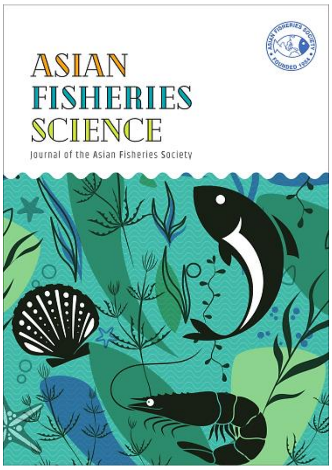



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# Length-Based Stock Assessment of Smith's Barb, *Puntioplites proctozystron* (Bleeker, 1865) (Cyprinidae) and Asian Redtail Catfish, *Hemibagrus nemurus*, (Valenciennes, 1840), (Bagridae) in a Multipurpose Reservoir in Thailand

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## Abstract

Catches from inland fisheries in Thailand are about 200,000 tonnes annually and plays an important role in food security and subsidiary income. However, fish stocks are seldom assessed because of the lack of catch and effort data. In this study, two fish stock assessment models, *viz.*, relative yield per recruit and length-based spawning potential ratio, were used to evaluate the status of two species as well as to highlight their applications to data-limited situation in Thailand. The study was conducted at Kangkrajan Reservoir, Thailand, for two targeted species, *viz.*, Smith's barb, *Puntioplites proctozystron* (Bleeker, 1865) and Asian redtail catfish, *Hemibagrus nemurus* (Valenciennes, 1840) using length frequency data. The data were collected throughout 2019. Both species showed isometric growth. Von Bertalanffy growth parameters were estimated. Asymptotic length, curvature parameter and theoretical age at length zero were 36.2 cm TL, 0.39 $yr^{-1}$ and -0.28 yr for *P. proctozystron*, respectively, and 63.2 cm TL, 0.37 $yr^{-1}$ and -0.32 yr for *H. nemurus*. The exploitation rates reveal that both species are slightly overfished. Sizes at 50 % maturity and 50 % selectivities were 17.8 and 23.5 cm TL for *P. proctozystron*, respectively, and 15.6 and 20.8 cm TL for *H. nemurus*. Considering both parameters, the size at first capture to sustain the fisheries of *P. proctozystron* and *H. nemurus* should be >18 cm and >30 cm, respectively, which can be achieved by mesh-size regulations.

**Keywords:** relative yield per recruit, length-based spawning potential ratio, length frequency data, growth, exploitation rate

## Introduction

Inland capture fisheries in Thailand yield approximately 200,000 tonnes annually with a market value of almost USD500 million. These figures underscore the important role of this activity in providing animal protein and generating significant income for the country, as it does in neighbouring countries of Cambodia, Vietnam and Lao PDR (Funge-Smith & Bennett, 2019). Inland fishing grounds include river channels, floodplains, lakes and swamps, as well as reservoirs. Over 20,000 reservoirs are recorded in Thailand, ranging in size from less than 1 ha to more than 10,000 ha; fishery activities are among the common means of livelihood for people living near these bodies of water (De Silva and Amarasinghe, 2009; Jutagate et al., 2012). There are about 50 common targeted fish species in Thai reservoirs and the average fish yield is estimated to be roughly 40 $kg.ha^{-1}$ per year, which is supported by high primary production, particularly during the rainy season (Jutagate et al., 2012; Hiroki et al., 2020). The existing inland fisheries regulations in Thai reservoirs include closed areas and seasons, banning of destructive fishing methods, and control of mesh size of fishing gear (stretched mesh size under 4 cm is prohibited).

Inland fisheries regulations can also be derived from stock assessment methodologies to determine, for example, allowable catch, optimum fishing effort, and landing size limitations (Lorenzen et al., 2016; Amarasinghe et al., 2017). Moreover, although developing and improving science-based management for reliable fishery production is ranked among the "Ten Steps of Responsible Inland Fisheries (Rome Declaration)," many inland fisheries are managed without the use of stock assessment (Lorenzen et al., 2016; Lynch et al., 2020). The main reasons for this include a lack of data to support quantitative stock assessment methods, the complex nature of fisheries, the possibility to enhance by stocking strategies, and the smaller scale of economic contribution when compared to marine fisheries (Lorenzen et al., 2016; Fitzgerald et al., 2018; Funge-Smith & Bennett, 2019). This is also the case for inland fisheries in Thailand, where fish stock assessments receive less attention in the implementation of fisheries management and regulations. On the other hand, Thai marine fisheries have been rigidly regulated, both in terms of input and output, based on stock assessments since 2015 (Kulanujaree et al., 2020). The clearly documented recovery of Thai marine fish stocks has prompted the Department of Fisheries, via the Inland Fisheries Research and Development Division, to pragmatically apply stock assessment to fisheries management of inland waters.

