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Examining Water Quality Indices Method in Varied Climatic Regions – Sutami Reservoir Case Study

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ABSTRACT

Monitoring and analyzing reservoir water quality are crucial for ecological and environmental strategies. This study examines the differences between the water quality index (WQI) of Indonesia (WQI-INA), Malaysia (DOE-Malaysia), Oregon (WQI-Oregon), and Italy (PI-Prati), considering the tropical climate of Indonesia and Malaysia, and contrasting with the temperate climate of Oregon and the Mediterranean climate of Italy. Using data from the Sutami Reservoir in Indonesia from 2015 to 2021, the study assesses water quality parameters such as BOD, COD, DO, NH_3, NO_3, total suspended solids, total phosphorus (TP), and pH at various depths (0.3, 5, and 10 meters) across three sites (upstream, midstream, downstream). The results show varied classifications: WQI-INA rated the reservoir as "pretty good," WQI-Oregon as "poor," and both DOE-Malaysia and PI-Prati as "slightly polluted." Spatial analysis of vertical distribution revealed "slightly polluted" (WQI-INA), "moderately polluted" (WQI-Oregon and PI-Prati), and "heavily polluted" (DOE-Malaysia). These discrepancies arise from differences in local environmental standards, regulatory requirements, and specific water quality concerns included in each index. The Sutami Reservoir water quality status was declared using WQI-INA, however, other methods were employed to simulate the worst-case scenarios and inform preventive actions. The Sutami Reservoir hyper-eutrophic conditions indicate a pollution load capacity of 65.22 tons per year. Critical parameters such as pH and TP highlight significant water quality and pollution issues. Recommendations for water quality treatment under heavy pollution conditions include applying 12.09–120.87 tons of lime, using 78.75–393.75 kg of chemical buffers, oxygen diffusion, controlling riparian vegetation over 2.37–23.7 hectares, dredging 37,100 m^3 of sediment per year, and reducing nutrient sources through community involvement.

Keywords: reservoir, climate, water quality index, pollution index, water quality treatment.

INTRODUCTION

Ensuring the quantity, quality, and uninterrupted flow of water within a watershed is essential for water resilience, a concept vital for national food and energy security (Rather et al., 2022). The primary problem impacting the reservoir is water pollution, resulting in degraded water quality (Mosley et al., 2015). The introduction of liquid waste into the reservoir has compromised the water's state. This deterioration is mainly due to high concentrations of pollutants, including both organic and inorganic substances (Bhateria et al., 2016). Upstream, the pollution stems from agricultural runoff, while downstream, it comes from industrial and domestic waste (Anh et al., 2023). This influx of contaminants raises the nutrient levels in the water, leading to eutrophication.

When the pollutant load surpasses certain limits, the water quality further declines, disrupting the aquatic ecosystem, especially the phytoplankton, which are the main producers in the reservoir (Cantonati et al., 2020). High levels of pollutants like phosphorus also diminish the reservoir's capacity. Therefore, it is essential to accurately determine the reservoir's pollution load capacity to maintain its equilibrium and avoid ecological disturbances (Chen et al., 2024). Similar challenges are encountered in the Sutami Reservoir and its surrounding areas.

Regular monitoring and analysis of reservoir water quality are essential for ecological and environmental strategies (Chou et al., 2018). In tropical regions of developing countries, water quality monitoring is typically conducted twice a year and often lacks periodic consistency (Chouler et al., 2015). Observations are usually divided between the rainy season and the dry season, resulting in partial monitoring (Lestari et al., 2015). Additionally, the analysis of water quality status by calculating the WQI sometimes relies on standards developed by the country based on subtropical region formulations (Uddin et al., 2015). This WQI influences the procedural manual applied to the status, potentially leading to excessive treatment that can disrupt the ecological balance of the reservoir's waters. Ideally, the impact of poor water quality on reservoir pollution and the subsequent ecological balance should also be assessed (Syeed et al., 2023). In developing countries, strategies are generally chosen objectively, taking budget constraints into account. However, many developing countries face challenges in determining appropriate actions due to numerous water quality parameters already being significantly degraded (Chapagain et al., 2022).

An ideal water quality monitoring system for reservoirs in tropical regions should conduct assessments five times a year at different of stratification: twice during the rainy season, twice during the dry season, and once in the middle of the year (Xiang et al., 2021). This monitoring technique aims to provide comprehensive and representative observations. The WQI assessment should be customized to local conditions, although it's crucial to compare it with WQI standards used by other countries, a practice that remains uncommon with periodic data (Akhtar et al., 2021). Evaluating the ecological balance of water is paramount by assessing the trophic status index and pollution load capacity, along with the Pollution Index (PI) (Mamun et al., 2021). Furthermore, establishing robust correlations among monitored quality parameters through periodic data collection helps pinpoint parameters that genuinely necessitate treatment. This method facilitates the identification of the most suitable water treatment strategies.

Indonesia, near the equator, experiences a tropical climate with consistently high temperatures year-round and significant rainfall. Malaysia, situated in a tropical rainforest climate, maintains high temperatures and humidity throughout the year, with abundant and evenly distributed rainfall across all seasons. Italy is not a subtropical country but rather has a Mediterranean climate with hot, dry summers and cool, wet winters, where most of the rainfall occurs during the winter season. Whereas, Oregon is located in a region with a temperate maritime climate, featuring cool and wet winters and cool and dry summers. The primary aim of this study is to investigate the differences between WQI used by the Ministry of Environment and Forestry of Indonesia (WQI-INA), the Department of Environment of Malaysia (DOE-Malaysia), the Prati Index made in Italy (PI-Prati), and the Oregon Department of Environmental Quality (WQI-Oregon). This investigation utilizes data collected over seven years (2015–2021) from the Sutami Reservoir in Indonesia. This research systematically measures and analyzes key water quality parameters, including biological oxygen demand (BOD), chemical oxygen demand (COD), dissolved oxygen (DO), ammonia (NH_3), nitrate (NO_3), total suspended solids (TSS), total phosphorus (TP), and pH, at various depths and locations within the reservoir. It classifies the trophic status of the reservoir and determines the pollution load capacity, particularly focusing on the phosphorus (TP) and total nitrogen (TP) levels. Based on the findings, the study proposes water quality treatment recommendations to improve and sustain the water quality of the Sutami Reservoir.

MATERIAL AND METHODS

This study was conducted in part of the Brantas watershed located at Sutami Reservoir, Province of East Java, Indonesia (112°42'58" – 112°36'21" EL dan 8°02'50"– 8°12'10" SL) Figure 1. The Sutami Reservoir is situated downstream at the junction of the Brantas River and Lesti River, serving as the terminal point of the inundation area designed to capture sediment flowing into the reservoir, raw water, irrigation, and hydroelectric power plant. The upstream watersheds that impact the water supply to the

Sutami Reservoir include the Upper Brantas River Sub-Watershed and the Lesti River Sub-Watershed. The Upper Brantas River Sub-Watershed contributes a surface water potential volume of 1.526 billion m^3 annually, equivalent to an average discharge of 48,405 m^3 per second. With an inundation area spanning 2370 km^2, the Sutami Reservoir has a total storage capacity of 21.5 million m^3, with 2.5 million m^3 reserved as active storage and approximately 19 million m^3 allocated for sediment retention. Water supply to the Sutami Reservoir comes from the Amprong River and Lesti River, both of which are upstream tributaries of the Brantas River, with an average monthly discharge of 55.2 m^3 per second and an annual rainfall of 2065 mm.

