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Further Development of Small Hydropower Facilities Will Significantly Reduce Sediment Transport to the Pantanal Wetland of Brazil

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Small hydropower (SHP) facilities, which are defined by installed capacities <10–50 MW, are increasingly being built around the world. SHPs are viewed as less environmentally harmful than larger dams, although there has been little research to support that assertion. Numerous SHPs have been built, and many more are in development or proposed, in rivers that drain into the Pantanal, a world-renowned floodplain wetland. Three river systems with the largest contributions of sediments to the Pantanal—the Cuiabá, upper Taquari, and Coxim rivers—remain largely undammed. The upland tributaries transport sediments into the Pantanal, thereby affecting geomorphological dynamics and biological productivity of downstream floodplains. This study presents measurements from upstream and downstream of current hydropower facilities, most of which are SHPs, throughout the upland watersheds of the Upper Paraguay River basin to reveal how these facilities may affect the transport of suspended sediments and of bedload sediments. In addition, a predictive model using artificial neural networks (ANNs) estimates the impact of building 80 future SHPs on sediment transport based on observations at current facilities as well as the spatial distribution of future facilities. More than half of current facilities retained suspended sediments: 14 of the 29 facilities showed >20% net retention of suspended sediments, two others retained between 10 and 20%, seven were within 10%, and six showed >10% net release. Bedload sediment transport was a small component of total sediment transport in rivers with high total sediment loads. Multiyear series of satellite images confirm sediment accumulation in several cases. Model predictions of the impacts of future hydropower facilities on suspended sediment concentrations and transport show retention of a large fraction (often much >20%) of sediment inputs. Summing riverine transport rates for inflows into the Pantanal indicates that currently envisioned future hydropower development

would reduce the suspended sediment transport by ∼62% from the current rate. This study shows that if SHPs are built on sediment-rich rivers, this may prove problematic for the facilities as well as for downstream ecosystems. These results support recommendations that several river systems presently lacking dams in their lower reaches should be excluded from future hydropower development to maintain the sediment supply to the Pantanal.

Keywords: hydroelectricity, dams, tropical, sediments, bedload

INTRODUCTION

One of the most important effects of the construction of dams on rivers is the retention (trapping) of sediment (Syvitski et al., 2005). Conventional storage dams with reservoirs that are large relative to the river channel (i.e., high reservoir capacity to inflow ratios) often have sediment trapping efficiencies exceeding 90% when newly constructed (e.g., Kondolf et al., 2014b), though the efficiency may decline over time if sediment infilling reduces reservoir capacity. As reservoir capacity decreases relative to inflow discharge, sediment trapping will decline and ultimately reach a point where it is negligible because flow and turbulence maintain sediment transport through the reservoir. Toward that end of the continuum, the design of the hydropower facility, the particle size distribution of transported sediments, and the seasonal patterns of discharge and sediment transport become important variables, although relatively few studies have considered the effects of smaller dams on sediment transport (Csiki and Rhoads, 2010).

The possible retention of sediments by small hydropower (SHP) facilities is important to understand because most hydroelectric dams being built around the world today are SHPs. Given their small size, they would seem to be less environmentally harmful than larger dams, but the effects of modern SHP designs on riverine transport of sediments have seldom been investigated, and almost no research exists outside of developed regions in the North America and Europe (Mbaka and Mwaniki, 2015; Couto and Olden, 2018). Despite the paucity of information, many countries have enacted policies that promote SHPs, including minimal environmental review. Where multiple SHPs are or will be located in series along river systems, their cumulative effects on sediment transport to downstream ecosystems deserve attention (Kibler and Tullos, 2013; Athayde et al., 2019).

The Amazon, Paraná, and Paraguay river watersheds of South America have a large number of existing and proposed SHPs (Couto and Olden, 2018), including in the watershed of the Upper Paraguay River basin in Brazil that drains to the Pantanal floodplains (**Figure 1A**). The Pantanal, which is internationally recognized as a globally important wetland ecosystem, is a 140,000-km^2 complex of coalesced alluvial fans, much of which is subject to seasonal inundation by riverine overflow that commonly lasts for months (Hamilton et al., 1996). The upland tributaries transport sediments into the Pantanal, which affect the geomorphological dynamics of channel and floodplain features, aquatic-terrestrial connectivity, and soil fertility of downstream floodplains. Floodplain lands subject to inundation by sediment-rich river water tend to be more productive (Hamilton, 2002; Junk et al., 2011), and sediment-rich rivers maintain dynamic changes in channel and floodplain geomorphology, which in turn increase floodplain ecosystem diversity (e.g., the Taquari River fan in the Pantanal: Jongman, 2005). In addition to impacts on the transport of sediments and associated nutrients, many species of migratory fishes important to fisheries in the region ascend the upland tributaries to spawn and dams present migration barriers (Campos et al., 2020).

In the Pantanal watershed, as of 2018 there were 47 hydropower facilities in operation (hereafter "current hydropower facilities"), all but four of which are SHPs, with an additional 138 projects under construction, planned, proposed, or identified by the government as prospective sites (hereafter "future hydropower facilities") [Agência Nacional de Águas [ANA], 2018; **Figure 1A**]. Many of the current and future projects are closely situated along river reaches, creating "cascades" where one project begins a short distance below the end of an upstream one.

In light of the ongoing construction and planning of future SHPs in the Pantanal watershed, there is an urgent need to understand how numerous SHPs on the tributaries may, in aggregate, alter the transport of sediments and nutrients from the uplands into the Pantanal. In recognition of these needs, the present study is part of a multidisciplinary research program that has examined many dimensions of the issues surrounding hydroelectric facilities in the tributaries of the Pantanal, including hydrology (Collischonn et al., 2019; Figueiredo et al., in review), sediment transport (this study), nutrient transport (Oliveira et al., in press), and fish and fisheries. Here we present measurements from above and below a number of current hydropower facilities throughout the Pantanal watershed to reveal how these facilities may trap sediments and thereby affect downstream sediment transport to the Pantanal. In addition, we develop a predictive model using artificial neural networks (ANNs) to estimate the impact of future hydropower development on sediment transport into the Pantanal, based on observations at current facilities as well as the distribution of future facilities. A companion paper in this journal (Oliveira et al., in press) presents a complementary examination of how SHPs affect nutrient transport to the Pantanal, including particulate forms associated with sediment transport; the two studies are parts of the same project but are presented separately because of their distinct methodologies and the different ecosystem implications of changes in sediment and nutrient transport. We conclude both

