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Original Article

Impacts of an urban flood control infrastructure on the limnology and ichthyofauna of a basaltic Cuesta stream (southeast Brazil)

Impactos de uma infraestrutura para controle de cheias urbanas sobre a limnologia e ictiofauna de um riacho de Cuesta basáltica (sudeste do Brasil)

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Abstract

Strategies for flood control associated to extreme precipitation events in urban areas are urgent, in order to prevent not only material damages but also to avoid human losses. The construction of flood contention reservoirs ("piscinões") has become a common engineering intervention in urban and peri-urban areas. However, there is a lack of studies focused on the evaluation of environmental impacts of this type of construction. This study intended to verify the ecological effects of a retention reservoir built directly on the course of the Cascata stream, Botucatu (SP). Three sampling sites were selected, located upstream the reservoir, in the reservoir and downstream. Samplings were carried out in July (winter – dry) and November (late spring – rainy) 2020. *In situ* measurements were obtained through a multiparameter probe (temperature, pH, electrical conductivity, dissolved oxygen, total dissolved solids, and oxidation-reduction potential) and water samples were collected for laboratory determinations (nitrogen, total phosphorus, thermotolerant coliforms, and chlorophyll-a). For fish sampling, manual trawls, sieves and hand nets were used, with a sampling effort of 10 throws per artefact and site. Despite the small distance between the sampling points (~1,300 m) considerable changes in the limnological conditions and fish community structure were observed. The studied environment is originally a small river surrounded by riparian forest, but this characteristic was abruptly changed in the reservoir stretch, with the direct exposition of a much larger water surface to intense solar radiation and atmosphere exchanges. Consequently, as evidenced by the PCA analysis, there was a considerable (stream-reservoir increase) of temperature, dissolved oxygen and chlorophyll. However, this spatial trend was partially disturbed by an accidental sewage-pipe rupture (posteriorly fixed) adjacent to the first sampling point, due to a previous event of extreme precipitation, which resulted in increased values of nutrients, chlorophyll, conductivity and thermotolerant coliforms. Eleven fish species were collected (two non-native), belonging to seven families and five orders. The upstream reference point (despite not be pristine), was characterized by the predominance of native species, while the reservoir condition favored the development of large populations of the non-native species. Despite the urgency of effective actions to prevent floods in urban areas, construction of contention reservoirs directly on stream courses should be avoided, due to their negative ecological impacts.

Keywords: contention reservoir, fluvial interruption, non-native species proliferation, "piscinão".

Resumo

Estratégias de controle de cheias associadas a eventos extremos de precipitação em áreas urbanas são urgentes, a fim de prevenir não apenas danos materiais, mas também perdas humanas. A construção de reservatórios de contenção de cheias ("piscinões") tornou-se uma intervenção comum da engenharia em áreas urbanas e periurbanas. No entanto, existe uma carência de estudos voltados para a avaliação dos impactos ambientais desse tipo de infraestrutura. Este estudo teve como objetivo verificar os efeitos ecológicos de um reservatório de contenção construído diretamente no leito do córrego Cascata, Botucatu (SP). Foram selecionados três pontos amostrais, localizados a montante do reservatório, no reservatório e a jusante. As amostragens foram realizadas em julho (inverno – seco) e novembro (final da primavera – chuvoso) de 2020. Foram feitas medidas *in situ* com sonda multiparamêtros (temperatura, pH, condutividade elétrica, oxigênio dissolvido, sólidos totais dissolvidos e potencial oxido-redução) e amostras de água foram coletadas para determinações laboratoriais (nitrogênio, fósforo total, coliformes termotolerantes e clorofila-a). Para a amostragem de peixes, foram utilizadas rede de arrasto manual, peneira e puçá, com um esforço amostral de 10 lances por artefato e local. Apesar da pequena distância entre os pontos de amostragem (~1.300 m), foram observadas mudanças consideráveis nas condições limnológicas e na estrutura da comunidade de peixes. O ambiente de estudo é originalmente um pequeno rio acompanhado por vegetação ripária, mas esta condição foi abruptamente alterada no trecho do reservatório, com a exposição direta de uma superfície de água muito maior à intensa radiação solar e trocas com a atmosfera. Consequentemente, conforme evidenciado pela ACP, houve um considerável aumento (riacho-reservatório) da temperatura, oxigênio dissolvido e clorofila. Contudo, houve um distúrbio desta tendência de variação espacial devido à ruptura de uma tubulação de esgoto (posteriormente reparada), adjacente ao ponto 1, decorrente de um evento extremo de precipitação, que elevou as concentrações de nutrientes, clorofila, condutividade e coliformes termotolerantes. Onze espécies de peixes foram coletadas (duas não nativas), pertencentes a sete famílias e cinco ordens. O ponto de referência a montante (apesar de não ser pristino), caracterizou-se pela predominância de espécies nativas, enquanto que a condição de reservatório favoreceu o desenvolvimento de grandes populações das espécies não-nativas. Apesar da urgência de ações efetivas para prevenir enchentes em áreas urbanas, as construções feitas diretamente no curso dos córregos devem ser evitadas, devido aos seus impactos ecológicos negativos.

Palavras-chave: reservatório de contenção, disrupção fluvial, proliferação de espécies não nativas, "piscinão".

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1. Introduction

Along the last decades, Brazil experienced an expressive increase in the urbanization indexes (IBGE, 2022). In the 1970's the proportion of rural and urban population were almost the same, but in 2010's people living in the cities corresponded to 80% of the total population (IBGE, 2011). According to the census carried out in 2022, in the last two decades the concentration of population in cities with more than 100,000 inhabitants increased 75% (IBGE, 2022). This social trend generated considerable modifications not only in the city areas but also expand to adjacent landscapes, affecting aquatic and terrestrial ecosystems (Tucci, 2007). The suppression of natural vegetation, increase in soil impermeability and alteration of pluvial drainage promote the increase of the runoff peaks, resulting in recurrent summer floods (Penna et al., 2019). Such a process, associated to the present scenario of climate change and variability – extreme droughts and intense precipitations in short time-periods, tends to intensify the drainage problems in urban areas (Buckeridge and Ribeiro, 2018).

