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Tailwater fish of a Brazilian dam: abundance estimation and protection from turbine-induced mortality

Peixes da zona de defluência de hidrelétrica brasileira: estimativa da abundância e proteção contra morte induzida por turbina

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Abstract: Aim: To determine for *Pimelodus maculatus*, the fish most affected by the operation and maintenance (O&M) of the Amador Aguiar II Hydropower Dam, Araguari River, Brazil, (i) the most suitable fishing gear for its sampling, (ii) the seasonal variation in catches, (iii) the abiotic variables that most influence catches and (iv) the best period of the year to schedule O&M risky to the species. **Methods:** We collected fish by hook-and-line, cast net, and gillnet in the first 300 m downstream of the dam every two months for three consecutive years. We analyzed the catches of *P. maculatus* and its temporal variation as a function of fishing gear type, year's season, dissolved oxygen, water temperature, water transparency, rainfall, turbine discharge, spillway discharge, and tailwater discharge. **Results:** We captured 5,117 individuals of 32+ species. *Pimelodus maculatus* (52.6% of the total) was the most sampled species for all fishing gear types. Gillnet captured 70.2% of all *P. maculatus*, followed by hook-and-line (22.6%) and cast net (7.3%). The bycatch of gillnet (55.4%) was much higher than that of cast net (10.9%) and hook-and-line (7.6%). Temporal variation in the catch of *P. maculatus* by the three types of fishing gear showed synchrony. Between the two best fishing gear types for sampling *P. maculatus,* gillnet caught more individuals but caused more bycatch and fish death than hook-and-line. Season of the year and water temperature were the abiotic variables that most influenced temporal variation in the number of *P. maculatus* sampled. We sampled more individuals during the wet season when the water temperature was higher. **Conclusions:** For any O&M activity that poses a risk of fish death, particularly turbine dewatering, we recommend scheduling it for the dry season when the catch of *P. maculatus* near the dam is lower. Additionally, we advise sampling fish in the tailwater before the O&M using gillnet or hook-and-line, with the latter preferred due to its lower bycatch and fish mortality.

Keywords: fish death; fishing gear; *Pimelodus maculatus*; abiotic variables; Paraná River basin.

Resumo: Objetivo: Determinar para *Pimelodus maculatus*, o peixe mais afetado pela operação e manutenção (O&M) da usina de Amador Aguiar II, rio Araguari, Brasil, (i) o petrecho de pesca mais adequado à sua amostragem, (ii) a variação sazonal nas capturas, (iii) as variáveis abióticas que mais influenciam suas capturas, e (iv) o melhor período do ano para programar O&M de risco à espécie. **Métodos:** Coletamos peixes bimestralmente nos primeiros 300 m a jusante da usina com anzol, tarrafa e rede de emalhar por três anos consecutivos. Analisamos a abundância de *P. maculatus* e sua variação temporal em função de petrecho de pesca, estação do ano, oxigênio dissolvido, temperatura da água, transparência da água, pluviosidade, vazão turbinada, vazão vertida e vazão defluente. **Resultados:** Capturamos 5.117 indivíduos de 32+ espécies. *Pimelodus maculatus* (52,6% do total) foi o peixe mais amostrado nos três petrechos de pesca. Rede de emalhar amostrou 70,2% dos *P. maculatus*, seguida do anzol (22,6%) e da tarrafa (7,3%). A captura acidental na rede de emalhar (55,4%) foi bem superior à do anzol (7,6%) e tarrafa (10,9%). Variação temporal nas capturas de *P. maculatus* pelos três tipos de artes de pesca apresentou sincronia. Entre os dois melhores petrechos de pesca para a amostragem de *P. maculatus*, a rede de emalhar capturou mais indivíduos, mas causou mais captura acidental e morte de peixes do que a pesca com anzol. Estação do ano e temperatura da água foram as variáveis abióticas que mais influenciaram a variação temporal do número de *P. maculatus* amostrados. Capturamos mais indivíduos na estação chuvosa quando a temperatura da água era maior. **Conclusões:** Para qualquer atividade de O&M que represente risco de morte de peixes, particularmente drenagem da turbina, recomendamos agendá-la para a estação seca, quando a captura de *P. maculatus* perto da usina é menor. Além disso, aconselhamos a amostragem de peixes nas proximidades da usina antes da O&M com rede de emalhar ou anzol, sendo esse último preferido por causa da menor captura acidental e morte de peixes.

Palavras-chave: morte de peixe; petrechos de pesca; *Pimelodus maculatus*; variáveis abióticas; bacia do rio Paraná.

1. Introduction

The tailwater zone (TZ) of hydropower dams, the region immediately downstream that receives turbine and spillway discharges, is inhabited by a diverse and abundant fish fauna (Loures & Godinho, 2016). Many individuals of migratory fishes agglomerate in the TZ during the migratory season, searching for an upstream passage (Godinho & Kynard, 2009). Fish of the TZ, but mainly those that are migratory, can be affected (i.e., killed, injured, or trapped inside the dam) by various types of operation and maintenance (O&M) of hydropower dams (Andrade et al., 2012). Turbine startup and turbine dewatering are among the riskiest types of O&M for fish (Godinho & Loures, 2016; Rêgo et al., 2016a). The number of TZ fish affected by a single O&M event may reach the thousands and directly relate to their abundance in the TZ (Rêgo et al., 2016a).

