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Research paper

Isolated and Cumulative Water Quality Effects of two Small Hydropower Plants of a Pantanal Tributary

Efeitos Isolados e Acumulativos da Operação de Pequenas Centrais Hidrelétricas na Alteração da Qualidade da Água de um Tributário do Pantanal

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ABSTRACT: The construction of small hydropower plants (SHP) can cause several changes in river ecosystems, especially when designed in cascade. Thus, this study aimed to quantify the effects of two SHP operating in cascade and evaluate the individual and cumulative water quality effects on the Ponte de Pedra Stream. The study was developed at the SHP José Gelázio da Rocha and Rondonópolis, both located in Rondonópolis county, state of Mato Grosso, about 15 water quality parameters from the environmental monitoring of the power plants, collected every six months between 2006 to 2013. To evaluate water quality effect, we used the paired Wilcoxon test, and the percentage of change in relation to the natural point, upstream of the hydroelectric plants. The Wilcoxon test showed that downstream of the José Gelázio PCH there was a significant change in all five parameters, causing a 3% increase in temperature, and a 28% reduction in color, 22% in dissolved solids, 20% in total solids and 12% in suspended solids. Downstream of the Rondonópolis PCH there was a significant change in only two parameters, reducing the temperature by 3% and increasing pH by 1.5%. Regarding the cumulative effects, the reservoirs significantly changed two parameters, causing an 18% increase in total phosphorus and a 48% reduction in total solids. These effects are associated with increased exposure of water to solar radiation and the particle retention process, due to increased hydraulic retention time in the reservoirs. The cumulative effects of the cascade system were 15% greater than the sum of the individual effects, indicating that projects in cascade tend to potentiate the isolated effects.
Keywords: cascading hydroelectric dams; particle retention, hydraulic retention time.

RESUMO: *A construção de pequenas centrais hidrelétricas (PCH) pode causar diversas alterações nos ecossistemas fluviais, principalmente quando planejadas em cascata. Sendo assim, esta pesquisa teve como objetivo quantificar os efeitos da operação de duas PCHs em cascata e avaliar seus efeitos isolados e acumulativos na alteração da qualidade da água do Ribeirão Ponte de Pedra. O estudo foi desenvolvido nas PCHs José Gelázio da Rocha e Rondonópolis, ambas localizadas no município de Rondonópolis, estado de Mato Grosso. Foram utilizados 15 parâmetros de qualidade de água oriundos do monitoramento ambiental dos empreendimentos, coletados semestralmente entre os anos de 2006 e 2013. Para avaliar o efeito do empreendimento sobre a qualidade da água, foi utilizado o teste pareado de Wilcoxon, e a porcentagem de alteração em relação ao ponto natural, a montante das hidrelétricas. O teste de Wilcoxon mostrou que a jusante da PCH José Gelázio houve alteração significativa de cinco parâmetros, ocasionando um aumento de temperatura de 3%, e redução de 28% da cor, 22% dos sólidos dissolvidos, 20% dos sólidos totais e 12% dos sólidos suspensos. A jusante da PCH Rondonópolis houve alteração significativa apenas dois parâmetros, reduzindo a temperatura em 3% e aumentando o pH em 1,5%. Quanto ao efeito acumulativo, os reservatórios alteraram significativamente dois parâmetros, provocando um aumento de 18% nas concentrações de fósforo total e redução de 48% dos sólidos totais. Estes efeitos são associados ao aumento da exposição da água a radiação solar e ao processo de retenção de partículas devido ao aumento do tempo de retenção hidráulica nos reservatórios. Com isso, observa-se que os efeitos acumulativos do sistema em cascata foram 15% maiores que a soma dos efeitos individuais, indicando que empreendimentos em cascata tendem a potencializar os efeitos isolados.*
Palavras-chave *hidrelétricas em cascata; retenção de partículas; tempo de retenção hidráulica.*

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INTRODUCTION

Hydropower generation is an important factor in enhancing the quality of life by boosting economic productivity, but it is potentially a source of environmental changes (Ortiz Flórez, 2014). The construction of reservoirs, including run-of-river systems, can cause significant impacts on biota, water quality, hydrological patterns, and river morphology (Kuriqui *et al*., 2021).

In recent decades, small hydropower plants (SHPs) have come to be considered as a sustainable alternative for energy generation (Mayeda; Boyd, 2020). This model has also attracted investors due to the simplification of licensing processes and the possibility of decentralized management and operation. However, research on the ecological impacts of SHPs indicates that, in certain situations, the environmental effects per megawatt of energy produced can be significantly higher than those recorded in conventional hydropower plants that operate under regulation (Zarfl *et al*., 2014; Kelly, 2019). Therefore, the effects of the installation and operation of hydroelectric plants must be known since the magnitude and duration of the changes vary according to the characteristics of each reservoir (Figueiredo *et al*., 2021).

The major debate about this topic does not focus on the individual impacts of these undertakings, as most of them are well-documented and assessed in the environmental licensing process, with approvals granted by government environmental managers. Instead, the discussion lies on the cumulative effects of the implementation of two or more of these projects on the same river, whose impact on the environment can be quite significant (Kuriqui *et al*., 2021). This aspect is usually overlooked by managers. This rapid development of the sector has led to an unbridled proliferation of these enterprises, ignoring their cumulative and synergistic effects on the environment, especially about changes in water quality. This issue is particularly relevant when projects are built upstream of rivers with extensive floodplains (Kingsford, 2000), as they can have direct and indirect consequences for the ecological functioning of these delicate ecosystems (Oliveira *et al*., 2020; Fantin-Cruz *et al*., 2020).

