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Water Quality of the Pamukkulu Dam Reservoir for Sustainable Water Resources Utilization

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ABSTRACT

Pamukkulu Dam, located in Takalar Regency, South Sulawesi, is a vital infrastructure facility that supplies irrigation water to the local agricultural sector. However, changes in rainfall patterns associated with climate change and increasing anthropogenic activities within the catchment area may adversely affect reservoir water quality. Effective water quality management is therefore essential to ensuring the long-term sustainability of the dam's irrigation function. This study aimed to characterize the water quality of the Pamukkulu Dam Reservoir and assess its compliance with the Class IV water quality standards applicable to irrigation under Indonesian Government Regulation No. 22 of 2021. A descriptive quantitative approach was employed, involving water sampling at six strategically selected locations during the rainy and dry seasons across the preconstruction and postconstruction periods. Physical, chemical, and microbiological parameters were subsequently analyzed in an accredited laboratory. The results revealed that several water quality parameters failed to meet the applicable standards, including dissolved oxygen (DO) concentrations below the minimum requirement and total phosphate, hydrogen sulfide (H_2S), iron (Fe), manganese (Mn), nickel (Ni), and oil and grease concentrations exceeding their respective permissible limits. These findings suggest potential contamination associated with anthropogenic activities, although the specific pollution sources require further investigation. Such water quality deterioration may threaten the ecological

INTRODUCTION

Water is an essential resource for human survival, economic development, and social well-being (Ahmad et al., 2023; Henderson & Loreau, 2023). However, global challenges, including accelerating climate change and rapid population growth, increasingly threaten the availability and quality of freshwater resources (United Nations, 2023). These challenges underscore the importance of maintaining adequate water supplies while ensuring that water quality meets the requirements of various uses, particularly agricultural irrigation, which plays a crucial role in supporting agricultural productivity in regions such as Takalar Regency. The

development of water infrastructure, including dams, is essential for regulating water availability, supporting irrigation systems, supplying raw water, and mitigating flood risks. Nevertheless, the complex hydrological and ecological processes associated with dam operations necessitate integrated management approaches that address both water quantity and quality to ensure the sustainable utilization of water resources (Noerhayati et al., 2024).

Pamukkulu Dam, located in Takalar Regency, South Sulawesi, serves as strategic water infrastructure supporting agricultural activities through the provision of irrigation water. However, dam construction transforms the natural hydrological characteristics of river systems by converting flowing water into an impounded reservoir environment. This transformation alters flow patterns, increases hydraulic residence time, promotes sediment accumulation, and intensifies interactions among water, sediments, and surrounding environmental conditions. These changes may influence the physical, chemical, and microbiological characteristics of reservoir water, potentially affecting its suitability for irrigation and other uses. Consequently, systematic water quality monitoring is essential to maintaining the operational sustainability of Pamukkulu Dam while protecting the ecological integrity of its aquatic environment (Utomo et al., 2025).

The transition from a flowing river system to an impounded reservoir involves complex hydrodynamic and biogeochemical processes that influence water quality. Reduced flow velocities and increased water residence times may promote thermal and chemical stratification, sediment deposition, nutrient accumulation, and changes in microbial activity. These processes can alter dissolved oxygen concentrations, nutrient availability, and microbial communities, potentially affecting aquatic ecosystem stability. Elevated nitrogen and phosphorus concentrations may contribute to eutrophication, while substantial fluctuations in dissolved oxygen can adversely affect aquatic organisms (Chapman, 1996; Wetzel, 2001). Similar water quality challenges have been observed in reservoir systems across Indonesia, although their severity varies according to watershed characteristics, land use, anthropogenic pressures, and reservoir management practices (Sulistiawaty, 2026; Sustama et al., 2023). Understanding these processes is therefore essential for evaluating water quality changes associated with reservoir development and identifying potential environmental risks.

