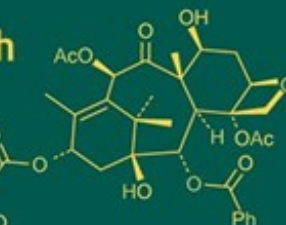


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Length-based population dynamics and stock assessment of *Notopterus notopterus* (Pallas, 1769) from a tropical lentic ecosystem

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ABSTRACT

The study evaluates the biometrics, growth, and exploitation status of *Notopterus notopterus* (bronze featherback) with the objective of building a quantitative base for sustainable fishery management in Pench Reservoir, Maharashtra. A sample of 400 fish was collected over a period of eight months, and LWR, Fulton's K-condition, and population dynamics were computed from the length-based analysis. The pooled LWR depicts that there exists a highly significant positive allometric growth ($b = 3.2665$), which implies favourable lentic environment where the fish stock can grow relatively deep body due to its length. The average K-value ($K = 0.7858$) showed fluctuations on a temporal basis with reductions recorded during the onset of summer season, implying the effects of the environment and physiological stressors on the fish stock. The growth and mortality parameters were evaluated through the TropFishR method using high resolution 1 cm binned data. A simulated annealing procedure gave the asymptotic length (L_{∞}) of 37.22 cm and growth parameter (K) of 0.505 yr^{-1} . With the replacement of traditional temperature-based assumptions for mortality by growth based empirical estimates, mortality parameters were found out as $Z = 1.21 \text{ yr}^{-1}$, $M = 0.74 \text{ yr}^{-1}$, and $F = 0.47 \text{ yr}^{-1}$. Length-Structured Virtual Population Analysis together with Beverton and Holt relative yield per recruit model showed that the present exploitation rate ($E = 0.39$) is consistently below the target biological reference point ($F_{0.1}$ $F_{0.1} = 0.65 \text{ yr}^{-1}$). The stock of *N. notopterus* can be said to be sustainably exploited with mortality being natural rather than the artisanal harvesting. It is suggested to maintain the present gear selectivity to keep the juvenile cohorts alive.

Keywords: Population dynamics, *Notopterus notopterus*, Sustainability, Pench Reservoir

1. Introduction

The bronze featherback, *Notopterus notopterus* (Pallas, 1769), is a teleost fish of economic and ecological significance with a broad distribution in Indian subcontinent waters, comprising rivers, flood plains, and reservoirs (Gupta *et al.*, 2022) [1]. It has significant nutritional value and is consumed extensively, making it one of the target species in inland commercial and artisanal fisheries (Gupta *et al.*, 2022) [1]. Inland capture fisheries are globally recognized as critical for food security and artisanal livelihoods, yet they remain highly vulnerable to overexploitation and habitat degradation (Welcomme *et al.*, 2010; Cooke *et al.*, 2016) [3, 2]. Furthermore, freshwater ecosystems harbour disproportionately high biodiversity that currently faces severe and compounding conservation challenges (Dudgeon *et al.*, 2006) [4]. The sustainable management of *N. notopterus* populations in lentic environments requires constant monitoring of the biological and population dynamics indicators because they are susceptible to regional variation in the environment and the fishing pressure (Chandran *et al.*, 2020) [5].

Biometry of the fishes is crucial for proper management of the fisheries. Foundational stock assessment heavily relies on these quantitative baselines to evaluate population health and structure (Hilborn *et al.*, 1992) [6]. Establishing accurate, region-specific biometric scaling is also increasingly emphasized by global repositories like FishBase to support broader ecosystem-level modelling (Froese *et al.*, 2026) [7]. The length-weight relationship (LWR) is a key formula that can be used to estimate biomass from lengths, analyse ontogenetic growth patterns (isometric vs allometric) and estimate the condition of the fish stock in the habitat (Froese, 2006) [8]. For fish with unique morphological features like *N. notopterus* with a laterally compressed body, which ends with an uninterrupted anal-caudal fin, a precise definition of what to measure, that is, whether to use Total Length (TL) or Standard Length (SL), is necessary for consistency in internal mathematics during biomass estimation (Froese, 2006) [8]. Additionally, Fulton's condition factor (K) helps to estimate the well-being and health of the fish at different seasons (Le Cren, 1951) [9]. Seasonal variations in K for the pooled sexes should be interpreted carefully, considering the impacts of the combination of local prey

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availability, changes in water level, environmental stress and reproduction on K (Le Cren, 1951; Gupta *et al.*, 2022) [9, 1].

