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RESEARCH ARTICLE

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Water quality impacts of small hydroelectric power plants in a tributary to the Pantanal floodplain, Brazil

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Abstract

Small hydroelectric power (SHP) facilities are proliferating around the world, including in Brazil where legislation encourages SHP over other hydropower development, defining SHP as facilities with installed capacities of 3–30 MW and reservoirs <13 km^2. SHP facilities are often diversion designs with small or no reservoirs, while other SHPs have more conventional dams that create extensive reservoirs. This study seeks to understand the relative impacts of these two different designs on downstream water quality, comparing a conventional SHP system on the main stem to a complex of smaller SHPs with diversion designs in lower-order reaches of the São Lourenço River. This river delivers nutrients and sediments to the Pantanal, one of the world's largest floodplain ecosystems. Samples collected upstream and downstream of each set of facilities over a range of flows revealed that the conventional SHP reservoir significantly reduced pH, dissolved oxygen, total iron, suspended solids, and turbidity consistent with observations in many other reservoirs. In contrast, water quality changes downstream of the smaller SHPs were less pronounced and could be attributable to natural variability. An analysis of energy production versus water quality impacts suggests that SHPs on the smaller tributaries are favorable compared to the conventional SHP in terms of water quality impacts. With the proposed addition of dozens of new facilities in the upland watersheds draining into the Pantanal, this study improves our understanding of the relative impacts of different designs of SHPs on downstream water quality, while recognizing that water quality is just one of several potential impacts to be considered.

KEYWORDS
dams, hydroelectricity, rivers, small hydropower, water quality

1 | INTRODUCTION

Hydropower generation is considered to be one of the most viable and promising sources of renewable energy in many parts of the world where its potential has not been fully exploited. Tropical river systems in particular hold considerable undeveloped hydropower potential (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). According to Winemiller et al. (2016), most of the existing and proposed dams for the Amazon, Congo, and Mekong basins, which together hold a third of the world's freshwater biodiversity, are relatively small and located in upland tributaries rather than on the main stems of those rivers. Thus, most future hydropower installations will be on rivers of lower discharge and higher gradient.

Hydropower facilities vary widely in design as well as size. Dams and reservoirs are often distinguished as either storage dams, in which the volume of water impounded varies, often greatly, over time, and run-of-river dams, in which the volume of water impounded is approximately stable (even though water releases can vary over short time scales) (Csiki & Rhoades, 2010; Kaunda, Kimambo, & Nielsen, 2012). Run-of-river designs may employ diversion channels, often with minimal impoundment of the water, or they may have reservoirs with power produced at the dam. Most smaller facilities now being built around the world are run-of-river designs with diversion channels (Kibler & Tullos, 2013).

National policies often encourage energy production from hydropower, increasingly because hydropower is generally considered to have lower impact on the climate compared to fossil fuel sources of electricity (Capik, Yılmaz, & Cavusoglu, 2012; cf. Fearnside, 2016). In addition, small hydropower (SHP) and run-of-river facilities are widely considered to be less socially disruptive compared with larger dams and their extensive reservoirs (Ferreira, Camacho, Malagoli, & Júnior, 2016; Okot, 2013). In recent years, SHP facilities have proliferated throughout the world, with tens of thousands in operation and thousands more planned (Couto & Olden, 2018; Kibler & Tullos, 2013), although SHPs typically contribute only a small percentage of total hydropower generation in countries with the most SHP development (Lange et al., 2019).

Only a few studies have examined the premise that SHPs are less harmful to the environment than the equivalent energy production by larger facilities, and SHPs in tropical regions have hardly been considered (Athayde et al., 2019). Several authors have noted the lack of comprehensive analyses that consider the synergistic and cumulative effects of multiple SHP installations in river networks (Athayde et al., 2019; Gleick, 1992; Hennig, Wang, Feng, Ou, & He, 2013; Kelly-Richards, Silber-Coats, Crootof, Tecklin, & Bauer, 2017; Kibler & Tullos, 2013). In the Nu River system of China, Kibler and Tullos (2013) found that the cumulative biophysical effects of multiple SHPs (defined in China as <50 MW) may be greater than the impacts of larger facilities, noting that hydrological impacts of SHPs included dewatering of river channels by diversion facilities and the potential to modify downstream hydrological regimes and water quality. When diversion designs are used, the original river channel receives reduced flows, and the cumulative effect of multiple diversion channel facilities along a river can be detrimental to the riverine ecosystem. For example, in China's Namtarbet River system, reaches as long as 90 km are completely dewatered by hydropower diversions during the dry season (Hennig et al., 2013).

Timpe and Kaplan (2017) analyzed the effects of dams on flow regimes throughout the Amazon as well as in the northern Pantanal watershed and concluded that SHPs had large effects when scaled to installed capacity. A review of studies of downstream effects of SHPs by Mbaka and Mwaniki (2015) found that most of the studies had been performed in North America (57.4%), followed by Europe (22.3%), Asia (13.8%), Africa (3.2%), and Australia (3.2%); until recently no studies had been conducted in South America.

A complicating factor to understanding the environmental impacts of SHPs is the lack of a standardized definition for SHP; each country currently adopts its own definition (Kelly-Richards et al., 2017). These definitions range from facilities with installed power less than 1.5 MW in Sweden (Penché, 2004) to up to 50 MW in China (Hennig et al., 2013). The definition of SHP adopted by Brazil includes facilities with installed capacities between 3 and 30 MW and with reservoir areas up to 13 km^2 (ANEEL, 2015).

The Pantanal of Brazil is one of the world's largest contiguous wetlands outside of the Arctic and is widely recognized for its biodiversity (Junk, da Silva, da Cunha, & Wantzen, 2011). Within the Pantanal watershed, 47 hydropower facilities are in operation, the majority of which are SHPs, and an additional 124 projects are under construction or planned, all of which are SHPs (ANA, 2018). The proliferation of hydropower facilities in the watersheds upstream from the Pantanal is a particular cause for concern because they could block the migration of fishes from the floodplains to upstream spawning reaches (de Campos et al., 2020), and they can reduce sediment and nutrient transport into the Pantanal wetland (Fantin-Cruz et al., 2020; Fantin-Cruz, Pedrollo, Girard, Zeilhofer, & Hamilton, 2015; Oliveira et al., 2020).

