Estratégia reprodutiva de *Hypomasticus copelandii*: o piau-vermelho pode se adaptar a pequenos trechos lóticos e a ambientes lênticos ou depende da migração para completar seu ciclo de vida?

Reproductive strategy of Hypomasticus copelandii: the piau-vermelho can adapt to small lotic stretches and lentic environments, or depends on the migration to complete its life cycle?

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Resumo

Introdução: O conhecimento sobre o ciclo reprodutivo dos peixes é essencial para a conservação e exploração dos estoques pesqueiros. Os peixes podem migrar por vários motivos durante diferentes períodos de seu ciclo de vida, envolvendo a migração reprodutiva, mudanças de habitat de juvenis e a deriva de larvas de peixes. **Objetivo:** Nosso principal objetivo foi investigar se *H. copelandii* pode se adaptar a pequenos trechos lóticos e ambientes lênticos ou se depende da migração para completar seu ciclo de vida na natureza. **Metodologia:** Para a realização do estudo, as amostragens foram realizadas em dois afluentes do rio Doce, ambos contendo pequenas centrais hidrelétricas (PCH) em seus cursos, no rio Corrente Grande (CGR) e no rio Manhuaçu (MR). Em CGR foram capturados 408 exemplares (64 fêmeas, 109 machos e 235 juvenis), enquanto no MR foram capturados 64 fêmeas, 76 machos e 45 juvenis. **Resultados:** Nossos resultados mostram que o barramento dos rios causado pela construção das usinas e sua operação, não resultou em efeitos negativos diretos sobre as populações de *H. copelandii*. Para ambos os rios, foi mostrado a manutenção da atividade reprodutiva e do processo de recrutamento. **Conclusão:** Assim, é possível afirmar que *H. copelandii* pode adaptar sua estratégia reprodutiva, obtendo sucesso reprodutivo em trechos

lóticos muito pequenos ou em um corpo d'água semi-lêntico, indicando que suas estratégias reprodutivas não são apenas um fenômeno genético, mas que podem sofrer adaptações ecológicas, temporais e espaciais a partir de pressões ambientais.

Palavras chave: Peixes neotropicais; Migração reprodutiva; Bacia do rio Doce; Alterações ambientais.

Abstract

Introduction: *The fish reproduction knowledge is essential to support fish management, conservation and exploitation of the fish stocks. Fish species migrate for various purposes during different periods of their life cycle, and this involves spawning migration, habitat shifts of juveniles and drift of larval fish.* ***Objective:*** *Our main objective was to investigate whether the H. copelandii can adapt to small lotic stretches and lentic environments or depends on the migration to complete its life cycle.* ***Methodology:*** *Samplings were carried out on two tributaries of the Doce River, both containing small hydroelectric power stations in their courses, in Corrente Grande River (CGR) and in the Manhuaçu River (MR). In the CGR 408 specimens (64 females, 109 males and 235 juvenile) were captured, while in the MR were captured 64 females, 76 males and 45 juveniles.* ***Results:*** *Our results shows that the blockage of rivers caused by the construction of the power plants and their operation did not result in a direct negative effect on H. copelandii populations. For both rivers, our study demonstrates the maintenance of reproductive activity and the recruitment process, inserting new individuals into the environment.* ***Conclusion:*** *So, we showed that H. copelandii can adapt their reproductive strategy, getting reproductive success in very small lotic stretches or a semi lentic water body, indicating that the reproductive strategies of H. copelandii is not only a genetic phenomenon but can undergo ecological adaptations. Thus, the reproductive strategies of H. copelandii could undergo temporal and spatial changes and could be conditioned by environmental pressure.*

Keywords: *Neotropical fish; Reproductive migration; Doce River basin; Environmental changes.*

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1. Introduction

The biological and fish reproduction knowledge is essential to support fish management, conservation and exploitation of the fish stocks[1,2]. In the case of fish as a natural resource, the irrational exploitation and degradation become urgent and imperative that knowledge[3]. Among the many important biological aspects, the study of the reproductive process is a fundamental element, once its success depends on the recruitment and, consequently, the maintenance of viable populations, maintaining the environmental balance[4, 5]. According to scientific literature[6], know the strategies and tactics of the life cycle of fish allows better understand how these adapt to the environment and how they interact with the biotic and abiotic factors of the environment in which they live. With Brazil having one of the largest hydrographic networks in the world and one of the greatest ichthyofaunistic riches on the planet, its rivers are perfect environments for evaluating the reproductive strategies of freshwater fish.

The Doce River basin has a total area of approximately 82,000 km^2, of which 86% are in the state of Minas Gerais. In this state, its main tributaries in the right margin are the Chopotó, Casca, Matipó, Cuieté and Manhuaçu rivers, while for the left margin are the Piracicaba, Santo Antônio, Suaçuí Grande e Corrente Grande[7]. This hydrographic basin is impounded in several stretches of the longitudinal profile for hydroelectric purposes, discontinuing existing migration routes.

In the Corrente Grande River, east of the state of Minas Gerais, were installed two small hydroelectric power plants (PCH): Barra da Paciência (18°56'23.55"S / 42°29'10.79"W) and Corrente Grande (18°56'50.81"S / 42°31'45.51"W), which started operating in January 2011. These PCH's were installed very close to each other, with the PCH Barra da Paciência (BPC) inserted just downstream from PCH Corrente Grande (CRG), consequently, the final stretch of the BPC reservoir stood a few meters from the powerhouse of CRG, which suppressed almost completely the lotic environment between the two power plants.

In the Manhuaçu River, also at east of the state of Minas Gerais, where was installed at least four small hydroelectric power plants (PCH Neblina, PCH Pipoca, PCH Areia Branca and PCH Cachoeirão), sampling were made in the direct influence area of the PCH Pipoca (19°45'20.70"S / 41°46'48.02"W), which is located 10 km downstream from the PCH Neblina and 22 km upstream from the PCH Areira Branca, and which started operating in October 2010.

Species of the family Anostomidae are endemic Characiforms of South America, with a wide distribution within the continent excepting river systems of the Pacific side. Several species of Anostomidae family, particularly those of the genus *Leporinus*, are important component of commercial and recreational fisheries, with a wide acceptance of its flesh for human consumption[8]. *Leporinus copelandii* which recently had its nomenclature

updated to *Hypomasticus copelandii*, popularly known as piau-vermelho (**Figure 1**), is a medium-sized species, native to the basins of the Doce and Paraíba do Sul Rivers. According to literature[9,10], *H. copelandii* is a migratory species and is a total spawner, with relevance for human consumption. Andrade and Vidal Junior[11] cite their potential in sport fishing and zootechnical use, however, a decline of *H. copelandii* population is reported in some studies[12,13].

