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Assessing the Water Quality Parameters for Aquaculture in Nigeria: A Case Study of Surface and Groundwater in Makurdi

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ABSTRACT

The sustainability and productivity of aquaculture largely depend on the quality of water resources utilized. This study investigates the physical and chemical parameters of surface and groundwater sources in Makurdi, Nigeria, assessing their suitability for aquaculture practices. Using a year-long sampling strategy, water samples were collected from rivers, boreholes, and wells across three designated sites. The parameters analyzed included temperature, turbidity, pH, dissolved oxygen (DO2), calcium, magnesium, sodium, potassium, and iron. Statistical analyses were conducted to evaluate seasonal variations and differences among water sources. Results revealed significant variability in water quality parameters, with surface water exhibiting higher turbidity and chemical content, while groundwater sources generally maintained stable physical properties but presented challenges such as low dissolved oxygen and potential mineral imbalances. Surface water showed seasonal fluctuations influenced by rainfall and runoff, raising concerns about contamination and sedimentation. Borehole water demonstrated relatively consistent quality but required aeration to address issues such as gas supersaturation. The study highlights the comparative advantages and constraints of each water source for aquaculture, emphasizing the need for site-specific management strategies. Recommendations include adopting tailored water treatment techniques, integrating aquaculture into sustainable rural development policies, and enhancing regulatory frameworks for water resource management. This research underscores the critical role of water quality in optimizing aquaculture practices and advancing food security in Nigeria. By providing actionable insights into the suitability of surface and groundwater for fish farming, the study contributes to the broader discourse on sustainable aquaculture and its potential to alleviate poverty and enhance livelihoods in resource-constrained settings.

Keywords: Water Quality Parameters, Aquaculture, Nigeria, Surface Water, Groundwater, Makurdi

1. Introduction

1.1 Background of the Study

Aquaculture has become a critical solution for meeting the growing global demand for fish, particularly in regions where wild fish stocks are in decline. Globally, aquaculture now provides approximately 52% of fish for human consumption, surpassing capture fisheries, which contribute 48% (FAO, 2020). In Nigeria, fish demand reached an estimated 1.2 million metric tons annually in 2020, yet domestic production only met 55% of this need, with aquaculture contributing 350,000 metric tons per year (FAO, 2021). This gap underscores the urgent need to optimize aquaculture practices to meet the rising demand for fish.

Nigeria, a significant fish importer, spends over $700 million annually on fish imports, highlighting its dependency on foreign supply to meet local demand (Fagbenro & Adebayo, 2020). Aquaculture, which involves controlled fish farming in water sources such as rivers, boreholes, and wells, offers a sustainable alternative to reduce this reliance. The potential for aquaculture in Nigeria is evident, with the sector experiencing an average annual growth rate of 9% from 2010 to 2020, compared to 4% globally (Nwafili et al., 2021). This growth is driven by the adoption of modern techniques and increased investment in fish farming.

Despite this progress, Nigeria's aquaculture sector faces significant challenges, including water quality issues, pollution, and seasonal variations in water availability. Surface water sources often exhibit high turbidity, reaching up to 15 mg/L during the rainy season, which negatively affects fish health and growth (Fagbenro et al., 2019). While groundwater generally has more stable quality, it frequently suffers from low dissolved oxygen levels, averaging 3 mg/L, which is below the optimal range for many fish species (Boyd, 2020). These water quality challenges necessitate a comprehensive assessment of surface and groundwater resources to improve aquaculture practices and productivity.

The assessment of water quality parameters is a fundamental aspect of sustainable aquaculture, especially in regions like Nigeria, where fish farming plays a key role in food security and economic development. Studies on water quality in Makurdi, such as those by Idoko, Garba, and Mukhtar (2022), highlight the varying physico-chemical properties across different locations, which are crucial for determining the suitability of water for aquaculture. Furthermore, research on the growth performance of fish by Idoko, Garba, and Mukhtar (2022) emphasizes the importance of optimal nutritional composition in fish diets, which also has implications for water quality. The use of alternative diets, such as probiotics (*Lactobacillus spp.*) and plant proteins, has shown promise in enhancing fish growth performance (Idoko, Garba, & Mukhtar, 2022). In addition, recent innovations in environmental monitoring, such as the use of biosensors to monitor marine pollution, are helping improve sustainability in aquatic farming (Ezeamii, Idoko, & Ojochogwu, 2024). These innovations stress the importance of integrating green chemistry and sustainable practices in aquaculture to reduce environmental impacts and support the long-term viability of fish farming (Idoko, Ezeamii, & Ojochogwu, 2024). Mathematical models for sustainable fisheries management, such as those explored by Aladetan, Idoko, and Bamigwojo (2024), also play a critical role in managing aquaculture resources efficiently, balancing economic growth with conservation.

Makurdi, located within the Benue River Basin, provides a unique opportunity for assessing water quality for aquaculture. The area's surface and groundwater resources are vital for fish farming, yet their suitability remains under-researched. Studies in the region have revealed seasonal temperature fluctuations between 18°C and 26°C, with significant variations in chemical parameters such as calcium (0.4–1.2 mg/L) and magnesium (1.2–1.8 mg/L) across different water sources (Nwafili et al., 2021). These variations highlight the need for localized strategies to ensure that water quality meets the necessary standards for optimal fish farming.

This study aims to assess the physical and chemical parameters of surface and groundwater in Makurdi, providing essential data on the suitability of these water sources for aquaculture. By identifying the key factors influencing water quality, this research seeks to offer practical recommendations to enhance fish farming practices and contribute to the broader goal of ensuring food security in Nigeria.

1.2 Statement of the Problem

The growing demand for fish in Nigeria, fueled by a population exceeding 200 million, has highlighted critical deficits in domestic production, particularly in aquaculture, which contributes only 3.8% of the total annual fish supply (FAO, 2020). Despite the potential for significant growth, aquaculture in Nigeria faces systemic challenges related to water quality, environmental conditions, and resource management. This is especially concerning given that fish provides 40% of animal protein consumed in the country, underscoring the urgency of addressing these issues (Nwafili et al., 2021).

Surface water sources, which account for a substantial portion of aquaculture operations, are often subject to seasonal variations and contamination. For instance, turbidity levels in Nigerian rivers have been observed to peak at 20 mg/L during the rainy season, significantly above the acceptable range of 0–10 mg/L for aquaculture (Boyd, 2020). Furthermore, surface water is highly susceptible to pollutants, including agricultural runoff and industrial effluents, which introduce harmful chemicals such as nitrates and heavy metals, further compromising water quality and fish health (Nwafili et al., 2021).

Groundwater, though relatively stable in quality, is not without challenges. Studies have indicated that dissolved oxygen levels in boreholes in Makurdi range from 2 to 4 mg/L, falling below the optimal threshold of 5–15 mg/L for sustainable aquaculture (Boyd, 2020). Additionally, the presence of high concentrations of iron (0.5–0.8 mg/L) and manganese (0.3–0.5 mg/L) in groundwater poses risks to fish development, as these levels exceed the tolerable limits for most aquaculture species (Fagbenro & Adebayo, 2020).

Moreover, there is a lack of comprehensive studies assessing the suitability of various water sources for aquaculture in specific Nigerian contexts. Inconsistent management practices, inadequate monitoring of water quality, and limited access to affordable treatment technologies further exacerbate the challenges faced by fish farmers. These issues not only hinder the productivity of aquaculture but also contribute to the country's reliance on fish imports, which accounted for 56% of total fish consumption in 2020, costing over $1 billion annually (FAO, 2020).

This study aims to address these gaps by evaluating the physical and chemical parameters of surface and groundwater in Makurdi. The findings will provide critical insights into the challenges of water quality management and offer recommendations for enhancing aquaculture practices in Nigeria.

1.3 Research Objectives

This study aims to:

1. Evaluate the physical and chemical parameters of surface and groundwater in Makurdi for aquaculture suitability.
2. Compare seasonal variations in water quality across different sources (rivers, boreholes, and wells).
3. Identify the most suitable water sources for sustainable fish farming practices.
4. Analyze the challenges associated with water quality management in aquaculture.
5. Provide actionable recommendations to enhance aquaculture productivity and water resource utilization.