Apart from biometrics, evaluation of the population dynamics parameters is crucial for effective management of the fisheries so as to prevent overexploitation and ensure the survival of the population (Mildenberger *et al.*, 2017) [10]. In many cases where the fish lives in tropical inland waters and the determination of the age through hard parts is impossible or very expensive, LFD becomes very reliable (Mildenberger *et al.*, 2017) [10]. Previously, length-based stock assessments involved computations carried out using older-generation software. However, today's statistical computing has provided us with much more rigorous tools. The TropFishR software package in the R programming language uses sophisticated optimization methods such as Simulated Annealing in Electronic Length Frequency Analysis (ELEFAN) for very precise and reliable estimation of growth and mortality (Mildenberger *et al.*, 2017) [10]. This modern computational approach extends classic organic growth theories (Von Bertalanffy, 1938) [11] and foundational length-frequency paradigms (Sparre *et al.*, 1998) [12] by successfully overcoming the subjective biases inherent in earlier graphical assessment methods (Taylor *et al.*, 2017) [13].

Furthermore, the quality of stock assessment determines the results of diagnostics of the stock's exploitation status. The ability to precisely separate total mortality (Z) into natural mortality (M) and fishing mortality (F) is crucial. Modern fisheries science has abandoned outdated empirical equations that systematically overestimated natural mortality (Pauly, 1980) [14] and moved towards more contemporary and life-history-based mortality estimators, such as that proposed by Then *et al.* (2015) [15]. At the same time, determining the actual exploitation status requires abandoning simplistic approaches and determining stock-specific Biological Reference Points (BRPs) through Y/R (yield-per-recruit) and B/R (biomass-per-recruit) modelling (Beverton *et al.*, 1966) [16]. Establishing such definitive reference points is a cornerstone of quantitative population dynamics (Beverton *et al.*, 1957) [17] and ensures that harvest strategies remain ecologically viable without crossing into growth or recruitment overfishing thresholds.

Pench Reservoir, located in Nagpur district, Maharashtra state, is an important inland water body home to various aquatic organisms and local fishing industry. However, there is a lack of baseline quantitative information on demographic characteristics, growth performance, and current exploitation status of *N. notopterus* fish in Pench Reservoir. In order to formulate appropriate sustainable harvest strategies, it is required to move from generalized assumptions about a species to scientifically rigorous evaluation of the stock. Therefore, this study will provide a locally-relevant baseline assessment of *N. notopterus* fishery in Pench Reservoir by moving from generalized assumptions about the species. Specifically, the study will define the species' growth pattern using strictly standardized length-weight relationships and evaluate its physiological condition by analysing temporal changes in Fulton's condition factor. Using high-resolution length-frequency data and TropFishR analysis software, the study will estimate key population dynamic parameters, namely von Bertalanffy growth parameters. Finally, the use of contemporary empirical estimators, length-structured Virtual Population Analysis (VPA), and Y/R modelling will provide a precise estimation of mortality rates necessary for diagnosing the exploitation status of the stock.

2. Materials and methods

2.1 Data collection and standardization

Length data of *Notopterus notopterus* were collected during commercial fish catches at Pench Reservoir, Nagpur, Maharashtra, within an eight-month period of continuous sampling (from November 2022 till June 2023). In order to satisfy the strong assumptions of length-based population modelling and to ensure that the sampled data correctly reflect the demographic extraction of the fishery, sampling procedure was organized in a way that would allow to get randomized subsam-

ples of fish uncultured directly from total daily artisanal fish catch using various fishing gear.

In total, 400 valid samples were used in the quantitative matrix. For every individual, measurements of Total Length (TL, in cm up to 0.1 cm from the tip of the snout to the end of the caudal fin) and total body weight (W, in grams) were taken. Even though standard length (SL) was measured as well, only TL was used in all further regressions, calculations of virtual population, and graphical presentation to avoid morphometric mistakes caused by strongly elongated structure of anal-caudal fin of the species (Froese, 2006) [8]. In order to get enough mathematical precision and to reduce algorithmic artifacts during optimization process, the length measurements in raw form were divided into 10 mm (1 cm) class intervals to build the length-frequency (LFQ) matrix (Mildenberger *et al.*, 2017) [10].

2.2 Length-weight relationship and condition factor

The length-weight relationship (LWR) was modelled using the classical allometric power function $W = aL^b$, where W stands for total body weight (g), L for total length (centimeters), a is scaling constant, and b is allometric growth coefficient (Froese, 2006) [8]. The parameters a and b were calculated using ordinary least squares (OLS) linear regression of log-transformed values: $\log_{10}(W) = \log_{10}(a) + b \log_{10}(L)$. The 95% confidence interval was calculated for b, and Student's *t*-test was used to check whether the estimated growth coefficient is significantly different from the theoretical value of $b = 3.0$ (Froese, 2006) [8]. Validation of the growth pattern (parameters a and b) was used further uniformly in all biomass estimation steps.