The proliferation of hydropower plants in the Pantanal, recognized as the largest floodplain on Earth (Junk; Cunha, 2005), presents significant environmental challenges. Currently, there are 59 operational hydropower plants, with plans for an additional 91 on tributary rivers (SIGEL, 2024). Among these proposed projects, only one involves large dams, while most are designed within a reservoir cascade system, meaning two or more projects on the same watercourse. In this context, this study aimed to quantify water quality effects of operating two cascade SHPs and to evaluate their individual and cumulative water quality impacts of Ponte de Pedra Stream, a Pantanal floodplain tributary.

MATERIAL AND METHODS

STUDY AREA

This study was conducted in the area of influence of the reservoirs of SHP Engenheiro José Gelázio and Rondonópolis, installed in Ponte de Pedra Stream (**Figure 1**). This is a tributary of the Vermelho River, which is the most important tributary of the São Lourenço River, one of the main rivers forming the Brazilian Pantanal.

The Ponte de Pedra Stream watershed has 2,131 km^2 area, with 156 km length and

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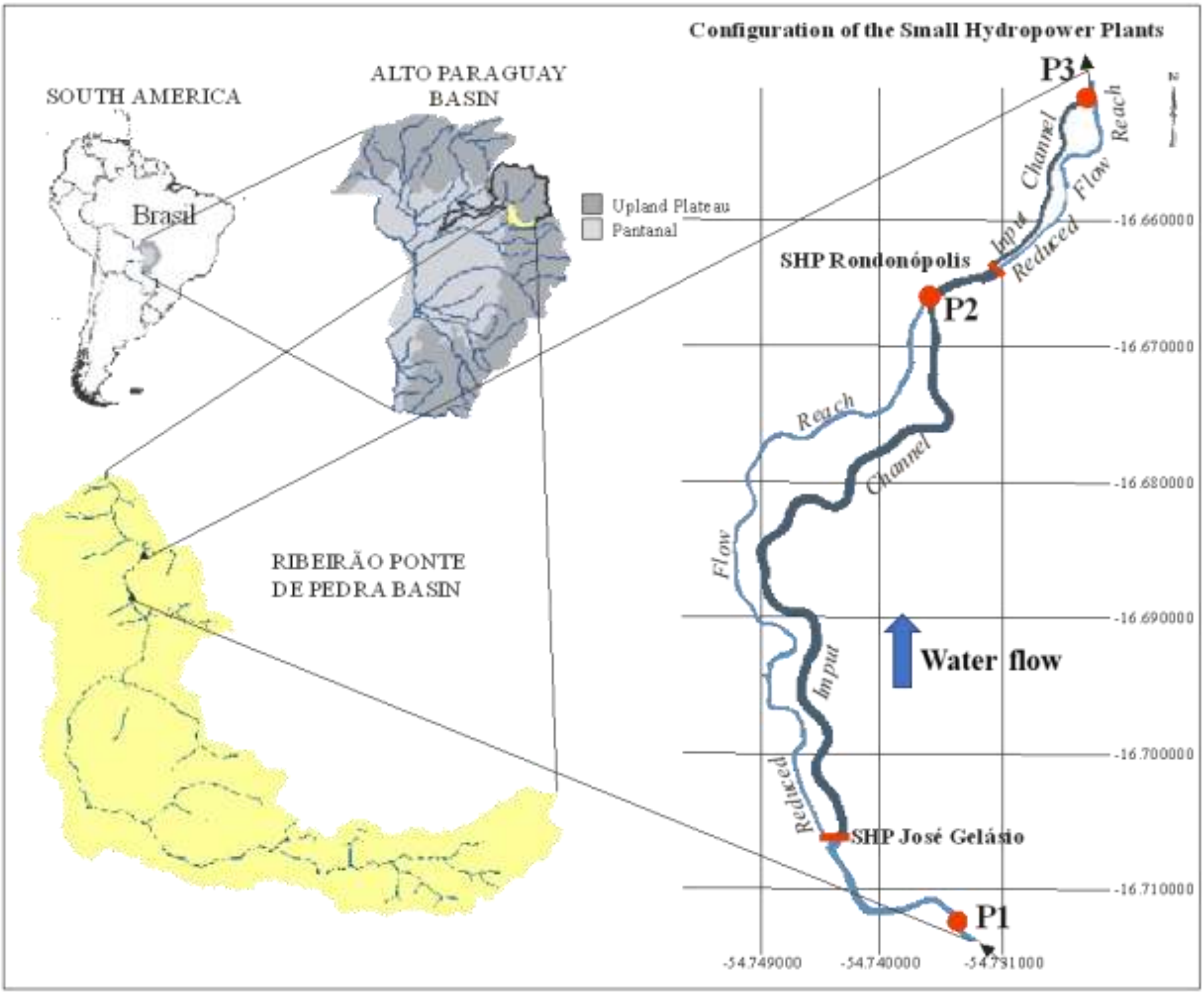
529.8 m slope from headwaters to the mouth. Its area covers Rondonópolis, Pedra Preta and Itiquira municipalities, in the southeast region of the state of Mato Grosso. This region contains temporary crops of soybean, corn, cotton and extensive cattle farming. The native vegetation is savanna, *Cerrado* and *Cerradão* types, associated with slopes and seasonal forest (Seplan, 2011).

Figure 1. SHP Eng. José Gelázio and Rondonópolis location and sampling sites in the Ponte de Pedra Stream basin watershed, Upper Paraguay River basin, state of Mato Grosso, Brazil



The SHP Engenheiro José Gelázio and Rondonópolis were designed in cascade, at the slope between the plateau and the plain of the Pantanal, 6.7 km away from each other. They started operation, respectively, in February and December 2007.