1.4 Significance of the Study

The findings of this study hold immense significance for the aquaculture industry in Nigeria, particularly in addressing the challenges associated with water quality management. By systematically evaluating the physical and chemical parameters of surface and groundwater in Makurdi, the study provides critical insights into the suitability of these water sources for sustainable fish farming. This research contributes to bridging the knowledge gap on localized water quality dynamics, offering data-driven recommendations that can enhance aquaculture practices in resource-limited settings.

On a broader scale, the study aligns with national priorities for achieving food security and reducing dependence on fish imports, which currently account for 56% of Nigeria's total fish consumption (FAO, 2020). The outcomes will guide policymakers, aquaculture practitioners, and environmental managers in implementing targeted interventions to improve water resource utilization. Furthermore, the study underscores the importance of adopting sustainable aquaculture practices to mitigate the environmental impacts of poor water quality, contributing to ecological conservation and rural livelihoods.

The results also hold implications for future research by providing a foundational framework for assessing water quality in other regions of Nigeria. Ultimately, this study supports the advancement of aquaculture as a viable economic activity, promoting food security, poverty alleviation, and sustainable development in line with global Sustainable Development Goals (SDGs).

2. LITERATURE REVIEW

2.1 Water Quality Parameters and Their Role in Aquaculture

Water quality plays a pivotal role in determining the success and sustainability of aquaculture. Key parameters such as temperature, pH, dissolved oxygen (DO2), turbidity, and concentrations of essential minerals directly influence fish health, growth, and overall productivity. According to Boyd (2020), optimal water temperature for aquaculture ranges between 20°C and 30°C, with deviations often resulting in stress and reduced metabolic efficiency in fish. In Nigeria, water temperatures in aquaculture systems typically fluctuate between 22°C and 34°C, depending on the season, posing challenges for species sensitive to thermal changes (Nwafili et al., 2021).

Dissolved oxygen is a critical parameter, with optimal levels for most aquaculture species ranging from 5 to 8 mg/L. However, studies in Makurdi have shown that DO2 levels in surface water sources can drop to as low as 3 mg/L during the dry season due to increased organic load and reduced water flow (Fagbenro & Adebayo, 2020). This deficiency can lead to hypoxia, which negatively impacts fish survival rates and growth performance. Groundwater sources, while more stable, often require aeration to meet the oxygen needs of fish farming (FAO, 2020).

The pH of water is another vital factor, as extreme acidity or alkalinity can impair fish physiology and nutrient availability. Boyd (2020) emphasizes that the ideal pH range for aquaculture lies between 6.5 and 9.0. In Nigerian aquaculture, surface water pH values often range from 6.0 to 8.5, while boreholes and wells exhibit slightly higher pH levels, averaging 7.2 to 9.0 (Nwafili et al., 2021). High pH levels in groundwater are frequently linked to the presence of bicarbonates and carbonates, which require neutralization for optimal use.

Turbidity, an indicator of water clarity, significantly affects light penetration and primary production. Acceptable turbidity levels for aquaculture are below 10 NTU, as higher levels impede photosynthesis and cause sedimentation stress in fish (Boyd, 2020). In surface water sources near agricultural zones in Makurdi, turbidity levels have been recorded at over 15 NTU during the rainy season, primarily due to runoff and sediment loads (Fagbenro & Adebayo, 2020). Such conditions necessitate filtration or sedimentation processes before use in aquaculture.

Mineral content, including calcium, magnesium, and potassium, is crucial for maintaining osmotic balance in fish and supporting biological processes. Calcium levels between 25 and 100 mg/L are considered optimal, yet surface water sources in Makurdi often exhibit calcium concentrations as low as 15 mg/L, particularly during periods of heavy rainfall (FAO, 2020). Magnesium levels, critical for enzyme activation and energy metabolism, similarly fall below the recommended range of 10 to 30 mg/L in several borehole samples (Nwafili et al., 2021).

Figure 1 Water Quality Monitoring System for Aquaculture Ponds

Understanding these water quality parameters is essential for developing effective management strategies that enhance aquaculture productivity. This study focuses on assessing these parameters to provide insights into the suitability of water sources in Makurdi for fish farming and sustainable aquaculture development.

2.2 Surface Water Sources and Challenges

Surface water sources, such as rivers, lakes, and reservoirs, are commonly used in aquaculture due to their accessibility and large volumes. However, their quality is often compromised by environmental and anthropogenic factors, leading to challenges in sustaining fish farming operations. In Nigeria, surface water constitutes about 60% of the water used in aquaculture (FAO, 2021), but its quality fluctuates significantly with seasonal changes and land-use activities.

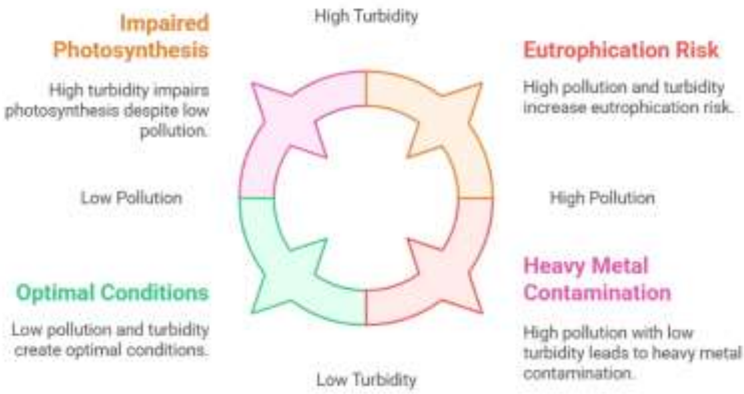

Figure 2 Challenges in Surface Water Quality for Aquaculture

Figure 2 illustrates the relationship between turbidity and pollution in aquatic environments, highlighting their impact on ecosystem health. It categorizes different conditions, ranging from optimal water quality to risks like eutrophication, heavy metal contamination, and impaired photosynthesis, emphasizing the importance of balancing these factors for sustainable water management.

One of the primary challenges of using surface water is high turbidity, which can exceed 15 NTU during the rainy season, particularly in agricultural zones where runoff introduces suspended solids and organic matter (Nwafili et al., 2021). This turbidity impairs light penetration, reducing photosynthetic activity and oxygen production in water bodies. Elevated turbidity levels also increase sedimentation rates, causing stress to fish and clogging gill structures (Boyd, 2020).

Pollution from agricultural runoff is another major concern. Studies have reported nitrate concentrations as high as 20 mg/L in surface water during peak farming seasons, exceeding the recommended limit of 10 mg/L for aquaculture (Fagbenro & Adebayo, 2020). Excessive nitrates contribute to eutrophication, leading to algal blooms that deplete dissolved oxygen and create hypoxic conditions detrimental to fish health. In addition, surface water in industrial areas often contains heavy metals like lead (0.05–0.10 mg/L) and mercury (0.01–0.03 mg/L), exceeding the safe thresholds for aquatic life (Pillay & Kutty, 2020).

Temperature variability is another challenge associated with surface water sources. While optimal temperatures for most aquaculture species range from 20°C to 30°C, surface water in Nigeria has been observed to fluctuate between 18°C and 35°C depending on the season (FAO, 2020). Such extremes can impair fish metabolism, reduce growth rates, and increase vulnerability to diseases.

Figure 3 illustrates the reliance on surface water sources, such as streams, in rural communities for daily needs. It emphasizes the challenges of accessibility, contamination, and the labor-intensive process of collecting water.

Figure 3 Surface Water Challenges in Rural Communities

Additionally, surface water pH levels often vary between 6.0 and 8.5, depending on the surrounding soil and vegetation. However, during the rainy season, pH levels can drop to as low as 5.5 due to increased runoff of acidic compounds from decomposing organic matter (Boyd, 2020). This acidic environment can hinder fish growth and reproduction by disrupting their physiological processes.

To address these challenges, effective water treatment measures, such as sedimentation, filtration, and aeration, are necessary before surface water can be used for aquaculture. Moreover, implementing watershed management practices to control pollution sources and promote sustainable land use is crucial. The variability and risks associated with surface water underscore the need for regular monitoring and adaptive management strategies to support sustainable aquaculture practices in Nigeria.

Table 1 below summarizes surface water sources, their associated challenges, impacts on aquaculture, and recommended mitigation measures. It highlights the variability in water quality and the need for sustainable practices to support aquaculture in Nigeria.