Fulton's condition factor (K) was determined monthly as the temporal indicator of physiological robustness of the stock using the equation $K = 100(W/L^3)$ (Le Cren, 1951) [9]. The fact that indices of condition obtained using combined-sex approach equalize physiological demands of spermatogenesis and oogenesis implies that temporal fluctuations in K should be interpreted as a whole. In other words, K fluctuations were considered as the indicators of overall physiological impact of successful foraging, variable hydrological regime of the reservoir and other environmental factors, not limited to gonadal maturity indices.

2.3 Length-based population dynamics

Population dynamics studies were conducted using the TropFishR package in the R statistical computing environment (R Core Team, 2023; Mildenberger *et al.*, 2017) [18, 10]. VBGF parameters – specifically asymptotic length (L_∞) and growth coefficient (K) – were estimated using ELEFAN module. SA was used to perform global optimization for parameters in 1 cm-binned LFQ matrix. The objective function R_n was applied to check the adequacy of the algorithm fit. Total mortality (Z) and its confidence interval were estimated using the descending right arm of a length-converted catch curve. Taking into account the systematic positive bias of estimators based on environmental temperature (Pauly, 1980) [14], natural mortality (M) was estimated using the statistically reliable growth-based estimator described by Then *et al.* (2015) [15]:

$$M = 4.118 \times K^{0.73} \times L_\infty^{-0.33}$$

Fishing mortality (F) was then calculated as the difference between total mortality and natural mortality ($F = Z - M$) which allowed estimating the contemporary exploitation rate ($E = F/Z$) (Beverton *et al.*, 1966) [16]. Length-structured Virtual Population Analysis (VPA) was used to allocate natural losses and fishing extraction among separate cohorts by harmonizing allometric parameters of fish within the same analysis. Finally, to estimate the current status of the fishery using the modern approach, Beverton and Holt Y/R modelling was applied to calculate $F_{\max}$ and $F_{0.1}$ Biological Reference Points (Beverton *et al.*, 1966) [16].

3. Results

3.1 Size and weight composition

Table 1. Summary of descriptive biometric parameters for *Notopterus notopterus*.

Parameter	Mean $\pm$ SD	Minimum	Maximum
Total length (cm)	24.45 $\pm$ 4.11	16.3	36.0
Standard length (cm)	22.41 $\pm$ 3.60	15.0	32.5
Weight (g)	125.67 $\pm$ 73.22	30	360
Fulton's <i>K</i>	0.7858 $\pm$ 0.1542	0.0504	1.9033

The sampled population (*N. notopterus*; $n = 400$) covered the wide range of body sizes, which were representative of the reservoir population demographics without introducing any algorithmic artefacts or manipulating the extreme values of variables. Total Length (TL) varied from 16.3 to 36.0 cm, and had an average value of 24.45 $\pm$ 4.11 cm. The total body mass was distributed between 30 and 360 g, having an average value of approximately 125.7 g throughout the study.

3.2 Pooled length–weight relationship

The length–weight regression resulted in the following formula: $W = 0.003323 \times TL^{3.2665}$ ($R^2 = 0.9088$, $r = 0.9533$). It shows a very high level of statistical significance and robust positive correlation between total body length and body weight. The 95% confidence interval of the allometric coefficient (b) equals to 3.1645–3.3684. The Student's t -test shows that the b value is statistically significantly greater than 3.0 (the theoretical cubic value; $t = 5.139$, $p < 0.001$). Hence, the sample has a positive allometry meaning that the individuals from Pench Reservoir tend to become relatively deep-bodied with increasing length (Figure 1).