To improve our understanding of the downstream impacts of SHPs on water quality in regions such as the Pantanal, the present work compares a complex of four SHPs with diversion channels to a run-of-river SHP with a relatively extensive reservoir, all within the São Lourenço River system in the upland plateau of the Pantanal watershed. Water quality variables were measured upstream and downstream from the SHPs at various discharges. In addition, the current and proposed future configurations of SHPs in the river system are evaluated in terms of the ratio of several metrics of environmental costs to their electricity production. This study compliments the broader-scale synoptic analyses of sediment and nutrient (total nitrogen and phosphorus) transport by Fantin-Cruz et al. (2020) and Oliveira et al. (2020) because here we present a more comprehensive analysis of water quality as affected by the SHPs of the São Lourenço system.

2 | STUDY SITE AND METHODS

2.1 | Study site

The study was carried out in the upper São Lourenço River watershed, which drains an area of 27,700 km^2 in the southeastern portion of the State of Mato Grosso in Brazil (Figure 1). The upper São Lourenço River is defined as upstream from the confluence of the São Lourenço and the Vermelho Rivers, west of the city of Rondonópolis. According to the Köppen system, the climate is Aw (Tropical Savanna Climate), with mean annual temperatures varying between 22.5 and 26.5°C. November is the hottest (mean, 27°C) and July is the coldest (mean, 21°C) month. Mean annual precipitation is 1,398 mm, with the highest observed values in the plateau areas. The rainy season occurs between October and April. The natural vegetation is savanna (known locally as Cerrado), but ~55% of the watershed has been converted to grain crops, sugarcane, or pasture (WWF-Brasil et al., 2015) (Figure 1).

In the upper São Lourenço River system, there are seven SHPs in operation (Table S1). On the Tenente Amaral tributary, there are five

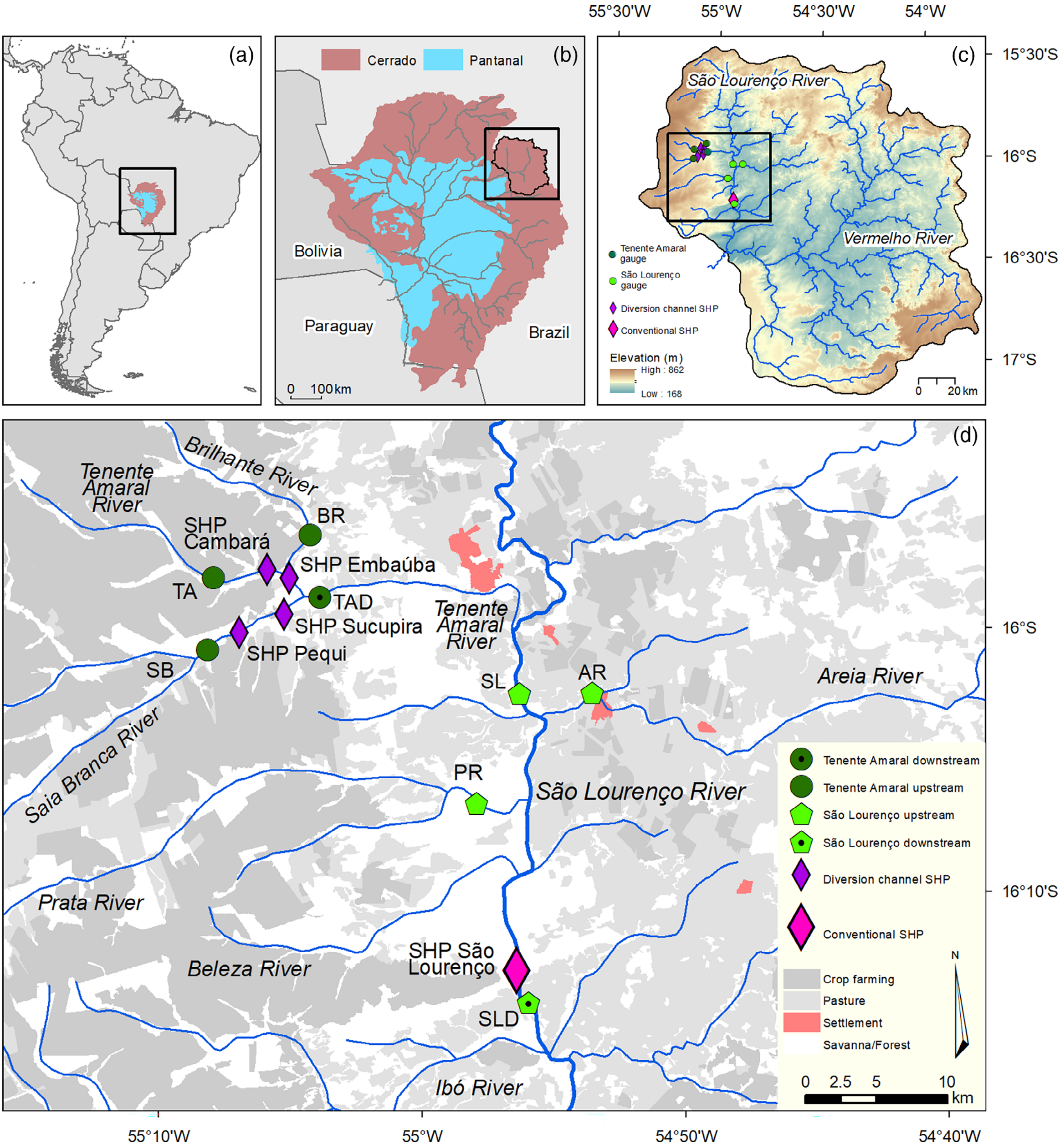

FIGURE 1 (a) The location of the Pantanal wetland in South America; (b) the Pantanal and its upland watershed, where the natural vegetation is Cerrado savanna, as well as the location of the São Lourenço River system; (c) watershed topography of the São Lourenço River; and (d) location of studied facilities, sampling sites, and land use and cover in the upper São Lourenço River. Land use and cover data are from Rosa et al. (2009). Collection point acronyms and coordinates are given in Table S2 [Color figure can be viewed at wileyonlinelibrary.com]

facilities with diversion channels (Pequi, Sucupira, Cambará, Embaúba and Tenente Amaral), and on the main stem there is one (SHP São Lourenço) without a diversion channel. The present study selected four out of the five SHPs with diversion channels and the single SHP without a diversion channel for water quality analysis (Figure 1). The four diversion SHPs are referred to as the Tenente Amaral Complex (TAC) of dams. SHPs of the TAC have a combined installed capacity of 18.5 MW and a total reservoir area of 0.13 km^2 while the São Lourenço SHP has an installed capacity of 29.1 MW and a reservoir area of 12.9 km^2.

