Modeling the linear growth of *Paretroplus dambabe* in the Makary zone of Lake Kinkony (Mitsinjo district, Madagascar)

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ABSTRACT

In this article, the growth parameters (asymptotic length **L_∞**, growth coefficient **K**, theoretical age **t_o**) of the *Paretroplus dambabe* fish, an endemic species of the Mahavavy Kinkony Complex in Mahajanga traditionally fished in the Makary area river, were studied. These parameters were determined from size frequencies using LFDA (Length Frequency Data Analysis V 5.0© 2001) software. The estimated values of **$L\infty$**, **K**, and **t_0** found for our species were then substituted into the Von Bertalanffy growth equation in order to plot the growth curve. The linear growth performance index **Φ** was calculated according to the equation of Pauly and Munro (1984). The results obtained show that the growth parameters of female and male *P. dambabe* fish in the Makary area are very similar and the growth curves have exactly the same profile. The asymptotic length **$L\infty$=26.19 cm**, established separately for males and females, overlap, indicating that there is no difference in growth between the sexes. The growth coefficient (K) differs slightly: females (**K=0.93 year^{-1}**) reach adult size faster than males (**K=0.83 year^{-1}**), probably due to adaptive strategies favoring early maturity.
The theoretical conventional age at which Paretroplus dambabe has zero length (t_0) is closer to zero for females (**t_0=−0.07 years**), indicating early growth, while that of males (**t_0=−0.23 years**) reflects initially slower growth. Female Paretroplus dambabe specimens have a higher size growth performance index **Φ** than males and, conversely, a shorter lifespan (**t_{max} = 3.22 years**) compared to males (**t_{max} = 3.61 years**).

Keyword :*modeling, Paretroplus dambabe,linear growth, Lake Kinkony.*

I. INTRODUCTION

Fish growth is a fundamental parameter for understanding population dynamics, stock structure, and the ecological strategies of aquatic species (Bagenal and Tesch, 1978). It reflects the interaction between the biological characteristics specific to each species and the environmental conditions of its habitat. Linear growth analysis, based on the relationship between length and age or size, is an essential tool for assessing the status of fish populations and guiding management and conservation strategies.

Paretroplus dambabe P. dambabe is a cichlid fish species endemic to the Mahavavy–Kinkony complex in northwestern Madagascar. Due to its restricted geographic distribution and increasing pressure from human activities such as fishing, habitat degradation, and environmental changes, this species is considered vulnerable (Kullander et al., 2008; Guillaume et al., 2011). These pressures can alter the ecological conditions of Lake Kinkony and directly influence the growth parameters of natural *P. dambabe* populations.

Linear growth in fish is influenced by several biotic and abiotic factors, including food availability, water temperature, habitat quality, pH, and dissolved oxygen concentration (Froese and Pauly, 2019). Variations in these parameters can affect growth rate, maximum size attained, and consequently, the survival and reproduction of individuals. The study of linear growth thus allows researchers to identify environmental conditions that are favorable or unfavorable to population development and to better understand their spatial and temporal dynamics.

Lake Kinkony, particularly the Makary area in the Mitsinjo district, is one of the main habitats of Paretroplus dambabe. This area is characterized by a mosaic of habitats including shallow areas, vegetated banks, and areas of high biological productivity, all favorable to the development and growth of this species (Guillaume et al., 2011). However, these habitats are subject to marked seasonal variations and anthropogenic pressures that can influence fish growth.

The main objective of this study is to model the linear growth of *Paretroplus dambabe* in the Makary area of Lake Kinkony, using morphometric and biological data collected in the field. The resulting model will be used to characterize length-age and length-size relationships and to assess the influence of local environmental conditions on the growth of this species. This growth modeling will provide crucial information for the sustainable management of *Paretroplus dambabe* by allowing the prediction of population trends in response to environmental variations. The results of this study could also be extrapolated to other endemic species in the Mahavavy Kinkony Complex basin, thus contributing to a better understanding of the ecology of this unique and fragile ecosystem (Guillaume et al., 2011; Kullander et al., 2008).

II-MATERIALS AND METHODS

II.1. EQUIPMENT

II.1.1 Study Area

The Makary Zone is located at 45°54'E, 16°09'S in the Lake Kinkony region, within the Mahavavy Kinkony Complex, an area of major ecological importance in northwestern Madagascar. The Mahavavy Kinkony Complex, recognized as a Wetland of International Importance (Ramsar Site No. 1665 since 2007), covers a vast mosaic of ecosystems composed of lakes, marshes, rivers, dry forests, and savannas.

Lake Kinkony, the second largest lake in Madagascar, is a central feature of this complex. It covers approximately 15,000 hectares during the wet season, but its surface area decreases during the dry season due to hydrological fluctuations, which depend primarily on the inflow from surrounding rivers, such as the Mahavavy. This lake is home to exceptional biodiversity, including endemic species of fish, waterfowl, and reptiles, as well as unique habitats essential to local flora and fauna.

The Makary Zone, located on the eastern shores of Lake Kinkony, is an area where human activities and biodiversity interact closely. It is characterized by a population heavily dependent on local natural resources for their livelihoods, such as fishing, agriculture, and livestock farming. Despite its ecological and economic importance, this zone is subject to various anthropogenic pressures, including deforestation, overexploitation of fisheries resources, and hydrological disturbances linked to climate change.

As an essential habitat for the endemic fish species Paretroplus dambabe, the Makary Zone plays a crucial role in studies on the ecology and population dynamics of this species. Its strategic location within the Mahavavy Kinkony Complex makes it a priority site for conservation efforts and the sustainable management of aquatic resources.