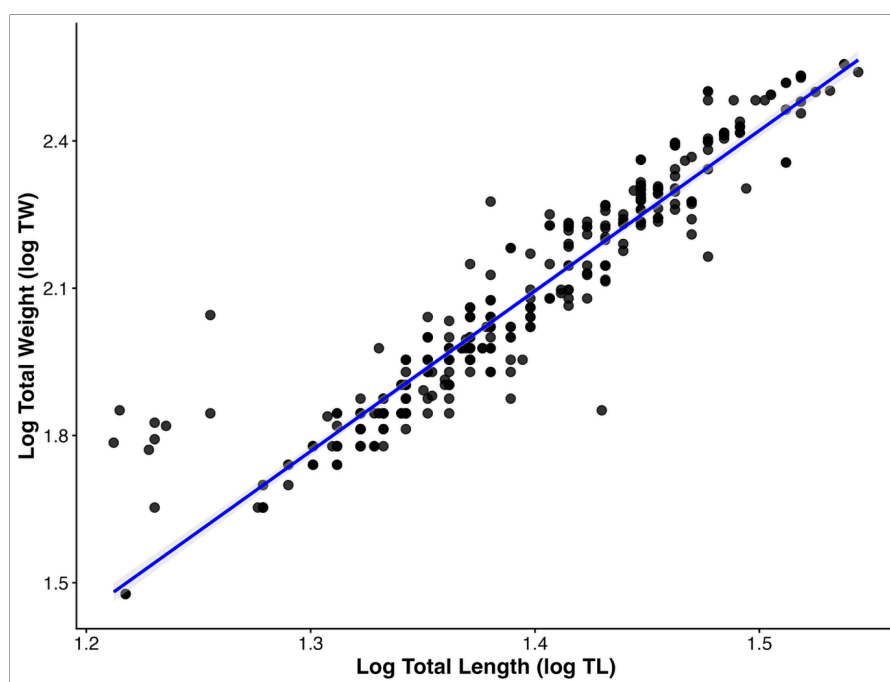


Figure 1. Log-transformed relationship between total length (log TL) and total weight (log TW) for *Notopterus notopterus* from Pench Reservoir.

3.3 Monthly variation in LWR

The analysis of the length–weight relationship on a monthly basis allowed observing the natural changes in the value of the allometric coefficient (b) with time. It varied from 1.4000 in April to its maximum – 3.5071 in June (Table 2). All months excepting November and April

had values of b exceeding 3.0, thus causing the positive allometry of the whole population. Deviations in November and April may be caused by changing feeding intensity, seasonal changes in environmental factors of the reservoir, or utilization of somatic energy reserves due to reproduction.

Table 2. Monthly length-weight relationship parameters for *Notopterus notopterus*.

Month	n	TL range (cm)	Weight range (g)	a	b
November	50	23.5–33.0	141–291	0.064415	2.3989
December	50	16.5–31.0	30–261	0.002976	3.2968
January	50	16.5–28.0	30–230	0.003212	3.2671
February	50	20.5–34.5	70–360	0.003106	3.3071
March	50	18.9–35.0	45–347	0.003526	3.2188
April	50	16.3–26.5	45–125	1.086394	1.4000
May	50	16.5–28.0	30–230	0.002218	3.3839
June	50	19.5–34.5	55–360	0.001518	3.5071

3.4 Monthly variation in condition factor (K)

Table 3. Monthly variation in Fulton's condition factor (K) for *Notopterus notopterus*.

Month	n	Mean K	SD	K range
November	50	0.8728	0.0822	0.6778–1.0865
December	50	0.7660	0.1235	0.3648–1.0477
January	50	0.7382	0.0794	0.6209–1.0477
February	50	0.8705	0.1394	0.5407–1.3672
March	50	0.6878	0.1100	0.0504–0.8861
April	50	0.8191	0.2842	0.5100–1.9033
May	50	0.7320	0.0762	0.6209–1.0477
June	50	0.8004	0.1234	0.6149–1.1741

In this study, Fulton's condition factor (K) served as an indicator of physiological state and relative health of fish within the stock. The population mean condition factor was 0.7858 ± 0.1542 . Temporal analysis showed clear monthly fluctuations with maximum K values occurring in post-monsoon and winter months of November (0.8728) and February (0.8705). The minimum value of the condition factor was recorded at the beginning of summer, in March (0.6878). As in-

dices were calculated in mixed sexes and condition factors do not depend on sex and maturity status, the evident decrease in K values is likely to be caused by the general physiological response to the environment. It is not solely due to the energy demands of gametogenesis but also depends on various environmental stressors, prey abundance, and changing thermal conditions of the Pench Reservoir (Gupta *et al.*, 2022) [1].

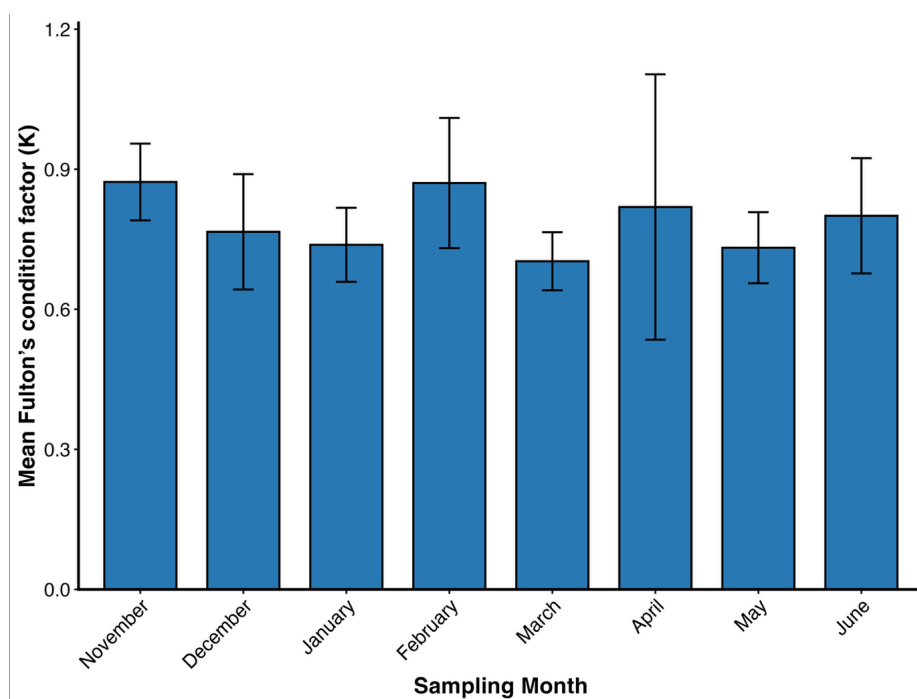
**Figure 2.** Monthly variation in mean Fulton's condition factor (K) of *Notopterus notopterus* from November to June.