Despite the interest that migratory species arousing for several decades, few studies have investigated the biological aspects, especially the reproductive strategies of the rheophilic species present in the Doce River basin. In this sense, our study is intended to contribute to improving the knowledge of reproductive aspects (breeding season, sex ratio, stage of gonad maturation, histological oocyte and spermatocyte development stages and if this species really need long stretches of lotic environmental to complete their reproductive cycle) of *Hypomasticus copelandii* (**FIGURE 1**) in a lotic system that have impoundments blocking the longitudinal profile, that impeding the upstream migration of the rheophilic fish species during the reproductive season. In summary, our objective is to verify whether *H. copelandii* is in fact a strictly migratory species or just rheophilic.

FIGURE 1 – *Hypomasticus copelandii* (TL 45 cm).

2. Methodology

Sampling area

Samplings were carried out on two direct tributaries of the Doce River, both containing small hydroelectric power stations in their courses. In the Corrente Grande River, samplings were performed in seven sites (**Table 1**, **Figure 2**) and in the Manhuaçu River, sampling were performed in four sites (**Table 2**, **Figure 3**).

For the influence area of PCH Corrente Grande and PCH Barra da Paciência, six sampling sites were selected for ichthyological collections (**Table 1**).For the influence rea of PCH Pipoca, four sampling sites were selected for ichthyological collections **(Table 2).**

TABLE 1 - Sampling sites at the Corrente Grande River.

Sampling sites	Descriptive location	Coordinates
IC01	Upstream from the reservoir of the PCH Corrente Grande	18°56'28"S 42°33'35"W
IC02	In the reservoir of PCH Corrente Grande	18°56'52"S 42°32'41"W
IC03	Between the dams of PCH's Corrente Grande and Barra da Paciência	18°56'53"S 42°31'20"W
IC04	In the reservoir of PCH Barra da Paciência	18°56'39"S 42°29'35"W
IC05	Between the dam and the powerhouse of PCH Barra da Paciência	18°57'41"S 42°29'33"W
IC06	Downstream from the powerhouse of PCH Barra da Paciência	18°57'3"S 42°27'43"W

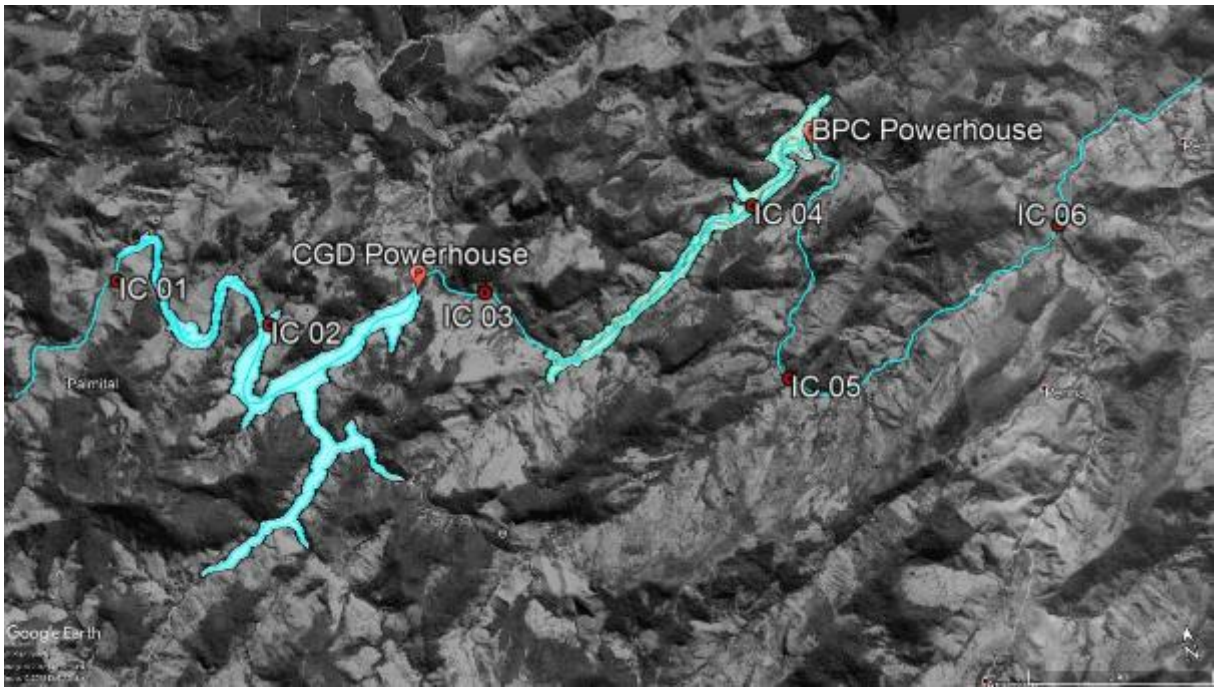

Figure 2 - Map of the sampling sites at the Corrente Grande River (Google Earth – 2021 adapted).

TABLE 2 - Sampling sites at the Manhuaçu River.

Sampling sites	Descriptive location	Coordinates
IC01	Upstream from the reservoir of the PCH Pipoca	19°48'5.83"S 41°47'15.82"W
IC02	In the reservoir of PCH Pipoca	19°46'41.59"S 41°47'42.51"W
IC03	Between the dam and the powerhouse of PCH Pipoca	19°45'24.02"S 41°47'22.52"W
IC04	Downstream from the powerhouse of PCH Pipoca	19°44'49.48"S 41°46'58.71"W