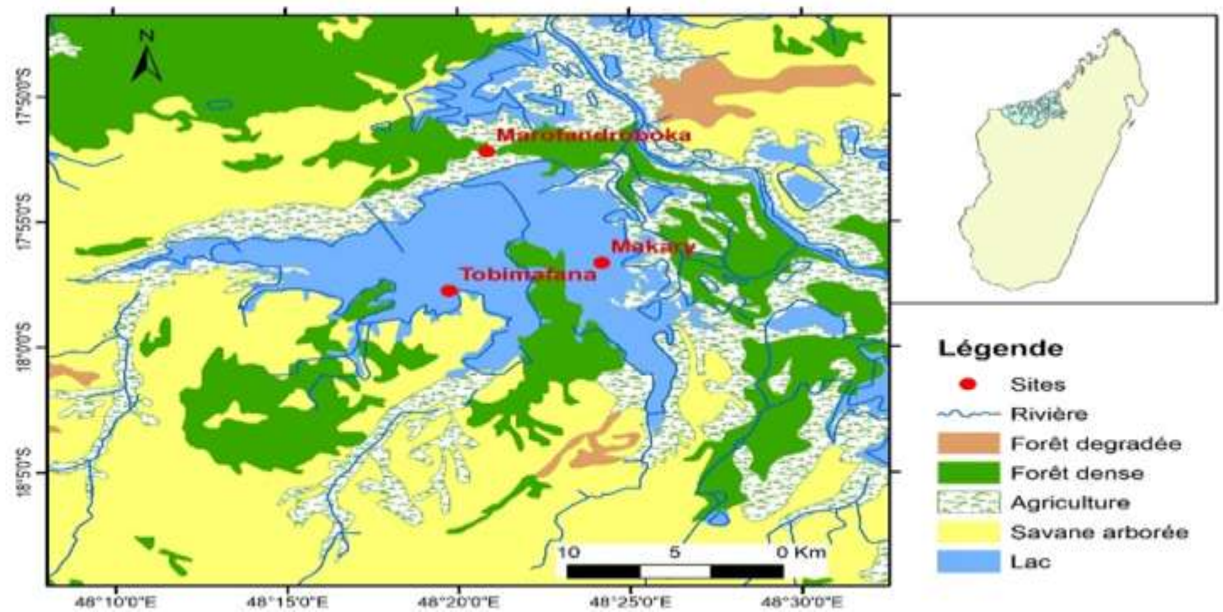

Figure 1: Location of sites and data collection stations in Lake Kinkony

II.1.2. Equipment used

The equipment described above enabled the collection of precise and reliable data on the biological and environmental characteristics of the study area. The following section details the methods used for collecting and analyzing this data.

a) Fish capture devices

- **Gillnets**

Gillnets of varying mesh sizes were used to capture a representative sample of the Paretroplus dambabe population, including individuals of different size classes, from juveniles to adults. The mesh size selection was adjusted according to the recommendations of Tesch (1971) and Bagenal & Tesch (1978) to minimize selectivity bias and ensure sample representativeness.

b) Morphometric measurement tools

- **Ruler and caliper**

Total length (TL) and standard length (SL) were measured using a millimeter ruler or caliper immediately after capture, as recommended by King (1995) and Froese (2006), to ensure the accuracy of biological data.

- **Precision electronic scale**

Each specimen was weighed using a precision balance to allow estimation of biomass and calculation of the condition index (Froese & Pauly, 2019).

- **Water quality sensors**

Temperature, pH, and dissolved oxygen were measured using portable sensors. These parameters are essential for understanding the factors influencing fish growth (Lorenzen et al., 2011).

c) Preservation and identification materials

- **Containers and preservatives**

The samples were transported in coolers or insulated plastic bags to preserve their integrity. Dead specimens were fixed in 10% formalin or ethanol for subsequent morphometric or histological analyses (Guillaume et al., 2011).

- **Labeling**

An individual labeling system was applied, specifying the spatio-temporal origin of each sample and its biological characteristics.

II.2. METHODS

All of these methodological protocols made it possible to build a complete database, from which statistical analyses were carried out to evaluate the growth dynamics and population structure of Paretroplus dambabe.

II.2.1. Data Collection Protocol

To ensure ecological and spatial representativeness of the species Paretroplus dambabe, a rigorous data collection protocol was established. The first step of this protocol consisted of selecting sampling sites adapted to the diversity of habitats present in the Makary basin.

a) Selection of areas
Sampling was carried out in severalareasrepresentationvesites in the Makary basin, chosen to reflect the diversity of Paretroplus dambabe habitats. These sites included:

- areas of varying depth, ranging from shallow shores to deeper central areas;
- contrasting habitats (sandy substrates, rocky substrates, aquatic vegetation, open areas) in accordance with Guillaume et al. (2011);
- breeding areas identified according to Morales-Nin et al. (1998), allowing consideration of the influences of reproductive cycles on growth.

b) Sampling frequency
Campaigns were conducted monthly for twelve months, from November 2021 to November 2022, to detect seasonal variations related to environmental conditions, temperature, or food availability (Froese & Pauly, 2019). Targeted sessions were conducted during breeding or migration periods observed in the field.

c) Capture methods
A combined method based on the use of gillnets of different sizes was employed, ensuring the collection of individuals of all size classes (Bagenal & Tesch, 1978). Catches were carried out in accordance with ethical standards for scientific fishing (FAO, 2011), with rapid handling to minimize stress and ensure the validity of measurements.

d) Age estimation
The age of the fish was estimated by non-lethal analysis of scales taken from the lateral region of the body. Readings were taken using binocular magnifiers, according to the classic method described by Bagenal & Tesch (1978), allowing for the establishment of precise age-growth relationships.

e) Environmental measures
Regular measurements of temperature, pH, dissolved oxygen, and salinity were taken at each site using multiparameter probes. These environmental data allowed for the examination of correlations between local conditions and growth rates (Lorenzen et al., 2011).

II.2.2. Growth Modelingde Paretroplus dambabe

1-Von Bertalanffy linear growth model

The most frequently used age-based growth model in fisheries research is the Von Bertalanffy growth function. The mathematical model of individual growth developed by Von Bertalanffy considers body length as a function of age. according to the following expression:

$$L(t)=L_{\infty}\left(1-e^{-K(t-t_0)}\right) \qquad (1)$$

Or :

L(t): The length of the fish at time t (the age);
L∞: Asymptotic length when t tends towards infinity or maximum theoretical length reached by the fish;
K: growth coefficient (or curvature parameter), parameter describing the shape of the curve, the speed at which the fish approached the maximum size L∞;
to: Time (Theoretical Age of the Fish) where the length is assumed to be zero. It designates the starting point of the growth curve on the time axis if the fish had grown according to the Von Bertalanffy growth model.

The linear growth performance index (Φ) was calculated according to the Pauly and Munro equation (1984):

$$\Phi = \mathrm{Log}_{10}\mathbf{K} + \mathbf{2}\,\mathrm{Log}_{10}\mathbf{L}_{\infty} \qquad (2)$$

Longevity (tmax), indicating the age at which 95% of the asymptotic size L∞ is reached, was estimated through the Pauly equation (1980).

$$t_{max} = \frac{3}{\mathbf{K}} \qquad (3)$$

tmaxlongevity

Kgrowth rate

2-Relationship between total length and standard length

The challenge in any biometric study is choosing a regression line that best represents the scatter plot obtained from the two dimensions being studied. Based on the measurements taken, we used a least-squares regression line to calculate the regression line for the total length-standard length relationship, both for men and women (Harchouche, 2006). For measurements with the same unit, the coefficient b of the LT line determines the type of relationship:

$$LT = a + bLS \qquad (4)$$

The constant a, or condition coefficient, can vary depending on ecological and physiological conditions (Ben Mariem, 1995). The term b designates the allometric coefficient (growth coefficient) reflecting the differential growth of a given trait relative to the reference trait (Gaâmour, 1999). For a height-height relationship, b is theoretically equal to 1; for a height-weight relationship, b is theoretically equal to 3. Three cases are possible:

- If $b = b_{Theoretical}$, there is isometry between the two characteristics,
- If $b < b_{Theoretical}$, then it is a lower bound allometry,
- IF $b > b_{Theoretical}$, allometry is upper bound (Ben Mariem, 1995).

