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PRIMARY RESEARCH PAPER

Changes in river water quality caused by a diversion hydropower dam bordering the Pantanal floodplain

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Abstract Diversion hydroelectric facilities are proliferating worldwide, yet how they alter water quality has seldom been assessed. This study evaluates effects of a nearly "run-of-river" diversion hydropower dam (210 MW capacity) on water quality in the Correntes River, a tributary to the Pantanal floodplain of Brazil. Water quality was analyzed from eight locations before and after reservoir construction. Relative to an upstream reference site, the reservoir significantly decreased turbidity (mean, 38%) and concentrations of total solids (23%), total phosphorus (28%), and nitrate (14%). Most changes occurred in the upstream segment of the reservoir (except for turbidity). Only turbidity and nitrate were affected by reservoir operator control of the hydraulic retention time, which ranged from 7.3 to 21.2 days. Overall, the most consequential changes in downstream water quality may be sediment and associated phosphorus retention, which over the long term could affect channel geomorphology and reduce floodplain biological productivity.

Keywords Hydroelectric dams · Sediment and nutrient retention · Hydraulic retention time · Dam operation · Ecological implications · Diversion hydropower

Introduction

Diversion hydropower dams are often promoted as an alternative for hydroelectric production that has less environmental impact and greater social acceptance than large dams. These are often nearly run-of-river

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operations that maintain relatively stable reservoir water levels and divert part of the river flow through a penstock leading to turbines. These plants may have no reservoir or one with a limited storage capacity compared to conventional hydropower reservoirs, although most have a dam or weir to divert flow into the penstock. Thus, power generation is subject to seasonal variations of river flow. Large numbers of diversion hydropower facilities are being built on rivers throughout the world, including Brazil (Martins et al., 2013), China (Hennig et al., 2013; Cheng et al., 2015), India (Kumar & Katoch, 2014), and Canada (Wang et al., 2014). While the environmental effects of large dams are well known, those of these smaller dams have scarcely been studied. Considering the proliferation of diversion hydropower dams in the world's river systems, the question arises as to their cumulative impacts on downstream ecosystems, even though the potential impacts of these projects are generally not evaluated at the watershed level. Attempts to estimate their cumulative environmental impacts suggest that a large number of smaller dams may have greater total impact per unit of energy generation than large dams (Gleick, 1992; Ziv et al., 2012; Kibler & Tullos, 2013), while acknowledging the paucity of studies of smaller dams. There is thus a pressing need to understand the cumulative ecohydrological impacts of diversion hydropower development and to learn how these kinds of dams might be better managed to reduce those impacts.

Artificial reservoirs create barriers to the longitudinal connectivity of a river, changing the hydrological regime and inducing physical, chemical, and biological changes in the impounded water that can extend well downstream from the reservoir (Ward & Stanford, 1995; Poff et al., 1997). Alterations in water quality may reflect changes in sedimentation processes of particles and nutrients, heat budgets, biogeochemical transformations, and thermal and chemical stratification within the reservoir (Friedl & Wüest, 2002). River impoundment has become so ubiquitous that it has substantially altered global fluxes of sediments and nutrients from continents to oceans (Vörösmarty et al., 2003; Seitzinger et al., 2005, 2010).

Creation of a reservoir along a river often changes the river's natural thermal regime, which in turn can affect other processes (Olden & Naiman, 2010), although these changes may be more marked and have more serious implications in non-tropical climates (e.g., for salmonid fish habitat). Deeper reservoirs may develop persistent thermal stratification and consequent oxygen depletion in bottom waters, depending partly on the depths of water release from the dam as well as hydraulic retention time in the reservoir, and this is a particular problem in warmer climates.

Riverine transport of particulate matter and associated nutrients often is reduced by reservoir sedimentation, causing a cascade of downstream impacts such as increased water transparency, reduction in availability of nutrients, and geomorphological changes in channels and floodplains (Graf, 2006; Kunz et al., 2011). Sedimentation of inorganic and organic matter typically results in net retention of phosphorus (Kennedy & Walker, 1990; Fonseca et al., 2011), while for nitrogen, net retention (or removal) has also been attributed to biological assimilation and/or denitrification. The formation of a reservoir tends to produce favorable conditions for denitrification including greater sediment–water contact, anoxic bottom waters, and high inputs of organic matter from upriver as well as in situ production (Abe et al., 2003).

The magnitude of downstream water quality impacts of reservoirs is influenced by the hydraulic retention time (HRT), which influences the duration of stratification and the rate of particle retention. Reservoirs with smaller HRTs generally have weaker stratification (Henry, 1999; Soares et al., 2008), and they retain less sediment and nutrients (Straškraba et al., 1995; Straškraba, 1999; Seitzinger et al., 2002; Reid & Hamilton, 2007). Similar effects are also observed where there is a seasonal cycle of HRT, which can be the result of natural hydrological seasonality or the reservoir operator's control (Soares et al., 2008, 2012). The dam operation can cause an increased fluctuation of daily outflows as well as attenuation of seasonal variability, causing significant impacts on downstream hydrology and water quality (Ahearn et al., 2005; Naliato et al., 2009).

Recent research has drawn attention to the potential of modifying operational control measures to minimize downstream effects of dams on both water quantity and quality (Nilson & Renöfält, 2008; Olden & Naiman, 2010; Renöfält et al., 2010). However, most of what is known about impacts of reservoirs on changes in water quality has been obtained from larger reservoirs with dams that are capable of controlling flows (McCartney et al., 2001). Given the ongoing proliferation of smaller hydroelectric facilities, research is needed on the applicability and generalization of such knowledge to reservoirs with little regulation capacity or with run-of-river storage environments (Príncipe, 2010). The limited available studies suggest that even run-of-river reservoirs can cause significant changes to downstream water quality, with implications for aquatic biota (Lessard & Hayes, 2003; Reid & Hamilton, 2007; Mantel et al., 2010).

Downstream impacts caused by reservoirs can be even greater when they are constructed upstream of floodplains (Kingsford, 2000). Reservoirs can have both direct and indirect effects on the ecological structure and function of floodplains, altering flood regimes as well as the sediment and nutrient content of flood waters. Reduced turbidity can favor aquatic primary production (i.e., by algae and submersed aquatic plants) and fishes that depend on visual feeding, and lower nutrient concentrations in flood waters can reduce biological productivity in the system (Roberto et al., 2009). Sedimentation and erosion processes that maintain floodplains in a dynamic successional state can also change due to reservoir capture of suspended sediments (Kondolf, 1997).

