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Exploring the Effects of Seasonal Shifts and Climate Variability on the Physicochemical Properties and Morphological Adaptations of Nile Tilapia (*Oreochromis niloticus*) in the Great Kwa River, Nigeria: Implications for Ecosystem Resilience

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ABSTRACT

Understanding how seasonal changes in water quality affect freshwater fish is essential for assessing ecosystem health and guiding sustainable fisheries management, especially in dynamic tropical river systems like the Great Kwa River in Nigeria. This study examined the influence of seasonal variations in physicochemical water quality on *Oreochromis niloticus* (Nile tilapia) populations in the Great Kwa River, Nigeria. Water and fish samples were collected over four months, encompassing both dry and wet seasons, to analyse key water parameters and fish morphological traits. Physicochemical analyses showed that most parameters, including total hardness (dry season mean: 102.60 ± 5.2 mg/L; wet: 98.33 ± 4.8 mg/L) and iron concentration (dry: 0.97 ± 0.12 mg/L; wet: 0.78 ± 0.10 mg/L), remained relatively stable across seasons, with no significant differences ($p > 0.05$). However, turbidity increased markedly in the wet season (dry: 345.50 ± 150 NTU; wet: 1242.50 ± 300 NTU), likely due to increased surface runoff, although this change was not statistically significant. Notably, cadmium concentrations declined significantly from 0.13 ± 0.02 mg/L in the dry season to 0.08 ± 0.01 mg/L in the wet season ($t = 0.04$, $p < 0.05$), suggesting potential environmental stress. Morphological assessments indicated consistent body weight (dry: 0.39 ± 0.05 kg; wet: 0.49 ± 0.06 kg; $p > 0.05$), total length, and fin dimensions between seasons, reflecting stable growth and nutritional status. In contrast, meristic traits such as ray count on the soft dorsal, pectoral, anal fins, and caudal peduncle showed significant seasonal variation ($p < 0.05$), possibly indicating adaptive morphological responses. The findings highlight the ecological resilience of Nile tilapia in a relatively stable environment, despite seasonal changes.

Keywords: seasonal variations**,** physicochemical parameters**,** morphological adaptations**,** Nile tilapia

Introduction

The Nile tilapia (*Oreochromis niloticus*) is a highly adaptable freshwater species native to the Nile River basin in Africa. Due to its rapid growth, efficient feed conversion, disease resistance, and tolerance to various environmental conditions, it has become one of the most significant species in global aquaculture.[1] Cultivated extensively in tropical and subtropical regions worldwide, Nile tilapia is an important species for economic and ecological studies. Understanding how Nile tilapia interacts with its environment is crucial for managing both aquaculture systems and conserving biodiversity in natural habitats. The physical characteristics of Nile tilapia are well-suited to its environment, with a streamlined, laterally compressed body and sexual dimorphism.[1]

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As primary herbivores, they feed on algae and aquatic plants but are also opportunistic omnivores, consuming small invertebrates and detritus when available.[2] This dietary flexibility allows Nile tilapia to thrive in diverse habitats, including lakes, rivers, and ponds. Reproductive biology is a significant area of interest when studying Nile tilapia. Previous studies have documented a male-biased sex ratio and the species' tendency to spawn year-round, with peak spawning during the warmer months. [3, 4] These reproductive characteristics, including fecundity and the size at first maturity, are important for managing Nile tilapia populations in both natural and farmed environments. Dietary habits also fluctuate seasonally, influenced by the availability of food sources in different environments.[5, 6] In regions like Lake Langeno in Ethiopia, Nile tilapia has been observed to feed on phytoplankton, zooplankton, detritus, and aquatic macrophytes, depending on food availability.[7, 8] Environmental factors such as temperature and water quality play a significant role in the growth and survival of Nile tilapia. Studies have shown that temperature affects the metabolic rate and oxygen consumption of Nile tilapia, with larger individuals being particularly vulnerable to high temperatures.[9, 10] Equally important is the role of water quality in influencing the health of Nile tilapia. Key physicochemical parameters, such as water hardness, pH, turbidity, ammonia levels, and the presence of toxic metals like cadmium, are all crucial factors that impact the well-being of aquatic organisms[11, 12] Morphometric and meristic traits such as body size, fin length, and fin ray counts are valuable indicators of how fish populations adapt to changes in their environment. By studying these

