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ANALYSIS OF PHYSICAL AND CHEMICAL PARAMETERS OF WATER QUALITY AS AN INDICATOR OF WATER POLLUTION IN THE LAENDE RIVER, MUNA REGENCY

Ian Adi Gunawan [1*], Ramadhan Tosepu [2], Surya Cipta Ramadhan Kete[3]

[1] Postgraduate of Public Health, Halu Oleo University, Kendari, Indonesia, 93232
[2] Faculty of Public Health, Halu Oleo University, Kendari, Indonesia, 93232
[3] Faculty of Forestry and Environmental Sciences, Halu Oleo University, Kendari, Indonesia, 93232

**Corresponding Email: ianadigunawan13@gmail.com*
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Abstract

Water is essential for life and is used for various daily needs. Rivers as one of the main water sources are often used by the community but are also used as waste disposal sites. The Laende River in Muna Regency has experienced a decline in water quality due to community activities, domestic and agricultural waste, and environmental damage in the river basin. This study aims to analyze the water quality of the Laende River based on physical and chemical parameters as indicators of pollution. The method used is descriptive quantitative through field surveys and laboratory analysis. Water samples were taken from three river segments: upstream, middle, and downstream. The parameters analyzed include temperature, TDS, TSS, pH, BOD, COD, DO, Fe, nitrate, and sulfate. The test results were compared with the class I river water quality standards according to PP No. 22 of 2021. The results show that the water quality of the Laende River decreases from upstream to downstream. The parameters of TSS in the upstream segment (44 mg/L), BOD (2.60–3.10 mg/L), COD (10.22–14.20 mg/L) and DO (4.48–5.31 mg/L) exceeded the established quality standards. This condition indicates significant organic pollution and anthropogenic activities along the river. This finding emphasizes the need for sustainable water quality management and control of pollution sources in the Laende River Watershed.

Keywords: *Pollution, Quality, Rivers, Water*

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1. Introduction

Water is a natural resource that is very important for the continuity of life, both for humans, animals, and plants. In everyday life, water is used for various purposes such as drinking, bathing, washing, agricultural irrigation and as an industrial medium (Zulhilmi et al, 2019). One of the water sources that is most widely used by the community is the river. Rivers not only act as a source of clean water, but also as a place to dispose of household, agricultural, and industrial waste. However, uncontrolled use of rivers can cause pollution and have a negative impact on the quality of the environment (Uyara et al, 2017).

Laende River, located in Muna Regency, Southeast Sulawesi, is one of the vital water sources for the surrounding community. This river is used for various domestic purposes, including bathing, washing, and garden irrigation. The many community activities around the river can trigger a decrease in the quality of river water which can indirectly also pose a health threat to the community who use the river water. This decrease in quality is caused by the increasing burden of pollution from household waste, agricultural runoff, and high sedimentation due to land conversion and deforestation in the river basin area (Perumdam Tirta Sugi Laende, Muna Regency, 2024).

To assess the level of pollution of a water body, a systematic and measurable analysis of water quality parameters is required. Physical parameters such as temperature, color, turbidity, and total suspended solids (TSS) provide an initial picture of the condition of the water, while chemical parameters such as pH, dissolved oxygen (DO), biological oxygen demand (BOD), chemical oxygen demand (COD) and heavy metal concentrations are important indicators for determining the presence of toxic or damaging contaminants (Zaman et al, 2023). The use of these parameters has become a standard method in various water quality studies, such as those developed by the American Public Health Association (APHA, 2017) and the Indonesian National Standards Agency (SNI 6989.59:2008).

Several previous studies have shown that increasing environmentally unfriendly human activities in river basins can significantly reduce water quality (Kurniawan et al, 2024);(Sukristiyono et al, 2021). Therefore, periodic monitoring and evaluation of river water quality is very important to support sustainable environmental management, as well as a basis for policy making in pollution control efforts.

The main problem in the context of the Laende River is the unavailability of comprehensive scientific data on water quality based on physical and chemical parameters as indicators of pollution. The unavailability of this data hampers efforts to plan river management appropriately and sustainably. Therefore, this study aims to analyze the water quality of the Laende River based on physical and chemical parameters to assess the level of pollution and to provide policy and technical recommendations for the conservation of water resources in Muna Regency.