In the upland watersheds draining into the Pantanal floodplains, one of the largest wetlands in the world (Junk & Cunha, 2005), reservoir construction and flow diversion for generating hydroelectricity are issues of major environmental concern. There are 43 hydroelectric facilities already in operation, with plans to build another 116 on rivers draining the upland catchments and supplying water to the floodplains. So far, the few studies undertaken in the region have been concerned only with the hydrological changes in the floodplain caused by the filling and operation of a single reservoir (Zeilhofer & Moura, 2009; Fantin-Cruz et al., 2011). There is no information about how downstream hydrology and water quality may be affected in a cumulative manner by widespread dam construction in the region, with potentially negative effects on ecological functions and services in downstream rivers and floodplains.

Here we report one of the first analyses of the water quality impacts of a diversion hydropower facility in a tropical setting. The objectives of the study were (i) to identify how a diversion hydropower reservoir affects river water quality; (ii) to determine whether the observed water quality changes are influenced by hydraulic retention time, which is partly under dam operator control; and (iii) to consider whether changing the reservoir operation could reduce undesirable changes in downstream water quality. Our hypothesis was that building a reservoir would alter water quality, the magnitude of the changes being determined by hydraulic retention time, which in turn can be managed to some degree by changes in the operation of the dam.

Methods

Study area

The study site was the Ponte de Pedra hydropower dam and reservoir on the Correntes River (Fig. 1; 17.60031°S, 54.81978°W), which began operation in July 2005. At present, there is just one other small dam, known as PCH Sta Gabriela, in operation on the Correntes River. That dam is about 50 km upriver from the Ponte de Pedra dam and the area of its reservoir is 0.7 km^2 (Souza Filho, 2013).

The Ponte de Pedra reservoir is in the upland plateau above the floodplain boundary and straddles the border between the Brazilian states of Mato Grosso and Mato Grosso do Sul, situated in a predominantly agricultural basin draining 3898 km^2. The reservoir's surface area is 14.5 km^2; its total volume is 111×10^6 m^3; its maximum depth is 30 m; its mean depth is 7.6 m; and its maximum effective length (fetch) is 7.5 km. Direct runoff from the watershed into the reservoir is negligible relative to the throughflow of river water because by far most of the reservoir's watershed drains into the river above the reservoir.

The dam diverts water from the reservoir to the turbines through an input channel drawing from the surface layer, returning the water via turbines to the river below an escarpment near the river's point of entry into the Pantanal floodplain, and thereby exploits the difference in elevation of 243 m between the floodplain and the mean reservoir surface. The reservoir has two areas of capture (Fig. 1): (Inset a) the diversion to the input channel with surface capture, carrying water to the turbines, and (Inset b) the dam off-take with sub-surface capture (depth 7.0 m) which

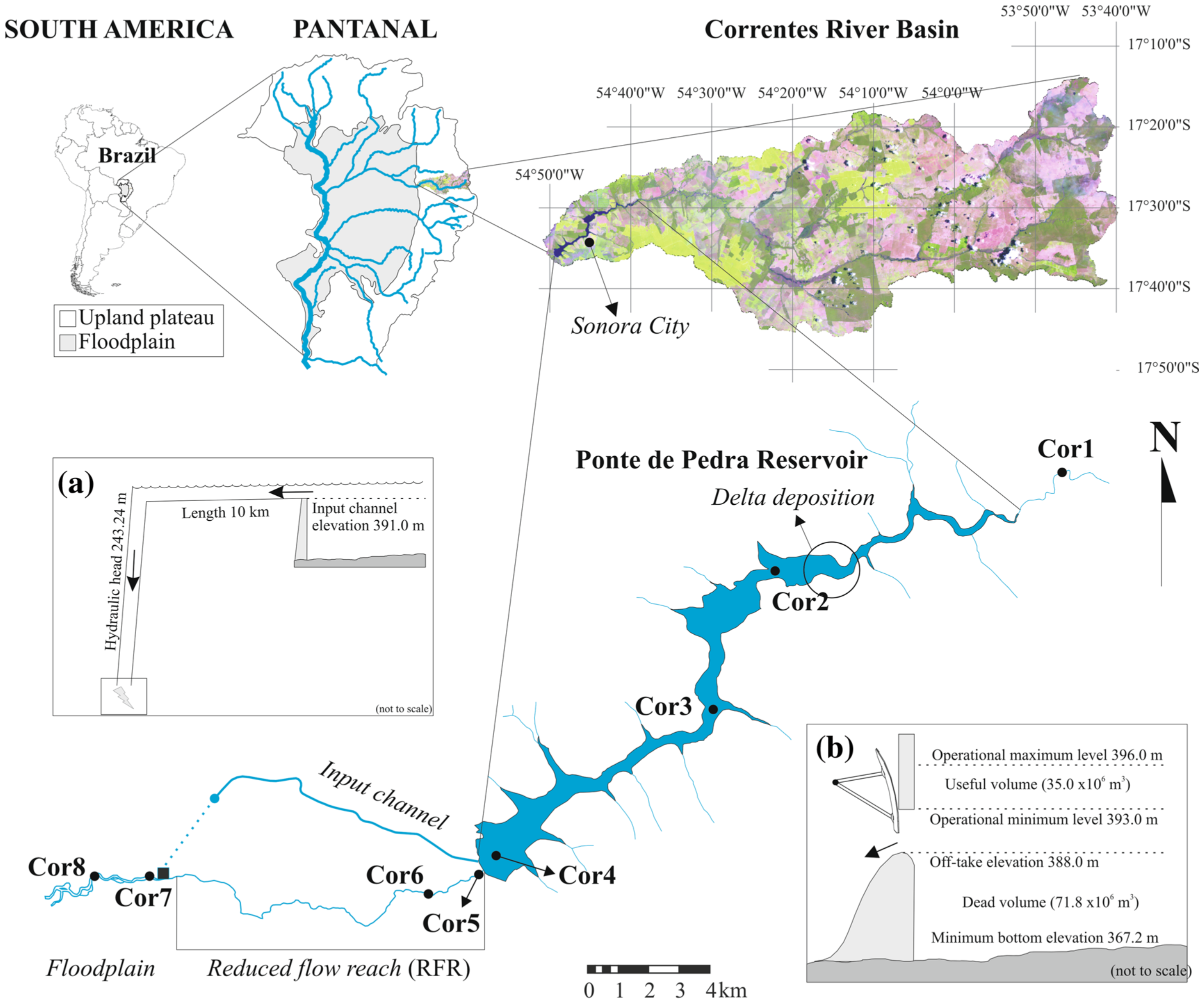


Fig. 1 Location and configuration of the Ponte de Pedra dam, its reservoir, and its drainage basin. Insets show schematic representations of **a** the input channel and **b** the dam and its off-take, respectively. Sampling points are also shown

delivers water to the original river reach where flow is reduced (reduced flow reach, RFR). In the RFR, a minimum flow of 10 $m^3 s^{-1}$ (~14% of mean annual flow: Gonçalves et al., 2011) is maintained by the off-take. Figure 1 also shows the location and vertical position of the reservoir input channel as well as the off-take from the dam to maintain flow in the original river channel.