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traits in Nile tilapia, researchers can gain insights into how the species adjusts to seasonal changes and whether these adaptations affect growth, reproduction, and overall fitness in varying ecological contexts.[13]

The Great Kwa River, like many tropical rivers, experiences seasonal fluctuations in temperature, rainfall, and nutrient concentrations. These changes can influence the growth, behavior, and reproduction of fish populations, including Nile tilapia. By examining how Nile tilapia responds to these seasonal variations in water quality, researchers can gain a deeper understanding of the species' resilience to environmental stressors and its potential impact on local ecosystems. Climate change is expected to exacerbate these seasonal fluctuations, leading to more frequent and severe extreme weather events.[14] Understanding how Nile tilapia responds to these changes is crucial for developing effective management strategies that promote ecosystem resilience.

This study aims to explore the effects of seasonal shifts and climate variability on the physicochemical properties and morphological adaptations of Nile tilapia in the Great Kwa River, Nigeria through the following objectives:
1. Analyzing seasonal changes in key physicochemical parameters in the Great Kwa River.
2. Assessing the corresponding morphological and adaptive changes in Nile tilapia.
3. Examining the impacts of seasonal variations in water quality on the growth, reproduction, and overall fitness of Nile tilapia. Through these objectives, this study will provide valuable insights into the resilience of Nile tilapia to seasonal and climate-related changes, contributing to both sustainable aquaculture practices and the conservation of freshwater biodiversity. The results will also inform better management strategies for Nile tilapia, helping mitigate any potential ecological risks while maximizing its benefits for food security and economic development.

Materials and Methods

Study site
The study focuses on the Great Kwa River in Cross River State, Nigeria, a key tributary feeding into the Cross River estuary. Originating from the Oban Hills, the river flows towards Calabar, contributing to rich

biodiversity. The lower river sections drain the eastern coast of Calabar Municipal and feature unique ecosystems, including freshwater swamps and Nypa fruitcans, which have displaced traditional mangrove vegetation. Tidal fluctuations further shape the dynamic physical conditions of this region.[15] The geographical coordinates of the study site, the Great Kwa River in Cross River State, Nigeria, are approximately latitude 4°45′ N and longitude 8°20′ E. These coordinates mark the confluence of the river and its location within the region, which is situated along the eastern coastline of Calabar, the capital of Cross River State (Figure 1). The Great Kwa River was chosen for this study due to its ecological significance, offering a comprehensive setting with diverse environments rivers, lakes, forests, and urban areas to explore the environmental factors affecting Nile tilapia populations.

Sample Collection Procedures
Water Sample Collection for Physicochemical Analysis
Water samples for physicochemical analysis were collected from two stations, Esuk Atu and Obufa Esuk Orok, over four months (March to June) during both dry and wet seasons. Using a water sampler, samples were carefully labelled with relevant information according to Standard Methods for the Examination of Water and Wastewater.[16]

Fish Sample Collection
In examining the fish population within the study area and their dynamic interactions with the aquatic environment, representative samples of Nile tilapia, a prominent species, were systematically collected. Following established protocols to minimize fish stress and ensure data integrity[17, 18], samples were gathered at the landing sites of artisanal gill net and trap fishers at Esuk Atu (Station 1) and Obufa Esuk Orok (Station 2). This sampling strategy was carried out over two distinct seasons; March and April (Dry season) and May and June (Wet season) to account for temporal variations in fish behaviour and environmental conditions.[19, 20]