The SHP José Gelázio has an installed generation capacity of 24.45 MW, with 0.13 km^2 flooded area, 4 m high dam, built in concrete and embankment, composed of bottom discharger, free spillway and superficial water abstraction through a diversion that flows the water to the adduction channel, in the open, 6.5 km long, coated with waterproof membrane. The penstock has 250 m long and 63 m vertical drop. The minimum flow maintained at the reduced flow passage is 2.7 m^3.s^{-1}, originating from the surface of the reservoir. The

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residence time of the reservoir water is < 2 days. The reservoir has proliferation of rooted aquatic macrophytes, mainly *Eichhornia azurea* (Kunth) Solmms 1843, *Pontederia* sp. (Pontederiaceae) and grasses (Poaceae). For this reason these plants are mechanically removed periodically.

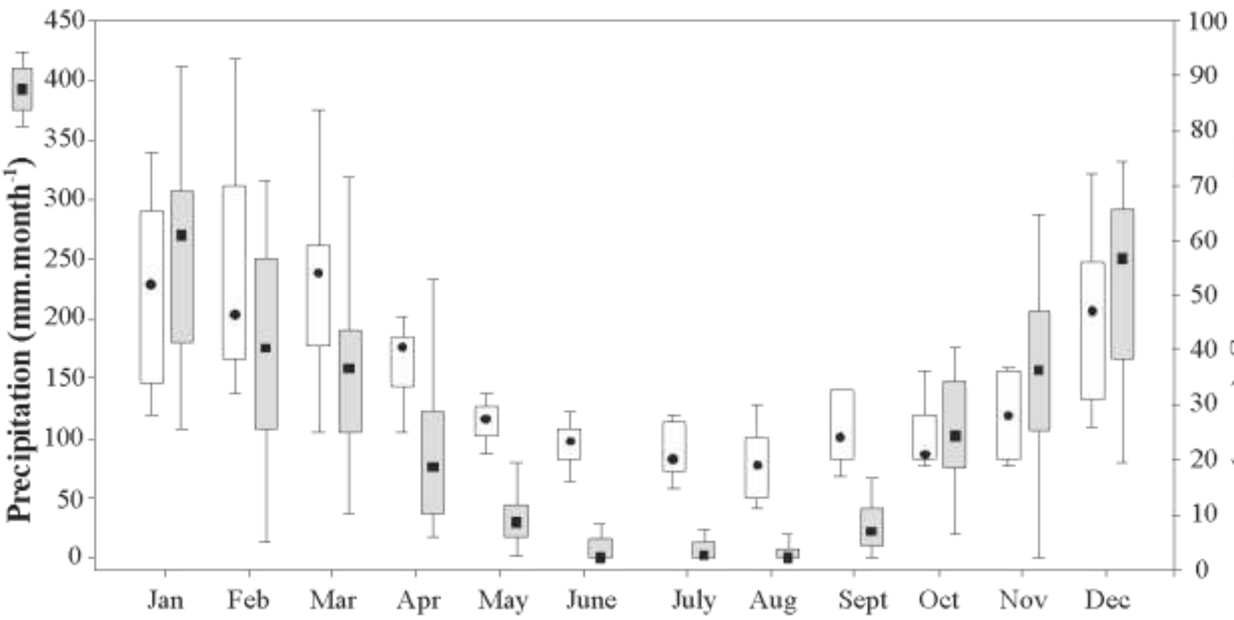
The SHP Rondonópolis is located downstream of SHP Eng. Jose Gelázio and has an installed generation capacity of 26.60 MW, with 0.02 km^2 flooded area, dam of 4 m high, built in concrete, with bottom discharger, free spillway and superficial water abstraction through a diversion that flows the water to the adduction channel, in the open, 1.4 km long, coated with waterproof membrane. The penstock has 250 m long and 62 m vertical drop. The minimum flow maintained at the reduced flow passage is 1.7 m^3.s^{-1}, also originating from the surface of the reservoir. The residence time of the reservoir water is also < 2 days.

The regional climate is hot and humid, classified as AW by Köppen (wet tropical), with 25.0°C average annual temperatures, ranging between 22.3 (July) to 27.1°C (October), and despite the remarkable seasonality the average monthly amplitude is small, 4.8°C (Fantin-Cruz *et al*., 2015b).

The median annual cumulative rainfall is 1,245 mm.year^{-1}, and 49% occur in the summer (maximum in January, 270 mm) and only 2% in the winter (minimum in July and August, 0 mm), which demonstrates a marked seasonality (**Figure 2**).

The median annual flow of the Ponte de Pedra Stream is 30.0 m^3.s^{-1}, the monthly variability is similar to rainfall, with a lag of one month, and maximum in March (54.0 m^3.s^{-1}) and minimum in August (19.0 m^{3}s^{-1}) (**Figure 2**).

Figure 2. Median monthly variation of rainfall in the Rondonópolis municipality from 2000 to 2015 (station 83410; Source: INMET) and the median monthly flow of the Ponte de Pedra Stream between 1995 to 2006 (station 6545500; Source: Hidroweb/ANA)



SAMPLING

For water quality assessment, water samples were taken at three sites along the longitudinal gradient of the Ponte de Pedra Stream. Site P1 is located upstream of SHP Eng.

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José Gelázio, outside of the backwater area, P2 is downstream of SHP Eng. José Gelázio and upstream of SHP Rondonópolis and P3 is located downstream of SHP Rondonópolis (**Figure 1**). Samples were taken every six months between 2007 to 2013, totaling 14 samplings.

