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Variability in cephalic morphometric and meristic characters of *Oreochromis niloticus* (Linnaeus, 1758) from three watercourses in Bunia (Ituri, D.R. Congo) and potential impact of some water abiotic factors

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ABSTRACT

In fishes, some structures are of particular interest and can be influenced by some environmental factors. This study assessed the variability of cephalic morphometric and meristic parameters of *Oreochromis niloticus* in three rivers of Bunia (D.R. Congo) and the influence of some abiotic factors. A total of 780 specimens were sampled across nine stations. Eight morphometric and three branchial meristic characters of fishes were measured and their average values calculated. The head length varied from 2.94 to 3.75cm, head width from 1.24 to 2.33cm, pre-narial distance from 0.43 to 1.07cm, inter-narial distance from 0.49 to 1.08cm, snout length from 0.86 to 1.67cm, eye diameter from 0.82 to 1.10cm, interorbital distance from 0.83 to 1.46cm and post-orbital length from 1.33 to 194cm. The number of upper and lower gill rakers respectively, varied from 3.06 to 4.18 and from 19.41 to 23.69. Significant inter-river variations has been noted with some morphometric and meristic parameters (p<0.001). Water temperature ranged from 23.43 to 25.08 °C, concentrations of suspended solids from 193 to 461 mg/L, water turbidity from 3.10 to 23.56 NTU, pH values from 6.69 to 7.24, dissolved oxygen concentrations from 6.69 mg/L to 8.01 mg/L and the electrical conductivity ranged from 95.16 µS/cm to 210.87 µS/cm. Most cephalic morphometric were significantly correlated with the water turbidity, suspended solids and dissolved oxygen concentrations (p<0.001). Meristic parameters showed no significant relationships with physico-chemical parameters, confirming their stability. Phenotypic plasticity would constitute the primary mechanism of adjustment of *O. niloticus* populations to local environmental constraints.

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INTRODUCTION

Fish represent the most diverse group of vertebrates in aquatic environments, with over 36,000 described species. Among them, the Cichlidae constitute one of the most remarkable families due to their exceptional taxonomic, ecological and evolutionary diversity. This family is recognised as a major biological model for the study of mechanisms of adaptive radiation, speciation and phenotypic plasticity in aquatic vertebrates (Muschick *et al.*, 2018; Vranken *et al.*, 2019).

Tropical Africa is one of the world's main centres of diversification for the Cichlidae. The Congo, Nile and African Great Lakes catchment areas are home to an exceptional wealth of species, characterized by high levels of endemism and great ecological diversity (Lévêque and Paugy, 2006; Snoeks and Vreven, 2018; Decru *et al.*, 2020). The Congo Basin, the world's second-largest river basin, represents one of the planet's most significant reservoirs of aquatic biodiversity. Cichlidae inhabit a wide variety of habitats there, ranging from large lakes to forest rivers, where they play a vital role in the functioning of food webs and in ensuring food security for riparian communities (Lévêque and Paugy, 2006; Vranken *et al.*, 2019).

Despite the considerable progress achieved through the pioneering work indicated above and many other researchers, a significant proportion of the ichthyological diversity of the Congo Basin remains insufficiently documented, particularly in secondary watercourses and medium-sized tributaries. This knowledge gap limits our understanding of species distribution patterns, population structure, and the adaptive mechanisms that shape their phenotypic variability.

The study of this variability relies heavily on the analysis of morphometric and meristic characters, which are fundamental tools in the taxonomy, systematics and evolutionary biology of fish. Morphometric characters quantify variations in form and anatomical proportions, meanwhile meristic characters provide information on the number of structures such as fin rays, scales or gill spines (Helfman *et al.*, 2009; Kwikiriza *et al.*, 2023; Bitner and Smolina, 2026). These approaches, which complement molecular methods, are widely used to distinguish between populations, detect local adaptations and assess phenotypic responses to environmental constraints (Bitjanyom *et al.*, 2012; Yoboue *et al.*, 2019).

In the Cichlidae, cephalic structures are of particular interest due to their high taxonomic, functional and ecological significance. The dimensions of the head, jaws, snout and sensory organs are closely associated with feeding strategies, ecological niche occupation and the adaptive processes that have accompanied the diversification of this group (Albertson and Kocher, 2006; Muschick *et al.,* 2018; Santos *et al.*, 2023). Cephalic morphology thus serves as an excellent indicator of the interactions between the genetic makeup of populations and environmental constraints.

Numerous studies have shown that the morphological variations observed within and between fish populations result from a complex interaction between genetic factors, environmental conditions and biogeographical history (Ndiwa *et al.*, 2016; Salzburger, 2018; Meier *et al.*, 2022). The physico-chemical and hydrological characteristics of the environment can significantly influence the development and expression of morphological traits (Van Steenberge *et al.*, 2015; Yoboue *et al.*, 2019; Kwikiriza *et al.*, 2023). Thus, in environments with strong currents, fish often develop more hydrodynamic shapes, whilst variations in turbidity, depth or food availability alter the size of sensory and feeding structures (Albertson and Kocher, 2006; Schneider and Meyer, 2017).