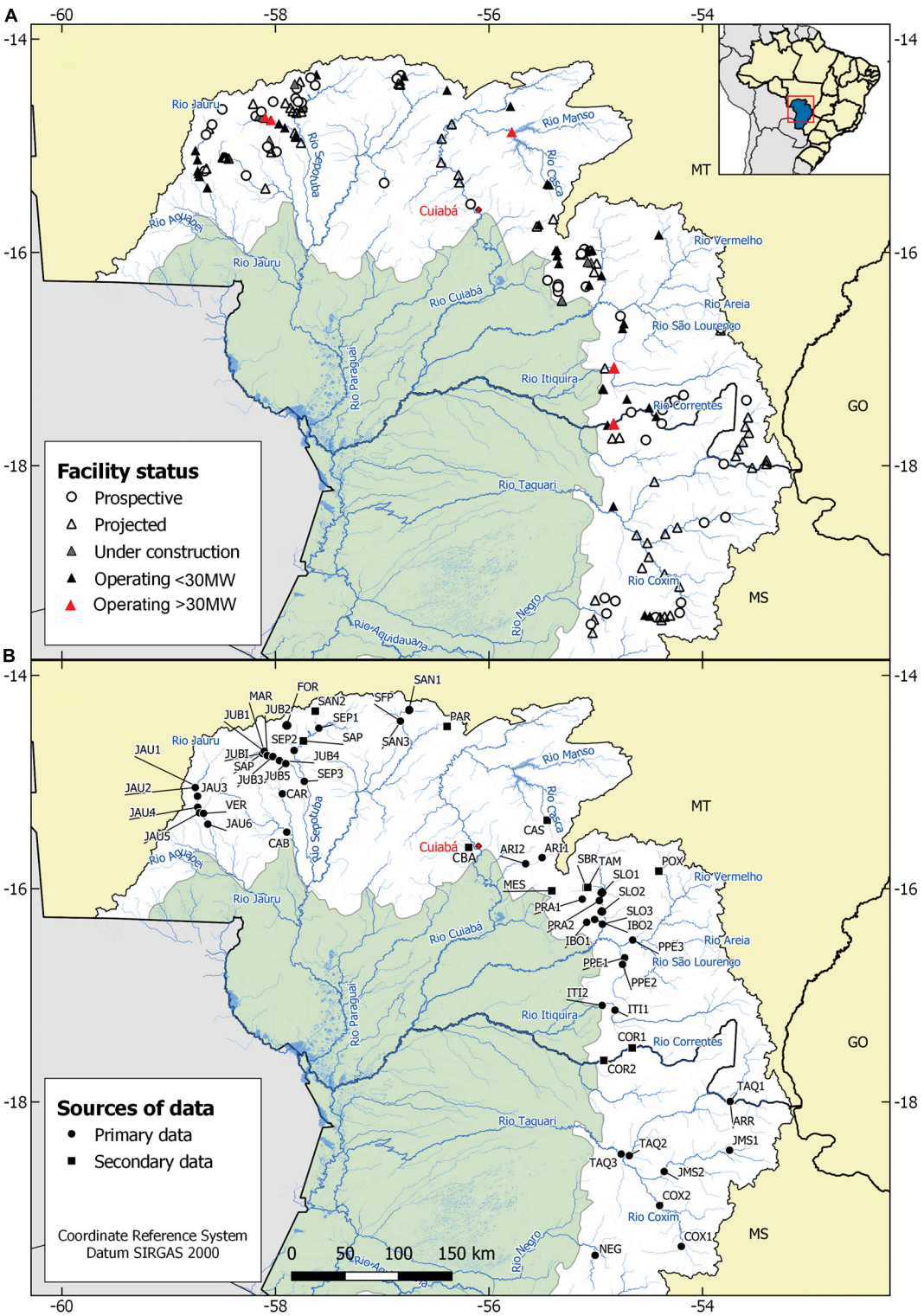

FIGURE 1 | (A) Hydropower facilities in the upland watershed of the Pantanal that are currently in operation as well as future projects that are under construction, planned, or identified as potential sites for hydropower development by either the Brazilian National Electric Energy Agency (ANEEL) or the state environmental agencies (depending on location). Red triangles indicate the four studied facilities with installed capacities >30 MW. **(B)** Sampling sites for sediment transport, including sampling conducted by the authors (primary data) as well as secondary data derived from environmental compliance reports submitted to state agencies (SEMA-MT and IMASUL) and from previous scientific studies. The Pantanal floodplains are shaded in green and rivers (*rios*) and other water bodies are shown in blue. Sampling site codes are identified in **Table 1**.

papers with recommendations developed from consideration of how both sediment and nutrient transport are impacted by future SHP development.

MATERIALS AND METHODS

Study Site

This study examines rivers in the Brazilian portion of the Upper Paraguay River basin that drain to the Pantanal wetland, which in turn drains to the Paraguay River. The upland watershed (150 to 1,400 m a.s.l.) represents 59% of the basin area and lies mainly within Brazil east and north of the Pantanal. Sloping terrain in much of the uplands favors rapid runoff and high sediment production. The Pantanal floodplains lie between 80 and 150 m a.s.l. The Köppen-Geiger climate classification is tropical savanna, with mean annual precipitation in the uplands ranging from 1,200 to 1,600 mm, with ∼80% of the annual rainfall in the rainy season from October to April (**Supplementary Figure S1**). The native vegetation in the uplands is Cerrado savanna. Soil erosion has been increased by conversion of extensive areas to cropland (29% of the upland watershed area analyzed in this study) or pasture (22%) (Zeilhofer et al., 2006). Cattle ranching, subsistence and recreational fishing, and ecotourism are major economic activities within the Pantanal, and the floodplains are globally recognized by conservation organizations because they harbor important populations of several endangered mammals and birds (Tomás et al., 2019).

Hydropower Facilities

The characteristics of the current hydropower facilities studied here, as well as the river reaches in which they occur, are given in **Supplementary Table S1**. All but six of these facilities are SHPs, with installed capacities <30 MW. Three exceed 100 MW. However, installed capacity is not always directly related to the degree to which the passage of river water is slowed, and thus to potential effects of these facilities on sediment transport. For example, two of the facilities that exceed 30 MW (Juba I and II, each 42 MW) have dams and reservoirs similar in size to the SHPs, and one of the SHPs (São Lourenço, 29 MW) creates a reservoir comparable in size to larger facilities such as the largest one studied here, Ponte de Pedra (176 MW). Therefore, we analyze the SHPs and larger facilities together in this study.

Many of the SHPs are located on lower-order rivers with low elevational gradients, and most are diversion designs, where a low dam with a small or non-existent reservoir diverts most of the river discharge into an artificial channel (headrace) that carries the water for up to several km to a powerhouse farther down the river valley (**Supplementary Table S1**), leaving the natural channel with as little as 10% of the discharge until the water is returned below the powerhouse. Most of these facilities are "run-of-river," meaning that they cannot alter discharge except on short time scales (Csiki and Rhoads, 2010; Kaunda et al., 2012; Figueiredo et al., in review).

Data on discharge and suspended sediment concentrations (SSCs) from upstream and downstream of current SHPs and several larger hydropower facilities, as well as in reaches where such facilities may be built in the future, were obtained from our own sampling and measurements (primary data) as well as from reports submitted by hydropower companies to the state environmental agencies as required for environmental compliance (secondary data). The SSC and discharge measurements conducted for environmental compliance followed the same field and laboratory methods we used, and analyses were conducted only by certified laboratories with appropriate quality assurance protocols. Secondary data were only included for reaches that we did not sample and the two data sources were never combined for a particular reach. Bedload sediment transport was estimated only where we sampled. The distribution of sampling sites with primary or secondary data is shown in **Figure 1B**, and sampling site codes used in figures are listed in **Table 1**.

Sample Collection and Analysis

Primary data on discharge, SSCs, and bedload sediment transport above and below current hydropower facilities were collected on 13 dates spanning the wet and dry seasons from October 2018 to May 2019 (some locations had fewer dates). The primary data set contains data for 17 hydropower facilities. In addition, on 6–13 dates we sampled a number of rivers at locations close to where SHPs may be constructed in the future. More detail on the sampling sites shown in **Figure 1** is in **Supplementary Table S2**.

At each sampling location we recorded the bathymetric profile of the channel cross-section and installed a staff gage unless one already existed there (a number of gages are maintained by hydropower companies). Discharge was measured across the channel profile on each sampling date using an acoustic Doppler current profiler (*SonTek RiverSurveyor-M9*) following the methods outlined in Agência Nacional de Águas [ANA] (2012). For nine rivers where discharge could not be measured—the Paraguai, Casca, Mestre, Saia Branca, Tenente Amaral, Caeté, Gloria, and Poxoréo rivers—a hydrological model provided estimates (Collischonn et al., 2019).

We collected depth- and flow-integrated water samples by the equal-discharge-increment method. Depth-integrated samples of the water column at each point were obtained with either a DH48 or DH59 integrating sampler depending on hydraulic conditions. Samples from each point were composited in a mixing bucket in volumetric proportion to the discharge contribution of each point, as determined from the profiler data using custom software from the Brazilian National Water Agency [Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina [EPAGRI], 2013]. We analyzed total SSC in water samples gravimetrically after collection of the sediment on filters (0.6 μm pore size). Laboratory analyses of SSC were conducted at Department of Sanitary Engineering at the Federal University of Mato Grosso.

Transported bedload material was collected using a Helley-Smith sampler, and sediment samples from river beds for granulometric analysis were collected using a BMH-60 rotary-bucket bed material sampler (Carvalho, 2008). The Helley-Smith sampler was deployed at three points across the channel. All sediment samples were dried at 105°C for 24 h before

TABLE 1 | List of sampling sites and hydropower facilities they pertain to, with codes for figures and tables.