The migratory *Pimelodus maculatus* Lacepède, 1803, is a species most affected by the O&M of hydropower dams in Southeast Brazil (Andrade et al., 2012; Rêgo et al., 2016a). For example, *P. maculatus* represented 90% or more of the fish trapped inside the turbine during dewatering for maintenance of the Amador Aguiar II Hydropower Dam (AAD), Araguari River, upper Paraná River basin, state of Minas Gerais (Rêgo et al., 2016b). Scheduling the O&M of hydropower dams for periods of lower abundance of *P. maculatus* in the TZ can reduce the number of fish affected by O&M (Andrade et al., 2012; Loures & Pompeu, 2012, 2015). The abundance of migratory fish in the TZ of Brazilian hydropower dams is seasonal, highest during the wet season (e.g., Loures & Pompeu, 2012; Carvalho et al., 2016). However, at the Igarapava Hydropower Dam, also in the upper Paraná River basin in Minas Gerais, the catch per unit effort (CPUE) of *P. maculatus* in the TZ did not show significant differences between wet and dry seasons (ALG personal data). Additionally, these seasons had a small effect on the passage of *P. maculatus* in the fishway of the Igarapava Hydropower Dam (Bizzotto et al., 2009). Therefore, determining the period of the year with the highest and lowest abundance of *P. maculatus* in the TZ of AAD can help reduce the number of *P. maculatus* affected by its O&M.

Various fishing gear can be used to estimate fish abundance (Hayes et al., 2012; Hubert et al., 2012), but they differ in selectivity and efficiency (Hubert et al., 2012). The most appropriate fishing gear for a given sampling depends on the study's objective, the habitat type, and the species to be sampled, among other factors. More than one type of fishing gear is commonly used to sample a greater variety of species (Grosser & Becker, 2005). According to Loures (2019), the fishing gear most frequently used to sample fish upstream and downstream in Brazilian hydropower dams are gillnet (100%), cast net (84%), sieve (41%), and hook-and-line (30%). Conditions at a TZ may not allow the use of some types of fishing gear. For example, turbulence at the TZ of Itutinga Hydropower Dam, Grande River, Minas Gerais, allowed hook-and-line, but not gillnet, for sampling *P. maculatus* (Loures et al., 2016).

In this study, we sampled *P. maculatus* in the TZ of AAD every two months over the course of three years to determine (i) the most suitable fishing gear (hook-and-line, cast net, or gillnet) for its sampling, (ii) the seasonal variation in catches, (iii) the abiotic variables that most influence catches and (iv) the best period of the year to schedule O&M that is risky to the species.

2. Material and Methods

2.1. Study fish

Pimelodus maculatus is native to the watersheds of the Paraná and São Francisco rivers (Reis et al., 2003), inhabiting lentic and lotic environments (Agostinho et al., 1995). It is a common fish in reservoirs (Dei Tos et al., 2002; Santos et al., 2010) and in the TZ of Brazilian hydropower dams (Souza et al., 2016). It is a medium–sized fish, reaching up to 36 cm in standard length (Langeani & Rêgo, 2014), and is essential for sport, subsistence and commercial fisheries (Braga & Gomiero, 1997; Peixer & Petrere Júnior, 2009).

The migratory condition of *P. maculatus* is controversial: it is classified as a migratory fish by Agostinho et al. (2003) and Arcifa and Esguícero (2012) but not by Oldani et al. (2007). According to Braga (2001), Dei Tos et al. (2002), and Maia et al. (2007), *P. maculatus* migrates from lentic habitats to spawn in lotic habitats. The species presents multiple spawning events (Agostinho et al., 2003) that can be restricted to the summer (Lima-Junior & Goitein, 2006) or extend throughout the year (Bazzoli et al., 1997).

2.2. Study area

The AAD, located in the upper Paraná River basin on the Araguari River, state of Minas Gerais, Brazil, started operation in 2007. It has a run–of–river type reservoir with an area of 45.1 km^2 (Loures & Godinho, 2016) and inflow controlled by upstream hydropower dams, notably the Nova Ponte Hydropower Dam.

The AAD is the most downstream dam of the Araguari River dam cascade, being located 75 km by river from its mouth (Figure 1). Downstream of the AAD, there is a remnant of the Araguari River and an arm of the Itumbiara Reservoir, the dam of which is on the Paranaíba River. The extension of this remnant varies from about 6 to 26 km, depending on the water level of the Itumbiara Reservoir (Rêgo et al., 2016b). Ninety–seven fish species are known in the Araguari River basin (Langeani & Rêgo, 2014).

2.3. Data collection

We carried out 19 bimonthly sampling campaigns from June 2010 to June 2013 (IBAMA collection license, nº1196–8/2009–2013). We sampled fish from the TZ of AAD using three types of fishing gear: hook-and-line, cast net, and gillnet. We define the TZ as the first 300 m of the Araguari River immediately downstream of the dam, where the dam and its tailwater discharge have modified the river morphology, flow velocity, and turbulence.

