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Stock Assessment of Tilapia (*Oreochromis aureus*) in a Mexican Reservoir Using Data-Limited Methods: A Multi-Model Approach

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Abstract

The Tilapia (*Oreochromis aureus*) sustains more than 90% of the fishery value and volume in the Vicente Guerrero Reservoir (VGR), Northeast Mexico, but stock status is uncertain due to lack of assessments. A total of 1,792 individuals (2020-2021) were analyzed. Von Bertalanffy growth, total (Z), natural (M) and fishing (F) mortality, and exploitation rate (E) were estimated. Under a data-limited framework, four complementary approaches were applied: the LBB model, length-based indicators, empirical reference points, and ecological risk assessment. Growth was negatively allometric (b=2.89). Estimated parameters were: L_∞=464 mm, K=0.2275 yr^{-1}, Z=3.591 yr^{-1}, M=0.3894 yr^{-1}, F=3.302 yr^{-1}, E=0.892. The LBB model estimated a relative biomass B/B_0=0.057 (95% CI: 0.042-0.072) and an F/M ratio of 8.48. Only 7.5% of individuals exceeded maturity length, 4.8% were at optimal length, and 2.6% were mega-spawners. Estimated fishing mortality exceeded the reference points (F_{MSY}=0.339 yr^{-1}; F_{limit}=0.508 yr^{-1}; F_{crash}=0.678 yr^{-1}) by 9.7, 6.5, and 4.9 times, respectively, classifying the stock as extreme high risk. The *O. aureus* stock in VGR is in biological collapse (B/B_0=5.7%; F/M=8.48). Increasing minimum capture length to at least 290 mm and reducing fishing effort by 80-90% is urgently required. The convergence of independent methods validates data-limited approaches for artisanal fisheries.

Keywords: *Oreochromis aureus*; data-limited fisheries; length-based Bayesian method (LBB); overfishing; stock collapse; ecological risk assessment; Vicente Guerrero Reservoir

Key Contribution: This study provides the first integrated stock assessment for tilapia (*Oreochromis aureus*) in the Vicente Guerrero Reservoir using four complementary data-limited methods (exploitation rate, LBB model, Froese's length-based indicators, and Zhou's ecological risk assessment). The convergence of all methods reveals a biological collapse (B/B_0 = 0.057; F/M = 8.48; 92% juveniles in catch), demonstrating that data-limited approaches can generate robust diagnoses for artisanal fisheries when traditional assessment data are unavailable.

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1. Introduction

Inland fisheries in Mexico represent an essential source of protein and income for riparian communities, particularly in the northeast of the country. Among these, the tilapia (*Oreochromis aureus*) fishery in the Vicente Guerrero Reservoir, Tamaulipas, Mexico (VGR), stands out for its socioeconomic importance, contributing more than 90% of the value and volume of the total catch in this water body [1]. Despite its relevance, the exploitation status of this resource has remained uncertain due to the lack of formal assessments integrating multiple methodological approaches, especially in a data-limited fisheries context, a common condition in most artisanal fisheries in the country.

Globally, overfishing remains a predominant threat to the sustainability of fishery resources. It is estimated that approximately one third of assessed fish stocks worldwide are exploited at biologically unsustainable levels [2]. In Mexico, several tilapia populations in reservoirs have shown signs of overexploitation, characterized by high fishing mortality rates and a reduction in mean catch length [3,4]. For the VGR, previous studies conducted more than a decade ago suggested an overexploited status [5,6], but these studies used limited methodological approaches, leaving a knowledge gap regarding the current stock condition and the need to update its status with more robust analytical tools.

In the last two decades, the development of methodologies for data-limited fisheries assessment has advanced significantly, offering viable alternatives when long time series of catch or fishing effort are unavailable. Methods such as the length-based Bayesian biomass model (LBB) [7], stock health indicators [8], and quantitative ecological risk assessment [9,10] have been widely validated in tropical and subtropical fisheries. Recent studies have demonstrated the effectiveness of these approaches in assessing cichlids and other commercially important species in Asia and Europe [11–14]. However, in Mexico, the integrated application of these tools in reservoirs remains scarce, and no study has combined LBB, Froese's indicators [8], and Zhou's risk approach [9,10] to assess the O. aureus stock in the VGR.

Based on the background of overexploitation reported for the 2010s, the following hypothesis is proposed: the O. *aureus* stock in the VGR is in a state of severe overexploitation or biological collapse. Specifically, the exploitation rate (E) is expected to exceed the reference point of 0.5 [15], the relative biomass (B/B_0) is expected to be below 0.4 [7], and the ecological risk is expected to be classified as high or extremely high [9]. Formally, the null hypothesis that the stock is exploited at a sustainable level is tested, i.e., that E is less than or equal to 0.5, B/B_0 is greater than or equal to 0.4, and the ecological risk is low or medium, against the alternative hypothesis that the stock is overexploited or in biological collapse, i.e., that E is greater than 0.5, B/B_0 is less than 0.4, and the ecological risk is high or extremely high.

Therefore, the general objective of this study was to determine the exploitation status of the O. *aureus* stock in the VGR using an integrated approach of data-limited methods. The specific objectives were: (1) to estimate the growth parameters of the Von Bertalanffy model [16] (VBM), the instantaneous rates of total (Z), natural (M), and fishing (F) mortality, and E using traditional methods implemented in the FiSAT II software package [17]; (2) to apply the LBB model to estimate B/B_0 and the associated biological reference points [7]; (3) to calculate Froese's three stock health indicators [8] based on length structure; and (4) to classify the ecological risk of the stock according to the reference points of Zhou et al. [10] and the risk categories of Zhou et al. [9]. The results confirmed the alternative hypothesis of severe overexploitation: the stock is in biological collapse, with recruitment overfishing and extremely high ecological risk, therefore, it is necessary to increase the minimum capture length to ≥290 mm and reduce fishing effort by 70-80%.