Water-shed	Tributary	Sampling site	Code	Hydropower facility names	
				Current	Future
Paraguay	Paraguay	Paraguay River, upstream and downstream of SHP Alto Paraguay	PAR	Alto Paraguai	
	Santana	Santana River, upstream SHP Diamante	SAN1	Santana I	
		Santana River at mouth, upstream of SHP Santana I	SAN2		Santana II
		Santana River, downstream of SHP Santana I	SAN3	Santana I	
	S. F. Paula	São Francisco de Paula River, downstream of proposed SHPs	SFP		Saíra, Jaçanã Alta, Biguá
Sepotuba	Maracanã	Maracanã River at mouth	MAR		Taquarinha, Medianeira
	Sapo	Sapo River, ∼13 km upstream of SHP rio Sapo	SAP		Lagoa Grande, Ponte Estreita
		Sapo River, upstream and downstream of SHP rio Sapo	SAP	Rio do Sapo	
	Formoso	Formoso River, ∼250 m upstream of mouth	FOR		Formoso I, II e III
	Jubinha	Jubinha River, upstream of SHP Juba I	JUBI	Juba I	Jubinha I, II e III
	Juba	Juba River, upstream of SHP Juba I	JUB1	Juba I	Juba III e IV
		Juba River, downstream of Juba I Hydroelectric Facility	JUB2	Juba I	
		Juba River, downstream of Juba II Hydroelectric Facility	JUB3	Juba II	
		Juba River, downstream of SHP Graça Brennand	JUB4	Graça Brennand	
		Juba River, downstream of SHP Pampeana	JUB5	Pampeana	Corredeira, Tapirapuã
	Sepotuba	Sepotuba River, downstream of Maracanã River	SEP1		Salto das Nuvens, Sepotuba
		Sepotuba River, downstream of Formoso River	SEP2		Paiaguás, Salto Maciel
		Sepotuba River lower mainstem, downstream Juba River	SEP3		
Cabaçal	Cabaçal	Cabaçal River lower mainstem, downstream of proposed SHPs	CAB		Cabaçal 1,2,3,4,5, and 6
	Caramujo	Caramujo River, downstream of proposed SHPs	CAR		Salto do Céu, Salto Cacau, Salto Vermelho I, Salto Caramujo
Jauru	Jauru	Jauru River, upstream of SHP Antonio Brennand	JAU1	Antonio Brennand	Estivadinho III, Alagados III, Trairão III
		Jauru River, downstream of SHP Antonio Brennand	JAU2	Antonio Brennand	
		Jauru River, downstream of SHP Ombreiras	JAU3	Ombreiras	
		Jauru River, downstream of Jauru Hydroelectric Facility	JAU5	Jauru	
		Jauru River, downstream of SHP Salto	JAU4	Indiavai + Salto	
		Jauru River, downstream of SHP Figueirópolis	JAU6	Figueirópolis	
	Vermelho	Vermelho River at mouth, downstream of proposed SHPs	VER		Rancho Grande, Progresso
Cuiabá	Casca	Casca River, upstream and downstream of SHP Casca II e III	CAS	Casca II e III	
	Mestre	Mestre River, upstream SHP Mestre and downstream SHP Santa Cecilia	MES	Mestre + Santa Cecília	
	Cuiabá	Cuiabá River lower mainstem at Passagem da Conceição hydrological station	CBA		Perudá, Angatu II, Angatu I, Iratambé I, Iratambé II, Guapira

(Continued)

TABLE 1 | Continued

Water-shed	Tributary	Sampling site	Code	Hydropower facility names	
				Current	Future
	Aricá	Aricá River, upstream of SHP São Tadeu I	ARI1	São Tadeu I	Aricá-Mirim I
		Aricá River at mouth, downstream of SHP São Tadeu I	ARI2		São Tadeu II
São Lourenço	Tenente Amaral	Saia Branca River upstream and downstream SHP Sucupira	SBR	Pequi	
		Tenente Amaral River, ∼10 km above mouth	TAM	Sucupia	Ipê, Mangaba
	Prata	Prata River, upstream of SHP Água Prata	PRA1	Água Prata	
		Prata River, downstream of SHP Água Prata	PRA2		Água Clara, Água Branca, Água Brava
	São Lourenço	São Lourenço River, upstream of São Lourenço Hydroelectric Facility	SLO1	São Lourenço	
		São Lourenço River, downstream of São Lourenço Hydroelectric Facility	SLO2		
		São Lourenço River lower mainstem, downstream of São Lourenço facility	SLO3		
	Ibo	Ibo River, upstream of SHP Sete Quedas Altas	IBO1	Sete Quedas Altas	Europa
		Ibo River, downstream of SHP Sete Quedas Altas	IBO2		
	Poxoréu	Poxoréu River, upstream and downstream of SHP Poxoréu	POX	Poxoréu	
	Ponte de Pedra	Ponte de Pedra River, upstream of SHP Eng. José Gelázio	PPE1	Eng. José Gelázio	
		Ponte de Pedra River, downstream of SHP Eng. José Gelázio	PPE2		
		Ponte de Pedra River, downstream of SHP Rondonópolis	PPE3	Rondonópolis	João Basso
Piquiri	Itiquira	Itiquira River, upstream of Itiquira hydropower facility	ITI1	UHE Itiquira	
		Itiquira River lower mainstem, downstream of Itiquira hydropower facility	ITI2		Itiquira III
	Correntes	Correntes River, upstream of Ponte de Pedra hydropower facility	COR1	UHE Ponte de Pedra	Água Enterrada, Santa Paula
		Correntes River lower mainstem, downstream of Ponte de Pedra facility	COR2		
Taquari	Ariranha	Ariranha River at mouth, downstream of proposed SHPs	ARR		Girassol, Dália, Lírio, Violeta, Orquídea, Primavera, Hortência
	Jauru	Jauru River at BR 359 bridge, upstream of proposed SHPs	JMS1		Jauruzinho, Barra do Piraputanga, Água Fria
		Jauru River, upstream of Coxim River and downstream of proposed SHPs	JMS2		Figueirão,Vila Jauru, Mundo Novo
	Coxim	Coxim River at Fazenda São José, upstream of Camapuã River	COX1		Entre Rios, Lagoa Alta, Ponte Vermelha, Calcutá, Maringá, Fazenda Caranda, Peralta, Água Vermelha
		Coxim River at MS-142 bridge, downstream of Jauru River	COX2		São Domingos, Sucuri
	Taquari	Upper Taquari River, upstream of Ariranha River	TAQ1		Taquarizinho, Barra do Ariranha
		Upper Taquari River at Silviolandia city	TAQ2		Pedro Gomes
		Taquari River below confluence with Coxim River	TAQ3		
Negro	Negro	Negro River, at Negro city	NEG		Rio Negro, Ouro Negro, São Francisco de Assis

In most cases "lower mainstem" refers to the river before its entry into the Pantanal, SHP, small hydropower facility.

weighing. Sediment granulometry was determined using dry sieving (Carvalho, 2008).

Suspended Sediment Data Compilation From Secondary Sources

The secondary data set contains SSC data for an additional 12 hydropower facilities, including water sampling both before and during their operation. In addition, we incorporated data on rivers not sampled during the present study that were available from the environmental agency of the State of Mato Grosso (SEMA-MT). Out of 980 sediment samplings in the secondary data set, we selected 401 that could be used to analyze the effects of current and future hydropower facilities. Selection criteria included correspondence in timing of the upstream and downstream samplings, and at least five dates of sampling. For cases where more than one location was sampled to represent upstream or downstream water quality, the mean was taken, weighted by the relative discharge in the case of more than one tributary coming together above a facility. Reported values that were below the detection limit of the SSC analyses (1 mg L^{-1} for primary data and 10 mg L^{-1} for secondary data) were substituted with the detection limit concentrations.

To estimate the total impacts of all current dams on sediment transport, the impact of the Manso dam in the Cuiabá River system was also considered (**Figure 1A**). The 212-MW Manso hydropower facility was constructed on the Manso River in the 1990s and creates an extensive reservoir of 427 km^2. We analyzed suspended sediment data for the Cuiabá River at the city of Cuiabá, downstream of the Manso River as well as additional tributary inputs that contribute suspended sediments. For the pre-reservoir period, 52 SSC measurements were made by the National Department of Sanitary Works (DNOS) between April 1977 and November 1981 (Barbedo, 2003). For the period after filling the reservoir, 79 SSC measurements were available between September 1999 and October 2016 [station 66260001: Agência Nacional de Águas [ANA], 2020]. These SSC measurements coincided with discharge measurements, allowing comparison of the SSC-discharge relationships.

Data Analysis

We assessed the effects of current hydropower facilities on SSCs and transport by comparing the median SSCs upstream and downstream of each facility, based on a combination of primary data (N = 13 dates in most cases) and secondary data (variable numbers of sampling dates). Transport was calculated as the median concentration times discharge, averaging the discharge estimates above and below each SHP location to avoid potential spurious results caused by the uncertainty inherent in discharge measurements as well as by short-term (sub-daily) fluctuations imposed by the hydropower facilities (hydropeaking: Figueiredo et al., in review).

Bedload sediment transport for cross sections represented by each sampling point was calculated from the Helley-Smith samples following Carvalho (2008):

$$Q_b = \left[\sum \frac{p(q_{i+1} - d_{i-1})}{E_{\mathrm{am}} \times l \times t}\right] \times 86.4 \qquad (1)$$

Where,

Q_b = total bedload sediment transport (load) in the channel (t d^{-1});
E_{am} = hydraulic efficiency of the sampler;
p = dry weight of the sediment sample (kg);
$(d_{i+1} - d_{i-1})$ = channel width of the cross-section represented by the sample (m);
l = width of the sampler opening (m);
t = time sampler was deployed (s).

Observed ratios of upstream to downstream SSCs and transport and bedload sediment transport were grouped into classes based on the percentage change in either direction (i.e., retention or release), similar to the sustainability boundary approach suggested by Richter et al. (2012) for analysis of flow regime alterations in river systems that lack detailed knowledge of the impacts of altered flows. Ratios of <10% were defined as undetectable changes, 10–20% as moderate, and >20% as high alterations.

In addition to comparing the median concentrations and transport rates for all sampling dates combined for each study reach, we conducted statistical analyses of the changes in suspended sediment and bedload transport observed across all individual sampling dates in each reach using a one-sample t-test for which the null hypothesis was zero change. Analyses were conducted after $\log_{10}$ transformation of the concentration changes to improve normality.