III. RESULTS AND DISCUSSION

III.1.INTERPRETATIONS OF RESULTS

III.1.1.Frequency distribution of length

The biometric characteristics of P. dambabe in the Makary area were studied on a total of 199 individuals. Males (n = 117) had a total length (TL) ranging from 5.1 to 21.9 cm, with a mean of 14.82 cm, and a standard length (SL) ranging from 3.8 to 16.4 cm (mean = 11.19 cm), showing considerable variability including juveniles. Females (n = 82) were generally larger, with a TL ranging from 12.2 to 19.1 cm (mean = 15.79 cm) and an SL ranging from 9.1 to 14.3 cm (mean = 11.91 cm), exhibiting a more homogeneous size distribution. For the entire population (combined), the LT ranged from 5.1 to 21.9 cm (mean = 13.56 cm) and the LS from 3.8 to 16.4 cm (mean = 10.27 cm). These results show that females are on average slightly larger than males and that the male population includes smaller individuals, while the LT remains consistently greater than the LS, in accordance with known morphological criteria for the species.

Table 1: Biometric characteristics of P. dambabe samples. Makary area

		MAKARY		
		LT (cm)	**LS (cm)**	**Effective**
MALE	**MAX**	21.9	16.4	117
	MIN	5.1	3.8	
	AVERAGE	14.82	11.19	
FEMALE	**MAX**	19.1	14.3	82
	MIN	12.2	9.1	
	AVERAGE	15.79	11.91	
CONFUSED	**MAX**	21.9	16.4	199
	MIN	5.1	3.8	
	AVERAGE	13.56	10.27	

To represent the length frequency distribution, the LFDA (Length Frequency Data Analysis V 5.0© 2001) software is used, allowing thus plot the data in the form of length-frequency histograms.LhasFigure 1 shows the histogram of length frequencies for male and female Paretroplus dambabe from the Makary site, calculated using LFDA software. The vertical axis represents length classes in centimeters, while the horizontal axis indicates the sampling period, 12 months. The red bars illustrate the observed frequencies for each size class, reflecting a clear and regular segmentation of the population into a demographic structure organized into distinct cohorts.

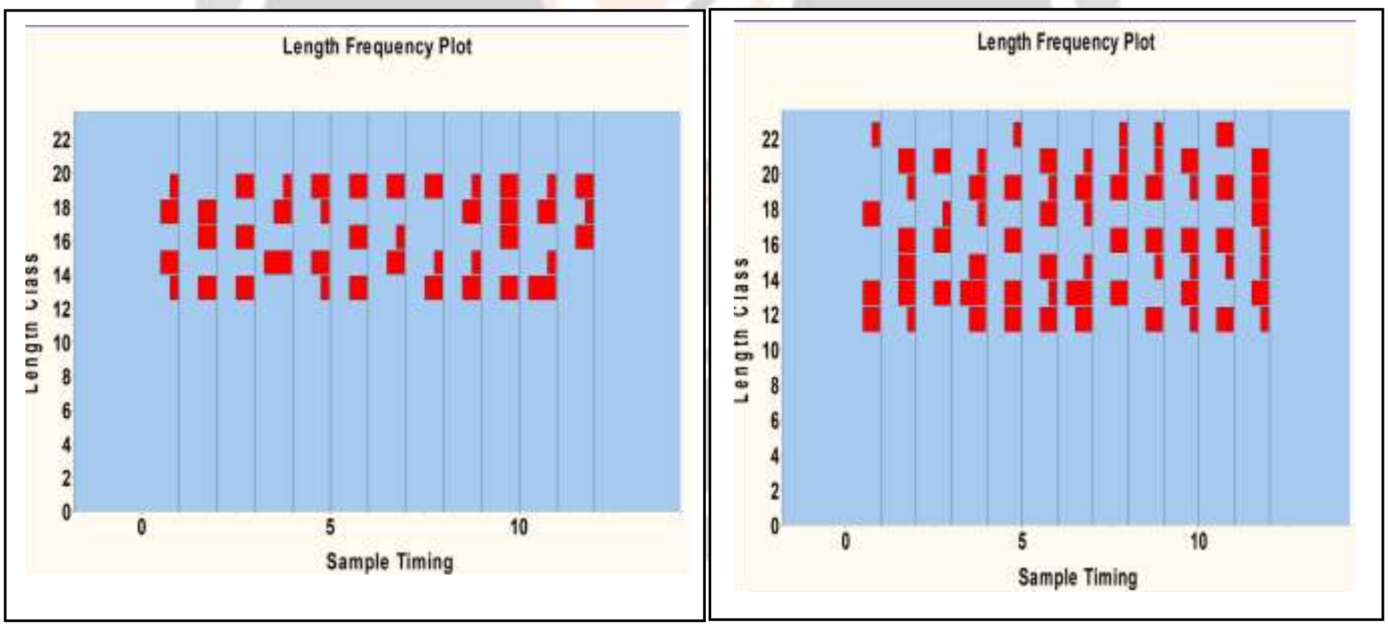

Figure1: Frequency histograms of male P. dambabe length (LEFT)And females (RIGHT). Makary Zone

By carefully examining these histograms, in the absence of other information, they will provide the main clues for a first estimation of the possible ranges of the growth curve parameters. In particular, the upper ends of the histograms give us an idea of the possible length values.

Figure 2 illustrates the experimental data obtained of total length-standard length of *P. dambabe* males and females in the Makary site.

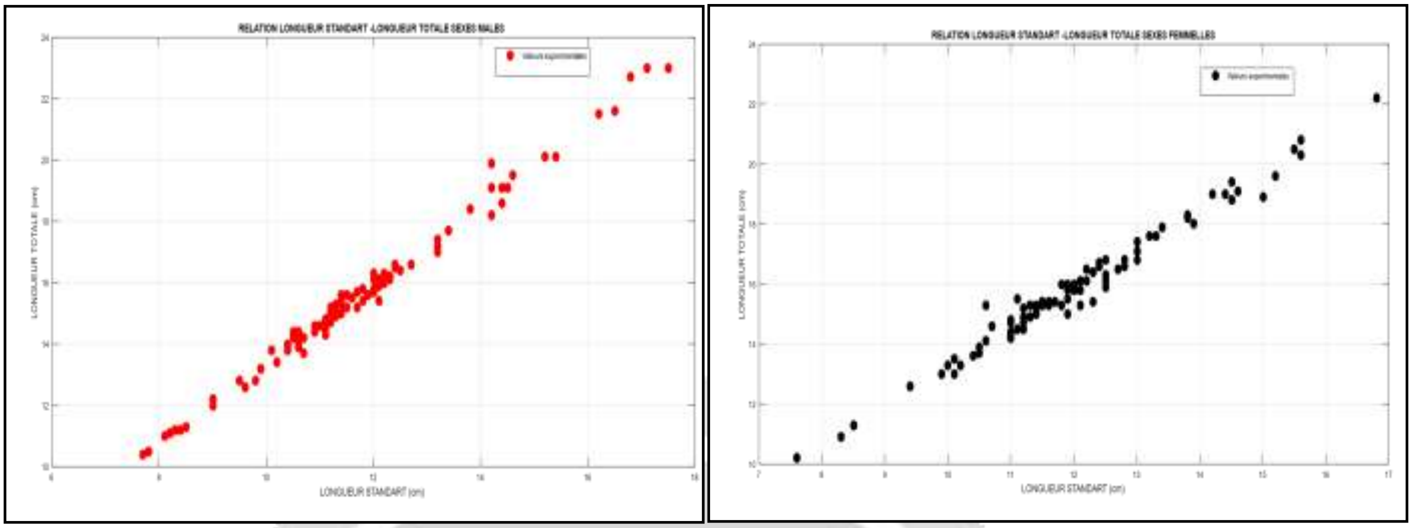

Figure 2: Total length data - standard length of P. dambabe males and females.SiteMakary

III.2- Results of the growth of *Paretroplus dambabe*

III.2.1-Results of linear growth by VON Bertalanffy

Figure 3 illustrates the evaluation of VON Bertalanffy growth parameters using the LFDA software for male (left) and female (right) P. dambabe. The red histograms show the length frequency graphs, and the yellow curves show the fitted VON Bertalanffy growth curves for male and female P. dambabe from Site Makary.