The primary method used for fish stock assessment in Thai marine fisheries is the surplus production model, which has also been suggested for river and lake fisheries in Asia (Halls et al., 2006; Yen et al., 2009). This method uses the relationship between catch and effort of the targeted stock to estimate the maximum sustainable yield and optimum fishing intensity. Although this model is useful and relatively simple in its calculation, the main difficulty in applying this method in Thai inland fisheries lies in obtaining accurate fishery statistics due to low proportion of the catches reaching landing sites and due to the nature of mixed-gear fisheries, similar to other ASEAN countries (Sam et al., 2003; Yen et al., 2009, Enomoto et al., 2011). Alternatively, length-based stock assessment methodologies can be used for analysing stock status through length frequency distributions generated from the catches and further implementation of the results for fisheries regulation. The most common model for this approach is the relative yield per recruit (Y'PR), which assesses changes in cohort biomass by balancing the gain and loss in weight of individuals (Amarasinghe et al., 2017). The optimum exploitation rate, i.e., maximum Y'PR, can be obtained by applying this model to the targeted stock and further used for management. Besides Y'PR, the length-based spawning potential ratio (LB-SPR) model (Hordyk et al., 2015a, b; 2016) is another promising length-based stock assessment method. This model examines the proportion of unfished reproductive potential left at any given level of fishing pressure, and it is commonly used to set the limit reference point for the fishery (Shephard et al., 2020).

Given the role of fish and the importance of artisanal fisheries to people living in the vicinity of reservoirs in Thailand, incorporating information on population dynamics and stock assessments of the targeted fishes are important for planning and management. In this study, the status of two fisheries-targeted species in a major reservoir in Thailand was investigated by using Y'PR and LB-SPR models, which demographically analyse the effect of harvest on the fish stocks. Results are used to describe the current fisheries of the targeted species in this reservoir and can be further applied for management recommendation. The methods presented herein can serve as a protocol for other reservoir fisheries in the country.

## Materials and Methods

### *Study site and data sampling*

The study was carried out in Kangkrajan Reservoir (12.902°N; 99.599°E; Fig. 1). This reservoir is located in Phetchaburi Province, central Thailand, and has a surface area of 4,960 ha at full storage. The dam was built across the Phetchaburi River and started impoundment in 1966 for multiple purposes, including fisheries. The annual fisheries yield of Kangkrajan Reservoir in 2019 was estimated to be 200 tonnes, with five fish species primarily targeted. Among these are Smith's barb, *Puntioplites proctozystron* (Bleeker, 1865) (Cyprinidae) and Asian redtail catfish, *Hemibagrus nemurus* (Valenciennes, 1840) (Bagridae), which contribute approximately 30 % to annual yield (Inland Fisheries Research and Development Division, 2021, unpublished data).

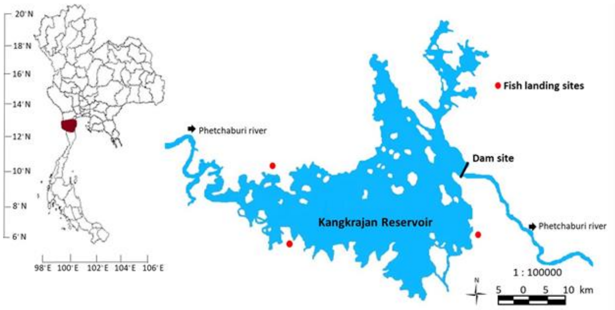


Fig. 1. Location of Kangkrajan Reservoir, and landing sites in the reservoir.

Sampling was conducted monthly from January to December 2019 at each of the three fish landing sites on the reservoir (Fig.1). Fish were caught by various fishing gears, with gillnets most common. Over 100 individuals of both species (Smith's barb and Asian redtail catfish) were collected each month for length frequency data (LFD). Total length (TL, nearest 0.1 cm) and weight (W, nearest 0.1 g) of each individual were measured to construct the basic linear length-weight relationship:

$$log_{10}W = log_{10}a + b(log_{10}TL) \quad (1)$$

where $log_{10}\ a$ is the regression intercept and *b* is the regression slope. The t-test was performed to verify if the regression b-value of each species different from 3, i.e. isometric growth. During the rainy season (i.e., from May to October 2019), females of various size classes were selected and identified by maturity stage, where stages I and II are immature and stages III to V are mature (Holden and Raitt, 1974).