2. Method

The research method used in this study is a descriptive quantitative method with a field survey approach and laboratory analysis. This study was conducted at the Laende

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River in Muna Regency, specifically in Lagasa Village, Duruka District, Muna Regency, with a village area of 1.14 km². The objective of this research is to assess the water quality of the Laende River based on physical and chemical parameters as indicators of pollution levels.

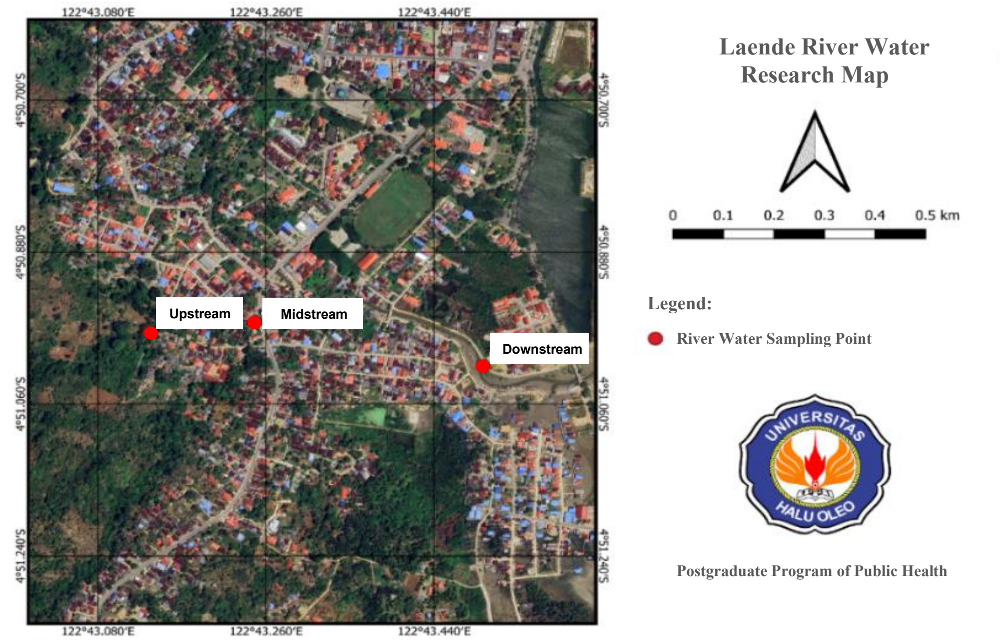
Data were collected through water sampling at several strategic points along the river flow, namely the upstream section (4°50'58.5"S, 122°43'08.2"E), midstream section (4°50'57.8"S, 122°43'14.9"E), and downstream section (4°51'00.9"S, 122°43'29.6"E), which represent different environmental conditions and levels of community activities in the surrounding areas.

The collected water samples were then tested both directly (in-situ) and through laboratory testing. The testing includes 2 river water parameters, namely physical and chemical parameters with a total of 10 test indicators: temperature, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), acidity level (pH), Biochemical Oxygen Demand (BOD), Chemical Oxygen Demand (COD), Dissolved Oxygen (DO), Dissolved Iron (Fe), Nitrate (as NO_3), and Sulfate (SO_4^{2-}). The measurement results are compared with water quality standards based on applicable regulations, such as Government Regulation Number 22 of 2021. The obtained data are analyzed descriptively and quantitatively to determine the level of river water pollution.