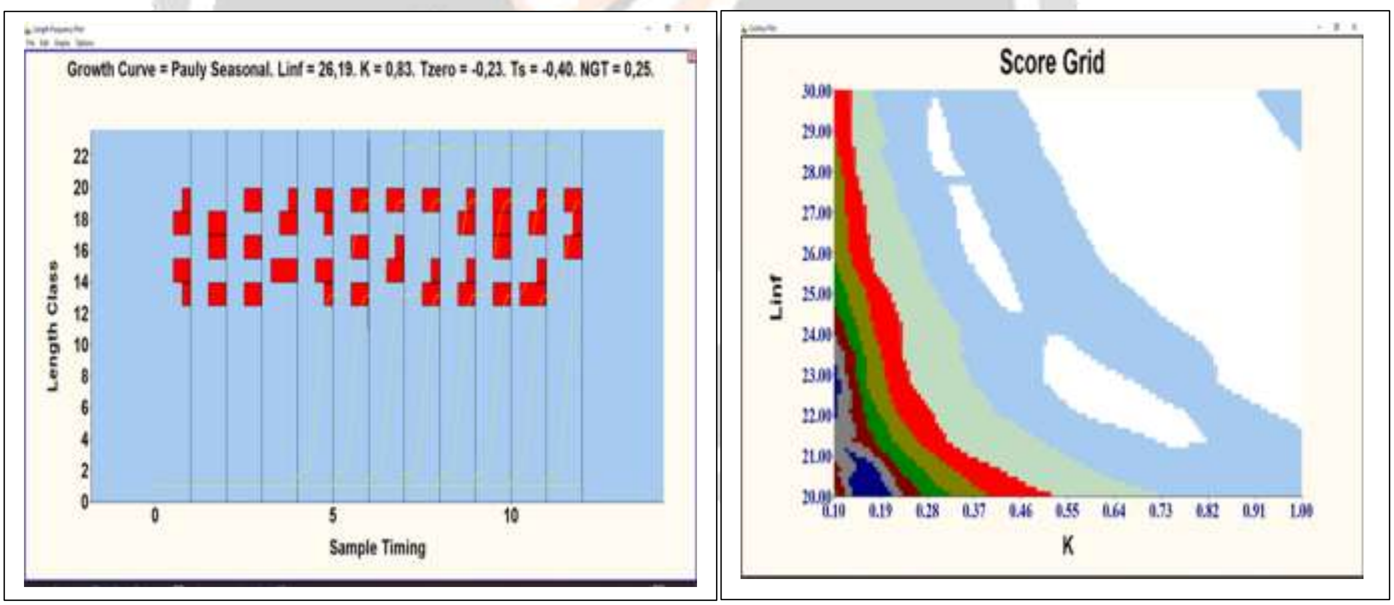

Figure 3: Frequency histograms with fitted VON Bertalanffy growth curve for P. dambabe male sexes (left) and contours indicating the adjustment scores of the L∞ and K combinations (right) of Zone Makary

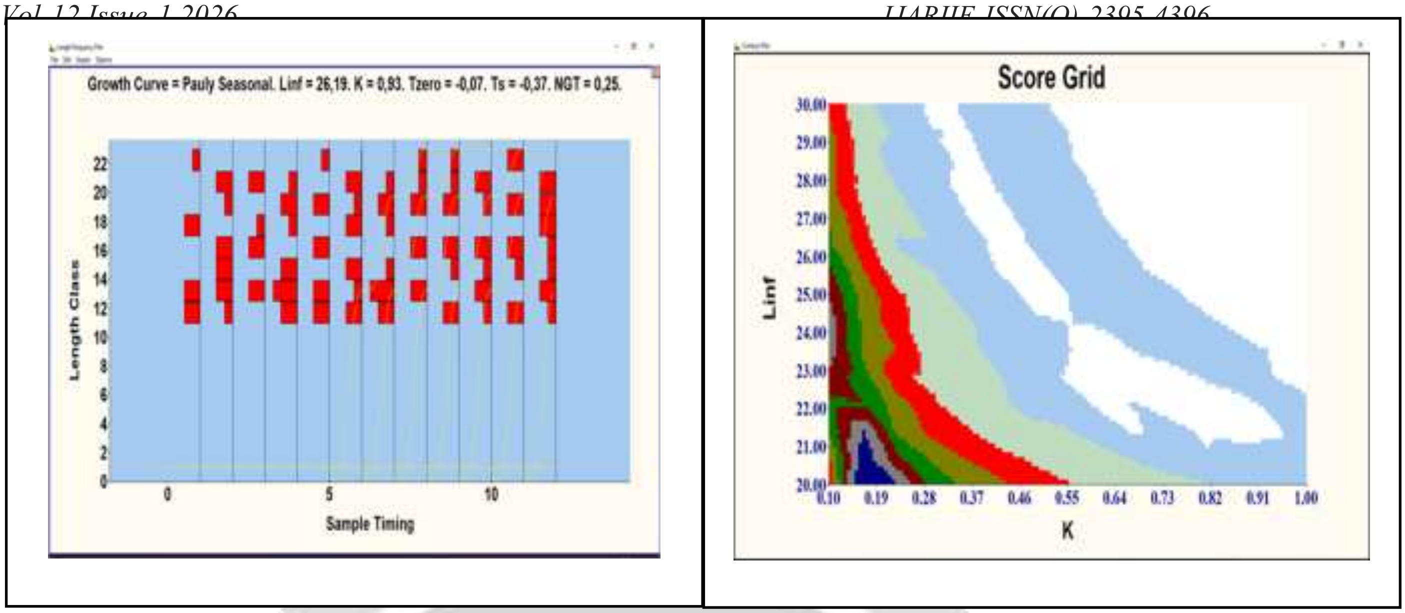

Figure 4: Frequency histograms with adjusted VON Bertalanffy growth curve for P. dambabe, female sexes (left) and outlines indicating the fit scores of the L∞ and K combinations (right) of Zone Makary