Despite having control gates for flow regulation, dam operations produced only modest changes in reservoir water levels (usually within a 2-m range, and always <3 m based on observations between July 2005 and September 2011). Our previous research examined the downstream hydrological alterations produced by the reservoir and the operation of the dam (Fantin-Cruz et al., 2015b), identifying significant but modest effects on the maximum flow of 90 days and the frequencies of high and low flow pulses.

The regional climate is wet-dry tropical with Köppen classification Aw; mean annual temperature is 25.0°C, varying from 22.3 (July) to 27.1°C (October) (Fig. 2a). Average annual rainfall is 1419 mm $year^{-1}$, of which 47% falls in summer (maximum in January, 232 mm) with only 2% in winter (minimum in June, 3 mm), thus showing a marked seasonality in climate (Fig. 2b). The natural vegetation is savanna but at present most of the upland basin above the dam is used for soybean agriculture. The floodplain portion of the basin is used mainly for low intensity cattle ranching.

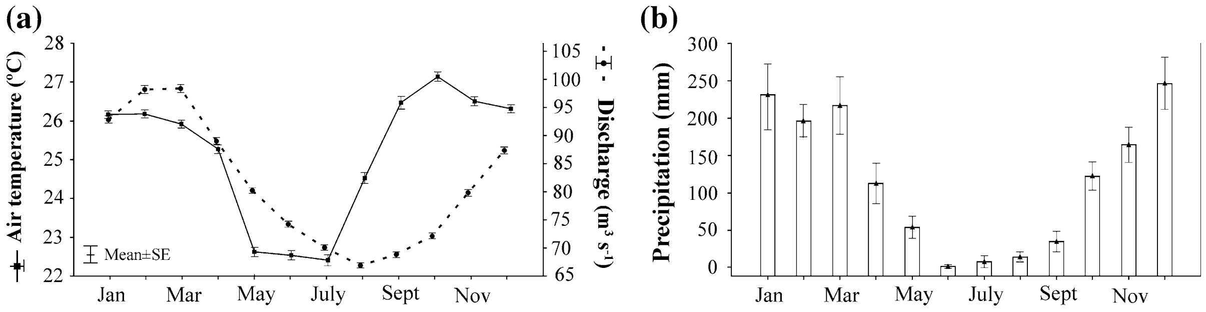


Fig. 2 **a** Monthly mean monthly air temperature, 2005–2011 (Site 31951; *Source* Sinda) and mean annual flow, 1970–2011 (Gauge site 01654000; *Source* Hidroweb/ANA). **b** Monthly rainfall. Air temperature and rainfall were measured at Coxim, located 96 km south of the Ponte de Pedra dam, from 2005 to 2011

Mean annual discharge in the Correntes River at Sonora is 73 $m^3\ s^{-1}$, or 3.6% of mean annual inflow of all tributaries entering the Pantanal (Gonçalves et al., 2011). Its monthly variation is similar to that of rainfall (Fig. 2b), with maxima in February–March (98 $m^3\ s^{-1}$) and minima in August (67 $m^3\ s^{-1}$). The operation of the hydroelectric facility is capable of altering the discharge through the reservoir by no more than about 9%.

A previous analysis of the limnology of the reservoir reported by Fantin-Cruz et al. (2015a) showed, based on vertical profiles of water quality, that the "dead volume" below the elevation of the off-take can become isolated by thermal stratification and diverge from surface waters in certain chemical variables. Dissolved oxygen concentrations became reduced in the deeper water during stratification but did not reach anoxia in any of the four sampling dates.

Data collection and analysis

Samples of water from were collected in the Correntes River from just beneath the surface (0.1 m) in the central part of the channel at 8 sites before and after the reservoir was built (Fig. 1). The upper 6 sites lie in the upland part of the basin (known as the *planalto* or plateau) and the lower 2 sites are within the floodplain reach (Fig. 1). Site Cor1 was the Correntes River channel upstream of the reservoir's backflooded area and served as the upstream reference site; sites Cor2, Cor3, and Cor4 were within the reservoir; Cor5 and Cor6 were in the reduced flow reach (RFR) downstream of the dam but above the return flow from the hydroelectric facility. Sites Cor7 and Cor8 were in the river downstream from the return of the diverted flow. Samples were collected at approximately three-month intervals between 2002 and 2011, 15 of the sampling dates being before reservoir construction (May 2002 to May 2005) and 26 afterward (November 2005 to September 2011).

Water quality variables included (i) water temperature and dissolved oxygen concentration, measured with a WTW oxygen meter in the field, and (ii) pH (Hach meter), electrical conductivity (APHA method 2520 B), turbidity (Hach meter), total phosphorus (TP; ABNT method NBR 12772), orthophosphate (PO_4^{3-}; APHA method 4500 E), nitrate (NO_3^-; ABNT method NBR 12620), ammonium (NH_4^+; APHA method 4500 NH3F), and total solids (dissolved plus suspended; APHA method 2540 A-D), all measured in the laboratory following preservation and standard analytical practices recommended in *Companhia de Tecnologia de Saneamento Ambiental* (CETESB, 1998), *Associação Brasileira de Normas Técnicas* (ABNT, 992a, b), and *Standard Methods for the Examination of Water and Wastewater* (APHA, 2005). Samples were refrigerated in polyethylene bottles, or in amber glass bottles acidified to pH <2 with sulfuric acid in the case of ammonium. For variables with values below the method detection limit, which occurred only three times for orthophosphate, the detection limit was recorded.

Daily hydraulic retention time (HRT) was estimated from the ratio between mean daily reservoir volume V (obtained from a volume vs. depth curve provided by the dam operator) and total outflow for the day Q:

$$\mathrm{HRT}_{(\mathrm{day})} = \frac{V_{(\mathrm{m}^3)}}{Q_{(\mathrm{m}^3\,\mathrm{day}^{-1})}}.$$

The HRT non-exceedance probability distribution was determined from the daily values of hydraulic retention time between July 2005 and September 2011. This curve gives the percentage of total time for which a given HRT was equaled or surpassed during the observation period. A hypothetical HRT distribution was also constructed by simulating a run-of-river operational management system, i.e., without flow regulation. For this, the operational minimum level in the reservoir (393.0 m) was fixed, and all the daily inflow was assumed to be released downstream directly or through the turbines.