As of 2019, in the upper São Lourenço River system, three more SHPs are under construction (Água Branca, Água Prata, and Água Brava), six are undergoing feasibility studies (Água Clara, Beleza, Mangaba, Europa, Buriti, and Jaciara), and two have obtained a preliminary license. With the exception of the Jaciara SHP, all are proposed to have diversion channels (Table S1).

2.2 | Data collection

Water sampling was conducted at eight sites between 2014 and 2015 (Figure 1 and Table S2). Sampling site selection was constrained by the rugged terrain and limited accessibility of the river channels, and in some cases we were not able to sample directly upstream or downstream from a particular facility when they were closely situated. Three rivers were sampled to characterize the inflow to the SHP São Lourenço, among which the Prata River was sampled only in the rainy and dry seasons and not during the transition season. The Beleza River, a small tributary that also contributes to the reservoir of the SHP São Lourenço, was not sampled after determining that its mean discharge was small ($\sim$2.3 m^3/s) relative to the sum of the other inflows ($\sim$109 m^3/s). Several smaller tributaries also could not be sampled, and thus the unmeasured watershed area contributing to the outflow from the SHP São Lourenço amounts to 7% of the total watershed.

During each sampling period, samples were collected in consecutive days: 10 days in the dry-rainy transition (September to October 2014), rainy (March 2015) season, and 7 days in the dry (August 2015) season. We present data from 108 water samples collected on 27 dates at three locations upstream from the TAC, and from 81 samples from the three locations upstream and one location downstream from the São Lourenço SHP, each sampled on 27 dates except in the case of the Prata River, which was sampled on 17 dates.

Water temperature (°C), electrical conductivity (μS/cm corrected to 25°C), pH, total dissolved solids (mg/L), and dissolved oxygen (mg/L and % saturation) were measured in the field using either a Hanna HI 98196 multiparameter probe (transition season) or a YSI Professional Plus probe (dry and wet seasons). The probes were calibrated daily, or more frequently if the field crew determined a need. Laboratory analyses of water quality included the variables listed in Table S3. Laboratory analyses were carried out in accordance with APHA (2012) as well as Brazilian state and federal standards (methods are provided in Table S3).

Flow measurements for calculation of discharge were performed in the same river reaches as the water collection sites, with two measurements each in the rainy and transition seasons and one in the dry season. A single set of flow measurements was determined to be adequate during the dry season since discharges and water levels were stable. Water level gages were installed at these sections to monitor the water level during the days when water samples were taken. Discharge was measured by the sum of the products of the velocity and area at multiple vertical profiles in a cross-section. From these data, stage–discharge relationships were constructed to determine the discharge at each water quality sampling time. Air temperature data were obtained from the weather station in the city of Rondonópolis (INMET, 2018). Rainfall data were obtained from gages installed at the Pequi, Sucupira, and Cambará SHPs.

The hydraulic residence times of the reservoirs for the collection days were calculated as the total reservoir volume divided by the average daily discharge. Reservoir and dam characteristics were obtained from the Environmental Studies Reports and Environmental Diagnoses made available by the Secretary of the Environment of the State of Mato Grosso (SEMA-MT).

2.3 | Data analysis

Statistical analyses were done in R, version 3.2.1 (R Development Core Team, 2015), using nonparametric methods due to nonnormality (Kolmogorov–Smirnov) and heteroscedasticity (Levene) in the data. The analytical detection limit was adopted as the minimum for both statistical and graphical analyses of laboratory measurements. Where more than one river contributed to the inflow to an SHP, we calculated the discharge-weighted mean from upstream collection points.

Upstream–downstream comparisons were made by Friedman's paired test, a nonparametric test that analyzes the variance of two factors and tests the null hypothesis that the samples were extracted from the same population or from populations with the same median. The pairing of data by time ensured that the differences observed in the variable of interest are due exclusively to differences at the time of sampling. The Kruskal–Wallis test of multiple comparisons was used in the spatial and temporal analyses (precipitation, flow, and air temperature) in order to verify if independent samples come from different populations, testing the same hypothesis described for the Friedman test. In both cases, differences between upstream and downstream at a sampling period were considered significant at $\alpha = .05$.

2.4 | Environmental costs per unit of energy production

Decisions regarding the construction of new SHPs need to consider their integrated environmental costs in relation to their power production benefits. We conducted a comparison of the environmental costs per unit of energy production for different SHP configurations in the upper São Lourenço River system based on existing and proposed facility characteristics and installed capacity. The SHPs with diversion channels in operation in the basin (Table S1) were grouped as the Upper São Lourenço Complex (CASL). The results obtained from this set were compared to the São Lourenço SHP with its relatively extensive reservoir and no diversion channel.

The SHPs planned or proposed for installation in the CASL were added to the comparison, including facilities in two river systems that currently lack SHPs and were not sampled in this study—the Prata and Beleza Rivers, which enter the São Lourenço River upstream from the SHP São Lourenço. Facilities were characterized based on the availability of information in technical data sheets along with environmental reports and feasibility studies provided by SEMA-MT. The selected characteristics were as follows: upstream drainage area (km^2), reservoir area (km^2), reservoir volume (m^3), reservoir length (m), reservoir filling time (days), residence time of the reservoir (days), dam height (m), nominal fall (m), the length of the diversion (km), the length of reduced flow in the natural channel downstream from the dam due to the diversion (km), installed electrical generation capacity (MW), volume of earth moved (m^3), and volume of concrete used (m^3). The volumes of earth moved and concrete are low estimates for the CASL facilities due to the unavailability of data for four facilities (SHPs Tenente Amaral, Beleza, Ibó e Ibó-Guazú). The proportion of the river channel length with altered or diverted flows due to the SHPs was calculated by adding the reservoir length to the diversion channel length.

3 | RESULTS

3.1 | Discharge and water quality

Discharge rates on water sampling dates were significantly higher in the rainy season, but similar between the dry-rainy transition and dry seasons (Table 1). The discharge in the main channel of the São Lourenço River in the vicinity of the São Lourenço SHP was ~4–12-fold higher than the discharge in the vicinity of the TAC, with the greatest difference in the rainy season. The higher discharge downstream from the SHP São Lourenço compared to the sum of the three measured river inputs to the reservoir is likely attributable to a combination of unmeasured tributary inputs, which drain 7% of the total watershed area, and dam operations, which cause large short-term variability in downstream releases that invalidate comparisons on a particular day Coelho-Silva et al. (2019).

Air temperatures and rainfall differed significantly across all seasons (Figure S1). During the rainy season, the cumulative total precipitation was 180 mm with a median air temperature of 25.4°C. During the transition season, there were sparse rains with a cumulative total for the study interval of 33.2 mm, as well as the highest air temperatures, with a median of 28.4°C. During the dry season, there were no precipitation events, and the air temperature was cooler than in the other seasons (25.1°C).