3. Result and Discussion

3.1 Comparison of Laende River Water Quality Based on Indonesian Government Regulation No. 22 of 2021

Water quality testing of the Laende River was carried out directly at the research location and laboratory with 2 parameters, namely physical and chemical parameters of water. The water samples tested were obtained from 3 segments of the Laende River, namely the upstream segment (mouth of the Laende cave), the middle segment (residential areas) and the downstream segment (near the shoreline). The location of direct sample collection and testing can be seen on the following research map:



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The test results were then compared with the quality standards for class I river water according to Government Regulation No. 22 of 2021 concerning the Implementation of Environmental Protection and Management. In this study, a total of 10 parameters were tested, namely temperature, TDS, TSS, pH, BOD, COD, DO, Iron, Nitrate and Sulfate. The following is a table of the results of the Laende River water test in 3 segments of the Laende River:

No.	Parameter	Unit	Upstream	Middle	Downstream	Quality Standards (Class I)
Water Physics						
1.	Temperature	°C	27.7	29.5	32.4	Dev. 3
2.	TDS	Mg/L	177	536	1.44	1.000
3.	TSS	Mg/L	44	34	40	40
Water Chemistry						
4.	pH	-	6.97	6.97	7.16	6 - 9
5.	BOD	Mg/L	2.60	2.90	3.10	2
6.	COD	Mg/L	10.22	14.20	10.80	10
7.	DO	Mg/L	5.31	4.67	4.48	6
8.	Iron	Mg/L	0.25	0.50	0.40	0.3
9.	Nitrate	Mg/L	0.103	0.170	0.232	10
10.	Sulfate	Mg/L	0	6	88	300

3.2 Physical Parameters

3.2.1 Temperature

Temperature is the most important physical parameter in the metabolic process of aquatic organisms. Temperature can vary depending on the season, location according to latitude and sun line, time of measurement, and water depth and height above sea level. Temperature factors also affect the concentration of heavy metals in river flows, an increase in colder water temperatures will make it easier for heavy metals to settle into sediments. While high temperatures, heavy metal compounds will dissolve in water. Natural processes that occur in water are universally influenced by temperature and can affect biotic and abiotic components in it. The toxicity of heavy metals to biota is also one of the effects caused by temperature (Aanisa et al, 2024).

Direct temperature parameter measurements in the Laende River showed that the temperature parameter value in the upstream segment was 27.7°C, the middle segment

29.5^{o}C and the downstream segment 32.4, there was an increase in temperature from upstream to downstream of the river. Although there was an increase in temperature, the three research segments did not exceed the standard value of river water quality. According to Government Regulation of the Republic of Indonesia No. 22 of 2021, the standard quality of temperature parameters tolerated in river water is a deviation of 3. This means that the average water temperature obtained from the test must be reduced and increased by 3 to be used as the standard water temperature. From the test results above, the average water temperature of the Laende River was 29.86 ^{o}C, so that the minimum and maximum values of water temperature used as the standard quality in this study were 26.86 ^{o}C and 32.86 ^{o}C.

3.2.2 Total Dissolved Solids (TDS)

Total Dissolved Solids (TDS) value is a physical parameter of water and a measure of dissolved substances, both organic and inorganic substances contained in a solution. The total dissolved solids value includes the amount of material in water in the form of carbonate, bicarbonate, sulfate, nitrate, calcium, magnesium, sodium, and organic ions. The content of the total dissolved solids value in water can give a taste to the water, namely water becomes salty so that water containing the total dissolved solids value is drunk will cause salt accumulation in the human kidneys so that it will affect the physiological function of the kidneys. The TDS value can be caused by domestic waste that is not directly processed and is directly disposed of in waters, resulting in decreased water quality (Sulaeman et al, 2022).

The TDS parameter test values in the three segments of the Laende River are known to be the highest segment in the middle segment with a TDS value of 536 mg/L and the lowest in the downstream segment, namely 1.44 mg/L. While for the upstream segment it is 177 mg/L. Based on the standard value of class I river water quality according to Government Regulation of the Republic of Indonesia No. 22 of 2021, the permitted TDS value is 1,000 mg/L. This means that all test segments in the Laende River body still meet the established quality standards.

3.2.3 Total Suspended Solids (TSS)

Suspended solids, commonly referred to as Total Suspended Solids (TSS), consist of organic and inorganic particles that are insoluble in water. Organic suspended solids generally include living components such as phytoplankton, zooplankton, fungi, algae and bacteria, whereas inorganic suspended solids are typically composed of soil particles, clay minerals and fine sediments such as mud. These suspended solids float and cause minimal oxygen in the water. The higher the value of dissolved oxygen in water is caused by the decreasing value of TSS (Andara et al, 2014). Therefore, the low TSS value also affects the concentration of heavy metals in the river flow, with the low TSS value, the oxygen used to purify water and for reduce the burden of waste pollutants entering the river flow will not be disturbed. So that the value of heavy metals in the river flow becomes less and then settles in the river sediment (Aanisa et al, 2024).