Hook-and-line sampling was performed by a professional fisher for 6 h or by two fishers for 3 h each, during the daytime of a single day of each campaign using a number 8 hook and earthworm as bait. Cast net sampling employed forty casts made by a professional fisher in each campaign, 20 in the morning and 20 in the afternoon of the same day. The cast net had 5 cm stretched mesh and a radius of 2.7 m. We also standardized the sampling effort for gillnets throughout the campaigns by using three sets of gillnets totaling 403.8 m^2 of nets per campaign. Each set contains one net of each of the following stretched mesh sizes: 3, 4, 6, 7, and 8 cm. The height of the nets ranged from 1.44 m to 2.00 m, depending on the mesh size, and were either 10 m (mesh sizes 3 and 4 cm) or 20 m (other mesh sizes) in length. We set up the nets in the late afternoon of one day and retrieved them the next morning, resulting in a soak time of about 14 h.

We identified all captured fish, releasing live individuals back into the river and fixing dead ones in 10% formaldehyde. We identified all sampled fish to the species level using the references of Langeani & Rêgo (2014), Ota et al. (2018), and Froese & Pauly (2020), except for those of *Hypostomus*, which we grouped as *Hypostomus* spp, due to the taxonomic difficulties of the group. We deposited vouchers of most species in the DZSJRP fish collection of the Departamento de Zoologia e Botânica, Universidade Estadual Paulista (UNESP) at São José do Rio Preto, SP (DZSJRP 10844, 15510 to 15517, 15520, 15527 to 15530, 15534, 15535, 15539 to 15541, 15546, 15547, 15549, 15550, 15552, 15554, 15563, 15565, 15748, 15774, 18226, 19263 and 19292). We ensured that the capture of animals adhered rigorously to both national and international standards governing scientific research.

We obtained data for the following abiotic variables: dissolved oxygen (mg.L^{-1}), water temperature (°C), water transparency (m), rainfall (mm), turbine discharge (m^3.s^{-1}), spillway discharge (m^3.s^{-1}), and tailwater discharge (m^3.s^{-1}). We measured dissolved oxygen and water temperature with an oximeter and

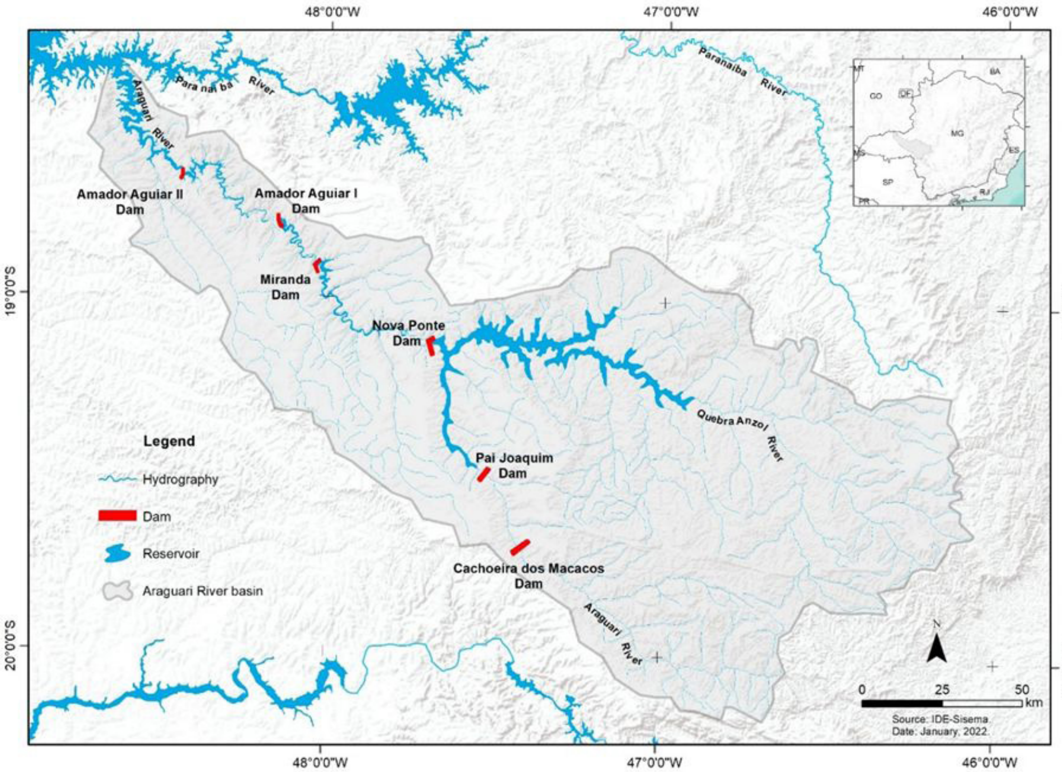

Figure 1. Map of the Araguari River basin shows the hydropower dams in operation.

water transparency with a Secchi disk lowered into the water in a location without noticeable flow. We measured limnological parameters between 8 and 11 h after removing the gillnets.

