A Modeling Assessment of Large-Scale Hydrologic Alteration in South American Pantanal Due to Upstream Dam Operation

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Natural river flow provides the conditions required to sustain freshwater ecosystems, and the greater the departure from the natural regime, the greater the loss of those ecosystems. In South America, new hydropower dams are continuously being constructed and planned in regions within and around the Amazon basin and in the Upper Paraguay river basin, a region notable for the Pantanal, a huge wetland ecosystem that is largely dependent on the flow regime of the Paraguay river and its tributaries. In this context, it is meaningful to examine the hydrological changes caused by the major Manso dam, that is operating since 2001 at the headwaters of one of the major tributaries of the Paraguay river. This was done for the same case study by other authors in previous studies using only gauging stations data. However, those previous assessments were limited due to the confounding effects of climate variability and the necessity of relatively long term observed time series. Here, we applied a modeling approach to evaluate the changes in hydrological regime caused by Manso dam operation. Our modeling approach was based on the combination of the MGB large-scale hydrologic model with the SIRIPLAN large-scale wetland model. The models were applied, using river reaches from 2 to 10 km, in two scenarios during the period from 2003 to 2015. In the first scenario we used naturalized streamflow at the dam site as input to the hydrological model. In the second scenario we used observed reservoir outflow time series as input to the hydrological model. Our results show that Manso dam has a regulation effect that decreases high flows, increases low flows and reduces lateral connectivity. The decrease in high flows is more pronounced in the region upstream of the Pantanal floodplain, but not limited to, while increase in low flows extends into Pantanal. Timing of maximum and minimum flows is less affected, except for the river reach immediately downstream of the dam. Our results improve the assessment of spatial patterns of hydrologic alteration, giving more confidence in the assessment of magnitude and spatial extension of the effects of Manso dam in the Pantanal region.

Keywords: Manso dam, indicators of hydrologic alteration, hydrological modeling, MGB, SIRIPLAN, Pantanal

INTRODUCTION

An underpinning assumption is that natural river flow provides the baseline for determining what is necessary for ecosystem maintenance, because ecosystems evolved under those conditions (Poff et al., 1997). In other words, a naturally variable regime of flow is required to sustain freshwater ecosystems, and the greater the departure from the natural regime, by water abstractions and flow regulation to maximize obtaining river goods, the greater the loss of those ecosystems (Poff et al., 2010).

River goods are defined as products that are of societal use when extracted or diverted from the river system (Brismar, 2002). Direct benefits or products include drinking, growing food, navigate, supporting industry and producing hydroelectric power. Besides, through river services, which are defined by Brismar (2002) as naturally generated and maintained processes by rivers that are of societal value, people can also collect indirect benefits, including recreation, soil wetting and fertilization of floodplains and deltas, cultural identity and ecosystem maintenance. Nevertheless, increases in water uses to maximize river goods normally result in decreased indirect benefits from river services. This occurs because river flow and water quality are major determinants of river ecosystem condition (Acreman, 2016).

Obtaining direct benefits from water by producing electric power in dams frequently leads to reduced indirect benefits (Ziv et al., 2012). Dams and reservoirs used for hydropower production impact ecosystems by river habitat fragmentation, habitat transformation from lotic to lentic, retention of sediments and nutrients and river flow alteration (FitzHugh and Vogel, 2011; Schmutz and Moog, 2018). Expanding hydropower have been considered one of the main emerging threats to freshwater biodiversity (Reid et al., 2019) and the alteration of river flow regimes for hydropower production is a critical factor responsible for decline in freshwater communities (Poff and Zimmerman, 2010). To put in a global perspective, according to Grill et al. (2019) only 37 per cent of rivers longer than 1,000 kilometers remain free-flowing over their entire length and 23 per cent flow uninterrupted to the ocean.

