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Spatial Environmental Gradients Drive Growth Variability in Nile Perch (*Lates niloticus*) Populations of Lake Nasser, Egypt

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ABSTRACT

Aims: Eutrophication impacts water quality and limits fish growth and body condition in large reservoirs. This study examined the effects of key physico-chemical factors and their north-south eutrophication gradients in Lake Nasser, Egypt, on Nile perch (*Lates niloticus*) growth across this transect.

Materials & Methods: Water physicochemical factors (i.e., Temperature, pH, Dissolved oxygen, turbidity, Total suspended solids, Total dissolved solids, Total Nitrogen, and Total Phosphorus) were assessed during the growth period for 1,992 specimens collected from three sites (Aswan, Garf Hussian, and Abou Simbel) from Jan 2022 to Dec 2023.

Findings: A clear downstream increase in overall turbidity, total Nitrogen, and total Phosphorus, coupled with a decrease in dissolved oxygen, correlated with the length-weight relationship of the fish caught in the various sites that demonstrated negative allometric growth ($b < 3$). The ELEFAN_SA model determined Von Bertalanffy growth factors showing positive growth toward lower asymptotic lengths at Aswan ($K = 0.095\ y^{-1}$; $L\infty = 168.6$ cm), maximum size potential at Garf Hussian ($K = 0.088\ y^{-1}$; $L\infty = 205.2$ cm), and reduced growth rate and asymptotic length at Abou Simbel ($K = 0.080\ y^{-1}$; $L\infty = 167.96$ cm). At the upstream oligotrophic site, DO and, to a lesser extent, TN were significant predictors of condition factor (K), whereas downstream, the relationships were weak.

Conclusion: These results show that, along a eutrophication gradient, spatial heterogeneity in water quality constrains the growth and condition of fish populations in reservoirs, and that variability in water quality is a critical factor that must be integrated into the ecosystem-based fisheries management of Lake Nasser.

Keywords: Environmental Parameters; Eutrophication Variation; Growth Factors; Limnology; Marine Ecology.

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Introduction

The growth and health of fisheries are profoundly influenced by various water quality factors, including total Nitrogen (TN), total Phosphorus (TP), dissolved oxygen (DO), turbidity, temperature, total suspended solids (TSS), and pH. Elevated levels of Nitrogen and Phosphorus can cause eutrophication, which degrades water quality and threatens fish species by altering habitat conditions and inducing toxicity[1,2]. These factors interact synergistically to shape the aquatic environment, affecting fish physiology, growth, and population dynamics. Therefore, understanding their combined impact is essential for sustainable fisheries management and aquaculture practices [3]. Lake Nasser (LN), a vast artificial reservoir formed by the construction of the High Aswan Dam on the Nile River, represents a unique freshwater ecosystem in southern Egypt [4]the water quality of the Lake Nasser must be profoundly investigated, and physico-chemical parameter changes of the water of the Lake Nasser should be continuously monitored and assessed. This work describes the present state of the physico-chemical (nitrate-nitrogen, nitrite-nitrogen, orthophosphate, total phosphate content, dissolved oxygen content, chemical oxygen demand, and biological oxygen demand. Since its creation, (LN) has played a pivotal role in regional water management, fisheries, and biodiversity conservation[5] the effects of heavy metal pollution on three aquatic habitats in the Aswan Governorate of Egypt-Lake Nasser, Aswan Reservoir, and the River Nile-were evaluated for the Nile tilapia (*Oreochromis niloticus*).

The population effects of ecosystem drivers, including the wider environment, food-web interactions, and associated density-dependent processes, often arise from their effects on the constituent individuals [6] however, there is a growing recognition of the degree of variation among individuals within a population, as well as the ecological consequences of this variation. Managing resources at an ecosystem level calls on practitioners to consider evolutionary processes, and ample evidence from the realm of fisheries science indicates that anthropogenic disturbance can drive changes in predominant character traits (e.g. size at maturity. Length and weight data could be used to spatially compare fish populations under varying environmental conditions [7] and, temporally, to track seasonal variations in fish growth [8] to assess the significance of the allometric factor and the validity of the condition factor; these biological factors often remain undetermined, because most fishery studies have been conducted for commercial-sized and/or adult populations. The exponent b (allometric factor), the condition factor is used to compare the "condition", "fatness," or well-being of fish. Both biotic and abiotic environmental conditions strongly influence it and can be used as an index to assess the status of the aquatic ecosystem in which fish live [9].

One of the main fish species in this lake is the Nile perch (*Lates niloticus*), a freshwater species endemic to African rivers and lakes [10]. Despite the ecological and economic importance of *L. niloticus* in LN, studies examining the interplay between spatial variation in environmental factors and their effects on the morphometric and growth dynamics of these species across different regions of the lake remain limited. Previous research has rarely integrated detailed water quality assessments with growth modeling to elucidate the drivers of regional differences in fish population structure.

