mahalona (17.55–19.82 mg/L) remain well below the established threshold. This spatial visualization enables the identification of areas with high sediment loads likely influenced by inputs from the catchment area due to erosion or anthropogenic activities, thereby serving as a scientific basis for formulating watershed management policies and lake conservation efforts (Siburian & Hafni, 2025).

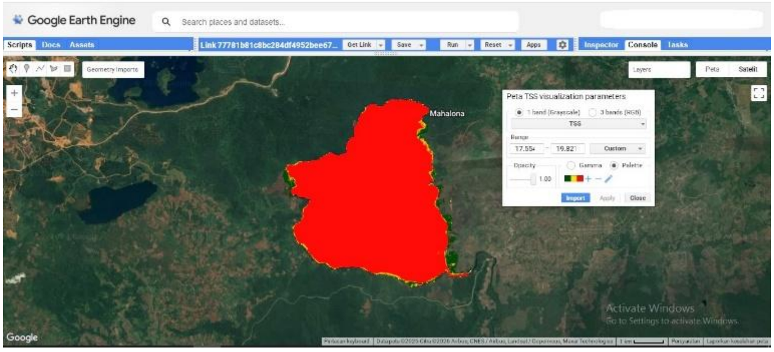

Figure 6 Visualization of the Spatial Distribution Map of TSS Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Analysis of Monitoring Results from Sentinel-2 Imagery for TSS Parameters in Lake Mahalona Waters during the Period (January 1, 2025 – November 1, 2025)

Based on Figure 7, fluctuations in TSS values of Lake Mahalona's water were observed throughout January to November 2025. In March 2025, the lowest TSS value recorded was 18.209 mg/L, indicating relatively clear lake water with low suspended solids content, well below the Class II and III standard of 50 mg/L established under Government Regulation No. 22 of 2021, indicating good water quality that supports aquatic life (Sani, 2024; Wiata & Mufti, 2024).

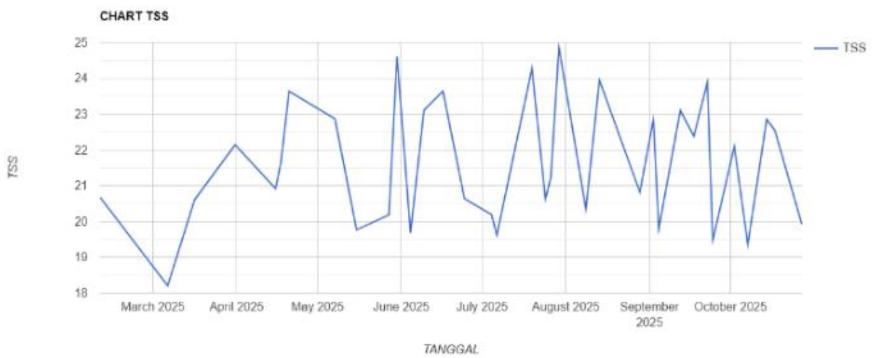

Figure 7. Trend Graph of TSS Parameters in Lake Mahalona Waters for the Period (January 1, 2025 – November 1, 2025)

However, the TSS value increased to 24.869 mg/L in August 2025, indicating increased turbidity due to a higher input of suspended solids. This phenomenon may possibly be associated with increased erosion in the catchment area due to heavy rainfall, surface runoff from agricultural land or settlements around the lake, or other anthropogenic activities. This pattern is consistent with findings in Lake Toba, where turbidity peaks occur during the August–September period, reflecting a strong seasonal influence on lake water quality (Siburian & Hafni, 2025; Supriyono et al., 2021). Although values remain below the 50 mg/L standard, the increase warrants attention as an early indication of rising sediment load into the lake's water body.

Visualization of Sentinel-2 Image Maps for BOD Parameters in Lake Mahalona Waters during the Period (January 1, 2025 – November 1, 2025)

Based on Figure 8, which is a result processed by GEE using the "BOD Map" layer, spatial mapping of the BOD parameter has been conducted, representing the amount of dissolved oxygen required by microorganisms to oxidize organic matter in the water. The spatially mapped BOD values enable the identification of zones with high organic pollution loads, which generally originate from domestic wastewater, agricultural activities, or organic matter inputs from the catchment area. Based on Government Regulation No. 22 of 2021, the BOD quality standard for Class II water is 2 mg/L (Rahim et al., 2022; Suyatno et al., 2024), making spatial BOD monitoring in Lake Mahalona a crucial tool for priority lake conservation and early detection of water quality degradation caused by anthropogenic pressures.