2. Materials and Methods

2.1. Study Area

The VGR is an artificial reservoir located in northeastern Mexico, between 23°45′ and 24°05′ N and 98°40′ and 98°57′ W (Figure 1), at an altitude of 131 meters above sea level. This reservoir: (a) is located within the municipalities of Padilla, Güemes, Casas, Abasolo, Jiménez, and Soto la Marina (Figure 1), in the State of Tamaulipas; (b) has a dam wall 423 m in length and 48 m in height; (c) has a capacity of 5,283 million cubic meters, with maximum depths of up to 44 m; and (d) is fed by the Purificación, Pilón, Corona, Grande, and Moro rivers, which downstream of the dam receive the name of the Soto La Marina River [1].

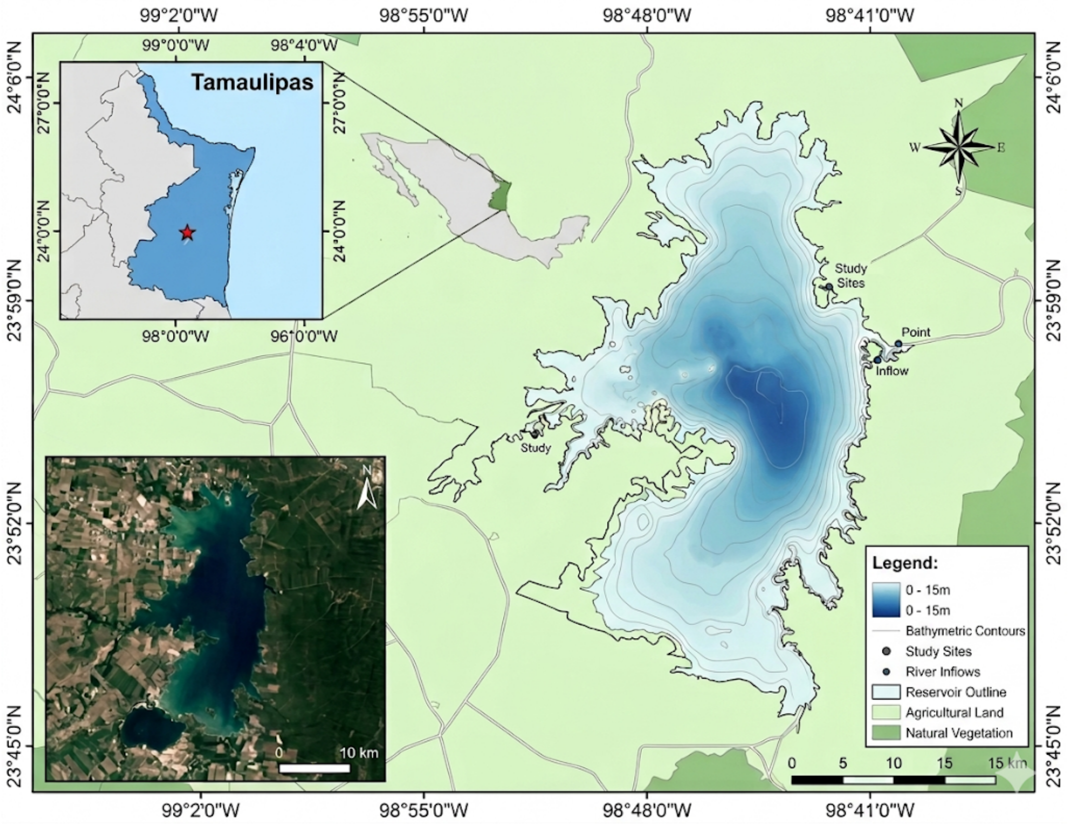

Figure 1. Location of the Vicente Guerrero Reservoir in northeastern Mexico.

2.2. Biological Sampling

Monthly samples were collected from commercial fishing during the annual period 2020-2021. Gillnets with mesh openings of 4.0 and 4.5 inches were used. For each captured organism, total length (TL) was measured to the nearest millimeter using a 30 cm ruler graduated in millimeters, and total weight (TW) was measured to the nearest gram using an Unline digital scale with a maximum capacity of 3 kg.

2.3. Length-Weight Relationship and Growth

The relationship between total length and total weight was estimated using the allometric equation of Ricker [18]: $TW = a * TL^b$, where "a" is the intercept on the ordinate axis and "b" is the allometric exponent. The parameters were estimated by least squares [19]. The hypothesis of isometric growth ($b = 3$) was tested using a Student's t-test [20].

Growth in length was modeled using the VBM [16]: $TL(t) = L\infty * [1 - \exp(-k * (t - t0))]$, where TL(t) is the length at age t, L∞ is the asymptotic length, k is the growth coefficient ($year^{-1}$), and t0 is the theoretical age at which length is zero. The parameters L∞ and k were estimated using the ELEFAN I method contained in the FiSAT II software package (FAO-ICLARM Stock Assessment Tools, version 1.2.2) [17]. The parameter t0 was estimated using the empirical relationship of Pauly [21]: $\log10(-t0) = -0.3922 - 0.2752 * \log10(L\infty) - 1.038 * \log10(k)$.

The uncertainty of the growth parameters was evaluated using jackknife and bootstrap techniques [22]. A total of 3,000 bootstrap resamples were generated with a 95% percentile-type confidence interval using IBM SPSS Statistics (version 18.0 for Macintosh; IBM Corp., Armonk, NY, USA) [23]. The quality of the parameter fit was compared with previous studies using the growth performance index Φ' [24]: $\Phi' = \log10(k) + 2 * \log10(L\infty)$. Two sets of parameters were considered statistically similar when the coefficient of variation of Φ' was less than 4% [25,26].