The water quality results as well as estimates of hydraulic residence times are shown in Figures 2 and 3 and Tables S4 and S5. The rivers of the TAC carry acidic, ionically dilute waters with moderate concentrations of available nutrients and low concentrations of suspended particulate matter. Upstream–downstream comparisons of the TAC using the Friedman test showed significant differences for all seasons combined only for pH and dissolved oxygen ($p \le .01$) and true color ($p \le .05$) (Table S4). The pH increased from upstream of the TAC to downstream, regardless of the season (transition season, $p = .011$; rainy, $p = .014$; dry, $p = .0081$). There were also significant downstream increases in conductivity ($p = .0014$) and dissolved solids ($p = .0014$) during the rainy season as well as dissolved oxygen ($p < .0001$) during the transition season. There was a significant downstream reduction in true color ($p = .014$) during the dry season. Hydraulic residence times of the SHPs in the overall TAC were short (1.0–1.9 days depending on season).

The water quality results for the São Lourenço SHP are shown in Figure 3 and Table S5. The river at this location is less acidic and has a somewhat higher ionic content but similar nutrient concentrations as the rivers of the Tenente Amaral system. A notable difference is the higher concentration of suspended particulate matter, much of which is attributable to the Areia River. Upstream–downstream comparisons using the Friedman test showed significant differences for all seasons combined for pH, dissolved oxygen, suspended solids, turbidity, and total iron ($p \le .01$) (Table S5). Water flowing through the São Lourenço SHP showed reductions in total iron ($p = .0015$), pH ($p = .011$), COD ($p = .014$), suspended solids ($p = .0015$), turbidity ($p = .011$), and dissolved oxygen ($p = .011$) during the transition season. During the rainy season, reductions were evident for total iron ($p = .045$), pH ($p = .045$), dissolved solids ($p = .045$), and electrical conductivity ($p = .045$). The water temperature increased downstream during the rainy season ($p = .045$). During the dry season, a downstream reduction was observed for total iron ($p = .0081$), turbidity ($p = .0081$), and dissolved oxygen ($p = .0081$). A small increase in electrical conductivity was observed during the dry season ($p = .0081$). The hydraulic residence times of the São Lourenço SHP were longer than those of the TAC SHPs (4.1–18 days depending on season).

Statistically significant changes in water quality between upstream and downstream sampling points are summarized in Table 2. The pH and dissolved oxygen tended to increase in water passing through the TAC but decrease through the São Lourenço SHP. Other changes in

TABLE 1 Mean discharge (m^3/s) of the Tenente Amaral and São Lourenço Rivers upstream and downstream from the hydropower facilities on those rivers

	Tenente Amaral River		São Lourenço River	
Season	Upstream from SHP complex	Downstream from SHP complex	Upstream from SHP São Lourenço	Downstream from SHP São Lourenço
Transition dry-rainy	15.2	18.0	55.1	66.2
Rainy season	19.5	22.9	199.4	283.6
Dry season	12.5	12.5	61.6	92.9

Note: Discharge was measured in conjunction with the water sampling in 2014 and 2015. River sampling locations are shown in Figure 1.