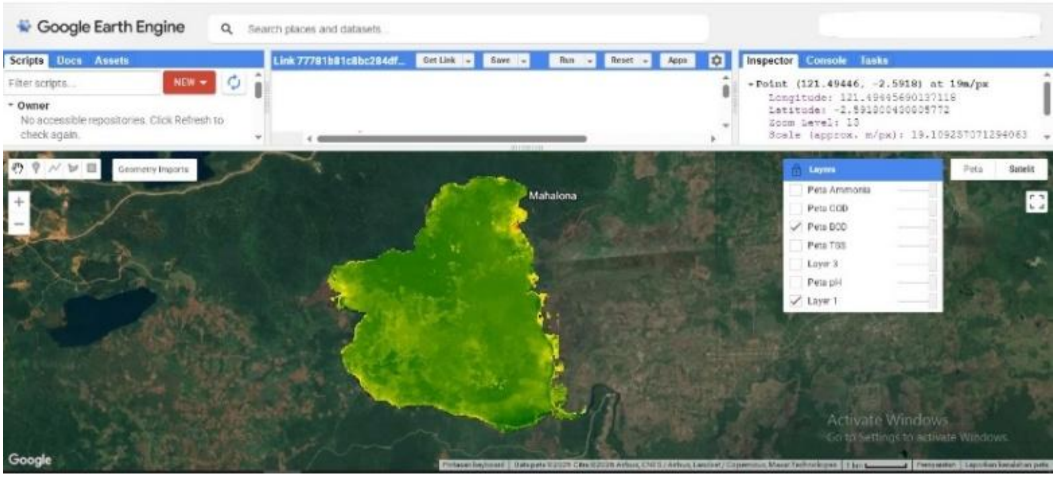

Figure 8. Visualization of Sentinel-2 Image Map for BOD Parameters in Lake Mahalona Waters during the Period (January 1, 2025 – November 1, 2025)

Based on Figure 9, a spatial distribution map of BOD values in Lake Mahalona's waters has been created, with satellite-derived estimated concentration ranges from 3.215 mg/L (green) to 7.266 mg/L (yellow to orange). This range indicates that the lake waters fall into the category of light to moderate pollution by organic matter, as BOD values exceeding 3 mg/L generally indicate increased microbial activity decomposing organic material from domestic waste, agricultural residues, or natural inputs from surrounding vegetation. Under Government Regulation No. 22 of 2021, the BOD standard for Class II is 2 mg/L and for agricultural use is 6 mg/L (UPT PSDAWS Madura, 2025; Serang Regency Environmental Agency, 2025) therefore, the mapped BOD values indicate that some areas of Lake Mahalona have already exceeded the Class II standard and are even approaching or surpassing the agricultural threshold, suggesting possible anthropogenic pressure from organic matter inputs in the watershed (Suryono & Lukman, 2018). Recent studies show that integrating remote sensing data, meteorological variables, and land-use information can achieve high BOD prediction accuracy using the Ridge Regression algorithm (Dawn et al., 2025).

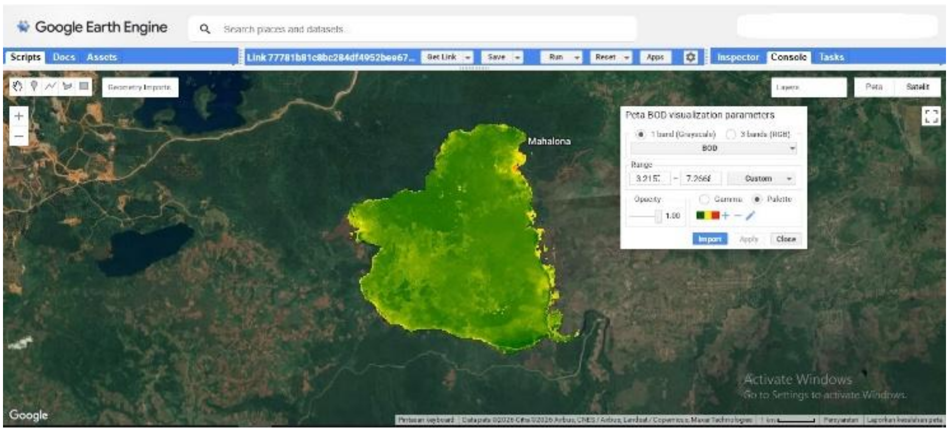

Figure 9. Visualization of the Spatial Distribution Map of BOD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Analysis of Monitoring Results from Sentinel-2 Imagery for BOD Parameters in the Waters of Lake Mahalona During the Period (January 1, 2025 – November 1, 2025)

Based on Figure 10, fluctuations in BOD values of Lake Mahalona's water were observed throughout January to November 2025. In August 2025, the lowest BOD value recorded was 3.411 mg/L, indicating relatively better water quality in the lake with a lower organic pollution load during that period (Alfrianti & Sudradjat, 2024).