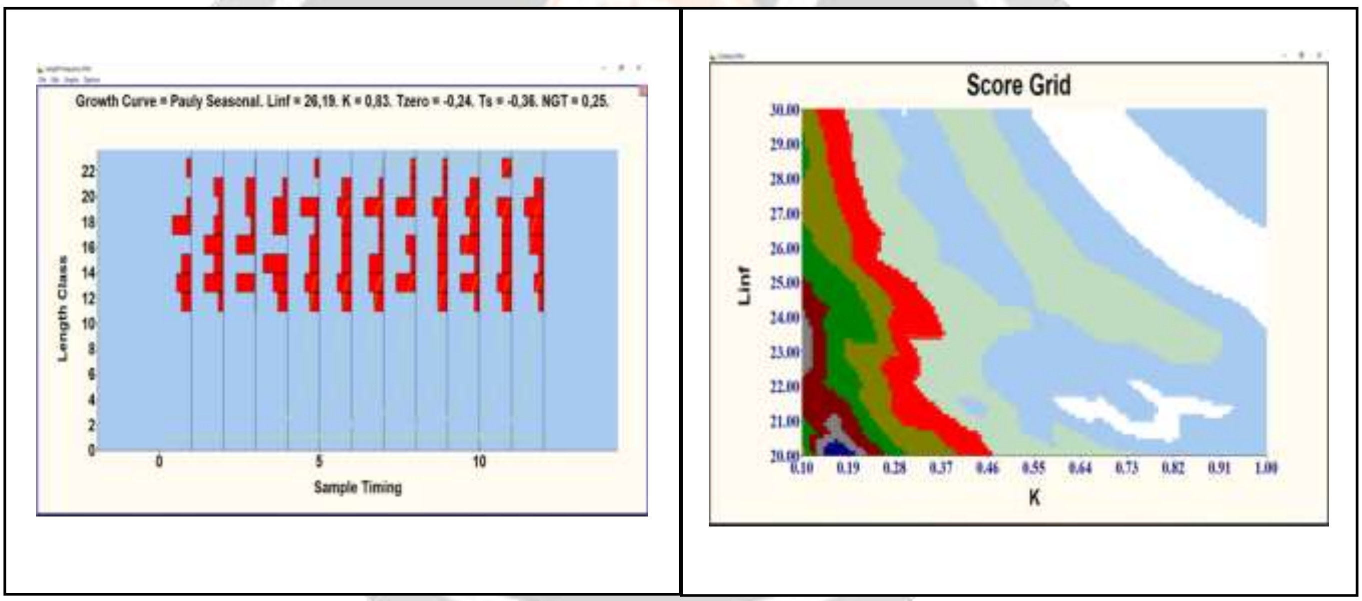

Figure 5 : Frequency histograms with adjusted VON Bertalanffy growth curve for P. dambabe sexes combined (left) and outlines indicating the adjustment scores of the combinations of L∞ and K (right) of Zone Makary.

The growth parameters of female and male P. dambabe fish in the Makary area are very similar, and the curves have exactly the same profile. The asymptotic length L∞ = 26.19 cm, established separately for males and females, overlaps, thus indicating that there is no difference in growth between the sexes. The growth constant (or catabolism constant) (K) is a parameter that describes the growth rate of the fish at which it reaches the asymptotic length L∞.
The growth coefficient (K) differs slightly: females (K=0.93**an**$^{-1}$) reach their adult size faster than males (K=0.83an^{-1}), probably due to adaptive strategies favoring early maturity. The theoretical initial time (t0) is closer to zero for females (t0=−0.07 cm), indicating early growth, while that of males (t0=−0.23 cm) reflects initially slower growth. Time t0 is often negative: The von Bertalanffy curve extrapolates growth back to early life to better fit data for young individuals. If initial growth is rapid, the model shifts the curve to the left so that the observed length at age 0 matches the formula. This results in a negative t0.

LFDA can produce a two-dimensional contour plot. The contours indicate the fit scores of the combinations of $L\infty$ and K; the vertical axis represents $L\infty$, ranging from 20 to 30 cm, indicating the maximum theoretical size attainable by the species, while the horizontal axis represents K, ranging from 0.1 to 1, reflecting the growth rate: high values indicating rapid growth and low values signaling slow growth.
The colored outlines indicate the fit scores of the $L\infty$ and K combinations, with dark areas (red, dark green, blue) corresponding to optimal fits, while white areas indicate inconsistencies with the data. The red area shows that the most probable values for modeling growth are
$L\infty$ = 24–26 and K=0.2–0.4an^{-1}, which suggests a moderate rapid growth, characteristic of tropical fish, and an asymptotic length adapted to the environmental and genetic conditions of this population.
Table 2 below shows the values of $L\infty$ of K, t0 and of the growth performance index Ø estimated for our species, then substituted into the Von Bertalanffy equation.

Table 2 presents estimates of Paretroplus dambabe growth parameters from the fitting of the Von Bertalanffy model, according to sex (males, females and population combined) at the Makary site.

Table 2: Synthesis of parameter values and growth equation of *P. dambabe* according to the model of Von Bertalanffy. Makary Zone

SEX	L∞	K	to	EQUATIONS Lt = L∞ (1-eK(t-t0))	Performance Index ϕ=Log10K+Log10 L∞	ϕ	Longevity (tmax)
Males	26.19	0.83	-0.23	Lt=26.19(1- $e^{-0.83(t+0.23)}$)	ϕ=Log100.83+Log1026.19	2,756	3.61
Females	26.19	0.93	-0.07	Lt=26.19 (1-$e^{-0.93(t+0.07)}$)	ϕ=Log100.93+Log1026.19	2,806	3.22
Confused	26.19	0.83	-0.24	Lt=26.19 (1-$e^{-0.83(t+0.24)}$)	ϕ=Log100.83+Log1026.19	2,756	3.22

The three fundamental parameters of the model are:

- $L\infty$: asymptotic length (cm)
- K: instantaneous growth coefficient (year^{-1})
- t0: theoretical age with zero length (years)

The growth parameters of Paretroplus dambabeofThe Makary site values were estimated using the Von Bertalanffy model, with a distinction between sex (males, females) and an overall analysis (sexes combined). The results are summarized in the table below:
All groups exhibit an identical value for asymptotic length ($L\infty$=26.19 cm), suggesting the absence of marked sexual dimorphism in terms of maximum height attained. However, notable differences appear in the growth coefficient (K) and the theoretical age at zero length (t0).
Females exhibit a slightly higher growth coefficient (K=0.93) than males (K=0.83 year^{-1}), indicating faster growth towards asymptotic size. Furthermore, their t0 is closer to zero (t0=−0.07 months) compared to that of males (t0=−0.23 months), suggesting an earlier onset of growth in females.
The model applied to the combined population (sexes combined) has parameters very similar to those of males, which could reflect either an overrepresentation of males in the sample, or a greater
The adjusted growth equations are expressed as follows:

- In males, the resulting equation is : Lt = 26.19(1-$e^{-0.83(t+0.23)}$)
- In females, the following equation is observed : Lt =26.19 (1-$e^{-0.93(t+0.07)}$)
- For individuals of both sexes, the equation is Lt =26.19 (1-$e^{-0.83(t+0.24)}$)

These results highlight a slight differentiation in the growth pattern between the sexes, although the maximum height reached remains the same.
Such differentiation may be linked to physiological, behavioral, or environmental factors, particularly those related to reproductive strategies or resource availability..From these growth parameters, we can plot the curves linked to the mathematical models of individual growth developed by Von Bertalanffy as a function of age.(Figure 6).
We obtain curves that rise rapidly, then reach a plateau, indicating the phase of strong juvenile growth followed by stabilization in adulthood. This stabilization may be due to biological (maximum size attained) or environmental limitations. The Von Bertalanffy growth curves established separately for male and female Paretroplus dambabe overlap, thus indicating that there is no difference in growth between the sexes. Analysis of the Von Bertalanffy growth parameters for Paretroplus dambabe in the Makary area reveals very similar dynamics, and the curves have

exactly the same profile. The maximum asymptotic length ($L\infty$=26.19 cm) is identical for males, females, and both sexes combined. This situation reflects homogeneity in environmental conditions and the absence of sexual dimorphism in size.