Data were interpreted as concentrations rather than fluxes because we did not observe predictable relationships between concentrations and discharge, and discharge was variable between sampling dates, precluding estimation of daily mass balances. Since the discharge varied relatively little over the study transect (i.e., the hydroelectric facility was close to being a run-of-river operation and the reservoir had little gain or loss of water), consistent changes in concentrations should reflect changes in fluxes. Measurements for each variable were standardized relative to the value measured at the Cor1 reference site, upriver of the influence of the reservoir, and compared by sampling date. Variables were standardized as follows:

- for $\mathrm{Cor}_{(1)} < \mathrm{Cor}_{(i)}$

$$P_{\mathrm{Cor}(i)}\% = +\left(1 - \left(\frac{\mathrm{Cor}(1)}{\mathrm{Cor}(i)}\right)\right) \times 100$$

- for $\mathrm{Cor}_{(1)} > \mathrm{Cor}_{(i)}$

$$P_{\mathrm{Cor}(i)}\% = -\left(1 - \left(\frac{\mathrm{Cor}(i)}{\mathrm{Cor}(1)}\right)\right) \times 100,$$

where $P_{\mathrm{Cor}(i)}$ is the percentage variation relative to reference site at sampling site i; $\mathrm{Cor}_{(i)}$ is the value at the site i, and $\mathrm{Cor}_{(1)}$ is the value at the reference site. This variation can be positive or negative, according to whether the variable is larger or smaller than its value at the reference site.

To evaluate the effects of constructing the reservoir and operating the dam on each water quality variable, we used Analysis of Variance (ANOVA) with blocking in which the pre- and post-reservoir periods were regarded as treatments, and each sampling site as a block. This method of analysis controls for possible environmental changes that might be related to a pre-existing longitudinal gradient in the river.

After identifying which water quality variables were significantly altered by reservoir installation, those variables were then analyzed to show whether there were longitudinal differences (between sampling sites) after the reservoir was built using a one-way ANOVA in which the treatments were the sampling sites (Cor2 to Cor8). Where significant differences were found, an a posteriori Tukey test was used; only significant results are presented here.

The influence of HRT on the observed changes in water quality was also evaluated, using linear regression. This analysis used the mean of the sampling sites as being representative of each sampling date (except Cor1). The lag in response time between a change in daily HRT and the change in variable values was analyzed using the cross correlations of the lagged series (HRT_{t-1}; HRT_{t-2}; HRT_{t-3}…), until the best fit was found.

For variables significantly affected by HRT, the equation of the best-fit line was used to define the HRT values for which the water quality within and below the reservoir remained within the limits of natural variability. These limits were defined as the 10th and 90th percentiles of the pre-reservoir observations, again using the mean of all sampling sites. All analyses used the Software R, version 2.11.1 (R Development Core Team, 2011).

Results

Characterization of water quality

Water quality in the Correntes River before construction of the Ponte de Pedra reservoir was characterized by a mean temperature of 25.6°C, high dissolved oxygen (7.6 mg l^{-1}), slight acidity (pH 6.14) and low electrical conductivity (3.8 µS cm^{-1}), turbidity (11 NTU), and total solids (60 mg l^{-1}). Mean nutrient concentrations were moderate for total phosphorus (0.156 mg l^{-1}), although they were low for the more readily assimilable inorganic nutrients: orthophosphate (0.015 mg l^{-1}), nitrate (0.050 mg N l^{-1}), and ammonium (0.017 mg N l^{-1}). After reservoir construction, the mean values for most variables changed

Table 1 Water quality variables in the Correntes River, before and after construction of the Ponte de Pedra reservoir (mean ± standard deviation for sites Cor2–Cor8)

Variables	Pre-reservoir	Post-reservoir
Water temperature (°C)	25.6 (±0.7)	25.9 (±0.7)
Dissolved oxygen (mg l^{-1})	7.6 (±0.4)	7.0 (±0.6)
Electric conductivity (μS cm^{-1})	3.8 (±0.7)	3.2 (±0.7)
pH	6.14 (±0.21)	6.13 (±0.12)
Turbidity (NTU)	11 (±7)	6 (±2)
Total solids (mg l^{-1})	60 (±36)	46 (±13)
Nitrate (mg N l^{-1})	0.050 (±0.027)	0.042 (±0.011)
Ammonium (mg N l^{-1})	0.017 (±0.011)	0.022 (±0.007)
Total phosphorus (mg l^{-1})	0.156 (±0.096)	0.055 (±0.030)
Orthophosphate (mg l^{-1})	0.015 (±0.003)	0.018 (±0.010)

little (Table 1), except that turbidity (6 NTU), total solids (46 mg l^{-1}), and total phosphorus (0.055 mg l^{-1}) decreased, and ammonium increased (0.022 mg l^{-1}). Little algal growth occurred in the water column of the reservoir; chlorophyll-a concentrations usually remained <3 μg l^{-1} (Fantin-Cruz, unpublished data). The changes in water quality variables are analyzed further below.