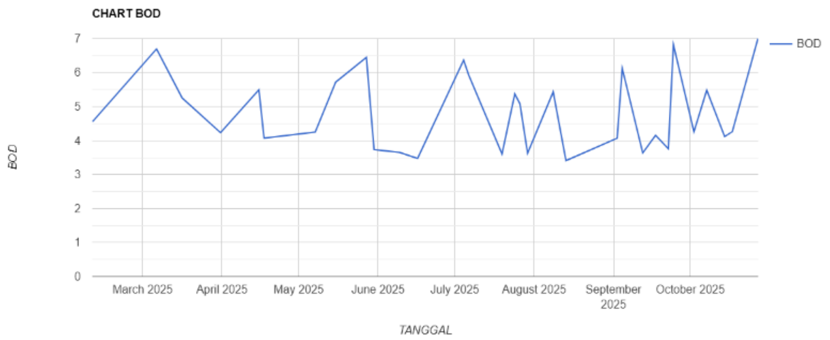

Figure 10. Trend Graph of BOD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

However, the BOD value increased to 6.999 mg/L in October 2025, suggesting potential organic loading possibly linked to domestic wastewater discharge, agricultural activities around the lake, or other pollution sources, thereby exceeding the quality standards set forth in Government Regulation No. 22 of 2021 (Alfrianti & Sudradjat, 2024; Sani, 2024; Suyatra, 2019).

Visualization of Sentinel-2 Image Maps for COD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Based on Figure 11, which is a processed result from GEE displaying the "COD Map" layer, spatial mapping has been conducted of the chemical parameter measuring the total oxygen required to chemically oxidize organic and inorganic matter in the water body. The COD parameter is a key indicator in water quality studies as it represents pollution levels originating from various sources, including industrial, domestic, and agricultural runoff containing chemical compounds difficult to break down biologically. Recent research in the Malili Lake Complex indicates that although COD values remain relatively low, there is a trend of increase over the observation period, suggesting anthropogenic pressure (Suryono & Lukman, 2018). Based on Government Regulation No. 22 of 2021, the COD quality standard for Class II is 12 mg/L (Serang Regency Environmental Agency, 2025), making periodic spatial COD monitoring through GEE a crucial tool for priority lake conservation, including consideration of potential impacts from mining activities around PT Vale Indonesia's operational area (Kumparan, 2024; SINDOnews, 2022).