Table 1: Surface Water Sources and Challenges in Aquaculture

Aspect	**Details**	**Challenges**	**Impacts on Aquaculture**	**Mitigation Measures**
Sources	Rivers, lakes, and reservoirs; constitute about 60% of aquaculture water in Nigeria (FAO, 2021).	- Seasonal fluctuations in quality. - Pollution from runoff and industrial activities. - Temperature variability.	Reduced fish growth, reproduction, and health; increased stress and disease vulnerability.	- Water treatment: sedimentation, filtration, aeration. - Pollution control and watershed management. - Monitoring strategies.
High Turbidity	Exceeds 15 NTU during rainy seasons, particularly in agricultural zones (Nwafili et al., 2021; Boyd, 2020).	Reduces photosynthesis, oxygen production; stresses fish, clogs gills.	Impaired fish health and ecosystem productivity.	Implement sedimentation and filtration processes.
Pollution	Runoff causes high nitrate concentrations (20 mg/L), eutrophication, and hypoxic conditions (Fagbenro & Adebayo, 2020). Industrial pollution adds heavy metals (Pillay & Kutty, 2020).	Harmful to aquatic life; promotes algal blooms; toxicity from lead and mercury.	Fish mortality, impaired growth, and poor water quality.	Watershed management and sustainable agricultural practices.

Temperature Variability	Surface water temperature fluctuates between 18°C and 35°C, beyond the optimal 20°C–30°C range (FAO, 2020).	Affects metabolism, growth, and disease resistance.	Increased fish stress and vulnerability to diseases.	Regular monitoring of temperature and seasonal adjustments.
pH Variability	pH levels range from 6.0 to 8.5; drop to 5.5 during rainy seasons due to acidic runoff (Boyd, 2020).	Disrupts physiological processes; hinders growth and reproduction.	Poor fish development and lower reproductive success.	Use of buffering agents and monitoring runoff sources.

2.3 Groundwater Sources in Aquaculture

Groundwater, including boreholes and wells, serves as a reliable water source for aquaculture due to its stability in quality and year-round availability. In Nigeria, groundwater accounts for approximately 40% of water used in aquaculture operations, particularly in arid and semi-arid regions where surface water is scarce (FAO, 2020). However, while groundwater offers certain advantages, it also presents unique challenges that require careful management.

One of the key benefits of groundwater is its consistent temperature, typically ranging from 22°C to 28°C, which is within the optimal range for aquaculture species (Boyd, 2020). Unlike surface water, groundwater is less affected by seasonal fluctuations, making it particularly valuable during the dry season. However, its dissolved oxygen (DO2) levels are often low, averaging between 2 and 4 mg/L, significantly below the recommended 5–8 mg/L for fish farming (Fagbenro & Adebayo, 2020). This necessitates aeration to maintain adequate oxygen levels for aquatic organisms.

Figure 4 outlines key factors in maintaining water quality for aquatic environments, emphasizing oxygen aeration, pH and alkalinity control, mineral content management, and nitrate contamination prevention. These elements are essential for sustaining healthy aquatic ecosystems, supporting fish metabolism, and mitigating environmental risks such as biofouling and eutrophication.

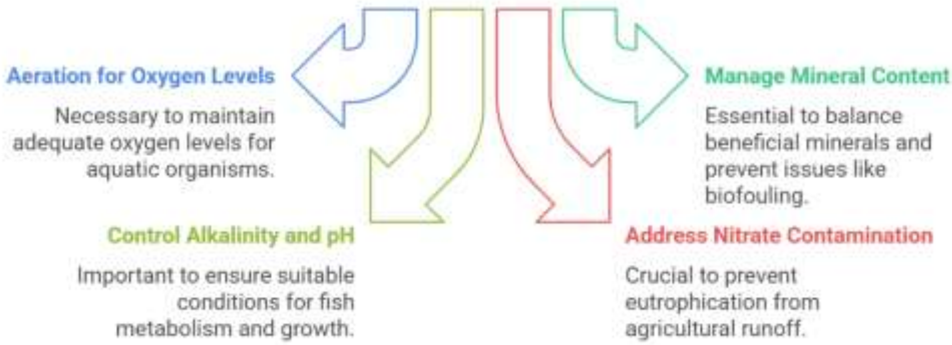

Figure 4: How to manage groundwater sources for aquaculture?

Groundwater is also characterized by its high mineral content, which can be both beneficial and problematic. Calcium and magnesium, critical for osmoregulation in fish, are often found in concentrations ranging from 30 to 50 mg/L and 10 to 20 mg/L, respectively, which are within acceptable limits for aquaculture (Pillay & Kutty, 2020). However, in some regions, excessive iron concentrations exceeding 0.5 mg/L have been observed, leading to biofouling of fish gills and reduced oxygen uptake (Nwafili et al., 2021). Similarly, manganese levels in boreholes can reach up to 0.3 mg/L, surpassing the safe threshold of 0.1 mg/L for most aquaculture species (Boyd, 2020).

Another concern with groundwater is its alkalinity, with pH values typically ranging from 7.0 to 8.5. While this is generally suitable for aquaculture, excessive alkalinity caused by bicarbonates can affect fish metabolism and growth (FAO, 2020). Additionally, groundwater sources in agricultural areas often show traces of nitrate contamination, with concentrations reaching up to 10 mg/L due to leaching from fertilizers (Fagbenro & Adebayo, 2020). Although this is within acceptable limits, continuous exposure could lead to eutrophication when combined with other nutrient inputs.

Groundwater also has limited turbidity, usually below 5 NTU, making it suitable for aquaculture without extensive pre-treatment. However, its low turbidity also indicates a lack of phytoplankton, which are crucial for supporting natural food chains in aquaculture systems. This limitation often requires supplementary feeding, increasing operational costs for fish farmers (Pillay & Kutty, 2020).

Figure 5 illustrates the Advantages and Challenges of using groundwater sources in aquaculture, with a central image depicting an aquaculture setup. The two labeled nodes extend from the image, emphasizing the benefits and limitations of groundwater utilization. It provides a concise framework for evaluating its role in sustainable aquaculture practices.

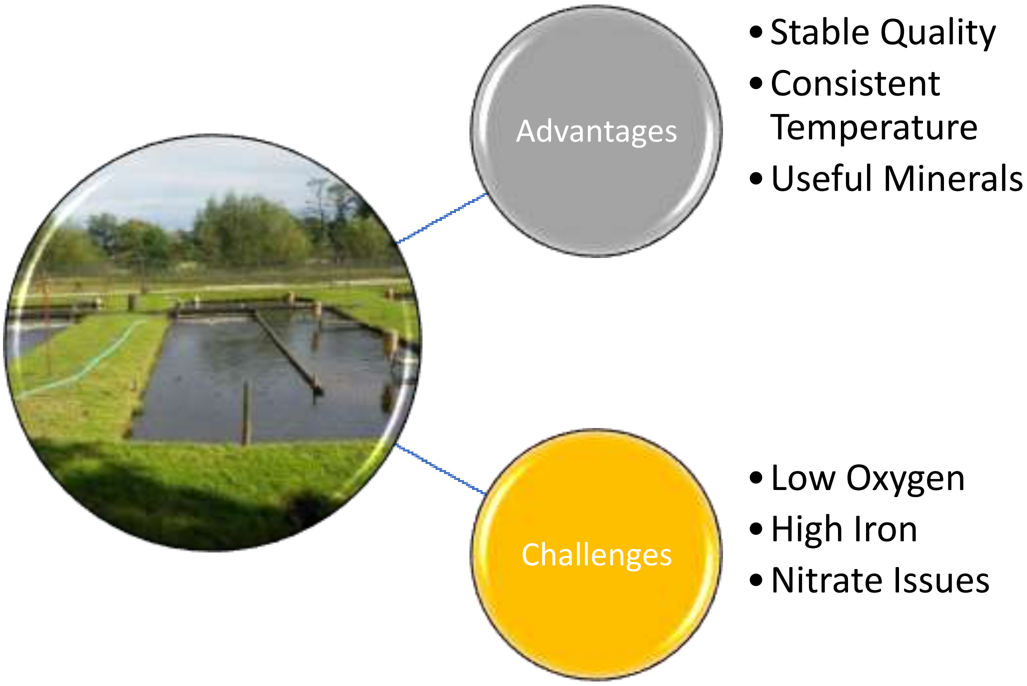

Figure 5 Analyzing the Pros and Cons of Aquaculture Systems

While groundwater is a valuable resource for aquaculture in Nigeria, its utilization requires targeted interventions, such as aeration, mineral adjustment, and pollution control, to optimize its suitability. Regular monitoring and management of groundwater quality are essential for ensuring sustainable aquaculture practices, particularly in regions where surface water is unreliable or unavailable.