We used rainfall data for 1976 to 2013 from five climatological stations (codes 1848004, 1848006, 1848009, 1848010, and 1848049; ANA, 2024) located around the AAD at straight-line distances ranging from 27.3 to 36.5 km. We calculated the mean daily rainfall (MDR) for the five stations using the daily rainfall for each station. We defined the mean daily rainfall (MDR) on the day we set the gillnets as $rain_1$. We then calculated $rain_3$ as the average of $rain_1$ and the MDR of the previous two days, $rain_7$ as the average of $rain_1$ and the MDR of the last six days, and similarly for $rain_{15}$ and $rain_{30}$. We defined the dry (April to September) and wet (October to March) seasons based on MDR. From 1976 to 2013, the wet season contributed 86.2% of the annual rainfall, and each month of the wet season contributed between 13.2% and 19.4% to the yearly total, while each month of the dry season contributed between 0.5% and 7.1%.

We downloaded data on the daily discharge of the turbine and spillway from the *Operador Nacional do Sistema Elétrico* (ONS, 2024) and summed both discharges to obtain daily tailwater discharge (Q). As with rain, we used Q of the day, and we set the gillnets as Q_1, the mean of Q_1 plus the Q of the two previous days as Q_3, and so forth for Q_7, Q_{15}, and Q_{30}.

2.4. Data analysis

We determined the number of individuals sampled per species and richness for each fishing gear type. We used a Venn diagram to display the species shared and unique to each fishing gear type. We also constructed species dominance curves with species ranked in decreasing order of number of individuals sampled (Brower & Zar, 1984). We included *Hypostomus* spp. in these analyses.

For *P. maculatus*, we determined the number of individuals sampled (N) per campaign by each fishing gear type. We tested the significance of the Spearman's Rank correlation (r_s) of N among the three types of fishing gear. We then used a generalized linear model (GLM) to evaluate the effect of predictor variables on N. Due to a high correlation between the series of variables derived from rainfall ($r_s > 0.50$) and Q ($r_s > 0.65$), we included in the model the variable from each series that had the highest correlation with N (i.e., $rain_{30}$ and Q_{30}). Consequently, we tested the effects of fishing gear type (hook-and-line, cast net, and gillnet), season (dry and wet), water physicochemical parameters (dissolved oxygen, temperature, and transparency), $rain_{30}$, Q_{30}, and the interactions of fishing gear with water physicochemical parameters, $rain_{30}$ and Q_{30} on N.

We performed all analyses in R version 4.3.2 (R Core Team, 2023). Initially, we investigated collinearity between quantitative variables based on variance inflation factor (VIF) values using the "vif" function from the "car" package (Fox & Weisberg, 2019). We eliminated the variables with the highest VIF values one by one, and only variables with VIF < 5 remained in the models. We then excluded non-significant terms ($p > 0.05$) one by one using the drop1 command, which removes one variable at a time, and compared the Akaike Information Criteria (AIC) across different models, selecting the one with the lowest AIC to prevent overfitting (Zuur et al., 2009). A non-significant variable was retained in the final model to address underdispersion.

We initially built the models using the Poisson distribution but replaced it with the Negative Binomial distribution from the "MASS" package (Venables & Ripley, 2002) due to overdispersion. In both cases, we used a log link function. We tested the final model for the presence of influential values, Cook's distances, data fit, normality of residuals, and homogeneity of variances. We assessed model fit using the "DHARMa" (Hartig, 2022) and lmtest (Zeileis & Hothorn, 2002) packages.

3. Results

We captured 3,777 individuals of 32 species, plus 1,340 fish from an undetermined number of species within the *Hypostomus* genus that could not be identified. *Pimelodus maculatus* was the most sampled fish (52.6% of the total). Gillnet was the fishing gear that captured the greatest number of species and individuals (30 species plus *Hypostomus* spp. and 82.8% of the total number of individuals), followed by hook-and-line (9; 12.8%) and cast net (7; 4.3%). Twenty species plus *Hypostomus* spp. were collected exclusively by gillnet, while hook-and-line and cast net had only one exclusive species each (Figure 2). *Pimelodus maculatus* was the dominant species captured by all three types of fishing gear used.

The species dominance curves indicate that *P. maculatus* was less dominant in gillnet samples than in cast net and hook-and-line samples (Figure 3). This species represented 44.6% of the individuals caught by gillnets, 89.1% by cast net, and 92.4% by hook-and-line.

Temporal variation in the number and percentage of *P. maculatus* caught by the three types of fishing gear presented synchrony (Figure 4). However, *P. maculatus* was only captured by cast net in the campaigns where hook-and-line and gillnet had their highest captures. The number of *P. maculatus* caught by the three fishing gear types was positively correlated (hook-and-line x cast net: $r_s = 0.69$, $p = 0.01$; hook-and-line x gillnet: $r_s = 0.87$, $p \leq 0.001$; and cast net x gillnet: $r_s = 0.79$, $p \leq 0.001$). The number of captured fish was generally lower during the dry season campaigns compared to the wet season campaigns, except for August 2010 and April 2011.