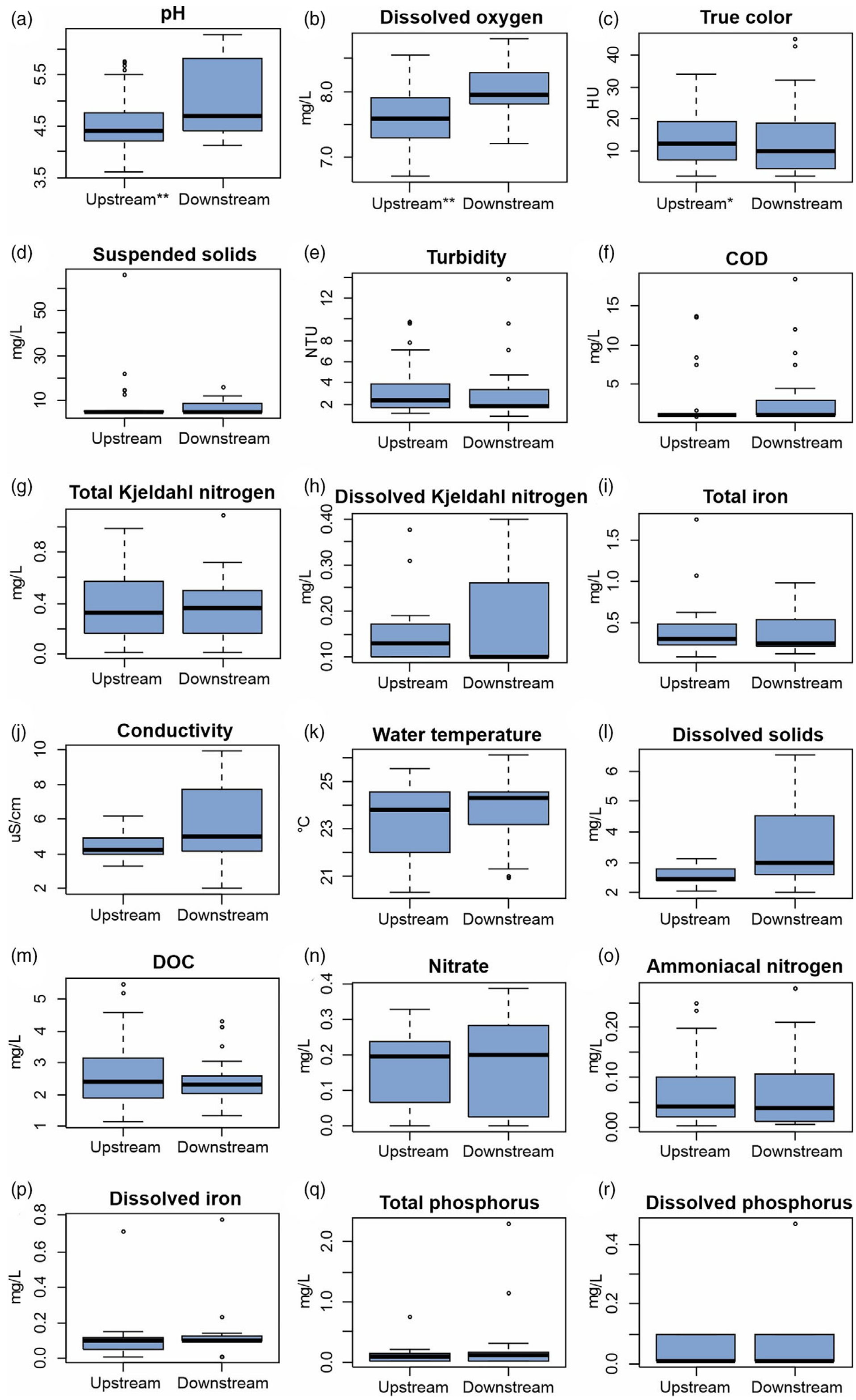

FIGURE 2 Water quality comparisons between sampling points upstream and downstream from the Tenente Amaral Complex of small hydropower facilities with diversion designs. Data for all seasons were combined. Units are in mg/L except for pH, true color (HU), electrical conductivity (μS/cm), water temperature (°C), and turbidity (NTU). Upstream–downstream comparisons using the Friedman test showed significant differences for all seasons combined only for pH and dissolved oxygen ($p \leq .01$) and true color ($p \leq .05$) (Table S4) [Color figure can be viewed at wileyonlinelibrary.com]

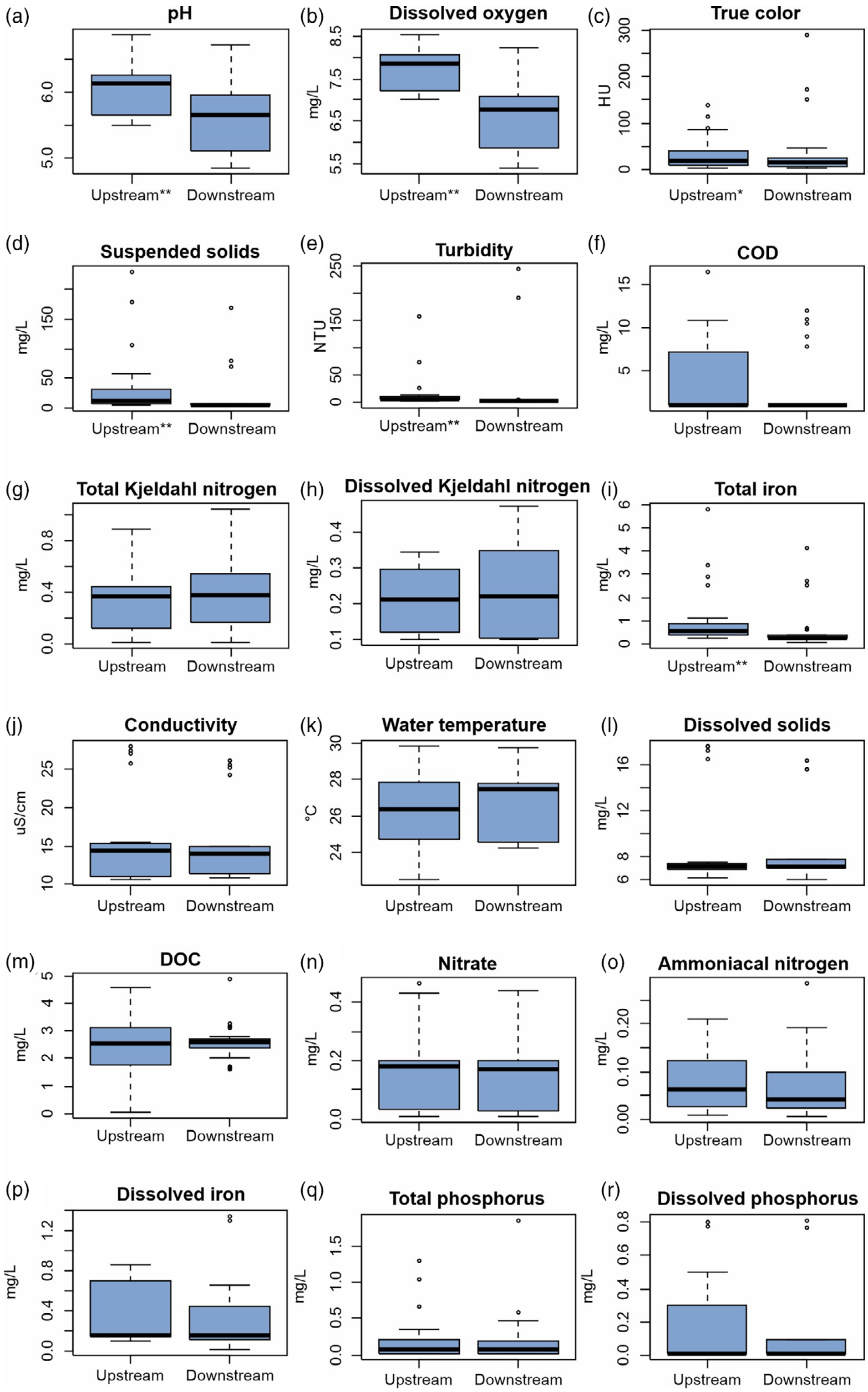

FIGURE 3 Water quality comparisons between sampling points upstream and downstream from the São Lourenço small hydropower facility, which is not the diversion design. Data for all seasons were combined. Units are in mg/L except for pH, true color (HU), electrical conductivity (μS/cm), water temperature (°C), and turbidity (NTU). Upstream–downstream comparisons using the Friedman test showed significant differences for all seasons combined for pH, dissolved oxygen, suspended solids, turbidity, and total iron (all $p \leq .01$) and true color ($p \leq .05$) (Table S5) [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Summary of significant changes in water quality between upstream and downstream sampling points based on the Friedman test

	Tenente Amaral complex				São Lourenço SHP			
Variable	All seasons	Transition	Rainy	Dry	All seasons	Transition	Rainy	Dry
pH	↑	↑	↑	↓	↓	↓	↓	
Conductivity			↑				↓	↑
Dissolved solids			↑				↓	
Dissolved oxygen	↑	↑			↓	↓		↓
True color	↓			↓				
Total iron					↓	↓	↓	↓
Suspended solids					↓	↓		
COD						↓		
Turbidity					↓	↓		↓
Temperature							↑	

Note: Black arrows identify the direction of changes at $p \leq .05$ level of significance and red arrows indicate $p \leq .01$. Other variables measured in the TAC and São Lourenço SHP did not present significant upstream–downstream differences.

water flowing through the TAC were inconsistently observed. In contrast, more marked and consistent changes in water quality were evident as water passed through the São Lourenço SHP, particularly those related to suspended particulate matter (total iron, suspended solids, and turbidity). Turbidity and concentrations of suspended solids were considerably higher in inflowing water at the São Lourenço SHP compared to the TAC (Tables S4 and S5).