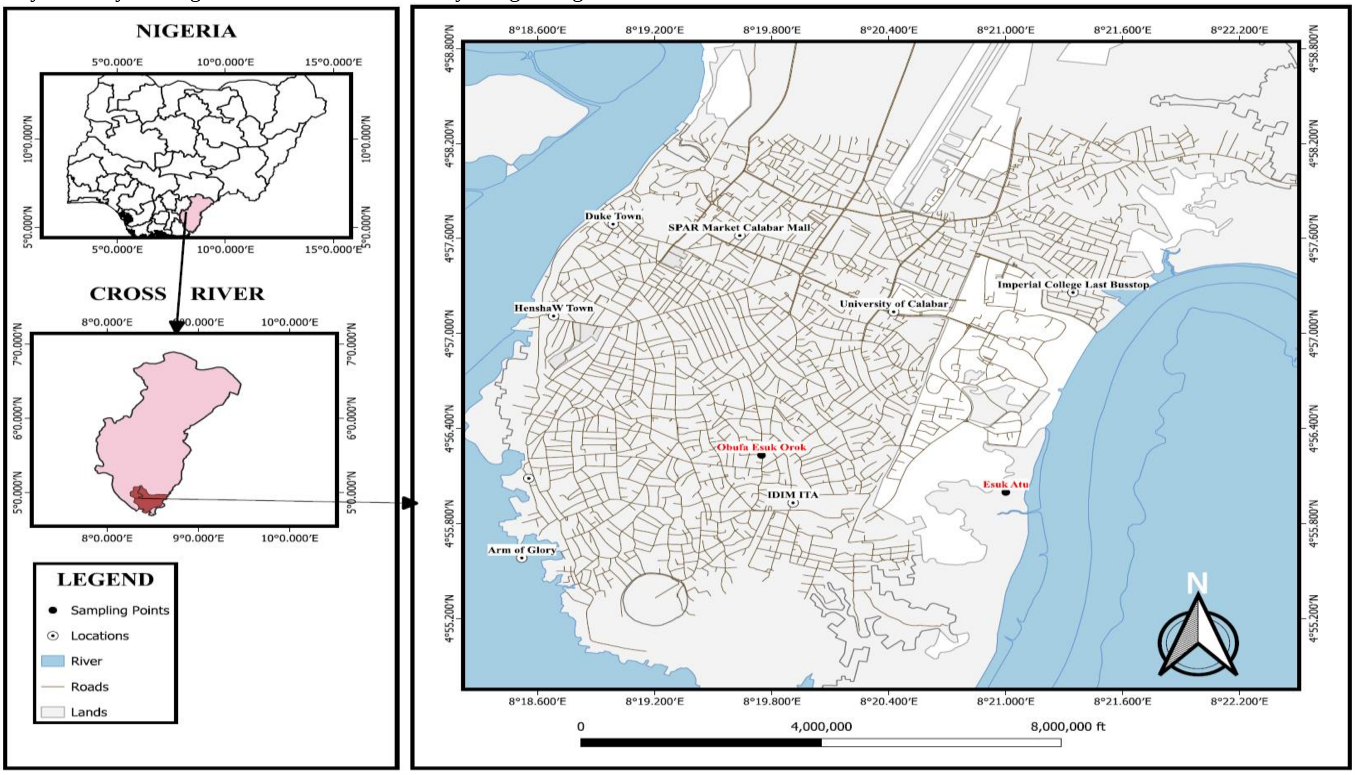

Figure 1: Map of the study location[1]

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The Nile tilapia specimens collected underwent a thorough process of identification, measurement, and documentation. Biological parameters, including length and weight, were systematically recorded, providing a comprehensive dataset for subsequent analyses of fish population dynamics and biology.[21, 22] These measurements are crucial for understanding growth patterns, reproductive health, and overall population structure, contributing valuable insights into the ecology of the species. Data collection was conducted with care to minimize stress on the fish, ensuring the accuracy and reliability of the results. This approach aligns with best practices for aquatic species sampling[23, 24], supporting the study's objective to assess the dynamics of Nile tilapia populations concerning seasonal variations and environmental conditions. The precision of these procedures ensured that the data collected were robust and relevant to the study's goals, offering a solid foundation for further analyses of the fish population's biology and ecology. Nile tilapia specimens were collected from artisanal gill nets and traps at Esuk Atu (Station 1) and Obufa Esuk Orok (Station 2) during the dry (March to April) and wet (May to June) seasons. Fish were identified, measured for length and weight, and documented following established guidelines to minimize stress and ensure data accuracy, aligning with best practices for aquatic species sampling.[23, 24]

Laboratory Procedures for Analysing Water Quality Parameters
Physicochemical Analysis
A comprehensive physicochemical analysis of water samples was conducted to understand the environmental conditions of the aquatic ecosystem. Several key physicochemical parameters were rigorously examined to assess the quality and health of the water including:

Temperature Measurement
Water temperature was accurately measured using a calibrated Digital Thermometer (Model: DT-8801, Manufacturer: CEM, Country: USA), ensuring the precise recording of thermal variations within the ecosystem.[16].

pH Determination
The pH Meter (Model: pH-700, Manufacturer: Thermo Fisher Scientific, Country: USA). This measurement provided essential information about the water's chemical composition and its suitability for aquatic life.[25].