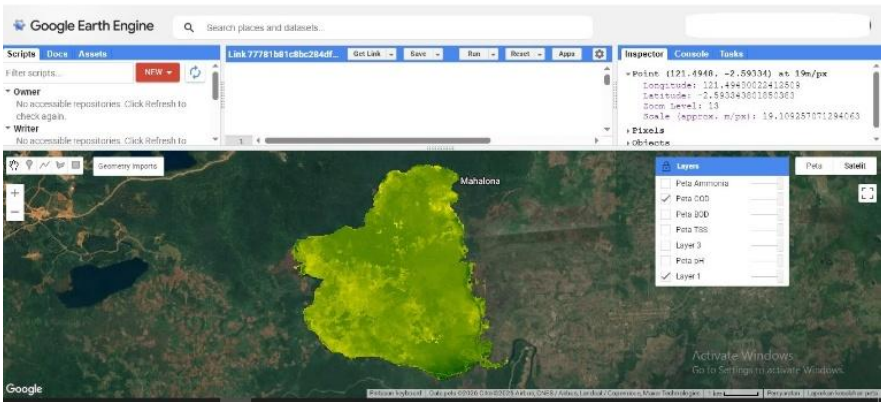

Figure 11. Visualization of Sentinel-2 Image Maps for COD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Based on Figure 12, a spatial distribution map of COD values in Lake Mahalona's waters has been created, with satellite-derived estimated concentration ranges from 2.857 mg/L (green) to 6.116 mg/L (yellow). This relatively low range indicates that pollution levels from organic and inorganic substances requiring chemical oxidation remain in the low to moderate category, with no significant accumulation of chemical pollutants from domestic, industrial, or agricultural activities around the lake. The mapped COD values (2.86–6.12 mg/L) remain below the 12 mg/L threshold established under Government Regulation No. 22 of 2021, consistent with Lake Mahalona's characteristics as part of an oligotrophic ancient lake system with low biological productivity (Suryono & Lukman, 2018). This spatial visualization enables tracking of potential sources of chemical pollution entering the water body, serving as a scientific basis for lake management and pollution load capacity determination.

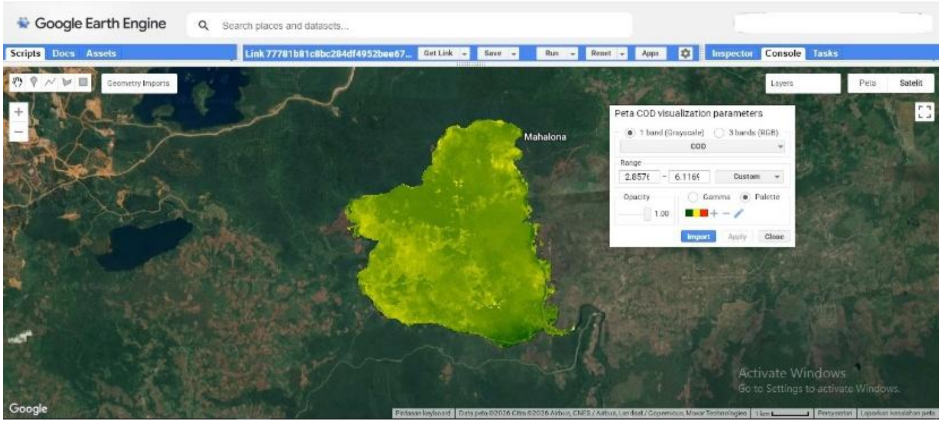

Figure 12. Visualization of the Spatial Distribution Map of COD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Analysis of Monitoring Results from Sentinel-2 Imagery for COD Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Based on Figure 13, fluctuations in COD values of Lake Mahalona's water were observed throughout January to November 2025. In August 2025, the lowest COD value recorded was 3.039 mg/L, indicating excellent water quality with very low levels of organic matter requiring chemical oxygen for oxidation. This value is far below all lake water quality standards based on Government Regulation No. 22 of 2021, even for Class I (raw drinking water) which requires a maximum of 10 mg/L, indicating minimal chemical pollution load during that period.

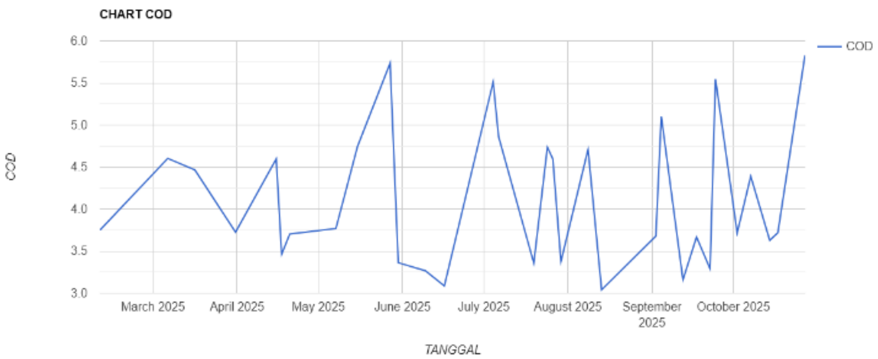

Figure 13. Trend Graph of COD Parameters in Lake Mahalona Waters for the Period (January 1, 2025 – November 1, 2025)

However, the COD value increased to 5.83 mg/L in October 2025, indicating a rise in the concentration of organic and inorganic substances that can be chemically oxidized. Although this value remains below the Class I standard (10 mg/L), this nearly twofold increase warrants attention as an early warning sign of possible pollutant inputs potentially associated with domestic wastewater, agricultural activities using fertilizers and pesticides, or other anthropogenic activities within the watershed (Agustina & Muliadiasa, 2023; Government Regulation No. 22 of 2021).