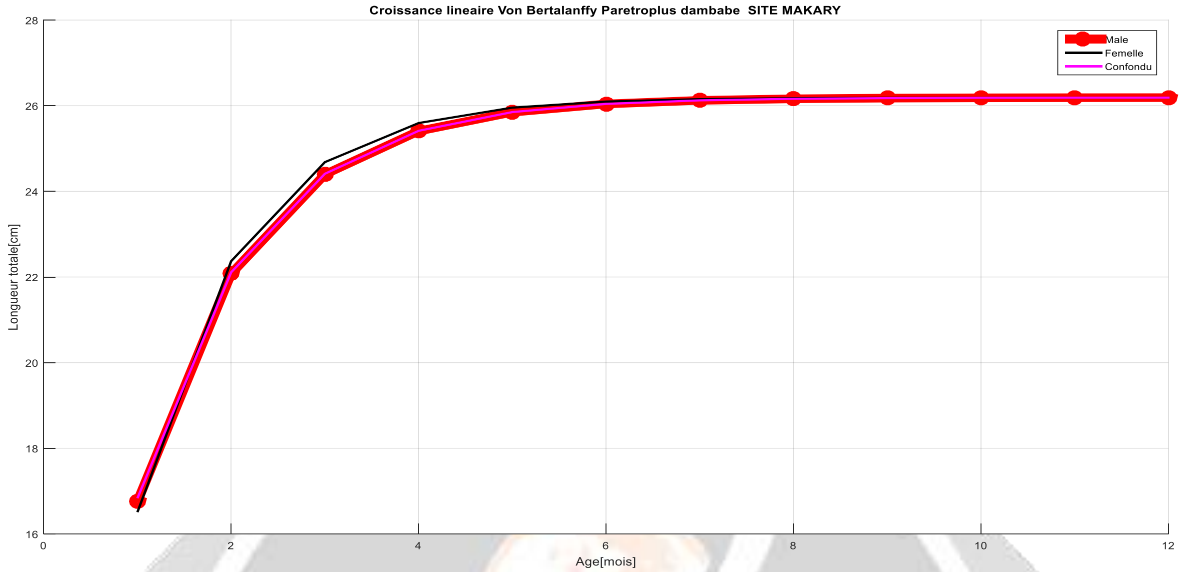

Figure 6: Linear growth curve by Von Bertalanffy for the *Paretroplus dambabe* females, males, and both sexes combined. Site Makary

III.2.2 - Results of biometric relationships

III.2.2.1-Relationship between total length and standard length of the Makary site

The analysis of the morphometric relationship between total length (LT) and standard length (LS) in male individuals of *Paretroplus dambabe* from the Makary site made it possible to fit a linear model of the type

LT=a+bLS

on the basis of the data processed using the MATLAB software.

The model's slope (p1) is estimated at 1.303, with a 95% confidence interval between 1.276 and 1.33, indicating a strong positive correlation between the two variables. The intercept (p2) is 0.2967, with a relatively wide confidence interval (-0.02589 to 0.6192), suggesting low statistical significance for this parameter. The coefficient of determination (R^2 = 0.9902) and the adjusted R^2 (0.9901) reveal excellent goodness of fit, explaining more than 99% of the total variance observed in the data. Furthermore, the sum of squared errors (SSE = 6.271) and the root mean squared error (RMSE = 0.264) indicate very low dispersion of the residuals around the regression line, reflecting the model's accuracy. These results highlight the relevance of the linear model in representing the LT–LS relationship, and make it a robust tool to support growth and population dynamics analyses of P. dambabe in the Mahavavy-Kinkony complex, particularly in the context of applying the Von Bertalanffy model.

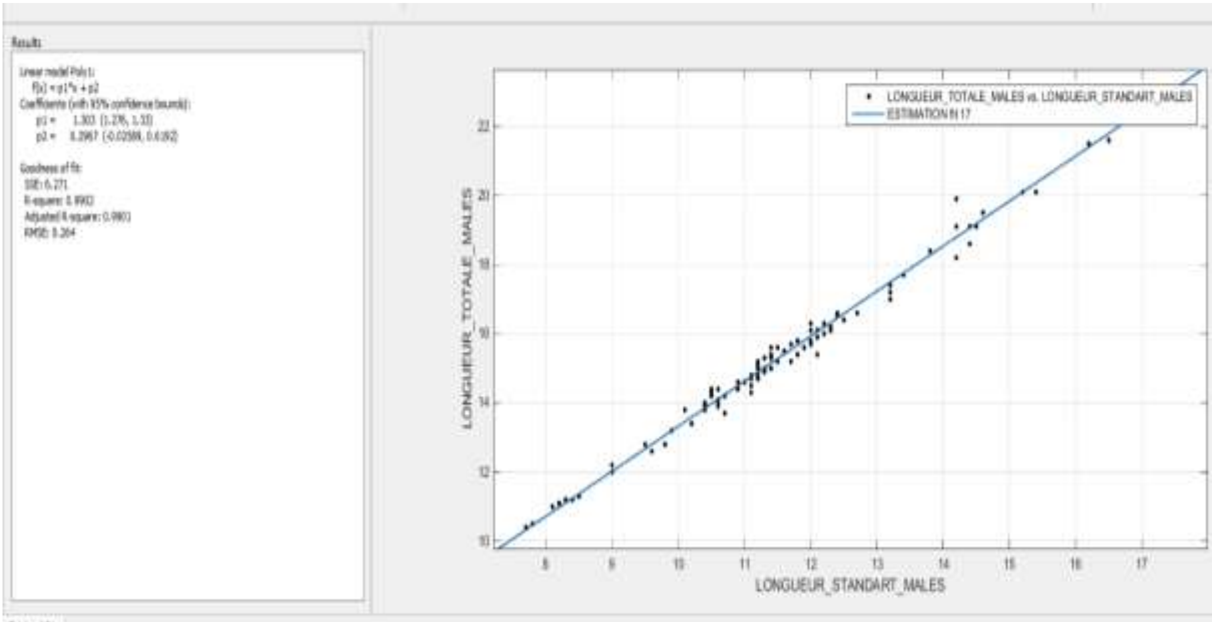

Figure 7: Relationship between total length and standard length of male dambabe fish from the Makary site