2.4. Derived Biological Parameters

The critical age (tcrit) was estimated as the age at which the marginal variation of biomass per recruit is zero, using the expression derived from the Beverton and Holt yield-per-recruit model [27]: tcrit = t0 - (1/k) * ln(M/(M + b*k)). The maximum age was calculated using two methods: (a) Taylor [28]: A0.95 = t0 + (2.996/k), which corresponds to the time required to reach 95% of the theoretical maximum length; and (b) Pauly [21]: 3/k.

Recruitment length (Lr) and length at first capture (Lc) were determined based on 25% and 50% of the captured fish, respectively [30,31]. Subsequently, Lr and Lc were converted to age at first capture (Tc) and recruitment age (Ty) using the inverse von Bertalanffy equation [32]: Tc (or Ty) = t0 - (1/k) * ln(1 - (Lc or Lr)/L∞). The maximum length was also converted to maximum age (tmax) using the inverse von Bertalanffy equation [32].

2.5. Instantaneous Mortality Rates

Z was estimated using the following methods implemented in FiSAT II: (a) linearized catch curve [21]; (b) Jones and Van Zalinge method [33]; (c) Beverton and Holt method [30]; (d) Powell-Wetherall method [34,35]; and (e) Ssentongo and Larkin method [36].

M was estimated using 10 methods (Table 1). For the Pauly (1980) method, an average water temperature of 27 °C was used [37]. To select a reference M value, the criterion of Beverton and Holt [38] was applied, who suggest that for teleost fish, the M/k ratio should fluctuate between 1.5 and 2.5. The method that produced an M/k ratio closest to 2.0 was selected.

Table 1. Methods used to calculate natural mortality (M) of *Oreochromis aureus* in the Vicente Guerrero Reservoir, Tamaulipas, Mexico.

Method	Estimators
Beverton and Holt [39]	$M=\frac{bk}{e^{0.25}t_{max}{}^{k}{}_{-1}}$
Taylor [28]	$M=\frac{bk}{b+kt_0}$
Taylor [40]	$M=\frac{5}{t_{max}}$
Alverson & Carney [41]	$M = 3k(1-\alpha)/\alpha$
Pauly by length [29]	$M = 0.0066 - 0.279\log_{10}L_\infty + 0.6543\log_{10}k + 0.4634\log_{10}T$
Pauly by weigth [29]	$\log M = 0.2107 - 0.0824\log W_\infty + 0.6757\log K + 0.4687\log(T)$
Hoenig [42]	$\log(M) = \alpha - \beta \cdot \log t_{max}$
Alagaraja [43]	$M = \frac{-\ln(0.01)}{t_{max}}$
Djabali et al. [44]	$\log_{10}M = 0.0278 - 0.1172\log_{10}L_\infty + 0.5092\log_{10}k$
Hewitt & Hoening [45]	$M = 3/t_{max}$

Definitions: b = allometric exponent; k = growth coefficient (year^{-1}); tmax = maximum age; t0 = theoretical age at zero length; α = 0.62 (Alverson and Carney model); L∞ = asymptotic length; W∞ = asymptotic weight; T = water temperature (27 °C) [37]; α = 1.44 and β = 0.982 (Hoenig model); L∞, W∞, k, and t0 are parameters of the Von Bertalanffy growth model.

F was calculated by subtraction: F = Z - M, using the Z value from the Powell-Wetherall method [34,35] as it presented the best coefficient of determination, and the M value selected by the M/k criterion.

2.6. Exploitation Rate and Reference Points

E was calculated as E = F/Z. The obtained values were evaluated against two reference points: that of Gulland [15], which establishes an optimal level of E = 0.5 (F = M), and the more conservative one of Patterson [46], with E = 0.4 (F = 2/3 M).

2.7. Stock Assessment Using the Pauly and Soriano Quadrant Method

To determine the exploitation status and propose management strategies, the relative yield-per-recruit (Y′/R) model of Beverton and Holt [27] modified by Pauly and Soriano [47] was used. This analysis is based on the relationship between the exploitation coefficient (E = F/Z) and the selection ratio (lc = Lc/L∞). The results were projected onto an isopleth diagram divided into four quadrants (A, B, C, D), defined by the critical values of E = 0.5 and lc = 0.5, under the assumption of an M/k ratio > 2. The classification of the fishery status was carried out according to the criteria of Pauly and Soriano [47], based on the following quadrant definitions: a) Quadrant A (Underexploitation): E < 0.5; lc > 0.5 (capture of large specimens with low effort); b) Quadrant B (Developing fishery): E < 0.5; lc < 0.5 (capture of small organisms with low effort); c) Quadrant C (Developed fishery): E > 0.5; lc > 0.5 (capture of large specimens with high effort); and d) Quadrant D (Overexploitation): E > 0.5; lc < 0.5 (capture of small individuals with high effort).

2.8. Stock Assessment Using the Bayesian Biomass Model of Froese et al. [7]

To assess the stock status in a data-limited context, biological parameters and reference points were derived from the equations used in the length-based Bayesian biomass model (LBB) proposed by Froese et al. [7]. The input data for these equations (L∞, M/K, F/K, and Lc) were those obtained in this study. The following biological reference points were calculated: Optimal length (L_{opt}), which is the length at which the biomass of an unexploited cohort is maximum [7,48], estimated using the following equation: Lopt = L∞ (3/(3+M/K)); and optimal length at first capture (Lc_{opt}), which is the length that maximizes catch and biomass for a given fishing pressure [7,49], calculated using the following model: Lc_{opt} = (L∞ (2+3(F/M)))/((1+(F/M))(3+(M/K))).