Visualization of Sentinel-2 Image Maps for Ammonia Parameters in Lake Mahalona Waters During the Period (January 1, 2025 – November 1, 2025)

Based on Figure 14, which is a processed result from GEE displaying the atmospheric ammonia loading pressure above Lake Mahalona, spatial mapping of the ammonia parameter has been conducted as a key indicator for evaluating potential nitrogen input through atmospheric deposition to the lake system. Layer, spatial mapping of ammonia parameters has been conducted—a key indicator in evaluating water quality and levels of organic pollution. Ammonia in water bodies generally originates from the decomposition of organic matter, domestic wastewater, and fertilizer runoff from agricultural activities in the catchment area; its presence at elevated concentrations may indicate potential organic pollution pressure in aquatic systems. Free ammonia is toxic to aquatic organisms; even at low concentrations, it can disrupt fish respiratory and osmoregulatory systems (Warsa & Husna, 2006). Based on Government Regulation No. 22 of 2021, the total ammonia quality standard for Class II is set at 0.2 mg/L. Spatial mapping of ammonia using the GEE platform enables efficient and periodic estimation of atmospheric ammonia loading pressure above the lake surface, which is ecologically relevant for assessing potential external nitrogen input through atmospheric deposition in oligotrophic lake systems (Ellis et al., 2015; Hayashi et al., 2020).

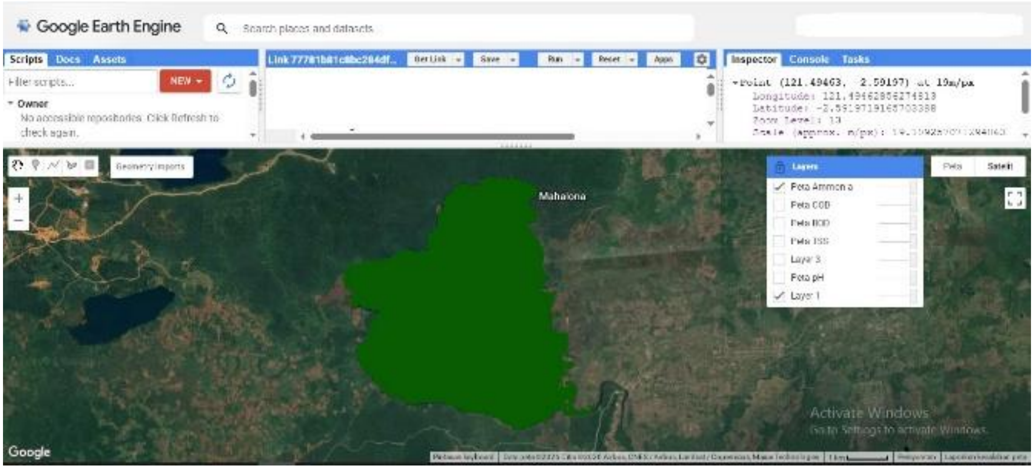

Figure 14. Visualization of the Sentinel-2 Image Map for Ammonia Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Based on Figure 15, the spatial distribution of ammonia concentrations in Lake Mahalona's waters has been mapped, with atmospheric ammonia pressure indicators yielding uniform estimated values of 0.001 mg/L across the monitored area, reflecting the spatial resolution limitations of the GEOS-CF dataset at this lake scale, represented by the color green. This spatial homogeneity is attributable to the coarse spatial resolution of the GEOS-CF atmospheric model relative to the lake surface area, rather than reflecting actual chemical homogeneity within the water column, and should be interpreted as an atmospheric loading indicator rather than a definitive measure of dissolved ammonia. Previous limnological studies in the Malili Lake Complex noted that ammonia concentrations in Lake Mahalona vary between 20–342 μg/L (0.02–0.342 mg/L) depending on depth and season, with higher values typically observed in the deep layer (hypolimnion) due to organic matter decomposition (Awalina & Hartoto, 2002). The mapped ammonia value (0.001 mg/L) is far below the 0.2 mg/L threshold under Government Regulation No. 22 of 2021, consistent with Lake Mahalona's characteristics as an oligotrophic ancient lake system with minimal anthropogenic pressure. Ammonia is a key parameter in water quality monitoring because it is toxic to aquatic organisms; even at low concentrations, it can disrupt respiratory systems, osmoregulation, and cause fish mortality if tolerance thresholds are exceeded (Mondal et al., 2025; Santanumurti, 2020).