The observation periodically was conducted for 8 years starting from 2015 to 2021. The water quality parameter was analyzed on BOD, COD, DO, NH_3, NO_3, TSS, TP, and pH. Accordingly, several water quality monitoring points were used in completing this research, including the Sutami Reservoir Monitoring Station in the upstream, middle, and downstream areas as shown in Figure 1. The downstream and middle station was

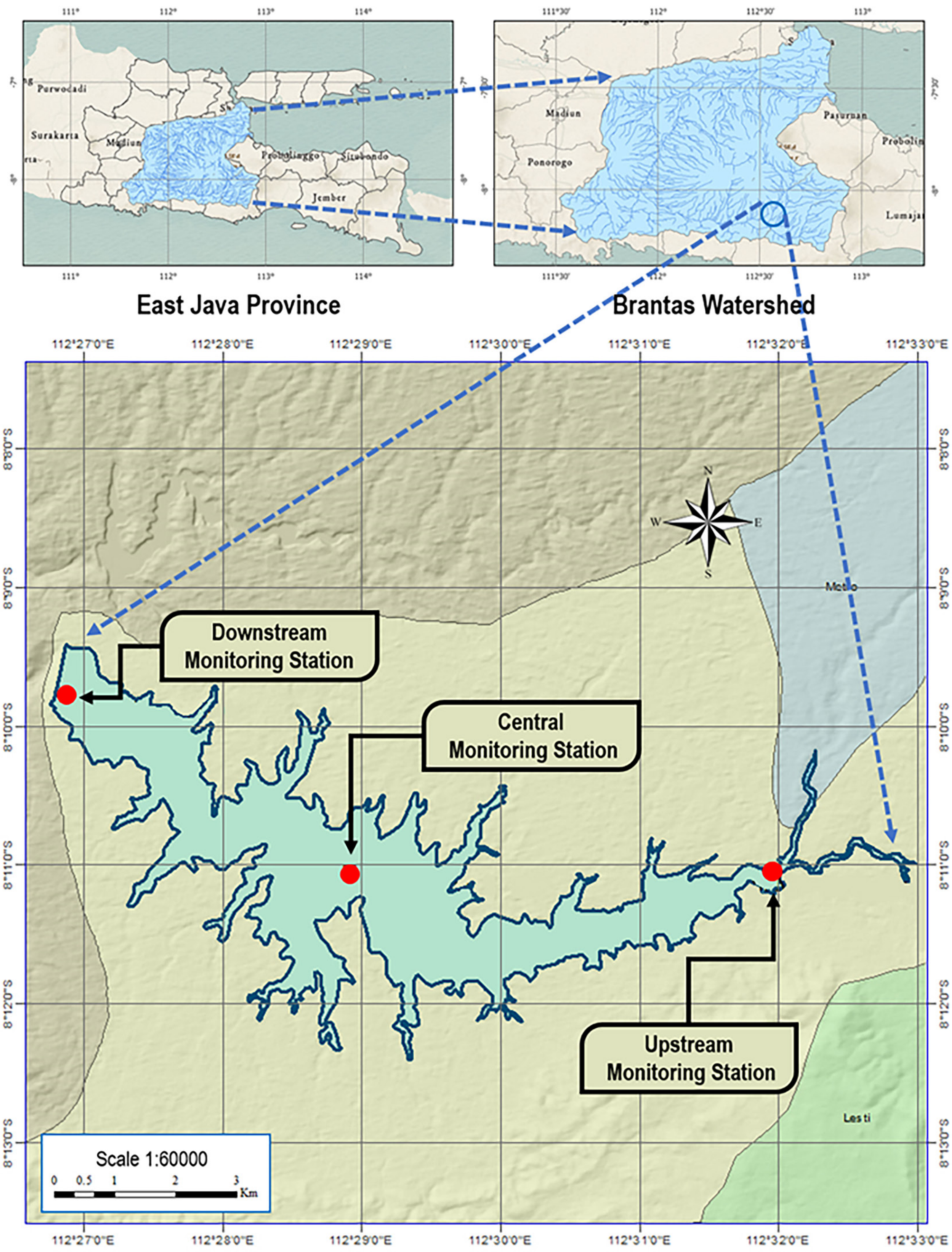

Figure 1. Sutami Reservoir map and 3 location monitoring points

observed at three depths (0.3 m, 5 m, and 10 m), whereas the upstream only had two depths (0.3 m, and 5 m) because of the limitation of depth.

The BOD was measured using Environmental Protection Agency (EPA) Methods (procedures for measuring BOD in wastewater samples). The method to measure the COD was used Dichromate Method followed the procedure of EPA (procedures for measuring COD in wastewater samples). For NH_3 intensity analyzed using Colorimetric Methods published International Organization for Standardization (ISO) standard specifies a manual spectrometric method for the determination of ammonium in water samples. Whereas NO_3 is determined by Spectrometric method using cadmium reduction ISO standard specifies a spectrometric method for NO_3 in water samples using cadmium reduction. Determination of phosphorus using the Ammonium molybdate spectrometric method following ISO standard specifies a spectrometric method. The in-situ instrument was used for DO, pH, and TSS helped the instruments of the DO Meter (Model HI9146-04N, Hanna Instruments, Canada), pH meter (Model Hi9811-51 Portable pH, Hanna Instruments, Canada), TSS Meter (Model Partech 740, Partech Instruments, USA).

Determination of distribution of water quality status characteristics

The WQI used is the WQI-INA, developed from the formula by Dewi et al. (2016), which refers to regulations from the Ministry of Environment and Forestry of Indonesia. The WQI-INA will be compared with the DOE-Malaysia (Fulazzaky et al., 2010) and the WQI-Oregon (Cude et al., 2001; Dunnette et al., 1979). For the pollution index analysis, the Prati method (PI-Prati) (Prati et al., 1971) will be used. While the WQI-INA method consists of 8 parameters and the weight value was proportionalized as shown in Table 2. The DOE-Malaysia method was invented by the Malaysian Department of the Environment (DOE) as a water quality index. The formula of the DOE-Malaysia method can be expressed following Equation 2. The WQI-Oregon is a single number that expresses water quality by integrating measurements of 6 parameters as shown in Equation 3.

$$WQI_{IKA-INA} = \sum_{i=1}^{n} wi.SI_i \tag{1}$$

$$WQI_{DOE-Malaysia} = \frac{1}{n}.\sum_{i=1}^{n} SI_i \tag{2}$$

$$WQI_{Oregon-USA} = \sqrt{\frac{n}{\sum_{i=1}^{n}.\frac{1}{{SI_i}^2}}} \tag{3}$$

$$IP_{Prati} = \sum_{i=1}^{n} wi.SI_i \tag{4}$$

where: SI_i is the sub-index value for parameter i, w_i (which ranges from 0 to 1) is the corresponding parameter weight value following the equation in Table 2, and n is the total number of parameters. The PI-Prati method is an index of surface water according to the water quality classification system. The parameters were calculated by the Prati index method following Equation 4 according calculated sub index of 7 parameters as shown in Table 2. WQI and PI methods determine different classifications to describe the status of water quality in the Sutami reservoir following the criteria in Table 1.