This morphology-environment relationship has been documented in several African regions. In West Africa, Omoniyi and Agbon (2008) observed morphometric variations in *Sarotherodon melanotheron* associated with salinity gradients. Ibor *et al.* (2017) highlighted marked sexual dimorphism in *Hemichromis fasciatus*, whilst Olanrewaju *et al.*

(2026) demonstrated that several cephalic characters effectively distinguish Cichlidae from the Ogun River (Nigeria). In East Africa, the pioneering work of Liem (1974), followed by that of Albertson and Kocher (2006), demonstrated that the diversification of craniofacial structures is closely linked to the occupation of distinct trophic niches among the Cichlidae of the Great Lakes.

In the Congo Basin and the Lower Guinea region, several taxonomic studies have also highlighted the diagnostic importance of cephalic characters. Lamboj (2005) just as Stiassny and Schliewen (2007) used morphometric head characters to describe *Nanochromis sabinae* and *Congochromis pugnatus*, respectively. Lamboj and Snoeks (2000) indicated that some cephalic proportions effectively distinguish *Divandu albimarginatus*, whilst Tougas and Stiassny (2014) emphasised the importance of cephalic length in the diagnosis of *Lamprologus markerti*. These studies confirm the value of cephalic morphometric and meristic characters in taxonomic, ecological and evolutionary studies of African cichlids.

In the eastern part of the Congo Basin, a few studies already suggest significant morphological variability among Cichlidae. Decru *et al.* (2017), whilst studying populations of the genus *Haplochromis* from the Ituri River, highlighted significant differences in snout length, premaxillary pedicle length and eye diameter compared with populations from the Edouard-George hydrological system (lakes located between the DR Congo and Uganda).

These authors interpreted these differences as adaptations to riverine habitats, but their study did not assess the direct influence of the environment's physico-chemical parameters on this variability.

The Ituri Province, situated in the east of the Democratic Republic of the Congo, has a dense and diverse river network forming part of the Congo Basin. This region constitutes a major ecological and biogeographical transition zone, home to a particularly rich fish fauna.

However, its aquatic ecosystems are under increasing pressure from urbanization, agriculture, mining, deforestation and hydrological changes (Depecker *et al.*, 2022; WWF, 2022). The rivers of the Bunia region (Nyamukau, Ngezi and Shari) exhibit significant seasonal variations in physico-chemical parameters that are likely to influence the morphology of fish populations (Kisezo *et al.*, 2019).

Despite the ecological, economic and fisheries importance of Cichlidae in this region, knowledge of the variability in their cephalic morphometric and meristic characters remains very limited. The available studies are essentially limited to faunal inventories or isolated taxonomic descriptions, without an integrated analysis of the relationships between morphological variability and abiotic factors. Less data are available about variability in the cephalic morphometric and meristic characters of *Oreochromis niloticus* from the Nyamukau, Ngezi and Shari rivers. Less is also known about the potential influence of water physicochemical characteristics on these fish's parameters. The overall objective of this study is to determine the variability in the cephalic morphometric and meristic characteristics *of Oreochromis niloticus* in three rivers in Bunia region and to assess the influence of some abiotic factors on this variability.

MATERIALS AND METHODS

Study area

The study was carried monthly from October 2024 and March 2025 in Bunia town, the capital of Ituri Province, situated in the north-east of the Democratic Republic of the Congo.

This ecological transition zone between the East African highlands and the lowlands of the Congo Basin is home to remarkable aquatic and terrestrial biodiversity (Depecker *et al.*, 2022).

According to the Köppen-Geiger classification, the region has a humid tropical highland climate (type Aw/Am) with equatorial influence, moderated by altitude (Peel *et al.*, 2007).

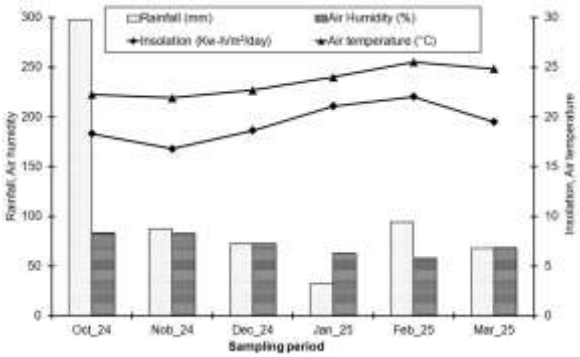

Fig. 1. Meteorological factors (rainfall, air temperature, insolation and air humidity) at Bunia during the sampling period

The average annual temperature ranges between 22 and 25 °C, with maximum temperatures of around 29 °C. Annual rainfall, ranging from 1100 to 1500 mm, follows a bimodal pattern (Mposo Nsangua *et al.*, 2025). Meteorological data at Bunia during the studying period are presented in Fig. 1.

During the study period (October 2024 to March 2025), the Bunia region experienced marked seasonal variation in meteorological conditions, Solar radiation ranged from 16.78 to 22.02 Kw-h/m²/day, with the highest values recorded between January and February 2025. Monthly rainfall varied from 32.20 to 297.80 mm, reaching a maximum in October 2024 and a minimum in January 2025. Mean air temperature remained relatively stable (21.92–25.51 °C), while relative humidity ranged from 58.10 to 83/38%, with the highest values recorded in October-November. These data indicate a gradual transition from a humid period to a relatively drier period during the study.

The Bunia river system forms part of the Ituri-Aruwimi sub-basin within the Congo River basin (Lévêque and Paugy, 2006; Snoeks and Vreven, 2018; Decru *et al.*, 2020). The Nyamukau, Ngezi and Shari rivers, selected for this study, are small to medium-sized perennial watercourses with riverbeds dominated by sand, silt and clay. The rapid population growth in Bunia, combined with urbanisation, agriculture, artisanal mining and deforestation, exerts increasing pressure on these aquatic ecosystems (Kisezo *et al.*, 2019; WWF, 2022).