In the austral regions, the occurrence extreme rains in summer is mainly associated to two atmospheric phenomena: cold fronts and South Atlantic convergence zones (Lima et al., 2010). In São Paulo metropolitan area, the number of days with rains higher than 50 mm increase about 30% from since the 1960's. In case of rains higher than 100 mm, the number of days incremented from two to seven (INMET, 2020). Extreme rains and their consequences in southeastern Brazil have affected more people than any other disasters in the XXI century (Marengo et al., 2023). In the last summer (February 2023), more than 600 mm registered in 24 hours in the northern coastal zone São Paulo State, in addition to substantial material damages, resulted in the loss of 54 human lives (Queiroz, 2023).

Despite the aggravation of the problems, the adaptation agenda of the Brazilian cities to climate crises is still incipient, for instance instruments for flood control, landslides and plans for risk reduction, due to the competition with other urgent healthy and educational questions (Queiroz, 2021). One of the strategies for prevention of flood risks in urban areas is the construction of contention reservoirs, which can be closed (underground) or opened infrastructures. These last one popularly known in Brazil as "piscinões". The operational concept is that in conditions of heavy precipitation these reservoirs storage the excess of water, with further slowly release until reaching an equilibrium situation (Penna et al., 2019).

According to the National Sanitation System of Information (Brasil, 2020), 170 Brazilian cities declared to have reservoirs for flood control, most (92) in Southeast region. Despite the fact that "piscinões" are an important and useful alternative to minimize inundations, there is some debate about this engineering alternative, given the high costs related to construction, including land expropriations, operation and maintenance (Dias and Antunes, 2010), as well as the impact on the landscape harmony (Penna et al., 2019). In terms of ecological impacts on natural aquatic ecosystems, we could not find any information in the literature.

In this context, the present work aimed to evaluate the environmental impacts caused by a flood contention reservoir, directly constructed in the course of a Cuesta stream, by comparison among sampling points longitudinally distributed – upstream the reservoir, in the reservoir and downstream the reservoir. We expected that the limnological characteristics and ichthyofauna attributes indicate the sudden transformation of a riparian forest stream into a lentic ecosystem inserted in an open landscape. Additionally, we tried to evaluate if the environmental transformation would favor the establishment of non-native species of fish in the system.

2. Material and Methods

2.1. Study area and sampling periods

The studied environment (Figure 1) is a typical small stream (4.23 km long; 5.55 km^2 of drainage area; 81.5 L s^{-1} of mean flow) (Belluta et al., 2016) of the Cuesta geologic formation. The stream, named Cascata, drains small rural properties and suburban areas of Botucatu city, in the center of São Paulo State, Brazil. A conspicuous characteristic of the Cuesta streams, despite their short courses (maximum around 22 km), is the steep gradient (~ 22 m/km), between 900 to 450 m of altitude (Moretto and Nogueira, 2003).

The construction of the contention reservoir (3.88 km^2 and the storage capacity is 158,000 m^3) in the Cascata stream was concluded in 2019, in order to mitigate floods in the downtown area.

Data for the present study were obtained in three sampling sites located upstream (P1) (22K 759354 m E- 7466528 m S) of the reservoir, in the reservoir (P2) (22K 760046 m E- 7466973 m S) and downstream the reservoir (P3) (22K 760502 m E - 7467064 m S). The longitudinal distance between P1 and P2 is ~ 900 m and between P2 and P3 ~ 400 m. The P3 is located just a few meters before the Cascata stream mouth into the Água Fria stream. Samplings were carried out during July (winter – dry season) and November (late spring – beginning the rain season) of 2020.

2.2. Limnological and water quality characterization

In order to characterize the limnological conditions the following environmental variables were measured, *in situ*, using a Horiba multiparameter probe (model U50): temperature, pH, electrical conductivity, oxygen, total dissolved solids and redox potential. At each sampling point, measurements were taken three times, and the average values were used in the results. As this stream flows directly towards an urban area, we also took samples for determination, in laboratory, of some water quality indicators: total nitrogen, total phosphorus, chlorophyll-a, biochemical oxygen demand (BOD), thermotolerant/fecal coliforms, total suspended solids and total dissolved solids (APHA, 2017).

2.3. Ichthyofauna sampling and identification

For fish collection a 1.0 m × 0.8 m sieve, 1 mm of mesh size, was manually introduced (two persons together) bellow the marginal aquatic vegetation and quickly raised at ten different points (standardized efforts) of the littoral zone of each sampling site. Samplings were performed under the license SISBIO 13.794-1 (M. G. Nogueira), controlled by the federal agency ICMBIO. As the study is part of a monitoring program of an infrastructure that requires a valid license to operate, fish sampling procedures were also analyzed and authorized by the official São Paulo State Environmental Agency – SMA/DeFAU (Secretaria de Meio Ambiente/Departamento de Fauna) (Authorization 3643605 emitted in 27th November 2019).

The captured individuals were identified according to the morphological characteristics (Graça and Pavanelli, 2007; Langeani and Rêgo, 2014; Ota et al., 2018), photographed, individually counted and measured (standard length) and then released back to the stream/reservoir stretches. In case of the non-native species, *Oreochromis niloticus* (Linnaeus, 1758) and *Poecilia reticulata* (Peters, 1859), all the individuals (mandatory according to Authorization 3643605 SMA/DeFAU) were euthanized in Eugenol solution before fixed in 10% formalin. In the laboratory, this material was transferred to 70% alcohol, counted and measured (standard length) (Mitutoyo digital caliper 0-150mm).

2.4. Data analysis

For descriptive analyzes data were organized in tables and graphics (Sigmaplot). The limnological dataset was used in a Principal Components Analysis (PCA) (Primer 6 & Permanova), with log-transformed data (x + 1), except for pH.