Assessing the water quality of Pamukkulu Dam Reservoir is essential to ensuring that its water resources meet both quantitative and qualitative requirements for sustainable agricultural activities while minimizing potential environmental and public health risks (World Health Organization, 2022). In Indonesia, Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation of Environmental Protection and Management provides a regulatory framework for assessing water quality through standards established for different water use classifications (Republik Indonesia, 2021). In particular, Class IV water quality standards apply to water intended for agricultural irrigation and other designated uses requiring comparable water quality. Comparing measured physical, chemical, and microbiological parameters with these regulatory standards provides an objective basis for determining the reservoir's suitability for irrigation. Such comparisons also facilitate the identification of parameters that comply with or exceed permissible limits, thereby supporting the development of targeted water quality management strategies. This regulatory assessment is particularly important for ensuring that water resources from Pamukkulu Dam remain suitable for agricultural applications while maintaining environmental sustainability.

Accordingly, this study aimed to assess the water quality of Pamukkulu Dam Reservoir through a comprehensive examination of selected physical, chemical, and microbiological parameters. The measured values were compared with the applicable Class IV water quality standards established under Government Regulation of the Republic of Indonesia No. 22 of 2021. This assessment was intended to provide scientific evidence regarding the reservoir's suitability for irrigation and to support evidence-based decision-making in sustainable water resources management. The study's contribution lies in its site-specific characterization of reservoir water quality and its integration of laboratory measurements with regulatory compliance assessments. By identifying parameters that may compromise irrigation suitability, the findings were expected to inform water quality monitoring priorities, pollution control measures, and long-term reservoir management strategies at the regional level.

Global freshwater resources are increasingly threatened by climate change, population growth, and anthropogenic activities, which collectively influence water availability and quality. Although dam development contributes significantly to water resource regulation and agricultural productivity, the transformation of riverine environments into reservoirs introduces hydrological and biogeochemical changes that may affect water quality. Despite the strategic importance of Pamukkulu Dam for irrigation in Takalar Regency, comprehensive quantitative assessments of its reservoir water quality remain limited, particularly regarding compliance with regulatory standards and implications for sustainable water resource utilization. Furthermore, publicly accessible scientific evidence concerning the suitability of its water for agricultural irrigation remains insufficiently documented. To address these gaps, this study investigated two research questions: (1) What are the physical, chemical, and microbiological characteristics of water in Pamukkulu Dam Reservoir? and (2) To what extent does the reservoir's water quality comply with the Class IV water quality standards established under Government Regulation of the Republic of Indonesia No. 22 of 2021? Correspondingly, the study pursued three objectives: to characterize the reservoir's water quality using selected physical, chemical, and microbiological parameters; to evaluate compliance with the applicable regulatory standards for irrigation; and to examine the implications of the findings for sustainable water resource utilization and management. By integrating water quality characterization with regulatory compliance assessment, this research sought to provide a scientific foundation for improving reservoir management, safeguarding irrigation water quality, and supporting the long-term sustainability of agricultural water resources in Takalar Regency.

METHOD

Research Location and Time

Pamukkulu Dam is located in Kale Ko'mara Village, North Polombangkeng District, Takalar Regency, South Sulawesi Province, approximately 50 km from Makassar City, at coordinates 5°24′03″ S and 119°35′33″ E. The associated Pamukkulu Irrigation Area extends across Cakura and South Polombangkeng Districts. The dam is situated within the Pappa River Basin, where the Pappa River originates in mountainous terrain and generally flows from southeast to northwest. The surrounding landscape is predominantly characterized by agricultural land, including dryland farms, plantations, and rain-fed rice fields. Industrial activity along the river is relatively limited, with no major industrial zones identified in the

immediate vicinity. These land-use characteristics, together with surrounding settlement patterns and agricultural activities, were considered relevant environmental factors in assessing the physical, chemical, and microbiological water quality of Pamukkulu Dam Reservoir.