Trophic status and pollution load capacity determination

Eutrophication itself is classified into four categories of trophic states, namely the trophic status of oligotrophs (TN ≤ 650 µg/L, TP < 10 µg/L), mesotrophic (TN ≤ 750 µg/L, TP < 30

Table 1. Rating scale of the WQI models

DOE - Malaysia	WQI - INA	WQI - USA	PI - Prati
0 ≤ x < 60; very polluted 60 ≤ x < 80; slightly polluted x > 80; clean	0 – 36; bad 36 – 51; marginal 51 – 70; currently 70 – 80; pretty good 80 – 90; good 90 – 100; very good	0 – 60; very poor 60 – 79; poor 80 – 84; fair 85 – 89; good 90 – 100; excellent	0 – 1; good quality 1 – 2; acceptable quality 2 – 4; polluted 4 – 8; heavily polluted 8 – 16; very heavily polluted

Table 2. Sub-index equations of WQI

IP-Prati	WQI-Oregon
1. DO $y = -0.08x + 8; 50 \le x < 100$, $y = -0.08x - 8; 100 \le x$ 2. BOD $y = 0.66666x$ 3. COD $y = 0.10x$ 4. NH_3-N $y = 2^{[2.1\log(10x)]}$ 5. TSS $y = 2^{[2.1\log(0.1x-1)]}$ 6. pH $y = -0.4x^2 + 14; 0 \le x < 5$, $y = -2x + 14; 5 \le x < 7$, $y = x^2 - 14x + 49; 7 \le x < 9$, $y = -0.4x^2 + 11.2x - 64.4; 9 \le x < 14$ 7. NO_3-N $y = 2^{[2.1\log(0.25x)]}$	1. DO $y = 0.0081x^2 + 0.3302x + 3.5955; x<40$ $y = 0.0522x^2 - 3.7369x + 95.977; 40<x<60$ $y = -0.0118x^2 + 2.8764x - 69.6; 60<x<100$ $y = -0.0068x^2 + 1.0809x + 60.145; 100<x<140$ 2. BOD $y = 0.2314x^2 - 8.9686x + 99.571; x<15$ $y = 0.05x^2 - 3.27x + 56.95; 15 < x < 30$ 3. TSS $y = 0.028x^2 - 2.4668x + 99.736; x<30$ $y = 0.005x2 - 1.15x + 83; 30 < x < 100$ 4. pH $y = 4.5854x^2 - 23.656x + 29.497; x<6$ $y = -18.746x^2 + 280.54x - 957.43; 6<x<9$ $y = 5.5174x^2 - 131.2x + 781.48; x>9$ 5. TN $y = 0.1x^2 - 5.4x + 98.5; x<30$ $y = 0.0014x^2 - 0.4069x + 27.127; x>30$ 6. TP $y = 22.273x^2 - 80.555x + 99.755; x<1.5$ $y = 1.25x^2 - 13.65x + 49.15; 1.5 < x < 4$ $y = 0.2459x^2 - 4.4724x + 28.149; 4 < x < 10$
DOE- Malaysia	WQI-INA
1. DO (w = 0.22) $y = 0$ for x £ 8 $y = -0.395 + 0.03x^2 - 2.\ 10^4x^3; 8 < x < 92$ $y=100$ for x ³ 92 2. BOD (w = 0.19) $y = 100.4 - 4.23x$; x £ 5 $y = 108e^{(-0.055x)} - 0.1x; x > 5$ 3. COD (w = 0.16) $y = -1.33x + 99.1$; x £ 20 $y = 103e^{(-0.0157x)} - 0.04x; x > 20$ 4. NH_3 (w = 0.15) $y = 100.5 - 105x$; x £ 0.3 $y = 94e^{(-0.573x)} - 5\lvert x - 2\rvert ; 0.3 < x < 4$ $y = 0$ for x ³ 4 5. TSS (w = 0.16) $y = 97.5e^{(-0.00676x)} + 0.05x$; x £ 100 $y = 71e^{(-0.0061x)} - 0.015x; 100 < x < 1000$ $y = 0$; x ³ 1000 6. pH (w = 0.12) $y = 17.2 - 17.2x + 5.02x^2; x < 5.5$ $y = -242 + 95.5x - 6.67x^2$; 5.5 £ x < 7 $y = -181 + 82.4x - 6.05x^2$; 7 £ x < 8.75 $y = 536 - 77.0x + 2.76x^2$; x ³ 8.75	1. DO (w = 0.1638) $y= -1.3949x^4 + 10.848x^3-23.437x^2+23.484x-2^{-10}; x<4$ $y = 4.5854x^2 - 23.656x + 29.497; x<6$ $y = -18.746x^2 + 280.54x - 957.43; 6<x<9$ $y = 5.5174x^2 - 131.2x + 781.48; x>9$ 2. BOD (w = 0.12944) $y= 0.4458x^3-3.4443x^2-1.3145x+99.149; x < 5$ $y= 0.0287x^3-0.9446x^2+5.9997x+52.218; x < 20$ $y= 0.0073x^3-0.606x^2+14.795x-88.323; x < 40$ 3. COD (w = 0.13746) $y= 0.0204x^2-1.4479x+99.614; x<20$ $y= 0.0692x^2-6.0926x+173.01; x<50$ 4. NH_3 (w = 0.10538) $y= 18703x^6-36932x^5+27566x^4-9960.8x^3+1744.5x^2$ $-187.12x+100; x<0.7$ $y= 644.68x^3-1507.1x^2 +1092.2x-228.14; x<1$ 5. TSS (w = 0.08477) $y = -0.001x^2 + 0.2287x + 80.082; x<50$ $y = -0.0005x^2 + 0.0071x + 89.636; 50<x<150$ $y = -5.\ 10^{-5}x^2 - 0.1x + 96.166; 150<x<500$ 6. pH (w = 0.20275) $y= 0.1035x^4-0.4796x^3+1.5586x^2+2.2036x-2.5054; x<5$ $y= -0.381x^5+14.77x^4-225.01x^3+1673.7x^2-6045x+8520.9; x<10$ $y= 7.6265x^2-181.88x+1087.8; x<12$ 7. NO_3-N (w = 0.07904) $y= -0.0046x^3+0.2002x^2-4.0745x+97.77; x<30$ $y= 10^{-6}x^4+2.10^{-5}x^3-0.0168x^2+0.3103x+36.034; x<70$ $y= 0.0039x^2-0.8417x+47.227; x<100$ 8. TP (w = 0.09737) $y= -0.1347x^5+2.483x^4+16.702x^3+50.051x^2-73.42x+100$; x £ 5 $y= -16.328x+109.15$; x £ 6 $y= -0.4975x+14.165$; x £ 7

μg/L), eutrophic (TN ≤ 1900 μg/L, TP < 100 μg/L), and hypertrophy (TN ≥ 1900 μg/L, TP ≥ 100 μg/L) following the Trophic status classification by Marselina, et al (2017). Following the determination of water quality status, a distribution mapping of the water quality characteristics was generated using the Inverse Distance Weighted (IDW) method within the ArcMap 10.8 software. Additionally, to ascertain the allowable pollution load capacity for the Sutami Reservoir, it was necessary to calculate the trophic status level utilizing the TP parameter and the water pollution load quantity based on Regulation No. 28 of 2009 by the State Minister of Environment, concerning the Load Capacity of Water Pollution in Lakes and/or Reservoirs (Government of Indonesia, 2009).