3.2 | Environmental costs per unit of energy production

The comparison of the environmental costs per unit of energy production for the existing diversion SHPs (CASL complex) with those of the non-diversion SHP (São Lourenço SHP) in the São Lourenço River system indicates that the diversion SHPs have smaller total reservoir size (area, volume, and length) per unit power generated than the non-diversion São Lourenço SHP (Table 3). The CASL complex dams also disturbed less land during construction and used less concrete per unit power generated. The CASL complex has a higher total installed electrical generating capacity, but the generation of firm energy (i.e., maximum continuous energy) is about 17% lower than that provided by São Lourenço SHP. On the other hand, hydrological alterations due to the diversion channels (reduced flows in the natural channels) are present only in the CASL complex since they are inherent characteristics of diversion designs.

The conclusions are similar if the 11 additional facilities that are planned in the watershed are included in the analysis (Table 4). For those metrics that could be estimated, the 15 diversion channel SHPs are better in terms of environmental cost per unit energy generated compared to the three facilities without diversion channels. The results indicate that the SHPs with diversion channels would have smaller reservoirs, and require less earth movement and use of concrete, per unit power generated in relation to those lacking diversion channels. It should be noted, however, that the last two metrics (earth movement and concrete volumes) are underestimated due to the absence of data from four of the facilities (SHPs Tenente Amaral, Beleza, Ibó, and Ibó-Guazú).

From the perspective of impacted river channel length, the Saia Branca River is currently the most affected tributary, in that 90% of its mean annual discharge is diverted from reaches equivalent to 21% of the natural channel length (Table 5). The Tenente Amaral and Ibó basins were similar to each other in the percentage of their lengths affected by diversion channels (10.1 and 11.9%, respectively) and reduced discharges (4.7 and 5.5%). These two rivers drain smaller basins with very favorable characteristics for the installation of diversion SHPs due to the higher topographic relief in the basins (i.e., nominal fall data in Table 4). In the main stem of the upper São Lourenço River, 3.9% of the total length is occupied by the Upper São Lourenço SHP reservoir, which does not have a diversion channel.

Assuming that all proposed facilities will be built, the Ibó, Prata, and Beleza tributaries will be the most affected with 15–20% of their channel lengths impacted by reservoirs and diversion channels. The impacts of SHPs on the Tenente Amaral, Saia Branca, and São Lourenço rivers will not change as much in the future, with percentages of affected channel lengths remaining similar to current levels.

4 | DISCUSSION

4.1 | Changes in water quality

This study has documented how water quality is affected by two alternative SHP designs: small dams with diversion channels and little impoundment of water upstream from the dams (four facilities in the Tenente Amaral Complex, TAC) versus a non-diversion facility that creates a relatively large reservoir (São Lourenço SHP). The four diversion SHPs impound little water and have short water residence times (1–1.9 days in aggregate: Table S4), whereas the São Lourenço

TABLE 3 Environmental costs per unit of energy production assessed by comparing facility characteristics with installed electrical generation capacity (MW or kW), including only operational SHP facilities, grouped for comparison between facilities in the upper São Lourenço River system that have diversion channels and the SHP São Lourenço River that is not a diversion design

Metric	Unit	Upper São Lourenço complex (CASL)	SHP São Lourenço	CASL/SHP São Lourenço (%)
Installed capacity	MW	38.9	29.1	134
Drainage area	km^2/kW	27.9	199	14.1
Reservoir area	km^2/kW	0.01	0.4	2.9
Reservoir volume	10^2 m^3/MW	0.2	3.5	4.5
Reservoir length	Km/MW	0.1	0.8	13.0
Reservoir filling time	Day/MW	0.1	0.7	19.8
Residence time	Day/MW	0.2	0.3	50.1
Dam height	m/MW	0.1	1.0	13.5
Nominal fall	m/MW	1.6	0.7	224
Diversion channel length	Km/MW	0.4	0.0	—
Diverted natural channel length	Km/MW	0.3	0.0	—
Volume of earth moved	m^3/MW	15,300	21,600	71.0
Volume of concrete	m^3/MW	2,050	3,380	60.5
Firm energy	MW/MW	0.5	0.6	83.4

TABLE 4 Environmental costs per unit of energy production assessed by comparing facility characteristics with installed electrical generation capacity (MW), including both operational and planned SHP facilities, grouped for comparison between facilities with and without diversion channels

Metric	Unit	SHPs with diversion channels	SHPs without diversion channels	With/without diversion (%)
Installed capacity	MW	114	38.1	
Drainage area	km^2/MW	15.1	152	10
Reservoir area	km^2/MW	0.04	0.4	9
Reservoir length		NA	NA	NA
Reservoir volume		NA	NA	NA
Reservoir filling time		NA	NA	NA
Residence time		NA	NA	NA
Dam height	m/MW	0.1	0.6	20
Nominal fall	m/MW	0.6	0.4	157
Diversion channel length	Km/MW	0.3	0.0	-
Diverted natural channel length		NA	NA	NA
Volume of earth moved	m^3/MW	17,100	18,600	92
Volume of concrete	m^3/MW	1,460	2,590	56
Firm energy	MW/MW	0.5	0.6	85

Abbreviation: NA, data not available at the time of publication.

SHP creates a larger reservoir that has longer residence times (4.2–18 days: Table S5).

Water passing through the diversion SHPs showed fewer and less marked changes in water quality (Figure 2, Tables 2 and S4), whereas the reservoir of the São Lourenço SHP caused more changes that suggest sedimentation of particulate matter (i.e., reductions in suspended solids, turbidity, and total iron: Figure 3, Tables 2 and S5). Fantin-Cruz, Pedrollo, Girard, et al. (2015) recorded reduced turbidity and suspended solids downstream from the Ponte de Pedra reservoir. The Ponte de Pedra facility is also located in the Pantanal watershed and has characteristics similar to the São Lourenço SHP, with a mean water residence time of 14 days, although its dam generates more power than the São Lourenço (210 MW installed capacity). These observations are consistent with many studies of reservoirs that have

TABLE 5 Percentage of total river channel length in the upper São Lourenço River system impacted by diversion channels and reservoirs of current and projected future SHPs

	Diversion channel + reservoir length (%)		Reduced flow rate (%)
Sub-Basin	Current	Future	Current
Tenente Amaral	10.1	11.6	4.7
Saia Branca	20.6	20.6	13.7
Ibó	11.9	20.1	5.5
São Lourenço	3.9	5.5	0.0
Prata	NA	20.1	NA
Beleza	NA	15.4	NA

Note: The future scenario includes both operational and proposed facilities. Reductions in discharge have not been published for proposed facilities. NA means that the data are not applicable either because there are no reservoirs, or the facilities lack diversion channels. Source: Environmental Studies Reports provided bythe data were obtained from Mato Grosso State Secretariat for the Environment.

shown water residence time to be a key variable explaining sediment and nutrient retention and the growth of phytoplankton (Straskraba, 1999). A residence time threshold above approximately 7 days has been shown to impact water quality (e.g., Reid & Hamilton, 2007).