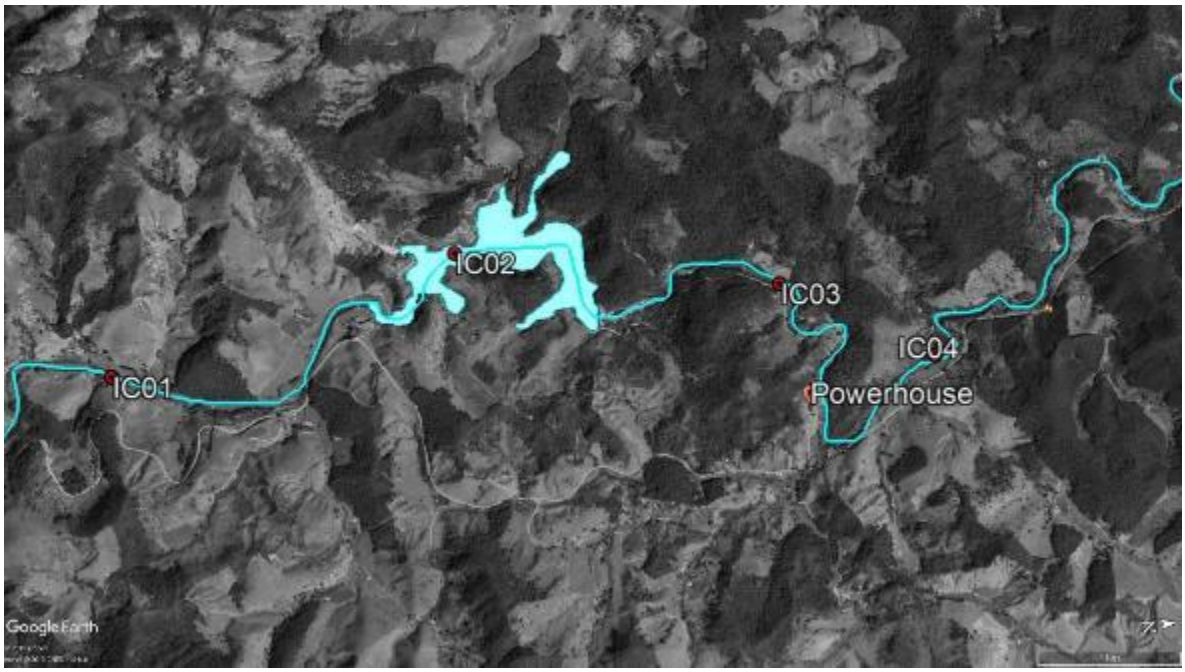

FIGURE 3 - Map of the sampling sites at the Manhuaçu River (Google Earth - 2021 adapted).

Catching fish and laboratory procedures

Fishes were caught using gillnets with mesh sizes ranged from 3 to 14 cm (stretched measure) from 2008 to 2017 in the Corrente Grande River (CGR) and from 2005 to 2017 in the Manhuaçu River (MR). To CGR were conduct ichthyological sampling during three years before the start of operation, and through five after the beginning of its operation. To MR were conduct ichthyological sampling during three years before the start of operation, and through seven after the beginning of its operation. The gill nets had 10 m long with height varying from 1.5 to 2.8 m and were utilized with soaking time of approximately 12 h.

In the CGR a total of 408 specimens (64 females, 109 males and 235 juvenile) were captured, while in the MR were captured 64 females, 76 males and 45 juveniles, a total of 185 fish. From all fish were measured the length (cm) and body weight (g). The fish, which were still alive in the nets, were handled in accordance with the Animal Experimentation Guidelines established by the Brazilian College of Animal Experimentation (COBEA) and were euthanized with lethal dose of Eugenol (Indian clove oil). The fish collections were authorized by the State Forest Institute of Minas Gerais (IEF 018.012/2016 and 018.015/2016).

Gonad fragments from each captured specimen were fixed in Bouin's solution for 12 hours, embedded in paraffin, cut in 5 µm sections and stained with haematoxylin-eosin (HE) using routine histological techniques. Gonadal maturation was analyzed based on histological characters, distribution of cells from the oogenic and spermatogenic lineages. Gonadal maturation stages of males and females were determined using macroscopic and microscopic characteristics of the gonads and the distribution of oocytes and spermatogenic cells, and spawning type was determined by considering the frequency distribution of the different gonadal maturation stages and the histological characteristics of spawned ovaries[14].

Data analysis

To study population structure, total length (TL - cm) and body weight (BW - g) from males, females and juveniles were measured and analyzed separately. The size of the smallest males and females reproductively active was used to define size at first gonadal maturation.

The relationship between weight and body length for males and females, was performed through the graphical distribution of individual empirical points of these variables, verifying that the relationship between the two variables was the potential kind, being represented by the formula: $BW=aTL^b$, where: BW = total weight in grams; TL = total length in cm; (a) a = linear coefficient = Condition factor related to the degree of fattening the individual; (b) = angular coefficient associated with the type of individual growth[15].

The sex ratio per standard length class, environment, and season was established. Significant differences from 1:1 was analyzed using the G test[16]. The reproductive period of H. copelandii was established through analysis of the distribution (frequency) of the stages of the reproductive cycle throughout the year. The sampling periods were grouped in quarters, being NDJ (November, December and January), FMA (February, March and April), MJJ (May, June and July) and ASO (August, September and October), were the highest frequencies of individuals in reproductive activity were used were used as indicators of the breeding season. In addition, the distribution of gonadal maturation stages along the sampling points was used as indicators of spawning areas. The recruitment sites were indicated by sampling points with the highest frequencies of young individuals

3. Results

Population structure

In the Corrente Grande River were caught 173 adult specimens of *H. copelandii*, 109 males (63%) and 64 females (37%), i.e., a rate significantly different from that expected for natural populations (1:1). Analyzing the sample period, it is also possible to observe an increase in rates of capture of males and females over the years, especially after the operation of the PCH's Barra da Paciência e Corrente Grande. Furthermore, we highlight the occurrence of juveniles from the start of operations of PCH's BPC and COG (**Figure 4**), indicating thus, that the blockage of the river caused by the construction of the PCH's and their operation did not result in a direct negative effect on *H. copelandii* populations.