RESULTS AND DISCUSSION

Water quality of Sutami Reservoir

The assessment of WQI relies on the average values for each reservoir depth level, which are subsequently compared to the concentrations at the upstream, midstream, and downstream sections on an annual basis (Figure 2).

BOD represents the quantity of DO need by microorganisms to break down organic substances (Lokman, et al., 2021). The BOD levels in the Sutami Reservoir stem from diverse origins, including domestic, industrial, and agricultural waste, among others. The analysis findings reveal that in 2015, the BOD levels at different monitoring points in the Sutami Reservoir were 4.33 mgL^{-1}, 3.05 mgL^{-1}, and 3.62 mgL^{-1} for upstream, midstream, and downstream locations, respectively (Figure 2a). By 2021, there was a notable increase in BOD concentration to 8.50 mgL^{-1}. Mathematically, plotting the BOD data against time showed a hyperbolic trend represented by the equation $y = 0.137x^2 + 1.964x – 1.25$. Deriving this equation allowed for the determination of a BOD increase rate of 0.274 mgL^{-1} per year. In 2015, the BOD levels surpassed the acceptable range of 3–6 mgL^{-1} for unpolluted water quality, thereby making the river water unsuitable for recreational activities, freshwater fish farming, livestock, and agriculture [14–28]. The rising BOD concentrations signify water pollution, with levels ranging between 6–12 mgL^{-1} from 2018 to 2021, and concentrations exceeding 12 mgL^{-1} indicating heavy pollution, projected to occur by 2032.

COD represents the number of chemicals that can undergo oxidation in water, encompassing organic substances like carbohydrates, proteins, and fats, as well as inorganic compounds such as sulfides and nitrites (Aktas, et al., 2024; Rahardjo, et al., 2024). Discharge of industrial waste from sectors like chemical plants, food processing facilities, paper mills, and organic household waste (including detergents and other domestic residues) may lead to a degradation in water quality, disrupting aquatic ecosystems if not appropriately managed (Mishra, et al., 2023). Thus, the monitoring and regulation of COD are vital to sustaining favorable water conditions. Monitoring data depicted in Figure 2b spans a period of 7 years, revealing an annual increase trend of 0.346 mgL^{-1}y^{-1}. The rate of COD escalation is determined by the equation $y = 0.173x^2 + 3.76x – 7.236$. In 2015, the water quality in the Sutami Reservoir was deemed excellent as the COD levels ranged from 0–10 mgL^{-1} ($COD_{2015} = 9.654$ mgL^{-1}). However, this situation drastically shifted to a range of 15.006–26.303 mgL^{-1} between 2016 and 2021. By 2016, the water quality transitioned to an acceptable status (10–20 mgL^{-1}), but within 3 years, it deteriorated to slightly polluted due to COD levels exceeding 20 mgL^{-1}. Despite this, water from the Sutami Reservoir remains suitable for recreational activities, freshwater aquaculture, livestock, and agricultural purposes (Khalik, et al., 2023).

DO in water originates from natural processes such as photosynthesis by aquatic plants, and oxygen can also enter water through contact with air at the water's surface or through natural aeration events like waterfalls or fast-flowing rivers (Chapman, 1992). However, water DO quality is influenced by human activities, such as water pollution, reduction of aquatic vegetation, or discharge of waste containing organic matter that requires oxygen for decomposition (Khatri, et al., 2014). The measurement results of DO in Figure 2c clearly show extreme DO levels in 2016 with a value of 3.096 mgL^{-1}. However, periodically, DO levels increase gradually with a linear DO rate of 0.258 mgL^{-1}y^{-1} derived from the DO trend over time with the equation $y = 0.258x + 3.443$, reaching 5.183 mgL^{-1} in 2021. The percentage conversion value of DO saturation in 2021 is 42.814% sat, indicating that the water quality status is polluted (20–50% sat), but the reservoir water can still be used for recreational activities, freshwater

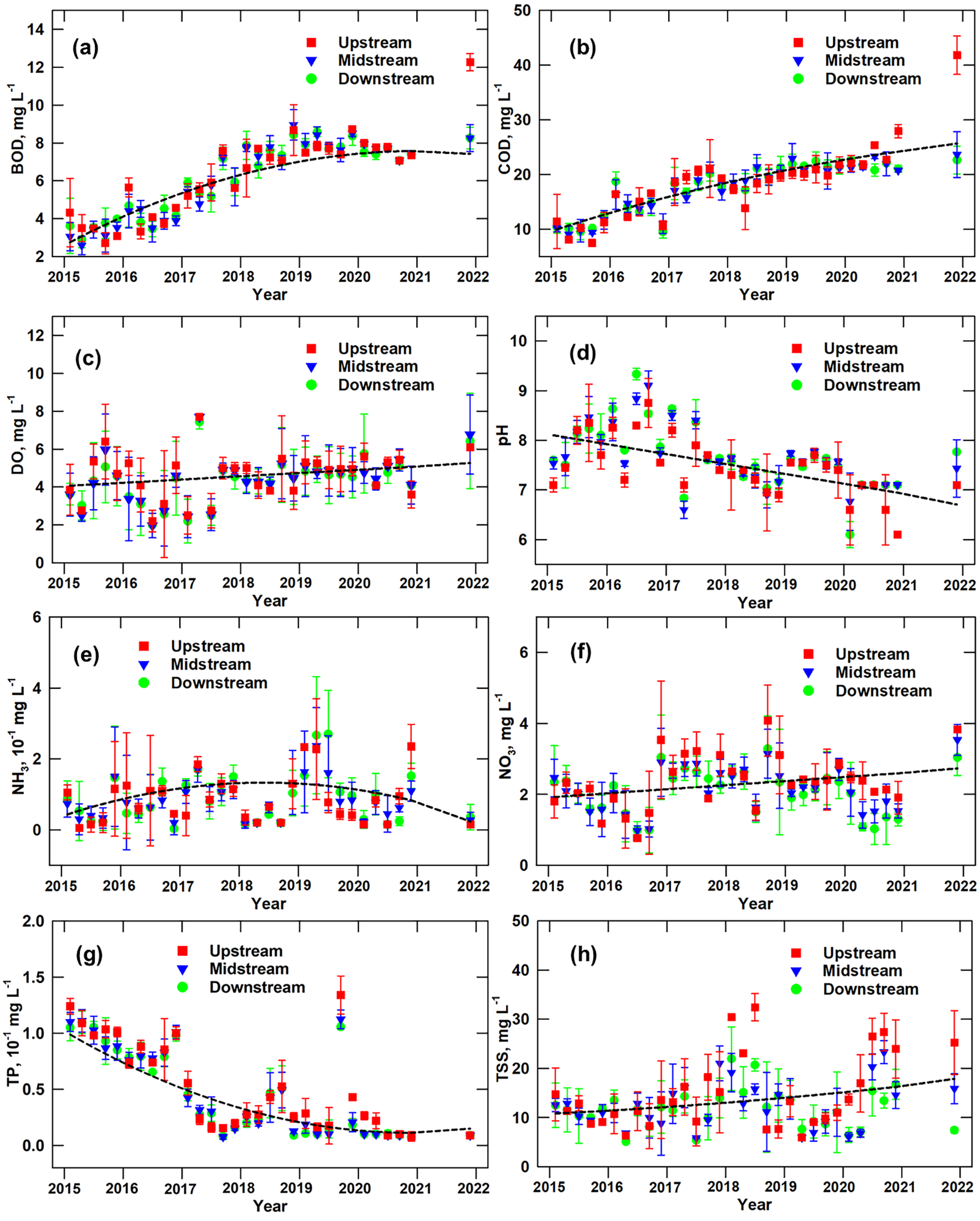

Figure 2. The water quality parameters of Sutami Reservoir on (a) BOD, (b) COD, (c) DO, (d) pH, (e) NH_3, (f) NO_3, (g) TP, and (h) TSS averages from different depth level observations

fish farming, livestock, and agriculture. Reservoirs can be considered good and have low pollution levels if DO is within the range of 50–75% sat and 75–88% sat, respectively (Firmahaya, et al., 2022). Therefore, based on the existing trend, it is predicted that the Sutami Reservoir will transition to a low pollution status by 2026.