There are very few studies, if any, that take the longitudinal gradients of water quality in Lake Nasser, and the fishery's economic and ecological importance, and describe the gradients in fish population growth and body condition of key fish populations. The available studies are mostly on monitoring water quality or on age and growth dynamics [10, 11, 15]. However, studies on age and growth that also integrate relevant, detailed physicochemical data, growth modeling data (e.g., the Von Bertalanffy Growth Function (VBGF)), condition indices, and the eutrophication gradient are virtually nonexistent. This is why we fail to recognize the environmental factors that limit growth and incorporate water-quality variability into the fishery management of large tropical reservoirs.

Regular environmental assessments indicate that monitoring aquatic communities in LN and its associated khors, "the lake's natural side-arms," is crucial for a comprehensive evaluation of the lake's environmental status [11]. Hence, we hypothesize that spatial variation in key environmental factors across LN will create site-specific limitations on the growth and body condition of Nile perch. More specifically, this study intends to: (i) use multivariate analysis of the water quality data to describe the north-south eutrophication gradient, (ii) analyze and contrast the length-weight relationships and von Bertalanffy growth factors of Nile perch in the three regions (Aswan, Garf Hussian, Abou Simbel), and (iii) analyze the condition factor (Kc) in relation to each water quality variable and with the composite eutrophication index from principal component analysis (PCA).

This study is the first to assess the north-south gradient of eutrophication along (LN) by integrating [1] longitudinal water quality variation by PCA indices, [2] site-specific von Bertalanffy (ELEFAN_SA) growth factors for Nile perch, and [3] condition factor among individual and composite environmental predictors. In contrast to previous (LN) studies on water quality [11], growth studies [10,12], or single-site fisheries [5]the effects of heavy metal pollution on three aquatic habitats in the Aswan Governorate of Egypt-Lake Nasser, Aswan Reservoir, and the River Nile-were evaluated for the Nile tilapia (*Oreochromis niloticus*), we identify multiple spatially-explicit growth constraints and establish a more comprehensive baseline for the ecosystem-based management of Lake Nasser, thus resolving the most conspicuous absence in the integration of environmental fish population gradient analysis.

Materials & Methods

Study Area

Lake Nasser, a large artificial reservoir on the Egypt-Sudan border, extends between latitudes 21.8°N–24.0°N and longitudes 31.3°E–33.1°E (Figure 1). It covers approximately 5,248 km^2, measures about 550 km in length, reaches a maximum width of about 35 km, and has depths ranging from 25 m to 183 m. The Egyptian sector spans 324 km and features a complex shoreline with numerous side channels ("khors") that provide important fish habitat [12–14]. The lake is ecologically heterogeneous and subdivided into three main zones:

1. Northern Region (Aswan): Characterized by narrow, rocky shorelines and steep underwater slopes, it benefits from regulated flows and sediment retention by the Aswan High Dam, resulting in higher dissolved

oxygen, lower turbidity, and stable water quality.

2. Central Region (Garf Hussain): Marked by wider, gently sloping embayment and floodplain khors; this zone experiences seasonal floods that enhance nutrient cycling and primary productivity, Increased turbidity and organic matter.

3. Southern Region (Abou Simbel): Featuring broad sandy shores and open waters, it receives higher sediment and nutrient loads, leading to greater turbidity and eutrophication pressures. These environmental stresses contribute to lower dissolved oxygen and less stable water quality [15].

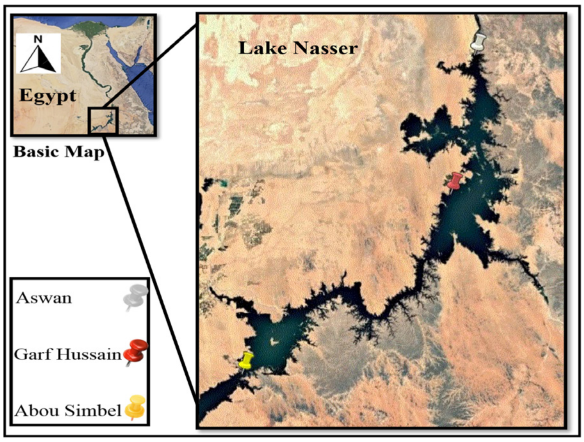

Figure 1) Satellite images showing the location of Lake Nasser, Egypt.

Sampling

Fish Sampling

Specimens of Nile perch (*Lates niloticus*) were collected monthly over two years using gill nets, from Jan 2022 to Dec 2023, to assess growth patterns across Lake Nasser, Egypt. Sampling was conducted systematically across three distinct regions (Aswan, Garf Hussain, and Abou Simbel) to ensure spatial representation of the study area. For each captured specimen, the total length (measured from the tip of the snout to the end of the caudal fin) was recorded to the nearest 0.1 cm, and the total body weight was measured to the nearest 0.1 g using calibrated measuring instruments.

Water Sampling

Water samples were collected concurrently with fish sampling, from the three sites (n=288 composite samples; Jan 2022–Dec 2023; 12/site/month) using 5-L PVC Van Dorn fish samplers, integrated from three horizontal replicates (10 m apart) according to the APHA (2017) guidelines, from three different depths (surface 0-1 m, mid-water 5-10 m, near-bottom 15-20 m). For each sitemonth combination (3 sites × 24 months = 24 units), water quality factors were averaged across depths and replicates. These mean values were then assigned to all individual fish specimens (n = 1,992) captured during the same sitemonth, while each fish retained its own measurements of total length (TL), total weight (TW), and condition factor (Kc). This approach links fish to the specific environmental conditions they likely experienced and is commonly used in reservoir fishery studies [15].