The selection of the Nyamukau, Ngezi and Shari rivers is based on (i) their ecological importance and their representativeness of the local river network, (ii) the potential presence *of Oreochromis niloticus*, (iii) contrasting environmental conditions likely to influence morphological variability, and (iv) the lack of detailed data on their fish communities.

Description of sampling stations

The locations of the sampling stations are shown in Fig. 2. Sampling campaigns were carried out in three watercourses in the Bunia region, each comprising three stations selected to cover the different hydrographic sectors. The geographical coordinates of the georeferenced sites are presented in Table 1.

Fig. 2. Geospatial analysis of urban and peri-urban sampling stations in Bunia (Ituri, DR Congo) (From Kalombo Kamutanda, 2025, modified)

Hydromorphometric parameters at sampling stations and physicochemical parameters of water samples

The hydromorphometric parameters assessed were the width of the watercourse bed and its depth. The physico-

chemical parameters of the water included temperature, dissolved oxygen, pH, electrical conductivity, turbidity and suspended solids. Temperature, dissolved oxygen, pH and electrical conductivity were measured *in situ* using a pre-calibrated DO700 Meter multi-parameter analyser, whilst turbidity and suspended solids were determined in the laboratory from water samples collected at each site.

Table 1. Geographical coordinates of the sampling stations

Watercourse	Stations	Latitude (°N)	Longitude (°E)	Altitude (m)
Nyamukau	Nyam I	1° 31' 35.88"	30° 18' 17.36"	1413.03
	Nyam II	1° 32' 59.63"	30° 15' 13.01"	1257.82
	Nyam III	1° 34' 37.12"	30° 15' 02.12"	1244.09
Ngezi	Ngezi I	1° 34' 51.03"	30° 15' 18.05"	1242.50
	Ngezi II	1° 33' 53.41"	30° 14' 22.13"	1227.20
	Ngezi III	1° 35' 03.85"	30° 13' 06.24"	1197.04
Shari	Shari I	1° 34' 07.80"	30° 11' 17.19"	1143.82
	Shari II	1° 34' 08.55"	30° 11' 17.74"	1153.28
	Shari III	1° 34' 09.29"	30° 11' 18.29"	1162.73

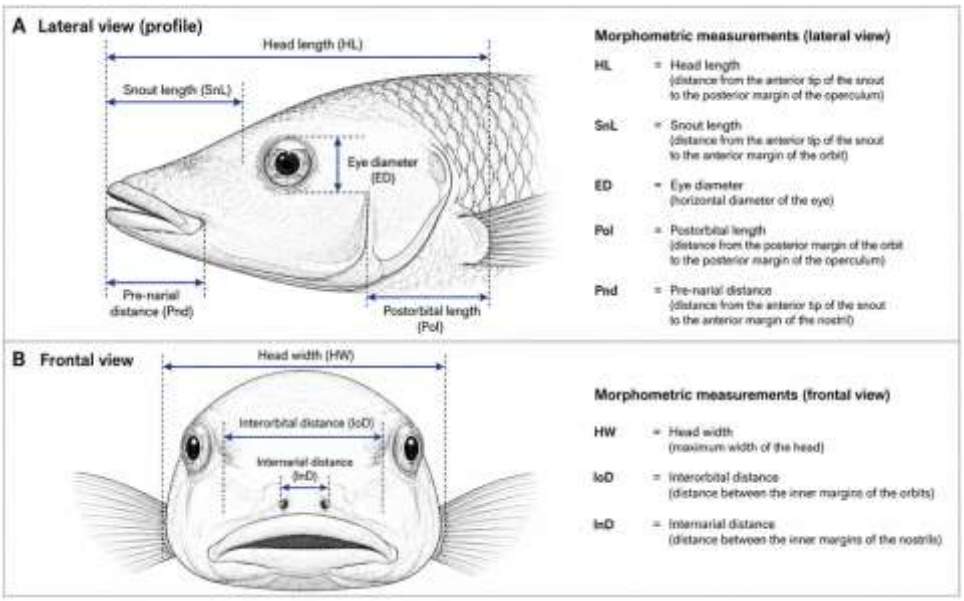

Fig. 3. Main cephalic morphometric views in fish (left-side profile and frontal view) (Bitjanyom *et al.*, 2012; Chukwuka *et al.*, 2019; Kwikiriza *et al.*, 2023)

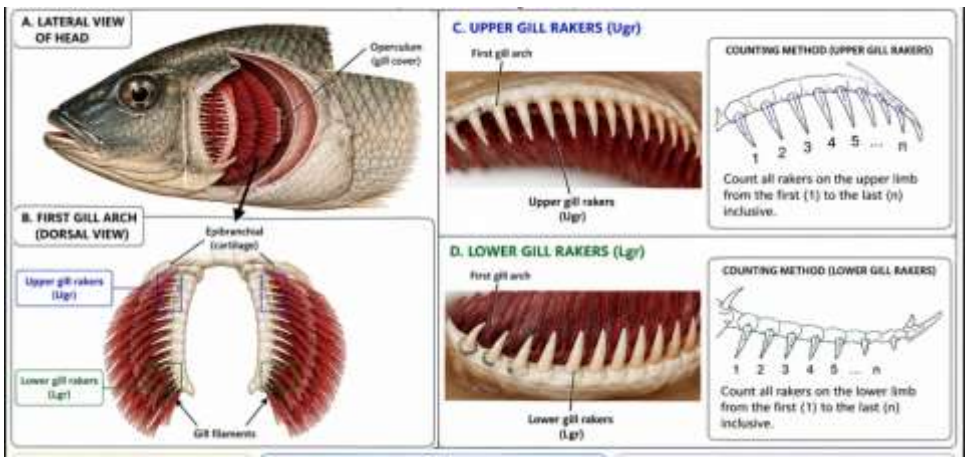

Fig. 4. Upper, lower and total number of gill rakers for meristic counts (Lévêque and Paugy, 2006; Helfman *et al.*, 2009)