## Estimation of growth, maturity and mortality parameters

Growth of the two species was assumed to follow the von Bertanlaffy growth function (VBGF), which generates the three parameters of asymptotic length ($L_\infty$), curvature parameter (*K*) and theoretical age at length zero ($t_0$) as:

$$L_t = L_\infty\left(1 - e^{-K(t-t_0)}\right) \quad (2)$$

Estimation of $L_\infty$ and *K* was done using the ELEFAN routine in FiSAT II version 1.2.2 (Gayanilo et al., 2005) by correcting the LFD following the stepwise procedure explained by Amarasinghe and De Silva (1992); $t_0$ was calculated following the formula by Pauly (1979):

$$log_{10}(-t_0) = -0.3922 - 0.275 log_{10} L_\infty - 1.308 log_{10} K \quad (3)$$

In addition, during the steps of correcting the LFDs, probabilities of capture were also generated by detailed analysis of the ascending part of the length-converted catch curve, (Pauly, 1986). Length at proportion (i.e. percentage) of maturity was estimated by the equation:

$$P = \frac{1}{1+e^{(a-bL)}} \quad (4)$$

where P is the proportion of mature fish in each size class (1 cm interval), and *a* and *b* are the equation coefficients. The total mortality coefficient (*Z*) was computed by the length-converted catch curve method (Pauly, 1983). In this method, a catch curve is constructed from LFD and VBGF growth parameters, then $N/\Delta t$, i.e., number of fish in a given length group divided by the time needed to grow through that length class, is plotted against relative age ($t$-$t_o$) of the length class to estimate *Z* from the descending part of the length-converted catch curve (Pauly, 1983). Natural mortality coefficient (*M*) was estimated using Pauly's equation (1980):

$$log_{10}M = -0.006 - 0.279 log_{10} L_\infty + 0.6543 log_{10} K + 0.4634 log_{10} T \quad (5)$$

where *T* is the mean annual habitat temperature (set at 29.0 °C in this study). The fishing mortality coefficient (*F*) was determined by subtracting *M* from *Z*, i.e., $F = Z - M$.

## Length-based stock assessment methods

### Relative yield per recruit (Y′PR) analysis

Y′PR (Beverton and Holt, 1957) is used to examine the optimum fishing intensity. It requires fewer input parameters using the modified version by Pauly and Soriano (1986) by incorporating probabilities of capture, which is more appropriate to short-lived species and can be written as:

$$Y'PR = \sum P_i\left(\left((Y'PR)_i \cdot G_{i-1}\right) - \left((Y'PR)_{i+1} \cdot G_i\right)\right) \quad (6)$$

$$(Y'PR)_i = EU^{(M/K)}\left\{1 - \frac{3U}{(1+m)} + \frac{3U^2}{(1+2m)} - \frac{3U^3}{(1+3m)}\right\} \quad (7)$$

where $P_i$ is the probability of capture between $L_i$ and $L_{i+1}$, $(Y'PR)_i$ refers to the Y′PR computed from the lower limit of class i, $G_i = \prod r_j$, where $r_j = (1-c_i)^{S_i}/(1-c_i)^{S_i}$, as $c_i = L_C/L_\infty$ and $S_i = (M/K)(E/(1-E))P_i$; *E* = exploitation rate, i.e., *F/Z*; $U = 1-(L_C/L_\infty)$, where $L_C$ is size at first capture; *m* = *K/Z*. Y′PR was, then, calculated for both target species using input values of *M/K*, $L_\infty$ and $L_C$ incorporating probabilities of capture. Values of *E*, meanwhile, ranged from 0 to 1, corresponding to *F* values ranging 0 to ∞.