Prediction of Impacts of Future Hydropower Facilities

Artificial neural networks were developed to predict the impacts of new hydropower facilities on total suspended solid concentrations and bedload sediment transport. As one of the most commonly used artificial intelligence tools, ANNs are well suited to model phenomena subject to controls that are complex, incompletely understood, and likely non-linear [American Society of Civil Engineers [ASCE], 2000]. The ANN model architecture was a three-layer feedforward network with a non-linear (unipolar sigmoid) activation function (**Supplementary Figure S2**), similar to ANNs that have been applied to study floodplain inundation in the Pantanal (Fantin-Cruz et al., 2011) as well as elsewhere (Dawson et al., 2006).

The ANN models were trained with a data set representing 32 locations (including primary and secondary data). The back-propagative algorithm (Rumelhart et al., 1986), along with training acceleration techniques (Vogl et al., 1988) as well as other needed functions, were custom programmed in the MATLAB R2012b environment. Overfitting was avoided using the cross-validation technique (Hecht-Nielsen, 1989).

For cross-validation training, the data were divided into three samples (53% for training, 26% for validation, and 20% for verification), using a systematic sampling method to provide a representative distribution of the 32 locations for all samples. The extreme values (maximum and minimum) of all variables were included in the training samples and all input data of the future hydropower facilities were within the domain of the trained

ANN, ensuring that model predictions were within the ranges of the training data.

The complexity of the ANNs (number of neurons in the intermediate layer) was defined by the architecture search with the lowest possible complexity that still had the same approximation and generalization capacity of a purposely oversized ANN that was trained without overfitting. These approximation and generalization capacities were verified by the performance of the application to the validation sample, since the verification sample, by definition, cannot participate, neither in training nor in the definition of the ANN architecture (Hecht-Nielsen, 1989).

In the present study, input variables that were considered for the ANNs included contributing watershed area, reservoir area and volume, soil classification [11 classes in the contributing watersheds: Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2018], land use and cover [8 classes: Empresa Brasileira de Pesquisa Agropecuária [EMBRAPA], 2015], and upstream concentrations of suspended sediments. Sufficient information was available for 80 of the 138 potential future hydropower facilities.

The potential watershed yields of sediment to river systems were estimated from the Soil and water assessment tool (SWAT), the full results of which are posted online (Mingoti et al., 2020). Details of this SWAT model are presented by Neitsch et al. (2011) and Arnold et al. (2012). The SWAT model was run for each watershed for the year 2017 using spatial data on climate, topography, soils, and land use and cover. Annual and monthly inputs were estimated for the contributing watersheds above each current and future hydropower facility.

The ANN model was trained with measured concentrations of suspended sediments (n = 571 measurements) above and below 34 current hydropower facilities, as well as the contributing watershed area and reservoir area and volume for each facility (**Supplementary Table S1**). Pearson linear correlations between input and output variables indicated the best predictive variables for each model. Overall performance of the ANNs was evaluated by the Nash-Sutcliffe model efficiency coefficient.

Impacts of Damming on Total Sediment Transport to the Pantanal

We estimated the total sediment transport to the Pantanal from the most downstream sampling points on each major tributary (**Figure 1**). In addition, the aggregate impact of current hydropower facilities was estimated by comparing current sediment transport with the total sediment retention by all current facilities, including the Manso dam. These estimates of total sediment transport and retention at present were then compared with the ANN model predictions of the impacts of future hydropower development on sediment transport.

Remote Sensing of Sediment Accumulation

Time series of optical satellite imagery were visually examined for evidence of sediment accumulation in reservoirs among the study sites. Publicly available imagery was obtained from the Landsat 5 Thematic Mapper, Landsat 7 Enhanced Thematic Mapper Plus, Landsat 8 Operational Terra Imager, China–Brazil Earth Resources Satellite 4, and Sentinel 2 satellites. Two cases are presented here as instructive examples—the Itiquira and São Lourenço hydropower reservoirs.

RESULTS

Sediment Concentrations and Transport

Rivers flowing from the upland watershed into the Pantanal, sampled at points below any hydropower facilities, showed a wide range of SSCs and transport (**Figure 2** and **Supplementary Tables S3, S4**). The sites in **Figure 2** are ordered by increasing discharge, which shows that with the exception of the Coxim River (COX2), rivers below the median discharge had relatively low SSCs and transport. Most of the rivers with the highest SSCs and transport are as yet largely undammed (**Figure 1A**), including the Vermelho, Coxim, upper Taquari, Miranda, and Aquidauana rivers, although the Cuiabá River still carries relatively high SSC loads in spite of a large upstream reservoir (Manso) on one of its principal tributaries (Manso River) that traps nearly all suspended sediment inputs (Carvalho and Lôu, 1990).

Bedload sediment transport in rivers flowing from the upland watershed into the Pantanal was small compared to the

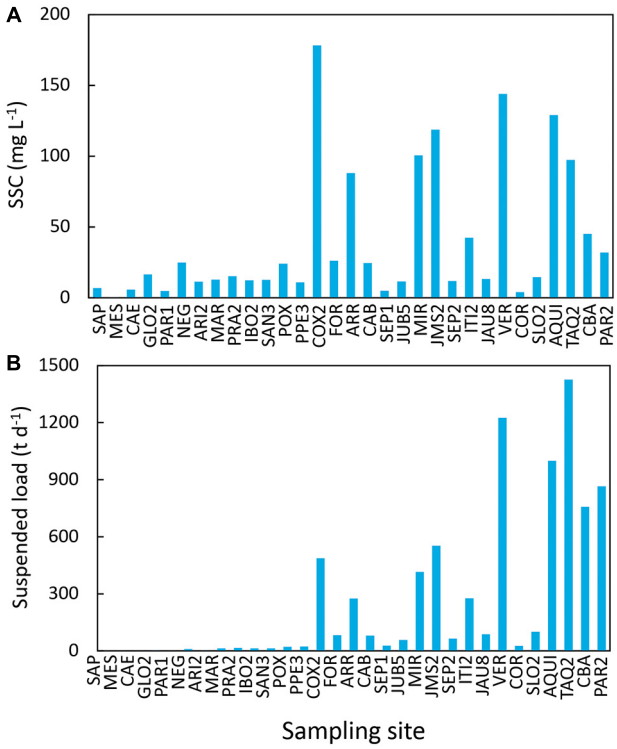

FIGURE 2 | (A) Suspended sediment concentrations (SSC) and **(B)** loads (transport) in rivers that drain into the Pantanal, for sampling sites below any hydropower facilities. Sites are ordered by increasing discharge and their codes are identified in **Table 1**.

suspended sediment load in the rivers with high total sediment loads (**Figure 3**). Bedload comprised the largest percentage of total sediment transport in the Negro and Formoso rivers, which carried low SSCs.

Upstream-Downstream Comparisons to Show Dam Effects

Concentrations and transport of suspended sediments upstream and downstream of 29 current hydropower facilities are compared in **Figure 4** and **Supplementary Table S3**. The changes between upstream and downstream are presented as both concentrations, which bear on the nutrient availability and aquatic ecology of downstream waters, and rates of transport (i.e., t d^{-1}), which bear on the overall sediment supply from the upland watersheds to the Pantanal. For a given hydropower facility, the ratios between concentrations and transport covary because we assumed that discharge did not change and therefore we used the mean of upstream and downstream discharge measurements to calculate transport. We do not consider bedload here because it was a small proportion of total sediment transport except in some rivers with low total sediment transport (**Figure 3**).

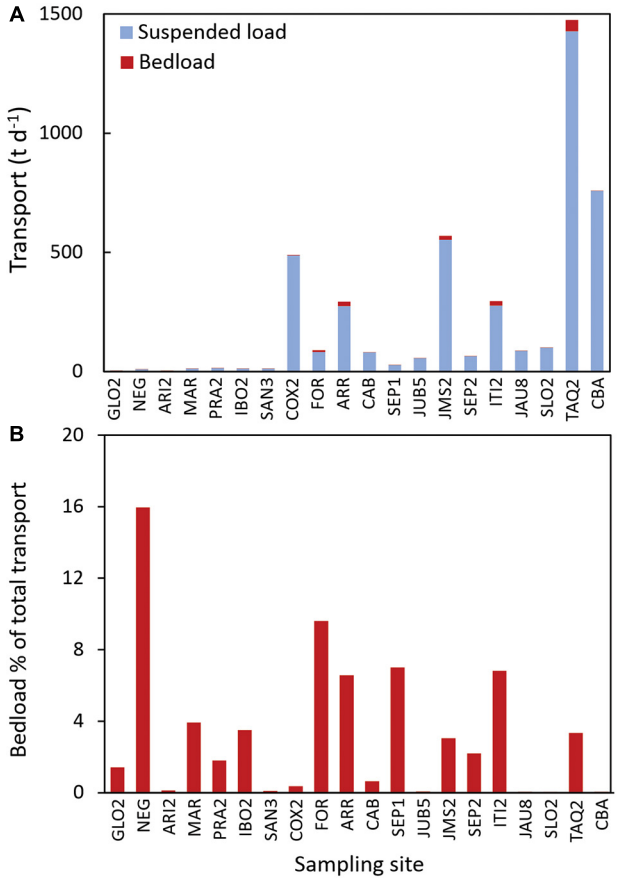

FIGURE 3 | (A) Suspended and bedload sediment transport and **(B)** bedload as percent of total sediment transport (i.e., bedload plus suspended) in rivers that drain into the Pantanal, for sampling sites below any hydropower facilities. All sites shown here have bedload data but in some cases the bars are too small to be visible in **(B)**. Sites are ordered by increasing discharge and their codes are identified in **Table 1**.