The morphometric relationship between total length (TL) and standard length (SL) of female Paretroplus dambabe individuals from the Makary site was analyzed using a simple linear model, fitted using MATLAB. The resulting equation is of the form **TL = p1·SL + p2**, with a slope (p1) estimated at 1.28 (95% confidence interval: 1.242–1.319), indicating a proportional increase in total length relative to standard length. The y-intercept (p2) is 0.4731, although its confidence interval (-0.009463 to 0.0366) suggests non-significant variability in this component. The model's goodness of fit is demonstrated by a high coefficient of determination ($R^2 = 0.9796$) and an adjusted R^2 of 0.9793, indicating that over 97% of the observed variance is explained by the model. Furthermore, the sum of squared errors (SSE = 8.98) and the root mean square error (RMSE = 0.3141) reveal a low dispersion of the residuals, reflecting good accuracy of the estimates. These results confirm the suitability of the linear model for describing the LT–LS relationship in this species within the Mahavavy-Kinkony complex and provide a reliable basis for future studies of population growth and dynamics.

The relationship between total length (TL) and standard length (SL) in Paretroplus dambabe (both sexes) at the Makary site was assessed using a linear regression model based on data processed in MATLAB. The resulting model is of the form TL = a + bSL, with an estimated slope of 0.9582 (95% CI: 0.8092–1.107), indicating a moderate linear relationship between the two morphometric variables. The p-intercept (p^2) is 4.286 (95% CI: 2.504–6.067), suggesting a significant contribution to the regression line. However, the goodness of fit is relatively low, as evidenced by a coefficient of determination R^2 of 0.4682 (adjusted $R^2 = 0.4653$), meaning that less than half of the observed variability in total length is explained by the standard length. This poor model performance can be attributed to significant inter-individual variability related to the combination of the two sexes, which can exhibit significant morphological differences.

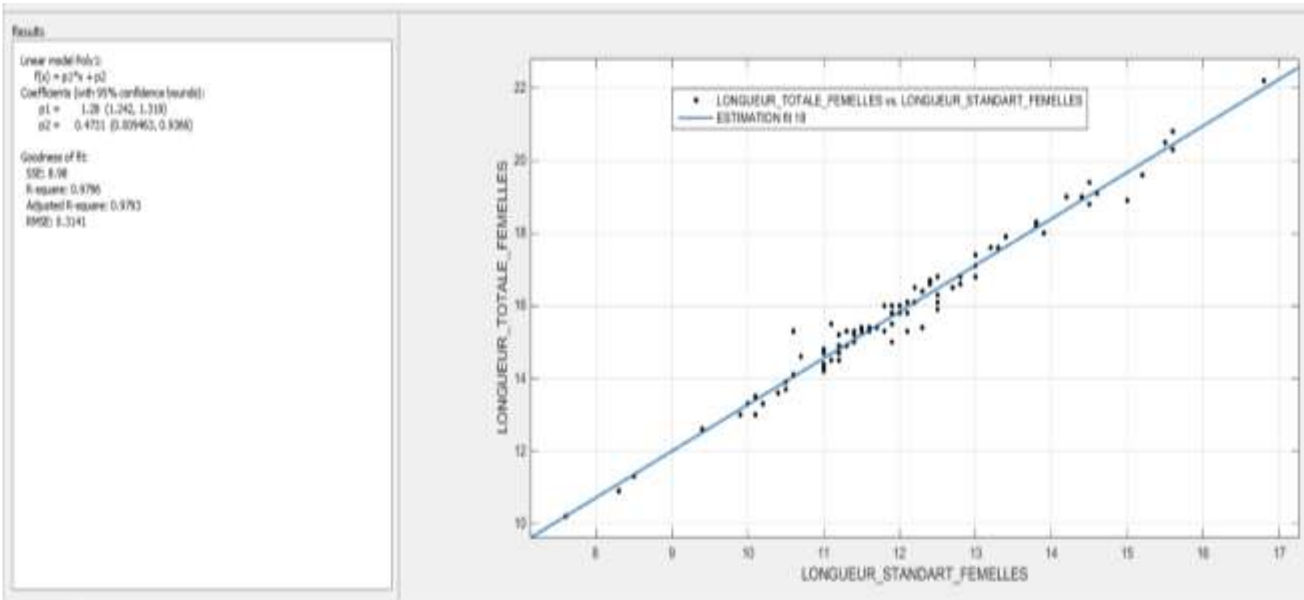

Figure 8: Relationship between total length and standard length of female dambabe fish from the Makary site

In terms of fit error, the sum of squared errors (SSE = 665.2) and the root mean square error (RMSE = 1.907) reveal a significant dispersion of residual values around the fitted line, indicating limited model accuracy in predicting total lengths. These results highlight the limitations of a single linear model applied to a mixed (sex-inclusive) population and suggest the need for separate sex adjustments or more complex statistical approaches (nonlinear or mixed-effects models) to better represent the species' growth dynamics. Such approaches would allow for more refined modeling, particularly within the context of integration into the Von Bertalanffy growth model, by improving the quality of estimates of basic morphometric parameters.

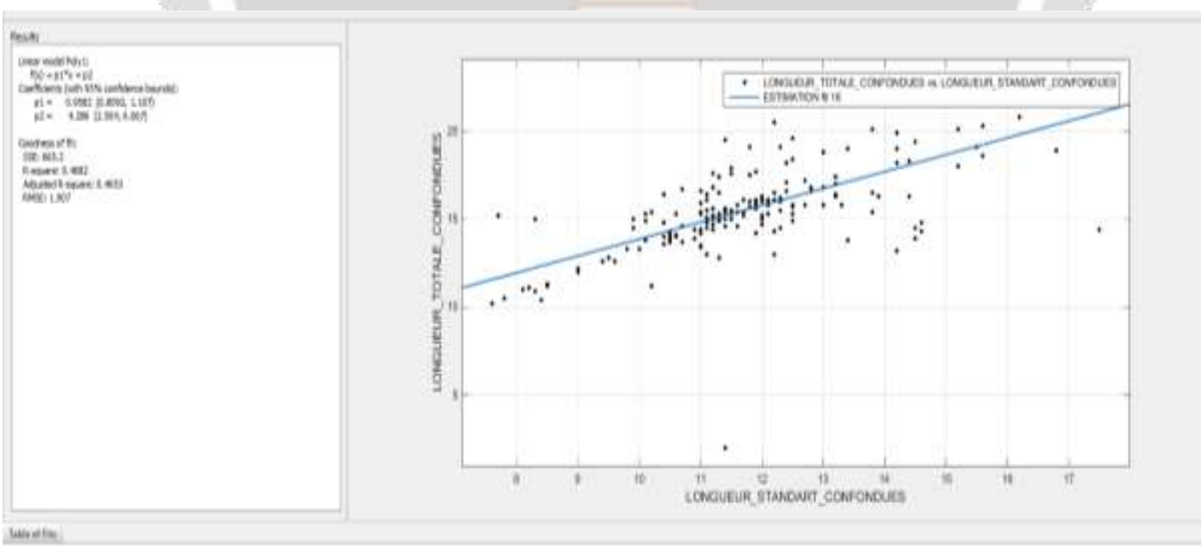

Figure 9: Relationship between total length and standard length of dambabe fish (sexes not included) from the Makary site