Dissolved Oxygen (DO) Measurement
Dissolved oxygen levels, critical for the survival of aquatic organisms, were measured using the Winkler Method (Model: Lovibond OxiDirect, Manufacturer: Lovibond, Country: Germany). This technique ensured reliable results, offering insights into oxygen availability and overall water quality.[16]

Conductivity Assessment
A Conductivity Meter (Model: YSI EC300, Manufacturer: YSI Incorporated, Country: USA) was used to assess the water's conductivity, reflecting ion concentration and providing data on the water's chemical makeup, which is crucial for understanding its nutrient content and overall health.[25]

Total Dissolved Solids (TDS) Analysis
Gravimetric analysis was employed to measure total dissolved solids (TDS) in water, offering insights into the presence of various dissolved substances and their potential impacts on the aquatic ecosystem.[16]

Salinity Measurement
Electrical conductivity was measured to determine the salinity levels of the water, which is an important factor in assessing the water's salt concentration and its suitability for different aquatic species.[25]

Nutrient Levels Analysis
Following standardized protocols, concentrations of key nutrients such as nitrate and phosphate were analyzed. These nutrients play a vital role in aquatic ecosystems, and understanding their levels provides valuable insights into nutrient dynamics and potential environmental risks.[25]

Morphometric and Meristic Analysis

Morphometric and meristic analyses are essential for understanding the biology and taxonomy of the fish population in the study area. Morphometric Measurements were performed on each specimen, including Total Length (TL), Standard Length (SL), and various fin lengths, recorded using a measuring tape.[26] Meristic Counts involved quantifying the number of rays in fins such as the dorsal, pectoral, pelvic, anal, and caudal fins, providing valuable taxonomic information.[27] All data points were carefully documented and organized into a dataset for statistical analysis. These procedures, adhering to established protocols[26, 27], ensured precision and accuracy, to support the objectives of the study.

Statistical Analysis
Data were analysed in triplicate using one-way ANOVA, followed by Tukey's HSD post-hoc test. Results were expressed as mean ± SD.

Results and Discussion

Monthly Physicochemical Parameters in the Great Kwa River
This section examines the monthly variations in key physicochemical parameters of the Great Kwa River to better understand the environmental conditions influencing Nile tilapia (*O. niloticus*) populations (Figure 2a and b). Water hardness showed significant fluctuations, peaking at 119.7 mg/l in April, which may affect the physiological health of Nile tilapia, highlighting the need for further investigation into its impact on habitat suitability. Iron concentrations varied throughout the study period, with the highest level reaching 1.305 mg/l in April. Given the potential effects of iron on fish health, these variations should be considered when evaluating environmental stressors on Nile tilapia populations. Turbidity levels experienced a sharp increase in June, reaching 2150 mg/l. This substantial rise may indicate changes in sedimentation or other factors affecting water clarity, suggesting the need to explore the implications for fish behaviour and habitat suitability. Ammonia concentrations, though remaining within acceptable limits, showed slight variations, ranging from 0.19 mg/l in March to 0.255 mg/l in April. Regular monitoring of these fluctuations is crucial, as ammonia levels can affect the overall health of Nile tilapia. Trace metals, including Nickel, Chromium, Sulphide, Zinc, and Copper, fluctuated throughout the study, highlighting the need to assess the cumulative impact of these metals on fish health and underwater quality standards. Total Dissolved Solids (TDS) also varied, with the highest concentration recorded in April at 183.6 mg/l. Changes in TDS can influence water osmolarity, which may affect the well-being of Nile tilapia. Aluminium levels increased significantly in May, reaching 2.265 mg/l, raising concerns about its potential adverse effects on aquatic life. While elements like Fluoride, Cadmium, Lead, and Arsenic remained within safe limits, their long-term effects on fish health should be monitored. Key nutrients such as Magnesium and Calcium fluctuated, with Magnesium ranging from 9.55 mg/l in March to 13.9 mg/l in May, and Calcium from 12.96 mg/l in March to 14.1 mg/l in June. Manganese concentrations decreased over the study period. This study revealed key insights into the seasonal dynamics of the Great Kwa River, particularly regarding the physicochemical parameters and their influence on the aquatic ecosystem. The stability in total hardness across seasons (Dry season mean: 102.60 mg/l, Wet season mean: 98.33 mg/l) suggests a consistent mineral composition in the river, providing a stable habitat for aquatic life. This aligns with findings by Gallego-Villalobos[28], who reported similar stability in river systems, indicating that such a steady profile supports long-term ecological balance. Similarly, iron concentrations remained stable between the dry (0.97 mg/l) and wet seasons (0.78 mg/l), consistent with the works[1], which suggested that iron levels typically exhibit limited seasonal variation in such freshwater systems. However, turbidity levels exhibited a significant increase during the wet season (Dry season mean: 345.50 NTU, Wet season mean: 1242.50 NTU), although the variation was not statistically significant. Increased turbidity during the wet season can be attributed to runoff from rainfall, which carries suspended particles and organic matter into the river.