Fourteen of the 29 current hydropower facilities showed upstream:downstream SSC ratios >20% above the 1:1 line, indicating net retention of suspended sediments (**Figure 4**). Two others fell between 10 and 20% retention, seven were within 10%, and six showed >10% release. Two of the reaches with the highest SSCs and transport—ITI2 on the Itiquira River and SLO2 on the São Lourenço River—also showed large absolute values of net retention. That is not the case for the next three reaches with relatively high SSCs (POX, CAS, and PPE3), which also retained a large fraction of the suspended sediment input but had much lower rates of transport. Summing all of the riverine transport rates for above and below the 29 facilities studied here shows a total net retention of suspended sediments of 140 kt y^{-1} (i.e., from 518 to 378 kt y^{-1}).

The nearly complete retention of sediments by the large reservoir on the Manso River can be added to the above estimate. Comparison of the SSC-discharge relationships for the Cuiabá River before and after construction shows that damming the Manso River reduced suspended sediment transport downstream in the Cuiabá River at the city of Cuiabá by ∼60% (**Supplementary Figure S3**). The total retention by all dams in the upland watershed draining to the Pantanal is thus estimated to be 865 kt y^{-1}, amounting to a 32% reduction in aggregate sediment transport by current hydropower facilities (**Figure 5**).

Net sediment retention by individual hydropower facilities (not including Manso) was best predicted by the upstream SSC concentration and the water residence time in the reservoir, which together explained 54% of the variation using a regression tree (**Supplementary Figure S4**). Facilities where the upstream SSC exceeded 18 mg L^{-1} showed a mean SSC retention of 59%. Residence time was a significant predictor for reaches with SSC < 18 mg L^{-1}, with net retention (mean, 31%) only when the residence time exceeded 1.8 days.

A similar upstream:downstream comparison for the 16 sites that have bedload sediment transport measurements shows that two reaches with the largest absolute rates of bedload sediment transport–SLO2 and ITI2–showed large deviations from the 1:1 line, but in opposite directions (**Figure 6**). The SLO2 reach retained virtually all of its bedload, whereas the ITI2 reach showed net release (the Itiquira reservoir was largely infilled with sediment). Among the reaches with much lower rates of bedload sediment transport, most showed net retention of most of the bedload, although JAU2 on the Jauru River in Mato Grosso (Jauru-MT) showed net release (**Figure 6B**). Several reaches showed bedload retention rates that were so small that any net changes may be inconsequential to downstream ecosystems. Summing all of the riverine transport rates for above and below the 17 facilities with measurements of bedload shows a total net retention of bedload sediments of 2.01 kt y^{-1} (i.e., from 8.64 to 6.64 kt y^{-1}). Actual total retention is considerably larger because bedload was only measured on a subset of the reaches with hydropower facilities.

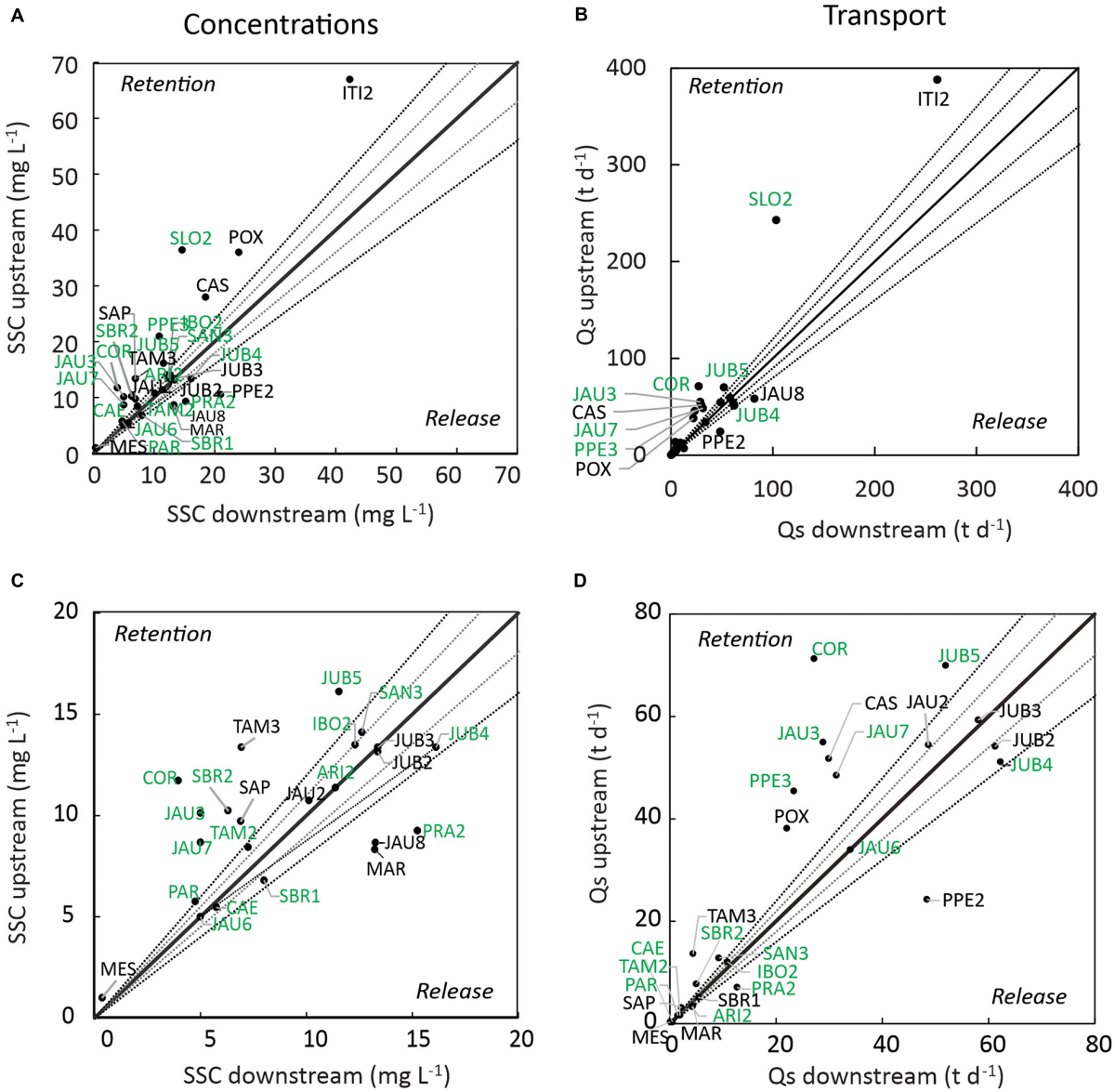

FIGURE 4 | Comparisons of changes in water-column concentrations (SSC) and transport (Qs) of suspended sediments between upstream and downstream of current hydroelectric facilities based mainly on primary data collected in this study as well as some secondary data. **(A,B)** All data on concentrations and transport, respectively; **(C,D)** the same data with high values excluded. Solid line shows the line of parity and dashed lines show bounds of ±10 and ±20% around that line; points above the line indicate net retention and those below indicate net release between the upstream and downstream sampling points. Upstream:downstream ratios that deviate considerably from 1:1 are identified with the codes shown in **Table 1**; codes in green font indicate cases where the statistical analysis of the changes across all individual sampling dates showed significant ($p < 0.05$) differences from zero.

Dividing sediment transport rates for rivers at their points of entry into the Pantanal by watershed areas gives specific sediment yields, which range from 3.38 to 45.5 t km^{-2} y^{-1}. These are compared against potential sediment production estimated by Mingoti et al. (2020) using the SWAT model in **Figure 7** and **Supplementary Table S5**. The ratio of transport to potential production, known as the sediment delivery ratio, ranged from 0.0015 to 0.0098 with the highest ratios in the Cuiabá (0.0098), upper Taquari (0.0092), and Coxim (0.0081) rivers. The sum of sediment transport by upland rivers into the Pantanal was 1.91 Mt y^{-1}, or 23 t km^{-2} y^{-1}, and the overall sediment delivery ratio was 0.0074.