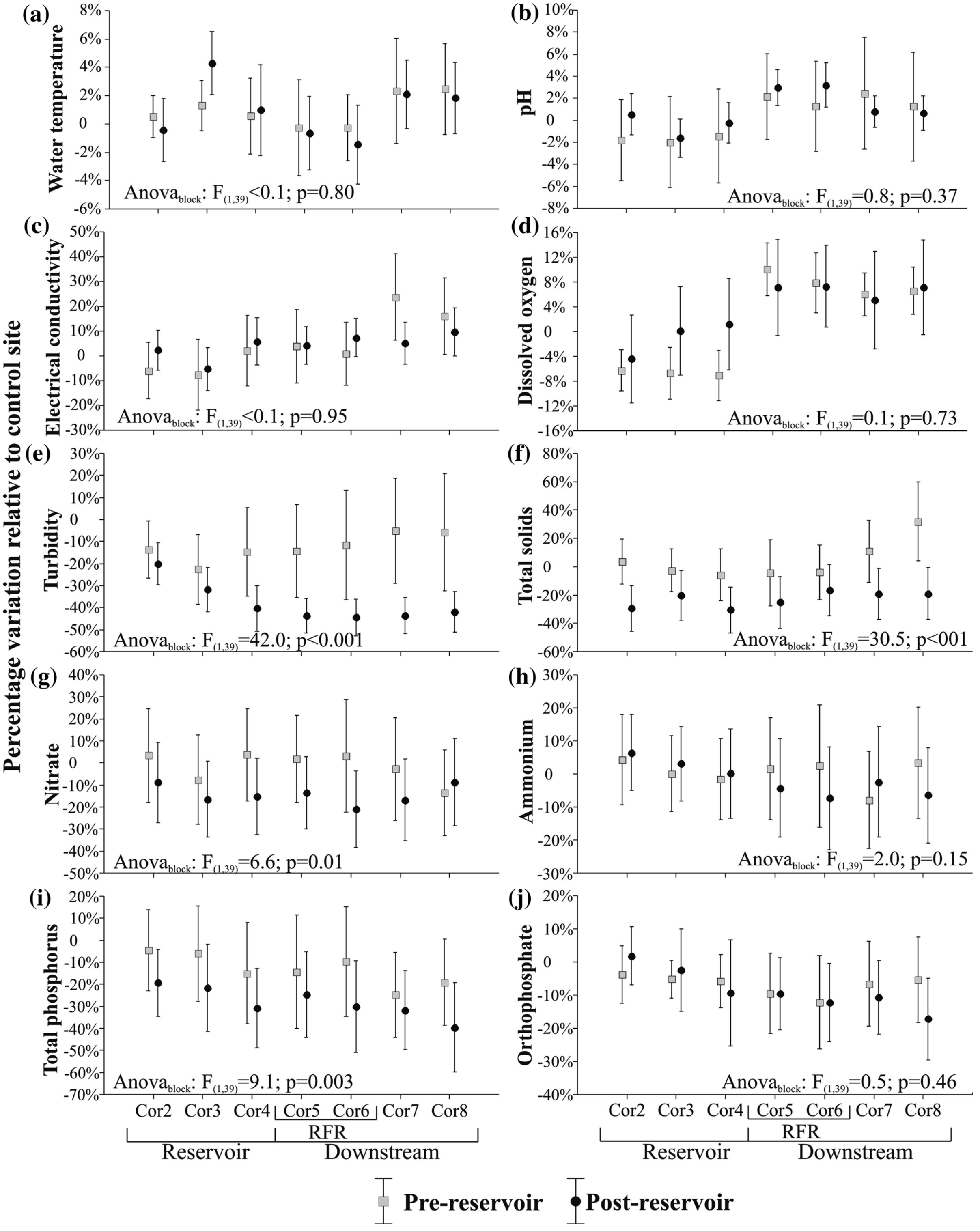
Range of natural variation among the sampling sites

Natural variability in water quality along the longitudinal gradient of the Correntes River prior to impoundment showed differences relative to the reference site for which four classes of variation were defined: (1) the class including water temperature and pH with variation between −2 and +2% (Fig. 3a, b); (2) the class including electrical conductivity (Fig. 3c) and total solids (Fig. 3f) in which variation was small in the upper part of the river (−8 to +4.0%), but larger in its lower part (+11 to +32%); (3) the class including turbidity and total phosphorus with variation between −4 and −25% (Fig. 3e, i); and (4) the class including oxygen, nitrate, ammonium, and orthophosphate with variation between −13 and 10% (Fig. 3d, g, h, e, j).

Effects of the reservoir

After the reservoir was filled, four water quality variables were significantly reduced relative to the reference site: turbidity (ANOVA $F = 42.0$, $P < 0.001$), total solids ($F = 30.5$; $P < 0.001$), nitrate ($F = 6.6$; $P = 0.01$), and total phosphorus ($F = 9.1$; $P = 0.003$). After reservoir construction, longitudinal variation in turbidity showed mean variation between −20 and −44% (Fig. 3e), total solids between −19 and −30% (Fig. 3f), nitrate between −9 and −21% (Fig. 3g), and total phosphorus −19 and −39% (Fig. 3i) relative to the reference site. Of these variables, only turbidity showed significant differences between sampling sites within the reservoir ($F_{6:175} = 4.1$; $P = 0.001$; non-significant differences are not given), and the site Cor2 was the only site with variation significantly lower than the others (Tukey, $P < 0.05$). Thus, the reductions in turbidity, total solids, nitrate, and total phosphorus resulting from the reservoir were maintained downstream from it, including the reach where flow was reduced.

The mean magnitudes of the observed changes post-reservoir construction were −38% for turbidity, −28% for total phosphorus, −23% for total solids, and −14% for nitrate. Cross-correlation analysis showed that the best correlation between the hydraulic retention time HRT and these four variables occurred with a time lag of 16 days (i.e., change in the limnological variables tended to occur 16 days later than changes in HRT). However, although the lag time was equal for the four variables, only turbidity and nitrate showed any significant influence of HRT brought about by reservoir operation (Fig. 4a, e, c). Furthermore, it was found that the changes were not always negative, since total solids and nitrate showed increases relative to the reference site on six sampling dates (23%), total phosphorus on two, and turbidity on only one (Fig. 4). Thus, for most of the time, but not always, the reservoir caused reductions in these variables relative to the reference site.


Percentage variation relative to control site
(a)
Water temperature
8%
6%
4%
2%
0
-2%
-4%
-6%
Anova_block: F(1,39)<0.1; p=0.80
(b)
pH
10%
8%
6%
4%
2%
0
-2%
-4%
-6%
-8%
Anova_block: F(1,39)=0.8; p=0.37
(c)
Electrical conductivity
50%
40%
30%
20%
10%
0
-10%
-20%
-30%
Anova_block: F(1,39)<0.1; p=0.95
(d)
Dissolved oxygen
16%
12%
8%
4%
0
-4%
-8%
-12%
-16%
Anova_block: F(1,39)=0.1; p=0.73
(e)
Turbidity
30%
20%
10%
0
-10%
-20%
-30%
-40%
-50%
-60%
Anova_block: F(1,39)=42.0; p<0.001
(f)
Total solids
80%
60%
40%
20%
0
-20%
-40%
-60%
Anova_block: F(1,39)=30.5; p<001
(g)
Nitrate
40%
30%
20%
10%
0
-10%
-20%
-30%
-40%
-50%
Anova_block: F(1,39)=6.6; p=0.01
(h)
Ammonium
30%
20%
10%
0
-10%
-20%
-30%
Anova_block: F(1,39)=2.0; p=0.15
(i)
Total phosphorus
20%
10%
0
-10%
-20%
-30%
-40%
-50%
-60%
-70%
Anova_block: F(1,39)=9.1; p=0.003
(j)
Orthophosphate
20%
10%
0
-10%
-20%
-30%
-40%
Anova_block: F(1,39)=0.5; p=0.46
Cor2
Cor3
Cor4
Cor5
Cor6
Cor7
Cor8
RFR
Reservoir
Downstream
Cor2
Cor3
Cor4
Cor5
Cor6
Cor7
Cor8
RFR
Reservoir
Downstream
Pre-reservoir
Post-reservoir