Water Analysis

Total dissolved solids (TDS), water temperature (°C), dissolved oxygen (DO), turbidity, and pH were recorded using the water checker (U-10 Horiba Ltd.). Total Nitrogen (TN), total Phosphorus (TP), and total suspended solids (TSS) were measured according to APHA [16]. Chemical analysis of water samples was conducted at the FISHAQU Lab in the Faculty of Fish and Fisheries Technology.

Length-Weight Relationship and Condition Factor

The length-weight relationship was described by equation [1], where W is body weight, L is total length, b is the growth exponent (length-weight factor), and a is a constant [17].

$$W = aL^b \qquad \text{Eq. [1]}$$

Condition Factor

The absolute condition factor was calculated according to equation [2] [18]:

$$K = W/L^3 * 100 \qquad \text{Eq. [2]}$$

where W is fish body weight (g), and L is fish total length (cm).

Growth Factors

The growth factors were estimated using the Electronic Length Frequency Analysis (ELEFAN) method[19]. Data analysis was performed with the TropFishR v. 4.4.1 R package. To model *L. niloticus* growth, growth factors were optimized using the ELEFAN algorithm with simulated annealing (ELEFAN_SA) [20]. The growth performance index Ø was estimated using equation 3[21].

$$\varnothing = 2\log L_\infty + \log K \qquad \text{Eq. [3]}$$

Statistical Analyses

Descriptive statistics (mean ± SD; range) were calculated for all waterquality variables (temperature, pH, DO, turbidity, TDS, TSS, TN, TP) and fish metrics (TL, TW, Kc) by site. Differences among sites were tested using oneway ANOVA followed by Tukey's HSD post hoc test (α = 0.05). Length–weight relationships were fitted to the model $W=aL^b$ after logtransformation, and deviations of from isometry (b = 3) were evaluated with onesample ttests. Von Bertalanffy growth factors (L∞, K,Ø) were estimated from lengthfrequency data using the ELEFAN_SA routine in the TropFishR v4.4.1 package in R Core [22]. Relationships between TL, TW, Kc, and individual water quality variables were first explored using Pearson correlation and simple linear regression models of the form K = a + bx. To characterize the main spatial gradient in water quality, we performed a principal component analysis (PCA) on standardized turbidity, TSS, TN, TP, and DO using the correlation matrix; scores of the first principal component (PC1) were then used as an additional environmental predictor in multiple linear regression models of Kc that included DO, TN, and site.

Findings

Environmental Factors Analysis

Water quality variables were assessed monthly at each of the three study sites over two years from Jan 2022 to Dec 2023. Temperature showed no considerable differences among sites, ranging from 23.16 ± 0.27 °C (Aswan) to 24.36 ± 1.50 °C (Garf Hussain), indicating relatively stable thermal conditions across the study area. Similarly, pH did not differ significantly among sites ($p > 0.05$), with values ranging from 8.27 ± 0.08 (Aswan) to 8.49 ± 0.16 (Abou Simbel). In contrast, (DO) varied significantly among sites. Aswan had the highest DO concentration (7.84 ± 0.64 $mg.L^{-1}$), which was significantly greater than both Garf Hussein (7.12 ± 0.26 $mg.L^{-1}$) and Abou Simbel (6.93 ± 0.18 $mg.L^{-1}$). No significant difference in DO was detected between Garf Hussein and Abou Simbel ($p > 0.05$). Turbidity, TSS, TDS, TN, and TP all increased progressively from Aswan downstream to Abou Simbel. Turbidity rose from 1.05 ± 0.10 NTU (Aswan) to 1.72 ± 0.38 NTU (Abou Simbel), while TSS increased from 1.02 ± 0.13 to 1.46 ± 0.30 $mg.L^{-1}$ and TDS from 176.1 ± 4.8 to 189.6 ± 13.1 $mg.L^{-1}$. TN and TP showed significant increases downstream ($p < 0.05$; Table 1), with TN rising from 474.2 ± 8.9 to 568.6 ± 15.2 $mg.L^{-1}$ and TP from 13.5 ± 1.0 to 23.0 ± 4.85 $mg.L^{-1}$. Scatterplots of condition factors (K) versus DO and K versus

TN are shown in Figures 2 and 3, respectively.