The estimated fishery reference points were relative yield per recruit (Y′/R), relative catch per unit effort (CPUE′/R), unexploited biomass in the exploitable range ($B_0' > Lc / R$), current relative biomass (B/B_0), and a proxy for the biomass associated with Maximum Sustainable Yield ($(B_{MSY/B_0})_{proxy}$). The models for the aforementioned reference points were as follows:

$$\frac{\mathrm{Y'}}{\mathrm{R}}=\frac{\mathrm{F/M}}{1+\mathrm{F/M}}(1-\frac{\mathrm{L_c}}{\mathrm{L_\infty}})^{\mathrm{M/K}}[1-\frac{3(1-\mathrm{L_c/L_\infty})}{1+\frac{1}{\mathrm{M/K+F/K}}}+\frac{3(1-\mathrm{L_c/L_\infty})^2}{1+\frac{2}{\mathrm{M/K+F/K}}}-\frac{(1-\mathrm{L_c/L_\infty})^3}{1+\frac{3}{\mathrm{M/K+F/K}}}]$$

$$\frac{\mathrm{CPUE'}}{\mathrm{R}}=\frac{1}{1+\frac{\mathrm{F}}{\mathrm{M}}}(1-\frac{\mathrm{L_c}}{\mathrm{L_\infty}})^{\frac{\mathrm{M}}{\mathrm{K}}}[1-\frac{3(1-\mathrm{L_c/L_\infty})}{1+\frac{1}{\mathrm{M/K+F/K}}}+\frac{3(1-\mathrm{L_c/L_\infty})^2}{1+\frac{2}{\mathrm{M/K+F/K}}}-\frac{(1-\mathrm{L_c/L_\infty})^3}{1+\frac{3}{\mathrm{M/K+F/K}}}]$$

$$\frac{\mathrm{B_0'>L_c}}{\mathrm{R}}=(1-\frac{\mathrm{L_c}}{\mathrm{L_\infty}})^{\frac{\mathrm{M}}{\mathrm{K}}}[1-\frac{3(1-\mathrm{L_c/L_\infty})}{1+\frac{1}{\mathrm{M/K}}}+\frac{3(1-\mathrm{L_c/L_\infty})^2}{1+\frac{2}{\mathrm{M/K}}}-\frac{(1-\mathrm{L_c/L_\infty})^3}{1+\frac{3}{\mathrm{M/K}}}]$$

$$\frac{\mathrm{B}}{\mathrm{B_0}}=\frac{\mathrm{CPUE'/R}}{\mathrm{B_0'>L_c/R}}$$

Where: L∞ = asymptotic length; K = growth coefficient; Lc = length at first capture ($L_{50\%}$); F = instantaneous fishing mortality rate; and M = instantaneous natural mortality rate. For the proxy of the biomass associated with Maximum Sustainable Yield ($(B_{MSY/B_0})_{proxy}$), the above equations were re-run under optimal management assumptions (F/M = 1 and Lc = L_{c_opt}).

2.9. Froese Overfishing Indicators [8]

To complement the stock status assessment and provide a diagnosis based exclusively on the length structure of the catch, the three empirical indicators proposed by Froese [8], known as the "three simple rules" for sustainable fishing, were applied as follows:

Indicator 1: "Let them spawn" – This indicator evaluates the proportion of individuals in the catch that have reached the length at first sexual maturity ($L_{maturity}$). The objective is that 100% of the captured fish have had at least one opportunity to reproduce before being extracted. It is calculated as: $P_{mature} = ((N_{L \geq Lmaturity})/N_{total})) \times 100$; where: P_{mature} is the proportion of mature individuals; $N_{L \geq Lmaturity}$ is the number of individuals with length equal to or greater than the length at first sexual maturity; and N_{total} is the total number of individuals in the sample. For this indicator, the length at first sexual maturity ($L_{maturity}$) was estimated using the empirical relationship of Froese and Binohlan [50]: $\log10(L_{maturity}) = 0.9469 \times \log10(L\infty = 464) - 0.1162$

Indicator 2: "Let them grow" – This indicator evaluates the proportion of captured individuals that are within the optimal length range ($L_{opt} \pm 10\%$), where cohort biomass is maximum and yield per recruit is optimized. It is calculated as: $P_{opt} = (N_{0.9Lopt \leq L \leq 1.1Lopt})/ N_{total}) \times 100$; where: P_{opt} = percentage of captured individuals within the optimal length range; $N_{0.9Lopt \leq L \leq 1.1Lopt}$ = number of captured individuals whose length (L) falls between 90% and 110% of L_{opt}; and N_{total} = total number of individuals captured in the sample.

Indicator 3: "Let mega-spawners live" – This indicator evaluates the proportion of large individuals (mega-spawners) (P_{mega}) in the catch, which contribute disproportionately to recruitment and population resilience. The threshold length for mega-spawners is defined as $L_{mega} = 1.1 \times L_{opt}$. It is calculated as: $P_{mega} = (N_{L \geq 1.1Lopt})/ N_{total}) \times 100$; where: $N_{L \geq 1.1Lopt}$ = number of captured individuals whose length is greater than or equal to 110% of the optimal length; and N_{total} = total number of individuals in the sample.

Diagnostic criteria. A stock is considered sustainably exploited when all three criteria are simultaneously met: (a) $P_{mature} \approx 100\%$ (ideally, or at least > 50% as an acceptable minimum); (b) $P_{opt} \approx 100\%$ (ideally, or at least > 50% as an acceptable minimum); and (c) $P_{mega} \approx 30\text{-}40\%$ (indicative of an untruncated length structure). Conversely, failure to meet these criteria allows diagnosis of the following scenarios:

- Recruitment overfishing: when P_{mature} is significantly lower than 100%, indicating that fishing removes juvenile individuals before they can reproduce.
- Growth overfishing: when P_{opt} is significantly lower than 100%, indicating that fish are captured before reaching the length of maximum yield.
- Length structure truncation: when P_{mega} is lower than 30%, indicating the loss of the oldest and largest individuals.