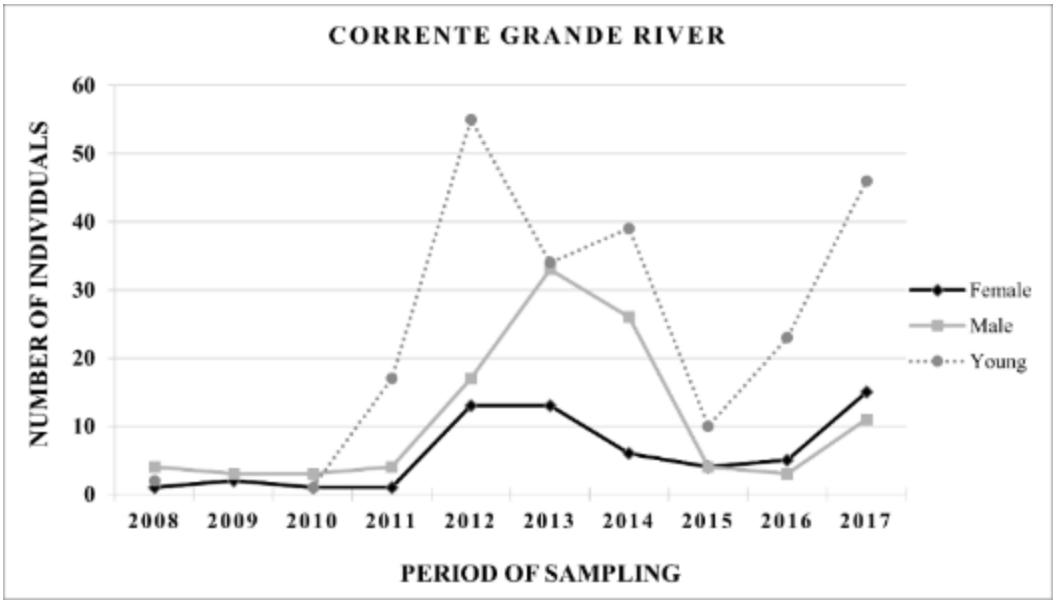

FIGURE 4. Occurrence of females, males and young individuals of Hypomasticus copelandii in the Corrente Grande River, before and after the beginning of operation of the PCH's Barra da Paciência and Corrente Grande.

In the Manhuaçu River were caught 140 adult specimens of *H. copelandii*, 76 males (54.3%) and 64 females (45.7%), i.e., a sex ratio close to 1:1. Analyzing the sample period, it is also possible to observe an increase in rates of capture of males and females over the years, especially after the operation of the PCH Pipoca. Furthermore, we highlight the frequent occurrence of juveniles from the start of operations of PCH (**Figure 5**), indicating thus, that the blockage of the river caused by the construction of the PCH and their operation also did not result in a direct negative effect on *H. copelandii* populations.

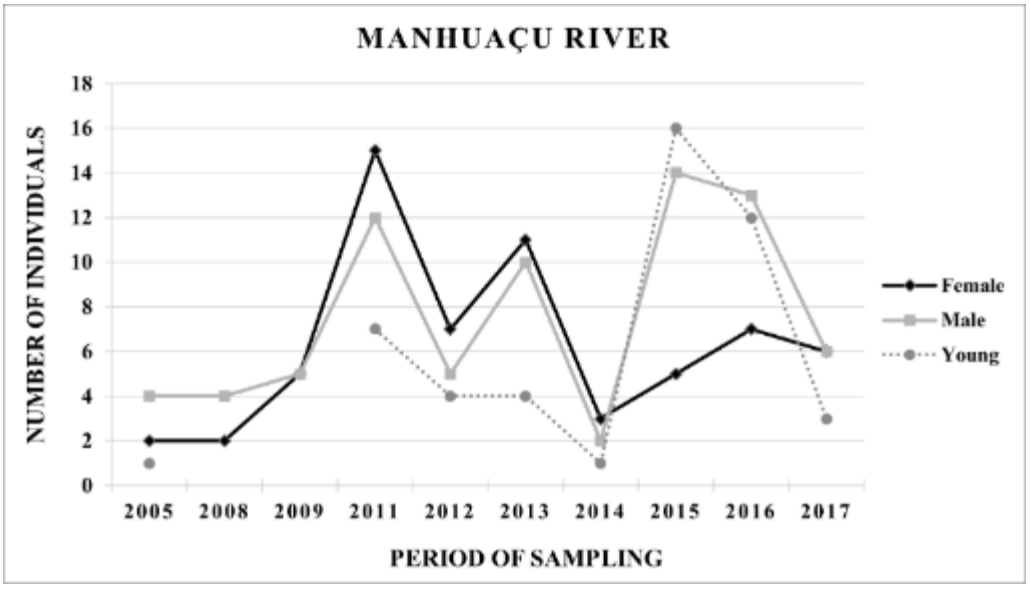

FIGURE 5. Occurrence of females, males and young individuals of Hypomasticus copelandii in the Manhuaçu River, before and after the beginning of operation of the PCH Pipoca.

For fish caught in the Corrente Grande River the total length of females ranged from 17.0 to 48.0 cm with a mean of 22.0 cm, the males ranged from 14.0 to 58.0 cm with a mean of 21.8 cm, while the young fish ranged from 9.0 to 16.9 cm and 10.6 cm in average (**Table 3**). The body weight of females ranged from 25.0 to 1036.0 g with an average 202.5 g, male 25 to 1,439.0 g and 238.3 g of average, while young fish ranged from 9.0 to 47 g and 21.9 in average.

TABLE 3 - Amplitudes of length and body weight of *H. copelandii* caught at the Corrente Grande River.

	Total length (cm)			**Body weight (g)**		
	Min.	**Máx.**	**Méd.**	**Min.**	**Máx.**	**Méd.**
Female	17.0	48.0	22.0	25.0	1036.0	202.5
Male	14.0	58.0	21.8	25.0	1439.0	238.3
Young	9.0	16.9	10.6	9.0	47.0	21.9

For fish caught in the Manhuaçu River the total length of females ranged from 17.0 to 56.0 cm with a mean of 23.6 cm, the males ranged from 17.0 to 47.5 cm with a mean of 24.1 cm, while the young fish ranged from 12.0 to 16.5 cm and 11.3 cm in average (**Table 4**). The body weight of females ranged from 31.0 to 996.0 g with an average 256.4 g, male 36.0 to 840.0 g and 273.4 g of average, while young fish ranged from 14.0 to 39.0 g and 24.3 in average.

TABLE 4 - Amplitudes of length and body weight of H. copelandii caught at the Manhuaçu River.

	Total length (cm)			Body weight (g)		
	Min.	**Máx.**	**Méd.**	**Min.**	**Máx.**	**Méd.**
Female	17.0	56.0	23.6	31.0	996.0	256.4
Male	17.0	47.5	24.1	36.0	840.0	273.4
Young	12.0	16.5	11.3	14.0	39.0	24.3

In the Corrente Grande River the lower length classes obtained the largest numbers of individuals, evidencing the presence of young individuals in the population and consequently, showing the recruitment process (**Figure 6**). Adult fish were more representative between body lengths of 17 to 37 cm.