The results of measuring water samples in 3 segments of the Laende River carried out in the Laboratory showed that in the upstream segment it was 44 mg/L, the middle

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segment was 34 mg/L and the downstream segment was 40 mg/L. The values in the middle and downstream segments were within the standard quality standards, while in the upstream segment it exceeded the standard water quality value according to Government Regulation No. 22 of 2021 of 40 mg/L.

3.3 Chemical Parameters

3.3.1 Degree of Acidity (pH)

The pH parameter is the degree of acidity used to measure the acidity or alkalinity of water so that it can determine the suitability of the water. A good pH level is a level that still allows biological life in the water to run well. If the pH concentration is not neutral in river water, it will complicate the biological process, thus disrupting the water purification process (Gozali & Widada, 2021).

Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning the Implementation of Environmental Protection and Management, for the designation and quality standards of class I river water, the tolerated pH is 6 - 9. Based on the results of the pH test of the Laende River water which was carried out directly at the research location, it was found that the pH parameter values in three segments, namely the upstream segment pH value 6.97, the middle segment 6.97 and the downstream segment 7.16 with an average pH of 6.96. The three segments are still at values that meet the river water quality standards.

The pH level is an important parameter in assessing water quality, which is influenced by natural factors and human activities. Acidic or alkaline substances can reduce dissolved oxygen and increase pollution (Hamzani et al, 2022). Water is categorized as acidic if the pH is <6.5 and alkaline if the pH is >7.5. Changes in pH are generally caused by the entry of domestic and industrial waste that can disrupt the aquatic ecosystem (Suliana et al, 2023). In the upper reaches of the Laende River, activities such as bathing and washing with detergent can increase the pH of the water (Anggeraeni et al, 2020). In addition, agricultural waste in the form of fertilizers and pesticides also contributes to increasing water pH, as explained by Amru and Makkau (2023) (Amru & Makkau, 2023).

3.3.2 Biochemical Oxygen Demand (BOD)

Biochemical Oxygen Demand (BOD) is a characteristic of water that shows the level of dissolved oxygen needed by microorganisms to break down and decompose organic matter. And it is easily interpreted that BOD is the amount of organic matter that is easy to break down by microorganisms in the water. BOD is used as one of the parameters for monitoring river water quality and pollution that occurs in river water or other waters (Daroini & Arisandi, 2020).

BOD parameter testing in this study was carried out in the Laboratory. The results of this parameter test were found in the upstream segment to be 2.60 mg/L, the middle segment to be 2.90 mg/L and the downstream segment to be 3.10 mg/L. The test results exceed the quality standards for class I river water based on Government Regulation No. 22 of 2021 where the required quality standard is 2 mg/L.

High BOD reflects organic pollution from easily decomposed waste, such as leaves in the upstream and leftover food, vegetables and fruits that are dumped directly into the river in the middle and downstream segments. This organic waste increases the activity of microorganisms that require large amounts of dissolved oxygen, causing a decrease in oxygen levels in the water. This condition risks causing hypoxia which can disrupt the life of aquatic biota (Asmawati et al, 2019);(Pratiwi et al, 2023). Therefore, high BOD values are an important indicator that the Laende River is experiencing significant pollution pressure and requires serious handling.

3.3.3 Chemical Oxygen Demand (COD)

Chemical oxygen demand or commonly referred to as COD is a description of the amount of dissolved oxygen needed by microorganisms in water to reduce or oxidize organic materials that cannot be decomposed or are easily decomposed in water (Alfatihah et al, 2022). High COD levels indicate that the amount of organic waste that does not undergo rapid biological decomposition will accumulate in larger amounts, thus requiring a larger amount of oxygen to decompose the waste through chemical processes (Hasanah et al, 2023).