The following attributes were determined for the fish fauna: richness, absolute and relative abundance, Shannon Diversity (H') and Pielou Equity (J') indices, and individual standard size variation (cm).

In order to better understand the establishment process for the two non-native species populations, the standard-length measurements were compared to the size of the first sexual maturity (LS50). Particularly, for the non-native species *P. reticulata*, an ovoviviparous fish with internal fertilization, it was determined the population sex ratio, through observation of the individual gonads. For both analyzes it was used box-plot graphic representations (Sigmaplot).

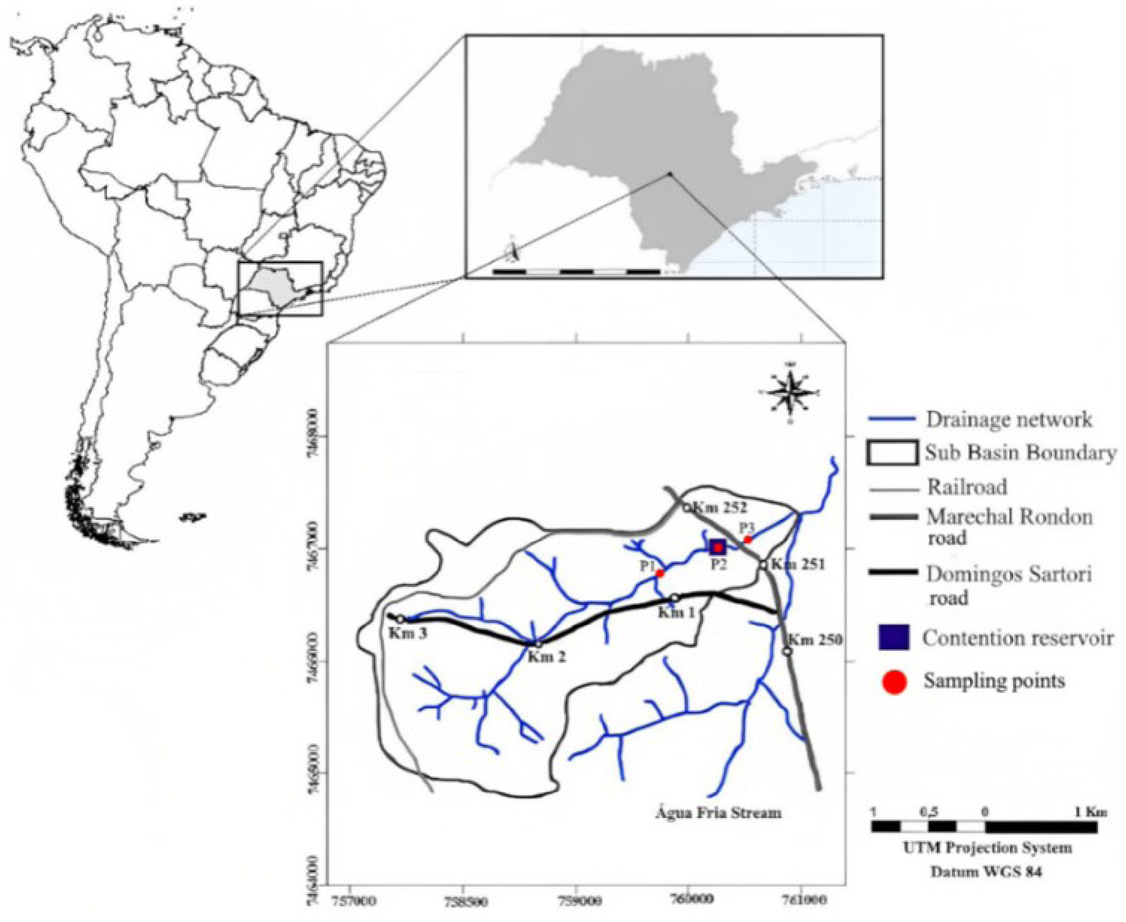

Figure 1. Map of the studied area – Cascata stream (Botucatu, São Paulo, Brazil) with the location of the sampling points (P1, P2 and P3). Adapted from Belluta et al. (2020).

3. Results

3.1. Limnological characteristics

The ordination of the sampling points using the PCA is shown in Figure 2 (correlation values in Table 1). The data variability explanation by the first two components was 67% (PC1 41.8% and PC2 25.2%), what can be considered moderate. For both periods the P1 (upstream) exhibited a more differentiated positioning compared to P2 (reservoir) and P3 (downstream).

In July, lower values of pH and, especially of dissolved oxygen, determined the positioning of P1 in the extreme of the upper left quadrant of the PCA. The oxygen concentration at P1, 4.1 mg/L, was much lower than at P3, 7.8 mg/L and P2, 12.4 mg/L. Another important variable for the differentiated positioning of P1 was the lower concentration of chlorophyll at P1 (4.3 µg/L), mainly when compared to P2, 51 µg/L (3.5 µg/L at P3). In November, the spatial separation among the sampling points was also evidenced. Although the three points were positioned on the negative side of PC1, P1 remained more distanced in the lower quadrant, while P2 and P3, closer each other, in the upper quadrant.

Other variables that influenced in the positioning of P1 were the higher values of conductivity (July), total solids (July), total nitrogen (July and November) and total phosphorus (July and November). However, the values of these last variables, as well as a huge quantity of thermotolerant coliforms concentration (see Supplementary Material), were consequence of an accidental sewage pipe rupture adjacent to P1 (posteriorly repaired) prior the first sampling.

Despite the moderate correlation of temperature with the first two components, there was a considerable variation among the sampling locations, especially in July, between 16.9 °C (23.2 °C in November) at P1 and 24.0 °C (25.9 °C in November) at P2. At P3, in turn, there was a tendency for the temperature to decrease again, to 21.1 °C (25.4 °C in November).

Data on limnological variables (*in situ* measurements and laboratory determinations) are shown in the Supplementary Material.