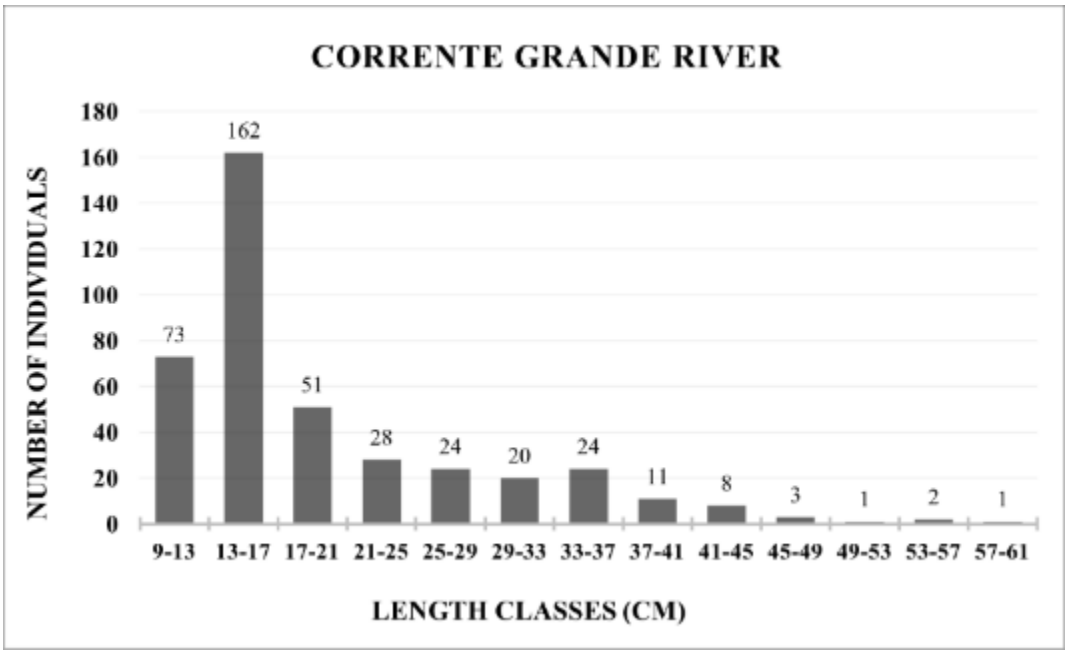

FIGURE 6. Distribution of length classes and body weight for H. copelandii caught in the Corrente Grande River.

In the Manhuaçu River the lower length classes also obtained representative numbers of young individuals (12-17 cm), showing thus the recruitment process (**Figure 7**). Adult fish were more representative between body lengths of 32 to 37 cm.

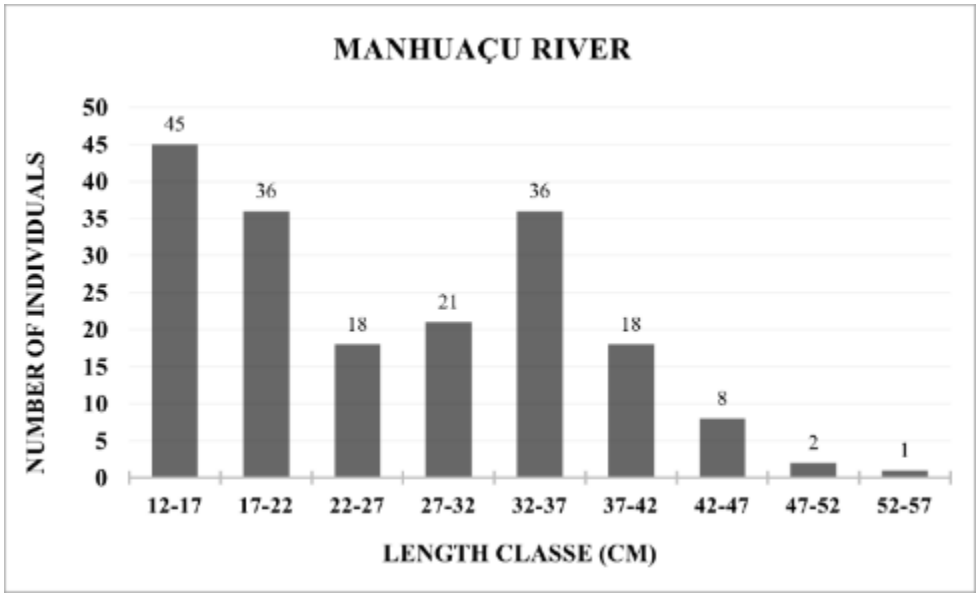

FIGURE 7. Distribution of length classes and body weight for H. copelandii caught in the Manhuaçu River.

As in the temporal analysis, our results showed wide spatial distribution of *H. copelandii* throughout the sampled area of the two analyzed rivers, with males and females recorded upstream, downstream and between PCH's Corrente Grande e Barra da Paciência (IC01 to IC06) (**Figure 8**), furthermore, a considerable number of juveniles occurred between the two power plants (IC03 and IC04), like that registered for the Manhuaçu River (**Figure 9**). Thus, our results show that the implementation and operation of the plants in question and the blockade to the fish migration imposed by them, associated with the reduction of the lotic stretches of the Corrente Grande and Manhuaçu rivers, seems to have not negatively affected the reproductive process of *H. copelandii* and its perpetuation in the studied areas.

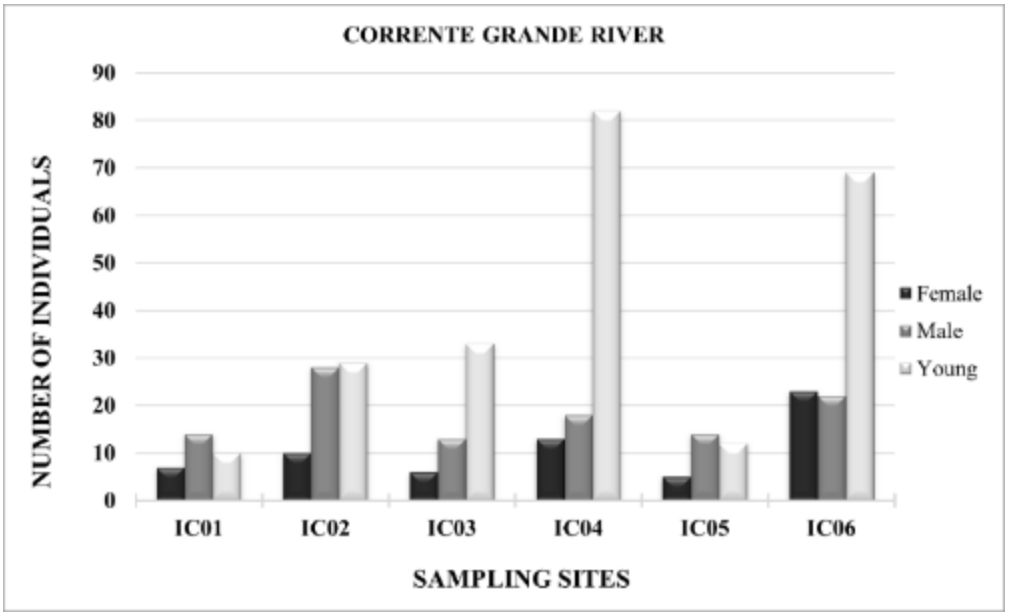

FIGURE 8. Numerical occurrence of females, males and young individuals of *H. copelandii* caught in the Corrente Grande River.