Ichthyological sampling

Fish sampling was carried out between October 2024 and March 2025 using multifilament gillnets of various mesh sizes (3; 3.5; 4; 5; 6; 7 and 8 cm), enabling the capture of individuals belonging to different size classes. The sampling protocol was standardised across all stations, with one fishing operation per week at each station. After capture, the specimens were fixed in a 5 per cent formalin solution, then rinsed, labelled and stored under refrigeration until their transfer to the laboratory for morphometric and meristic analyses.

Determination of cephalic morphometric parameters of fish

Taxonomic identification of the specimens was carried out on the basis of the morphological, morphometric and meristic characters described in the reference works (Lévêque and Paugy, 2006; Snoeks and Vreven, 2018). Morphometric measurements were taken on the left side of each specimen using a digital calliper (accuracy 0.1 mm). Eight cephalic variables were recorded: head length, head width, pre-narial distance, inter-narial distance, snout length, eye diameter, interorbital distance and post-orbital length (Fig. 3).

Determination of cephalic meristic parameters in fish

Two cephalic meristic characters were counted: the number of gill rakers in the upper branch and the lower branch of the first gill arch. The total number of gill rakers was obtained by adding the numbers from both branches (Fig. 4).

Data analysis

Cephalic morphometric characters were compared between the different sampling sites using analysis of variance (ANOVA), whilst cephalic meristic characters were analyzed using the Kruskal-Wallis test. In addition, Pearson's correlation coefficients were calculated to assess the potential relationships between the measured physico-chemical parameters of the water and the cephalic morphometric and meristic variables.

RESULTS

Hydromorphometric parameters of the sampling stations

Overall, the Shari river has the largest dimensions, with a maximum width of 45 m and a depth of up to 10 m. In contrast, the Nyamukau is the narrowest and shallowest watercourse, with a width ranging from 10 to 25 m and a maximum depth of 6 m (Table 2). The Ngezi has intermediate characteristics, with a width ranging from 12 to 22 m and a depth ranging from 1 to 4 m (Table 2).

Physico-chemical parameters of water samples

The mean values of the physico-chemical parameters showed variability between sampling stations. Water temperature ranged from 23.43 °C (Shari III) to 25.08 °C (Ngezi I).

Average concentrations of suspended solids ranged from 193 mg/L (Ngezi I) to 461 mg/L (Nyamukau I), whilst turbidity ranged from 3.10 NTU (Nyamukau I) to 23.56 NTU (Shari III). Average pH values ranged from 6.69 (Ngezi II) to 7.24 (Shari II). Dissolved oxygen concentrations varied from 6.69 mg/L (Shari III) to 8.01 mg/L (Nyamukau III), whilst electrical conductivity ranged from 95.16 µS/cm (Nyamukau I) to 210.87 µS/cm (Nyamukau III) (Fig. 5).

Cephalic morphometric parameters of fish

The mean values (± standard deviation) of the eight cephalic morphometric parameters have been measured at the nine sampling stations along the three watercourses studied. Overall, the mean values vary between the watercourses (Fig. 6). The Ngezi stations generally show the highest values for most parameters, whilst those at Shari record the lowest, with the exception of eye diameter, for which the values remain relatively similar across the sites. The Nyamukau stations generally show intermediate values.

At the level of each watercourse, differences between stations remain small. Values are relatively stable at Nyamukau, decrease slightly from Station I to Station III at Ngezi, and relatively increase gradually from Station I to Station III at Shari for most parameters.

Table 2. Hydromorphometric characteristics of the sampling stations

Watercourse	Stations	Average width (m)	Average depth (m)
Nyamukau	Nyam I	15-25	2-6
	Nyam II	12-18	1-3
	Nyam III	10-15	1-3
Ngezi	Ngezi I	12-20	1-4
	Ngezi II	14-20	1-3
	Ngezi III	16-22	1-4
Shari	Shari I	20-30	2-8
	Shari II	20-40	2-8
	Shari III	25-45	2-10