Water quality parameters measured were: water temperature, dissolved oxygen and pH, measured in the field, and true color, turbidity, total alkalinity, hardness, conductivity, biochemical oxygen demand, total nitrogen, total phosphorus, total iron, total solids, dissolved solids and suspended solids were analyzed in the laboratory. Sampling and analyses were performed according to Standard Methods for the Examination of Water and Wastewater (APHA, 2012). The database is part of the environmental quality monitoring program of Tractebel Energia SA, manager of the project and was made available by the contractor and by the Environmental Secretariat of the State of Mato Grosso (SEMA).

DATA ANALYSIS

To evaluate the effect of the two cascading reservoirs on each water quality parameter in the Ponte de Pedra Stream, we applied the nonparametric paired Wilcoxon test. This test compares whether the position measurements between two samples (upstream and downstream) are equal at a 5% significance level. In this sense, the test was applied to each project individually, that is, pairing the samples of upstream and downstream of the SHP Eng. José Gelázio, and upstream and downstream of the SHP Rondonópolis.

In order to evaluate the cumulative effect of both developments, we paired the upstream samples of José Gelázio and the downstream samples of Rondonópolis. This test controls possible noise caused by interannual climate variability, which could be attributed to the impoundment. Its application has proven to be a simple and effective option for quantification of changes caused by reservoirs, even with limited data (Fantin-Cruz *et al*., 2015).

The magnitude and direction of water quality change caused by the projects were analyzed after standardizing each parameter in relation to the value measured at the site P1 (control). This site keeps the natural characteristics of the Ponte de Pedra Stream, as it is not subjected to the effects of the impoundment. Standardization was made as follows:

For P(1)<P(i):

$$T_{P(i)}\% = +\left(1-\left(\frac{P_{(1)}}{P_{(i)}}\right)\right)\times 100 \tag{1}$$

For P(1)> P(i):

$$T_{P(i)}\% = -\left(1-\left(\frac{P_{(i)}}{P_{(1)}}\right)\right)\times 100 \tag{2}$$

Where:
TP(i) = rate of change relative to the control condition of any site, expressed as a percentage;
P(i) = value of the parameter measured at any site;
P(1) = value of the parameter measured in the control site.

The rate of change can be positive or negative, according to increase or decrease in the parameter value relative to the control. This standardization limits the variation between

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+100% and -100%. This procedure allows better quantification of the isolated effect of the reservoir formation on water quality, since comparisons are made between sites of the same sampling and not in relation to a historical average. In this way, any changes that may have occurred between samplings, which did not occur due to the impoundment, are removed, such as seasonal variations, increased or decreased nutrient or sediment load due to changes in the use of the basin, extreme climatic periods, among others (Fantin-Cruz *et al*., 2016).

In order to observe existing changes in water quality, the standards of Resolution No. 357/2005 of the National Environmental Council (NEC) for class 2 rivers, such as Ponte de Pedra Stream, were also considered.

RESULTS

WATER QUALITY CHARACTERIZATION

Water quality of the Ponte de Pedra Stream was spatially characterized by a median temperature ranging from 24.8°C to 25.4°C, good oxygenation (in relation to class 2 rivers), whose DO median varied between 7.00 and 7.12 mg.L^{-1}, pH slightly acidic, with a median between 5.79 and 6.04, low electrical conductivity values (5.4 to 5.7 μScm^{-1}), low hardness (2.00 to 4.10 mg.L^{-1}), low alkalinity (2.24 to 7.78 mg.L^{-1}) and COD ranging from 7.5 to 11 mg.L^{-1} **(Table 1**).

Besides these parameters, the median turbidity was between 9.80 and 10.24 NTU, color between 40 and 76 mg.L^{-1}, dissolved iron from 0.345 to 0.451 mg.L^{-1}, total solids between 41 and 75 mg.L^{-1}, dissolved solids between 25.0 and 62.6 mg.L^{-1} and suspended solids of 10 mg.L^{-1}. Regarding the concentration of nutrients, the total phosphorus showed intermediate median values (from 0.025 to 0.093 mg.L^{-1}) and Kjeldahl nitrogen of 0.50 mg.L^{-1}.

Table 1. Water quality parameters (median and quartiles) in the Ponte de Pedra Stream, in the area of influence of SHP José Gelázio and Rondonópolis

Parameters	Upstream SHP José Gelásio	Upstream SHP Rondonópolis	Downstream SHP Rondonópolis	Class 2 river
Water temperature (ºC)	24.8 (22.7/25.8)	25.4 (23.35/26.2)	25.3 (23.4/26.3)	-
Dissolved Oxygen (mg.L^{-1})	7.00 (6.64/7.38)	7.07 (6.66/7.225)	7.11 (6.36/7.43)	≥ 5.0
pH	5.79 (5.61/6.19)	5.80 (5.65/5.98)	6.03 (5.90/6.16)	6-9
Electr. Conductivity (μS cm^{-1})	5.60 (4.62/6.44)	5.4 (4.38/6.62)	5.7 (5.17/7.01)	-
Hardness (mg.L^{-1})	2.0 (2.0/3.3)	2.7 (2/4.6)	4.1 (2/5.9)	-
Alkalinity (mg.L^{-1})	2.24 (1.50/8.36)	7.78 (1.00/10.60)	7.05 (1.75/10.27)	-
Color (mg Pt.L^{-1})	76 (41/82)	40 (26/64)	47 (35/69)	≤ 75
Turbidity (NTU)	10.2 (8.4/15.0)	9.8 (7.5/16.1)	9.8 (7.7/14.6)	≤ 100
Total Solids (mg.L^{-1})	75 (58/85)	41 (24/78)	59 (21/72)	-
Suspended Solids (mg.L^{-1})	10 (8/10)	10 (8/10)	10 (8/12)	-
Dissolved Solids (mg.L^{-1})	62 (46/79)	25 (19/65)	44 (18/59)	≤ 500
Total Kjeldahl Nitrogen (mg.L^{-1})	0.500	0.500	0.500	-