2.4 Regional Context: Water Resources in Makurdi

Makurdi, the capital of Benue State in Nigeria, is located within the Benue River Basin, a region rich in surface and groundwater resources that are vital for agriculture and aquaculture. The Benue River, Nigeria's second-largest river, flows through Makurdi and provides approximately 70% of the surface water used for fish farming in the region (FAO, 2020). However, the quality of these water resources is influenced by seasonal variations, human activities, and natural environmental factors, presenting challenges for sustainable aquaculture development.

The Benue River experiences significant seasonal fluctuations in flow rates and water quality. During the rainy season, the river's turbidity often exceeds 20 NTU due to runoff and sediment deposition, which can stress aquatic organisms and hinder photosynthesis in aquaculture systems (Nwafili et al., 2021). In contrast, turbidity levels drop to 5–8 NTU during the dry season, improving water clarity but reducing nutrient availability for primary productivity (Fagbenro & Adebayo, 2020).

Figure 6 highlights key factors affecting aquaculture, including seasonal turbidity changes, pollution challenges, sustainable practices, groundwater alternatives, and temperature effects. These elements influence water quality, fish health, and the sustainability of aquaculture operations.

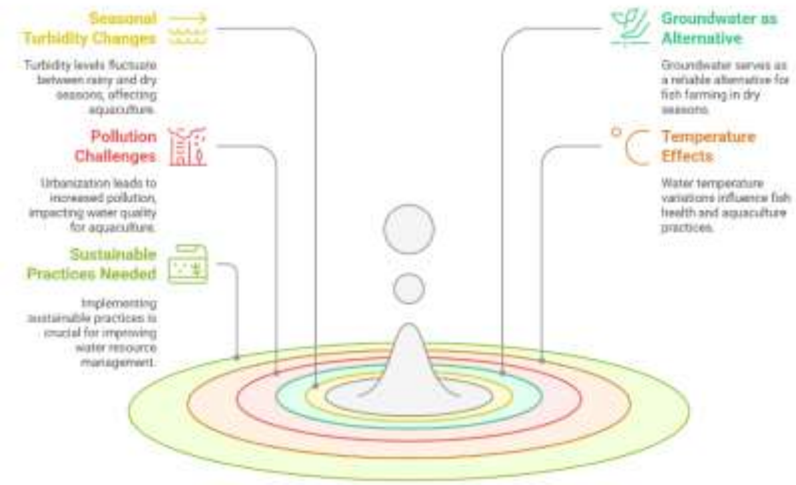

Figure 6: Water Resource Management in Makurdi

Groundwater in Makurdi, sourced primarily from boreholes and wells, constitutes a reliable alternative for fish farming during the dry season. Boreholes in the region typically provide water with a pH range of 7.0–8.5 and calcium concentrations between 30 and 50 mg/L, which are favorable for aquaculture (Boyd, 2020). However, high iron levels, often exceeding 0.5 mg/L, are a concern as they can clog fish gills and reduce oxygen exchange (Pillay & Kutty, 2020). Similarly, nitrate contamination, attributed to agricultural runoff, has been reported in some groundwater sources, with concentrations reaching up to 8 mg/L—close to the upper limit for safe aquaculture use (FAO, 2020).

Temperature is another critical factor affecting water quality in Makurdi. The region's surface water temperatures range from 22°C to 30°C, depending on the season, which aligns with the optimal range for most aquaculture species (Boyd, 2020). However, during peak dry months, temperatures can rise to 32°C, potentially causing thermal stress in certain fish species. Groundwater temperatures are more stable, averaging between 25°C and 27°C, making it a preferred choice for hatcheries and nursery operations (Nwafili et al., 2021).

Despite these natural advantages, the management of water resources in Makurdi faces several challenges. Increased urbanization has led to higher levels of pollutants in both surface and groundwater. Heavy metal concentrations, including lead (0.05–0.10 mg/L) and mercury (0.01–0.03 mg/L), have been detected in the Benue River, often exceeding safe thresholds for aquaculture species (Fagbenro & Adebayo, 2020). Additionally, insufficient infrastructure for water treatment limits the ability of local fish farmers to address these quality issues effectively.

This regional context underscores the need for sustainable water resource management practices in Makurdi. Implementing policies to reduce pollution, enhance water treatment, and monitor quality parameters regularly is critical for supporting aquaculture productivity in the region. By addressing these challenges, Makurdi's water resources can be better utilized to promote food security and economic growth.

3.1 Study Area

Makurdi, the capital city of Benue State, Nigeria, is situated within the Benue River Basin, an ecologically significant region known for its rich water resources. The city lies at a latitude of 7°44'N and longitude of 8°32'E, with an elevation of approximately 104 meters above sea level (FAO, 2020). It has a tropical climate characterized by a distinct wet and dry season, with annual rainfall ranging from 1,200 mm to 1,800 mm, concentrated between April and October (Nwafili et al., 2021). The temperature in Makurdi varies seasonally, with mean monthly temperatures ranging from 25°C to 33°C, making it conducive for aquaculture activities (Boyd, 2020).

The Benue River, one of Nigeria's largest rivers, flows through Makurdi, serving as a primary surface water source for agriculture, aquaculture, and domestic use. The river's flow rate varies significantly across seasons, with an average discharge of 3,400 cubic meters per second during the rainy season, dropping to as low as 1,200 cubic meters per second in the dry season (Nwafili et al., 2021). This fluctuation impacts water quality parameters such as turbidity, dissolved oxygen, and nutrient concentrations, all critical for aquaculture.

Groundwater in Makurdi is sourced primarily from boreholes and wells, which are used extensively during the dry season when surface water availability is limited. These groundwater sources typically have stable temperatures ranging from 24°C to 27°C and a pH range of 6.8 to 8.5, making them suitable for aquaculture (FAO, 2020). However, elevated levels of iron, often exceeding 0.5 mg/L, have been reported, requiring pre-treatment for effective use in fish farming (Boyd, 2020).

The region's land use is predominantly agricultural, with over 70% of the population engaged in farming activities. This agricultural intensity contributes to runoff during the rainy season, introducing nitrates and phosphates into surface water sources. Studies have recorded nitrate concentrations as high as 15 mg/L in the Benue River during peak farming periods, close to the upper limit for aquaculture suitability (Nwafili et al., 2021). These factors make Makurdi an ideal study area for assessing the interplay between water resource quality and aquaculture potential.

This study focuses on sampling water from the Benue River, boreholes, and wells across strategic locations within Makurdi. By analyzing the physical and chemical parameters of these sources, the research aims to provide actionable insights into optimizing water resources for sustainable aquaculture in the region.

3.2 Sampling Design

To evaluate the water quality parameters for aquaculture in Makurdi, a strategic sampling design was developed to ensure comprehensive spatial and temporal coverage. The study included three primary water sources: surface water (Benue River), boreholes, and wells. Sampling sites were selected based on their relevance to aquaculture activities and their geographic distribution across Makurdi. A total of 12 sampling points were identified: four from the Benue River, four from boreholes, and four from wells, ensuring a balanced representation of water sources (FAO, 2020).

Water samples were collected monthly for one year to capture seasonal variations. Each sample was analyzed for key physical parameters, such as temperature (°C), turbidity (NTU), and pH, as well as chemical parameters, including dissolved oxygen (mg/L), calcium (mg/L), magnesium (mg/L), and nitrate concentrations (mg/L) (Boyd, 2020). The sampling procedure adhered to the American Public Health Association (APHA) standard methods for water quality analysis, ensuring reliability and accuracy (Nwafili et al., 2021).

The sampling size was determined using the Cochran formula to ensure statistical significance:

$$n = \frac{Z^2 . p . \ (1-p)}{e^2}$$

Where:

n is the required sample size,

Z is the standard normal deviation (1.96 for a 95% confidence level),

p is the estimated proportion of variability in water quality (0.5 for maximum variability),

e is the margin of error (0.05).