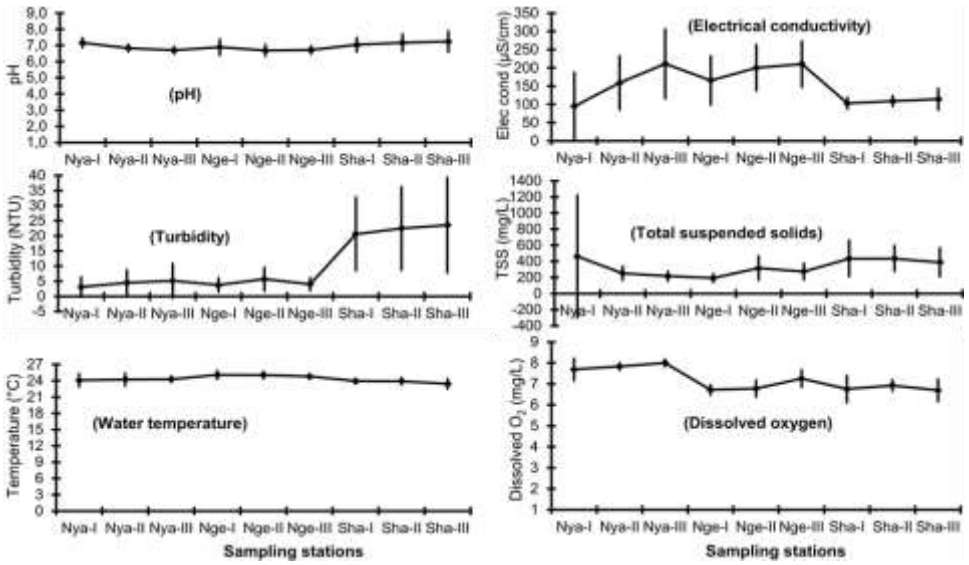

Fig. 5. Mean values of water pH, electrical conductivity, turbidity, total suspended solids, temperature and dissolved oxygen in each water station during the sampling period

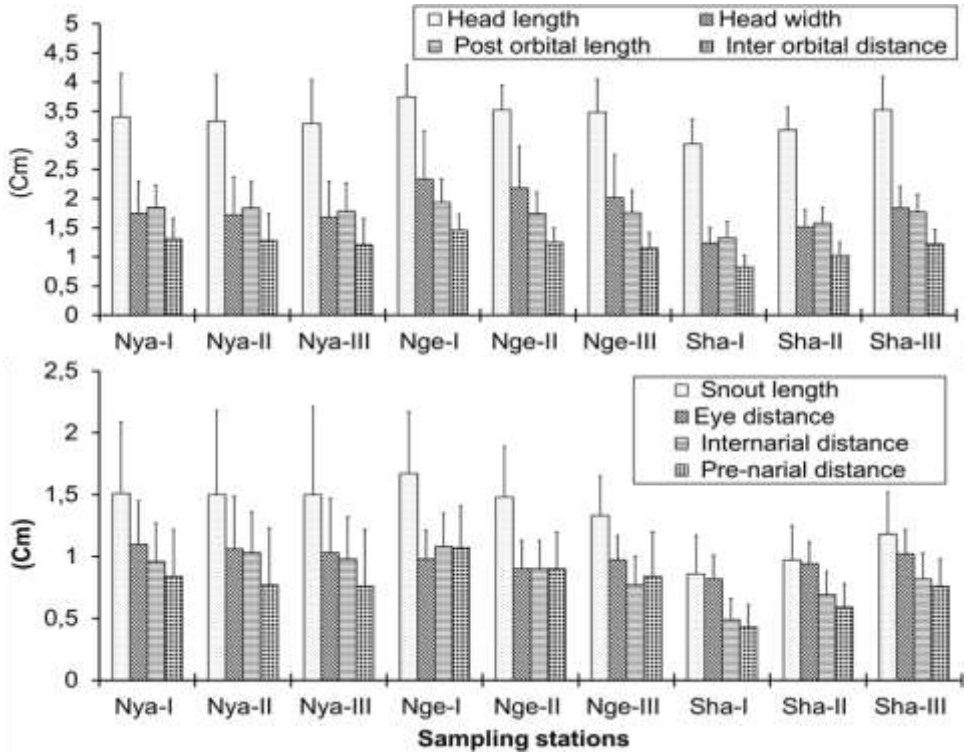

Fig. 6. Mean values of cephalic morphometric parameters of fishes at each sampling station

Standard deviations are generally higher at Nyamukau and Ngezi than at Shari. Among the characteristics studied, head width and snout length showed relative variations between watercourses, whilst eye diameter appears to be relatively the most stable characteristic.

Cephalic meristic parameters of fish

The mean values (± standard deviation) of the cephalic meristic parameters have been measured at the nine sampling stations on the three watercourses studied. Overall, the values of the meristic parameters vary between watercourses. The Nyamukau stations have the highest values for the number of lower gill rakers and the total number of gill rakers, while those at Ngezi have the lowest values for these two parameters, but the highest for upper gill rakers. The Shari stations occupy an intermediate position for lower gill rakers and total number of gill rakers and have the lowest upper gill rakers values (Fig. 7).

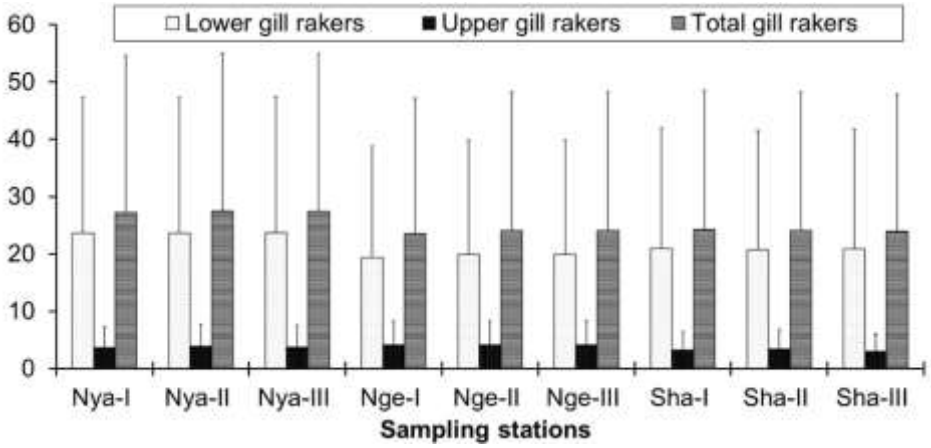

Fig. 7. Mean values of cephalic meristic parameters of fishes at each sampling station