Water temperature, water transparency and rainfall showed seasonality while the other abiotic variables did not (Figure 5). The highest water temperature occurred during the wet season, plus April, and the lowest during the rest of the dry season. Water transparency gradually increased throughout the dry season and decreased during the wet season. The months with the highest $rain_{30}$ were October to April, while the lowest were June and August.

The initial model was composed of 12 terms, two of which were categorical variables (fishing gear type and season), five were continuous variables (dissolved oxygen, water temperature, water transparency, $rain_{30}$ and Q_{30}) and the interactions of fishing gear type with dissolved oxygen, temperature, transparency, $rain_{30}$ and Q_{30}. The correlations of N with continuous variables of the model were: dissolved oxygen ($r_s = -0.19$, $p = 0.15$), temperature ($r_s = 0.58$, $p < 0.001$), transparency ($r_s = -0.21$, $p = 0.12$), $rain_{30}$ ($r_s = 0.44$, $p < 0.001$) and Q_{30} ($r_s = 0.25$, $p = 0.06$). All VIF values were below 5, but above 3 for temperature and $rain_{30}$ ($r_s = 0.84$, $p < 0.001$).

The final model, after exclusion of non–significant variables and interactions, had four variables (fishing gear type, season, temperature, and dissolved oxygen) and the interaction Fishing gear:temperature (Table 1). The model without dissolved oxygen presented underdispersion (Dispersion test: $p = 0.04$). We included the non-significant dissolved oxygen in the model to eliminate underdispersion (Dispersion test: $p = 0.12$). The final model had no influential values, Cook's distances were less than 1 and the lack-of-fit test was not significant ($p = 0.24$). The residuals present a normal distribution (Shapiro–Wilk test: $W = 0.98$, $p = 0.58$), but the variances were not homogeneous (studentized Breusch–Pagan test: $BP = 14.67$, $df = 7$, $p = 0.04$).

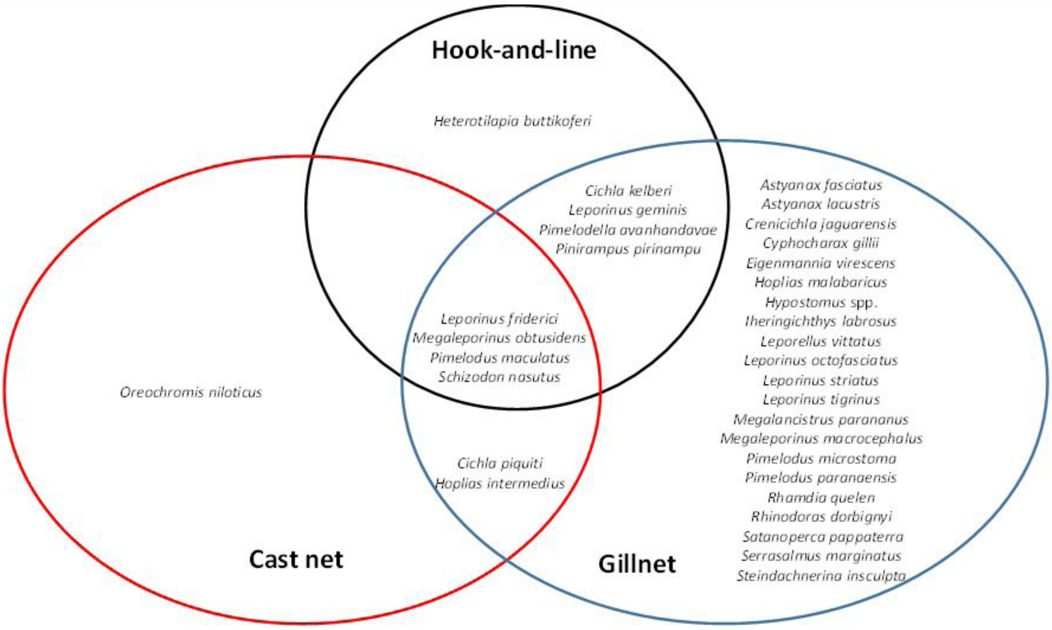

Figure 2. Venn diagram showing fish taxa collected by hook-and-line, cast net, and gillnet in the tailwater zone of the Amador Aguiar II Hydropower Dam, Araguari River.

The N was influenced by fishing gear (higher in gillnets and lower in cast nets), season (higher in the wet season and lower in the dry), and temperature (N increased with higher temperatures). Among the interactions tested, only the interaction between fishing gear type and temperature was significant (Table 1).

We recorded six catch peaks (N > 125 individuals), all using gillnets. Five peaks occurred during the wet season and one during the dry season, all at water temperature of ≥ 27 °C. We found no relationship between these peaks and rainfall.