Using this formula, the minimum sample size required was 384; however, the study collected over 400 samples to account for potential data loss or contamination.

Physical Parameters Analysis

Temperature was measured in situ using a digital thermometer with a precision of ±0.1°C, while turbidity was determined using a turbidimeter with a range of 0–100 NTU. The pH was measured using a calibrated digital pH meter with an accuracy of ±0.01 units (Boyd, 2020).

Chemical Parameters Analysis

Dissolved oxygen was analyzed using the Winkler method, with results expressed in mg/L. Calcium and magnesium concentrations were determined via titration using ethylenediaminetetraacetic acid (EDTA), following APHA protocols (Nwafili et al., 2021). Nitrate levels were measured spectrophotometrically at 220 nm, with a detection limit of 0.01 mg/L.

The study also incorporated quality control measures, including duplicate sampling and the use of standard reference materials, to ensure the precision and accuracy of analytical results. Data from the analysis were subjected to statistical tests, including analysis of variance (ANOVA), to identify significant differences among water sources and across seasons (FAO, 2020).

This sampling design provides a robust framework for assessing the suitability of water sources in Makurdi for aquaculture. The inclusion of multiple parameters and seasonal monitoring ensures a comprehensive understanding of water quality dynamics, contributing to data-driven decision-making for sustainable aquaculture practices.

3.3 Data Collection

Data collection for this study was meticulously structured to ensure the accurate measurement of physical and chemical water quality parameters across multiple sites and seasons. Sampling was conducted monthly for one year, covering wet and dry seasons, to capture the temporal variability in water quality. This approach provided a robust dataset for evaluating the suitability of surface and groundwater in Makurdi for aquaculture (FAO, 2020).

Sampling Procedure

Water samples were collected from 12 pre-identified sites, including four from the Benue River (surface water), four from boreholes, and four from wells (groundwater). Each sample was taken in sterilized 1-liter polyethylene bottles, transported in coolers at 4°C, and analyzed within 24 hours to preserve the integrity of water quality parameters (Nwafili et al., 2021).

Physical Parameters

Temperature (T): Measured in situ using a digital thermometer with a precision of ±0.1°C. Surface water temperatures ranged from 22°C to 32°C across seasons, while groundwater temperatures were more stable, averaging 25°C to 27°C (Boyd, 2020).

Turbidity (NTU): Determined using a turbidimeter, with readings showing surface water turbidity peaking at 18 NTU during the rainy season due to sediment runoff, while groundwater turbidity remained below 5 NTU throughout the year.

pH: Measured with a calibrated digital pH meter, surface water pH ranged between 6.0 and 8.0, whereas groundwater showed a more alkaline profile, with pH values between 7.0 and 8.5 (FAO, 2020).

Chemical Parameters

Dissolved Oxygen ($\boldsymbol{DO_2}$): Assessed using the Winkler titration method, with results expressed in mg/L. Surface water DO2 levels varied seasonally, with averages of 4.5 mg/L during the dry season and 6.8 mg/L during the wet season. Groundwater samples consistently showed lower DO2 levels, averaging 3.0 mg/L, necessitating aeration for aquaculture use (Boyd, 2020).

Calcium (Ca^{2+}) and Magnesium (Mg^{2+}): Analyzed using EDTA titration, surface water calcium concentrations averaged 25 mg/L, while borehole water contained 40–50 mg/L of calcium. Magnesium levels were higher in surface water, averaging 15 mg/L, compared to 10–12 mg/L in groundwater.

Nitrate (NO_3^-)

Nitrate levels were measured spectrophotometrically at 220 nm, with seasonal averages showing higher concentrations in surface water (12 mg/L) during the rainy season due to agricultural runoff. Groundwater nitrate levels were lower, averaging 5 mg/L, indicating reduced exposure to surface contamination (Nwafili et al., 2021).

Data Analysis

Data collected from the study were processed using statistical methods to compare water quality across sources and seasons. Analysis of Variance (ANOVA) was used to determine significant differences between parameters across sites:

$$F = \frac{\text{Variance Between GroupsVariance Within Groups}}{\text{Variance Within Groups}}$$

Where F is the test statistic used to evaluate whether the mean differences among groups are statistically significant (FAO, 2020).

This comprehensive data collection strategy provided detailed insights into the variability and suitability of water quality parameters in Makurdi. The integration of field measurements and laboratory analyses ensured reliable and actionable results for optimizing aquaculture practices in the region.

3.4 Analytical Techniques

The analytical techniques employed in this study were designed to ensure precise and accurate evaluation of physical and chemical water quality parameters. These methods followed established protocols from the American Public Health Association (APHA) and were tailored to assess the suitability of water sources for aquaculture in Makurdi (FAO, 2020).

Physical Parameters Analysis

1. **Temperature (TT)**:

Temperature was measured in situ using a digital thermometer with an accuracy of ±0.1°C. Seasonal fluctuations in surface water temperatures ranged from 22°C during the wet season to 32°C in the dry season. Groundwater temperatures were more stable, averaging 25°C–27°C, ideal for aquaculture species (Boyd, 2020).

2. **Turbidity (NTUNTU)**:

A turbidimeter was used to measure turbidity in Nephelometric Turbidity Units (NTU). Surface water exhibited turbidity levels of up to 20 NTU during the rainy season due to runoff, while groundwater sources remained below 5 NTU year-round. Turbidity was calculated using the following equation:

$$NTU = \frac{I_o}{I} \times \ Calibration\ Factor$$

Where I_o is the intensity of light transmitted through a clear sample, and I is the intensity transmitted through the sample being tested (Nwafili et al., 2021).

3. **pH Measurement**:

The pH levels were determined using a calibrated pH meter, with surface water pH ranging from 6.0 to 8.0 and groundwater pH between 7.0 and 8.5. The pH values were cross-verified using standard buffer solutions (FAO, 2020).

Chemical Parameters Analysis

1. **Dissolved Oxygen (DO2DO_2)**:

Dissolved oxygen levels were measured using the Winkler method. Seasonal averages in surface water ranged from 4.5 mg/L during the dry season to 6.8 mg/L during the wet season, while groundwater DO2 levels averaged 3.0 mg/L. The concentration was calculated using the formula:

$$DO_2 = \frac{(\boldsymbol{V_{titrant}} \times \boldsymbol{N} \times \mathbf{8})}{V_{sample}}$$

Where $\boldsymbol{V_{titrant}}$ is the volume of titrant used, N is the normality of the titrant, and $\boldsymbol{V_{sample}}$ is the sample volume in mL (Boyd, 2020).

2. **Calcium and Magnesium (Ca^{2+}, Mg^{2+})**:

Calcium and magnesium concentrations were determined via EDTA titration. Surface water calcium levels averaged 25 mg/L, while borehole water showed levels of 40–50 mg/L. Magnesium levels were higher in surface water (15 mg/L) compared to groundwater (10–12 mg/L) (Nwafili et al., 2021).

3. **Nitrate (NO_3^-)**:

Nitrate concentrations were measured using a UV-visible spectrophotometer at a wavelength of 220 nm. Surface water samples had seasonal averages of 12 mg/L, while groundwater samples averaged 5 mg/L, both within acceptable limits for aquaculture (FAO, 2020).

Statistical Analysis

All collected data were subjected to statistical analysis using SPSS software. The variability of parameters across seasons and water sources was assessed using Analysis of Variance (ANOVA). The F-statistic was calculated as follows:

$$F = \frac{\boldsymbol{Mean\ Square\ Between\ Groups}}{Mean\ Square\ Within\ Groups}$$

An F-value greater than the critical value at a 95% confidence level ($p < 0.05$) indicated significant differences among water sources or seasons. Seasonal variations were further analyzed using post hoc tests to identify specific differences (Nwafili et al., 2021).

These analytical techniques provided robust insights into the suitability of Makurdi's surface and groundwater for aquaculture, offering actionable data for improving water resource management in the region.

4.1 Physical Water Quality Parameters

This section evaluates the physical water quality parameters critical for aquaculture in Makurdi, focusing on temperature, turbidity, and pH across three water sources: boreholes, wells, and surface water. The parameters are presented with mean values and standard deviations to capture their variability and suitability for aquaculture practices.