Table 3. Comparison of cephalic morphometric parameters of fish between sampling stations for each watercourse

Fish parameters	Nyamukau		Ngezi		Shari	
	CV(%)	*p*-value	CV (%)	*p*-value	CV (%)	*p*-value
Head length	28.2	0.644	14.71	0.0014	16.8	< 0.001
Snout length	34.2	0.991	29.36	< 0.001	31.4	0.004
Head width	35.3	0.707	35.34	0.0291	22.7	< 0.001
Eye diameter	34.5	0.589	23.45	0.0282	21.5	0.008
Post-orbital length	27.4	0.495	21.47	0.0009	18.9	< 0.001
Interorb. distance	36.2	0.263	22.71	< 0.001	24.8	< 0.001
Inter-nar. distance	32.3	0.305	29.85	< 0.001	34.6	< 0.001
Pre-narial distance	32.6	0.41	37.18	< 0.001	36.9	< 0.001

Interorb. distance: Interorbital distance ; Inter-nar. distance: Inter-narial distance

At the level of each watercourse, variations between stations remain small. The values are relatively stable at Nyamukau, increasing slightly from station I to station III at Ngezi for lower gill rakers and total number of gill rakers, while upper gill rakers remains virtually constant. At Shari, lower gill rakers varies little between stations, while upper gill rakers and total number of gill rakers show a slight decrease from station I to station III (Fig. 7).

Standard deviations are relatively lower at Nyamukau than at Ngezi and Shari for lower gill rakers and total number of gill rakers, while those for upper gill rakers remain relatively low across all stations.

Comparison of cephalic morphometric parameters of fishes amongst sampling sites of each the watercourses

Table 3 presents, for each of the three watercourses, the coefficients of variation (CV) from the analysis of

variance (ANOVA) and the associated probabilities (P) for the eight cephalic morphometric parameters, in order to assess the differences between the sampling stations. At Nyamukau, no significant differences were observed between the stations for any of the parameters studied (p>0.05). The coefficients of variation ranged from 27.4 to 36.2 per cent, indicating comparable variability between the stations (Table 3). At Ngezi, significant differences were recorded for all parameters (p<0.05), most of which were highly significant (p<0.001). The coefficients of variation range from 14.71 to 37.18%, and the highest value relate to the Pre-narial distance (Table 3). Similarly, at Shari, all parameters showed significant differences between sites (p<0.01), with coefficients of variation ranging from 16.8 to 36.9% (Table 3).

Overall, the analyses show no significant differences between the Nyamukau sampling sites, in contrast to those at Ngezi and Shari, where significant differences are obvious for all cephalic morphometric parameters.

Comparison of cephalic meristic parameters of fish amongst sampling stations and amongst the three watercourses

Table 4 presents, for each of the three watercourses, the coefficients of variation (CV), the H values from the Kruskal-Wallis test and the associated probabilities (P) for the three cephalic meristic parameters, in order to assess the differences between sampling stations. No significant differences has been noted between sampling stations within the same watercourse for all the parameters studied (p>0.05). However, a comparison between the three watercourses reveals highly significant differences for each of the meristic characters (p<0.001) (Table 4).

The results obtained are broadly consistent with those of the analyses of variance (ANOVA). Both tests show no significant variation between sampling sites for Lower gill rakers and Total gill rakers. Regarding Upper gill rakers, the ANOVA highlights a significant difference in the Shari watercourse (p= 0.0436), while the Kruskal-Wallis test indicated no significant difference (p= 0.0773) (Table 4).

Table 4. Comparison of cephalic meristic parameters of fishes between sampling stations for each river

Parameter	Nyamukau		Ngezi		Shari	
	CV(%)	p-value	CV(%)	p-value	CV(%)	p-value
Lower gill rakers	8.97	0.932	19.27	0.726	21.46	0.887
Upper gill rakers	31.9	0.600	31.7	0.995	26.9	0.077
Total gill rakers	11.8	0.970	21.3	0.823	20.4	0.937

Table 5. Comparison of cephalic meristic parameters of fishes across the 3 considered rivers

Parameter	Across Nyamukau # Ngezi # Shari	
	H	p-value
Lower gill rakers	113.31	< 0.001
Upper gill rakers	80.88	< 0.001
Total gill	110.94	< 0.001

Table 5 presents the comparison of branchial meristic traits among *Oreochromis niloticus* populations from the Nyamukau, Ngezi, and Shari rivers. Highly significant differences were detected for all variables examined. The number of lower gill rakers showed the highest H value (p<0.001), followed by the total number of gill rakers (p<0.001) and the number of upper gill rakers (p<0.001). Significant differences among the three river populations for each branchial meristic trait analyzed (Table 5).