Figure 1. Sampling Locations at Pamukkulu Dam

Water quality sampling was conducted at six locations, comprising four sampling points in the upstream area and dam reservoir and two downstream points at the outlet structure and V-notch weir. These locations were selected to assess spatial variations in water quality across the reservoir system and its associated downstream structures.

Water samples were collected during three monitoring periods representing preconstruction and postconstruction conditions under different seasonal conditions. Preconstruction sampling was conducted in February 2016 during the rainy season to establish baseline river water quality before dam construction. Postconstruction sampling was conducted in July 2024 during the dry season and February 2025 during the rainy season to assess water quality following reservoir formation. Comparisons across these monitoring periods were used

to characterize spatial and temporal variations in water quality and identify potential changes associated with dam construction and seasonal hydrological conditions.

Table 1. Water Sampling Schedule

Time	*Season*	*Remarks*
February 2016	Rainy	Pre-construction
July 2024	Dry	Post-construction
February 2025	Rainy	Post-construction

Research Design

This study uses a descriptive quantitative approach to evaluate water quality conditions based on the measurement results of predetermined parameters. The sampling method was designed to take into account the representativeness of the water conditions at the research location, so that the data obtained can describe water quality objectively. A total of 6 (six) sampling points were strategically determined based on the characteristics and function of each location within the Pamukkulu Dam water system. Each sampling point was documented using geographic coordinates to ensure location accuracy and data collection consistency, as well as to support subsequent research. Sampling depth varied according to the characteristics of the water body studied, while the sampling time was set in periods representing normal conditions or specific variability, with accompanying weather conditions recorded to anticipate their potential influence on water parameters. The water sampling method was carefully designed to minimize contamination and changes to sample characteristics, in line with the guidelines set out in the Indonesian National Standard (SNI) 8995:2021 on Methods for Sampling Surface Water and Wastewater. The use of standard-compliant sample containers, such as dark glass bottles for certain organic parameters or clean plastic bottles for inorganic parameters, is crucial. After collection, samples were immediately preserved using appropriate methods, such as the addition of acid or cooling, to maintain their integrity until analysis in an accredited testing laboratory (Badan Standardisasi Nasional, 2008, 2021). These principles are reinforced by the methodology described by Creswell (2014) on quantitative research design and by Sugiyono (2019) on data collection techniques, which emphasize the importance of objectivity and validity at every stage of research.

Testing Location

The laboratory is located on the Environmental Engineering campus, Faculty of Engineering, Universitas Diponegoro, Semarang, so samples will be transported from the research location to the laboratory using the following methods:

1. Metal Parameters
   To preserve samples for water quality testing related to metals, HNO3 will be added.
2. Non-Metal Parameters
   To preserve samples for water quality testing related to metals, H2SO4 will be added.

To ensure the integrity of the water samples to be analyzed in the laboratory, packaging was carried out immediately after collection using cool storage facilities. The samples were then shipped by air cargo from Makassar to Semarang. As an additional precaution, each water sample was placed in a special container in the form of a styrofoam box lined with ice to keep

the temperature below 4°C. The purpose was to halt chemical reactions and prevent degradation of sample quality during transport. With an estimated shipping time of one to two days, sample quality is ensured to remain intact for laboratory analysis.

Testing Parameters

In this study, a series of crucial water quality parameters will be measured and analyzed, including dissolved oxygen (DO), total phosphate, hydrogen sulfide (H_2S), iron (Fe), manganese (Mn), nickel (Ni), copper (Cu), hexavalent chromium (Cr^{6+}), and oil and grease. These parameters were selected because of their significant relevance to the health of the aquatic ecosystem and their potential impacts on aquatic organisms and water resource use. Dissolved oxygen (DO) is a vital indicator for aquatic life, where low levels can indicate organic pollution or eutrophication. Phosphate compounds, as a major nutrient, play a role in the eutrophication process, which can trigger algal proliferation and an overall decline in water quality.