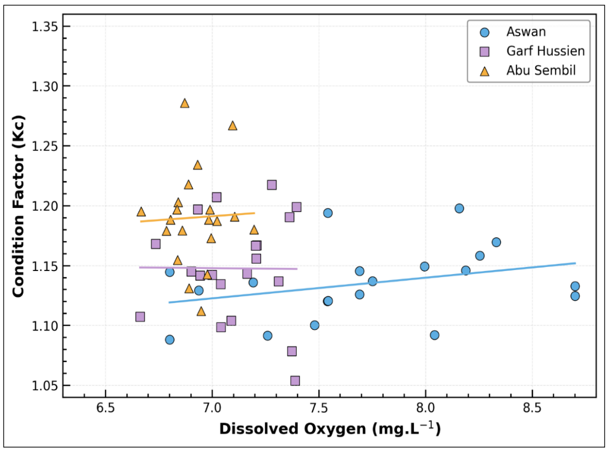

Figure 2) Relationship between condition factor (K) of Nile perch and dissolved oxygen (DO) across the three study sites in Lake Nasser.

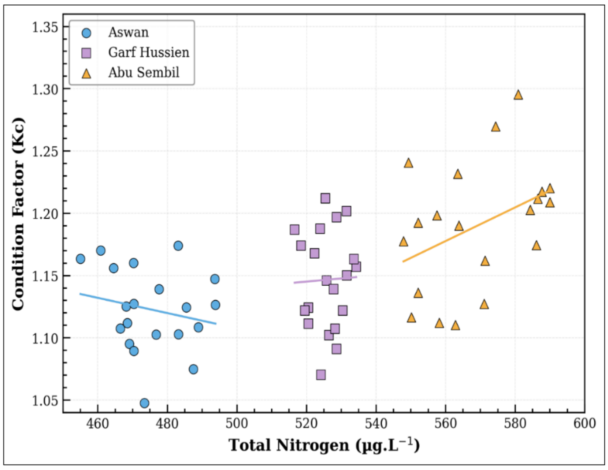

Figure 3) Relationship between condition factor (K) of Nile perch and total Nitrogen (TN) across the three study sites in Lake Nasser.

Length-Weight Relationship and Condition Factor

A total of 1,992 *L. niloticus* were collected from Aswan, Garf Hussein and Abou Simbel in 2022–2023, Means of total length (TL), total weight (TW), and condition factor (Kc) at Aswan were 28.96 ± 9.2 cm, 393.8 ± 1308 g, 1.126 ± 0.17, respectively, while at Garf Hussian 29.68 ± 8.98 cm, 420 ± 1647g, 1.152 ± 0.24, respectively, and at Abou Simbel were 31.77 ± 10.23 cm, 506.28 ± 692 g, 1.172 ± 0.19, respectively (Table 2).

Length-weight relationships for each site exhibited an excellent fit, with a coefficient of determination (R^2)>0.95. The allometric coefficient (b) varied moderately among sites. At Aswan, b = 2.99 (95% CL:2.87–3.03), and since the confidence interval includes 3, growth is isometric (weight increases proportionally to the cube of length). At Garf Hussain, b = 2.84 (95% CL:2.76–2.92), with the entire confidence interval below 3, indicating significant negative allometric growth (fish become slimmer as length increases). At Abou Simbel, b=2.95 (95% CL:2.92–3.07); although the point estimate is below 3, the upper confidence limit exceeds 3, so isometric growth cannot be statistically rejected. The log–log regression intercepts and slope factors vary across sites, indicating moderate spatial variation in length-weight scaling as shown in Figure 4.

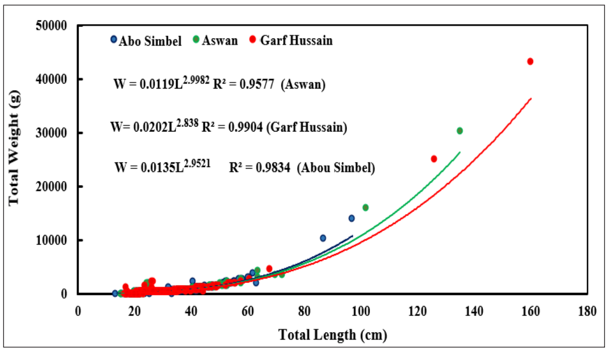

Figure 4) Length-weight relationship for *Lates niloticus* from three sites in Lake Nasser.

Growth Factor

Estimates of von Bertalanffy growth factors from length–frequency distributions using the ELEFAN SA routine showed species-specific growth discrimination among the sampling sites (Figures 5-7). Hence, at the Aswan site, the estimated asymptotic length (L∞) was 168.6 cm while the growth coefficient (K) was 0.095 y^{-1}. The theoretical

Table 1) Environmental Factors Across three sites on Lake Nasser (Aswan, Garf Hussain, and Abou Simbel).

Water Quality Factors	Unit	Sites		
		Aswan	Garf Hussein	Abou Simbel
Temp	°C	23.16±0.27	23.52±0.43	24.36±1.5
PH	–	8.27±0.08	8.362±0.31	8.49±0.16
DO	$mg.L^{-1}$	7.84±0.64b	7.12±0.26a	6.93±0.18a
Turb	NTU	1.05±0.1a	1.19±0.21a	1.72±0.38b
TDS	$mg.L^{-1}$	176.1±4.8a	182.4±5.2ab	189.6±13.1b
TSS	$mg.L^{-1}$	1.02±0.13a	1.23±0.2ab	1.46±0.3b
TP	$mg.L^{-1}$	13.5±1b	20.1±2.1a	23±4.85a
TN	$mg.L^{-1}$	474.2±8.9a	524±4.3b	568.6±15.2c

Note: (a, b, c): Denote statistical groupings (ANOVA). Same letters = no significant difference; different letters = significant difference ($p < 0.05$). Temp = Water temperature, pH = Measure of water acidity/alkalinity, DO = Dissolved oxygen, Turbi = Turbidity, TDS = Total dissolved solids, TSS = Total suspended solids, TP = Total Phosphorus, TN = Total Nitrogen.