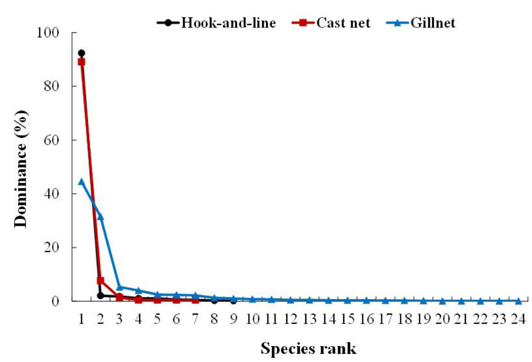

Figure 3. Dominance curves for fish species sampled in the tailwater zone of the Amador Aguiar II Hydropower Dam, Araguari River, per fishing gear type.

4. Discussion

We found that about one third of all fish species known for the Araguari River basin inhabit the TZ of AAD despite its area being a tiny fraction of the basin. The dominant species in the samples, *P. maculatus*, is also the species most affected by the O&M of AAD (Rêgo et al., 2016a). Hook-and-line and gillnet were the most appropriate fishing gear types for estimating the abundance of *P. maculatus* in the TZ of AAD. To reduce mortality of the species due to O&M of AAD, we recommend (i) that turbine maintenance be carried out in the dry season, when the catches of *P. maculatus* in the TZ is lower and (ii) that turbine startup be carried out at times when the abundance of *P. maculatus* inside the turbine is lower. Preliminary study on diel variation of *P. maculatus* abundance inside the draft tube of AAD using DIDSON indicates that abundance in the wet season is lower during nighttime (Braga et al., 2022). If this pattern is confirmed by more robust data, O&M that pose a risk to *P. maculatus* should be conducted at night to minimize mortality.

In the area of AAD, the wet season lasts for six months, beginning in late spring and ending in early fall. Peaks in water temperature occur during the wet season because the hottest months of the year fall within this period. As the wet season progresses, water transparency gradually decreases. In undammed rivers of a similar order in the same region, water transparency decreases abruptly at the beginning of the wet season (ALG personal observation). The difference in water transparency trends between the study site and undammed rivers is due to sedimentation of silt in the three large upstream reservoirs. The lack of seasonality in the discharges of AAD is due to flow regulation by the most upstream large dam.

Pimelodus maculatus was the most abundant species in the samples. The species is often dominant in fish assemblages in the TZs of hydropower dams in Southeast Brazil (Souza et al., 2016), an important reason for it being the species most affected by O&M (Rêgo et al., 2016a). The ability of *P. maculatus* to spawn in short river stretches (Agostinho et al., 2003), associated with its high trophic plasticity, apparently make it abundant in many reservoirs (e.g., Dei Tos et al., 2002; Maia et al., 2007).

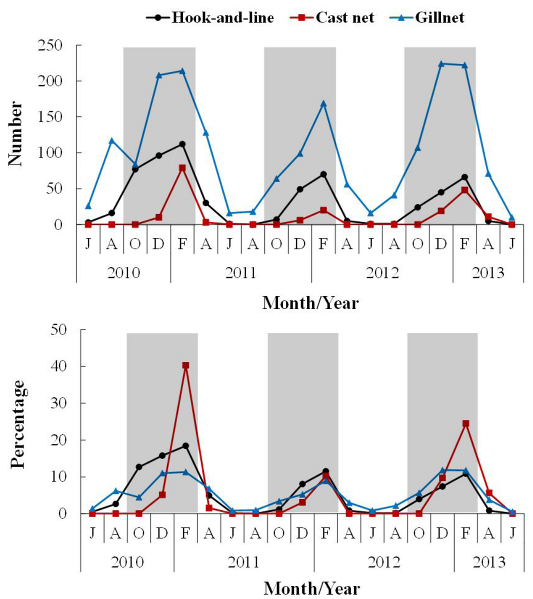

Figure 4. Temporal variation in the number (top panel) and percentage (bottom panel) of *Pimelodus maculatus* sampled per fishing gear type in the tailwater zone of the Amador Aguiar II Hydropower Dam, Araguari River. Shaded areas correspond to the wet season. For each fishing gear type and month, the percentage is the number of fish captured in that month divided by the total number of fish captured by that fishing gear type.

Gillnet and hook-and-line were the most efficient gear types for sampling *P. maculatus* while hook-and-line and cast net were the most specific. Gillnet captured most *P. maculatus* and depended less on the skill of the fisher. Because gillnet provided lower dominance and far superior richness than did the other two gear types, it was the least specific gear for *P. maculatus* and the one with the highest bycatch. Gillnet is notorious for high mortality among the fish it captures (Buchanan et al., 2002; Bettoli & Scholten, 2006). High bycatch and mortality were the two major disadvantages of using gillnet to sample *P. maculatus*.

The three fishing gear types showed similar trends in temporal variation in the number of *P. maculatus* captured. Cast net, however, captured some individuals only when the captures by gillnet and hook-and-line were at their highest. This indicates that cast net only captures *P. maculatus* when the species is at high density. At the TZ of the São Simão Hydropower Dam, Carvalho et al. (2016) found a strong negative correlation between CPUE of *P. maculatus* and water transparency; higher CPUE was observed only when water transparency was below 1.5 m. They suggested two possible mechanisms for the lower CPUE with higher water transparency:

Table 1. The final generalized linear model of the effects of fishing gear type and environmental factors on the number of *Pimelodus maculatus* captured in the tailwater zone of the Amador Aguiar II Hydropower Dam, Araguari River.