3.2. Fish fauna

Eleven fish species were captured in the Cascata stream, representing seven families and five orders (Table 2). Two species are non-native: *P. reticulata*, recorded at the three sampling sites, and *Oreochromis niloticus* (Linnaeus, 1758), found only in the reservoir (P2). Figure 3 shows the variation in richness. In July, six taxa were found at P1 and P2, while at P3 only one taxon was recorded. In November, the same richness was observed at P1 and P3, both with the presence of seven taxa. At P2, and higher richness was recorded in the second campaign, nine species.

For the numerical abundance (Table 2; Figure 4), a higher number of individuals was sampled in November, compared to July, except at P1. In July, the most abundant fish at P1 were representatives of the Characidae family, especially *Serrapinnus notomelas* (Eigenmann, 1915), with 106 individuals out of 149.

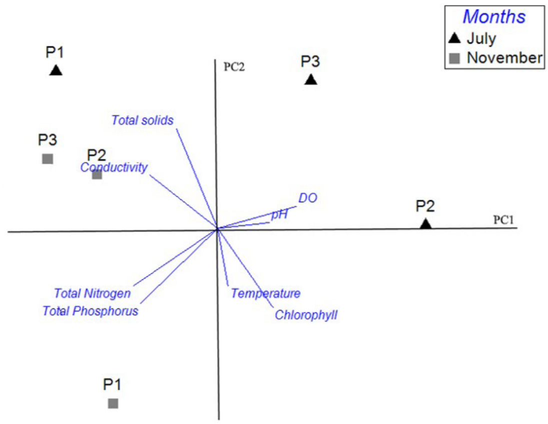

Figure 2. Graphical results of the principal components analysis (PC1 and PC2) based on the limnological characteristics of the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

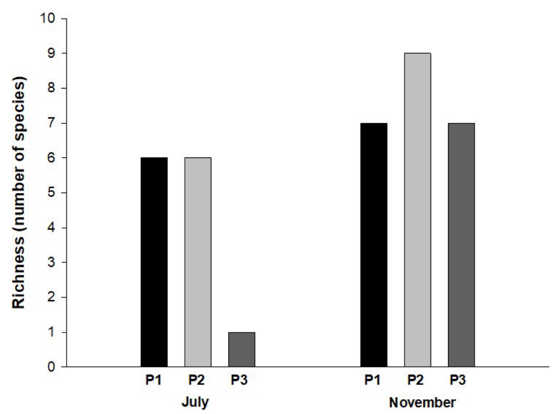

Figure 3. Richness (number of species) of the ichthyofauna sampled at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Table 1. Principal components analysis correlations among the limnological variables and components one and two, considering the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Variables	PC1	PC2
Temperature	0.058	-0.322
pH	0.294	0.033
Conductivity	-0.382	0.299
DO	0.445	0.125
Chlorophyll	0.311	-0.442
Total Phosphorus	-0.434	-0.420
Total Nitrogen	-0.476	-0.323
Total Dissolved Solids	-0.233	0.561

Table 2. Taxonomic list and numerical abundance of fish fauna at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Taxa	Popular name	July			November		
		P1	P2	P3	P1	P2	P3
Characiformes							
Characidae							
Psalidodon anisitsi (Eigenmann, 1907)	Lambari	32	25	-	38	2	-
Psalidodon paranae (Eigenmann, 1914)	Lambari	7	27	-		4	3
Serrapinnus notomelas (Eigenmann, 1915)	Pequira	106	5	-	30	1	-
Erythrinidae							
Hoplias malabaricus (Bloch, 1794)	Traíra	-	-	-	1	1	1
Cichliformes							
Cichlidae							
Geophagus brasiliensis (Quoy & Gaimard, 1824)	Acará/Cará	2	2	-	1	1	4
Oreochromis niloticus (Linnaeus, 1758)*	Tilápia	-	30	-	-	82	-
Cyprinodontiformes							
Família Poeciliidae							
Poecilia reticulata Peters, 1859*	Guaru/Lebiste		307	40	5	400	383
Gymnotiformes							
Gymnotidae							
Gymnotus sylvius Albert & Fernandes-Matioli, 1999		1	-	-	1	-	-
Siluriformes							
Heptapteridae							
Imparfinis schubarti (Gomes, 1956)	Bagrinho	-	-	-	-	-	2
Rhamdia quelen (Quoy & Gaimard, 1824)	Jundiá	-	-	-	-	2	2
Loricariidae							
Hypostomus ancistroides (Ihering, 1911)	Cascudo	1	-	-	2	1	2
	TOTAL	**149**	**396**	**40**	**78**	**494**	**397**

*Non-native species.

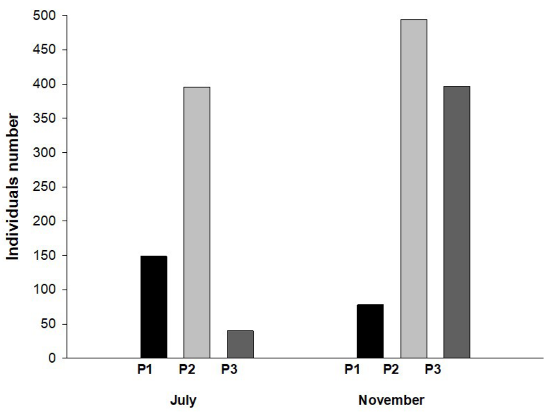

Figure 4. Numerical abundance of the fish fauna at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

At P2, 396 individuals were collected, representing the families Characidae, Cichlidae and mainly the non-native species of Poeciliidae, *P. reticulata*, with 307 specimens. At P3, 40 individuals were sampled, all from *P. reticulata*. In November, at P1, the most numerous species were *Psalidodon anisitsi* (Eigenmann, 1907) and *S. notomelas*. At P2, the numerical abundance was the highest, with 494 individuals, with marked dominance of *P. reticulata* (400 individuals). Finally, at P3, 397 specimens were recorded and *P. reticulata* was also the most numerous species, with 383 individuals.