2.10. Biological Reference Points According to Zhou et al. [10]

To establish fishing mortality reference points based on empirical evidence, the meta-analysis of Zhou et al. [10] was applied. This study, conducted on 245 fish populations worldwide, proposes estimators of fishing mortality associated with Maximum Sustainable Yield (F_{MSY}) and other reference points derived directly from M, according to taxonomic group. For teleosts (such as O. *aureus*), the estimated relationship is $F_{MSY} = 0.87 \times M$ (with a standard deviation of 0.05). Additionally, two complementary reference points were defined: F_{proxy}, an indirect estimator of F_{MSY}, approximately 15% lower than F_{MSY} (i.e., $F_{proxy} \approx 0.85 \times F_{MSY}$); and $F_{0.5r}$, the fishing mortality that reduces the reproductive potential per recruit to 50% of the virgin level, estimated as $F_{0.5r} = 0.5 \times M$. These reference points were compared with the fishing mortality estimated in the present study to assess the stock exploitation status.

2.11. Ecological Risk Assessment According to Zhou et al. [9,10]

As a complement to the previous methods, the data-limited assessment approach proposed by Zhou et al. [9,10] was used to establish biological reference points, evaluate exploitation status, and classify the ecological risk level of the O. *aureus* stock in the VGR. This approach allows estimating F from M and a vulnerability multiplier (ω) specific to the taxonomic group. Since tilapia is a bony fish (teleost), a value of $\omega = 0.87$ was used to calculate the following reference points [10]: $F_{nms} = 0.87 \times M$; $F_{lim} = 1.5 \times F_{nms}$ and $F+ = 2.0 \times F_{nms}$.; where: F_{nms} is the fishing mortality associated with maximum multispecies yield, F_{lim} is the limit fishing mortality (precautionary threshold), and F_{crash} is the fishing mortality at collapse (unsustainability threshold). Based on these reference points, an ecological risk category was assigned according to the comparison with the F estimated in the present study [9]. Table 2 presents the risk categories, their conditions, ecological consequences, and provisional management rules.

Table 2. Biological reference points, ecological risk categories, ecological consequences, and provisional management rules (modified from Zhou et al. [9]).

Risk category	Condition	Ecological consequence
Low (L)	$F < F_{nms}$	No overfishing. The population remains above 50% of the virgin level.
Medium (M)	$F_{nms} \leq F < F_{lim}$	Overfishing is occurring, but the population may be sustainable.
High (H)	$F_{lim} \leq F < F_{crash}$	May drive the population to very low levels in the long term.
Extremely high (E)	$F \geq F_{crash}$	The population is unsustainable in the long term – possibility of local extinction.

To account for uncertainty in the estimates, Zhou et al. [9] also define precautionary risk categories based on the lower limit of confidence intervals: (a) Precautionary medium risk (m): $F \geq \min(F_{nms})$ or $F + 90\%\ CI \geq F_{nms}$; (b) Precautionary high risk (h): $F \geq \min(F_{lim})$ or $F + 90\%\ CI \geq F_{lim}$; and (c) Precautionary extremely high risk (e): $F \geq \min(F_{crash})$ or $F + 90\%\ CI \geq F_{crash}$. In the present study, the risk category was assigned based on the point estimate of F and, complementarily, considering its 95% confidence interval for the precautionary approach.

2.12. Required Reduction in Fishing Effort

To estimate the fishing effort (f) reduction necessary to achieve sustainable levels, a direct proportionality relationship between F and f was assumed, expressed as $F = q \times f$, where q is the catchability coefficient [31,51]. Under this widely accepted assumption in fisheries science [52,53], the percentage reduction in effort required to decrease fishing mortality from a current value ($F_{current}$) to a target value (F_{target}) was calculated as follows: Fishing effort reduction = $((F_{current} - F_{target}) / F_{current}) \times 100$

This approach has been used in numerous fisheries management studies to recommend effort adjustments [54,55]. In the present study, the reference level $F_{MSY} = 0.339$ year^{-1} [10] was used as the target value, and complementarily, the collapse threshold $F_{crash} = 0.678$ year^{-1} was also considered.

3. Results

3.1. Growth

A total of 1,792 specimens were analyzed. Sizes ranged from 180 to 440 mm in total length and weights from 102 to 1,322 grams. The length-weight relationship model was exponential, expressed as follows: $TW = 0.00004125\ (TL)^{2.8964}$, with a coefficient of determination of $r^2 = 0.8659$ (Figure 2). The Student's t-test indicated that the slope value was significantly different from 3 ($t = -54.5704$, $p < 0.05$), denoting negatively allometric growth. The mean values of the von Bertalanffy growth parameters were: $L\infty = 464$ mm; $k = 0.2275$ year^{-1}; $t_0 = -0.3295$; and $Rn = 0.2261$, with standard errors of 3.216, 0.025, and 0.138, respectively. The Student's t-test indicated that the t_0 value was not significantly different from zero ($t = -5.503$, $p < 0.05$). The asymptotic weight ($W\infty$) was 1,356 g. The maximum age estimated by Taylor's method [28] was 12.84 years, and 13.18 years according to Pauly's model [29]. The critical age (t_{crit}) and critical length (L_{crit}), with their respective confidence intervals, were: 2.13 years (2.05 – 2.23 years) and 283 mm (275 – 292 mm), respectively. The Φ' test [24] yielded a value of 4.68, which is acceptable.