Correlations between physico-chemical parameters of water, meteorological factors, and the cephalic morphometric and meristic parameters of fishes

Pearson correlation coefficients between the morphometric/meristic head characteristics of the fish and the physico-chemical parameters of the water on one hand, and between these morphometric/meristic head characteristics and the meteorological factors on the other hand, have been

calculated. It can be noted that temperature is weakly and positively correlated with several morphometric characteristics, notably head length, snout length, eye diameter, interorbital distance and pre-narial distance (Table 6). Turbidity shows the strongest positive correlations with the majority of morphometric characteristics, particularly head length, head width, snout length, eye diameter, Pre-narial distance and the interorbital distance (p<0.001), while post-orbital length is weakly and negatively correlated with this parameter. Suspended solids also showed significant positive correlations with several morphometric traits (p< 0.05) (Table 6).

Table 6. Correlation coefficient values between the cephalic morphometric/meristic parameters of fishes and the water physicochemical parameters/meteorological factors across the 9 river sampling stations

Morphometric and meristic parameters	Water physico-chemical parameters						Meteorological factors			
	Temp	Turb	SS	pH	E. cond.	DO	Rainfall	Air H.	Air T.	Insol.
Head length	0.12*	0.28**	0.18**	0.08	-0.04	-0.15*	-0.97*	-0.88	0.92	0.89
Snout length	0.14*	0.22**	0.15*	0.10	-0.02	-0.12*	-0.88	-0.73	0.79	0.75
Head width	0.11	0.25**	0.17**	0.07	-0.03	-0.14*	-0.99**	-0.91	0.95*	0.92
Eye diameter	0.18**	0.20**	0.13*	0.11	-0.07	-0.17**	-0.98*	-0.93*	0.96*	0.94*
P. orb. length	-0.06	-0.13*	-0.09	-0.05	0.03	0.07	-0.96*	-0.87	0.91	0.88
Interorb. dist.	0.13*	0.19**	0.14*	0.09	-0.05	-0.13*	-0.97*	-0.90	0.94*	0.91
Inter-nar. dist.	0.10	0.17**	0.12*	0.07	-0.04	-0.10	-0.94*	-0.85	0.89	0.86
Pre-narial dist.	0.15*	0.21**	0.16**	0.10	-0.03	-0.13*	-0.97*	-0.89	0.93*	0.90
Lower g. rakers	0.09	0.05	0.03	0.04	-0.02	-0.01	-0.92	-0.83	0.87	0.84
Upper g. rakers	0.11	0.04	0.02	0.06	-0.01	0.02	-0.98*	-0.93*	0.96*	0.94*
Total gill rakers	0.10	0.05	0.03	0.05	-0.02	-0.01	-0.90	-0.81	0.85	0.82

P. orb. length: Post-orbital length; Interorb. dist.: Interorbital distance; Inter-nar. dist.: Inter-narial distance; Pre-narial dist.: Pre-narial distance; Lower g. rakers: Lower gill rakers; Upper g. rakers: Upper gill rakers; Temp: temperature; Tub.: turbidity ; SS: suspended solids ; DO dissolved oxygen ; E. Cond.: electrical conductivity; Air H. : air humidity ; Air T.: air temperature ; Insol. : insolation.

Conversely, dissolved oxygen is significantly and negatively correlated with several morphometric characteristics, notably head length, snout length, head width, eye diameter, interorbital distance and Pre-narial distance (p< 0.05). However, no significant correlation was observed between pH or electrical conductivity and the traits studied (>0.05) (Table 6).

With regard to meristic characters, no significant correlation was found with the physico-chemical parameters analysed (p>0.05) (Table 6). Regarding meteorological factors, rainfall and relative humidity were strongly and negatively correlated with all morphometric variables (p<0.05), whereas air temperature and solar radiation showed strong positive correlations (p<0.05). Meristic parameters were significantly associated with meteorological factors, particularly the number of upper gill rakers (p<0.05). Overall, meteorological factors showed stronger correlations with both morphometric and meristic parameters than the water physicochemical parameters.

DISCUSSION

Variability in fish cephalic morphometric parameters

The results reveal a marked inter-population differentiation in cephalic morphometric characters in *Oreochromis niloticus*, in contrast to meristic characters, which remain relatively conserved. This distinction reflects a differential response of phenotypic traits to environmental conditions and is consistent with the concept of craniofacial modularity described in Cichlidae (Albertson and Kocher, 2006; Conith and Albertson, 2021).

Meanwhile meristic characters are strongly controlled by genetic and developmental mechanisms (Zogbaum *et al.*, 2021), morphometric characters exhibit greater plasticity, particularly in trophic and sensory structures such as the snout, buccal dimensions, eye diameter, and interorbital and pre-narial distances, which are known for their sensitivity to variations in food resources and environmental conditions (Zogbaum *et al.*, 2021).

Conversely, structures providing mechanical support to the head remain more conservative due to the biomechanical constraints governing them (Burress *et al.*, 2020; Popoola and Ebiwonjumi, 2021).

The differences observed among the three rivers illustrate this phenotypic plasticity.

Populations from Nyamukau, inhabiting a relatively stable environment, exhibit low morphometric variability, whereas those from Shari, subjected to high turbidity, elevated suspended solids concentrations and low oxygenation, show the most pronounced cephalic modifications. Populations from Ngezi occupy an intermediate position, reflecting a gradual response to environmental constraints. These observations are consistent with the work of Van Steenberge *et al.* (2015) and Ndiwa *et al.* (2016), according to which morphological differentiation in Cichlidae is primarily determined by the ecological conditions of their habitats. They also confirm that the most constraining environments promote greater morphological plasticity, whereas stable environments maintain a relatively conservative phenotype (Decru *et al.,* 2017; Tiarks *et al.*, 2024). Overall, these findings support the model of Salzburger (2018) and Muschick *et al.* (2018), according to which phenotypic plasticity constitutes an essential mechanism of adaptation of Cichlidae to local environmental gradients.