Model terms	Coefficiente	SE	z	p
Intercept	-81.21	16.47	-4.93	<0.001
Fishing gear (hook-and-line)	70.24	15.83	4.44	<0.001
Fishing gear (gillnet)	77.98	15.79	4.94	<0.001
Season (dry)	-0.97	0.33	-2.95	0.003
Temperature	3.06	0.60	5.11	<0.001
Dissolved oxigen	0.30	0.18	1.66	0.100
Fishing gear (hook-and-line):temperature	-2.56	0.59	-4.36	<0.001
Fishing gear (gillnet):temperature	-2.81	0.59	-4.79	<0.001

SE = standard error, z = z statistic and p = p–value.

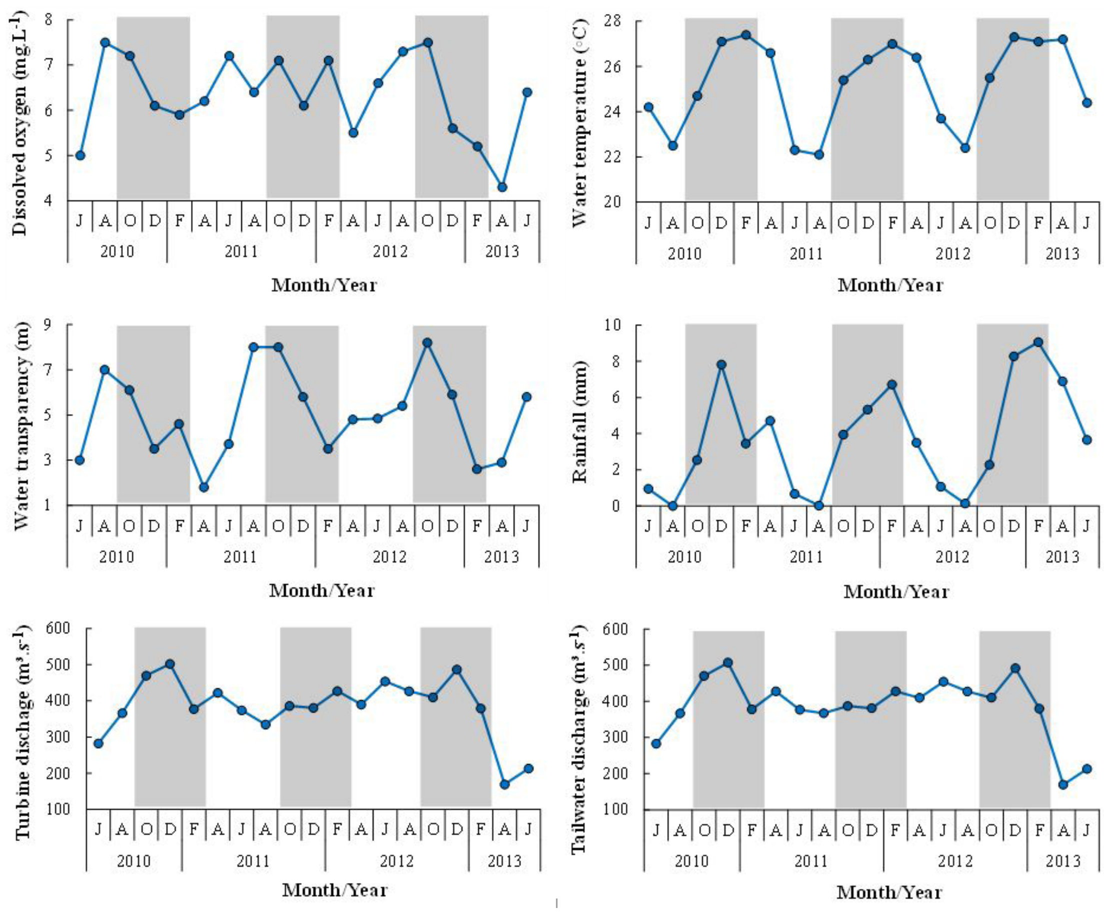

Figure 5. Temporal variation of abiotic factors at the tailwater zone of the Amador Aguiar II Hydropower Dam, Araguari River. Dissolved oxygen, temperature and transparency of the water are measurements on the day we removed the gillnets, while rainfall, turbine discharge and tailwater discharge represent the means of the 30 previous days. The shaded area represents the wet season.

P. maculatus might be hiding from predators in areas inaccessible to the cast net, and the increased likelihood of the cast net being seen by fish, which would increase their chances of escape. At the TZ of AAD, water transparency never reached less than 1.5 m, which may explain why the number of *P. maculatus* captured by cast net was not significantly influenced by water transparency. Thus, in addition to depending on fish density and fisher skill, cast net efficiency may also depend on water depth, water transparency, flow velocity and the absence of logs or other submerged structures (Gomiero, 2010; Carvalho et al., 2016). Due to all these restrictions, cast net proved to be the least effective gear for sampling *P. maculatus* at AAD.