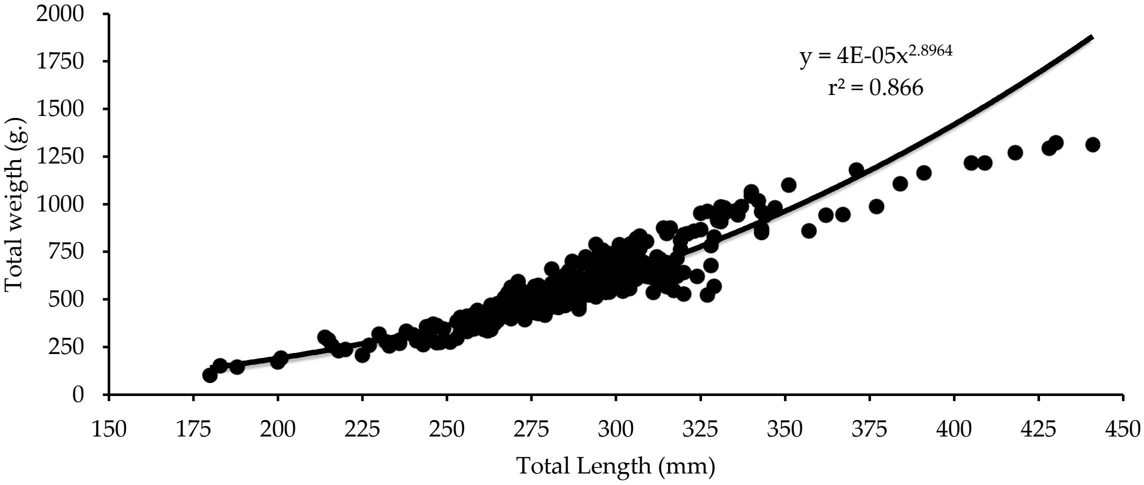

Figure 2. Length-weight relationship of tilapia (*Oreochromis aureus*) in the Vicente Guerrero Reservoir, Tamaulipas, Mexico.

3.2. Instantaneous Rates of Total (Z), Natural (M), and Fishing (F) Mortality, and Exploitation Rate (E)

These instantaneous rates varied as follows: Z = 3.591 – 3.799; M = 0.234 – 0.579; and F = 2.986 – 3.494 (Supplementary Material, Tables S1, S2, and S3). The model that presented the best fit for estimating Z was the Powell-Wetherall method [34,35] (Z = 3.591, r^2 = 0.9722). To select an M value to be used as input for the remaining models to assess the tilapia resource, the M/k criterion with a fluctuation range of 1.5 – 2.5 proposed by Beverton and Holt [30] was used, and the midpoint (M/k = 2) was defined as optimal. Consequently, the M value that generated the value closest to 2 was that proposed by Beverton and Holt [39], with a mean M value of 0.3894, a range of 0.3490 – 0.4283, and an M/k value of 1.711. The selection length ratio Lc/L∞ was 0.588, and the selection values were as follows: $L_{25\%}$ = 250 mm, $L_{50\%}$ = 273 mm, and $L_{75\%}$ = 295 mm; where the second corresponds to the length at first capture, assuming that 50% of the fish are vulnerable to capture. The E values ranged between 0.833 and 0.934 (Supplementary Material, Table S4) when using different Z and M values. Based on the selected Z (3.591) and M (0.3894) values, due to their better fit to the data, F was estimated at 3.302 and E at 0.892.

3.3. Stock Assessment According to Pauly and Soriano

The Lc/L∞ value of 0.588 places this fishery resource at an overfishing level according to the criterion of Pauly and Soriano [47]. In this study, using the values Lc/L∞ = 0.588 and E = 0.892, the tilapia stock in the VGR falls into Quadrant "D", which represents an exploitation regime where small fish are captured and a high level of fishing effort is present, indicating an overfished status, where possible interventions include increasing mesh size and reducing fishing effort.

3.4. Stock Assessment Using the LBB Model of Froese et al. [7]

The LBB model [7] yielded the following derived parameters: M/K = 1.71, F/M = 8.48, F/K = 14.50, L_{opt} = 297 mm, Lc_{opt} = 285 mm, Y'/R = 0.046, CPUE'/R = 0.0054, B_0'/R = 0.1766, B/B_0 = 0.057 (95% CI: 0.042–0.072), and $(B_{MSY/B_0})_{proxy}$ = 0.20. The B/B_0 value (0.057) is well below the sustainability threshold (>0.4), F/M (8.48) exceeds the reference level (F/M = 1) by 8.5 times, and Lc/Lc_{opt} = 0.96 is less than 1. In conclusion, the stock is in biological collapse: biomass is only 5.7% of unexploited biomass, fishing pressure is unsustainable, and capture length is suboptimal, requiring urgent management measures.

3.5. Froese Overfishing Indicators [8]

Based on the length structure of the catch (n = 1,792 specimens), the three stock health indicators proposed by Froese [8] were calculated: $L_{maturity}$ = 290 mm, L_{opt} = 297 mm, and $L_{mega\text{-}spawners}$ = 326 mm.

None of the three indicators met the sustainability threshold (Table 3). Only 7.5% of captured individuals exceeded $L_{maturity}$, meaning that more than 92% of the catch are juveniles that have not had the opportunity to reproduce, evidencing severe recruitment overfishing. Only 4.8% of individuals were within the L_{opt} range (267–326 mm), while the rest were captured before reaching the length that maximizes yield per recruit, constituting a clear diagnosis of growth overfishing. Finally, mega-spawners (> 326 mm) represented only 2.6% of the catch, well below the 30-40% considered indicative of a healthy population [8], reflecting severe truncation of the size structure and the loss of larger individuals, which contribute disproportionately to recruitment.

Table 3. Froese overfishing indicators [8] for *Oreochromis aureus* in the Vicente Guerrero Reservoir.

Indicator	Froese's rule	Value (%)	Sustainability threshold	Status
1. Let them spawn	Let them spawn (% ≥ $L_{maturity}$)	7.5	≥ 50% (minimum)	Not met
2. Let them grow	Let them grow (% within L_{opt} ± 10%)	4.8	≥ 50% (minimum)	Not met
3. Let mega-spawners live	Let mega-spawners live (% ≥ L_{mega})	2.6	30 – 40%	Not met

3.6. Biological Reference Points According to Zhou et al. [10]

Based on the estimated M (0.3894 year⁻¹), the Zhou et al. [10] reference points were: F_{MSY} = 0.339 year⁻¹, F_{proxy} = 0.288 year⁻¹, and $F_{0.5r}$ = 0.195 year⁻¹. The F estimated in the present study (3.302 year⁻¹) exceeded these reference points by 9.7, 11.5, and 16.9 times, respectively, confirming a state of severe overexploitation.