Variability in fish cephalic meristic parameters

In contrast to morphometric characters, cephalic meristic characters, particularly the number of gill rakers, exhibit more limited variability, although significant differences were observed among populations from the three rivers. This relative stability confirms the conservative nature of meristic traits in Cichlidae, whose expression is largely determined by genetic and developmental mechanisms (Decru *et al.,* 2017; Zogbaum *et al.*, 2021). Gill rakers thus appear to respond to strong functional and biomechanical constraints, limiting their variability despite the environmental differences encountered by *Oreochromis niloticus* populations. This trend is consistent with the observations of Popoola and Ebiwonjumi (2021), who reported low variability in meristic characters across different tilapia populations.

Although occasional correlations have been identified between gill raker number and certain physico-chemical parameters, notably conductivity in the Nyamukau River, these relationships remain weak and localised. They suggest a limited influence of ionic conditions on the development of the branchial apparatus, as previously proposed by Ndiwa *et al.* (2016), without however challenging the overall conservative nature of these structures.

Thus, despite some sensitivity to local conditions, meristic characters retain a strong taxonomic and phylogenetic value, confirming their utility for species discrimination and evolutionary studies in Cichlidae (Snoeks and Vreven, 2018; Vranken *et al.*, 2019; Decru *et al.*, 2020).

Potential impact of abiotic water factors on fishes parameters variability

Turbidity emerges as the primary factor explaining the cephalic morphometric variability observed in *Oreochromis niloticus*. The positive correlations obtained with the majority of cephalic characters indicate that increasing turbidity is accompanied by modifications in sensory and trophic structures of the head. By reducing water transparency, turbidity limits visual capacities, alters the availability of food resources, and promotes morphological adjustments likely to enhance environmental perception, prey capture and respiratory exchange (Burress *et al.*, 2020; Tiarks *et al.,* 2024; Ekpo *et al.,* 2025). This interpretation is supported by the populations of the Shari river, which simultaneously exhibit the highest turbidity levels and the largest cephalic dimensions.
Suspended solids reinforce the effects of turbidity by acting simultaneously on branchial function, trophic resource availability and reduced visibility (Septya *et al.*, 2025). In the Shari river, their association with high turbidity and low dissolved oxygen content

creates a set of environmental constraints favouring more pronounced morphological plasticity, as also reported by Hess *et al.* (2017), Decru *et al.* (2017) and Ronco *et al.* (2021). Suspended solids thus appear as a complementary factor amplifying the morphological responses induced by environmental conditions.

Negative correlations between dissolved oxygen and certain cephalic characters suggest that populations inhabiting less oxygenated environments develop relatively larger cephalic dimensions in order to improve their respiratory capacities (Binning *et al.,* 2010a; Tran-Ngoc *et al.*, 2016). However, the hydrodynamic constraints associated with a larger head probably limit the extent of these modifications. Dissolved oxygen therefore acts primarily as a modulating factor, in interaction with turbidity and suspended solids (Binning *et al.,* 2010b; Ndiwa *et al.*, 2016).

Compared with the aforementioned factors, temperature, pH and electrical conductivity exert a more limited influence on morphometric variability. Temperature appears to intervene indirectly on cephalic growth through its effects on metabolism, while conductivity is only associated with a few local correlations with gill rakers (Ndiwa *et al.*, 2016). The absence of a significant effect of pH is probably explained by the narrow range of its variations, which remain within the ecological tolerance limits of the species.

Overall, this study showed a hierarchy in the influence of abiotic factors, dominated by turbidity, followed by suspended solids, dissolved oxygen and temperature, whereas pH and conductivity play a secondary role. This organisation is consistent with the concept of craniofacial modularity in Cichlidae (Albertson and Kocher, 2006; Conith and Albertson, 2021) and confirms that phenotypic plasticity constitutes the primary mechanism of morphological differentiation among the studied populations (Ghalambor *et al.*, 2007; Muschick *et al.*, 2018). In the longer term, these adjustments could represent the initial steps of an evolutionary divergence (Schneider and Meyer, 2017; Salzburger, 2018), underscoring the importance of preserving environmental gradients to maintain the adaptive potential of natural *O. niloticus* populations (Snoeks and Vreven, 2018; DeLorenzo *et al.*, 2022; WWF, 2022).

CONCLUSION

This study reveals significant cephalic morphometric differentiation among populations of *Oreochromis niloticus* from the Bunia region, reflecting marked phenotypic plasticity in trophic and sensory structures, particularly snout length and narinal distances. These morphological adjustments, consistent with the craniofacial modularity model, contrast sharply with the stability of meristic characters, thereby confirming the reliability of the latter as taxonomic markers for specific discrimination in Cichlidae. The analysis highlights that turbidity, suspended solids and dissolved oxygen constitute the primary drivers of this morphological divergence, whereas temperature, pH and electrical conductivity exert only a secondary influence. By demonstrating that phenotypic plasticity constitutes the preferred adaptive mechanism of the species in response to local environmental gradients, this work underscores the critical importance of preserving the diversity of aquatic habitats in the Bunia region in order to safeguard the adaptive potential of natural *O. niloticus* populations in the face of increasing anthropogenic pressures.

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