Research Instruments

Research instruments refer to devices, both software and hardware, used by researchers to collect or process data in order to achieve the study's objectives. In the context of water quality research, collaboration was established with the Environmental Engineering Laboratory, a private KAN-accredited company that focuses on water quality testing. The list of research instruments used is as follows:

The laboratory equipment used for data collection is described in Table 2:

Table 2. Laboratory Instruments

No	Name	Brand / Type	Description / Purpose
1	AAS	Perkin Elmer – AA400	
	Hollow Cathode Lamp – Fe		Fe measuring instrument
	Hollow Cathode Lamp – Mn		Mn measuring instrument
	Hollow Cathode Lamp – Cr		Cr measuring instrument
	Hollow Cathode Lamp – Cu		Cu measuring instrument
	Hollow Cathode Lamp – Pb		Pb measuring instrument
	Hollow Cathode Lamp – Co		Co measuring instrument
	Hollow Cathode Lamp – Ni		Ni measuring instrument
	Electrodeless Discharge Lamp - Cd		Cd measuring instrument
	Electrodeless Discharge Lamp – Zn		Zn measuring instrument
2	pH meter	Lutron / PH – 208	Measures the degree of acidity
3	TDS, CD, Salt meter	Lutron / WA 2017	Water quality measuring instrument
4	DO meter	Lutron	DO measuring instrument
5	Analytical balance	Ohaus – PR224	Weighing instrument, precision 0.0001 g
6	Oven	Mermet UN55	Heating device
7	Hot plate stirer	Thermo Scientific	
8	COD reactor	Hanna Instrument	Heating device
		HI 839800-02	Reaction tubes

Data Analysis and Presentation Methods

The research method uses primary and secondary data obtained from several stakeholders related to Pamukkulu Dam, such as: BBWS Pompengan Jeneberang as the owner and manager of the dam, and PT. WIKA-DMT, KSO as the implementing contractor, which holds water quality data collected during construction. The research sequence can be illustrated in the flowchart in Figure 2:

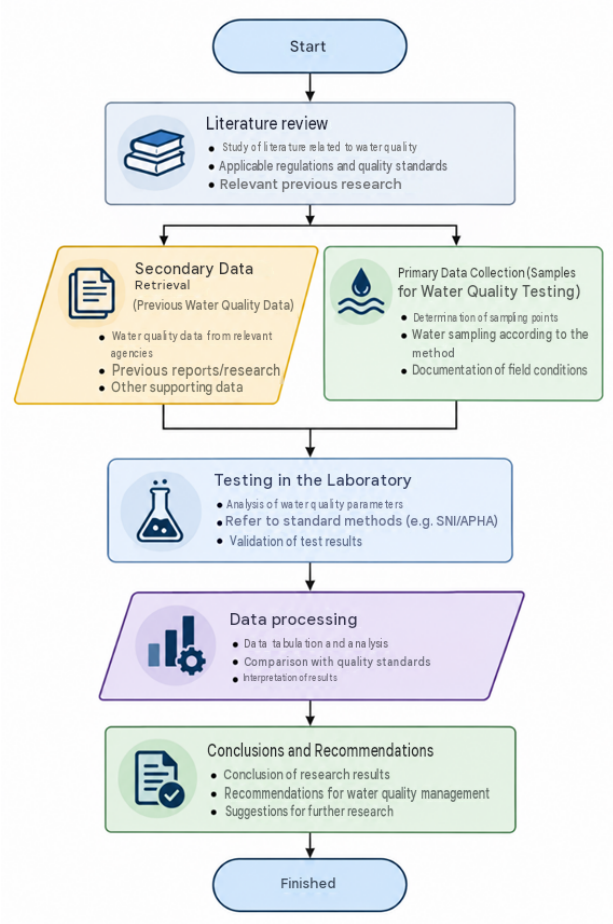


Figure 2. Research Flowchart

Quality Standard Reference

This study evaluates the water quality of Pamukkulu Dam based on Indonesian national standards through Government Regulation Number 22 of 2021. This regulation, set out in Appendix VI, classifies surface water quality standards for various designations. Given the potential use of the dam water for recreation, fisheries, livestock, and irrigation, the Class 2 classification serves as the comparison reference. This assessment is crucial for evaluating the quantitative suitability of the water for its intended functions. The water quality analysis results were measured against these quality standards, covering physical, chemical, and microbiological parameters, to identify whether the values comply with or exceed the required limits. This evaluation forms the basis for interpreting the suitability of the water for its planned use and for sustainable management recommendations, ensuring scientific objectivity and accountability.

RESULTS AND DISCUSSION

Research Site Conditions

General Description of the Research Site

Takalar Regency in South Sulawesi is one of the areas with a high geographic dependence on water availability, both to sustain the agricultural sector and to meet domestic needs. To anticipate the various water resources management needs in the region, the government, through the Pompengan Jeneberang River Basin Center (Balai Besar Wilayah Sungai Pompengan Jeneberang), built Pamukkulu Dam, which was inaugurated in July 2024. The dam has an effective storage capacity of 81.71 million m^3 and is designed to support various strategic functions, including irrigation water supply for an area of 6,188 ha, raw water supply of 160 liters/second, electricity generation through a micro-hydro power plant (PLTMH) with a capacity of 4.3 MW, and flood control with a discharge reduction capability of up to 406.14 m^3/second. The presence of a dam with such diverse functions is expected to strengthen water security and support the productivity of the agricultural sector in South Sulawesi. Pamukkulu Dam is located in Takalar Regency, South Sulawesi Province, at approximately 5°30′ S and 119°30′ E, with a river basin (DAS) area of about 395.54 km^2.

On the other hand, the dam and its catchment area also face potential water quality degradation due to various activities upstream and around the reservoir. Agricultural activities can contribute pollutants through surface runoff that carries sediment, fertilizer residues, and pesticides, thereby potentially increasing the concentrations of nutrients and chemical compounds in the water. Activities from settlements around the river and the reservoir area can also add organic matter, detergents, and pathogenic microorganisms. In addition, livestock activities have the potential to increase the pollutant load in the form of organic matter, nitrogen, phosphorus, and bacteria, while erosion in the catchment area can increase suspended solids content and accelerate sedimentation. Therefore, water quality management of Pamukkulu Dam needs to be carried out in an integrated manner, taking into account land-use characteristics and the various community activities upstream and around the reservoir area.



Figure 3. View of Pamukkulu Dam

Technical Data of the Dam

Technically, according to data from BBWS Pompengan Jeneberang, the owner and manager of Pamukkulu Dam, the dam has the following characteristics:

- Total storage capacity: ± 101.61 million m³
- Effective storage: ± 81.71 million m³
- Dead storage: ± 4.34 million m³
- Normal water level elevation: +126.00 m
- Minimum water level elevation: +91.5 m
- Maximum flood discharge (QPMF): 1,597.18 m3/s
- Design flood discharge (Q1000): 1,026.44 m3/s
- Spillway capacity: 1,200.00 m³/s
- Spillway length: 480 m
- Crest width: 80 m

These characteristics show that the dam is designed not only to store water but also to control major floods. However, as reported in international research (Fluixá-Sanmartín et al., 2018), spillway capacity must always be re-evaluated because climate change projections indicate an increase in design flood discharge in many countries.