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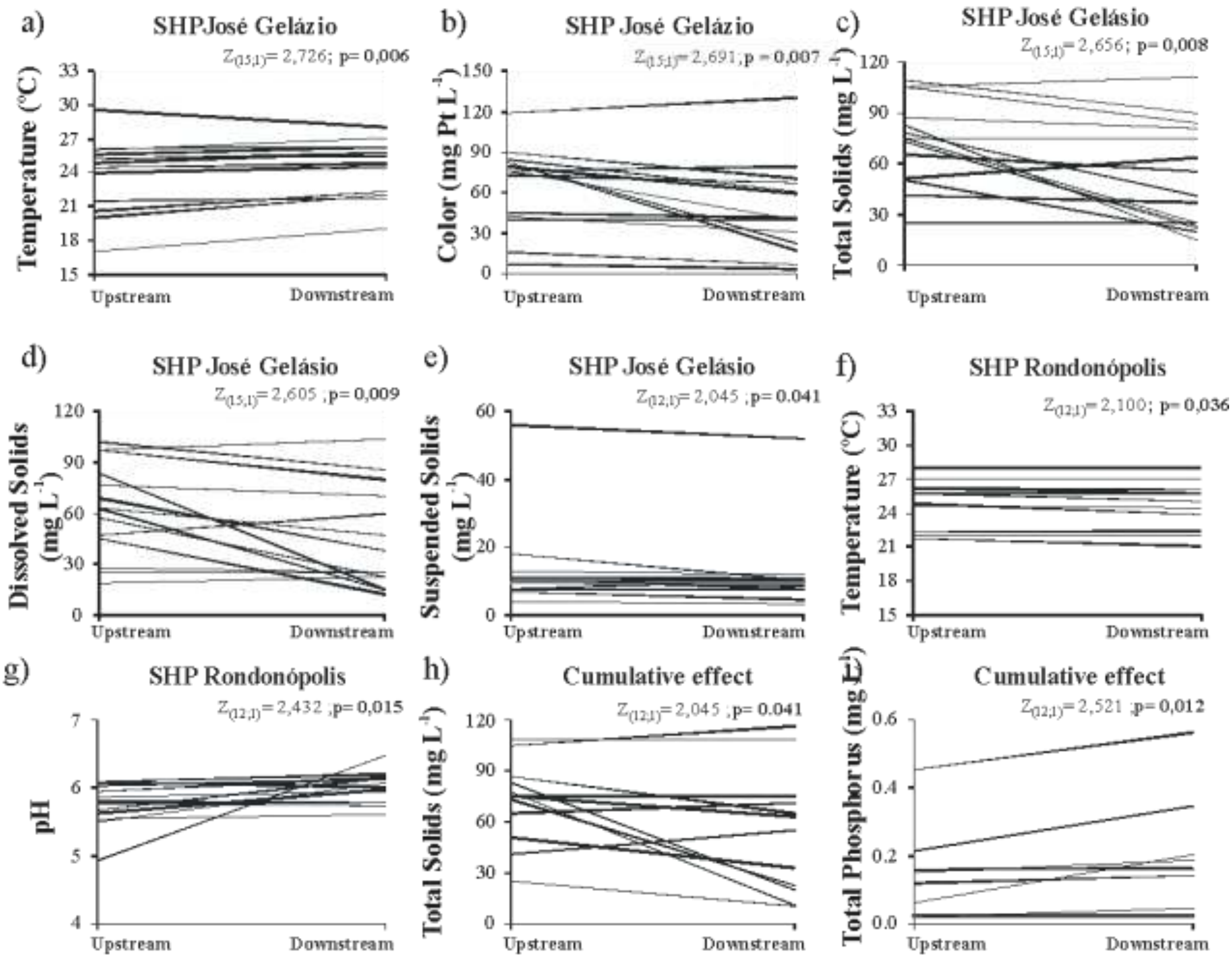
	(0.336/0.593)	(0.301/0.504)	(0.412/1.062)	
Total Phosphorus (mg.L^{-1})	0.025 (0.023/0.134)	0.030 (0.025/0.152)	0.093 (0.025/0.190)	0,1
Chemical Oxygen Demand (mg.L^{-1})	11.0 (5.0/15.4)	8.4 (5.4/14.5)	7.5 (4.8/16.3)	≤ 5.0
Dissolved Iron (mg.L^{-1})	0.345 (0.276/0.500)	0.451 (0.262/0.500)	0.430 (0.284/0.501)	≤ 0.3

ISOLATED AND CUMULATIVE CHANGES

Analyzing the isolated effects of the reservoirs of SHP Eng. José Gelázio and Rondonópolis on the 15 parameters of water quality, it was observed that the first development significantly changed five parameters (temperature, color, total solids, dissolved solids and suspended solids, **Figure 3a** to **3e**).