Table 2) Length, weight, and Condition Factor (Kc) factors of *Lates niloticus* from Aswan, Garf Hussain, and Abou Simbel in Lake Nasser, Egypt.

Sites	N	Length		Weight		Mean			Regression Coefficient			95% CL of b
		Min	Max	Min	Max	TL	TW	Kc	a	b	R^2	
Aswan	573	15	137.8	38	30500	28.96 ± 9.2[a]	393.8 ± 1308[a]	1.126± 0.17b	0.0119	2.99	0.96	2.87-3.03
Garf Hussain	879	16.3	159.3	49.8	40000	29.68 ± 8.98[a]	420 ±1647[a]	1.152± 0.24a	0.0202	2.84	0.99	2.76-2.92
Abou Simbel	540	13.3	98.3	29.9	15000	31.77 ± 10.23[b]	506.28 ± 692[b]	1.172± 0.19a	0.0135	2.95	0.98	2.92-3.07

Note: N = Number of samples, TL = Total length, TW = Total weight, K = Condition factor, [a] = Not significantly different, [b] = Significant differences, ± Values: Standard deviation, CL = Confidence limits; R^2 = Determination coefficient.

Table 3) Pearson correlation (r) between fish metrics (TL, TW, Kc) and waterquality variables at the three study sites in Lake Nasser.

Sites	Metric	Temp	PH	DO	Turbi	TDS	TSS	TP	TN
Aswan	TL	0.33	0.2	0.23	-0.14	-0.04	0.03	-0.02	-0.02
	TW	0.3	0.27	0.33	-0.19	-0.07	0.01	0	-0.09
	Kc	0.02	-0.21	0.49	-0.15	0.02	0.01	0.11	-0.42
Garf Hussain	TL	-0.1	-0.03	-0.09	0.5	-0.11	-0.26	-0.07	0.07
	TW	0.13	0.15	0.01	0.23	0.27	-0.18	-0.19	0.05
	Kc	0.31	0.15	0.19	-0.15	0.06	0.33	0.23	0.03
Abou Simbel	TL	-0.12	0.2	0.08	0.31	0.26	-0.04	0.37	0.26
	TW	-0.01	0.16	0.1	0.29	0.41	-0.18	0.5	0.35
	Kc	0.07	0.05	0.07	0.1	0.06	0	0.19	0.05

Note: Temp = Water temperature, pH = Measure of water acidity/alkalinity, DO = Dissolved oxygen, Turbidity, TDS = Total dissolved solids, TSS = Total suspended solids, TP = Total Phosphorus, TN = Total Nitrogen.

age at zero length (tanchor) was 0.97, the amplitude of seasonal growth oscillation (C) was 0.78, while the relative timing of the seasonal oscillation (ts) was 0.31. Growth performance index (ϕ′) was 3.43 while the maximum Rn value was 0.584.

At Garf Hussian, L_∞ was 205.2 cm while K = 0.088 y^{-1}, with tanchor = 0.22, C = 0.74, while ts = 0.83. The corresponding ϕ′ was 3.73, while the maximum Rn value was 0.93. At Abou Simbel, L_∞ was 167.96 cm while K = 0.08 y^{-1} with tanchor = 0.92, C = 0.885, while ts = 0.11. Growth performance index (ϕ′) was 3.35 while the maximum Rn value was 0.806.

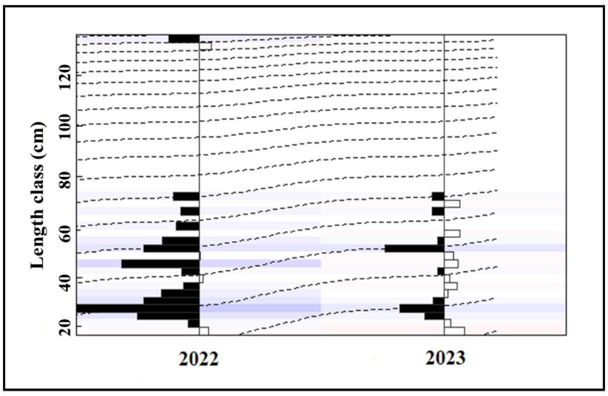

Figure 5) Length-frequency histograms with the growth curves obtained through the bootstrapped ELEFAN with SA analysis superimposed for *Lates niloticus* in the Aswan site.