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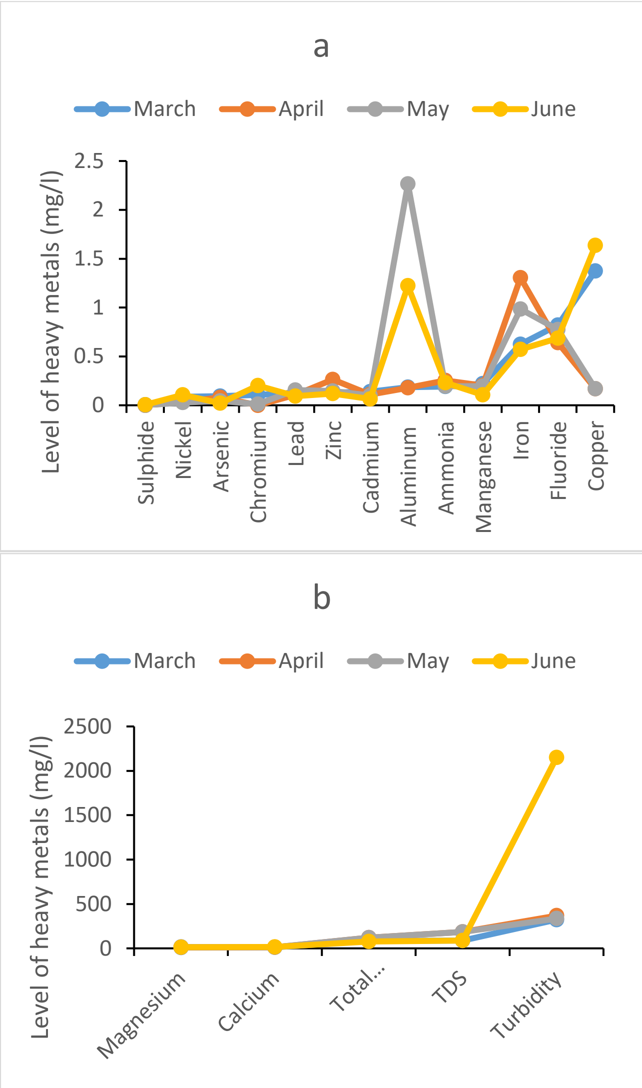
While this increase in turbidity may not directly impact water quality in terms of toxicity, it can have implications for aquatic life by reducing light penetration, which is essential for photosynthesis and primary production. This observation corroborates earlier findings where it was noted that high turbidity could alter aquatic habitats by impacting visibility and light availability.[29]



Figures 2: Monthly variations in key physicochemical parameters of the Great Kwa River. a = heavy metals, b = physicochemical parameters

One of the most notable findings was the significant variation in cadmium levels (Dry season mean: 0.13 mg/l, Wet season mean: 0.08 mg/l). Although cadmium levels decreased in the wet season, the presence of this toxic metal still raises concerns for the ecological health of the river. Previous studies emphasized the need for continuous monitoring of heavy metals, as they can accumulate in aquatic organisms, leading to long-term ecological damage.[30]

Seasonal Variation in Physicochemical Parameters

This study provides an in-depth analysis of seasonal variations in key physicochemical parameters within the Great Kwa River, Nigeria, comparing the dry and wet seasons. The mean values, standard errors (SE), t-test results, and significance levels (P<0.05) for each parameter are presented. Total hardness showed minimal variation between the dry (102.60 mg/l) and wet seasons (98.33 mg/l), with a t-test result of 0.93 indicating no statistically significant difference. A similar trend was observed for other parameters, including iron concentrations, turbidity, ammonia, nickel, chromium, sulphide, zinc, copper, TDS, aluminum, fluoride, lead, arsenic, magnesium, calcium, and manganese, where the differences between the dry and wet seasons were not statistically significant. These results are confirmed by the t-test outcomes and p-values, which exceeded the 0.05 threshold, as shown in Table 1.