COD testing usually produces a higher oxygen demand value than BOD because many materials that are stable to biological reactions can be oxidized. High COD content in river water indicates the presence of pollutant sources such as waste that can disrupt the balance of the river ecosystem. Increased COD can cause a decrease in water quality because it requires more oxygen to oxidize organic and inorganic materials. This can cause a decrease in the concentration of dissolved oxygen in water and have a negative impact on aquatic life. The results of COD measurements in the Laende River have not met the quality standards for Class I river water quality standards stipulated in Government Regulation Number 22 of 2021 with a standard quality value of 10 mg/L. In the upstream segment of the Laende River, the COD parameter test value was 10.22 mg/L, the middle segment was 14.20 mg/L and the downstream segment was 10.80 mg/L.

The high COD values in all segments of the Laende River are thought to be caused by the accumulation of inorganic and organic waste such as plastic, diapers, and other household waste around the river flow. This waste contains compounds that are difficult to degrade biologically, so it is more dominant to experience anaerobic decomposition (Fitri et al, 2016). High COD reflects a high pollutant load, both easily and difficult to decompose, and indicates an increased need for oxygen for the decomposition process of organic compounds in water. This condition causes a decrease in dissolved oxygen levels which have a direct impact on the life of aquatic biota. Lack of oxygen in water can inhibit the respiration, growth, and reproduction of aquatic organisms, and even cause the death of organisms not because of waste toxins, but due to oxygen deficiency (Alfatihah et al, 2022).

3.3.4 Dissolved Oxygen (DO)

Dissolved Oxygen (DO) is the main indicator in assessing water quality because it is closely related to the level of organic material pollution (Sofiana et al, 2022). The decrease in DO levels is generally caused by the high load of waste from industrial and residential activities along the river, which causes the accumulation of pollutants (Pratiwi & Noviana, 2016). Dissolved oxygen plays an important role in the aerobic decomposition process of organic matter, so the higher the DO level, the more optimal the water's ability to reduce pollution loads (Aruan & Siahaan, 2017). High DO also helps reduce heavy metal concentrations by increasing natural oxidation processes (Yulis & Desti, 2018).

The ability of water to recover from pollution is called self-purification, which depends on the interaction between biotic and abiotic factors, including dissolved oxygen levels and water flow. According to Napitupulu and Putra (2024), DO below the standard indicates disruption of the natural recovery process, thus extending the time needed for the river to return to a clean condition (Napitupulu & Putra, 2024).

The results of the measurement of Dissolved Oxygen (DO) levels in the Laende River showed a value of 5.31 mg/L in the upstream segment, 4.67 mg/L in the middle, and 4.48 mg/L in the downstream. All three values are below the class I quality standard according to PP No. 22 of 2021, which requires DO > 6 mg/L. The decrease in DO concentration from upstream to downstream is thought to be caused by increased activity of microorganisms in decomposing organic matter and COD compounds, which consume dissolved oxygen. Environmental factors such as fluctuating temperature, humidity, and rainfall also affect the availability of oxygen in the waters. This finding is in line with the research of Gea et al. (2024), which reported low DO in the Arbes River due to unstable environmental conditions and high activity of microorganisms that decompose organic waste (Gea et al, 2024).

3.3.5 Iron (Fe)

Iron (Fe) is a transition metal that is naturally abundant in the environment, but its concentration in water bodies can increase significantly due to anthropogenic activities. The main sources of increased Fe content in water include domestic waste (kitchen, bathroom, laundry), detergent, rusty pipes, and metal waste such as cans. (Sulistia, 2018). Although Fe is an essential element needed by living things in small amounts, its presence in high concentrations can be toxic and disrupt the balance of aquatic ecosystems and human health.

Long-term exposure to high Fe content in drinking water can cause gastrointestinal disorders such as nausea, vomiting, and diarrhea, as well as damage to internal organs such as the liver and kidneys. These chronic effects can also increase the risk of heart disease and some types of cancer (Sirait et al, 2024);(Rompas et al, 2024). Children, especially infants, are more susceptible to exposure to this heavy metal because they are still in the developmental stage, and the accumulation of Fe in the body can interfere with the growth process. In addition, Fe concentrations above 1 mg/L can cause skin and eye irritation, while levels of more than 10 mg/L cause water to smell like rotten eggs. Thus, although the presence of Fe in certain amounts is necessary, it is important to control and monitor Fe levels in water to maintain water quality and prevent long-term health risks.