Figure 2 illustrates the dynamic nature of the condition factor across the sampling period. The periodic decline in K values during the onset of summer (March and May) suggests a physiological response to en-

vironmental stressors, changes in the availability of preferred prey items, or the mobilization of somatic energy reserves for reproductive maturation.

3.5 Growth parameters and model optimization

The growth parameters were estimated in an accurate manner using the TropFishR ELEFAN simulated annealing (SA) method. The resolution of the length-frequency matrix was chosen to be 1 cm to avoid the loss of modal structure of the data. The optimal von Bertalanffy growth parameters were found with asymptotic length (L_{∞}) of

37.22 cm and growth coefficient (K) of 0.505 yr^{-1} . The quality of convergence and accuracy of mathematical model for these parameters were confirmed by R_n score, thus providing reliable input for mortality estimation. The growth performance index (ϕ') of the studied *N. notopterus* was 2.84, which means the moderate to fast growth rate typical for this species in favourable lentic environments (Figure 3).

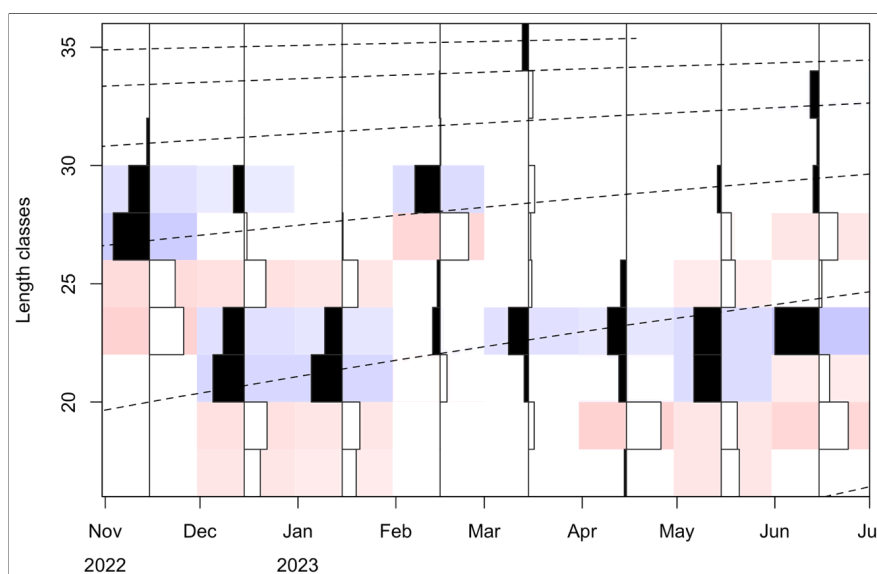


Figure 3. von Bertalanffy growth curves for *Notopterus notopterus* fitted over the length-frequency data using TropFishR.

3.6 Mortality and exploitation rate

The total mortality (Z) and its variance were estimated based on length-converted catch curves of the pooled LFQs data and were $1.21 \pm 0.11 \text{ yr}^{-1}$ (Figure 4). In order to deal with overestimation problems inherent to traditional temperature-based models, the natural mortality (M) was calculated based on the contemporary growth-based empirical estimator suggested by Then *et al.* (2015) [15]. Based on previ-

ously obtained parameters ($L_{\infty} = 37.22 \text{ cm}$ and $K = 0.505$), M was estimated to be 0.74 yr^{-1} .

Therefore, the fishing-induced mortality ($F = Z - M$) was quantitatively obtained as 0.47 yr^{-1} . The exploitation rate ($E = F/Z$) of *N. notopterus* in Pench Reservoir is 0.39. The current exploitation status indicator reveals that although fishing continues, the fish stock is not under the threat of recruitment overfishing, as the natural mortality dominates the mortality of the total population.