The pH levels in water bodies can be influenced by various natural and human-made factors. Natural elements like geology, vegetation, and organic decay, as well as human activities such as pollution, industrial discharge, and household waste, can impact water pH (Ahn, et al., 2023). Measurements taken at the research site indicate that the average pH of the water at monitoring points falls within the normal range of 6.90–8.27 as shown in the Figure 2d, indicating excellent status. Water with a pH of approximately 6.5–7.5

is considered normal and conducive to life. pH levels between 7.5 and 8.1 are still suitable for recreational activities, freshwater fish cultivation, animal husbandry, and agriculture (WHO, 2017). However, the Sutami Reservoir exhibits a concerning trend of declining pH values, decreasing linearly at a rate of 0.199 y^{-1}-pH, as indicated by the equation $-0.199x + 8.314$. This decrease is attributed to domestic and agricultural waste, which is expected to lead to a slight deterioration in pollution status by 2030, with pH levels dropping below 5.

NH_3 in water can stem from various sources including organic decay, plant and animal residues, agricultural runoff, industrial discharge, and decomposing waste (Rahardjo, et al., 2023). The NH_3 concentration in water can naturally fluctuate over time, influenced by factors such as water temperature, pH, DO levels, and the presence of microorganisms that metabolize NH_3 (Rahardjo, et al., 2023). Periodic assessments of NH_3 in the Sutami Reservoir (Figure 2e) reveal a notable rise in concentration between 2015 and 2019, averaging from 0.042–0.168 mgL^{-1}-NH_3-N, shifting from excellent to acceptable conditions, respectively. By 2021, gradual increases in DO and pH decreases have stabilized NH_3 levels, dropping to 0.049 mgL^{-1}-NH_3-N. The NH_3 concentration is conducive for aquaculture, aiming for levels < 0.05 mgL^{-1}, and can serve as untreated drinking water, given that the NH_3 level is < 0.5 mgL^{-1} (Zhang, et al., 2022). Typically, NH_3 levels in natural water bodies are below 0.1 mgL^{-1} (Rahardjo, et al., 2022). Elevated NH_3 levels may indicate organic contamination from domestic, industrial, or agricultural sources in the vicinity of the Sutami Reservoir.

NO_3 found in water originates from bacterial nitrification processes that change the nitrogen cycle in well-oxygenated aquatic environments, as well as from the decomposition of organic matter like fallen leaves or remnants of organisms in water (Wu, et al., 2023). Additionally, rainwater carries nitrogen oxides (NO_x) resulting from human activities such as burning fossil fuels, and nitrogen fertilizers used in agriculture contribute to NO_3 levels (Moloantoa, et al., 2022). Industrial waste containing nitrogen, like that from fertilizer plants, can also release NO_3 into water. The NO_3 concentrations in the Sutami Reservoir water remain excellent, below 4 mgL^{-1}, specifically ranging from 1.386 to 2.524 mgL^{-1} NO_3-N. Despite being well below the pollution threshold, the NO_3 trend depicted in Figure 2f demonstrates a linear annual increase at a rate of 0.115 $mgL^{-1}y^{-1}$ according to the equation 0.115x + 1.811. Elevated NO_3 levels can negatively impact water quality and aquatic ecosystems by fostering excessive algae growth, leading to eutrophication and degradation of water quality (Yang, et al., 2008).

The application of phosphorus fertilizers in the upper reaches of the Sutami Reservoir for agricultural purposes in 2015 led to a notable rise in TP levels within the water system. Typically, natural water bodies contain TP levels that seldom exceed 1 mgL^{-1}, while the accepted TP concentration for drinking water stands at 0.2 mgL^{-1}. Examination findings of TP levels in the Sutami Reservoir water reveal an average concentration of 0.105 mgL^{-1} at monitoring sites, subsequently exhibiting a parabolic decrease described by the equation $y = 0.003x^2 - 0.035x + 0.133$, reaching 0.009 mgL^{-1} by 2021, with a rate of 0.006 $mgL^{-1}y^{-1}$. TP levels in the Sutami Reservoir remain below 0.2 mgL^{-1} as shown in Figure 2g, enabling the water to be utilized for recreational activities, freshwater aquaculture, livestock, and agriculture. The highest recommended TP concentration for rivers and documented water bodies is 0.1 mgL^{-1} (Chapman, 1992).

The primary reason for the increase in TSS is usually linked to unregulated human activities and a lack of sustainable management practices across various sectors like agriculture, industry, urban development, and construction. In the Sutami Reservoir, the TSS levels have consistently risen over the years, going up from 11.42 mgL^{-1} in 2015 to 17.31 mgL^{-1} in 2021 following a parabolic pattern ($y = 0.062x^2 + 0.569x + 10.861$) at a rate of 0.124 $mgL^{-1}y^{-1}$. Despite this increase, the TSS concentrations remain within the water quality standards of 25–80 mgL^{-1} as shown in Figure 2h, allowing the water to continue being utilized for recreational purposes, livestock, agriculture, and freshwater aquaculture. Elevated turbidity levels may interfere with the osmoregulation process of aquatic organisms (Nyanti, et al., 2018).

Water quality index of Sutami Reservoir

The Sutami Reservoir WQI, calculated using the WQI-INA method, is illustrated in Figure 3a based on annual average data. According to Table 2, eight sub-index parameters are used to determine the

WQI-INA, calculated annually with Equation 1. The results indicate that the water quality status of the Sutami Reservoir is "pretty good" (Table 1), remaining in the range of 70–80 from 2015 to 2021. Although the water quality status in 2021 is still good, the trend shows a decline towards a WQI below 70 at a rate of 0.406 points per year. By standardizing the status values of each WQI in Table 1, the vertical distribution at various depths (0.3 m, 5 m, and 10 m) can be determined using spatial analysis, as shown in Figure 4a, with a status of "slightly polluted." For the comparison the Sutami Reservoir was calculated using the WQI-Oregon method is presented in Figure 3b from the annual average data. According to Table 2, six sub-index parameters are used to determine the WQI-Oregon, calculated annually with Equation 3. The results indicate that the water quality status of the Sutami Reservoir is "poor" (Table 1), remaining in the range of 60–79 from 2015 to 2021. Although the water quality status in 2021 is poor, the trend shows a decline towards a WQI below 60 (very poor) at a rate of 0.24 points per year. The vertical distribution can be determined using spatial analysis, as shown in Figure 4b, with a status of "moderately polluted."