### Length-based spawning potential ratio (LB-SPR) model

The LB-SPR model is equilibrium-based, and assumes that the LFD is representative of the exploited population at a steady state. The *SPR per se* is the proportion of unfished reproductive production left in a population under fishing pressure, i.e., the *SPR* equals 100 % if the stock is unfished and is reduced from the unfished level (*SPR*X % or <100 %) depending on the amount of harvested adults (Prince et al., 2020). The LB-SPR was recently developed (Hordyk et al., 2015a; 2015b) and utilises the fact that the size structure of an exploited population and its *SPR* are a function of relative fishing pressure (*F/M*), and the two life-history ratios *M/K* and $L_m/L_\infty$ (Prince et al., 2020). The analysis requires length data as inputs which follow the formula of *SPR* (Hordyk et al., 2015a; b). The analysis also requires the lengths at maturity of 50 % ($L_{50}$) and 95 % ($L_{95}$) for the population, which are estimated from equation (4), as well as selectivity at length values for 50 % ($SL_{50}$) and 95 % ($SL_{95}$), as described by the logistic curve, which are obtained during the length-converted catch curve analysis. Details of the analytical steps of LB-SPR can be found in Hordyk et al. (2015a). The LB-SPR analysis was conducted using the LB-SPR package in R (Hordyk, 2019).

# Results

There were 3,563 individuals of *P. proctozystron* and 2,162 individuals of *H. nemurus* collected during the year of sampling. The average total length of *P.*

*proctozystron* was 20.8 ± 4.0 cm, with a range of 7.5 to 33.5 cm. Mean TL was 29.0 ± 6.0 cm for *H. nemurus*, with a range of 13.5 to 58.5 cm. The obtained regression slope ($b$) of the length-weight relationship of both species indicates isometric growth; the $b$-values for both species were not significantly different from 3 (t-test, $P > 0.05$).

$$log_{10}W = -2.00 + 3.092(log_{10}TL)$$

with $R^2$ = 0.90 for *P. proctozystron* (8)

$$log_{10}W = -2.28 + 3.138(log_{10}TL)$$

with $R^2$ = 0.98 for *H. nemurus* (9)

The overall LFDs of the two targeted species are shown in Figure 2. The estimated $L_{50}$ of *P. proctozystron* and *H. nemurus* were 17.8 and 16.5, respectively. A majority of the catches of both species were above these levels (Fig. 2). The estimated size at selection values ($SL_{25}$, $SL_{50}$ and $SL_{75}$) are also presented in Figure 2, and clearly show that $SL_{50}$ was larger than $L_{50}$ for both species. A striking difference illustrated by the LFDs of the two species is that nearly all of the harvested *P. puntioplites* were smaller than $SL_{75}$, whereas a significant proportion of *H. nemurus* was larger than $SL_{75}$.

After correcting the LFDs, the $L_\infty$ and $K$ of each species were estimated, and the growth curves were superimposed on the restructured LFDs (Fig. 3), resulting in a goodness-of-fit index (Rn) of 0.122 for *P. proctozystron* and 0.134 for *H. nemurus*. The $t_0$ was estimated by equation (3), and then the VBGF of each species was described as:

$$L_t = 36.2\left(1 - e^{-0.39(t+0.28)}\right)$$

for *P. proctozystron* (10)

$$L_t = 63.2\left(1 - e^{-0.37(t+0.32)}\right)$$

for *H. nemurus* (11)

The index of growth performance ($\emptyset'$) was calculated as:

$$\emptyset' = 2log_{10}l_\infty + log_{10}K,$$

which is more or less constant for a similar taxon or shape (Munro and Pauly, 1983). The $L_\infty$ of both species were converted to standard length, according to the equation provided in FishBase (Froese and Pauly, 2021), and were 26.4 cm and 51.0 cm for *P. proctozystron* and *H. nemurus*, respectively. This

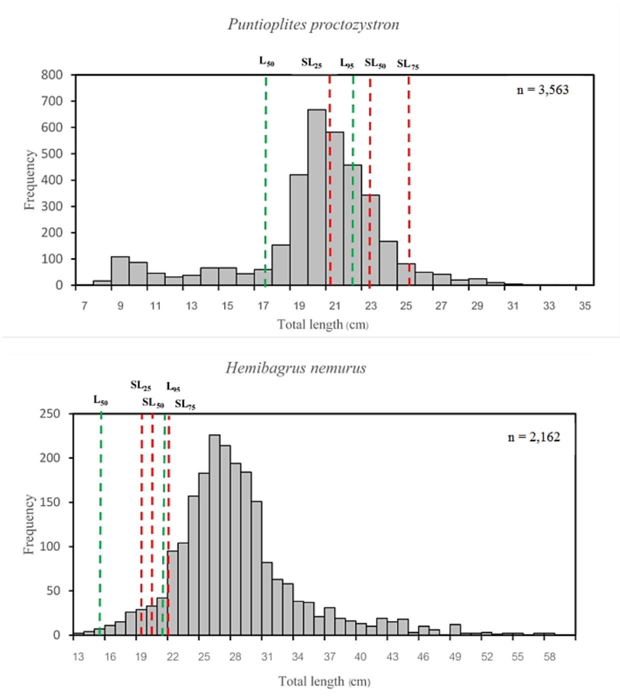


Fig. 2. Overall length frequency distributions of (a) *Puntioplites proctozystron* and (b) *Hemibagrus nemurus* in Kangkrajan Reservoir from one year of data collection.