Figure 5 shows the relative abundance of the different taxonomic orders. In July, at P1, the most abundant order was Characiformes, with only few representatives of Cichliformes, Gymnotiformes and Siluriformes. In the reservoir (P2), the dominant order was Cyprinodontiformes, followed by Characiformes and Cichliformes. At P3, only Cyprinodontiformes occurred.

During November, a higher number of orders was found at P1, with dominance of Characiformes, followed by Cyprinodontiformes, Siluriformes, and few representatives of Cichliformes and Gymnotiformes. At P2, the most abundant order was Cyprinodontiformes, but it was also found Cichliformes, Characiformes and Siluriformes. At the last sampling point (P3), similar to the previous one, the most expressive order was Cyprinodontiformes, in addition to a few representatives of Siluriformes, Cichliformes and Characiformes.

The values of the Shannon diversity index (H') and Pielou's equity index (J'), applied to the fish assemblages data, are presented in Figure 6. In July, the Shannon Diversity Indexes were low and similar, H' = 1.21 at P1 and H' = 1.20 at P2. For P3, H' = zero, due to the presence of only one species (*P. reticulata*). The equity values for this campaign can be considered low too, J' = 0.47 at P1 and J' = 0.46 at P2. For P3, J' = zero. In November, there was a higher variation for the indexes, characterized by a decreasing longitudinal gradient. The highest value was found at P1, H' = 1.67, followed by P2, H' = 0.87, and the P3, H' = 0.31. The same trend for equity, with J' = 0.59 at P1, J' = 0.27 at P2, and J' = 0.11 at P3.

The percentage relation between the number of individuals of native and non-native species is shown in Figure 7. A clear longitudinal increase in the dominance of non-natives was seen in both campaigns. In July, at P1, only native species were sampled. Nevertheless, for the other two sampling points the non-native species predominated. At P2, the proportion of native species corresponded to only 14.9% of the total number of individuals, while at P3 non-natives represented 100% of the collected specimens, exclusively represented by *P. reticulata*. In November the results were similar. At P1, there was a wide predominance of native species (93.6%). At P2, the opposite occurred, and non-native species predominated over native ones, representing 97.6% of the assemblage, as well as in P3, where non-native species accounted for 96.47% of the total.

All specimens sampled in both campaigns, totaling 1,554 individuals, were measured and the results are presented in Table 3. In July, for the species in common between P1 and P2, the average size of specimens collected at P2 was larger. In November *P. anisitsi* also reached a larger size at P2, compared to P1. There were also considerably larger mean values for *P. anisitsi* at P2 in November, compared to the same point during July. The same trend was observed for *S. notomelas*, smaller at P1 compared to P2, in both campaigns. However, the exotic species, *P. reticulata*, was larger in the river sections compared to the reservoir, considering the month of November when it occurred in high abundance at all three sites. Seasonally, a reduction in the average size of both exotic species was observed in the spring period compared to the winter, especially for *O. niloticus*.

The absolute abundances for the non-native species captured in both campaigns, *P. reticulata* and *O. niloticus*, are presented in Figure 8, respectively. In July, *P. reticulata* was absent in the captures at P1. The highest abundance occurred at P2 (reservoir), with 307 specimens. At P3, 40 individuals were collected. During the second campaign, in November, *P. reticulata* was found at the three points. Lower abundance occurred at P1, with only 5 individuals, and the maximum, 400 individuals, at P2, followed by P3, with 383 individuals. The second considered species, *O. niloticus*, only occurred in the reservoir (P2), for both sampling months. In July, with 30 individuals, and in November, with 82 individuals.

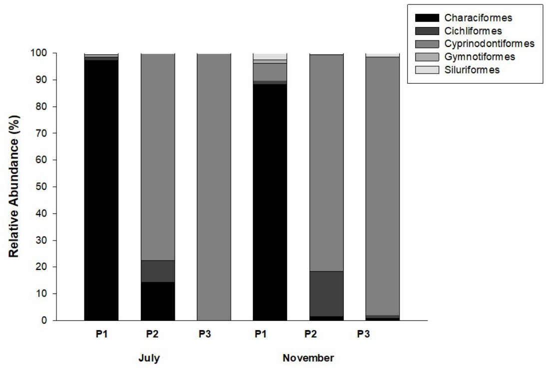

Figure 5. Relative abundance of fish fauna per taxonomic orders sampled at the sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

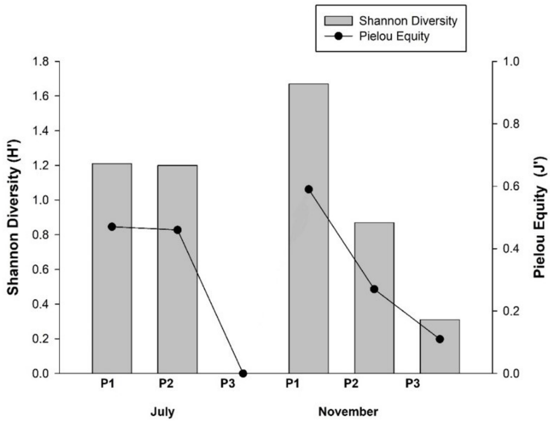

Figure 6. Shannon Diversity (H') and Pielou Equity (J') of the fish fauna assemblages at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