The second comparison of WQI at a similar environment, Sutami Reservoir calculated using the DOE-Malaysia method is shown in Figure 3c based on annual average data. According to Table 2, six sub-index parameters are used to determine the WQI DOE-Malaysia, calculated annually with Equation 2. The results show that the water quality status of the Sutami Reservoir is "slightly polluted" (Table 1), remaining in the range of 60–80 from 2015 to 2021. Although the water quality status in 2021 is still slightly polluted, the trend indicates a decline towards a WQI below 60 (very polluted) at a rate of 0.376 points per year. The vertical distribution using spatial analysis, as shown in Figure 4c, the status of Sutami was "heavily polluted." The Sutami Reservoir PI calculated using the PI-Prati method is displayed in Figure 5 from the annual average data. According to Table 2, seven sub-index parameters are used to determine the PI-Prati, calculated annually with Eq. 4. The results show that the water quality status of the Sutami Reservoir is "acceptable quality" (Table 1), remaining in the range of 1–2 from 2015 to 2021. Although the water quality status in 2021 is acceptable, the trend indicates an increase toward a PI above 2 (polluted) at a rate of 0.038 points per year. By standardizing the status values of each WQI in Table 1, the vertical distribution at various depths (0.3 m, 5 m, and 10 m) can be determined using spatial analysis, as shown in Figure 5 with a status of " moderately polluted."

The comparison of each country's WQI method, based on local environmental standards (such as climate, geology, hydrology, and surrounding land

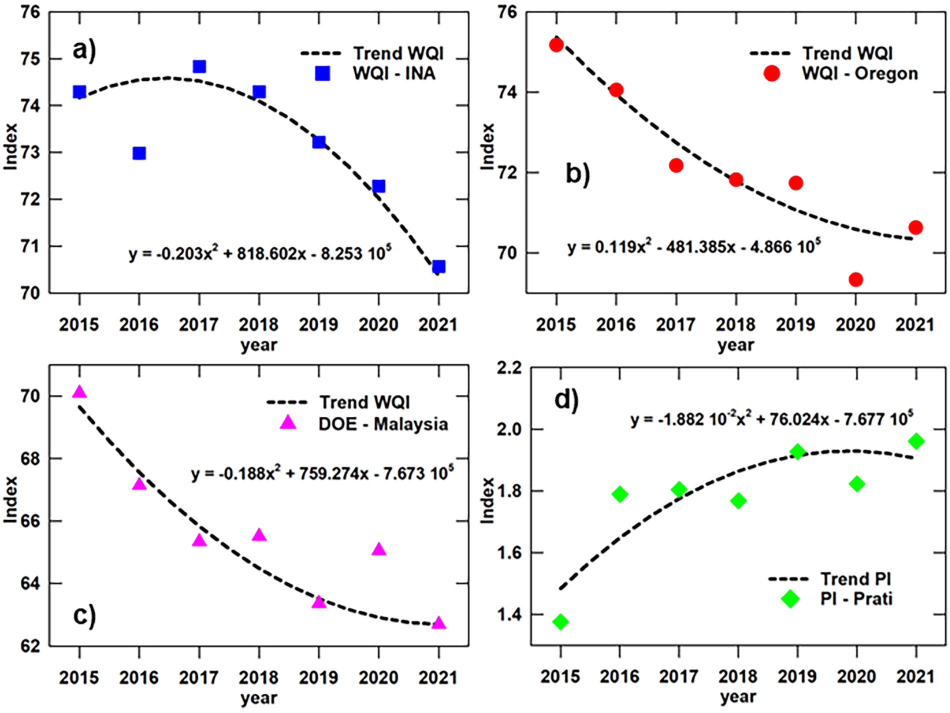

Figure 3. Water quality and pollution index analysis of Sutami Reservoir using (a) WQI-INA, (b) Oregon-USA, (c) DOE-Malaysia, and (d) PI-Prati

use), regulatory requirements, and relevant water quality concerns, which are weighted or aggregated to calculate the index score, affected the state of water quality in the Sutami Reservoir. Furthermore, climate influences precipitation (amount, frequency, and intensity), water temperature, evaporation rate, and seasonal patterns in a region, leading to variations in index components and their respective thresholds, which can result in different numerical values for the index. Therefore, while the WQI-INA is suitable for monitoring the water quality status of the Sutami Reservoir, it must be compared with other WQI methods to identify potential extreme results. Employing other methods to simulate worst-case scenarios can inform preventive actions.

Tropic state index and pollution load capacity

Figure 6a illustrates the N/P ratio discrimination for phosphorus-limited sites. During the dry season, an $N/P < 20$ indicates a high phosphorus concentration for the average across depth levels and all monitoring points. Conversely, an $N/P > 20$ indicates phosphorus limitation during the rainy season. An $N/P = 16$ suggests that either nitrogen or phosphorus may limit phytoplankton productivity, or that both elements could be co-limiting; however, no station recorded an N/P ratio of 16 (O'Donnell, et al., 2017). Nitrogen has a more significant role in controlling the growth of autotrophic biota when the $N/P = 20$ (Dauda, et al., 2018). In contrast, during the rainy season, when phosphorus levels are extremely low and often undetectable, all stations were nitrogen-limited. Phytoplankton may be absent during the rainy season due to phosphorus limitation, indicating that certain phytoplankton are sensitive to changes or imbalances in the N. For the calculation of water pollution load capacity in the reservoir, it is essential to first determine its trophic status classification. The trophic status of the Sutami Reservoir was analysed during the dry season of 2021 by averaging seasonal data to determine the trophic status category at various depths. The trophic status classification forms the basis for this determination. Figure 6b is the area ratio calculation of the trophic status classification for the Sutami Reservoir recapitulation from spatial analysis in 2021 data.

During the dry season, the Sutami Reservoir exhibited 40% eutrophic and 60% hypereutrophic conditions upstream, indicating that this area contributes to wastewater rich in TN and TP. Midstream and downstream monitoring stations at Depth I showed similar results, with 20% eutrophic and 80% hypereutrophic conditions, suggesting that wastewater accumulates from upstream and midstream. As a result, the predominant trophic status at the surface is eutrophic, reflecting high nutrient levels, particularly TP, which leads to water pollution. Despite these conditions, efforts by Jasa Tirta 1 to reduce phosphorus and nitrogen levels through limiting fishery activities in the reservoir and agricultural activities around it have led to a decrease in P and NH_3 levels, as shown in Figures 2e and 2g. However, controlling nitrification remains a significant challenge, especially regarding NO_3 levels.