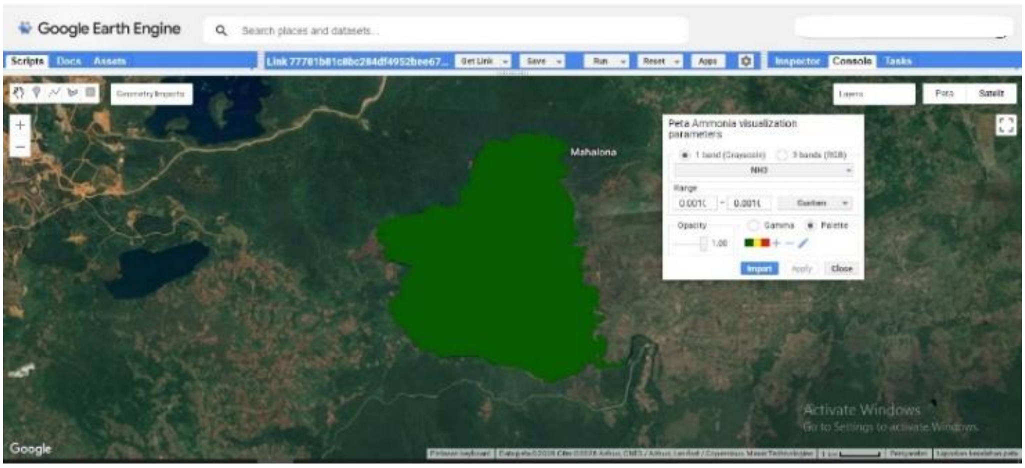

Figure 15. Visualization of the Spatial Distribution Map of Ammonia Parameters in the Waters of Lake Mahalona for the Period (January 1, 2025 – November 1, 2025)

Analysis of Monitoring Results from Sentinel-2 Imagery for Ammonia Parameters in Lake Mahalona Waters during the Period (November 1, 2025 – November 6, 2025)

Based on Figure 16, fluctuations in ammonia levels of Lake Mahalona's waters were observed during the period from November 1 to November 6, 2025. On November 2, 2025, the lowest estimated atmospheric ammonia pressure indicator was 0.001 mg/L, indicating excellent water quality with ammonia levels that are nearly undetectable. This value is far below all established quality standards, including Government Regulation No. 22 of 2021 for all water classes (the ammonia standard for lake water is 0.2 mg/L for Class II and III) as well as the aquatic life water quality criteria recommended by the US EPA (chronic criteria of 1.9 mg/L at pH 7.0 and 20°C) (U.S.

Environmental Protection Agency, 2020), indicating the absence of significant organic pollution pressure from domestic wastewater, fish feed residues, or agricultural runoff around the lake during that period.

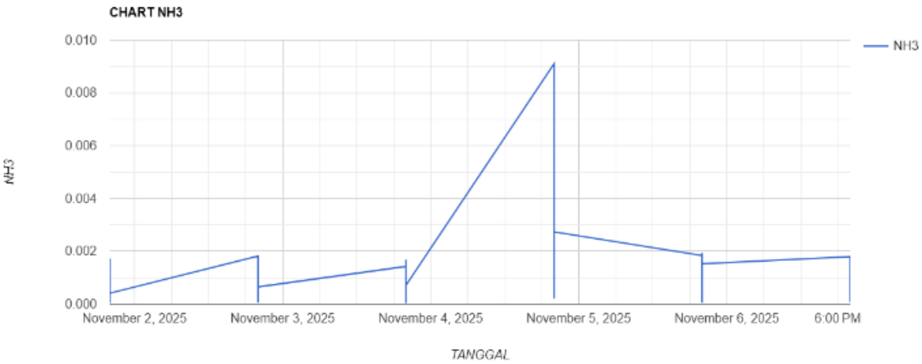

Figure 16. Graph of Ammonia Levels in Lake Mahalona from November 1, 2025, to November 6, 2025

However, ammonia levels increased to 0.009 mg/L on November 5, 2025, indicating that the lake water is beginning to receive organic matter undergoing both anaerobic and aerobic decomposition. Although this value remains well below required quality standards, the ninefold increase in ammonia concentration over just three days warrants attention as an early warning sign of possible organic loading potentially linked to domestic wastewater, agricultural activities in the watershed, or uneaten feed from aquaculture operations around the lake (Prasetyo, 2018; Rika, 2011). These rapid daily fluctuations reflect the temporal dynamics of organic matter input and require further monitoring to prevent ammonia accumulation, which can be toxic to aquatic biota, particularly if changes in pH and temperature increase its toxicity (U.S. Environmental Protection Agency, 2020).