Water Quality Analysis

Water quality testing was carried out at two strategic locations: upstream of the river, +5.9 km from the dam (5025'34.55" S - 119038'20.15" E), to represent the original river conditions, and downstream of the dam, +1.5 km away (5023'39.14" S - 119034'45.42" E), to measure the impact of dam construction on water flow. This design allows the upstream data to serve as a baseline control, while the downstream measurements reflect the cumulative impacts of dam construction, reservoir impoundment, backwater effects, and modified flow patterns. A study by Pinayungan et al. highlights the importance of water quality and composition data at two points, upstream and downstream, to provide a complete picture of the cumulative impacts of dam construction and the effects of altered flow patterns (Pinayungan et al., 2025). Figure 1.1 shows the water sampling locations in the upstream and downstream parts of Pamukkulu Dam. Sampling was carried out in two seasonal conditions, namely the rainy season and the dry season, to obtain a picture of water quality under different hydrological conditions. The data in Table 2.1 cover one **pre-construction** and two **post-construction** sampling periods. In the pre-construction stage, samples were taken in **February 2016**, representing the river water quality in the rainy season before the dam had any influence on the water system. Subsequently, post-construction sampling was carried out in **July 2024** during the dry season and **February 2025** during the rainy season, to describe the water quality after Pamukkulu Dam began operating.

Comparison of Water Quality Test Results with Quality Standards

The water quality test results of the Pamukkulu Dam reservoir were then compared with the quality standards set out in Government Regulation Number 22 of 2021 according to the relevant water class. The comparison shows that most parameters are within the required limits, but several parameters have values above the quality standard threshold. These parameters include Dissolved Oxygen (DO), total phosphate, hydrogen sulfide (H_2S), iron (Fe), manganese (Mn), nickel (Ni), and oil and grease. This condition indicates several aspects of water quality that require attention in the management and utilization of the Pamukkulu Dam reservoir water. It also indicates a potential for pollution that needs to be examined in greater depth. Based on

water quality theory, decreasing DO levels can be caused by increased activity of aerobic microorganisms that consume dissolved oxygen, often triggered by the input of organic matter from agricultural or domestic runoff (Wetzel, 2001). Increased phosphate levels can drive eutrophication, a nutrient enrichment process that triggers excessive algal growth and subsequently reduces oxygen levels as algal biomass decomposes (Smith & Shapiro, 1981). The presence of hydrogen sulfide, Fe, Mn, Ni, and oil and grease above the quality standards potentially originates from anthropogenic pollution sources such as industrial waste, agriculture, or runoff from contaminated urban areas, all of which can negatively affect aquatic ecosystems and human health if consumed (Chapman, 1996). These findings are relevant to studies of river water quality in urban areas that also show the accumulation of similar pollutants due to development pressures. The comparison of test results and quality standards is attached in the following table:

Table 3. Water Quality Data of the Pamukkulu Dam Reservoir

Parameter	Unit	Standard (Class 1 / 2)	EIA Document (Upstream / Downstream)	Construction Document (Upstream / Downstream)
Physical Quality				
Temperature	°C	±3 / ±3	26 / 25.6	28 / 28
Total Dissolved Solids (TDS)	mg/L	1000 / 1000	96 / 169	162 / 172
Total Suspended Solids (TSS)	mg/L	40 / 50	17 / 97	10 / 15
Color	TCU	15 / 50	– / –	<5 / <5
Chemical Quality				
pH	–	6–9 / 6–9	8.26 / 8.10	7.58 / 6.84
BOD	mg/L	2 / 3	1.12 / 1.07	3.7 / 4.1
COD	mg/L	10 / 25	8.8 / 7.04	16 / 22
Dissolved Oxygen (DO) (minimum)	mg/L	6 / 4	6.42 / 6.39	6.8 / 5.8
Sulphate (SO_4^{2-})	mg/L	300 / 300	<0.5 / 5.2	<2 / <2
Chloride (Cl^-)	mg/L	300 / 300	4.27 / 2.34	17 / 11
Nitrate (NO_3-N)	mg/L	10 / 10	1.129 / 0.65	1 / 1
Nitrite (NO_2-N)	mg/L	0.06 / 0.06	0.013 / 0.012	0.002 / 0.003
Ammonia (NH_3-N)	mg/L	0.1 / 0.2	<0.001 / <0.001	0.01 / 0.06
Total Nitrogen*	mg/L	15 / 15	– / –	1 / 1
Total Phosphate-P*	mg/L	0.2 / 0.2	<0.01 / 1.09	0.31 / 0.24
Fluoride (F^-)	mg/L	1 / 1.5	<0.01 / <0.01	0.4 / 0.3
Hydrogen Sulfide (H_2S)	mg/L	0.002 / 0.002	<0.002 / <0.002	0.003 / 0.004
Cyanide (CN^-)*	mg/L	0.02 / 0.02	<0.01 / <0.01	<0.01 / <0.005
Iron (Fe), dissolved	mg/L	0.3 / –	0.08 / 0.69	0.23 / 0.36
Cadmium (Cd), dissolved	mg/L	0.01 / 0.01	<0.01 / <0.001	0.004 / 0.005
Cobalt (Co), dissolved*	mg/L	0.2 / 0.2	<0.001 / <0.001	0.04 / 0.08
Manganese (Mn), dissolved	mg/L	0.1 / –	0.003 / 0.014	0.16 / 0.2
Nickel (Ni), dissolved	mg/L	0.05 / 0.05	– / –	0.064 / 0.11
Zinc (Zn), dissolved	mg/L	0.05 / 0.05	0.02 / 0.04	0.026 / 0.041
Copper (Cu), dissolved	mg/L	0.02 / 0.02	<0.003 / 0.004	0.015 / 0.024

Parameter	Unit	Standard (Class 1 / 2)	EIA Document (Upstream / Downstream)	Construction Document (Upstream / Downstream)
Lead (Pb), dissolved*	mg/L	0.03 / 0.03	<0.005 / <0.005	<0.02 / <0.02
Hexavalent Chromium (Cr VI)*	mg/L	0.05 / 0.05	0.025 / 0.15	0.002 / 0.005
Oil and Grease*	mg/L	1 / 1	<0.02 / <0.02	1.2 / 1.4
Detergent/surfactant (MBAS)	mg/L	0.2 / 0.2	<0.01 / <0.01	0.02 / 0.05
Microbiological Quality				
Fecal coliform*	MPN/100 mL	100 / 1000	<2 / 7	64 / 88
Total coliform*	MPN/100 mL	1000 / 5000	<2 / 11	140 / 210

Implications for Sustainable Water Resources Management

Effective catchment management highlights the importance of upstream pollutant control, because the water quality of a water body is the accumulation of interactions among hydrology, land use, human activities, and physical and biogeochemical processes. The relationship between land use and water quality, as shown by Siqueira et al. (2023), underscores the need for river basin (DAS)-based management of water quality, rather than focusing only on the reservoir water body. Water quality management at Pamukkulu Dam needs to be directed at controlling pollutants at their source. Steps that can be taken include reducing runoff from agricultural and residential land, controlling the input of organic matter and nutrients, protecting vegetation along riverbanks, and tracing the sources of metal, oil, and grease pollutants. The source-control approach is considered more sustainable because it can reduce the pollutant load before it enters the water body, compared with relying only on treatment after pollution has occurred.

In addition to controlling pollutant sources, the management of Pamukkulu Dam needs to be supported by water quality monitoring activities that are carried out regularly and take risk levels into account. The parameters identified as exceeding the quality standards, such as DO, total phosphate, hydrogen sulfide, Fe, Mn, Ni, and oil and grease, need to be a focus of the monitoring program. These parameters can provide an overview of oxygen conditions in the water, increases in nutrient content, processes occurring within the water body, and the influence of human activities on water quality. Monitoring at different times and locations is also necessary because reservoir water quality can change due to seasonal factors and hydrological conditions (Kim et al., 2021). Thus, the results of this study can be used as one basis for developing a more targeted water quality monitoring program at Pamukkulu Dam.