◀ **Fig. 3** Variation in water quality variables along the longitudinal gradient of the Correntes River before and after construction of the Ponte de Pedra reservoir (mean ± standard error of percentage deviation from the reference site on the same sampling dates). Results of the block ANOVA comparing pre- with post-reservoir values are shown. *RFR* reduced flow reach, around which water was diverted to the hydroelectric facility

Based on the model generated by the relations of turbidity and nitrate with HRT (Fig. 4a, c), the HRT range could be estimated for which no large changes in these variables would occur. With the knowledge that turbidity varies between −31 and −6% and nitrate between −19 and 16% (10th and 90th percentiles) under natural conditions, these values were taken as the limits for natural variability. This meant that for the reservoir to operate without changing downstream water quality, the range of HRT should be <13.0 days for turbidity, and between 10.2 and 14.6 days for nitrate. The probability distribution curve for HRT over the 6 years of observations showed that the reservoir operated outside of these HRT ranges for 63% of the time in the case of turbidity, and 43% of the time in the case of nitrate (Fig. 5a). In the hypothetical case in which the reservoir were operated as a fully run-of-river storage, the operation time spent outside these HRT ranges would be less, 3% in the case of turbidity and 40% in the case of nitrate (Fig. 5b).

Discussion

Causes of water quality changes in and below the reservoir

The results show that constructing the Ponte de Pedra reservoir changed four of the ten water quality variables analyzed. These changes are likely related to physical sedimentation of particulate matter (affecting turbidity, total solids, and total phosphorus) as well as to biological uptake (nitrate and possibly total phosphorus). These changes are in agreement with other research showing that reservoirs act as sinks for sediments and nutrients (e.g., Friedl & Wüest, 2002; Ahearn et al., 2005; Harrison et al., 2009; Ismail & Najib, 2011; Kunz et al., 2011), yet most studies have examined reservoirs with longer HRTs (often months or even years), and effects on water quality have rarely been documented for a nearly run-of-river reservoir in a tropical setting.

The observed decrease in nitrate could be attributable to denitrification as well as to biological

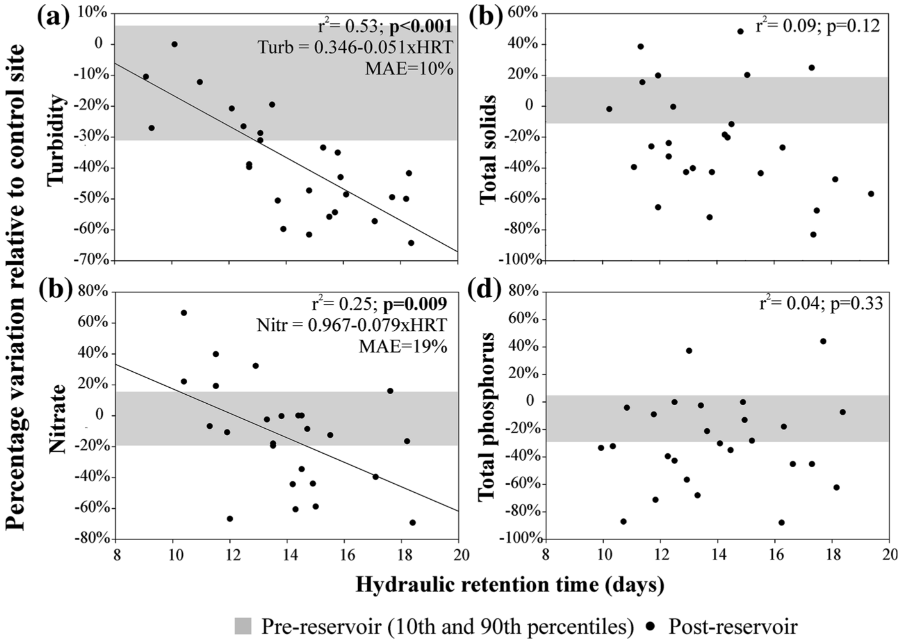


Fig. 4 Relationships between variables that were altered by building the Ponte de Pedra reservoir and managing the volume and thereby the hydraulic retention time of the reservoir. The shaded area shows the observed range of variability (10th to 90th percentiles) before the reservoir was constructed. Linear regression fits are depicted; *HRT* hydraulic retention time, *MAE* mean absolute error

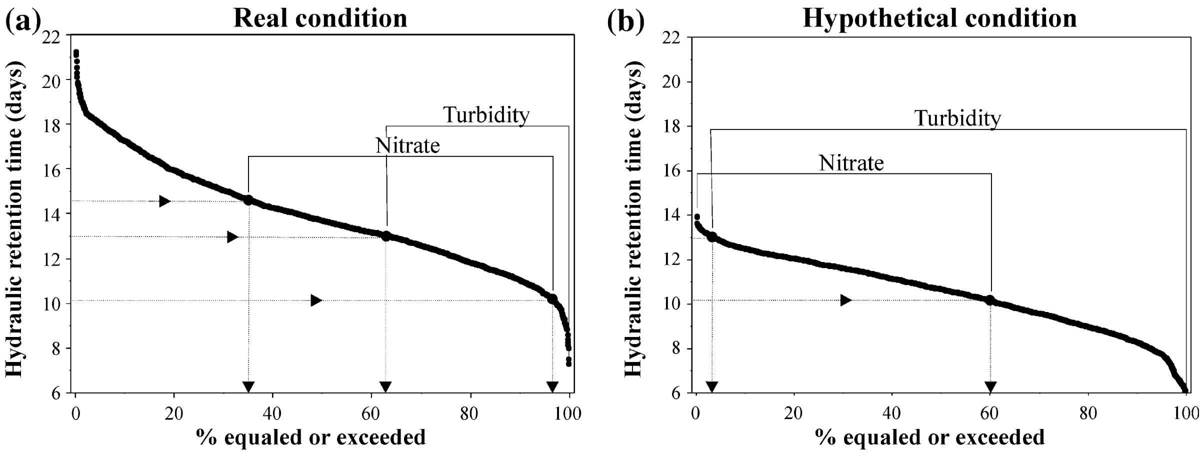


Fig. 5 Probability distribution of hydraulic retention time for operation of the Ponte de Pedra reservoir under **a** real conditions of varying storage and release of water, and **b** hypothetical conditions of full run-of-river operation (i.e., dam off-take gates kept open). The intervals given for turbidity and nitrate show the duration for which the reservoir operation maintained a range of hydraulic retention times that do not alter downstream water quality (particularly turbidity and nitrate) compared with the natural range

assimilation. Fantin-Cruz et al. (2015a) presented vertical profiles in the Ponte de Pedra reservoir showing evidence for reduced nitrate concentrations at intermediate depths, suggesting that nitrate uptake in the shallower waters has more impact on concentrations, even though dissolved oxygen was lower in the deepest waters. Net removal of nitrate as water passes through reservoirs has been demonstrated by other studies in both temperate and tropical climates (e.g., Stanley & Doyle, 2002; Abe et al., 2003; David et al., 2006; Kunz et al., 2011).