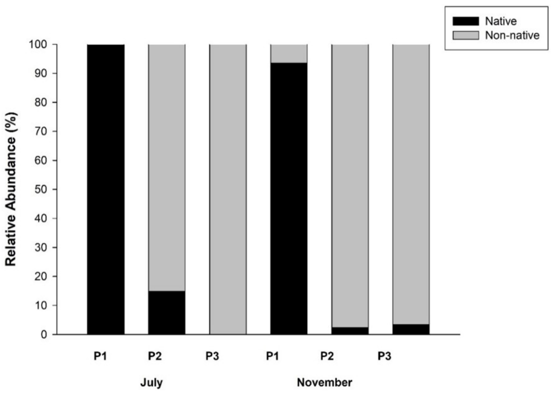

Figure 7. Relative abundance between of Native and Non-native specimens for the fish fauna at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Table 3. Variation of standard length, average value (minimum-maximum) for the fish fauna species at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Taxa	Standard Length (cm)					
	July			November		
	P1	P2	P3	P1	P2	P3
Psalidodon anisitsi	1.7 (1.0-6.0)	3.6 (1.7-5.0)	-	1.7 (1.0-4.6)	4.2 (3.9-4.5)	-
Psalidodon paranae	1.6 (1.0-4.8)	3.5 (1.7-5.4)	-	-	2.9 (2.4-3.5)	3.1 (1.2-5.8)
Serrapinnus notomelas	1.6 (1.0-3.1)	3.2 (3.0-3.4)	-	2.5 (1.6-3.3)	3.2	-
Hoplias malabaricus	-	-	-	12.2	6.6	4.3
Geophagus brasiliensis	2.9 (1.5-4.2)	5.4 (4.3-6.4)	-	11.7	8.0	2.8 (1.2-5.8)
Oreochromis niloticus	-	4.1 (2.1-6.6)	-	-	2.0 (0.7-4.5)	-
Poecilia reticulata	-	1.9 (1.1-3.0)	1.9 (1.2-2.9)	1.7 (1.0-2.3)	1.4 (0.7-2.8)	1.7 (0.5-3.1)
Gymnotus sylvius	18.4	-	-	24.8	24.8	-
Imparfinis schubarti	-	-	-	-	-	3.1 (2.8-3.4)
Rhamdia quelen	-	-	-	-	-	3.3 (1.8-4.8)
Hypostomus ancistroides	3.7	-	-	2.7 (1.0-24.8)	2.7 (1.0-24.8)	3.0

"-" indicates absence.

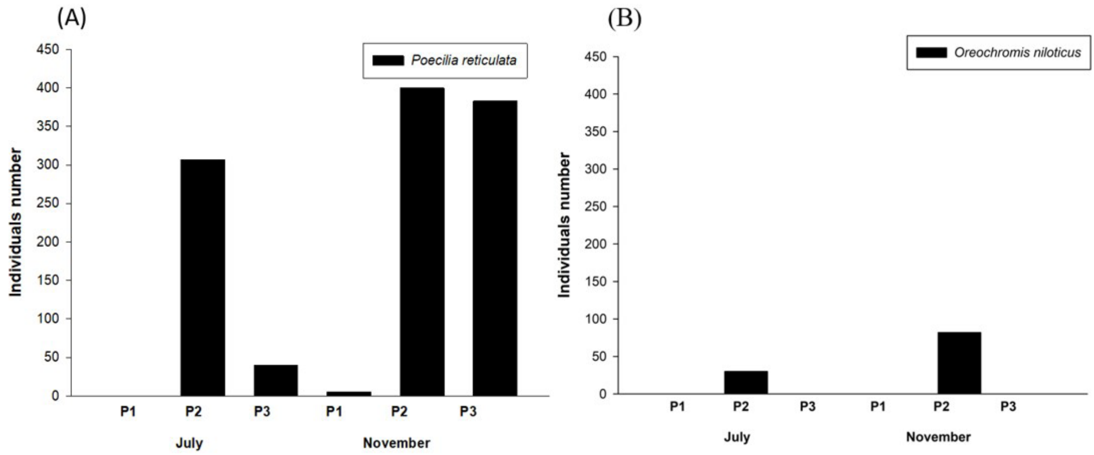

Figure 8. Numerical abundance of the non-native species *Poecilia reticulata* (A) *Oreochromis niloticus* (B) at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

Boxplot plots graphical representations, with length variation and highlighting the size of first gonadal maturation (LS50) for both *P. reticulata* and *O. niloticus*, according to Andrade et al. (2008) and Monteiro et al. (2020), respectively, are shown in Figure 9. For males of *P. reticulata* (Figure 9A), all sampled individuals were above the size of first gonadal maturation (1.12 cm), at the different points for both campaigns and exhibiting a very symmetrical distribution. For females (Figure 9B), there was a higher variation. In July (absent at P1), the specimens collected were larger than the first gonadal maturation (1.16 cm). At P3, most individuals were above the median value, showing a positive asymmetry. For the month of November, few juveniles were recorded at the three different points. At P1, the values were concentrated below the median size, with a negative symmetrical pattern. At P2, the median was close to the value of first gonadal maturation, thus part of the individuals was in the juvenile stage. Finally, at P3, similar to the previous campaign, there was an asymmetry pattern of variation. Regarding *O. niloticus* (Figure 10), all individuals found in the reservoir (P2) in July and November were below the size of first gonadal maturation (13 cm).

Figure 11 shows the relative abundance between males and females for *P. reticulata*. In July, at P1, as previously mentioned, individuals of this species were not sampled. At the second point (P2), 52.4% were males and 47.6% were females. At P3 there was a higher presence of females, representing 67.5%, compared to males, 32.5%. In November, at P1, females were 60.0%, while males accounted for 40.0%. At P2 there was equal distribution (50: 50) for males and females. Finally, at P3, females represented 52.2% of the population and males 47.8%.