Sampling by hook-and-line has the advantage of allowing the live release of virtually all caught fish, unlike gillnets, but its success is highly dependent on fisher skill (Monk & Arlinghaus, 2017; Hunt et al., 2021). Another problem with hook-and-line is saturation of the number of fish caught (Kuriyama et al., 2019). Saturation with hook–in–line happens because baiting, casting, retrieving and releasing fish take a certain amount of time, which limits the number of fish caught per fisher per hour to a maximum that will not be exceeded, even if fish abundance at the site increases. Saturation with hook-and-line occurred during the February 2011 campaign, when the highest fish catch with this gear, and with the two other gear types, took place. It was a matter of casting the hook and catching a fish. Saturation, on the other hand, did not occur with the cast net (some cast net throws did not catch fish) and apparently did not occur with the gillnets either (although there were many fish, there were also many empty meshes in the nets). Saturation is inherent to any fishing gear, but hook-and-line seems to have a more well-defined limit in this respect than cast net and gillnet.

Gillnet, and most likely hook-and-line, but not cast net, can be used to evaluate the risk of death of *P. maculatus* by O&M at AAD. The catches of tailwater fish has been used as a criterion to postpone or not O&M that is risky to fish because the number of fish deaths by O&M is related to fish captures (Rêgo et al., 2016a). For example, the greater the number of *P. maculatus* sampled in the TZ of AAD before turbine dewatering, the greater the amount trapped in the draft tube and the greater the risk of death during rescue. Gillnet has been used at AAD prior to turbine dewatering to predict the amount of *P. maculatus* to be rescued from the draft tube based on the number of *P. maculatus* sampled in the TZ (Rêgo et al., 2016a). Our data indicate that hook-and-line will likely provide the same prediction capability as of gillnet, whereas cast net will likely not because of its low efficiency.

Migration and higher metabolism are the two most likely ultimate factors explaining seasonal variation in the number of *P. maculatus* sampled. The number of *P. maculatus* captured changed significantly between dry and wet seasons. Among the abiotic variables that changed with the seasons, water temperature was the proximate factor that most influenced the seasonal variation in the number of *P. maculatus*. Rainfall was also an important proximate factor influencing the seasonal variation of *P. maculatus*. Although it was excluded from the GLM model due to its high correlation with water temperature, rainfall is represented in the model through the variable season. More individuals were captured when rainfall and water temperature were higher, a condition typical of the spawning season of the species (Godinho et al., 1977; Vazzoler et al., 1997; Braga, 2000; Dei Tos et al., 2002; Lima-Junior & Goitein, 2006). Loures & Pompeu (2012) also reported an increase in abundance of *P. maculatus* in the TZ of the Três Marias Hydropower Dam, São Francisco River, during the wet season. In fact, migratory movements of South American riverine fishes are known to be directly related to variation in fluviometric level (Lowe–McConnell, 1987) due to rainfall. If the increase in *P. maculatus* abundance in the TZ of AAD is indeed due to migration, this movement does not seem to be for spawning because fish with gonads in an advanced maturation stage are very rare in that TZ (Peressin et al., 2016). The influence of water temperature on captures of *P. maculatus* has already been shown elsewhere (Dei Tos et al., 2002; Carvalho et al., 2016; Peressin et al., 2016, 2021). Being ectothermic, higher water temperature increases fish metabolism (Garcia et al., 2008) and activity. Higher activity increases the catchability of fish by gillnet because movements of the individuals themselves result in their capture (Hubert et al., 2012) and by hook-and-line because fish search for more food.

To reduce mortality of *P. maculatus* by the O&M of AAD, we recommend conducting operations with a risk of fish death preferentially in the dry season when the catches of *P. maculatus* in the TZ is the lowest. If such O&M must be performed during the wet season, it may be safer to do so when the water temperature is below 27 °C, as *P. maculatus* catches in the TZ is lower. In both cases, the catches of fish in the TZ should be determined before conducting any O&M risky to fish to ensure safety. The best types of fishing gear for determining catches are gillnets and hook-and-line. The latter should be preferred due to its lower bycatch and reduced fish mortality.

Of the two operations that pose the highest risk to fish at AAD, namely turbine maintenance and turbine startup, the former is the easiest to schedule for the dry season because turbine maintenance is normally scheduled months or even years in advanced. Scheduling startup only for the dry season is not as viable as scheduling turbine maintenance for that period of the year. Turbine startup is more frequently done based on energy demand (Rêgo et al., 2016a), which varies much more during the day than between seasons of the year. Therefore, turbine startup occurs frequently during the day to meet energy demand. A more viable strategy for reducing fish mortality by turbine startup at AAD seems to be determining the hours of the day when fish abundance inside the turbine is the highest during turbine stops, which is the operation that precedes turbine startup. Thus, turbine startup would be avoided during such hours. Acoustic sonar, like DIDSON and ARIS, can be used to determine diel variation of fish abundance inside the turbine (Braga et al., 2022). Our recommendations are specific to AAD, but most likely can be applied to many other hydropower dams in Brazil with *P. maculatus* mortality by O&M.

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Data availability

The data set analyzed/produced in this study can be requested from the corresponding author due to the contractual clause with funder.

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