Figure 3. Water quality parameters significantly altered (p≤0.05) by the formation of the reservoir cascade of SHP José Gelázio and Rondonópolis considering the isolated and cumulative effects, according to the paired Wilcoxon test (Z)



The SHP Rondonópolis significantly changed only two parameters (temperature and

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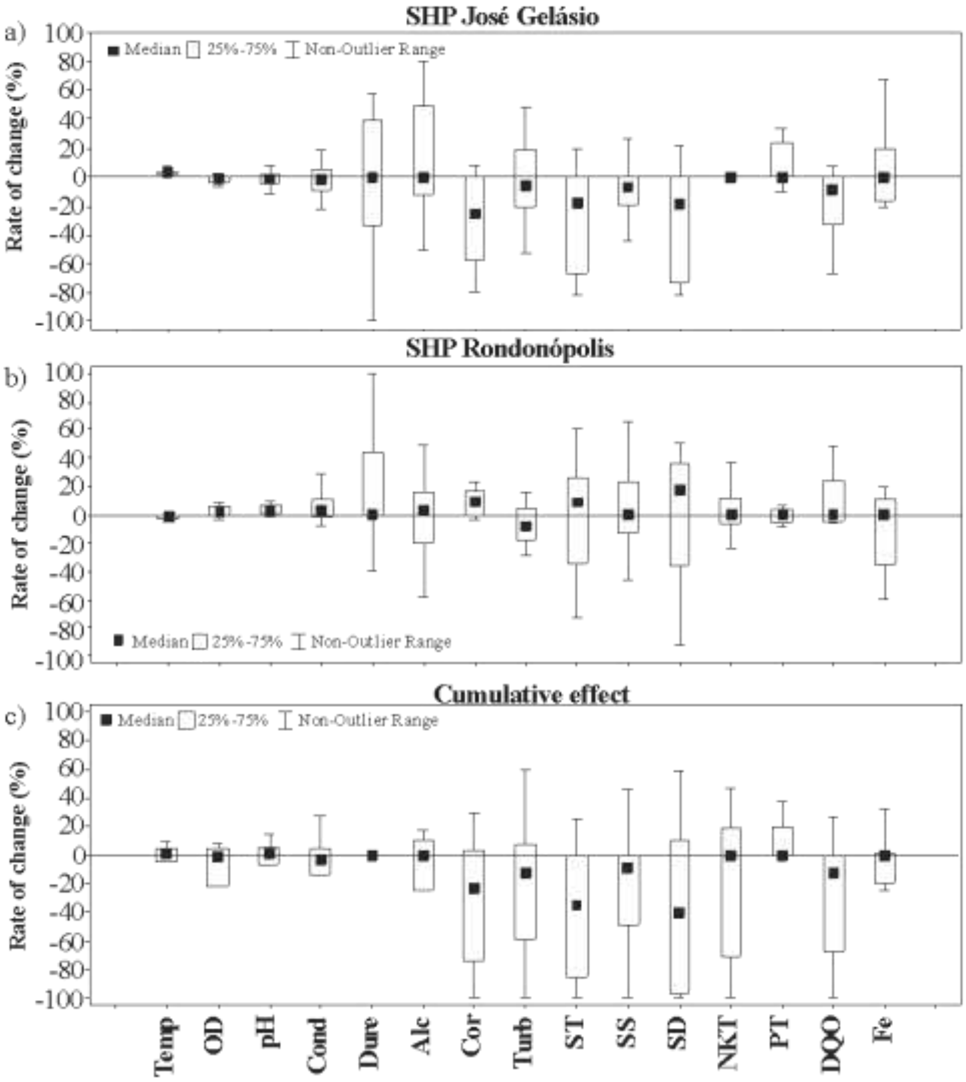
pH; **Figure 3f** and **3g**) and the cumulative effect of both SHP also significantly changed two parameters (total phosphorous and total solids; **Figure 3**i and **3h**).

Regarding the direction and magnitude of changes, the SHP José Gelázio promoted an increase in temperature median by 3%, reduction by 28% in color median, 22% in dissolved solids, 20% in total solids and 12% in suspended solids median (**Figure 4a**). SHP Rondonópolis also changed 3% water temperature, but in an inverse direction to that registered downstream of the SHP José Gelázio (**Figure 4b**). Another parameter changed was the pH, with 1.5% median increase (**Figure 4b**).

As for the cumulative effect of the projects, among the changed parameters, there were 18% increase total phosphorus median concentrations and 48% total solids reduction (**Figure 4c**).

Figure 4. Water quality parameters rate of change in caused by the formation of reservoirs of SHP José Gelázio and Rondonópolis considering the isolated and cumulative effects



The zero line indicates the natural situation, without change. Legend: Alk = alkalinity; Cond = electrical conductivity; COD = chemical oxygen demand; Dure = hardness; Fe = dissolved iron; PT = total phosphorus; NTK = Total Kjeldahl Nitrogen; DO = dissolved oxygen; ST = total solids; SD = dissolved solids; SS =