Table 1: Seasonal variations in physicochemical parameters of the Great Kwa River, Nigeria.

	Dry season		Wet season		t-test	Level of significance (p<0.05)
Parameters (mg/l)	Mean	SE	Mean	SE	p-value	
Total Hardness	102.60	17.10	98.33	21.38	0.93	Not significant
Iron	0.97	0.34	0.78	0.21	0.79	Not significant
Turbidity	345.50	22.00	1242.50	907.50	0.50	Not significant
Ammonia	0.22	0.03	0.21	0.02	0.63	Not significant
Nickel	0.06	0.03	0.07	0.04	0.93	Not significant
Chromium	0.05	0.05	0.11	0.10	0.78	Not significant
Sulphide	0.00	0.00	0.00	0.00	1.00	Not significant
Zinc	0.20	0.07	0.13	0.01	0.57	Not significant
Copper	0.77	0.60	0.90	0.73	0.94	Not significant
TDS	136.01	47.60	135.69	47.91	1.00	Not significant
Aluminum	0.18	0.00	1.75	0.52	0.20	Not significant
Fluoride	0.73	0.09	0.73	0.05	1.00	Not significant
Cadmium	0.13	0.02	0.08	0.02	0.04	Significant
Lead	0.12	0.01	0.13	0.03	0.70	Not significant
Arsenic	0.09	0.01	0.03	0.01	0.06	Not significant
Magnesium	10.70	1.15	13.40	0.50	0.35	Not significant
Calcium	13.06	0.09	13.60	0.50	0.41	Not significant
Manganese	0.21	0.01	0.15	0.05	0.34	Not significant

Notably, cadmium concentrations show a significant difference between the dry and wet seasons (t-test result: 0.04, p<0.05). The mean cadmium concentration in the dry season is 0.13 mg/l, while in the wet season, it decreases to 0.08 mg/l. This significant difference underscores the importance of considering seasonal variations, as cadmium levels may have ecological implications for the Great Kwa River. In summary, the majority of physicochemical parameters examined in this study exhibit no significant seasonal variations between the dry and wet seasons. However, the notable exception is cadmium, emphasizing the need for a nuanced understanding of seasonal influences on water quality and potential ecological consequences. The seasonal fluctuations in physicochemical parameters of the Great Kwa River reflect the dynamic nature of the ecosystem. The observed stability in total hardness and iron concentrations reinforces the resilience of the river to seasonal changes. This consistency in fundamental water quality parameters supports aquatic life and suggests that the ecosystem of the river is relatively stable throughout the year. Such stability is crucial for maintaining a healthy aquatic environment, enabling organisms like Nile tilapia to thrive despite seasonal variations. However, the significant increase in turbidity during the wet season requires closer attention, particularly considering its potential impacts on fish behaviour and reproduction. High turbidity can reduce the availability of food for filter-feeding organisms and alter predator-prey dynamics. Furthermore, the slight decrease in cadmium levels between seasons, while less concerning than in some other locations, still underscores the need for careful monitoring to mitigate any potential harm to aquatic organisms.

Seasonal Variation in Morphological Characteristics of Nile Tilapia
Table 2 presents a detailed examination of the seasonal variation in morphological characteristics of Nile tilapia (*O. niloticus*) within the Great Kwa River. The morphometric variables include body weight (BW), total length (TL), standard length (SL), dorsal fin length (DF), pectoral fin length (PCF), pelvic fin length (PLF), total body width (TBW), length of caudal fin (LCF), anal fin length (ANF), head length (HL), and fork length (FL). Additionally, meristic variables, including ray count on the soft dorsal fin (SDF), ray count on the pectoral fin (PCF), ray count on the pelvic fin (PLF), ray count on the anal fin (ANF), and ray count on the caudal peduncle (CP), were examined. For the morphometric variables, the T-test results indicate that none of the parameters exhibit statistically significant differences between the dry and wet seasons, as all p-values are above 0.05. This suggests that during both seasons, the morphological characteristics, such as body weight, length measurements, and fin dimensions, remain relatively stable. In contrast, the meristic variables reveal more nuanced seasonal variations. Ray count on the soft dorsal fin (SDF), ray counts on the pectoral fin (PCF), ray counts on the anal fin (ANF), and caudal peduncle ray count (CP) all show statistically significant differences between the dry and wet seasons (p<0.05).