3.7. Ecological Risk Assessment (Zhou et al. [9,10])

The biological reference points of Zhou et al. [10] were: F_{nms} = 0.339 year⁻¹ (maximum multispecies yield), F_{lim} = 0.508 year⁻¹ (biological limit), and F_{crash} = 0.678 year⁻¹ (collapse threshold). The estimated F exceeded these reference points by 9.7, 6.5, and 4.9 times, respectively. Given that F ≥ F_{crash}, the stock is classified in the extremely high ecological risk category (E), which implies that the population is unsustainable in the long term with a possibility of local extinction (Zhou et al. [9]). This diagnosis remains even under a precautionary approach, since the lower limit of the 95% confidence interval of F (2.97 year⁻¹) is still well above F_{crash} (0.678 year⁻¹).

3.8. Fishing Effort Reduction

Based on the proportionality principle between F and fishing effort (f) ($F = q \times f$; [31]), the effort reduction required to achieve sustainable exploitation levels was estimated. Using the reference value F_{MSY} = 0.339 year⁻¹ [10] as the target, the required effort reduction was nearly 90%. Considering a more conservative approach with the collapse threshold F_{crash} = 0.678 year⁻¹ as an intermediate target, the required reduction was 80%. Therefore, a fishing effort reduction of 80-90% is required to bring F to levels that allow stock recovery.

4. Discussion

The present study integrated multiple methodological approaches to assess the exploitation status of the Oreochromis aureus stock in the Vicente Guerrero Reservoir, Tamaulipas, Mexico. The results obtained through the exploitation rate (E = 0.892), the LBB model (B/B_0 = 0.057; F/M = 8.48), Froese's indicators [8], and the ecological risk assessment of Zhou et al. [9,10] converge on a

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unanimous diagnosis: the stock is in biological collapse, with biomass reduced to less than 6% of its virgin level and fishing pressure exceeding the sustainable level by more than eight times.

4.1. Consistency Among Methods and Comparison with Previous Studies

The convergence of independent methods (traditional, Bayesian, and empirical) strengthens the robustness of the diagnosis. The estimated exploitation rate (E = 0.892) far exceeds the Gulland reference point [15] (E = 0.5) and the precautionary limit of Patterson [46] (E = 0.4), indicating unsustainable fishing pressure. This value is comparable to those reported for tilapia populations in other Mexican reservoirs, such as Sanalona Reservoir in Sinaloa State [3], and exceeds the values reported for Aguamilpa Reservoir in Nayarit State [4].

The LBB model estimated a relative biomass (B/B_0 = 0.057) that is substantially below the sustainability threshold of 0.4 proposed by Froese et al. [7]. This value is among the lowest reported in the literature for tilapia populations assessed with this method, and is consistent with the F/M ratio of 8.48, indicating that F is more than eight times higher than M. In comparison, studies on tilapia populations in Africa and Asia have reported B/B_0 values between 0.2 and 0.6 for overfished stocks, and F/M values between 1.5 and 3.0 [11,12]. The magnitude of overexploitation in the VGR is, therefore, exceptionally severe.

More specifically, recent studies that have applied the same LBB method to cichlid populations confirm the severity of the case. Islam et al. [13] assessed O. *niloticus* in the Ganges River (Bangladesh) using LBB and reported B/B_0 = 0.35 and F/M = 2.8, values indicating overfishing but with a biomass still six times higher than that found in the present study. Similarly, Saha et al. [14] found B/B_0 = 0.28 and F/M = 3.2 for the same species in the Talma River (Bangladesh). These results highlight the urgency of implementing management measures in the VGR.

Froese's indicators [8] provided a complementary diagnosis based exclusively on the length structure of the catch. The proportion of mature individuals in the catch (7.5%) is drastically below the 50% threshold recommended as an acceptable minimum [8], indicating severe recruitment overfishing. This means that more than 92% of the captured fish are juveniles that have never had the opportunity to reproduce. This finding is consistent with the low proportion of individuals at optimal length (4.8%) and of mega-spawners (2.6%), the latter being well below the 30-40% considered indicative of a healthy population [8]. The absence of mega-spawners suggests severe truncation of the size structure, a classic symptom of collapsed fisheries where the oldest and most fecund individuals have been eliminated.

The ecological risk assessment of Zhou et al. [9,10] classified the stock in the extremely high risk category (E), with F exceeding the collapse threshold (F_{crash} = 0.678 year^{-1}) by 4.9 times. According to Zhou et al. [9], this category implies that the population is unsustainable in the long term, with a possibility of local extinction.

4.2. Validation of the Research Hypothesis

The null hypothesis proposed in this study postulated that the stock was exploited at a sustainable level ($E \leq 0.5$, $B/B_0 \geq 0.4$, low or medium ecological risk). The results obtained strongly reject this hypothesis. The alternative hypothesis, which proposed a state of overexploitation or biological collapse ($E > 0.5$, $B/B_0 < 0.4$, high or extremely high ecological risk), is accepted. The O. *aureus* stock in the VGR is not only overexploited but is also in a state of imminent biological collapse.

4.3. Implications of the Findings for Fisheries Management

The implications of these findings are critical for the sustainability of the fishery and the communities that depend on it. Tilapia contributes more than 90% of the value and volume of the total catch in the VGR [1], so the collapse of this stock could have significant socioeconomic consequences for the inhabitants of the municipalities of Padilla, Güemes, Casas, Abasolo, Jiménez, and Soto la Marina in the State of Tamaulipas.

The current length at first capture (Lc = 273 mm) is lower than the optimal length at first capture estimated by the LBB model (Lc_{opt} = 285 mm) and well below the length at first sexual maturity (Lm = 290 mm). This means that the current fishing gear used in practice (gillnets with mesh openings of 4.0 and 4.5 inches) is capturing individuals that have not reached sexual maturity. The Official Mexican Standard NOM-060-SAG/PESC-2014 [55] establishes a minimum capture length of 280 mm for tilapia in the VGR, but our results indicate that even this limit is insufficient. It is recommended to increase the minimum capture length to at least 290 mm (length at first maturity) or ideally to 297 mm (optimal length).