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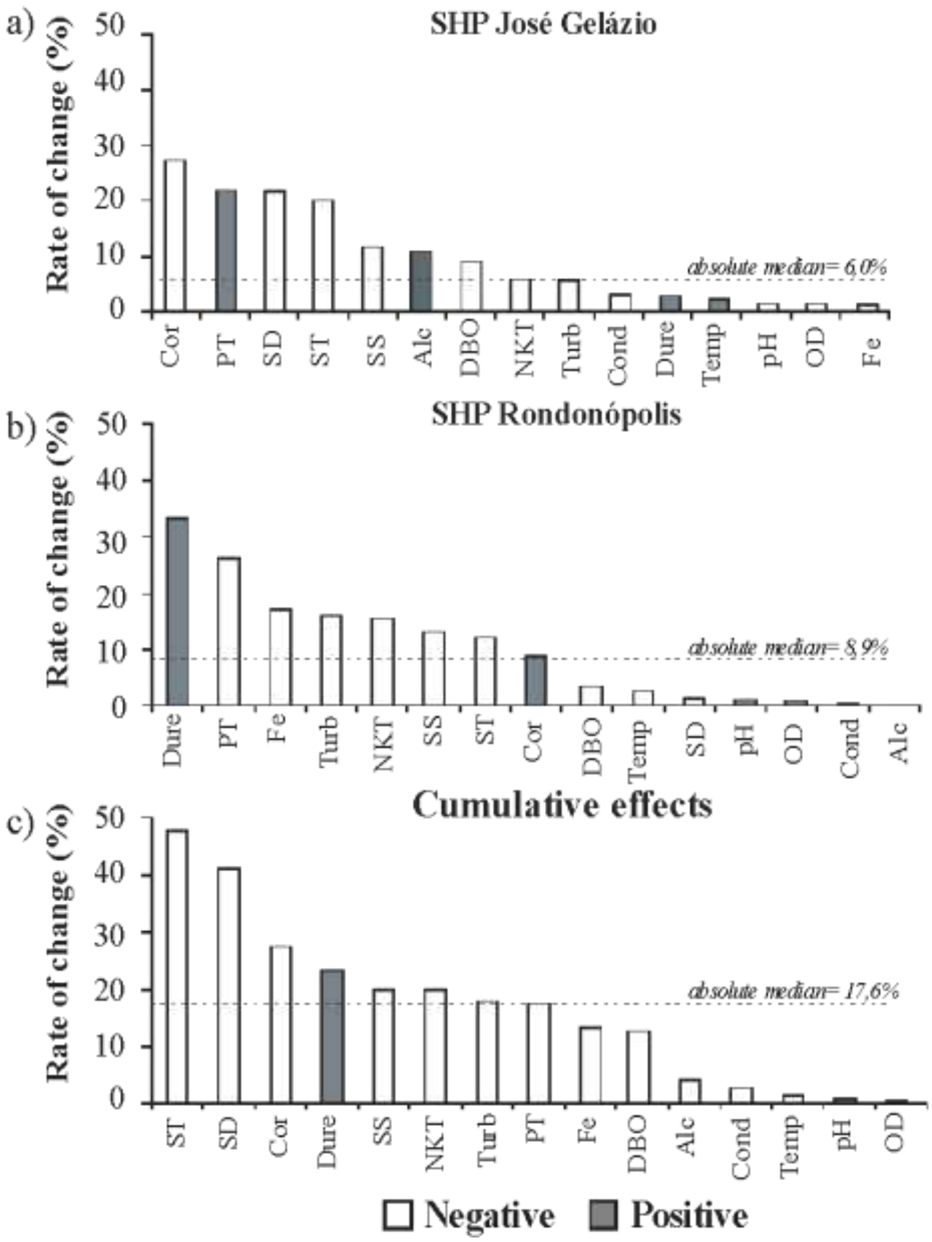
suspended solids; Temp = temperature; Turb = turbidity.

When considering water quality parameters absolute rate of change, the median of changes caused individually by each project was similar, 6.0% for the SHP José Gelázio and 8.9% for SHP Rondonópolis (**Figure 5a** and **5b**). However, the absolute changes caused by both projects, cumulatively, nearly doubled, with change of 17.6% of the medians, besides the increase in interquartile range (**Figure 5c**).

Figure 5. Water quality parameters median absolute rate of change resulting from the SHP José Gelázio and Rondonópolis reservoirs, considering both isolated and cumulative effects



Alk = alkalinity; Cond = electrical conductivity; COD = chemical oxygen demand; Dure = hardness; Fe = dissolved iron; PT = total phosphorus; NTK = Total Kjeldahl Nitrogen; DO = dissolved oxygen; ST = total solids; SD = dissolved solids; SS = suspended solids; Temp = temperature; Turb = turbidity

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DISCUSSION

Our results showed that the formation and operation of two reservoirs changed seven out of the fifteen water quality parameters analyzed. Five parameters changed are related to the physical characteristics of the water (temperature, color, total solids, dissolved solids and suspended solids) and the two are related to chemical characteristics (pH and total phosphorus), corroborating other studies that prove the reservoir influence on sedimentation, changes in temperature and nutrient (Fantin-Cruz, 2016; Silva *et al.,* 2019 e Cruz *et al.,* 2021).

In the SHP Eng. José Gelázio, the impoundment and the long adduction channel were decisive to the water temperature increase, due to the expansion of the water surface and the increased exposure to solar radiation, as well as superficial water abstraction, as is the case of this undertaking, this heat was transmitted to the river downstream (Olden; Naiman, 2010). A study carried out in the reservoir of the Ponte de Pedra hydropower plant reported no change in this parameter, assigning it to the position of the spillway and the inlet channel that takes water from the intermediate part of the reservoir and promotes circulation and homogenization, not developing thermal stratification at the top, even in the summer (Fantin-Cruz *et al*., 2015a). Recently, this parameter has gained attention as a management tool, to assess changes caused by reservoirs (Olden; Naiman 2010). Its importance lies in controlling the rate of chemical reactions and metabolic processes that structure aquatic ecosystems (Caissie, 2006).

The position of the SHP Eng. José Gelázio at the beginning of the cascade system may have been essential to reduce most of the load of solid material transported by the basin, indicated by the relatively high percentage of color and total and dissolved solids reduction (20-28%) and, unlike the downstream project, where the trend solid material change is smaller, since the load transported is also lower. Besides the input load on the system, the rate of solids change is also affected by the length and the hydraulic retention time of the reservoir (Fantin-Cruz *et al*., 2015a), which are higher in the first reservoir. Nevertheless, it was expected that the magnitude of the change caused by small projects was lower compared to those medium and large-sized, as the Ponte de Pedra Reservoir, which reduced 23% total solids (Fantin-Cruz *et al*. 2015b), and Manso Reservoir that reduced by 28% this parameter, whose hydraulic retention times are 14 and 429 days, respectively.