Predicting the Impacts of Future Hydropower Development

Among the potential input variables that were considered for the ANNs, the most significant predictor of sediment retention was the measured upstream SSC concentration, accounting for nearly half of the predictive capability of the model

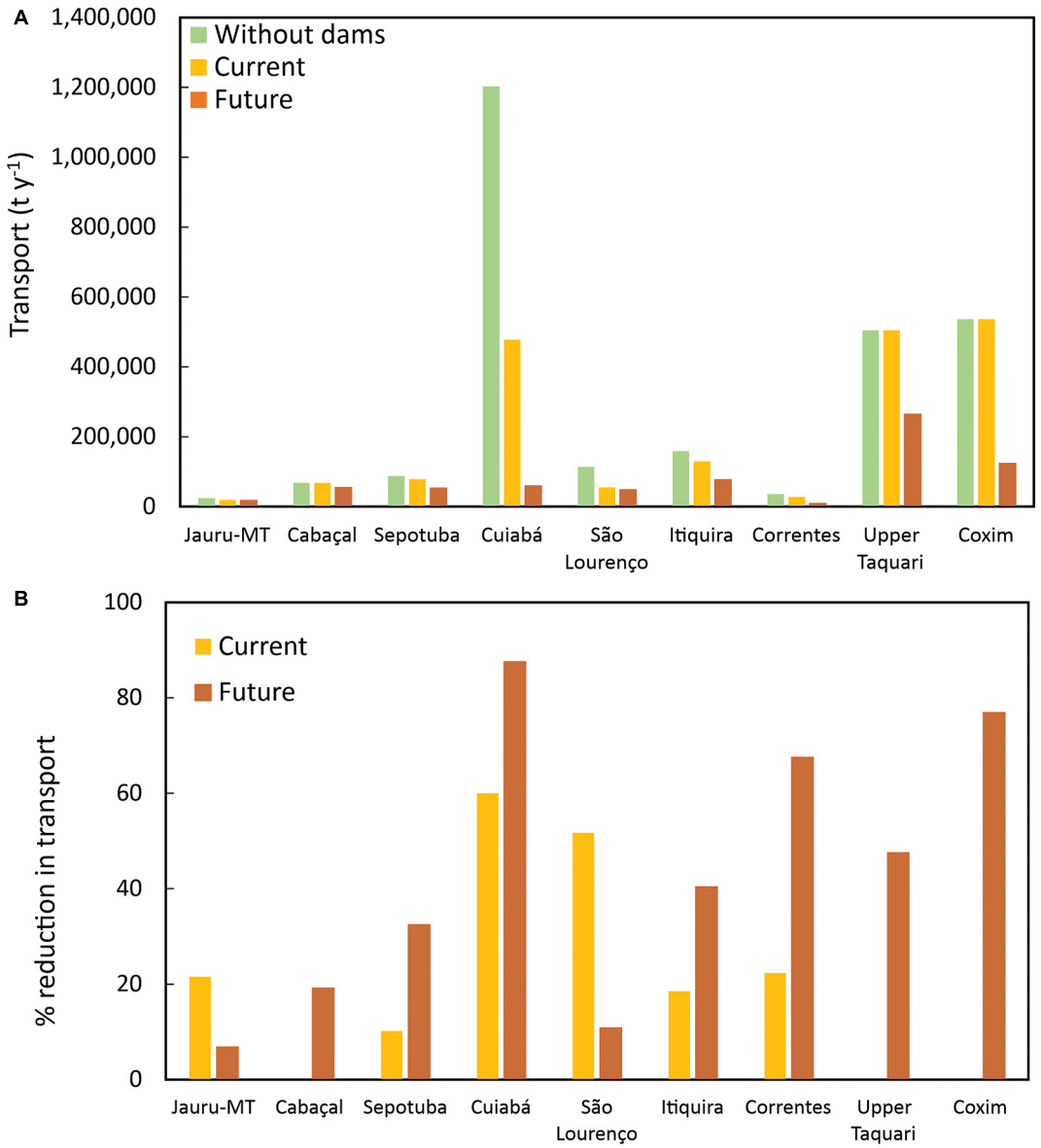

FIGURE 5 | Impacts of damming on total sediment transport to the Pantanal. **(A)** Annual suspended sediment transport to the Pantanal at present with and without current dams, as well as rates predicted by the neural network modeling were all future hydropower facilities to be built in each river system; **(B)** percent change between current rates and predicted future rates.

(**Supplementary Figure S5**). Also important were soil and land use classes (n = 11 and 10 classes, respectively) and watershed sediment yields from the SWAT model, together accounting for about 33% of the predictive capability. The contributing watershed area and reservoir area and volume were also significant, though less important, predictors of SSC. The performance of the ANNs was satisfactory as indicated by the Nash-Sutcliffe model efficiency coefficients, which were 0.889 for training and 0.826 for verification.

Model predictions of the impacts of future hydropower facilities on SSCs and transport show retention of a large fraction (often much >20%) of sediment inputs at most of the reaches across the range of concentrations and transport (**Figure 8**). The measured current and modeled future rates of suspended sediment transport by the major rivers flowing from the upland watershed into the Pantanal, based on the most downstream sampling points, are summarized in **Figure 5**.

Very large decreases in sediment transport are predicted for the three river systems with the largest contributions of sediments to the Pantanal—the Cuiabá, upper Taquari, and Coxim rivers. A number of rivers with lower rates of sediment transport are still predicted to show significant percent reductions if future SHPs are built (**Figure 5B**). Available data for a few smaller rivers with relatively low rates of transport are not shown (Negro-MS,

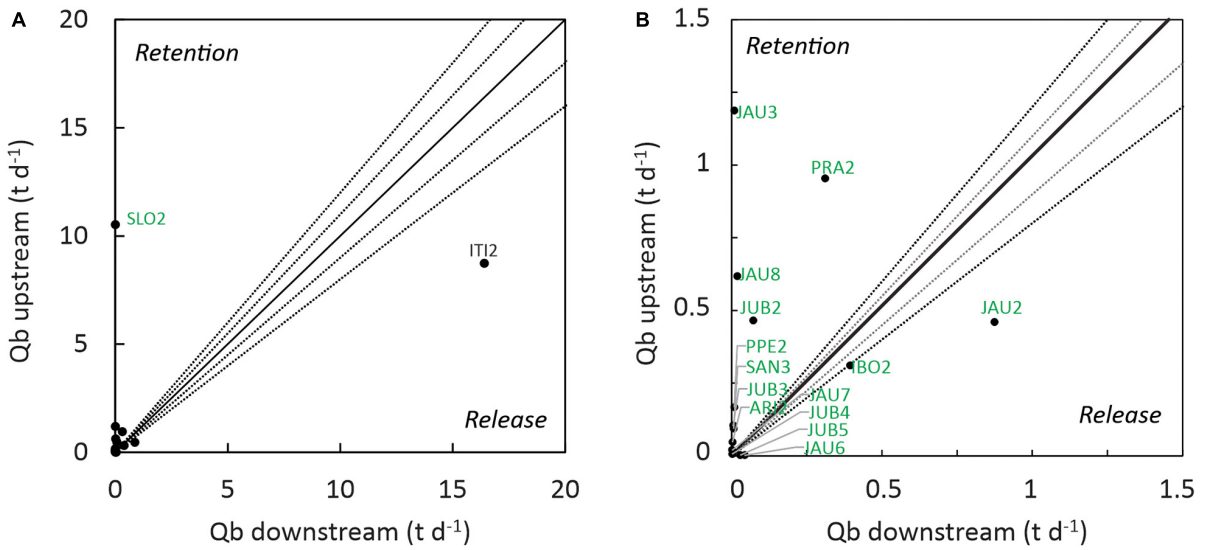

FIGURE 6 | Comparisons of changes in bedload sediment transport between upstream and downstream of current hydroelectric facilities based on primary data collected in this study. **(A)** All data; **(B)** the same data with high values excluded. Solid line shows the line of parity and dashed lines show bounds of ±10 and ±20% around that line; points above the line indicate net retention and those below indicate net release between the upstream and downstream sampling points. Upstream:downstream ratios that deviate considerably from 1:1 are identified with the codes shown in **Table 1**; codes in green font indicate cases where the statistical analysis of the changes across all individual sampling dates showed significant ($p < 0.05$) differences from zero.

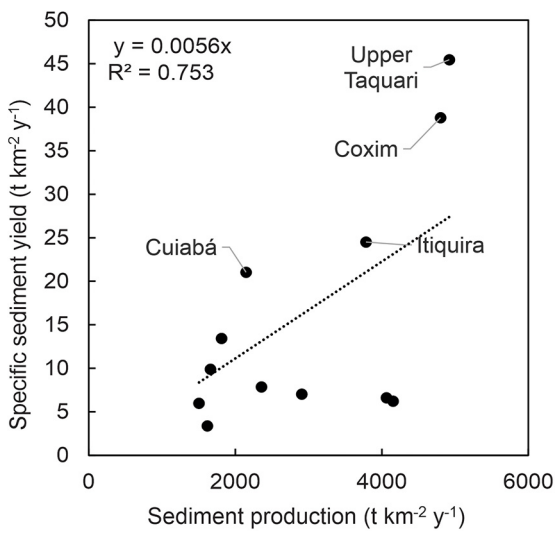

FIGURE 7 | Comparison of specific sediment yields measured in rivers near their points of entry into the Pantanal to potential sediment production in their watersheds as estimated using the SWAT model (Mingoti et al., 2020).