The small changes in water quality as water moved through the diversion SHPs of the TAC are not necessarily attributable to the facilities; river systems commonly show natural gradients from the headwaters downstream in variables like dissolved oxygen, pH, and conductivity. Dissolved oxygen and pH tend to increase in reaches with greater reaeration and/or more photosynthetic activity. Diversion SHPs tend to be located in higher gradient reaches and it is conceivable that reaeration of the diverted water as it returns to the river channel has a similar effect as reaeration in particularly turbulent portions of the natural channel from which the flow was diverted.

Dissolved oxygen concentrations tended to increase slightly as water moved through the diversion SHPs of the TAC, while they tended to decrease, albeit not greatly, as water moved through the São Lourenço SHP (Figures 2 and 3, Tables 2, S4, and S5). The decrease in dissolved oxygen in the latter reservoir was usually accompanied by a decrease in pH, as expected with respiratory carbon dioxide production. However, these small changes in dissolved gases would likely be inconsequential in the river downstream where reaeration rates are high.

Thermal stratification, which is a function of depth, fetch, and discharge relative to volume, is an important driver of biogeochemical processes in lakes and reservoirs, including depletion of dissolved oxygen in bottom waters (Wetzel, 2001). It is likely that the reservoir of the São Lourenço SHP was stratified during the dry and transition seasons. Similar seasonal stratification was recorded by Fantin-Cruz, Pedrollo, Girard, et al. (2015) in the Ponte de Pedra reservoir. The densimetric Froude number (DFr) is commonly used to predict thermal stratification of water bodies (USACE, 1974) and has been demonstrated to approximate conditions in Brazilian reservoirs (Cunha-Santino, Fushita, & Bianchini, 2017; Tucci, 1998). The smaller the value of the DFr, the more likely the reservoir is stratified. In this approximation, the average density gradient of the reservoirs is assumed to be 10^{-3} kg/m^4 and was calculated for the São Lourenço and Ponte de Pedra reservoirs using:

$$\mathrm{DFr} = 320\frac{L\,Q}{D\,V} \tag{1}$$

where DFr is the densimetric Froude number (unitless), L is the reservoir length (fetch) in meters (obtained from Google Earth images), D is the average reservoir depth in meters, Q is the river discharge in cubic meters per second, and V is the reservoir volume in cubic meters. The constant 320 has units of inverse seconds (s^{-1}). The depth, volume, and discharge for Ponte de Pedra reservoir were obtained from Fantin-Cruz, Pedrollo, Girard, Zeilhofer, and Hamilton (2016). The depth and volume for the São Lourenço reservoir were obtained from Souza-Filho (2013) while the median discharges for each season as recorded in this study were used. The approximate DFr for Ponte de Pedra reservoir was 0.65. The approximate DFr values for the São Lourenço reservoir were 0.47 during the dry season, 0.50 during the transition season, and 1.6 during the rainy season. During the dry and transition seasons, the approximate DFr values in the São Lourenço reservoir are lower than that of the Ponte de Pedra reservoir when it displayed persistent thermal stratification, indicating a high likelihood of seasonal stratification in the São Lourenço reservoir.

Persistent thermal stratification of the São Lourenço reservoir might be expected to explain, in part, the decrease in dissolved oxygen at its outflow if it were drawing water from the hypolimnion (Figure 3 and Table S5). However, the only publicly available information indicates that the 32-m high dam has a hydraulic head of 22 m, and therefore must draw its water from near the surface. Thermal profiles at the similarly sized Ponte de Pedra reservoir showed an epilimnion depth of approximately 10 m (Fantin-Cruz, Pedrollo, Bonecker, & Zeilhofer, 2015). Reaeration as water passes through and exits the dam would at least partly erase any departure of dissolved gases from atmospheric equilibrium.

As expected, given the tropical climate, water temperatures were little affected by either the diversion SHPs or the SHP São Lourenço (Figures 2 and 3, Tables 2, S4, and S5), which contrasts with the way reservoirs can strongly affect downstream water temperatures in temperate climates by attenuating seasonal and shorter-term changes in air temperatures (Olden & Naiman, 2010).

4.2 | Comparison with other studies of SHPs in the Pantanal watershed

Our results are consistent with the findings of a broad survey of hydropower facilities, most of which are SHPs, throughout the Pantanal watershed to evaluate their effects on transport of sediments (Fantin-Cruz et al., 2020) and nutrients (Oliveira et al., 2020) to the Pantanal. Sediment and nutrient retention were shown to be directly related to sediment loads in the rivers and water residence time in reservoirs. Effects of current SHPs on transport of total N and P were not detectable in most cases, although when these nutrients were retained, it was largely attributable to the trapping of particulate forms associated with sediments. Sediment retention was observed in the majority of cases; 14 of 29 hydropower facilities retained >20% of the suspended sediment load. Bedload was a small fraction of the total sediment loads except in rivers with very low loads. Both studies employed artificial neural network models to predict that future development of SHPs on rivers with relatively high discharge and sediment loads will lead to significant overall reductions in sediment and nutrient transport from the uplands to the Pantanal. Oliveira et al. (2020) also evaluated nutrient limitation based on concentrations and ratios of total N and P, and note that even modest nutrient retention by SHPs in the most nutrient-poor river systems, which include the Tenente Amaral system, may ultimately lead to decreased aquatic and floodplain productivity (oligotrophication) in downstream ecosystems. Earlier studies by Silva, Fantin-Cruz, Lima, and Figueiredo (2019) in the Jauru River and de Oliveira (2016) in the Correntes River showed that cascades of SHPs with longer aggregate residence times were associated with changes in water quality downstream.

4.3 | Caveats and other impacts beyond water quality

The conclusions reported here are limited to water quality based on near-surface samples from the river channels upstream and downstream from dams, taken at daily intervals on multiple but limited numbers of dates. In addition to potentially missing important high-flow events or the lowest annual flows, our sampling does not properly estimate sediment fluxes. Much of the sediment transport in these rivers occurs as coarse particles (especially sand), which tend to be unevenly distributed in the water column with higher concentrations near the bottom, and such material can be subject to temporary storage and remobilization in river channels (Bagnold, 1977; Mueller, Pitlick, & Nelson, 2005). Furthermore, sand accumulations upstream from SHP dams may be periodically removed by operators.