The iron metal content at the research location in 3 segments is known that in the upstream segment it is 0.25 mg/L, the middle segment is 0.5 mg/L and the downstream segment is 0.40 mg/L. Based on Government Regulation of the Republic of Indonesia No. 22 of 2021, the water quality standard for class I rivers for the heavy metal parameter iron (Fe) tolerated in rivers is 0.3 mg/L. The comparison between the test results and the water quality standards indicates that the Fe parameter values in the middle and downstream segments exceed the permissible limits, whereas the upstream segment remains below the standard threshold.

3.3.6 Nitrate (As NO_3)

Nitrate (NO_3) is the dominant form of nitrogen in natural waters that comes from the oxidation of ammonium by microorganisms through the nitrification process. This process requires oxygen, so it can reduce the level of dissolved oxygen in water (Arnanda, 2023). Nitrate is soluble and stable and is an important nutrient for plants. However, if the levels are excessive, nitrate can trigger eutrophication, which is the excessive growth of aquatic plants and algae that disrupts water quality and reduces oxygen levels, temperature, and other parameters (Amalia et al, 2021).

Based on Government Regulation of the Republic of Indonesia No. 22 of 2021, for the designation and quality standards of river water, the tolerated nitrate metal content is 10 mg/L. The nitrate metal parameter test values in the three segments of the Laende River are known to be the highest in the downstream segment with a value of 0.232 mg/L and the lowest in the upstream segment, namely 0 mg/L. While for the middle segment it is 0.170 mg/L. The values in all these segments still meet the established quality standards.

Domestic waste is one of the main sources of pollution that contributes to increasing levels of nitrogen in waters, especially in the form of nitrate. Nitrate also comes from various other sources such as industrial waste, agriculture, animal waste, and motor vehicle emissions (Rao et al, 2017).This nitrogen compound acts as a nutrient for aquatic plants, but in excessive concentrations it can trigger eutrophication, which is excessive growth of plants and algae that causes a decrease in dissolved oxygen levels. The concentration of nitrate in water is greatly influenced by seasonal factors, temperature, and rainfall, where the value tends to increase after heavy rain (Patricia et al, 2018).

In addition to impacting aquatic ecosystems, nitrates also pose serious health risks. One of the acute impacts is methemoglobinemia or blue baby syndrome, which occurs when nitrates in the baby's body are converted to nitrite, which then reacts with hemoglobin to form methemoglobin, thus inhibiting the transport of oxygen in the blood (Puspitasari, 2009). This condition is very dangerous and can be fatal, especially for babies under 4 months of age.

Long-term exposure to nitrate has also been linked to an increased risk of cancer, particularly stomach and colon cancer, as nitrate can be converted to carcinogenic nitrosamines. In addition, high nitrate concentrations in drinking water have also been associated with impaired immune, thyroid, and reproductive function (Hidayat & Volunteers, 2024). Therefore, monitoring and controlling nitrate levels in water bodies is very important to maintain environmental quality and public health.

3.3.7 Sulfate (SO_4^{2-})

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Sulfate (SO_4^{2-}) is a sulfur ion that is naturally present in water and can be formed more stable through reactions with other elements. High concentrations of sulfate are generally found in turbid water and can increase acidity and cause permanent hardness, thus reducing water quality and disrupting aquatic ecosystems (Kusmantoro et al, 2018). Although sulfates generally do not have a significant impact on health due to their stability, high levels can cause water to smell and taste bad, and cause corrosion in distribution pipes (Sultan, 2021).

The parameter value of metal sulfate in the upstream segment is 0.103 mg/L, the middle segment is 6 mg/L and the downstream segment is 88 mg/L. There is an increase in the level of metal sulfate from upstream to downstream of the river. The obtained test results still comply with the class I river water quality standards based on Government Regulation of the Republic of Indonesia No. 22 of 2021, which sets 300 mg/L as the threshold value for sulfate.