Note: (a) *Puntioplites proctozystron*: $L_{50}$ = 17.8 cm, $L_{95}$ = 22.6 cm, $SL_{25}$ = 21.1 cm, $SL_{50}$ = 23.5 cm, $SL_{75}$ = 25.9 cm; (b) *Hemibagrus nemurus*: $L_{50}$ = 15.6 cm, $L_{95}$ = 21.8 cm, $SL_{25}$ = 19.6 cm, $SL_{50}$ = 20.8 cm, $SL_{75}$ = 22.0 cm.

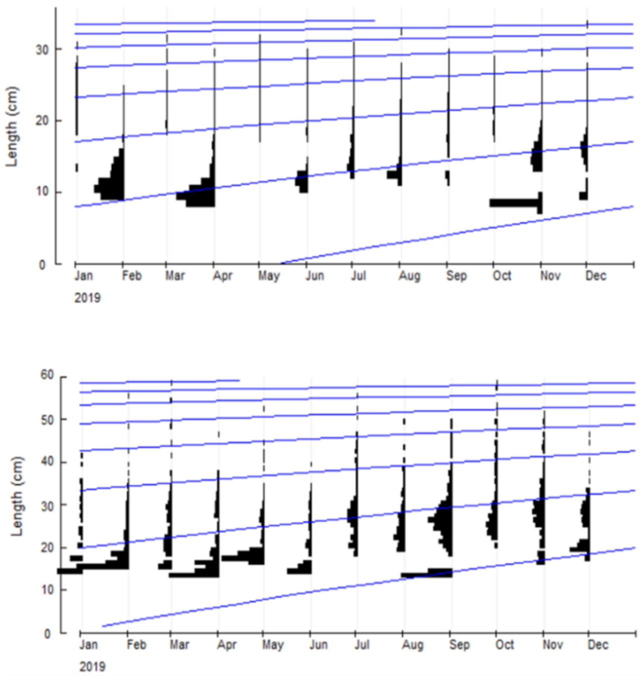


Fig. 3. Monthly length frequency distributions of (a) *Puntioplites proctozystron* and (b) *Hemibagrus nemurus* in Kangkrajan Reservoir, superimposed by VBGF curves.

index was, then, estimated at 2.43 for *P. proctozystron* and 2.98 for *H. nemurus*, by using the standard length of $L_\infty$. The obtained VBGF shows that the age range of the catches were between 1 and 3.5 years old for both species. Hence, the coefficients of relative age and ln($N/\Delta t$) in this age range were used to estimate the value of *Z*. The *Z*- (Fig. 4) and *M*- values for *P. proctozystron* were 2.44 and 0.93 year$^{-1}$, respectively, and as a consequence, the *F* value was 1.51 year$^{-1}$ and the exploitation rate (*E*) was 0.55. For *H. nemurus*, the *Z*-, *M*- and *F*- values were 1.78, 0.77 and 1.01 year$^{-1}$, respectively, with the *E* value of 0.57.