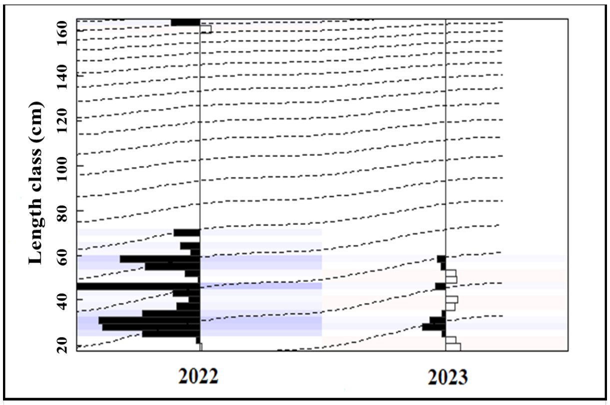

Figure 6) Length-frequency histograms with the growth curves obtained through the bootstrapped ELEFAN with SA analysis superimposed for *Lates niloticus* in the Garf Hussian site.

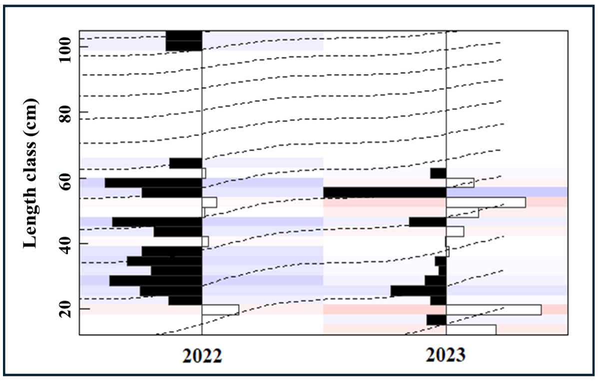

Figure 7) Length-frequency histograms with the growth curves obtained through the bootstrapped ELEFAN with SA analysis superimposed for *Lates niloticus* in the Abou Simbel site.

Relationships between Fish Metrics and Water Quality

Correlations and simple regressions between fish metrics (i.e., TL, TW, and Kc) and water quality variables are provided in Table 3. In Aswan, KC had a positive correlation with DO (r≈=0.49) and a negative correlation with TN (r≈-0.42). In contrast, the correlations of TL and TW with the environmental variables were lower in magnitude (r≤0.33). In Garf Hussian, TL was positively correlated with turbidity (r≈0.50), and the correlations of TL, TW, and Kc with the water quality variables were weak. For Abou Simbel, TW had positive correlations with TDS and TP (r up to ≈ 0.50), and the correlations of Kc with all variables were low (r≤0.19).

The simple linear regression model for individual water quality variables of Kc yielded low coefficients of determination (R^2 < 0.5). In response to changes in DO at Aswan, Kc ≈ 0.85 + 0.037 × DO (R^2 = 0.24, p = 0.016) and decreased with TN according to Kc ≈ 1.80 − 0.0014 × TN (R^2 = 0.18, p = 0.041). Single-variable models (R^2 < 0.12, p > 0.10) at Garf Hussien and Abou Simbel indicated that Kc was not significantly related to water quality variables.

Multivariate WaterQuality Gradient (PCA) and PC1 Scores

Principal component analysis (PCA) of turbidity, TSS, TN, TP, and DO identified the first principal component (PC1), which represented the main gradient of water quality in the study area. In relation to increased nutrients and turbidity and decreased DO, PC1 also increased (loadings not shown). Mean PC1 scores showed Aswan with a negative value (−2.16 ± 0.56), Garf Hussain with a value close to zero (0.11 ± 0.51), and Abou Sembil with a positive value (2.05 ± 0.88). This indicates a clear ordering among the three areas, with Aswan the least, Abu Sembil the most, and Garf Hussain, to some extent, in the middle of the three regions in terms of the eutrophication gradient (Table 4). Figure 8 shows the condition factor and individual PC1 scores across the sites.

Table 4) Summary statistics of PC1 scores (eutrophication index) for each sampling site.

Site	PC1 Mean	PC1 SD
Aswan	2.161 -	0.561
Garf Hussian	0.114	0.507
Abu Sembil	2.048	0.878

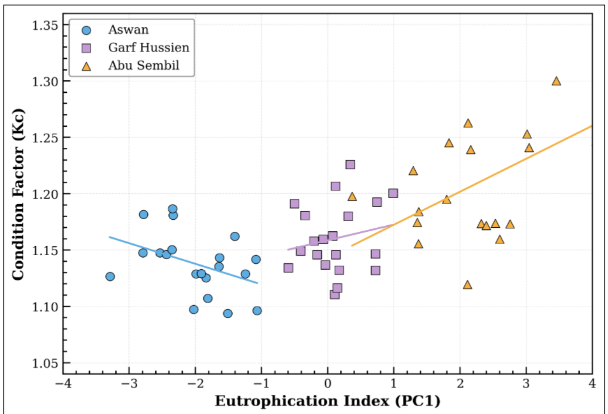

Figure 8) Relationship between condition factor (Kc) of Nile perch and the eutrophication gradient (PC1) across the three study sites in Lake Nasser.