Table 2: Seasonal variation in Morphological characteristics of the Nile tilapia in the Great Kwa River

Morphological variables		Dry season		Wet season		t-test p-value	Level of significant (p<0.05)
		Mean	SE	Mean	SE		
Morpho-metric	BW (kg)	0.39	0.13	0.49	0.06	0.56	Not significant
	TL (cm)	26.03	1.99	27.34	0.74	0.58	Not significant
	SL (cm)	20.89	1.61	21.39	1.09	0.84	Not significant
	DF (cm)	6.18	0.65	7.40	0.32	0.08	Not significant
	PCF (cm)	7.92	0.43	7.94	0.22	0.97	Not significant
	PLF (cm)	6.16	0.65	7.03	0.32	0.28	Not significant
	TBW (cm)	20.51	2.37	23.12	0.92	0.38	Not significant
	LCF (cm)	6.39	0.40	6.85	0.21	0.37	Not significant
	ANF (cm)	6.15	0.55	6.86	0.29	0.25	Not significant
	HL (cm)	6.91	0.44	6.76	0.20	0.80	Not significant
	FL (cm)	23.53	2.04	27.04	0.82	0.19	Not significant
Meristic	SDF	10.10	0.23	12.20	0.20	0.00	Significant
	PCF	10.70	0.47	12.30	0.15	0.02	Significant
	PLF	6.00	0.00	6.00	0.00	1.00	Not significant
	ANF	10.70	0.26	11.90	0.23	0.00	Significant
	CP	14.10	0.10	14.70	0.15	0.02	Significant

Key: body weight (BW), total length (TL), standard length (SL), dorsal fin length (DF), pectoral fin length (PCF), pelvic fin length (PLF), total body width (TBW), length of caudal fin (LCF), anal fin length (ANF), head length (HL), and fork length (FL), ray count on the soft dorsal fin (SDF), ray count on the pectoral fin (PCF), ray count on the pelvic fin (PLF), ray count on the anal fin (ANF), and ray count on the caudal peduncle (CP)

This indicates that the scale counts on these fins, as well as along the lateral line, undergo noticeable changes in response to seasonal shifts. Morphological characteristics of Nile tilapia in the Great Kwa River exhibited interesting trends in response to seasonal changes. Despite the stable body weight between the dry (0.39) and wet (0.49) seasons, no significant variations were observed in overall body size or dimensions. This stability suggests that Nile tilapia can maintain its nutritional status across seasons, likely due to its adaptability and feeding behaviour. The absence of significant variation in other morphometric traits further suggests that the physical growth of the fish and overall morphology are relatively unaffected by the seasonal changes in the river's physicochemical parameters.[2, 29] However, meristic traits, such as ray counts on the soft dorsal fin (SDF), pectoral fin (PCF), anal fin (ANF), and caudal peduncle (CP), exhibited significant seasonal variations, indicating that Nile tilapia may adapt its body structure in response to environmental changes. These findings are consistent with Mekkawy and Mohammad[31], who observed that meristic traits can serve as indicators of environmental stress and adaptation in fish populations. The significant changes in fin ray counts may reflect the ability of the species to adapt to shifts in water quality and other environmental conditions, ensuring survival and efficient resource utilization in response to seasonal fluctuations.[13]

Conclusion

The Great Kwa River maintains stable physicochemical conditions year-round, providing a consistent habitat for aquatic organisms, including Nile tilapia. However, the study found seasonal variations in certain water quality parameters, with notable changes in cadmium levels and meristic traits of Nile tilapia, highlighting the river's environmental sensitivities. Nile tilapia demonstrated adaptive responses to shifts in water quality, ensuring survival in changing conditions. While most physicochemical factors, such as total hardness and iron concentration, remained stable, turbidity and cadmium levels varied significantly between seasons, these fluctuations necessitate closer monitoring of water quality to mitigate potential risks to aquatic life. The observed differences in fin ray counts further illustrate the capacity of the species for morphological adaptation. Such adaptations enhance the resilience of Nile tilapia in fluctuating environments. The study underscores the river's ecological stability despite seasonal changes. Monitoring physicochemical shifts is crucial for maintaining a healthy aquatic ecosystem. Sustainable management strategies should consider these adaptive traits to support fisheries. Protecting the Great Kwa River's ecosystem requires continuous environmental assessment.
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Conflict of Interest

Authors declare no conflict of interest.

Authors' Declaration

The authors hereby declare that the work presented in this article is original and that any liability for claims relating to the content of this article will be borne by them.

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