Exploitation levels estimated using Y'PR analysis incorporating selection-ogive were based on five levels of length at capture ($L_C$). The first three lengths were obtained from the fishery and life history data, i.e., the smallest length in LFD, $L_{50}$ and $SL_{25}$. The remaining two lengths were based on the current exploitation rate ($E_{cur}$) as (i) the $L_c$ that produces the $E_{cur}$ equal to the exploitation rate of maximum yield ($E_{max}$) and (ii) the $L_c$ that produces the $E_{cur}$ equal to the exploitation rate for which the slope of the Y'PR is 1/10 of its value at the origin ($E_{0.1}$). The Y'PR of *P. protozystron* (Table 1) shows that the $E_{cur}$ already exceeds the exploitation rate that would produce $E_{max}$, based on the smallest size class as $L_C$. However, if the $L_{50}$ and $SL_{25}$ are used as $L_C$, $E_{max}$ is higher than $E_{cur}$, implying that increasing fishing effort to achieve $E_{max}$ is possible. The $E_{max}$ and $E_{0.1}$ of the $L_C$ at 10.8 cm and 17.6 cm were equal to $E_{cur}$, which could be the recommended $L_C$ for optimal exploitation of *P. protozystron* in Kangkrajan Reservoir. The Y'PR analysis of *H. nemurus* (Table 1) showed similar results, that under current fishing pressure, i.e., with $L_C$ at the smallest size class, $E_{cur}$ already exceeds $E_{max}$. Moreover, $E_{cur}$ was still above $E_{max}$ from the estimations obtained from both $L_{50}$ and $SL_{25}$ as $L_C$. To simulate the $E_{max}$ and $E_{0.1}$ as equal to $E_{cur}$, the analysis revealed that they were at lengths of 21.0 cm and 32.0 cm, respectively. The Y'PR results also reveal that the $E_{cur.}$ of both fish species are beyond $E_{0.5}$, i.e., the exploitation rate associated with a 50 % reduction of the biomass per recruit in the unexploited stock. Therefore, the *SPR* was applied to identify the suitable lengths at capture for the two studied species in Kangkrajan Reservoir.

For the LB-SPR analysis, the maturity sizes ($L_{50}$ and $L_{95}$) and the estimated values of *M*-mortality and growth parameter *K* were combined with the selectivity sizes. The size at 95 % selection ($SL_{95}$), the important input for LB-SPR, 0was estimated for *P. protozystron* and *H. nemurus*, using the probabilities

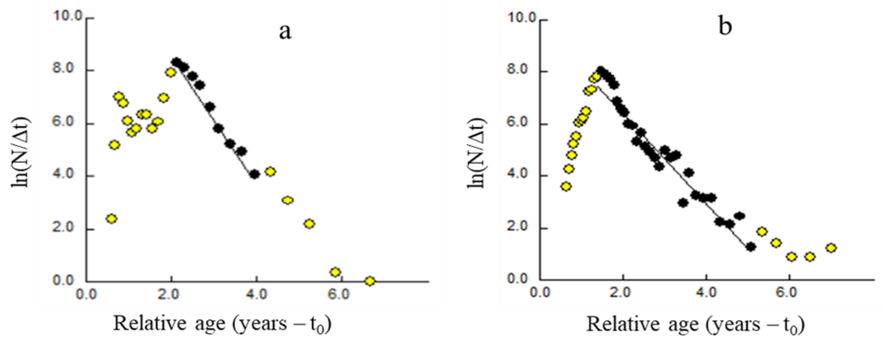


Fig. 4. Length-converted catch curves for estimating *Z*- values of (a) *Puntioplites proctozystron* and (b) *Hemibagrus nemurus* in Kangkrajan Reservoir.

Table 1. Estimated relative yield per recruit (Y'PR) values at three reference points of exploitation (*E*): $E_{0.1}$ = *E* corresponding to 10 % of slope of curve at the origin; $E_{0.5}$ = *E* corresponding to biomass per recruit of 0.5; $E_{max}$ = *E* corresponding to maximum Y'PR for (a) *Puntioplites proctozystron* and (b) *Hemibagrus nemurus* in Kangkrajan Reservoir.

(a) *Puntioplites proctozystron* ($E_{cur.}$ = 0.55)

| Length at capture (cm TL) | Reference points $E_{0.1}$ | $E_{0.5}$ | $E_{max}$ | Note |
|---|---|---|---|---|
| 7.5 | 0.35 | 0.27 | 0.46 | The smallest length in LFD |
| 17.8 | 0.55 | 0.35 | 0.65 | Maturity at $L_{50}$ |
| 21.1 | 0.57 | 0.36 | 0.70 | Selectivity at $SL_{25}$ |
| 10.8 | 0.40 | 0.29 | 0.55 | $E_{max}$ is equal to $E_{cur}$ |
| 17.6 | 0.55 | 0.35 | 0.65 | $E_{0.1}$ is equal to $E_{cur}$ |