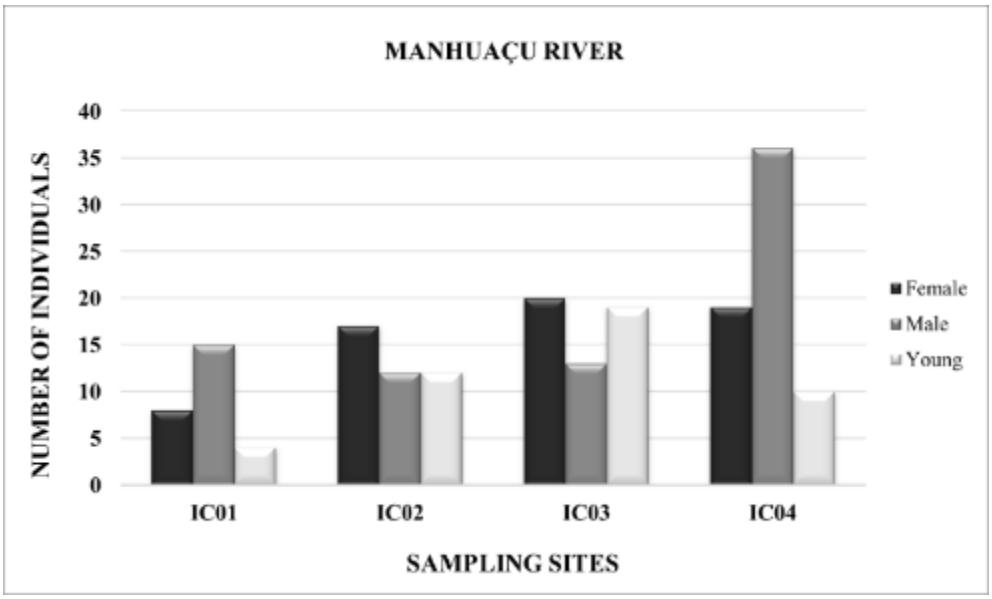

FIGURE 9. Numerical occurrence of females, males and young individuals of *H. copelandii* caught in the Manhuaçu River.

Body length-weight relationship

Through the angular coefficient is possible to determine the type of growth of the species. If b is equal to three, then growth is isometric; if greater than three is allometric-positive; and if less than three is allometric-negative17. According to our results (**Figure 10**), in the Corrente Grande River females of *H. copelandii* showed a positive allometric growth, males showed negative allometric growth while the young fish had b value much smaller than 3 and is therefore negative allometric.

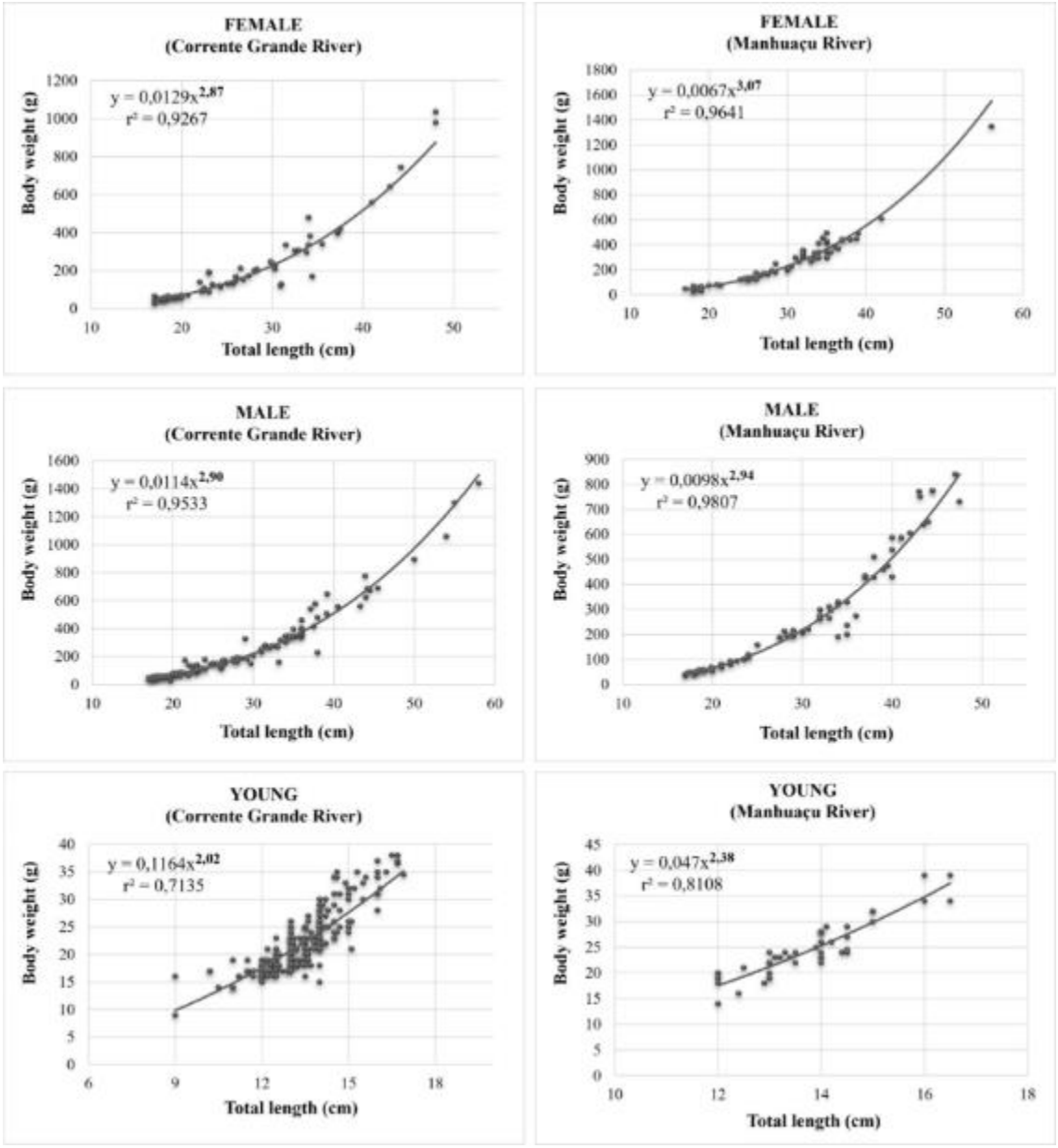

FIGURE 10. Length-weight relationship for females, males and young individuals of H. copelandii caught in the Corrente Grande and Manhuaçu rivers.