Water quality management also needs to be considered in the operational regulation of the dam. Sustainable dam management is oriented not only toward meeting water needs but must also pay attention to the condition of the aquatic ecosystem as part of an interrelated system. Water storage and release patterns can affect nutrient movement and water quality conditions downstream (Yu et al., 2023). Therefore, if water quality declines, monitoring results can be taken into consideration in determining the dam's operating pattern, so that irrigation water needs can still be met without neglecting the protection of the aquatic ecosystem.

In the long term, water quality management at Pamukkulu Dam can be directed toward the application of ecosystem-based approaches and *nature-based solutions*. Nutrient and pollutant control does not always have to rely on conventional treatment technology but can be combined with efforts such as maintaining riparian vegetation, building buffer zones, implementing constructed wetlands, soil conservation, and surface runoff management. This approach can be a more sustainable alternative because it utilizes the natural functions of ecosystems in reducing the pollutant load. The application of ecological and *ecohydrological engineering* approaches has also been developed as an alternative for restoring water bodies experiencing nutrient enrichment or eutrophication (Paul et al., 2021).

This is relevant for Pamukkulu Dam in preventing the entry of nutrients and pollutants while maintaining ecological functions, so that management does not merely pursue quality standards but also the natural capacity of the ecosystem.

Overall, water quality that exceeds the quality standards is a crucial signal to strengthen the integrated management of Pamukkulu Dam. The three main pillars of sustainable management include controlling pollutants at their source, adaptive and regular monitoring, and integrating water quality into dam operations. This approach is in line with the concept of holistic water resources management that balances ecosystem quality, human needs, and the sustainability of ecosystem services (Shaad et al., 2022), ensuring the use of the dam for irrigation while maintaining ecological functions and reducing the risk of future degradation of water resource quality.

CONCLUSION

This study achieved its objectives of characterizing the water quality of Pamukkulu Dam Reservoir and assessing its compliance with the water quality standards applicable to agricultural irrigation. The findings revealed that several key parameters failed to meet the applicable standards established under Indonesian Government Regulation No. 22 of 2021. Specifically, dissolved oxygen (DO) concentrations fell below the prescribed minimum, while total phosphate, hydrogen sulfide (H_2S), iron (Fe), manganese (Mn), nickel (Ni), and oil and grease concentrations exceeded their respective permissible limits. These results indicate potential water quality deterioration and contamination risks that require targeted management interventions to maintain the reservoir's suitability for irrigation and protect aquatic ecosystem health.

The findings highlight the importance of integrating water quality management into the operation and long-term management of Pamukkulu Dam to support sustainable water resource utilization. Noncompliance with established water quality standards emphasizes the need for comprehensive management strategies, including pollution control at potential sources, systematic and seasonally responsive water quality monitoring, and the incorporation of ecological considerations into reservoir operations. Future research should investigate the sources and seasonal variability of contaminants, assess their potential ecological and agricultural impacts, and evaluate the effectiveness of appropriate mitigation measures. Such efforts would strengthen evidence-based reservoir management and support an integrated approach that balances agricultural water demands with the long-term protection of aquatic ecosystems.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest. This research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

AUTHOR'S CONTRIBUTION

The first author acted as the main author who prepared the manuscript of this article. The second author was responsible for sampling and for observing the primary data in the field. The third author acted as sponsor and first supervising lecturer, reviewing the ideas, substance, and research data. The fourth author acted as second supervising lecturer, reviewing the writing aspects of the manuscript. All authors have read and approved the final version of this manuscript.

GENERATIVE AI STATEMENT

In preparing this manuscript, the authors used [name of AI tool] only for grammar improvement and language checking. AI was not used to generate ideas, data, analysis, or research conclusions. The entire content of the manuscript has been reviewed by the authors, and the authors take full responsibility for the content of this publication.

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