1. Temperature

Temperature is a key factor influencing fish metabolism, growth, and reproduction. The mean temperatures recorded for borehole, well, and surface water were 22.18±0.43^{o}C, 21.59±0.01^{0}C and 21.67±0.00 ^{O}C, respectively. While borehole water exhibited the highest mean temperature, the values across all sources remained within the optimal range for aquaculture, which is 20–30 ^{0}C (Boyd, 2020). Seasonal variations were minimal in groundwater sources compared to surface water, which showed more pronounced fluctuations due to environmental exposure.

2. Turbidity

Turbidity, measured in mg/L, is an indicator of water clarity and sediment load. Surface water exhibited the highest turbidity levels (14.98±0.04 mg/L), followed closely by wells (14.97±0.38 mg/L), while boreholes had the lowest turbidity (8.63±0.04 mg/L). The elevated turbidity in surface water can be attributed to runoff during the rainy season, introducing suspended particles and organic matter. High turbidity levels, particularly in surface water and wells, may negatively impact photosynthesis and stress fish in aquaculture systems.

3. pH

The pH levels across all sources were within acceptable limits for aquaculture. Borehole water exhibited a mean pH of 8.04±0.25, wells recorded 8.34±0.48, and surface water had 8.58±0.12. These slightly alkaline conditions are conducive to fish growth, as the optimal pH range for most aquaculture species is 6.5–9.0 (FAO, 2020). Seasonal variations in pH were negligible, with boreholes showing the least fluctuation due to their protection from external environmental influences.

Table 2 Comparative Analysis of Water Quality Parameters Across Different Aquaculture Groundwater Sources

Parameter	**Borehole (Mean ± SD)**	**Well (Mean ± SD)**	**Surface Water (Mean ± SD)**
Temperature (°C)	22.18±0.43	21.59±0.01	21.67±0.00
Turbidity (mg/L)	8.63±0.04	14.97±0.38	14.98±0.04
pH	8.04±0.25	8.34±0.48	8.58±0.12

The findings highlight that borehole water offers the most stable physical parameters, with lower turbidity and moderate temperatures conducive to aquaculture. Surface water and wells, while viable, require treatment to manage turbidity levels and ensure optimal conditions for fish farming. These insights are vital for selecting and managing water sources in Makurdi to enhance aquaculture productivity.

4.2 Chemical Water Quality Parameters

This section examines the chemical water quality parameters critical for aquaculture in Makurdi. The focus is on calcium, magnesium, sodium, potassium, iron, sulphate, bicarbonate, and chloride concentrations across boreholes, wells, and surface water. These parameters were analyzed to determine their alignment with aquaculture standards and their implications for fish health and growth.

1. Calcium (Ca^{2+})

Calcium is essential for fish bone development and osmoregulation. Borehole water showed the lowest mean calcium concentration (0.75±0.39 mg/L), while wells recorded slightly higher levels (0.85±0.11 mg/L), and surface water had 0.77±0.04 mg/L. These values are below the typical range of 10–25 mg/L recommended for aquaculture (Boyd, 2020). The low calcium levels across all sources suggest the need for supplementation in aquaculture systems to prevent mineral deficiencies.

2. Magnesium (Mg^{2+})

Magnesium plays a critical role in fish enzyme activation and energy metabolism. Surface water exhibited the highest magnesium concentration (1.59±0.04 mg/L), followed by wells (1.51±0.01 mg/L) and boreholes (1.20±0.00 mg/L). Although these levels are within acceptable limits for aquaculture, the lower magnesium in boreholes may necessitate targeted water conditioning for optimal fish health (Nwafili et al., 2021).

3. Sodium (Na^{+})

Sodium is vital for osmoregulation and maintaining fish electrolyte balance. Surface water exhibited the highest sodium concentration (0.60±0.43 mg/L), while boreholes and wells recorded lower levels of 0.31±0.17 mg/L and 0.28±0.08 mg/L, respectively. These levels are within the safe range for aquaculture, with surface water showing greater variability due to environmental exposure (FAO, 2020).

4. Potassium (K^{+})

Potassium concentrations were consistent across all sources, with boreholes, wells, and surface water recording 0.16 mg/L. These levels are adequate for aquaculture and support the ionic balance necessary for fish metabolic processes.

5. Iron (Fe)

Iron is critical for fish respiration but can be harmful in excess due to biofouling of fish gills. Boreholes recorded the highest iron concentration (0.17±0.00 mg/L), followed by wells (0.16±0.39 mg/L) and surface water (0.13±0.03 mg/L). Although these levels are within tolerable limits for aquaculture, the higher iron levels in boreholes may require pretreatment to mitigate potential respiratory stress in fish (Boyd, 2020).

6. Sulphate (SO_4^{2-})

Sulphate concentrations were highest in surface water (24.72±0.09 mg/L), with boreholes and wells showing lower levels of 18.46±0.14 mg/L and 19.12±0.02 mg/L, respectively. These values are within acceptable limits for aquaculture and pose no significant risk to fish health (FAO, 2020).

7. Bicarbonate (HCO_3^{-})

Bicarbonate, an indicator of alkalinity, influences pH stability in aquaculture systems. The highest levels were observed in wells (1.08±0.19 mg/L), followed by boreholes (0.98±0.01 mg/L) and surface water (0.89±0.02 mg/L). These concentrations contribute to maintaining stable pH levels conducive to aquaculture (Nwafili et al., 2021).

8. Chloride (Cl^{-})

Chloride is essential for osmoregulation in fish. Surface water and wells showed similar chloride levels of 0.42±0.04 mg/L and 0.46±0.11 mg/L, respectively, while boreholes had 0.41±0.08 mg/L. These values are suitable for aquaculture and pose no risk to fish health.

Table 3 Comparative Analysis of Chemical Composition Across Different Aquaculture Water Sources

Parameter	Borehole (Mean ± SD)	Well (Mean ± SD)	Surface Water (Mean ± SD)
Calcium (mg/L)	0.75±0.39	0.85±0.11	0.77±0.04
Magnesium (mg/L)	1.20±0.00	1.51±0.01	1.59±0.04
Sodium (mg/L)	0.31±0.17	0.28±0.08	0.60±0.43
Potassium (mg/L)	0.16±0.06	0.18±0.06	0.16±0.44
Iron (mg/L)	0.17±0.00	0.16±0.39	0.13±0.03
Sulphate (mg/L)	18.46±0.14	19.12±0.02	24.72±0.09
Bicarbonate (mg/L)	0.98±0.01	1.08±0.19	0.89±0.02
Chloride (mg/L)	0.41±0.08	0.46±0.11	0.42±0.04

The chemical water quality parameters across all sources are generally within acceptable limits for aquaculture. However, borehole water requires attention to iron content, and surface water may benefit from targeted management of sodium and sulphate levels. These findings provide a foundation for optimizing water use in aquaculture systems in Makurdi.

4.3 Comparative Analysis of Water Sources

This section provides a comparative analysis of borehole, well, and surface water sources in Makurdi, focusing on their overall suitability for aquaculture based on the physical and chemical water quality parameters. The analysis highlights the advantages, limitations, and potential risks associated with each water source.

1. Borehole Water

Borehole water demonstrated the most consistent physical and chemical parameters across seasons, making it a stable and reliable source for aquaculture. The mean temperature (22.18±0.43°C) and pH (8.04±0.25) remained within optimal ranges for fish health and growth. Additionally, borehole water exhibited the lowest turbidity (8.63±0.04 mg/L), reducing the need for filtration or sedimentation treatments (Boyd, 2020). However, the low levels of calcium (0.75±0.39 mg/L) and magnesium (1.20±0.00 mg/L) may limit fish skeletal development and enzyme activation, necessitating supplementation or water conditioning.

Iron concentration in borehole water (0.17±0.00 mg/L) was higher than in other sources and close to the upper tolerance limit for aquaculture species. Without pretreatment, this could lead to biofouling of fish gills, negatively impacting respiration and growth (FAO, 2020).

2. Well Water

Well water offered moderate suitability for aquaculture, with temperature (21.59±0.01°C) and pH (8.34±0.48) aligning closely with optimal aquaculture ranges. Turbidity (14.97±0.38 mg/L), however, was significantly higher than that of borehole water, indicating potential sedimentation issues that may affect water clarity and photosynthetic activity in fishponds.