Reproduction activity

In the Corrente Grande River the smallest male and female captured presenting morphological characteristics of reproductive activity measured 14.0 and 19.3 cm of total length, respectively. Meanwhile, to the Manhuaçu River, the smallest male and female captured presenting morphological characteristics of reproductive activity measured 21.0 and 24.0 cm of total length, respectively.

For both studied rivers, the reproductive activity of *H. copelandii* was concentrated in the quarters of ASO and NDJ (**Figure 11**). It is also worth mentioning the occurrence of reproductive activity in the FMA quarter for

both rivers, indicating that *H. copelandii* has a long reproductive period.

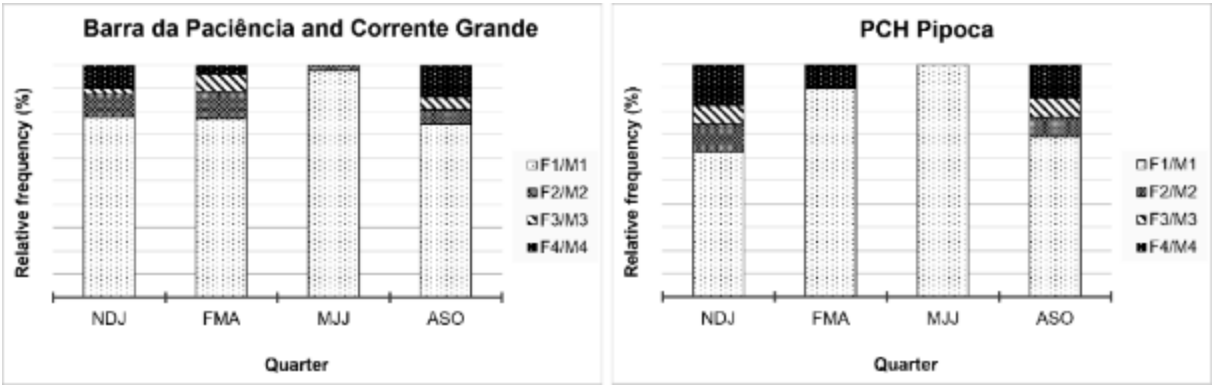

Figure 11. Distribution of gonadal maturation stages along the sampling periods (NDJ: November, December and January; FMA: February, March and April; MJJ: May, June and July) and ASO: August, September and October.

Our data showed reproductive activity along the entire sampled area in the rivers Corrente Grande and Manhuaçu (**Figure 12**), i.e., *H. copelandii* was able to reproduce in small lotic stretches as the area between PCH's Barra da Paciência and Corrente Grande (IC03), and until even in low water flow stretches as in the reduced flow section of the PCH Pipoca (IC03). Thus, demonstrating that *H. copelandii* does not require long stretches of lotic environments to complete its reproductive cycle.

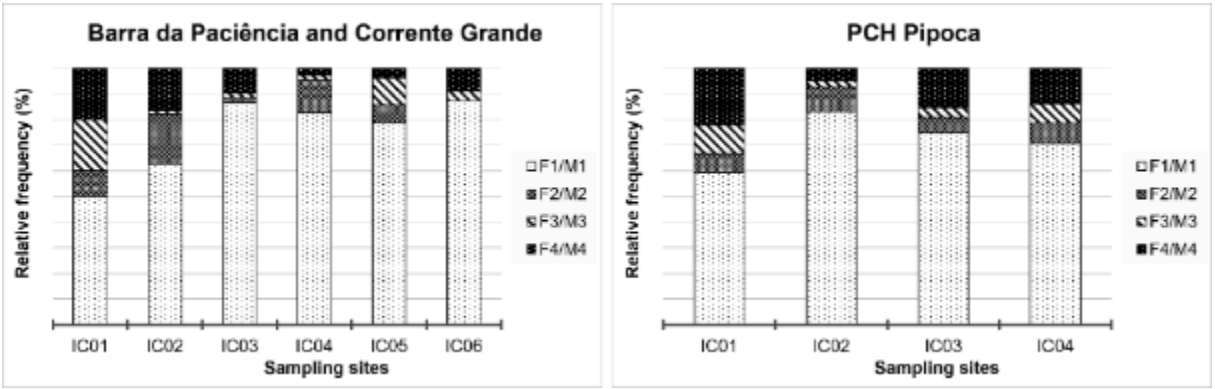

FIGURE 12. Distribution of gonadal maturation stages along the sampling sites.

Through microscopic and macroscopic analyzes of mature ovaries (**Figure 13 A, C**), it was possible to verify that in the Corrente Grande River as well as in the Manhuaçu River the ovarian development of *H. copelandii* was presented as being asynchronous

type, i.e. the oocytes mature in heterogeneous batch (**Figure 13 B**). The spawning also occurs in batches, being of the multiple spawning type, as can be visualized in **Figure 13 D**, where we present partially spawned ovaries (highlighted caudal region).