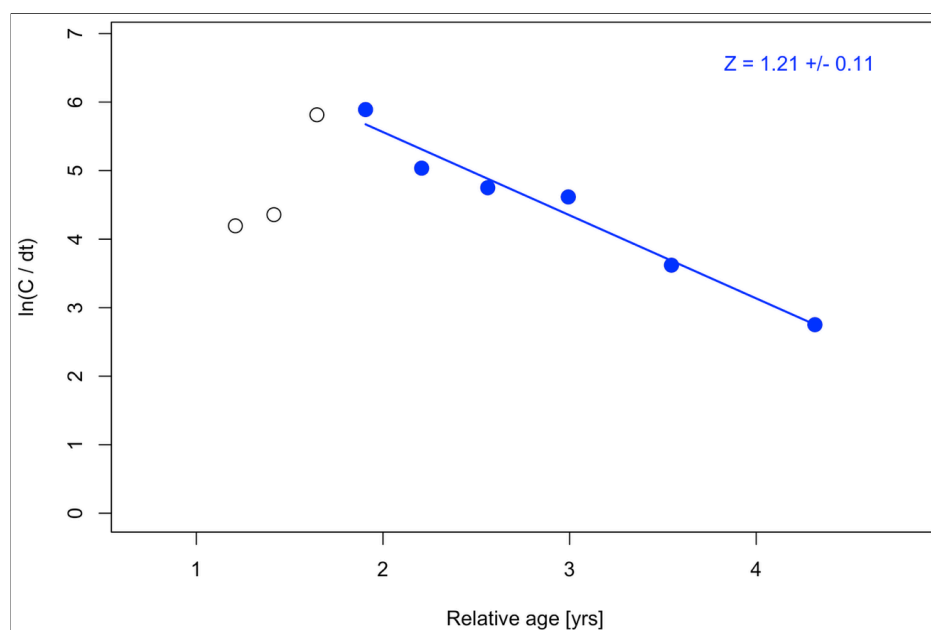


Figure 4. Length-converted catch curve for estimating total mortality (Z) of *Notopterus notopterus*.

3.7 Length-structured virtual population analysis (VPA) and reference points

Length-structured VPA was performed to quantify the population and separate natural mortality from fishing-induced mortality in various size groups. Updated total length-based positive allometric length-

weight coefficients ($a = 0.003323$, $b = 3.2665$) were used to estimate the biomass correctly.

The VPA output shows that there are the highest number of survivors in the small-size length classes and decreasing proportionally with increasing body sizes of fish. Taking into account low exploitation rate of the stock, one can say that mortality of the stock is mainly due to

natural causes in all intermediate length size classes. The contribution of fishing mortality (F) is marginal throughout the whole population and reaches its highest point in the length size classes 23 cm and 29 cm and drops to almost zero among the largest fish (Figure 5).

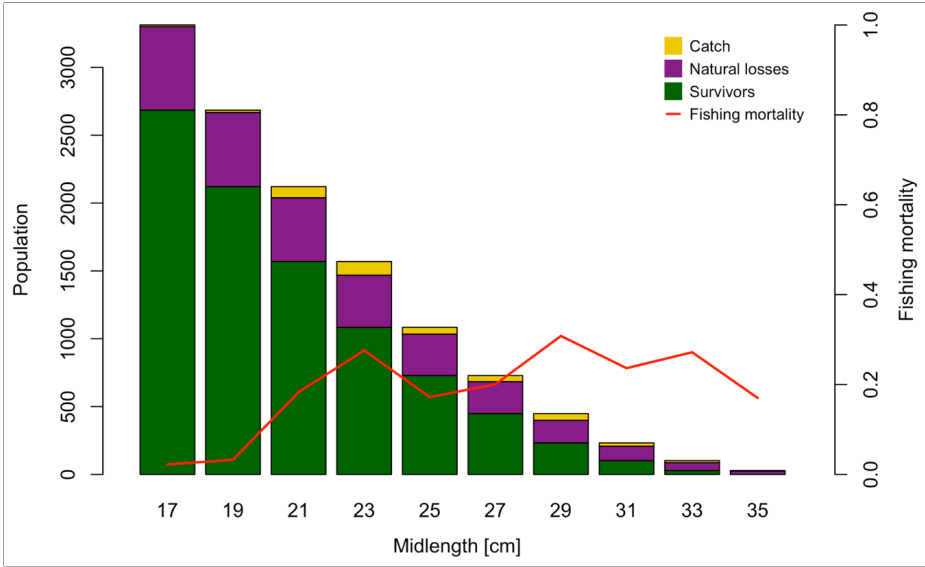


Figure 5. Length-structured Virtual Population Analysis (VPA) for *Notopterus notopterus*, illustrating survivors, natural losses, and fishing mortality by length class.