Sulfate (SO_4^{2-}) is an inorganic ion that is naturally present in water and can affect water quality, both in terms of taste and its impact on health. In high concentrations, sulfate can cause changes in the taste of water to become bitter and cause side effects on human health. Consuming water with high sulfate content has the potential to cause digestive disorders such as diarrhea, especially in sensitive individuals or children (Agusnar, 2018). The health hazards posed by sulfates depend largely on the type of sulfate compound and the level of exposure.

In addition to consumption, sulfate exposure can also occur through skin contact. Some individuals, especially those with high sensitivity, may experience irritation to the skin, eyes, or respiratory tract. Products containing sulfates, such as detergents and soaps, are known to reduce the levels of natural oils in the skin and hair, causing dry skin, dull hair, and the appearance of contact dermatitis or allergic reactions upon repeated exposure (Hidayat & Volunteers, 2024). Studies also show that sulfates can damage the skin's protective barrier, facilitating the penetration of foreign substances into body tissues.

From an environmental perspective, the disposal of household waste containing sulfate can pollute water bodies and soil and contribute to the overall degradation of environmental quality. Therefore, although sulfate is relatively stable, its presence in high concentrations needs to be monitored for both public health and ecosystem protection reasons.

4. Management Strategies

The management of Laende River water quality requires an integrated, comprehensive, and collaborative strategy involving the government, local communities, and relevant stakeholders. It is recommended that the Muna Regency Government, together with technical agencies, develop a sustainable watershed (DAS) management program for the Laende River, which includes periodic water quality monitoring every 3–6 months, strengthening the capacity of monitoring teams, and consistent enforcement of environmental regulations against parties proven to pollute the river. Furthermore, government intervention should focus on enhancing community capacity through educational programs and awareness campaigns on the importance of

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environmental management, proper domestic waste management practices, and the application of the reduce, reuse, and recycle (3R) principles. Active community participation is also expected in maintaining river cleanliness, avoiding the disposal of solid waste or domestic wastewater directly into the river, and supporting riverbank conservation activities and upstream reforestation. The synergy between government policies based on regulation and community empowerment driven by environmental awareness is a decisive factor in reducing pollution levels, restoring water quality, and ensuring the sustainability of the Laende River ecosystem.

5. Conclusion

Based on the results of the analysis of physical and chemical parameters carried out on three segments of the Laende River, it was found that water quality had degraded from upstream to downstream. Based on the results of measurements and comparisons with Government Regulation of the Republic of Indonesia No. 22 of 2021 concerning class I river water quality standards, it is known that the parameters that exceed the quality standard are the TSS parameters in the upstream (Laende Cave) recorded at 44 mg/L, exceeding the quality standard of 40 mg/L. BOD parameters (ranging from 2.60 - 3.10 mg/L), COD (10.22-14.20 mg/L), and DO (4.48 - 5.31 mg/L) in all segments are also not in accordance with the quality standard that BOD is 2 mg/L, COD is 10 mg/L and DO must be ≥ 6 mg/L.

However, this study has several limitations. First, the sampling was conducted within a single period, which limits its ability to represent significant seasonal variations in water quality. Second, microbiological analysis has not been carried out which plays an important role in identifying potential biological contamination which is also relevant in the context of public health. Third, this study has not integrated spatial data, such as mapping of pollutant source points or geographical distribution of water quality.

Therefore, for further research, it is recommended that data collection be carried out periodically in various seasons to obtain a more comprehensive picture of water quality fluctuations. Research can also be expanded by adding microbiological and toxicological parameters, as well as a spatial approach using Geographic Information Systems (GIS) to clarify the distribution and sources of pollutants. In addition, further studies on the effectiveness of domestic wastewater treatment technology and integrated watershed management strategies are expected to provide long-term solutions that support the protection and preservation of the Laende River ecosystem.

With a more holistic and collaborative approach, the results of this study are expected to be the initial foundation for policy makers, researchers, and the community in maintaining the quality of water resources sustainably.

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