Time series of satellite images provide evidence for substantial accumulation of sediments at the upper end of the São Lourenço SHP (Fantin da Cruz, 2018). Long-term retention of sediments may cause geomorphological destabilization of downstream channels, extending to the floodplains of the Pantanal if the cumulative effects become large enough. On the other hand, erosion and enhanced sediment transport in rivers of this region may have increased in recent decades through human activities, particularly agricultural land use (Guecker, Boechat, & Giani, 2009). The net balance between anthropogenic increases in river sediment loading from watershed land use versus decreases in sediment loads through retention in reservoirs is an open question in this region.

Another caveat is that our study does not examine a long cascade of SHPs like those that exist in many parts of the world. Effects that are too small to detect across one or a few SHPs can become important cumulative changes as more SHPs are built (Kibler & Alipour, 2017). Dewatering of the natural river channel by SHP diversion channels is likely to be ecologically significant, although complete dewatering as has been reported in China is less likely here; in Mato Grosso State, dam operators are required to maintain approximately 10% of the mean monthly discharge in the natural channel as "ecological flow."

It is important to point out that dams, including SHPs, have other kinds of ecological and social impacts besides affecting downstream water quality (Athayde et al., 2019; Olden & Naiman, 2010). Of particular relevance for SHPs in the watershed of the Pantanal include: (a) even low dams may act as barriers to fish migration, and more than 20 species of fishes migrate from the Pantanal upstream to spawn in upland tributaries (de Campos et al., 2020); (b) SHPs tend to be located in reaches of higher elevational gradients and may, therefore, degrade special habitats for river biota such as waterfalls, which also may be popular sites for recreation by people; and (c) the diversion channels act as a barrier to the movement of animals between adjacent uplands and the river valley, often being fenced off to prevent large animals from entering the water.

4.4 | Environmental costs per unit of energy production

The ratios of environmental costs per unit of energy production presented in Tables 3–5 allow comparison of the diversion SHPs in the TAC with the São Lourenço SHP, and clearly demonstrate the advantages of building SHPs on smaller rivers from the standpoint of water quality and habitat alteration. Naturally, this question is only pertinent if decision-makers can evaluate these projects on the scale of entire river networks, considering both current and potential future sites, and seek to optimize the environmental cost to energy benefit of overall dam portfolios.

The fragmentation of river systems by dams blocks migrations of fishes and other river animals (Grill et al., 2015; Liermann, Nilsson, Robertson, & Ng, 2012). In the case of the Pantanal watershed, where fishes tend to migrate upstream from the floodplains, a single dam on the lower reach of a tributary can block access to the entire upstream network. None of the facilities in existence in the region have fish passage systems. Our analysis of environmental costs per unit of energy production (Tables 3–5) indicates that the São Lourenço SHP, built in the main channel of the river system, fragmented a watershed area 86% larger than would set of SHPs distributed in smaller tributaries generating a similar amount of electricity. Furthermore, the reservoir created by the São Lourenço SHP influences the flow of six tributaries (Ribeirão Parnaíba, Pombas, Tenente Amaral, Areia, Prata, and Beleza rivers), while the CASL SHPs influence flows in just two tributaries (Tenente Amaral and Ibó).

In the specific case of the CASL SHPs, the basins are third and fourth order, representing about 10% of the main river flow, and are located in valleys with high slope. Waterfalls in these reaches may act as natural barriers, at least to larger migratory fishes that often do not occur in the upland tributaries (de Campos et al., 2020). Thus, the SHPs on the smaller tributaries may have less impact on migratory fish and fisheries.

The reservoir metrics per unit of hydropower generated (Tables 3 and 4) show that the CASL SHPs have smaller and shallower reservoirs, characteristics that imply less influence on water quality as well as less displacement of people and loss of productive land. The results also indicate that the construction of the CASL SHPs required moving smaller amounts of earth and using less concrete than the São Lourenço SHP.

Comparing the installed power generation capacity with the flooded area of the reservoir, the CASL SHPs had a generation potential of 77.8 MW/km^2 and the São Lourenço SHP had 2.2 MW/km^2. According to Souza-Filho (2013), the approximate average power generation per km^2 flooded from all of the facilities presently installed in the Pantanal watershed is 2.24 MW/km^2, a proportion very similar to that estimated for the São Lourenço SHP. Although not considered in this study, the reservoir flooded area per unit of hydropower generated also bears on the climate impact of hydropower, since within a given region the area of reservoirs would be proportional to the emission of greenhouse gases (particularly methane) (Almeida et al., 2019).

5 | CONCLUSIONS

This study found that a complex of four SHPs with diversion designs located on a tributary of the São Lourenço River in the watershed of the Pantanal had few effects on downstream water quality, which we attribute to the short water residence times (1–2 days in aggregate) of these facilities. In contrast, the São Lourenço SHP, which creates a much larger reservoir on the mainstem of the São Lourenço River with residence times of 4–18 days, produced changes in water quality that resemble those reported for larger reservoirs in direction, although they were more modest in magnitude. The analysis of environmental costs per unit of energy production suggests that SHPs on the smaller tributaries are favorable choices compared to the São Lourenço SHP in terms of direct environmental impact on the river ecosystem, including the material costs of building them. Building SHPs on lower-order rivers also produces less fragmentation of fish migration routes between the Pantanal and upland spawning sites (de Campos et al., 2020). More research is needed to develop a comprehensive understanding of environmental and social impacts, including the possibility of coarse sediment retention, an unknown fraction of which may originate from agricultural land use, and how that retention may affect downstream rivers and floodplains. The basin-wide analyses reported here demonstrate why hydropower projects must be evaluated at the scale of the entire river system rather than individually, considering environmental impacts per unit energy generated, to ensure that project locations and designs generate energy with the lowest possible environmental impacts.

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CONFLICT OF INTEREST

Lead author RFC is co-owner of Aquanálise S/A Ltda., a water analysis firm serving local government agencies and the private sector, including some hydropower companies in the State of Mato Grosso (Brazil) where this study was conducted. The firm has not analyzed samples on behalf of, nor consulted with, the parties who own or manage the hydropower facilities mentioned in this manuscript, and therefore this does not represent a conflict of interest. The remaining authors also declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, Hans M. Tritico, upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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