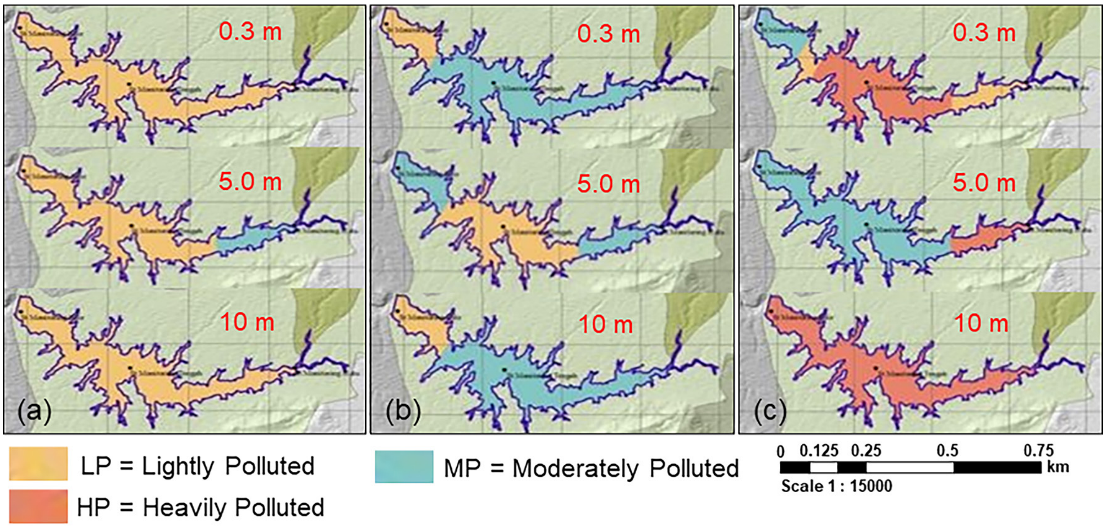

Figure 4. Spatial analysis comparison of Sutami Reservoir water quality status at different depth levels using, (a) WQI-INA, (b) WQI-Oregon, and (c) DOE-Malaysia in the year 2021

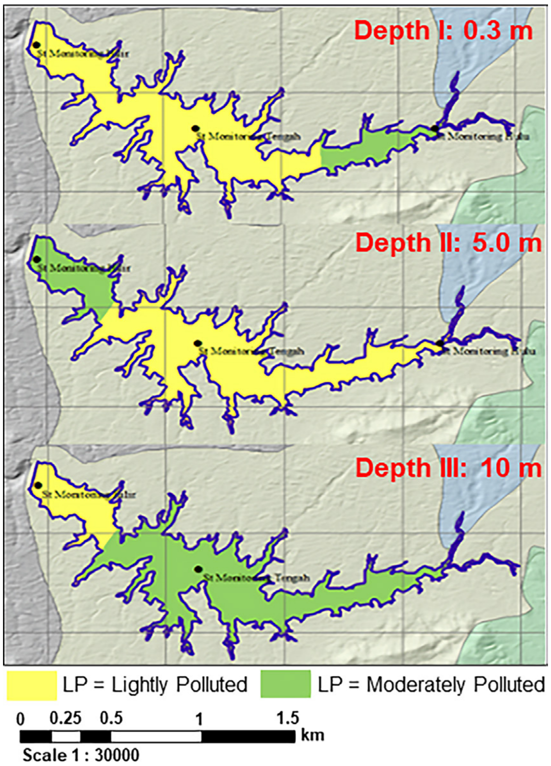

Figure 5. Water pollution distribution of Sutami Reservoir at different levels of depth using PI-Prati in 2021

The estimated phosphorus (P) waste load from fish farming activities in the Sutami Reservoir is 89.2 µg m^{-3} at the upstream, 86.733 µg·m^{-3} at the midstream, and 76.667 µg·m^{-3} at the downstream locations. The waste load allocation in the water is calculated using the total P approach (Cho, et al., 2003)., based on the standard TP, monitored TP in the water, and TP entering from the watershed.

$$P_d = P_{STD} - P_i - P_{DAS} \tag{6}$$

where: P_{STD} is the maximum permissible P concentration according to water quality standards (200 mg/m³), P_i is the average P concentration from monitoring in the Sutami Reservoir (0.0842 mg/m³), and P_{DAS} is the total P load from the watershed (0 mg/m³).

This results in a waste P load allocation of P_d = 199.916 mg/m³. The waste load carrying capacity for the Sutami Reservoir water is estimated using the total P approach entering the aquatic environment. The calculation of the waste load carrying capacity (L) starts with determining the total P waste load per unit area of the reservoir (Zhu, et al., 2019)., using the Equation:

$$L = \frac{0.01\,A\,P_d\,Z\left(\frac{Q}{V}\right)}{1 - \dfrac{1}{1 + 0.747\left(\frac{Q}{V}\right)^{0.507}}} \tag{7}$$

where: Z is the average depth of the Sutami Reservoir (31m), Q is the outflow water discharge from the Sutami Reservoir (Q = 794.89 m³/s = 1.044 × 10^9 m³/y), V is the water volume of the Sutami Reservoir (2.5 × 10^6 m³), and A is the area of the Sutami Reservoir (2370 Ha).

Therefore, the waste load carrying capacity of the Sutami Reservoir (L) is calculated to be 65.22 tons per year.

Water quality treatment of Sutami Reservoir

In the Sutami Reservoir, four key water quality parameters BOD, COD, TP, and pH are closely correlated, with correlation coefficients between 0.75 and 0.99, as depicted in Figure 7. This strong relationship is most notable during the dry season, from June to September, when poor water

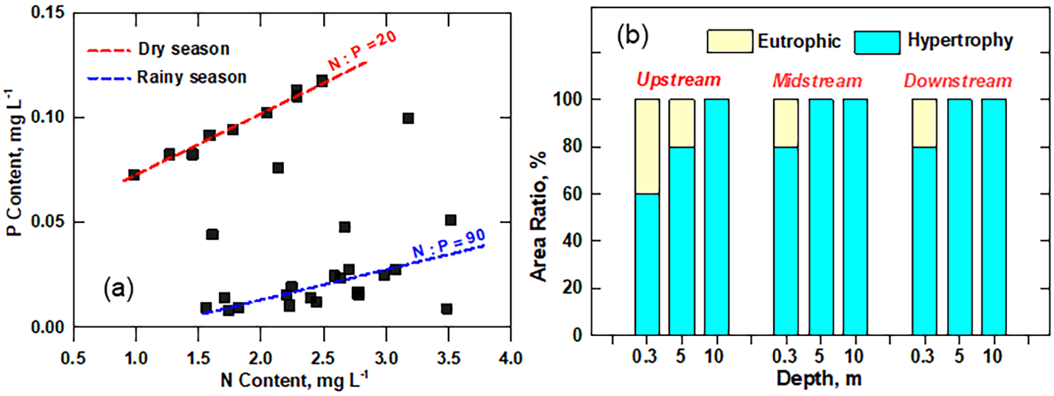

Figure 6. (a) N/P ratio in dry and rainy season and (b) trophic status in 2021 of Sutami Reservoir