For diagnosing the current exploitation status of the fish stock using a heuristic method-free approach, Beverton-Holt relative yield-per-recruit (Y/R) analyses were applied. The reference point ($F_{0.1}$) was fixed at 0.65 yr^{-1} , and the maximum sustainable fishing mortality (F_{max}) at 0.85 yr^{-1} . Since the current estimated value of fishing mor-

tality ($F = 0.47\text{ yr}^{-1}$) is strictly lower than $F_{0.1}$, the fish stock can be described as sustainably exploited. The list of all harmonized biological, growth, mortality, and exploitation indicators of the stock is presented in Table 4.

Table 4. Summary of modern biological, growth, mortality, and exploitation parameters for <i>Notopterus notopterus</i> from Pench Reservoir.	
Biological Parameter	<i>Notopterus notopterus</i>
Length-Weight Relationship	
Sample Size (<i>n</i>)	400
Intercept (<i>a</i>)	0.003323
Allometric Exponent (<i>b</i>)	3.2665 (Positive allometry)
Coefficient of Determination (<i>R</i> ²)	0.9088
Growth Parameters (VBGF)	
Asymptotic Length (<i>L</i> _∞)	37.22 cm
Growth Coefficient (<i>K</i>)	0.505 yr ⁻¹
Growth Performance Index (<i>ϕ</i> ′)	2.84
Mortality Parameters (Then <i>et al.</i>, 2015)	
Total Mortality (<i>Z</i>)	1.21 yr ⁻¹
Natural Mortality (<i>M</i>)	0.74 yr ⁻¹
Fishing Mortality (<i>F</i>)	0.47 yr ⁻¹
Exploitation Status (Beverton & Holt)	
Target Reference Point (<i>F</i> _{0.1})	0.65 yr ⁻¹
Limit Reference Point (<i>F</i> _{max})	0.85 yr ⁻¹
Exploitation Rate (<i>E</i> = <i>F</i> / <i>Z</i>)	0.39
Diagnostic Status	Sustainably Exploited (<i>F</i> < <i>F</i>_{0.1})

4. Discussion

4.1 Biometry and positive allometric scaling

Length-weight relationship serves as the basic mathematical foundation for length-based population dynamics. In the current research, the thoroughly validated, mathematically sound allometric exponent of *b* = 3.2665 was obtained for the pooled sample of *N. notopterus*. It implies the existence of clear positive allometric growth – as the bronze featherbacks grow in length in Pench Reservoir, they become proportionally deeper-bodied and structurally stronger (Froese, 2006) [8].

Similar morphometric variations and positive allometric scaling have been documented in other indigenous freshwater species across major Indian river systems, highlighting the significant role of local habitat conditions on somatic growth (Ahirwal *et al.*, 2023; Pise *et al.*, 2018) [19, 20]. Identifying these localized biometric traits is essential given the diverse ecological niches occupied by inland fishes across the subcontinent (Talwar *et al.*, 1991) [21]. From the biological perspective, the result becomes even more interesting as the studied riverine (lotic) population of the fish usually demonstrates negative or isometric allometry owing to the higher metabolic expenses on fighting against the constant currents. In the case of the studied population,

however, the presence of positive allometry shows that the environment in Pench Reservoir offers extremely advantageous foraging and low hydrodynamic pressure, which promotes better somatic accumulation. Also, the strict adherence to the use of Total Length (TL) instead of Standard Length (SL) ensured the absence of morphometric misrepresentation in the virtual biomass reconstruction.

4.2 Holistic interpretation of physiological condition

Fulton's condition factor (K) turned out to be a rather dynamic parameter throughout the eight-month sampling period. The drastic seasonal reduction that can be observed right at the beginning of summer (March, $K = 0.6878$) means that the fish experienced relatively higher physiological burden at the time. According to the previous local literature, it was usually associated with high energetic costs connected with the preparation of gonads before spawning. Nevertheless, since the current study used the biometric parameters obtained from the pooled sample of both genders, it makes it impossible to draw such particular conclusions without any data on Gonadosomatic Index (GSI) as well as macroscopic examination of gonads. As a consequence, the discussed somatic changes have to be interpreted as a whole. Most probably, the summer reduction of K is the complex physiological response to the local abundance fluctuations, changes in thermoregulation in the reservoir, parasitic infection, and the state of the reservoir's hydrology (Gupta *et al.*, 2022) [1]. Such holistic biometric fluctuations serve as crucial biological indicators of aquatic ecosystem stress, effectively integrating the impacts of environmental perturbations over time (Adams, 2002) [22]. Navigating these energetic trade-offs between somatic maintenance and reproduction is a fundamental aspect of life-history diversification in teleosts responding to fluctuating habitats (Winemiller *et al.*, 1992) [23].