Discussion

Fish growth is influenced by a complex interplay of environmental and anthropogenic factors, with water-quality factors such as temperature, pH, alkalinity, hardness, metals, suspended solids, and dissolved oxygen playing critical roles in regulating somatic growth, productivity, and survival in freshwater and marine systems. Fishing effort introduces both ecological and evolutionary pressures: intense harvesting selectively removes larger individuals, reducing biomass of target piscivores and invertebrate feeders, altering community structure and size spectra (steeper slopes indicating fewer large fish), and even inducing genetic shifts toward slower growth, lower fecundity, reduced larval viability, and reduced willingness to forage, which hinder population recovery [24]. In our study, the temperature range (23.16–24.36°C) and pH (8.27–8.49) were uniform across all sampled locations, suggesting a stable physicochemical corridor that permissively supports fish growth and development [25] . Nonetheless, a marked longitudinal heterogeneity was documented in DO, turbidity, and nutrient cargo, culminating in a demonstrable eutrophication gradient oriented from the Aswan Dam northerly zone to the Abou Simbel southerly sector. DO decreased gradient-wise from 7.84 mg.L^{-1} at Aswan to 6.93 mg.L^{-1} adjacent to Abou Simbel, a trajectory that, if persisting, could depress metabolic efficacy and undermine ecological suitability [26]. Simultaneously, turbidity levels elevated from 1.05 to 1.72 NTU, (TN) concentration escalated from 474.2 to 568.6 mg.L^{-1}, and (TP) grew from 13.5 to 23.0 mg.L^{-1}, patterns that reflect a typical eutrophication palette and that corroborate the sedimentary and organic matter accretion processes postulated for similar

aquatic basins [27,28].
The PCA-derived eutrophication index (PC1) consolidates evidence of a longitudinal trend. Smith et al. [27] and Davies-Colley & Smith [28] have described positive contributions of TN, TP, turbidity, and TSS, and a negative contribution of DO, as part of the eutrophication syndrome. For Aswan, the mean PC1 score is strongly negative; for Garf Hussian, it is close to zero; and for Abu Sembil, it is positive. This is consistent with the regional ordering in a north-south direction from more oligotrophic, oxygen-rich conditions to more nutrient-enriched, turbid, and Oxygen-poor waters [5,15] the effects of heavy metal pollution on three aquatic habitats in the Aswan Governorate of Egypt-Lake Nasser, Aswan Reservoir, and the River Nile-were evaluated for the Nile tilapia (*Oreochromis niloticus*). Despite the single reservoir setting, the multivariate analysis shows that the environmental domains occupied by the Nile perch are distinct.
Length–weight regressions exhibited pronounced negative allometric growth ($b<3$) across all sampled locations, with equivalent determination coefficients (R^2) exceeding 0.95, thereby confirming the presence of site-specific growth efficiency gradients likely mediating the influence of habitat quality and prey density, as corroborated by prior investigations [10,29,30]. The elevated K (1.17 ± 0.23) recorded at Abou Simbel, juxtaposed with persistently low DO and elevated turbidity, appears to represent an adaptive metabolic reconfiguration rather than a marker of overall fish vigor. This deviation has been associated with heightened energy sequestering in lipid depots or reserve organs, a physiological pathway frequently invoked in the context of chemical and trophic impairment in shallow aquatic systems. Analogous upregulation of body condition has been empirically noted in *Coptodon zillii* in similarly stressed stretches of the Nile [31]. The recorded depression of the invariant asymptotic length ($L\infty = 167.96$ cm) in concert with a restrained growth factor ($K = 0.08\ y^{-1}$) signals a decisive reallocation of metabolic capital. The current experimental factors suggest that the energy flux is consummated in survival-oriented reserves rather than lengthy somatic accretion. Such reallocation is consistent with the emerging literature detailing the plastic metabolic regimes of Nile perch and tilapia subjected to episodic hypoxia and eutrophication in lentic systems[1,6]however, there is a growing recognition of the degree of variation among individuals within a population, as well as the ecological consequences of this variation. Managing resources at an ecosystem level calls on practitioners to consider evolutionary processes, and ample evidence from the realm of fisheries science indicates that anthropogenic disturbance can drive changes in predominant character traits (e.g. size at maturity).
Moderate environmental conditions at Garf Hussain give the optimal range for growth of this species., indicated by intermediate DO (7.12±0.26 $mg.L^{-1}$) and nutrient concentrations (total Nitrogen: 524±4.3 $mg.L^{-1}$; total Phosphorus: 20.1±2.1 $mg.L^{-1}$), sustained the largest Nile perch recorded (maximum length 159.3 cm; maximum weight 40,000 g) and provided the highest estimated asymptotic length ($L\infty$=205.2 cm). Such factors reflect an equilibrium between energy absorbed through feeding and energy allocated to metabolism, a finding replicated in Nile River tributaries and in wider East African freshwater systems, where moderate productivity regimes appear to enhance growth.

In contrast, the Aswan site exhibited a relatively high growth rate (K = 0.095 y^{-1}) but a smaller asymptotic length (L∞ = 168.6 cm), suggesting faster growth toward a smaller maximum size. This dynamic growth may be linked to the unique environmental conditions at Aswan, which featured the highest DO concentration (7.84±0.64 $mg.L^{-1}$) and the lowest turbidity (1.05±0.1 NTU) among the studied locations. Enhanced somatic growth of Nile perch populations inhabiting relatively oligotrophic or less disturbed habitats (low-nutrient, well-oxygenated logistic regimes) has been noted [32].