Thus, the sedimentation process was important in reducing the levels of total and suspended solids of the water, besides causing siltation of this reservoir, which compromises power generation and favors the colonization of aquatic plants. The rapid reservoirs siltation is a common problem of the enterprises in the region, such as the hydropower plants of Itiquira and Ponte de Pedra and the SHP São Lourenço (Carvalho *et al*., 2000; Fantin-Cruz *et al*., 2015b), which has forced managers of reservoirs to develop control measures and sediment and aquatic plants removal in silted areas.

Furthermore, dissolved solids and color reduction can be related to the presence of large stands of aquatic macrophytes, once rooted species, such as *Eichhornia* sp., which have significant occurrence in the reservoir of the SHP José Gelázio. The metabolic changes of plants and organisms associated with the medium may have favored the alteration of water characteristics (Pompêo *et al*., 1997), mainly in the retention and absorption of substances, as well as the processing of humic substances which confer color to the water.

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With the significant reduction of the five water quality parameters downstream SHP José Gelázio (temperature, color, total solids, dissolved and suspended solids), we expected a lower number of significantly changed parameters as well as the magnitude of change downstream SHP Rondonópolis, in relation to the upstream reservoir. However, only the number of parameters showed significantly decreased, keeping the magnitude of the change quite similar as José Gelázio Reservoir.

The hydraulic characteristics of the SHP Rondonópolis reservoir reversed the water heating caused by the upstream reservoir, as showed by significantly water temperature reduce. This cooling was caused by its location on a river stretch which it runs through an incised valley with dense vegetation, making it difficult for sunlight to reach the water surface as well as the small flooded area and the length of the adduction channel, reducing the area with potential exposure to the sun. The effect of vegetation on the temperature of streams and rivers is considered one of the main drivers of the thermal water regime, so that sections or tributaries protected by a vegetation canopy have lower temperatures than open stretches or the main river (Caissie, 2006). Additionaly, as it is a fast flow stretch, it also favors the cooling of water by turbulence.

According to Bialkowski (2006), carbon dioxide is the most common cause of pH fluctuation. Photosynthesis, respiration and decomposition contribute to pH fluctuations due to the influence on the CO_2 levels, however, in the SHP Rondonópolis reservoir the reduced phytoplankton density (unpublished data) and the absence of aquatic plants associated with a water temperature reduction may have contributed to the increase of pH, since the temperature plays a key role in the aquatic environment, affecting the vast majority of physical, chemical and biological processes, which may have led to pH variation (Esteves, 2011).

When was analyzed the cumulative effect of these reservoirs in cascade, the major effect occurred on sedimentation and nutrient cycling, especially in the SHP José Gelázio reservoir. Apparently, the reduction in total solids and the increase in total phosphorus seem contradictory, once studies have shown that reservoirs are efficient sinks of sediments and nutrients (Friedl; Harison *et al*., 2009; Kunz *et al*., 2011; Oliveira *et al*., 2020). This is because the total phosphorus load entering the reservoir is transported in particulate form, in combination with bottom sediments or in suspension, and therefore the retention occurs by sedimentation (Fonseca *et al*., 2011).

In reservoirs, according to Straskraba and Tundisi (2013), there are a close relationship between the retention time and the phosphorus, which tends to increase with increasing retention time. In this perspective, the construction of dams and the reduced water flow may have affected phosphorus availability, hence the fact that there are higher concentrations of this element being released downstream by cumulative effect, caused by the physical structure of the hydraulic system and by chemical reactions together with the aquatic vegetation dynamics.

The increase in phosphorus probably also occurred due to extensive stands of aquatic plants in the SHP Eng. José Gelázio, since they participate intensively in nutrient cycling and can assimilate elements retained in the sediment through the roots and then release them in the water column by decomposition of organic matter, which are then transported downstream (Granéli; Solander, 1988). The increase in phosphorus can be considered a beneficial change to the Pantanal wetland, since the depletion of nutrients caused by reservoirs may compromise the ecological functioning of floodplains, as reported by Oliveira *et al.* (2019).

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CONCLUSIONS

Power generation has provided improvements in the population quality of life and strengthening of economic activities, but these positive aspects, among others, can not prevent the assessment of their environmental effects, aiming to stimulate the implementation of low-impact practices to allow integration of energy use, socioeconomic development and environmental protection. Even though the construction of hydropower plants has impacts, these developments contribute to the largest share of the energy matrix in Brazil and many other countries.

Small hydropower projects can have economic, social and environmental advantages compared to large projects, regarding the storage of water and residence time, and are therefore considered more sustainable. These evidences were confirmed in this study, indicating that small hydropower plants (SPH) have the potential to cause changes in water quality, but the impairment of the environmental quality of the water system can be considered low, since the limits of natural variability in water quality was maintained downstream of the developments. Furthermore, most of the parameters were within the standards of NEC Resolution 357 for class 2 rivers, and the observed changes related to the legal standard were already occurring upstream of the hydroelectric plants.

For the purposes of planning and management, projects with similar size and characteristics tend to cause similar magnitudes of changes. However, the cumulative effect of the cascade system proved to be 15% greater than the sum of the individual effects of each project, indicating that this type of structural design tends to potentiate the individual changes. Thus, the assessment of environmental impacts during the environmental licensing for hydropower plants should consider the cumulative impacts, which is not common in Brazil, especially in licensing conducted by the states. This study is a important evidence of the cumulative impacts of small dams and essential to support decision making, given the large number of hydropower plants in cascade projected to be constructed in Pantanal tributaries, with great uncertainty about the actual environmental impacts.

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