The relationship between total length (TL) and standard length (SL) of Paretroplus dambabe in the Makary area shows a strong correlation when sexes are analyzed separately. In males, the equation :

$$LT = 1.303 + 0.296\ LS$$

This shows a highly significant linear relationship ($R^2 = 0.99$) and a limiting allometry ($b < 1$). Similarly, in females, the relationship :

LT = 1.28 + 0.473 LS

exhibits a high coefficient of determination ($R^2 = 0.98$), also indicating a limiting allometry. In contrast, the analysis of individuals of both sexes gives a less pronounced relationship ($R^2 = 0.46$) with the equation :

LT = 0.958 + 4.286 LS,

characterized by a limiting allometry ($b > 1$). This difference highlights the influence of sex on the morphometric relationship LT–LS and justifies the separate analysis of males and females.

Painting3: Allometry coefficient and total length - standard length (TL-SL) regression equation

Site	Sex	has	b	R2	Allometry equation LT=a+bLS	Types of allometry
Makary	Male	1.3303	0.296	0.99	LT=1.303+0.296LS	Minorante
	Female	1.28	0.473	0.98	LT=1.28+0.473LS	Minorante
	Confused	0.958	4,286	0.46	LT = 0.958 + 4.286LS	Majorante

III.2.DISCUSSIONS OFRESULTS

III.2.1. Size structure and demographic organization of the population

The length frequency distribution of Paretroplus dambabe in the Makary area reveals a population structured into distinct size classes, reflecting the existence of cohorts corresponding to different growth stages. This demographic organization is generally interpreted as a reflection of regular recruitment and staggered reproduction, common characteristics of tropical fish species living in relatively productive lake ecosystems (Pauly, 1980; Sparre and Venema, 1998).

The presence of small individuals, particularly males, suggests good juvenile survival and sufficient availability of habitats favorable to early growth, especially shallow, vegetated coastal areas. Similar observations have been reported in other cichlids endemic to Madagascar, for which size structure is strongly linked to habitat heterogeneity and seasonal variations in environmental conditions (Kullander et al., 2008; Guillaume et al., 2011).

III.2.2. Size differences and absence of marked sexual dimorphism

The results indicate that females have, on average, slightly greater total and standard lengths than males. This trend is frequently observed in teleost fish and may be associated with specific reproductive strategies, with females needing to reach a sufficient size to maximize fecundity and egg production (Wootton, 1998; Froese and Pauly, 2019). However, the asymptotic length estimated by the von Bertalanffy model is identical for males and females ($L\infty$ = 26.19 cm), suggesting the absence of marked sexual dimorphism in terms of maximum size. This homogeneity could reflect a dominant influence of local environmental conditions on growth, limiting the expression of morphological differences between the sexes, as has been observed in several species of lake cichlids (Lévêque, Paugy, and Teugels, 1992).

III.2.3. Growth parameters and biological strategies

The growth coefficient (K) values indicate relatively rapid growth in P. dambabe, typical of tropical species living in environments with high primary productivity (Pauly, 1984). Females exhibit a slightly higher growth coefficient than males, suggesting a faster attainment of adult size. This phenomenon is often interpreted as an adaptive strategy favoring early sexual maturity, thereby increasing reproductive success in environments subject to ecological or anthropogenic pressures (Beverton and Holt, 1957; Wootton, 1998). The negative values the t_0 parameter observed in both sexes are consistent with the assumptions of the von Bertalanffy model and reflect rapid juvenile growth. According to Sparre and Venema (1998), a negative t_0 is common in fish and reflects more of a mathematical need to fit the model than an actual biological age.

III.2.4. Dynamics of von Bertalanffy growth curves

The growth curves obtained show a rapid increase in length at young ages, followed by a phase of slowing and stabilization in adulthood. This dynamic is consistent with the classical energetic model of fish growth, according to which energy is primarily allocated to somatic growth during juvenile phases, then progressively redirected towards reproduction after sexual maturity (Von Bertalanffy, 1938; Weatherley and Gill, 1987). The near-perfect overlap of male and female growth curves confirms that, despite slight differences in parameters, the overall growth dynamics are similar between the sexes. This similarity suggests a common response to the environmental conditions of Lake Kinkony, particularly in terms of food availability and habitat quality.

III.2.5. Morphometric relationship LT–LS and implications for modeling

Analysis of the relationship between total length (TL) and standard length (SL) reveals a strong linear correlation when sexes are considered separately, with high coefficients of determination. The understated allometry observed in both males and females indicates that total length growth is proportionally lower than standard length growth, which is consistent with morphological patterns reported for many cichlids (Froese, 2006). Conversely, the poor goodness of fit observed for both sexes combined underscores the importance of sex as an explanatory factor for morphometric variability. Similar results were reported by Ricker (1975), who emphasizes that combining biologically distinct groups can mask true allometric relationships. These observations confirm the need to perform sex-differentiated morphometric analyses to improve the accuracy of growth models, particularly when applying the von Bertalanffy model.

III.2.6. Implications for management and conservation

Estimated growth parameters suggest that the Paretroplus dambabe population in the Makary area exhibits relatively stable dynamics adapted to local conditions. However, the close dependence of growth on environmental conditions makes this species particularly vulnerable to anthropogenic disturbances affecting Lake Kinkony, such as the degradation of littoral habitats and fishing pressure (GGuillaume et al., 2011). The results obtained constitute an essential scientific basis for the development of sustainable management measures, including the definition of minimum capture sizes and the protection of key habitats for juveniles. They also contribute to a better understanding of the ecology of endemic species of the Mahavavy–Kinkony complex, an ecosystem of major importance for Malagasy biodiversity.

IV. CONCLUSION

This study characterized the linear growth of Paretroplus dambabe in the Makary zone of Lake Kinkony and modeled this growth using the von Bertalanffy model. The results show a cohort-structured distribution, a slightly larger mean size in females, and an identical asymptotic length for both sexes ($L\infty = 26.19$ cm), indicating the absence of marked sexual dimorphism. The higher growth coefficient (K) in females and a t_0 closer to zero suggest earlier growth initiation and rapid maturation, likely linked to reproductive strategies adapted to local environmental conditions. The strong correlation between total length and standard length in both males and females (minor allometry) confirms the reliability of the morphometric approach for estimating growth. However, the combined sex analysis shows a less robust relationship, highlighting the importance of sexual differentiation in morphometric studies. These results provide an essential scientific basis for the sustainable management of P. dambabe, particularly for planning conservation measures targeting juvenile cohorts and habitat protection. They also pave the way for comparative studies on other populations within the Mahavavy-Kinkony complex and on other endemic species to better understand population dynamics in this unique ecosystem.

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