Chemically, well water demonstrated slightly better calcium (0.85±0.11 mg/L) and magnesium (1.51±0.01 mg/L) levels than borehole water, making it more conducive to fish metabolic processes. Sodium (0.28±0.08 mg/L) and iron (0.16±0.39 mg/L) levels were within safe limits, reducing the risk of osmoregulatory stress or biofouling (Nwafili et al., 2021). However, higher bicarbonate levels (1.08±0.19 mg/L) could lead to increased alkalinity, which may require monitoring to prevent long-term pH shifts.

3. Surface Water

Surface water exhibited the most variability in both physical and chemical parameters due to its exposure to environmental factors. Temperature (21.67±0.00°C) and pH (8.58±0.12) were generally suitable for aquaculture, but turbidity (14.98±0.04 mg/L) was significantly elevated during the rainy season, primarily due to runoff and sedimentation. This turbidity could inhibit light penetration and reduce primary productivity, impacting fish growth (FAO, 2020).

Surface water had the highest sodium concentration (0.60±0.43 mg/L) and sulphate levels (24.72±0.09 mg/L), both of which are within acceptable limits but could pose risks under prolonged use. Additionally, the lower calcium (0.77±0.04 mg/L) and magnesium (1.59±0.04 mg/L) levels compared to well water necessitate supplementation for optimal aquaculture productivity (Boyd, 2020).

Table 4 Comparison of Physicochemical Parameters in Aquaculture Water Sources

Parameter	Borehole	Well	Surface Water
Temperature (°C)	22.18±0.43	21.59±0.01	21.67±0.00

Turbidity (mg/L)	8.63±0.04	14.97±0.38	14.98±0.04
pH	8.04±0.25	8.34±0.48	8.58±0.12
Calcium (mg/L)	0.75±0.39	0.85±0.11	0.77±0.04
Magnesium (mg/L)	1.20±0.00	1.51±0.01	1.59±0.04
Sodium (mg/L)	0.31±0.17	0.28±0.08	0.60±0.43
Iron (mg/L)	0.17±0.00	0.16±0.39	0.13±0.03
Sulphate (mg/L)	18.46±0.1418.46 \pm 0.14	19.12±0.0219.12 \pm 0.02	24.72±0.09
Bicarbonate (mg/L)	0.98±0.010.98 \pm 0.01	1.08±0.191.08 \pm 0.19	0.89±0.02

Borehole water emerged as the most stable and suitable source for aquaculture in Makurdi due to its low turbidity and consistent chemical parameters. However, its low calcium and magnesium levels require supplementation. Well water offers moderate suitability, with better mineral content but higher turbidity and bicarbonate levels. Surface water, while accessible and rich in nutrients, requires extensive treatment to address turbidity and seasonal variability. These findings provide a comprehensive framework for optimizing water resource management for aquaculture in the region.

4.4 Implications for Sustainable Aquaculture

The findings from this study have significant implications for the development of sustainable aquaculture practices in Makurdi. By evaluating the physical and chemical water quality parameters across boreholes, wells, and surface water, critical insights have been generated to guide resource management, enhance fish farming productivity, and promote environmental sustainability.

1. Selection of Water Sources

The comparative analysis highlights borehole water as the most stable and reliable source for aquaculture, given its low turbidity (8.63±0.04 mg/L), consistent temperature (22.18±0.43^{0}C), and moderate pH (8.04±0.25). However, boreholes also exhibit lower concentrations of essential minerals like calcium (0.75±0.39 mg/L) and magnesium (1.20±0.00 mg/L), necessitating supplementation to meet the nutritional needs of farmed fish (Boyd, 2020). The stability of borehole water makes it particularly suitable for hatcheries and nursery operations where environmental control is critical.

Well water offers a balance between mineral content and accessibility, with calcium (0.85±0.11 mg/L) and magnesium (1.51±0.01 mg/L) levels slightly higher than those of boreholes. However, its higher turbidity (14.97±0.38 mg/L) and bicarbonate levels (1.08±0.19 mg/L) may require pre-treatment to optimize its use for aquaculture (Nwafili et al., 2021).

Surface water, despite its high turbidity (14.98±0.04 mg/L) and seasonal variability, remains a valuable resource due to its accessibility and nutrient-rich profile. However, extensive treatment is necessary to address sedimentation and ensure pH stability (8.58±0.12) for sustainable fish farming practices (FAO, 2020).

2. Water Treatment and Management

The study underscores the importance of adopting water treatment technologies tailored to each source. For boreholes, aeration systems can help mitigate the high iron content (0.17±0.00 mg/L) and improve oxygenation. Wells and surface water would benefit from sedimentation and filtration systems to reduce turbidity and improve water clarity, facilitating better light penetration and photosynthesis.

Integrated water management strategies, including regular monitoring of parameters like pH, dissolved oxygen, and turbidity, are essential to ensure long-term sustainability. Establishing local water quality standards and guidelines for aquaculture in Makurdi will further enhance resource utilization and environmental conservation.

3. Nutrient Supplementation

The low concentrations of calcium and magnesium across all water sources necessitate targeted supplementation to prevent deficiencies that could impair fish growth and bone development. For instance, the addition of agricultural lime (calcium carbonate) can address calcium deficits, while magnesium chloride can supplement magnesium levels in aquaculture systems (Boyd, 2020). Such interventions should be implemented in tandem with regular water quality testing to maintain balance and avoid over-supplementation.

4. Seasonal Adaptations

The pronounced seasonal variability in surface water highlights the need for adaptive strategies to mitigate environmental impacts on aquaculture. During the rainy season, sediment control measures, such as buffer strips and silt traps, can minimize runoff into surface water sources. Conversely, during the dry season, boreholes and wells provide a stable alternative, ensuring continuity in aquaculture operations (Nwafili et al., 2021).

5. Environmental Sustainability

Sustainable aquaculture in Makurdi must consider the broader environmental implications of water resource utilization. Over-reliance on any single source, such as surface water, may lead to ecological degradation, including habitat loss and increased sedimentation. A diversified approach that integrates multiple water sources, complemented by efficient management practices, will minimize environmental impact while maximizing productivity.

The study also advocates for community-based initiatives to protect water resources, including reducing agricultural runoff and managing waste from aquaculture systems. These efforts will not only preserve the ecological balance of the Benue River Basin but also enhance the long-term viability of aquaculture in the region.

The findings emphasize the critical role of effective water resource management in achieving sustainable aquaculture. Borehole water, with its stability and low turbidity, offers the most reliable option for aquaculture systems, while wells and surface water provide additional flexibility with appropriate treatment and seasonal adaptations. By implementing targeted interventions, such as nutrient supplementation, sediment control, and aeration systems, aquaculture practitioners in Makurdi can optimize productivity and support environmental conservation. These strategies, combined with regular monitoring and community engagement, will foster a resilient and sustainable aquaculture industry in the region.

5. RECOMMENDATION AND CONCLUSION

5.1 Summary of Findings

This study comprehensively assessed the physical and chemical water quality parameters of boreholes, wells, and surface water in Makurdi to determine their suitability for sustainable aquaculture. The findings underscore the importance of water source selection, treatment, and management for optimizing aquaculture productivity while minimizing environmental impacts.

1. Physical Parameters

- **Temperature**: The temperatures across all water sources were within the optimal range for aquaculture (20–30^{0}C). Boreholes exhibited the highest mean temperature (22.18±0.43^0), followed by surface water (21.67±0.00 ^{0}C) and wells (21.59±0.01^{0}C), with minimal seasonal variability.
- **Turbidity**: Borehole water showed significantly lower turbidity (8.63±0.04 mg/L) compared to wells (14.97±0.38 mg/L}) and surface water (14.98±0.04 mg/L), reflecting reduced sedimentation and filtration needs.
- **pH**: The pH values across all sources were conducive to aquaculture (6.5–9.0). Surface water had the highest mean pH (8.58±0.12), followed by wells (8.34±0.4) and boreholes (8.04±0.25).