The observed retention of total phosphorus likely occurred mainly through sedimentation of particulate forms, since orthophosphate (the dissolved inorganic fraction) did not change significantly. A large proportion of the total phosphorus load entering reservoirs is transported in particulate form, in association with bedload sediment or in suspension (Fonseca et al., 2011), and for this reason its retention in reservoirs typically occurs primarily by sedimentation (Kennedy & Walker, 1990).

The reservoir did not have a significant effect on the other water quality variables (temperature, dissolved oxygen, conductivity, pH, and orthophosphate) except for nitrate. This is probably due to a combination of the hydraulic characteristics of the reservoir (short HRT), surface-water release at the dam, and the low nutrient availability in the river water.

Longitudinal variability

In the case of those variables that showed changes (except for turbidity at the site Cor2), the absence of longitudinal differences across the reservoir sampling sites shows that most changes occur in the reach upstream of the site Cor2, where the flow velocity is first reduced. This assertion is demonstrated *in loco* by a visible delta formed by sediment deposition at the upstream end of the reservoir (Fig. 1). It is there that the main processes occur that act to change water quality, since larger particles are deposited (total phosphorus and total solids), while high biological activity may contribute to nitrate removal (Gruca-Rokosz et al., 2009). In the case of the smaller particles contributing to turbidity, the velocity reduction upstream of Cor2 is not enough to allow them to sediment out and therefore there is little change in turbidity. Thus, although the Ponte de Pedra reservoir has a short mean hydraulic retention time (14 days), close to the 10 days proposed by Straškraba & Tundisi (1999) as the lower threshold for transition from a lotic to a lentic environment, it falls within the reservoir zonation described by Thornton (1990), with formation of a longitudinal gradient across which there are marked reductions in turbidity, suspended solids, and nutrients.

The changes in water quality observed within the reservoir were maintained in the river channel downstream of the dam, showing that the depth range of the off-take does not affect water quality relative to that recorded near the reservoir surface. The off-take depth range determines the water layer to be exported (Kennedy, 1999), and therefore its quality. The fact that water quality is maintained in the RFR can be explained by the homogeneity of the reservoir water down to 8-m depth (therefore extending below the reservoir off-take depth) even during the stratification period (Fantin-Cruz et al., 2015a).

Data on vertical profiles of water quality in the reservoir reported by Fantin-Cruz et al. (2015a) serve to establish what changes would have been caused downstream of the dam, relative to natural conditions, if the Ponte de Pedra dam had deeper (hypolimnetic) withdrawal. Under such circumstances, and assuming that the withdrawal did not change the chemistry of hypolimnetic waters, the significantly altered variables would be water temperature (mean −10%), pH (−4%), electrical conductivity (+35%), dissolved oxygen (−50%), and ammonium (+44%), while the characteristics of turbidity, total solids, nitrate, and total phosphorus would be maintained at levels similar to those for natural conditions (orthophosphate was not analyzed).

The Serial Discontinuity Concept (Ward & Stanford, 1983; Stanford & Ward, 2001), based on data from reservoirs where water is released at depth, has drawn attention to changes in water quality downstream from reservoirs, mainly in oxygen concentration, temperature, and nutrients. As demonstrated here, however, these findings cannot be extrapolated to reservoirs with short HRTs and surface release of water. Also, in terms of the number of affected variables, reservoirs with surface release tend to result in smaller changes of water quality relative to natural conditions observed in the river, as has been shown elsewhere (Viana, 2002; Lessard & Hayes, 2003; Naliato et al., 2009).

One of the main impacts envisaged prior to construction of the reservoir was a change in the natural thermal regime in the Correntes River, since formation of a lake, however small, increases exposure to solar radiation with consequent surface heating, which would be transmitted downstream in the case of reservoirs having surface release (Lessard & Hayes, 2003). However, such downstream heating was not seen in the relatively narrow and deep Ponte de Pedra reservoir (Fig. 3a), so the impacts caused by the reservoir were mostly related to sedimentation.

Effects of reservoir operation

Among the variables changed by the reservoir, only nitrate and turbidity were affected by operational control of the hydraulic retention time (HRT). Turbidity was the variable most sensitive to reservoir operation and with greatest change (−38%), showing that when HRT is longer, there is increased sedimentation rate of fine particles, which stay in suspension for longer (Thornton, 1990). By contrast, total solids and total phosphorus were less affected by changes in HRT, suggesting that changes in concentrations of these variables are governed by larger particles that were readily removed by sedimentation across the range of HRT variation. Moreover, the similarity is noted between the mean changes of total solids (−23%) and total phosphorus (−28%), suggesting an association between these two variables and sedimentation.

On the other hand, the influence of HRT on the magnitude of changes in nitrate could be attributed to the water–sediment contact available for biological assimilation and denitrification (Stanley & Doyle, 2002). The smaller change in nitrate (−14%) relative to the other variables could be attributed to the rate of denitrification, which can be less important compared with sedimentation (Burford et al., 2012), but requires special conditions (hypoxia and availability of nitrate). Similarly, in a reservoir in the Midwest USA, David et al. (2006) also reported a strong correlation between rate of nitrate removal and HRT, showing that the increase in HRT resulted in higher rates of denitrification. Even though that reservoir is located in a temperate climate and its primary function is to control floods, and even though it is three times larger than the Ponte de Pedra reservoir, both appear to function similarly regarding nitrate retention. Taking the equation proposed by David et al. (2006) relating nitrate retention rate and HRT, for a HRT of 14 days, the equation yields a nitrate retention rate of 18% in the Midwest reservoir, which is quite similar to the nitrate retention rate of 14%, and we have estimated for the Ponte de Pedra reservoir at that HRT. This therefore suggests that the efficiency of denitrification as a nitrate sink in the Ponte de Pedra reservoir was controlled by HRT.