These findings add to the accumulating body of evidence indicating that eutrophication-related nutrient loading can spur an apparent elevation in condition indices through the accrual of energy reserves, without proportionate growth responses, thereby jeopardizing long-term population viability [31]. To mitigate this paradox, fisheries management strategies must be predicated on the concurrent use of physiological markers (condition quotients) and refined growth modeling, coupled with systematic environmental surveillance, especially in the context of escalating anthropogenic and climate-driven stressors affecting freshwater systems across the African continent.

The analyses of correlation and regression suggest that the environmental factors affecting Nile perch performance are relatively limited and site-specific. At Aswan, Kc was positively correlated with DO and negatively correlated with TN. Regarding DO and TN, these two variables were the only significant predictors in simple linear models, consistent with the established role of oxygen and nutrient loading in fish energetics and growth [23,25,27,28]1976. At Garf Hussian and Abou Simbel, the growth and condition of fish (TL and TW) correlated positively and moderately with turbidity, TDS, and TP. However, none of the individual water-quality variables explained the variation in Kc. This reflects however, there is a growing recognition of the degree of variation among individuals within a population, as well as the ecological consequences of this variation. Managing resources at an ecosystem level calls on practitioners to consider evolutionary processes, and ample evidence from the realm of fisheries science indicates that anthropogenic disturbance can drive changes in predominant character traits (e.g. size at maturitythat the conditions of these sites result from a combination of environmental quality, food availability, population size and age structure, and fishing pressure rather than a single physico-chemical factor [6,24]. The PCA-based gradient clarifies this issue by suggesting that spatial growth limits along the eutrophication axes of (LN) are due to a multivariate pattern of water quality, more effectively captured when growth and condition metrics are integrated. PC1 corroborated the pronounced separation among upstream, intermediate, and downstream environments, while the VBGF factors and Kc reflected corresponding shifts in growth rate, asymptotic size, and body condition. The integrated approach of multivariate environmental indices and growth models to explain the impact of eutrophication and hypoxia on fish growth is endorsed in other systems[33,34].

This study contributes to the existing body of knowledge by showing that the impacts of eutrophication and nutrient enrichment on apparent high condition indices, driven by energy storage without associated increases in structural growth, negatively affect the long-term viability of populations [28,31]. Condition factor and water-quality factors for Nile perch in Lake Nasser reveal instrumental heterogeneity across the reservoir, highlighting the need for spatially and temporally adaptive management. Therefore, ecosystem-based fisheries management must, for the first time, systematically address longitudinal water quality, DO, and water-column-specific growth and condition metrics within the decision and management frameworks, as well as the monitoring frameworks. It is believed that an integrated approach to growth modeling, physiological factors, and adaptive management would facilitate the monitoring and management of the rapidly emerging impacts of eutrophication on growth and, in turn, support the ecological and economic sustainability of (LN) fisheries [14,15].

This study has some limitations; for instance, ecological variables such as prey availability and chlorophyll a were not recorded, and growth factors were extrapolated from length-frequency data without direct age validation. Also, the two-year biological and environmental dataset we have may not provide a clear long-term perspective on the data or on community-level dynamics in a large reservoir like Lake Nasser, where we know the hydrological regimes, nutrient loading, and fishing pressure vary over time.

Conclusion

This study demonstrates how the north-south spatial variability of water quality in (LN) presents a progressive gradient of eutrophication that correlates with site-specific von Bertalanffy growth model factors and the condition factor of Nile perch. Sites further downstream, which were more impacted, showed decreased growth performance and more poorly defined and variable condition-water quality relationships. These findings show that managing (LN) will require considering spatial structure and implementing adaptive, ecosystem-based fishery management that combines growth and condition (biotic) indicators with dissolved oxygen, nutrient, and turbidity (abiotic) indicators. The limitation of this study is that it integrates the social aspects and fishing methods that affect fish growth. Future research should incorporate social aspects and examine long-term variability to improve understanding of fish responses and support more effective management.

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Authors' Contributions

MAH Kassem designed the study, conducted the field sampling, performed the data analysis, and drafted the manuscript. **KY AbouelFadl** supervised the research, contributed to the study design, interpreted the results, and critically revised the manuscript. **R Kindong** assisted with data analysis and interpretation and reviewed the manuscript. **MMS Farrag** contributed to sampling and species identification and revised the manuscript. **AGM Osman** contributed to the study design, statistical interpretation, and final approval of the manuscript. All authors read and approved the final version of the manuscript.

Ethical Permission

Ethical approval: The Animal Use and Care Committee of the Faculty of Fish and Fisheries Technology at Aswan University in Egypt (FFT. No. 10/2025) approved the current study's standard operating procedure.

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Conflict of Interest

The authors state that there are no conflicts of interest with the publication of this work.

AI Use Declaration

The authors used AI tools for language editing. The authors have reviewed and edited the output and take full responsibility for the publication's content.

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