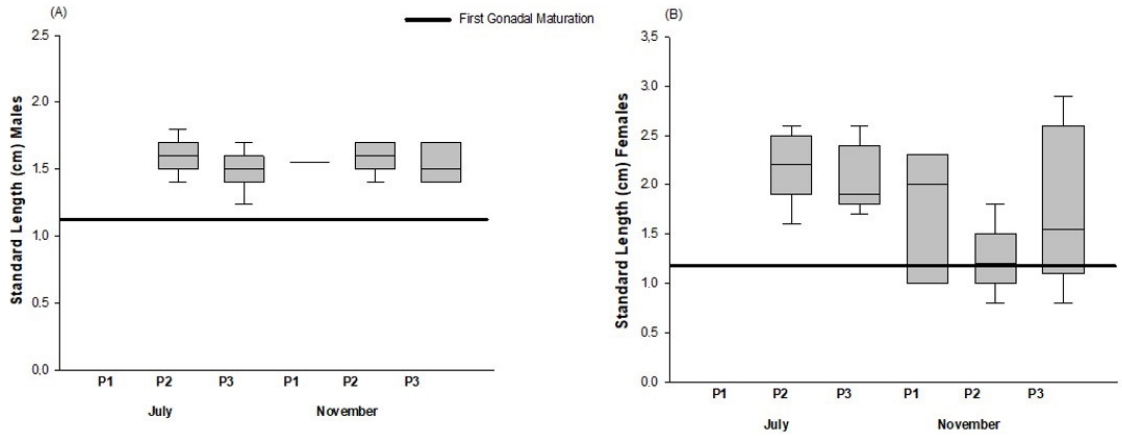

Figure 9. Variation in the standard length (cm) of the non-native species *Poecilia reticulata*, with reference to the values of first gonadal maturation (LS50) (continuous transversal line), for males (A) and females (B), at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

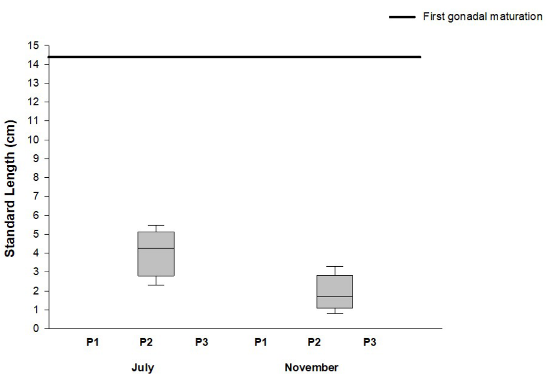

Figure 10. Variation in the standard length (cm) of the species *Oreochromis niloticus*, with reference to the value of first gonadal maturation (Ls50) (continuous transversal line), at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

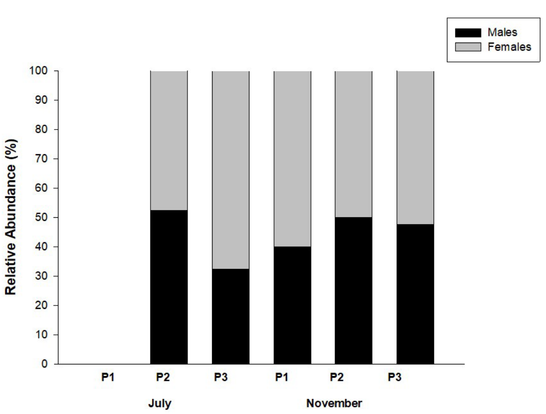

Figure 11. Percentage sex ration for the non-native species *Poecilia reticulata* at the different sampling points of Cascata stream (Botucatu, SP), in July and November 2020.

4. Discussion

Major changes in the limnological characteristics, as well as in the ichthyofauna structure, related to the construction of the flood contention reservoir, were identified. The abrupt transformation of a typical stream shaded by riparian forest (first sampling point), into a lentic environment, highly exposed to the incident solar radiation and atmospheric circulation (second sampling point) caused a disruption in the fluvial continuum (*sensu* Vannote et al., 1980). Indicatives of initial lotic conditions restoration could be observed right below the reservoir (third sampling point).

The limnological conditions of streams and rivers are highly influenced by the water basin biogeophysics characteristics, such as the geological nature, land use and occupation, precipitation/evaporation rates, integrity of the riparian vegetation, etc. (Rice et al., 2001). Smaller hydrographic basins/sub-basins are even more sensitive to natural (*e.g.* storm events) and human-induced modifications, which are transferred downstream to larger rivers and reservoirs (Damame et al., 2019).

For the considered geological region, the Cuesta geological formation of Botucatu, the study is unique, as it focused on impacts generated by stream damming. Other regional studies searched to evaluated anthropic effects related to water quality deterioration (sewage contamination, traffic road contamination and siltation), suppression of riparian forests and intensification of land use by agriculture practices (Uieda and Barretto, 1999; Moretto and Nogueira, 2003; Gralhoz and Nogueira, 2006; Oliveira et al., 2014; Belluta et al., 2016, 2020; Manoel and Uieda, 2018, 2019, 2021).

Despite of the small distance between the three sampling points, ~ 1.3 km, segregation among points, especially for the upstream one, representing the original stream condition, was evidenced through the PCA ordination. The limnological changes were remarkable, especially during the winter (July), with increases of 7 °C in the temperature, 8 mg/L for dissolved oxygen and 47 µg/L for chlorophyll concentration in almost-simultaneous measurements (interval of 1 to 2 hours). These magnitudes of variations were not seen in other studies that evaluated Botucatu Cuesta streams longitudinal gradients during similar hydrological periods (rainy season – spring/summer and dry season – autumn/winter); even considering longer river stretches. Moretto and Nogueira (2003) found maximum differences of 2 °C, < 0.5 mg/L and 3.1 µg/L, for the same variables: temperature, dissolved oxygen and chlorophyll respectively, in two Cuesta rivers (Capivara and Lavapés). Oliveira et al. (2014), studying four Cuesta rivers (Araquá, Capivara, Lavapés and upper Pardo) observed maximum differences of 5.9 °C for temperature and 6 mg/L for oxygen, but a very high difference for chlorophyll, 89.5 µg/L. In case of chlorophyll the highest value was associated to the phytoplankton exportation from a sewage treatment system plant (stabilization lagoon).

The longitudinal variations were of smaller amplitude in November (late spring), probably because this is the beginning of the rainy season (see Belluta et al., 2016 for Cascata basin rain/flow data), with the consequent increase of the stream flow that promotes a relative homogenization of the system.