4.3 Growth optimization and resolution

The transition from traditional software platforms to TropFishR analytics resulted in extremely accurate and statistically reproducible growth parameter estimation. The calculated values of asymptotic length ($L_{\infty} = 37.22$ cm) and growth coefficient ($K = 0.505$ yr⁻¹) characterize the studied population of teleosts as a fast-growing organism in the stable tropical inland waters. The simulated annealing algorithm optimization was achieved only through proper bin class interval configuration in the range of 1 cm (10 mm) based on raw lengths, therefore eliminating any artificial leveling and modal progression tracking. Thus, the values of L_{∞} and K serve as solid parameters for further natural mortality and yield calculation. Accurate estimation of these parameters also allows for the reliable calculation of the growth performance index (ϕ'), a vital mathematical metric for comparing somatic capacities across different environmental regimes (Pauly *et al.*, 1984) [24]. Embracing this level of rigorous growth modeling is essential to properly account for the inherent physiological plasticity of fish populations adapting to local lentic conditions (Lorenzen, 2016) [25].

4.4 Modernization of mortality and exploitation diagnostics

Certainly, the most important theoretical contribution is made by the systematic partition of Total Mortality ($Z = 1.21$ yr⁻¹). Previously, the local fisheries' researchers used empirical equation suggested by Pauly (1980) [14]. Modern meta-analysis has proved time and again that this temperature-based formula overestimates natural mortality in tropical freshwater fishes and, thus, increases fishing mortality artificially (Then *et al.*, 2015) [15]. Using this knowledge, the present research discards Pauly (1980) [14] formula and uses the advanced, growth-based natural mortality estimator by Then *et al.* (2015) [15], calculating M value equal to 0.74 yr⁻¹. Therefore, the fishing mortality becomes more realistic and equals to 0.47 yr⁻¹. The reliance on high-resolution, length-converted catch curves remains a highly powerful tool for these estimations, provided that the underlying biological inputs are free from historical biases (Pauly, 1983) [26]. Additionally, exploitation level diagnosis using Gulland's (1971) [27] $E = 0.5$ heuristic is known to be outdated and misleading due to potential recruitment overfishing of certain species. The current assess-

ment uses the modern, more complex approach based on explicit Beverton and Holt yield-per-recruit biological reference points. Given that the present fishing mortality ($F = 0.47$ yr⁻¹) is lower than the target reference point ($F_{0.1} = 0.65$ yr⁻¹), the stock is sustainably exploited, not heavily under-exploited as it would be diagnosed before. Adopting these precise biological reference points directly aligns with the broader ecosystem approach to fisheries, ensuring that harvest strategies strictly avoid recruitment overfishing while maintaining the long-term ecological integrity of the reservoir (Food and Agriculture Organization, 2003) [28].

5. Conclusion

This study has succeeded in developing a solid quantitative framework for the population dynamics, biometrics scaling, and exploitation status of *Notopterus notopterus* in Pench Reservoir, Maharashtra. Through its explicit shift away from the old methodology of analysis and strict alignment of anatomical measurements (through Total Length), the study manages to solve the internal inconsistency issues that normally arise during tropical inland stock assessment. The population of *N. notopterus* shows positive allometric growth ($b = 3.2665$), meaning that it has adapted well physiologically to the favorable lentic environment of the reservoir.

The use of high-resolution (1 cm binned) length-frequency data in TropFishR analytical environment produced credible growth parameters ($L_{\infty} = 37.22$ cm; $K = 0.505$ yr⁻¹). More importantly, through its abandonment of old empirical equations and adoption of modern natural mortality estimator formula put forward by Then *et al.* (2015) [15], the study managed to derive credible mortality parameters ($Z = 1.21$; $M = 0.74$; $F = 0.47$). Comparison of the above parameters to specific Beverton and Holt Yield-per-Recruit thresholds reveals that the fishery is exploiting the stock sustainably at ($E = 0.39$), which is far below the target reference point ($F_{0.1} = 0.65$ yr⁻¹).

Through the use of length-structured Virtual Population Analysis (VPA), it is confirmed that the cohort depletion is mainly driven by natural mortality among intermediate sized fishes and not artisanal fishing. In order to ensure the sustainability of this balance and avoid growth overfishing of the juvenile cohort, it is advised that management authority of the reservoir retain its existing gear selectivity policy and mesh size regulation. This new assessment approach provides vital localized knowledge for the Pench Reservoir and a template for assessing other commercially important freshwater teleosts in the Indian subcontinent.

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