(b) *Hemibagrus nemurus* ($E_{cur.}$ = 0.57)

| Length at capture (cm TL) | Reference points $E_{0.1}$ | $E_{0.5}$ | $E_{max}$ | Note |
|---|---|---|---|---|
| 13.5 | 0.36 | 0.28 | 0.46 | The smallest length in LFD |
| 16.5 | 0.42 | 0.27 | 0.50 | Maturity at $L_{50}$ |
| 19.6 | 0.46 | 0.30 | 0.54 | Selectivity at $SL_{25}$ |
| 21.0 | 0.46 | 0.31 | 0.57 | $E_{max}$ is equal to $E_{cur.}$ |
| 32.0 | 0.57 | 0.36 | 0.70 | $E_{0.1}$ is equal to $E_{cur.}$ |

of capture of 25.5 cm and 24.7 cm, respectively. Incorporated with $SL_{95}$, three (3) selectivity sizes, i.e., $SL_{25}$, $SL_{50}$ and $SL_{75}$, were used to reflect the size at which individuals in the stock become vulnerable to capture. The results (Table 2) clearly show that under the current fishing patterns, the *SPR* values of *P. protozystron* range between 0.40 and 0.69, and improve greatly at each increasing step of selectivity, i.e., from $SL_{25}$ to $SL_{75}$. Meanwhile, the *SPR* values for *H. nemurus* were all lower than for P. *protozystron* at all selectivity sizes, and ranged between 0.23 and 0.26.

Table 2. Spawning potential ratios of *Puntioplites proctozystron* and *Hemibagrus nemurus* at three selectivity sizes in Kangkrajan Reservoir.

| Fish species | $SL_{25}$ | $SL_{50}$ | $SL_{75}$ |
| --- | --- | --- | --- |
| *Puntioplites proctozystron* (Bleeker, 1865) | 0.40 | 0.57 | 0.69 |
| *Hemibagrus nemurus* (Valenciennes, 1840) | 0.23 | 0.25 | 0.26 |

# Discussion

Inland fisheries in many parts of Asia are not scientifically managed (Amarasinghe and De Silva, 2015; Bandara et al., 2020). As a result, many scientists and managers are unaware of the power of stock assessment methods, especially in relatively data-limited situations, and are unfamiliar with the methods (Lorenzen et al., 2016). This situation exists in Thailand, where inland fish stock assessment has been conducted, but mainly for fisheries of a few large reservoirs and only for a limited number of species of interest. This work shows the implications of applying two length-based fish stock assessment methods, i.e., relative yield per recruit (Y′PR) and spawning potential ratio (*SPR*), along with fish population dynamics parameters, as tools to understand and evaluate the stocks' status and generate reference points for future management.

The status of fishery-targeted stocks has never been reported for Kangkrajan Reservoir. This first attempt was made by using length frequency data from one year of sampling at landing sites. The sample sizes of the two targeted species were over 1,000 and covered all exploited sizes, which provided excellent data for simple length-based analysis (Suvarnaraksha et al., 2011). The analysis did not separate the targeted fishes by sex due to uncertainties regarding gear selectivity and life history between sexes. Although isometric growth was confirmed, a slight bias towards positive allometry in the growth of the targeted species is not surprising. Positive allometry indicates that fish are relatively plump and implies the optimum conditions for the growth of the targeted species in the studied environment (Froese, 2006). A recent study of Thai reservoirs showed the abundance of basic food resources in the systems, which can support large fish populations (Sakset et al., 2021). Tessier et al. (2017) also presented the positive allometric growth of a hemibagrid catfish *Hemibagrus wyckioides* (Fang and Chaux, 1949) and several cyprinids in a reservoir in Lao PDR. Importantly, the regression slopes (*b*) of the length-weight relationships for both fishes in this study were between 2.5 and 3.5, which meets the assumption of the Y′PR and LB-SPR models (Sparre and Venema, 1998; Froese and Binohlan, 2000; Hordyk et al., 2015 a, b).