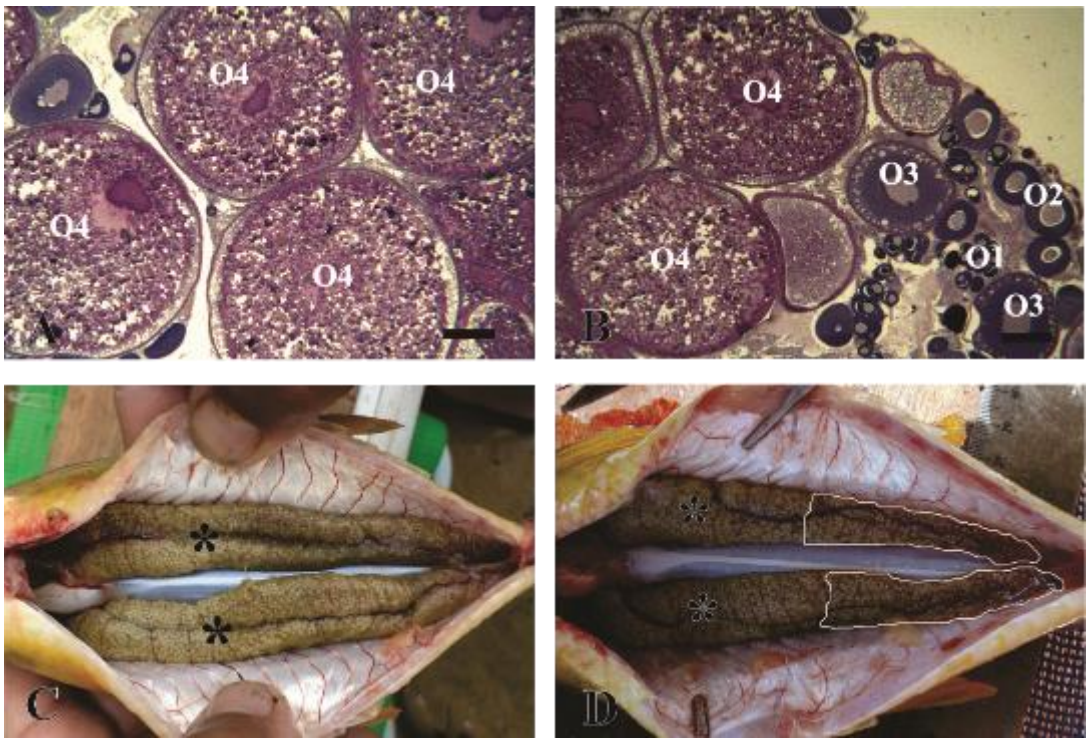

FIGURE 13. Microscopic and macroscopic images of *H. copelandii* mature ovary. O1 = initial perinucleolar oocytes; O2 = advanced perinucleolar oocytes; O3 = previtellogenic oocytes; O4 = vitellogenic oocytes; * = full mature ovaries.

4. Discussion

Knowledge about the biology of migratory species and distribution of critical habitats for its life cycle, such as spawning sites and nursery areas, is essential because some significant impacts, such as the existence of reaches not connected to spawning grounds or to high-quality nursery grounds, could endanger fish populations[18]. Moreover, information on the preferential spawning sites of a species is crucial since it constitutes basic ecological data on life history and can be used as a management tool in environments impacted or regulated by man[19].

Rheophilic and migratory are the groups of fishes most affected by the environmental transformation from lotic to lentic, once that their reproductive strategies are closely associated with characteristics of lotic environments[20,21]. Although some authors consider that *Hypomasticus copelandii* is a migratory species and is a total spawner[10,9], in the present study *H. copelandii* presented macroscopic and histological characteristics of a multiple spawner, and reaching

gonadal maturation, spawning and recruiting new individuals in a very small stretches of a river confined by two dams of hydroelectric power plants, i.e., in a river where the migration is not possible. This data showed that *H. copelandii* in rivers Corrente Grande and Manhuaçu, do not hold characteristics of migrating fish, adapting to the environment in which they are inserted. Corroborating these results, we observed an increase in rates of capture of adults and juveniles in the two studied rivers from the installation and operation of hydroelectric plants, showing that *H. copelandii* can adapt and reproduce in small lotic stretches where migration is not possible.

The predominance of males registered in the present study may be related to the trophic state of environments, once is know that in many cases food supply is a determining factor, and females predominate when food is abundant, while males predominate in oligotrophic environments[22]. Food would influence the metabolism through hormonal activity, causing changes in the production of individuals of one sex[23]. In both the studied area of the Corrente Grande River and in Manhuaçu, during most of the year, the water has oligotrophic characteristics.

Generally, in our study, a slight predominance of males in the longer length classes, and females in the shorter classes was observed. However, larger females have been frequently cited to another teleost, including some *Leporinus* as *L. friderici*[23]. Size is frequently associated with sexual dimorphism in fishes[24,25,26,23]. Our data also indicate differences in the types of growth for adults and young individuals, where adults showed greater increase in weight than in length, while young individuals showed greater increase in the length than in weight.

The different stages of oogenic development cells found clustered in ovaries of *H. copelandii* (e.g., oogonia, perinucleolar, vitellogenic and post-ovulatory follicles) indicate that the development of oocyte cohorts is group-synchronic and indicating multiple spawning type to *H. copelandii*. To *Leporinus taeniatus* at the São Francisco River basin[27], *H. copelandii* at the Paraiba do Sul River basin[28], *Leporinus amblyrhynchus*[29] and to *Schizodon knerii*[30] the spawning type also was fractional. Indorsing our hypothesis, after spawning and together with those post-ovulatory follicles, we found numerous pre-vitellogenic and vitellogenic oocytes forming an oocyte stock for the next spawning. Unlike from that observed in our work, Costa et al.[13] observed total spawning type in *H. copelandii* from lower Paraiba do Sul River.

Fishes that present total spawning have synchronous oocyte development and generally make reproductive migrations, while multiple spawners fish can reproduce in lentic environments[14,31], information that supports our hypothesis that *H. copelandii* does not depend on migration to complete their reproductive cycle, adapting thus to small lotic stretches where migration is not possible. Several *Leporinus* species have a migratory upriver migration during the reproductive season spawning in lotic environments[23,27]. However, spawning in lentic environments as

the reservoirs[32] or in lentic and semi-lotic environments in the floodplain areas for the Paraná River[33,34] has been reported for *L. friderici*, a fish considers as a migratory species by some authors.

It's well known that environmental variables trigger endogenous activities which, in turn, control the reproductive activity of Neotropical fish[35,36,31]. Usually the reproductive success of migratory Neotropical fish is linked to elevation of water flow[37] and water temperature[20,35], i.e. during the peak of rainy season. However, the reproductive period peak of *H. copelandii* in the studied area of Corrente Grande and Manhuaçu rivers was started during the dry season of the years studied (August/September/October). Thus, this information also disagrees with usually occurs with the Neotropical migratory freshwater fish, which reproduce during the rainy season[38,39].

5. Conclusion

In summary, the present study provides a comprehensive knowledge on the reproductive biology of *H. copelandii* in two rivers which had their natural conditions altered by the construction of hydroelectric power plants, i.e., they had their natural courses blocked and part of their lotic stretches transformed into reservoirs, reducing in this way, the available migratory routes. So, we showed that *H. copelandii* can adapt their reproductive strategy, getting reproductive success in some very small lotic stretches or a semi lentic water body. In this sense, we can admit that the reproductive strategies of *H. copelandii* is not only a genetic phenomenon but can undergo ecological adaptations. As reported by Lopes et al.[23] to *L. friderici*, the reproductive strategies of *H. copelandii* could undergo temporal and spatial changes and could be conditioned by environmental pressure.

6. Declaration of conflict of interest

The author of the article states that he is not in situations of conflict of interest of any kind.

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