Several important limitations of this study must be acknowledged to ensure appropriate interpretation of the findings. First and foremost, the absence of concurrent in-situ water quality measurements constitutes the most significant methodological constraint of this study. All water quality parameter estimates for pH, TSS, BOD, and COD were derived from empirical relationships applied to Sentinel-2 Level-2A surface reflectance data, without independent field validation at Lake Mahalona. While the empirical equations utilized are grounded in established satellite-based water quality monitoring principles, their accuracy in representing actual water column conditions at this specific lake cannot be confirmed without ground-truth data. Future studies are therefore strongly encouraged to incorporate systematic in-situ sampling campaigns to validate and potentially recalibrate these satellite-derived estimates for the unique limnological conditions of Lake Mahalona.

Second, the estimation of BOD and COD from multispectral satellite imagery is inherently indirect. Unlike TSS and chlorophyll-a, which have well-established optical proxies detectable by satellite sensors, BOD and COD are not optically active parameters and must be inferred through empirical correlations with spectrally measurable surrogates. This introduces additional uncertainty in the estimated values, and the results for these two parameters in particular should be treated as indicative approximations rather than precise measurements.

Third, the ammonia data in this study were sourced from the GEOS-CF atmospheric model, which operates at a spatial resolution considerably coarser than the lake surface area. Consequently, the uniform ammonia values observed across the entire lake do not reflect actual spatial heterogeneity within the water column, but rather represent atmospheric nitrogen loading pressure above the lake surface. Direct dissolved ammonia concentrations in the water body cannot be reliably inferred from this dataset alone.

Fourth, the temporal interpretation of observed parameter fluctuations, particularly the attribution of TSS increases to erosion and BOD and COD increases to domestic wastewater or agricultural activities, is based on plausible ecological reasoning and analogy with comparable lake systems rather than on direct watershed-scale evidence such as land-use analysis, hydrological data, or pollution source inventory. These interpretations should therefore be regarded as informed hypotheses warranting further investigation rather than definitive conclusions. Fifth, remote sensing-derived environmental estimates inherently contain uncertainty arising from atmospheric correction procedures, cloud and shadow masking, sensor radiometric limitations, algorithm selection, and temporal compositing. No formal uncertainty quantification was conducted in this study, which limits the ability to assign confidence intervals to the reported parameter ranges.

CONCLUSION

This study demonstrates that Google Earth Engine integrated with Sentinel-2 satellite imagery can effectively support spatial and temporal monitoring of water quality in Lake Mahalona, Towuti Subdistrict, East Luwu Regency, South Sulawesi Province, throughout the January–November 2025 observation period. The spatial mapping approach successfully visualized the distribution of five key water quality parameters, namely pH, total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), and atmospheric ammonia pressure, revealing distinct spatial patterns across the lake. The pH distribution indicated generally neutral water conditions, while TSS estimates showed a low and relatively uniform spatial pattern, suggesting favorable turbidity levels that continue to support adequate light penetration for aquatic life. In contrast, BOD displayed clear spatial variation, with certain zones of the lake exhibiting elevated organic pollution loads, whereas COD remained spatially low overall, indicating that chemical pollution pressures are still under control. Ammonia pressure was found to be spatially uniform across the lake, consistent with the oligotrophic character of Lake Mahalona, although this finding should also be interpreted with consideration of the spatial resolution limitations inherent to the GEOS-CF dataset.

The temporal analysis further revealed that water quality dynamics in Lake Mahalona are shaped by the interplay of seasonal variation and anthropogenic activity. pH remained consistently within normal standards throughout the observation period, while TSS showed a progressive upward trend that may be linked to intensified erosion and surface runoff from the surrounding watershed. Both BOD and COD exhibited fluctuating patterns with a notable increase during the later months of observation, pointing to a higher input of organic and chemical pollutants likely originating from domestic wastewater or agricultural activities in the surrounding area. Ammonia pressure, by comparison, remained stable throughout the shorter observation window available for this parameter, indicating no significant additional organic pollution pressure during that period.

When evaluated against the water quality standards set out in Government Regulation No. 22 of 2021, most parameters in Lake Mahalona, namely pH, TSS, COD, and ammonia, were found to remain within acceptable limits for Class.

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