Aricá Mirim, and Ribeirão Ponte de Pedra rivers), and the Taquari River is divided into its two major tributaries (upper Taquari and Coxim rivers) whose confluence is a short distance upstream of the border of the Pantanal. Summing all of the riverine transport rates for inflows into the Pantanal indicates that future hydropower development would result in reductions of 62% of the suspended sediment transport from the uplands to the Pantanal (i.e., from 1.93 to 0.73 Mt y^{-1}).

Remote Sensing of Sediment Accumulation

Two examples of reservoirs with readily visible sediment accumulation over time are shown in **Figure 9**. The São Lourenço dam created a long, relatively narrow reservoir, and the visible sediment infilling has occurred in its uppermost reach, effectively forming a delta in which shallow or periodically flooded areas have become colonized by floating and emergent wetland vegetation. The Itiquira dam created a wide reservoir along a short reach and has filled in considerably in spite of persistent efforts to recover the sand over the years, an operation that is visible at the end of the road on the southeastern edge of the reservoir.

DISCUSSION

This study presents a comprehensive analysis of SHP impacts on sediment concentrations and transport that is unprecedented in the literature and informs decisions about future hydropower development in the Upper Paraguay River basin and in similar settings elsewhere in Brazil and worldwide. In particular, our results are applicable to some of the major frontiers of SHP development that are in similar landscapes, including elsewhere in Latin America, east Africa, and Southern Asia (Couto and Olden, 2018).

Sediment Retention by Current and Future Hydropower Facilities

This study shows that sediment retention, while well known for larger dams and reservoirs, also is characteristic of SHP facilities,

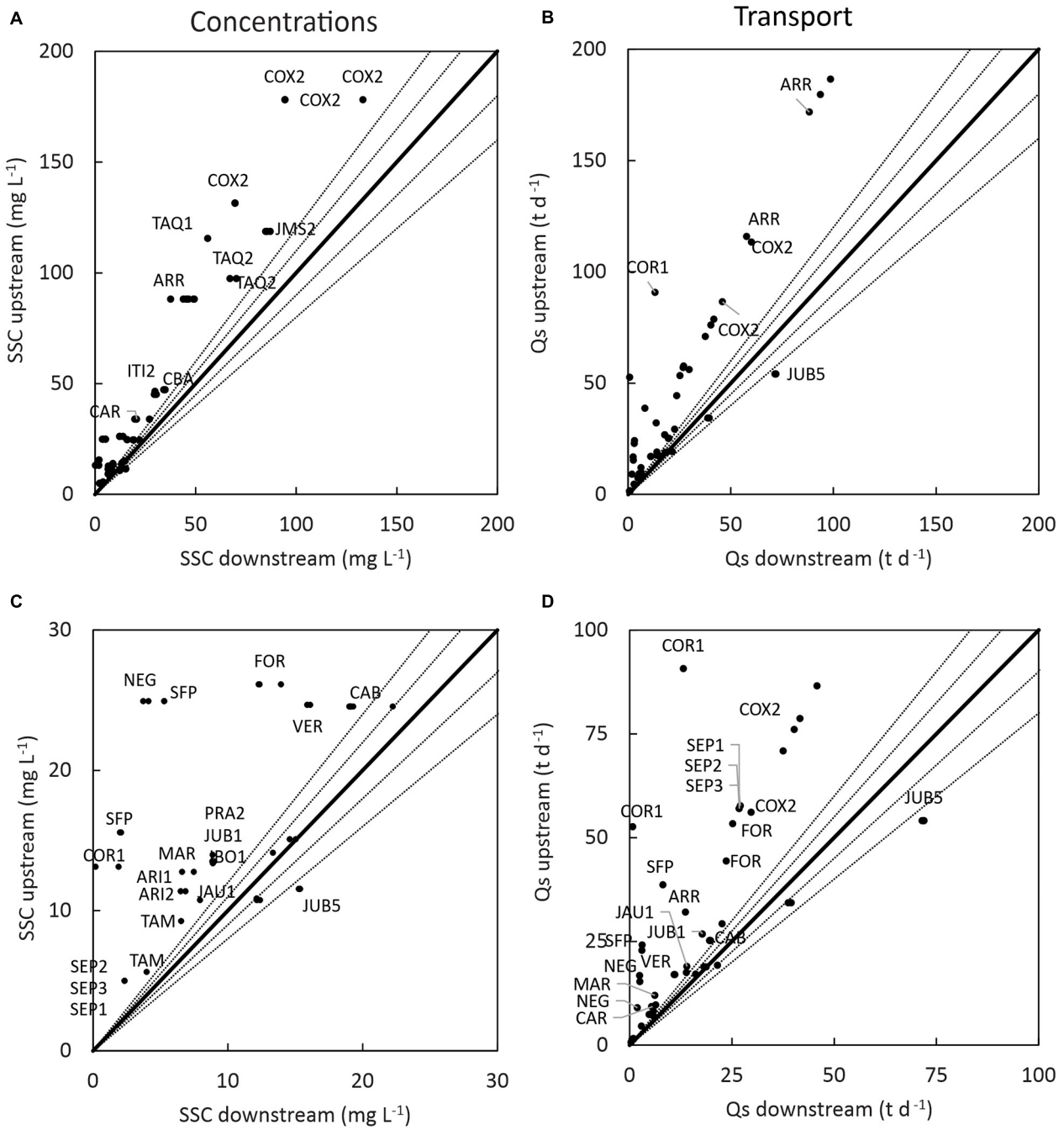

FIGURE 8 | Comparisons of neural network model predictions of changes in suspended sediment concentrations (SSC) and transport (Qs) between upstream and downstream of future hydroelectric facilities, with river systems labeled by codes in **Table 1**. **(A,B)** All data on concentrations and transport, respectively; **(C,D)** the same data with high values excluded. Solid line shows the line of parity and dashed lines show bounds of ±10 and ±20% around that line; points above the line indicate net retention and those below indicate net release between the upstream and downstream sampling points. Upstream:downstream ratios that deviate considerably from 1:1 are identified with the codes shown in **Table 1**.

and that without mitigation measures future construction of SHPs in the remaining undammed river systems with high sediment transport rates will reduce the total sediment transport from the upland watershed to the Pantanal by about 62% from the current rate. Many of the current hydropower facilities are on rivers with relatively low sediment concentrations and transport, and thus their impact on sediment transport from the uplands to the Pantanal has been modest. Nevertheless, certain tributaries with hydropower facilities are experiencing significant retention of suspended sediments, including the large effect of the dam