Studies over a wide geographical distribution have shown how lakes and reservoirs function as sinks for nitrogen and phosphorus, and that their rate of nutrient retention is positively related to hydraulic retention time (Straškraba et al., 1995; Seitzinger et al., 2002; Reid & Hamilton, 2007; Harrison et al., 2009; Kõiv et al., 2011). Global empirical models that use HRT and mean depth to estimate rates of retention of total phosphorus (Straškraba et al., 1995) and nitrate (Seitzinger et al., 2002), although developed largely in temperate regions, provide good estimates of mean rates of retention in the tropical Ponte de Pedra reservoir. For example, knowing that the Ponte de Pedra reservoir has a mean HRT of 14 days and a mean depth of 6.65 m, the models predict rates of retention of 25% for phosphorus and 13% for nitrogen, values similar to those observed in the reservoir (28% for phosphorus and 14% for nitrate). However, none of the models was able to predict accurately the time variation in these variables, although this was not unexpected because they were developed to estimate mean retention rates.

For most of the time, the Ponte de Pedra reservoir functions as a sink for phosphorus, while reducing turbidity. However, there were times when the reservoir acted as a net exporter of nitrogen and total solids (i.e., output concentrations were higher than input concentrations). Net nitrate production tends to happen when HRT is short, suggesting a modification in nutrient cycling. It is likely that the increase in velocity of flow through the reservoir caused greater mixing in the water column, potentially producing conditions favorable for nitrification because of the high availability of ammonium that accumulates in hypolimnetic waters during periods of stratification (Fantin-Cruz et al., 2015a). This alternation between retention or export of solids and nutrients has also been seen in other reservoirs, and has been attributed to various factors including large floods or dry periods (Garnier et al., 1999; Ahearn et al., 2005), input load variation (Harrison et al., 2009), or sediment re-suspension induced by wind action (Ismail & Najib, 2011).

The control of HRT by the dam operator determines the magnitude of changes in turbidity and nitrate. At the lower end of the range of HRTs, however, the reservoir stops retaining nutrients and sediment and exports them instead. This is very clear in the case of nitrate (Fig. 4c), which shows an optimum HRT range within which this variable varies within the range it would under natural conditions. The effect of the way in which the reservoir was operated shows up most clearly in the case of turbidity (solids and total phosphorus are not affected by HRT), when it is noted that the reservoir HRT over the study period produced effects similar to natural conditions for only 3% of the time. This serves as a reminder that one of the simplest ways to re-establish the ecological integrity of regulated rivers is to adjust flow releases so that they are closer to those occurring naturally (Nilsson, 1996). The hypothetical adoption of this measure would therefore make a substantial improvement to the reservoir's impact on turbidity, which would then stay within natural limits for 97% of the time, although there would be no benefit for nitrate.

Ecological implications for downstream floodplains

This study has clearly shown that the Ponte de Pedra reservoir operation changed the downstream transport of total solids, nitrate, and total phosphorus by the Correntes River to the Pantanal. Retention of solids and nutrients is a common characteristic of reservoirs, and can lead to impoverishment of downstream rivers and floodplains with consequent changes in primary and secondary production. Depending on the off-take depth, reservoirs with longer HRTs and higher nutrient availability can release high concentrations of phytoplankton that subsidize downstream food webs, but at Ponte de Pedra we observed low concentrations of phytoplankton, presumably because of nutrient limitation.

The variable most altered by building the reservoir was turbidity, a key ecological variable that determines the underwater light availability for plant and animal life (Wetzel, 2001). Reduced turbidity can result in marked changes in the aquatic biota, promoting the growth of submersed vegetation, and affecting the composition and dynamics of planktonic communities in the Pantanal (Loverde-Oliveira et al., 2009; Fantin-Cruz et al., 2010). Lower turbidity can also favor fish species that are visually oriented predators (Rodriguez & Lewis, 1997), which are found in the waters of the region (Machado, 2009). Furthermore, it can favor the spread of non-native species such as the Amazonian tucunaré (*Cichla* spp.), a large and aggressive visual-feeding carnivore that preys upon and competes with native species, disrupting fish communities and producing cascading effects on aquatic food webs (Harris et al., 2005).

With regard to nutrients, the main concern is oligotrophication of the floodplain. In the longer term, the nutrient retention could reduce floodplain fertility, since during floods the Correntes River is a source of particulate phosphorus to the floodplain. This impact has already been observed in the floodplain of the Paraná River in Brazil, where the Porto Primavera reservoir retains on average 70% of total phosphorus entering via the river (Roberto et al., 2009).

Conclusions

Observations of river and reservoir water quality before and after construction of the Ponte de Pedra reservoir demonstrate how it has affected downstream water quality in the Correntes River, one of the rivers supplying flood waters to the Pantanal floodplains. The reservoir significantly reduced turbidity, total suspended solids, total phosphorus, and nitrate. These effects were attributed to increased sedimentation and to the creation of conditions more favorable to nitrate uptake, likely including denitrification as well as assimilation. The main changes in water quality occurred in the upstream end of the reservoir, except in the case of turbidity, which showed a more gradual reduction as water flowed across the reservoir. The water quality of the sub-surface water withdrawal at the dam was comparable to that measured at the reservoir's surface because the water is withdrawn from the upper mixed layer.

The variable showing greatest average change following the reservoir's construction was turbidity (−38%), followed by total phosphorus (−28%), total suspended solids (−23%), and nitrate (−14%). However, only turbidity and nitrate were affected by the dam operator's control of reservoir HRT. Also, based on models derived from these relationships, it was estimated that the reservoir produced changes in water quality outside of the natural range (as observed at an upstream reference site) for 63 and 43% of the time in the case of turbidity and nitrate, respectively. In a hypothetical condition assuming fully run-of-river operation, an improvement was found only for turbidity, which would be outside its natural limits for 3% of the time, while other variables would be unaffected. Thus, modifying the dam's operation regime may not bring improvements in water quality great enough to justify their adoption unless turbidity was the primary concern.

Overall, the observed changes in water quality caused by the reservoir were not large, the main effect being the retention of total phosphorus, which could, in the long term, reduce biological productivity in the floodplain, with consequent implications for the system's ecological functioning. It is important to note, however, that the long-term impacts of reductions in sediment bedload by trapping in the reservoir (Carvalho et al. 2000)—a phenomenon that was not measured in this study—could include significant changes in river channel and floodplain geomorphology in downriver reaches. Ecological consequences of such changes are unknown in this system but the important role of sedimentation/erosion dynamics has been demonstrated in other parts of the Pantanal (Hamilton et al., 1998) and in many other river systems worldwide. Addition of sediment flushing features to dam designs could lessen the impact of sediment retention, although the episodic timing of flushing events may create problems downstream. Also important to consider is the cumulative impact of a series of these kinds of impoundments in a river network, which would depend on their spatial configuration with respect to watershed sources of sediments and nutrients. These naturally oligotrophic rivers may be particularly sensitive to nutrient impoverishment.

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