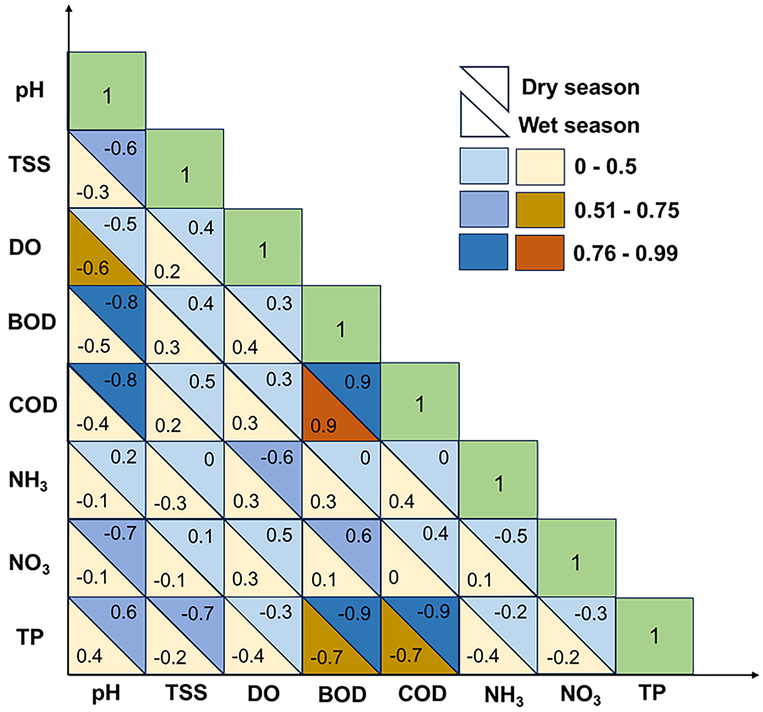

Figure 7. Correlation matrix of water quality parameters in Sutami reservoir

circulation leads to degraded water quality. Inadequate water circulation lowers pH levels, subsequently increasing BOD and COD concentrations. This occurs because aerobic microorganisms that break down organic matter flourish in such conditions, and the oxidation of organic and inorganic substances demands high oxygen levels. Consequently, as the number of microorganisms grows due to the decomposition and oxidation of organic pollutants, the demand for nutrients also rises, resulting in a significant consumption of TP, as illustrated in Figure 2g. High COD levels, caused by the presence of abundant biodegradable organic matter, lead to increased BOD levels since microorganisms require more oxygen to decompose the organic matter. Therefore, managing the water quality of Sutami Reservoir emphasizes regular control of pH and TP, particularly during the dry season.

Controlling and improving pH in the reservoir is a crucial aspect of water quality management to ensure ecosystem health and the sustainability of water resources. Liming is a commonly used method to raise the pH of overly acidic water, as it quickly increases pH and is relatively easy to implement. Lime applications (such as agricultural lime, calcite, or dolomite) are directly spread into the water or through channels that feed into the reservoir (Simoni et. al., 2022). However, strict monitoring is required to avoid over-treatment, which can make the water too alkaline. For the Sutami Reservoir, dolomite is applied at a 1–10 $g \cdot m^{-2}$ rate in the heavily polluted area. Suppose in Figure 4c at surface water (0.3 m) calculated 51% (using GIS) of 2370 Ha was heavy pollution, the treatment of the lime needs could be 12.087–120.87 tons.

Managing and reducing TP levels in the reservoir is essential to prevent eutrophication, which can lead to excessive algae growth and harm the aquatic ecosystem. A rapid and effective method for chemically reducing TP is by using Aluminum Sulfate ($Al_2(SO_4)_3$) to bind phosphorus in the water, causing it to settle at the bottom of the reservoir. Additionally, compounds such as ferric chloride ($FeCl_3$) or $CaCO_3$ can be added to the reservoir water to bind phosphorus, especially reducing dissolved phosphorus. However, careful management is needed to avoid significant changes in pH. For the Sutami Reservoir, the chemical buffer is applied at 1–5 $mg \cdot m^{-3}$ in the heavily polluted area. Otherwise, the maximum of the TP reduction in the reservoir is not more than 0.05 mgL^{-1} following regulation in Indonesia. For example, in the case of Figure 4c surface water (0.3 m) calculated at 63% of 2.5×10^6 m^3 volume in the heavily polluted area, the chemical buffer is $63\% \times 2.5 \times 10^6\ m^3 \times 0.05\ mgL^{-1} \times (1–5\ mg \cdot m^{-3}) = 78.75 – 393.75$ kg must be provided.

Aeration is another mechanical method to increase pH by boosting dissolved oxygen levels in water and reducing acid production from anaerobic microorganisms (Saalidong, et. al, 2022). Enhanced water oxygenation also supports biochemical processes that aid microorganisms in binding phosphorus. Utilizing mechanical aerators or water circulation systems such as pumps and paddlewheels improves oxygen diffusion and circulation. However, careful consideration of operational costs and ongoing equipment maintenance is essential. A practical approach involves installing paddlewheels horizontally at river inlets. Additionally, dredging TP-rich sediments from the reservoir bottom effectively removes phosphorus-containing sediment, thereby reducing the potential for phosphorus to re-dissolve into the water.

The waste load carrying capacity of the Sutami Reservoir (L) is 65.22 tons per year, if the density of the sediment in the location is 1.76 kg m^{-3}, the volume of the sediment was 37,056 m^3. Jasa Tirta 1 as the manager of the Sutami Reservoir must dredge the sediment of 37,056 m^3 annually.

Riparian vegetation (plants around the reservoir edges) helps absorb nutrients that can cause pH decreases (Yang et. al., 2023). The method involves planting native vegetation around the reservoir edges and protecting riparian areas from damage. Providing natural habitats improves reservoir bank stability and reduces nutrient pollution. This activity has been implemented for the management of the Sutami Reservoir but requires time to see significant results and initial maintenance. Managing aquatic vegetation involves using aquatic plants to absorb phosphorus from water, offering a natural and sustainable solution to reduce TP. Planting aquatic plants such as reeds or water hyacinths, known for their effectiveness in absorbing phosphorus, is crucial. The quantity and types of plants require management to prevent invasiveness and necessitate regular maintenance. Aquatic vegetation in the Sutami Reservoir is controlled within a ratio of 0.1–1% of the 2370 Ha total area (2.37–23.7Ha) to prevent blooming.

Reducing the influx of nutrients such as TN and TP into the reservoir can help prevent pH decline caused by excessive organic decomposition (Li et. al., 2023). This is crucial in preventing eutrophication and improving overall water quality. Methods to achieve this include controlling pollution sources such as agricultural, domestic, and industrial waste through improved waste treatment techniques and wise land management practices. Collaborative efforts with various stakeholders and educational programs related to Sustainable Development Goals (SDGs) have been undertaken for stakeholders around the Sutami Reservoir. However, implementing these programs requires adaptation over time.

CONCLUSIONS

The water quality analysis of the Sutami Reservoir over eight years (2015–2021) reveals critical insights into the impact of human activities and natural processes on the reservoir's health. Key water quality indicators, including BOD, COD, DO, pH, NH_3, NO_3, TP, and TSS, were systematically assessed to determine their trends and implications for the reservoir's ecosystem. The WQI-INA method suggested that the water quality status was rated by the reservoir as "pretty good," WQI-Oregon as "poor," and both DOE-Malaysia and PI-Prati as "slightly polluted." Spatial analysis of vertical distribution revealed "slightly polluted" (WQI-INA), "moderately polluted" (WQI-Oregon and PI-Prati), and "heavily polluted" (DOE-Malaysia). During the dry season, the reservoir trophic status predominantly showed eutrophic and hyper-eutrophic conditions, driven by high nutrient loads, particularly nitrogen and phosphorus. pH and TP are parameters that have a high correlation to COD and BOD, which affect water quality and pollution issues. Strategies for the sustainability of the Sutami Reservoir include lime applications, chemical buffers, aeration, riparian vegetation, and reducing nutrient sources through a community approach. The Sutami Reservoir water quality status was declared using WQI-INA, however, other methods were employed to simulate the worst-case scenarios and inform preventive actions.

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