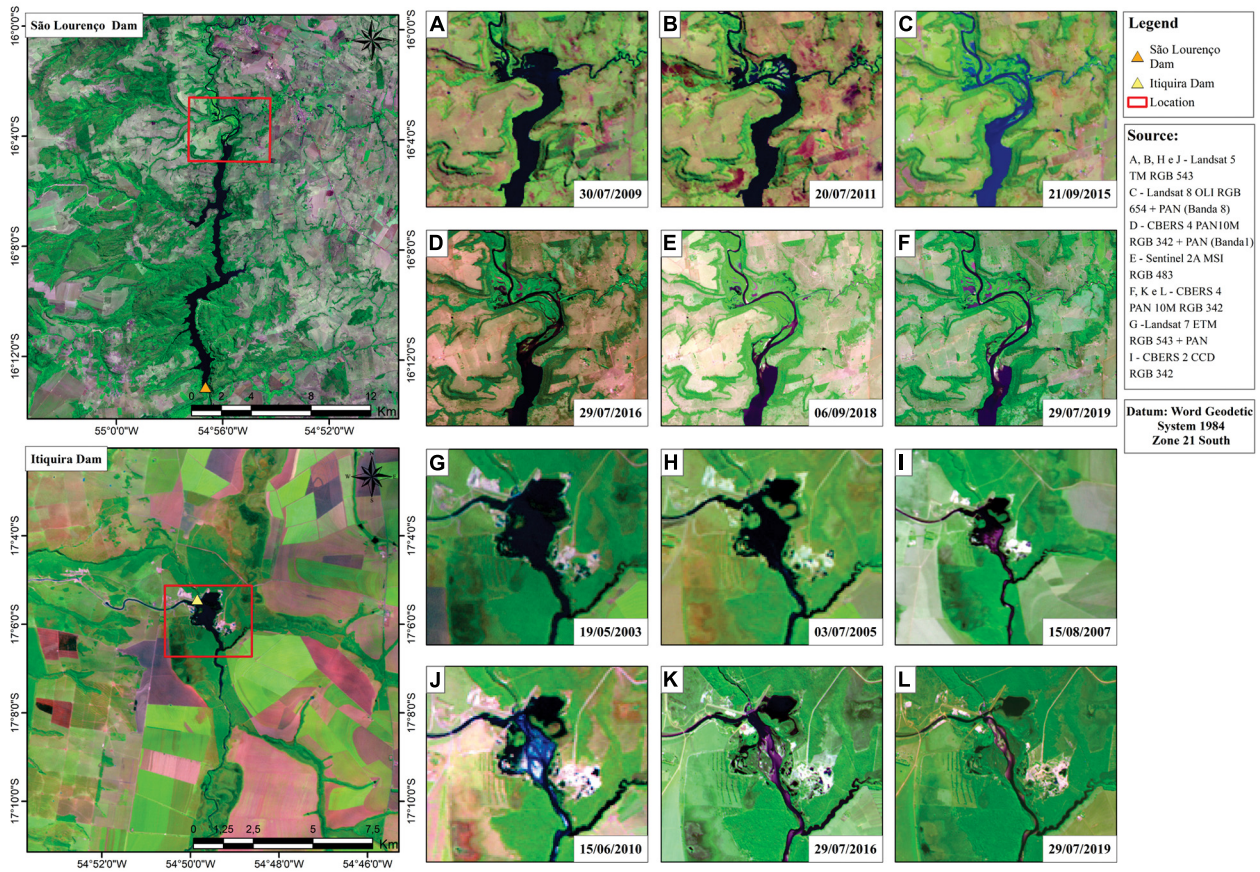

FIGURE 9 | Satellite images showing progressive sedimentation and infilling of reservoirs created by the **(A–F)** Itiquira dam (completed in 2002) and **(G–L)** São Lourenço dam (completed in 2009).

on the Manso River, and satellite images provide evidence of long-term accumulations of sediments above some dams.

The undammed river systems with high sediment loads reflect the combination of erodible soils and agricultural land use, including livestock grazing, in their watersheds, and our results show that damming those river systems may prove problematic for sediment management. The Coxim, upper Taquari, and Cuiabá rivers are particularly vulnerable to sediment trapping by future SHPs, which will likely result in serious problems of infilling above the dams. The sediment retention would also negatively impact downstream river channels and floodplains by altering the geomorphological dynamics, potentially creating a sediment starvation situation where river channels incise, banks become destabilized, and floodplain inundation and accompanying sediment and nutrient deposition are reduced, with negative consequences for fisheries, wildlife habitat, and agriculture and human settlements in the riparian zones (Kondolf et al., 2014a; Wohl et al., 2015).

The direct measurement of sediment retention reported in our study is superior to estimation using models developed to apply to a wider variety of rivers and hydropower facilities (reviewed in Tan et al., 2019). The Churchill (1948) model is considered appropriate for small reservoirs (Morris and Fan, 1998; Carvalho, 2008). Comparison of mean trap efficiencies based on our observations of sediment retention to those estimated with the Churchill model showed divergent results, however, with the Churchill model greatly overestimating sediment trapping at 11 of 16 facilities (data not shown).

A few previous studies in the region have predicted sediment trapping in spite of a lack of direct measurements upstream and downstream of the hydropower facilities. Based on considerably less available data on sediment transport and considering locations of current and future hydropower facilities as of 2010, and assuming 100% sediment trap efficiency by dams, Souza Filho (2013) estimated the potential future reduction in sediment loading to the Pantanal to total 52%, less than the 62.4% estimated in our forecasts. However, in the case of the Taquari River system, both the discharge and SSCs and therefore the rates of transport used by Souza Filho were considerably higher than our measurements (this could reflect a real change over time).

Sediment trapping behind individual dams has been estimated using standard approaches (including empirical observations of sediment transport and estimates of trap efficiency) for some projects prior to their construction. For the Manso dam, Carvalho and Lôu (1990) estimated a >95% trap efficiency, with time to complete infilling of ∼1,000 y. For the Itiquira dam,

which has a much smaller and shallower reservoir, Carvalho et al. (2000), using Churchill's trap efficiency model, estimated a lifetime of only 8–12 years (the shorter estimate accounted for a likely increase in soil erosion over time). In fact, since its construction in 2000, the Itiquira reservoir has largely filled in with sediment, as is evident in the satellite imagery.

Although bedload is a small component of total sediment transport in rivers flowing to the Pantanal, it is particularly susceptible to retention behind dams. Over long time periods, and particularly in rivers that are presently largely undammed and carry higher bedload transport (e.g., the Taquari and Cuiabá), the accumulation of bedload can result in significant infilling above these dams. While periodic removal may alleviate infilling problems, if removal entails downstream discharge of high sediment loads there may be ecological risks that require careful consideration (Kondolf et al., 2014a).

Recommendations for Future Hydropower Development

Decisions about whether and where to construct dams in the Upper Paraguay River basin should consider not only sediment transport but also other environmental and social impacts. Two other kinds of impacts that are particularly important are nutrient transport (Oliveira et al., in press) and river system connectivity for migratory fish (Campos et al., 2020).

Based on these results as well as our parallel study on nutrient transport (Oliveira et al., in press) and a recent analysis of migratory fish routes in the region (Campos et al., 2020), development of new SHPs on the remaining undammed tributaries to the Pantanal may present serious risks to downstream river and floodplain ecosystems. Although the numerous dams in the northern part of the watershed have only modestly reduced sediment and nutrient transport because many are on rivers with low rates of transport, our modeling indicates that future construction of dams on rivers with higher sediment loads is likely to substantially reduce sediment transport from the uplands to the Pantanal. Substantial reductions in river sediment transport will likely lead to geomorphic changes that harm river and floodplain ecosystems and compromise the services they provide to people. Retention of sediments also reduces nutrient transport because particulate forms comprise major fractions of total nitrogen and phosphorus transport. Oliveira et al. (in press) showed that the new dams could reduce total phosphorus transport to the Pantanal by 29% from the current rate, with retention mainly by sediment trapping.

Considering potential reductions in transport of sediments as well as nutrients (Oliveira et al., in press), we recommend that new hydropower facilities should not be built on undammed rivers entering the Pantanal that have particularly low sediment and nutrient concentrations and transport, as well as on those that have the highest absolute rates of sediment and nutrient transport to the Pantanal.

Much of the nutrient load of these rivers is in particulate form and is thus associated with suspended sediments (Oliveira et al., in press). River systems with low nutrient concentrations are likely to be most sensitive to reductions in nutrient availability. In response to trapping of sediments and associated nutrients by damming, these rivers and their floodplains likely would experience oligotrophication, with negative consequences for fisheries yields and overall river and floodplain ecosystem productivity, as has been observed with dammed rivers elsewhere (Stockner et al., 2000). This dam-induced oligotrophication may eventually affect the fertility of pastures used for cattle (Forsberg et al., 2017). In the Upper Paraguay River basin, particularly low nutrient concentrations occur mainly in the Sepotuba, Correntes, and São Lourenço river systems, though the latter is already dammed in its lower reach.

River systems that carry the largest quantities of sediments to the Pantanal also deserve protection because their high sediment loads affect river channels and floodplains not only within the Pantanal but also downstream along the Paraguay River beyond the Pantanal (Oliveira et al., 2019). River systems of particular importance to the sediment and nutrient budget of the Pantanal that remain undammed, at least in their lower reaches, include the Cuiabá and Taquari (including its tributary the Coxim River).

CONCLUSION

This study, together with one on nutrient transport (Oliveira et al., in press), presents a comprehensive analysis of SHP impacts that is unprecedented in the literature and informs decisions about future hydropower development in the Upper Paraguay River basin and in similar settings elsewhere in Brazil and worldwide. Current facilities retain suspended and bedload sediment, and model predictions for hydropower facilities that may be built in the future on rivers flowing into the Pantanal point to large reductions in sediment transport, with potential negative consequences for downstream river and floodplain productivity. Negative impacts may be either because the rivers carry low sediment and nutrient concentrations, thereby being sensitive to oligotrophication, or are particularly important overall sediment and nutrient sources to the Pantanal, thereby supporting ecosystem productivity in downstream rivers and floodplains including particularly the Paraguay River axis within the Pantanal. Considering current and potential future effects on both sediment and nutrient transport, we recommend no additional hydropower development on the Cabaçal, Sepotuba, Cuiabá, and Taquari/Coxim rivers. Maintenance of the natural transport of sediments and nutrients from the uplands to downstream rivers and floodplains, as well as the connectivity between the floodplains and upland rivers for migratory fishes, would protect the productivity and biodiversity of the Pantanal.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

IF-C, MO, MS, and SH conceived and carried out the study. IF-C, MO, LS, and MC conducted the field work and data analysis. JC, OP, and RM developed the modeling. IF-C, MO, and SH wrote the manuscript. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fenvs.2020.577748/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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