Modal groups were detectable in each month from the raw data, for both fishes, with apparent shifts in modal length over time; hence, the VBGF parameters were estimated. The growth of fish in any given species varies by stock, but can be validated by comparing the index of growth performance (Ø′). Each taxon has a particular distribution of Ø′ values which are different from other taxa, but are similar within species or genera when growth characteristics are similar (Munro and Pauly, 1983; Moreau et al., 1986). By applying $L_\infty$ and *K* obtained from FishBase (Froese and Pauly, 2021), the Ø′ values for *P. proctozystron* and *H. nemurus* were 2.60 and 2.87, respectively, which are within ± 0.2 of our estimated Ø′ values, and support the validity of the two VBGFs in this study (Moreau et al., 1986). Total mortality of both species was considerably high, i.e., *Z*-value was above 1.5 (Quinn II and Deriso, 1999). Amarasinghe et al. (2017) mentioned that the length-converted catch curve method may result in overestimated *Z*-values due to a gear selection effect at the upper range of length frequencies. This is why our analysis selected the age groups that dominated the catches in the fishery, i.e., between 1 and 3.5 years old. For natural mortality, Then et al. (2015) examined the two preferred methods for estimating *M*-value, i.e., the Hoenig (1983) method, which uses longevity data, and Pauly (1980), which uses VBGF parameters, and concluded that Hoenig's model generally produced higher *M* estimates than the Pauly method for stocks that experience high *M*-values, i.e., $M > 0.2$ yr$^{-1}$. Therefore, the *M*-values in this study were estimated by Pauly (1980). The *M/K* values for *P. proctozystron* and *H. nemurus* were 2.38 and 2.08, respectively, and within the typical range (1.1 to 2.5) reported for fishes (Beverton and Holt, 1957). The estimated *F*- values were higher than *M*- values for both species and implied high fishing pressures, i.e., $E_{cur} > 0.5$.

"Per-recruit" models are commonly used to evaluate size limits, slot limits or optimal mesh sizes in gillnet and seine fisheries (Lorenzen, 2016). When applying "per-recruit" models in inland fisheries in Asia, the most common practice is through examining the appropriate size at first capture, then adjusting mesh-size regulations (Amarasinghe and De Silva, 2015; Bandara et al., 2020). If the $E_{max}$ of the Y′PR is set as a reference point and the current fishing situation, i.e.

$E_{cur}$, is applied, the size at first capture should be > 10 cm for *P. proctozystron* and >20 cm for *H. nemurus*. However, managing the fishing mortality at $E_{max}$ level is risky and probably exceeds the fishing mortality at maximum sustainable yield from the surplus production model; hence, it is regarded as a less conservative reference point (Caddy and Mahon, 1995; Quinn II and Deriso, 1999). Moreover, the low exploitation level needed to attain $E_{0.5}$ at any given length in Table 1 makes it difficult to apply $E_{0.5}$ as a reference point, though Beverton and Holt (1957) suggested that a fishing stock is considered to be at a sustainable exploitation level when the exploitation rate does not exceed $E_{0.5}$, i.e., the point at which natural and fishing mortalities are at equilibrium. Alternatively, controlling fishing mortality at the more conservative $E_{0.1}$ is commonly recommended (Caddy and Mahon, 1995). Therefore, based on the $E_{0.1}$ reference point, the size at first capture should be >18 cm for *P. proctozystron* and >30 cm for *H. nemurus*.

However, the use of Y'PR as a reference point does not consider the effect of fishing mortality on the proportion of mature fish left in the population, hence its reproductive potential (Caddy and Mahon, 1995). The LB-SPR was then applied concurrently with Y'PR in this study. Pons et al. (2019) concluded that using length data from a broad range of sizes would result in low bias in the estimated *SPR*, which is compatible with the nature of inland fisheries in Thailand, where there is less size selection. Chong et al. (2020) also revealed that LBSPR was among the most consistent and accurate assessment methods but may be inconsistent in determining growth overfishing when the stocks are underexploited. In this study, the *SPR* value of *P. protozystron* at $SL_{50}$ was 0.57, which is beyond the general target range of 0.30–0.40 used for fisheries management purposes (Mace and Sissenwine, 1993). Though the *SPR* value of *H. nemurus* at $SL_{50}$ seemed low at 0.25, it was still in the acceptable range for replacement (0.20 – 0.30) (Mace and Sissenwine, 1993).

# Conclusion

The nature of open-access inland fisheries in Thai waters and their importance to the livelihoods of people living in the vicinity make the adoption of quantitative fish stock assessment essential for science-based fisheries management. Although such efforts to employ fish stock assessment in the management of Thai inland waters have been conducted, they remain uncommon, mostly due to limited budget and relatively poor available data. This study presents evidence that fish stock status and appropriate fisheries management measures can be achieved with reliable length frequency data, which were collected from fish landings at relatively low cost, and suitable stock assessment models. This study was conducted in Kangkrajan Reservoir, one of Thailand's large, multi-purpose reservoirs. The stock status of the two main targeted species indicates that they are slightly overexploited. By using Y'PR and LB-SPR, the size at first capture to sustain the fisheries of *P. proctozystron* and *H. nemurus* should be >18 cm and >30 cm, respectively, which can be applied by mesh size regulations.

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