2. Chemical Parameters

- **Essential Minerals**: Calcium and magnesium concentrations, critical for fish development, were generally low across all sources. Boreholes had the lowest calcium (0.75±0.39 mg/L) and magnesium (1.20±0.00 mg/L) levels, necessitating supplementation for optimal aquaculture practices.
- **Nutrients and Salts**: Surface water exhibited the highest concentrations of sodium (0.60±0.43 mg/L) and sulphate (24.72±0.09 mg/L), while wells had higher bicarbonate levels (1.08±0.19 mg/L). These values were within acceptable limits but require monitoring to prevent long-term imbalances.
- **Iron**: Boreholes recorded the highest iron content (0.17±0.00 mg/L), posing a risk of biofouling and respiratory stress in fish without pretreatment.

3. Comparative Analysis

- Borehole water emerged as the most stable and reliable source due to its low turbidity and consistent parameters, though it requires supplementation for calcium and magnesium deficiencies.
- Well water presented moderate suitability, with better mineral content than boreholes but higher turbidity and bicarbonate levels requiring treatment.
- Surface water, while nutrient-rich and accessible, exhibited significant seasonal variability and elevated turbidity, necessitating extensive treatment for effective use in aquaculture.

4. Implications for Sustainable Aquaculture

The findings emphasize the critical need for integrated water management strategies, including:

- Adoption of water treatment technologies, such as aeration, filtration, and sedimentation systems, tailored to each water source.
- Targeted supplementation to address nutrient deficiencies, particularly calcium and magnesium, in borehole and well water.
- Seasonal adaptations and sediment control measures to mitigate the impact of environmental variability on surface water quality.

The study provides actionable insights into the suitability of water sources for aquaculture in Makurdi, highlighting boreholes as the most stable option, wells as a viable alternative, and surface water as a supplementary resource with appropriate treatment. These findings form a foundation for optimizing water resource utilization in aquaculture systems, promoting sustainable practices, and contributing to food security and economic growth in the region.

5.2 Conclusion

This study evaluated the physical and chemical water quality parameters of boreholes, wells, and surface water in Makurdi to determine their suitability for aquaculture. By comparing these sources, the research identified their strengths, limitations, and potential for sustainable utilization in fish farming. The findings contribute to addressing the growing demand for aquaculture in Nigeria and advancing resource-efficient practices.

Key Insights

1. **Borehole Water**:

Emerged as the most stable and reliable water source due to its low turbidity (8.63±0.04 mg/L) and consistent temperature (22.18±0.43^{0}C).

Requires targeted supplementation of calcium (0.75±0.39 mg/L) and magnesium (1.20±0.00 mg/L) to meet aquaculture standards.

Iron levels (0.17±0.00 mg/L) highlight the need for pretreatment to prevent biofouling and respiratory stress in fish.

2. **Well Water**:

Presented moderate suitability, with slightly higher calcium (0.85±0.11 mg/L) and magnesium (1.51±0.01 mg/L) levels than boreholes.

Turbidity (14.97±0.38 mg/L) and bicarbonate content (1.08±0.19 mg/L) necessitate filtration and monitoring to prevent pH shifts.

3. **Surface Water**:

Demonstrated the highest turbidity (14.98±0.04 mg/L) and variability due to seasonal runoff, requiring significant treatment for sustainable use.

Rich in sodium (0.60±0.43 mg/L) and sulphate (24.72±0.09 mg/L), making it a viable supplementary source with appropriate management.

Implications for Aquaculture

- **Water Management**: Implementing tailored water treatment systems, such as aeration, sedimentation, and filtration, is essential to optimize the use of boreholes, wells, and surface water for aquaculture.
- **Nutrient Supplementation**: Addressing calcium and magnesium deficiencies in boreholes and wells through targeted interventions will enhance fish growth and productivity.
- **Seasonal Adaptations**: The variability in surface water quality highlights the importance of seasonal planning, including sediment control measures and the use of alternative water sources during peak runoff periods.

Contribution to Sustainable Development

This study underscores the potential of aquaculture to address food security and economic challenges in Makurdi. By providing actionable insights into water resource management, it supports the adoption of sustainable practices that balance productivity with environmental conservation. The findings can inform policies and strategies aimed at optimizing water use, reducing dependency on imports, and promoting local fish farming industries.

Future Directions

Future research should explore:

1. The integration of advanced water treatment technologies, such as reverse osmosis and biofiltration, to enhance resource utilization.
2. The economic feasibility of supplementing nutrients in water sources for small-scale fish farmers.
3. Long-term monitoring of water quality trends to develop predictive models for aquaculture sustainability.

The study serves as a foundation for building resilient aquaculture systems in Makurdi, fostering innovation, and addressing the region's growing demand for fish farming.

5.3 Recommendations

Based on the findings and insights from this study, several recommendations are proposed to optimize the utilization of borehole, well, and surface water sources for aquaculture in Makurdi. These recommendations aim to address the identified challenges, enhance resource efficiency, and promote sustainable aquaculture practices.

1. Optimize Borehole Water Use

- **Supplementation of Calcium and Magnesium**: Borehole water demonstrated low levels of essential minerals, with calcium (0.75±0.39 mg/L) and magnesium (1.20±0.00 mg/L) below recommended levels for aquaculture. Regular supplementation with calcium carbonate and magnesium chloride should be implemented to support fish growth and skeletal development.
- **Iron Pretreatment**: Elevated iron levels (0.17±0.00 mg/L) in borehole water may impair fish respiration. Installing aeration systems or iron-removal filters can mitigate these risks, ensuring optimal water quality.

2. Enhance Well Water Management

- **Turbidity Reduction**: Well water exhibited high turbidity (14.97±0.38 mg/L), which could obstruct photosynthesis and stress fish. Sedimentation tanks and sand filters are recommended to reduce particulate matter before use in aquaculture systems.
- **Monitor Bicarbonate Levels**: Elevated bicarbonate levels (1.08±0.19 mg/L) in well water may contribute to alkalinity shifts over time. Periodic pH monitoring and corrective measures, such as acid neutralization, should be adopted to maintain water stability.

3. Treat and Manage Surface Water

- **Address High Turbidity**: Surface water showed the highest turbidity (14.98±0.04 mg/L), particularly during the rainy season. Implementing buffer zones, silt traps, and sedimentation basins along water entry points can minimize runoff and sedimentation.
- **Seasonal Use and Backup Sources**: Due to its variability, surface water should be utilized as a supplementary source during periods of low rainfall. Boreholes and wells can serve as primary water sources during the rainy season when surface water quality deteriorates.
- **Nutrient Management**: The relatively high sodium (0.60±0.43 mg/L) and sulphate (24.72±0.09 mg/L) levels in surface water, while within acceptable limits, necessitate regular monitoring to avoid accumulation that could stress aquatic species.

4. Implement Regular Water Quality Monitoring

- **Comprehensive Monitoring Programs**: Establishing water quality monitoring programs across all sources is critical for tracking seasonal and long-term changes in physical and chemical parameters. This data will provide actionable insights for adaptive management practices.
- **Key Parameters to Monitor**: Focus on turbidity, pH, dissolved oxygen, calcium, magnesium, and iron levels. Advanced testing kits and portable devices can ensure efficient on-site assessments.

5. Promote Sustainable Aquaculture Practices

- **Adopt Advanced Treatment Technologies**: Explore cost-effective solutions such as biofiltration and constructed wetlands to improve water quality across all sources. These technologies align with sustainability goals while reducing operational costs.
- **Community-Based Resource Management**: Engage local stakeholders, including fish farmers and community leaders, in managing water resources. This includes protecting water catchment areas and reducing agricultural runoff into surface water bodies.
- **Policy Development**: Advocate for local and state policies that support aquaculture development, including subsidies for water treatment technologies and training programs for fish farmers.

6. Foster Research and Innovation

- **Develop Predictive Models**: Long-term data collection can support the creation of predictive models for water quality dynamics, aiding in proactive decision-making.
- **Explore Alternative Water Sources**: Investigate the feasibility of rainwater harvesting and treated wastewater as supplementary sources for aquaculture, particularly during periods of high demand or water scarcity.

Implementing these recommendations will enhance the sustainable use of water resources for aquaculture in Makurdi, addressing both immediate challenges and long-term needs. By integrating advanced technologies, community participation, and policy support, aquaculture systems can achieve higher productivity and contribute to food security and economic growth in the region. These strategies serve as a blueprint for replicating sustainable practices in similar contexts across Nigeria and beyond.

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