Furthermore, the current F (F = 3.302 $year^{-1}$) must be drastically reduced. The reference level for maximum sustainable yield (F_{MSY} = 0.339 $year^{-1}$) is approximately 10 times lower than the current F. The magnitude of the required fishing effort reduction (80-90%) is considerable but consistent with other studies on overexploited artisanal fisheries. For example, Worm et al. [56] documented that effort reductions of 50-80% were necessary to reverse the collapse of several fisheries globally. Melnychuk et al. [57] and Hilborn et al. [58] indicate that drastic effort reductions (70-90%) are often required in stocks that have fallen below 10% of their virgin biomass, as is the case with tilapia in the Vicente Guerrero Reservoir (B/B_0 = 0.057).

4.4. Study Limitations

Despite the robustness of the diagnosis, this study has several limitations that must be considered. First, the length frequency data used correspond to the period 2020-2021, but a continuous time series is not available to evaluate trends in biomass or mortality over time. This limits the ability to distinguish between interannual variability effects and long-term trends.

Second, the LBB method assumes that length frequencies are representative of the length composition of the exploited stock and that there are no extremely strong recruitment pulses that could bias the estimates [7]. Although several mesh sizes were used to capture a wide size range, the absence of very small individuals (less than 180 mm) in the samples could be due both to gear selectivity and to poor recruitment, exacerbated by overfishing.

Third, the estimation of M using the Beverton and Holt method [38] was based on the M/k ratio, which assumes equilibrium conditions. Although this value was selected because it met the plausibility criterion (M/k = 1.71 within the 1.5-2.5 range), different methods for estimating M yielded a range of 0.23 to 0.58 $year^{-1}$. This range of uncertainty could affect the absolute values of F and B/B_0, but it does not alter the qualitative conclusion of severe overexploitation, since even the lowest M value (0.23 $year^{-1}$) results in $F/M > 10$ and $B/B_0 < 0.1$.

Finally, the study did not consider the possible existence of environmental effects (such as fluctuations in water level, temperature, or water quality) on the population dynamics of tilapia. Future studies should integrate environmental variables into assessment models to better understand the factors contributing to stock collapse.

4.5. Future Research Lines

Based on the findings of this study, the following future research lines are suggested:

- Continuous monitoring: Implement a fishery monitoring program that generates annual time series of length frequencies, catch, and effort to assess the stock’s response to management measures.
- Recruitment assessment: Conduct specific studies on recruitment and juvenile survival, including sampling in nursery areas with finer mesh fishing gear.
- Integration of environmental variables: Incorporate assessment models that include environmental factors (temperature, water level, primary productivity) to understand their influence on population dynamics.
- Socioeconomic assessment: Conduct studies on the socioeconomic impacts of fishery collapse on riparian communities, as well as the viability of alternative management measures.

- Application of complementary methods: Apply other data-limited assessment methods such as LB-SPR (Length-Based Spawning Potential Ratio [59]), CMSY (Catch-Maximum Sustainable Yield [60]), or OCOM (One-step Catch-Only Model [61]) to compare and validate the results obtained.

5. Conclusions

Based on the integration of multiple assessment methods (exploitation rate, LBB model, Froese indicators [8], and Zhou's ecological risk assessment [9]), the following conclusions are drawn:

a) Rejection of the null hypothesis: The hypothesis that the *Oreochromis aureus* stock in the Vicente Guerrero Reservoir is at a sustainable exploitation level is rejected. The alternative hypothesis of severe overexploitation or biological collapse is accepted.

b) Stock status: The stock is in biological collapse, characterized by:

- Exploitation rate E = 0.892 (well above the 0.5 limit)
- Relative biomass $B/B_0 = 0.057$ (only 5.7% of virgin biomass)
- Relative fishing mortality F/M = 8.48 (8.5 times higher than sustainable)
- Proportion of mature individuals in the catch = 7.5% (recruitment overfishing)
- Proportion of mega-spawners = 2.6% (truncated size structure)
- Extremely high ecological risk (category E), with possibility of local extinction

c) Causes of overexploitation: The main causes of the collapse are: (a) excessive fishing mortality (F = 3.302 year^{-1}), which exceeds the collapse threshold by 4.9 times; and (b) a length at first capture (Lc = 273 mm) lower than the length at first sexual maturity (Lm = 290 mm) and the optimal length (L_{opt} = 297 mm), resulting in massive juvenile catch.

d) Management recommendations: To avoid the total collapse of the fishery and allow stock recovery, the following urgent measures are recommended:

- Increase the minimum capture length from 280 mm to at least 290 mm (maturity length) or ideally to 297 mm (optimal length). This implies respecting the use of the legally established gillnet with 5-inch (127 mm) mesh opening.
- Reduce fishing effort by at least 80% to bring current fishing mortality (F) closer to the reference level F_{MSY} = 0.339 year^{-1}.
- Implement temporary fishing bans during the main reproductive season.
- Establish fishery refuge areas where extraction is prohibited, allowing the recovery of mega-spawners.
- Strengthen surveillance and compliance with current fishing regulations.

e) Methodological contribution: This study demonstrates the utility of integrating multiple data-limited methods (LBB, Froese indicators [8], Zhou's risk assessment [9]) to obtain a robust diagnosis of stock status when long time series of catch or effort are unavailable. The convergence of independent methods strengthens confidence in the results and provides a solid basis for decision-making.

f) Urgency of action: Given the critical stock status ($SPR < 0.01$, $B/B_0 < 0.06$, extremely high risk), immediate management intervention is required. Each year of delay in implementing measures increases the probability of total collapse, with irreversible socioeconomic consequences for the communities that depend on this fishery.

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