Data obtained in the downstream stretch, below the contention reservoir, showed indicatives of a initial reestablishment of the lotic conditions, with intermediate values between the ones measured in P1 (stream condition) and P2 (reservoir condition) sampling points. The possibility of functional restoration below dam has already been observed for a much large system (hydropower plant reservoir) (Matsuura et al., 2015; Portinho et al., 2016). For very small fluvial systems, such as the one we have studied, such process might occur more rapidly.

Previous studies in the Cascata stream showed good water quality indicators, in terms of dissolved oxygen, biochemical demand of oxygen, electric conductivity and water quality index (Belluta et al., 2016). Therefore, the results we found recently indicating poor water quality (high concentrations of nitrogen, phosphorus and thermotolerant coliforms) were not expected. This fact was the consequence of the rupture of a local untreated sewage pipe, adjacent to sampling point 1, prior sampling. This accident occurred five months earlier, in February 2021, during an extreme rainfall event (270 mm in 12 hours), which caused considerable material damage around the entire city, including the decreeing of a state of public calamity in the municipality (Botucatu, 2020). The repair of the collection network was carried out in the month of August 2020, promoting improvements in the water quality indicators, as in the electric conductivity and thermotolerant coliforms we determined in November.

In terms of the fish fauna, eleven species (five orders) were found in the Cascata stream. This richness, obtained in only two samplings, is comparable to other studies carried out in the Botucatu Cuesta streams (first to fourth-order river stretches), including long-term researches (two decades), whose reported richness varied between 10 to a maximum of 26 species (Uieda and Barretto, 1999; Manoel and Uieda, 2018, 2019, 2021).

A higher number of fish was registered in the upstream of the contention reservoir, where the native species *S. notomelas* and *P. anisitisi* represented most of the sampled individuals. The native species are more sensitive to anthropogenic alterations, and their dominance, distributed in several size classes and interacting in balanced trophic structures, indicates higher environmental integrity (Oliveira and Bennemann, 2005).

In contrast, the non-native species prevailed in the contention reservoir as well as in the downstream stretch. Small rivers are more sensitive to human interventions, including the adverse effects caused by the occurrence of non-native species (Souza et al., 2009; Garcia et al., 2021). Our study evidences the well-established bioinvasion process for the species *P. reticulata* and *O. niloticus* in the Cascade stream.

During the winter sampling (July) *P. reticulata* was the only species found bellow contention reservoir. It was also the most abundant in the reservoir, at this same sampling period, as well as in the reservoir and downstream in the raining period (November). The sex ratio analysis showed there is a proportionality, a balanced distribution, between males and females.

The dominance of *P. reticulata* in Brazilian urban streams was associated to the water quality deterioration (increased phosphorus concentration) (Cunico et al., 2006). This Poecilidae fish, originally distributed in Central America and northern region of South America (Barboza de Andrade et al., 2005; Pires and Zuanon, 2021), was introduced in Brazil during the twentieth century for the control of the mosquito vector of the yellow fever (Miranda, 2012). *P. reticulata* has wide tolerance to environmental factors and high efficiency in terms of interspecific competition (Souza and Tozzo, 2013). It is a livebearing fish (Banet et al., 2016), and this reproductive strategy is a key-factor contributing for the establishment of high-density populations.

The second non-native species, *O. niloticus*, a Cichlidae from African, was introduced in the country during the 1930's, in order to increase fish production in the Northeast region of, and later, in the 1950's, in the Southeast region (Monteiro et al., 2020). The species is already fully established, for several years, in the region of the middle Tietê River (David et al., 2016), to where the waters of the Cascata stream drain. Extremely efficient in reproductive terms, omnivorous feeding habit and wide tolerance to environmental changes are characteristics that make it very competitive (Miranda et al., 2010; Vicente et al., 2014). The capture of this fish through conventional scientific fisheries is a great challenge, what results in underestimation of wild populations (David et al., 2016). We captured this species only in the contention reservoir, reaching relatively high numbers in both campaigns, what evidences that it is better succeeded in lentic conditions. Capture of juveniles indicate well-succeeded reproductive processes.

In general, the size analysis of the fish fauna showed higher values for the specimens captured in the reservoir. Probably is due to the higher availability of food resources, including phytoplankton, zooplankton, besides periphyton and macroinvertebrates associated with macrophytes (absent in the stream). The opposite was seen for *P. reticulata* and may be related to high intraspecific competition, since in the reservoir its abundance was higher.

The influence of seasonality on the size variation of the sampled individuals was evidenced for the exotic species, *P. reticulata* and *O. niloticus*. The smaller mean size of individuals in November, spring season, is probably a consequence of more frequent reproductive events, compared to July, winter season. For *P. reticulata*, this hypothesis is reinforced because individuals smaller than first gonadal maturity were found only in in November.

In addition to the prevalence of non-native species, another negative indicator related to the reservoir construction is the decreasing longitudinal gradient of the Shannon Diversity and Pielou's Equality indices, especially in the second campaign. In lotic ecosystems it is expected a progressive higher species richness, abundance and diversity (*fluvial continuum*), as a consequence of increased habitat heterogeneity, higher availability of shelter and food resources, increased flow conditions. Such trend, taken to the process of species addition, has already been proved for comparable (semi deciduous Atlantic Forest biome) Brazilian streams (Uieda and Barretto, 1999; Cunico et al., 2006).

5. Final Considerations

The implementation of effective actions in order to minimize floods in urban areas are very important for the society, as these events are too destructive social and economically. Despite the urgency, in view of the increasing extreme climatic events, more environmental friendly interventions must be seek by the public authorities. Our research showed that the typical limnological characteristics of a forest stream, such as natural low oxygen and chlorophyll concentrations, low pH and low temperature, are quickly affected by the reservoir construction. The predominance of the native fish fauna is replaced by large populations of non-native species. Therefore, due to the major ecological interference, the construction of contention reservoirs (piscinões) directly on the stream courses should be avoided.

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Supplementary Material

Supplementary material accompanies this paper.
Appendix - in situ measurements.
Appendix – analytical determinations.
This material is available as part of the online article from https://doi.org/10.1590/1519-6984.276585