While in North America and Europe most dams have been constructed before the second half of the XX century, in countries with emerging economies the pace of dam construction is still high (Zarfl et al., 2015; Winemiller et al., 2016). In South America, for example, new hydropower dams are being constructed and planned in regions within and around the Amazon basin, leading to considerable concerns about the possible environmental consequences (Finer and Jenkins, 2012; Tundisi et al., 2014; Pavanato et al., 2016; Forsberg et al., 2017; Latrubesse et al., 2017; Timpe and Kaplan, 2017; Anderson et al., 2018; Fraser, 2018; Santos et al., 2018). Only in the Brazilian Amazon, over 200 new hydropower dams are predicted to be constructed in the next 30 years (Timpe and Kaplan, 2017). When considering small hydropower plants, Couto and Olden (2018) estimated that 82,891 small hydropower plants were operating or under construction in 150 countries and that another 181,976 new plants may be installed if all potential capacity were developed in the next decades, most of them in countries such as Russia, China,

India, Brazil, and the United States. Despite being considered small, these dams also may have the capability to significantly alter the hydrological cycle, depending on its characteristic and the river they are located, especially considering hydrologic impact per megawatt (Timpe and Kaplan, 2017), to the point of affecting fauna and flora (Casas-Mulet et al., 2015; Bejarano et al., 2018; Mihalicz et al., 2019; Vehanen et al., 2020).

Regarding the expansion of the hydroelectric matrix in Brazil and its potential damages, besides the Amazon basin, another location where a large number of dams are planned is the Upper Paraguay river basin, a region that is notable for the Pantanal, a huge wetland ecosystem that is largely dependent on the flow regime of the Paraguay river and its tributaries. In this region, there is a debate about the potential impacts of new dam construction in the highlands (Planalto) on the ecosystems of the lower lying Pantanal (Bergier, 2013; Coelho da Silva et al., 2019; Medinas de Campos et al., 2020). In this context, it is worthwhile to carefully examine the hydrological changes that followed the construction of the major Manso dam, that started operation in 2000 at the headwaters of one of the major tributaries of the Paraguay river.

This task is not a completely original effort, since previous studies by Souza et al. (2009); Zeilhofer and de Moura (2009), and Timpe and Kaplan (2017) already analyzed hydrological changes downstream of the Manso dam. Zeilhofer and de Moura (2009) used streamflow data up to 2005, meaning that they analyzed only 4 years of data after the dam started to operate, while Souza et al. (2009) used slightly longer streamflow time series after the dam started to operate, by including data up to 2007. Both 4 and 6 years of data are normally considered to be unsatisfactory for the assessment of hydrological changes. Richter et al. (1997), for instance, propose a minimum of 20 years of pre and post-impact data. In the work by Souza et al. (2009), the authors tried to account for climatic variability by using benchmark gauging stations at rivers not influenced by Manso dam, but with limited success, since climatic variability plays an important role in the hydrological functioning of the region (Collischonn et al., 2001; Barros et al., 2004).

More recently, Timpe and Kaplan (2017) assessed hydrological regime changes due to the operation of several dams in Central and Northern Brazil, and showed that Manso dam has severe impacts on river regime, only second to the Balbina dam, on the Uatumã river, in the Amazon basin. However, their assessment was based on data from a single gauging station (Fazenda Raizama – ANA gauge 66231000) located just 15 km downstream of the dam. Therefore, the studies carried out on the impacts of the Manso dam have so far been restricted either in time, due to the low number of years used for the analysis of hydrological impacts, or in space, as they used few river gauges whose capacities to assess impacts are restricted to the locations where they are installed.

In order to overcome the limitations of previous studies, an alternative way to assess hydrologic alteration could be achieved by applying a distributed hydrological model with the ability of generating discharge time series at a multitude of points within the basin, and capable of representing scenarios with and without the dam operation in a realistic way. After proper parameter

calibration, this model could then be applied using observed time series of rainfall, generating results of the two scenarios (with and without the dam) for the same period of time, thus taking complete control of the influence of climatic variability. A further advantage of this method is that it generates results not only at places where observation gauges exist, but at several ungauged sites too, allowing an assessment of spatial patterns of hydrologic alteration.

This model-based methodology was previously adopted by Ryo et al. (2015) who used a distributed hydrological model to quantify the spatial patterns of flow regime alterations along the Sagami River basin network under natural and altered flow conditions. The use of hydrological models was also suggested by Poff et al. (2010) as a part of the ELOHA framework for the definition of environmental flows and advocated by Richter et al. (1997) and Kennen et al. (2008). However, adopting the model-based assessment of hydrological change approach in the Upper Paraguay river basin is particularly challenging, due to the complexities of the physical system, with large floodplains and lakes, and very mild slopes, as discussed by Paz et al. (2010).

In the present paper, we took advantage of previously developed hydrological models in the Upper Paraguay river basin (Paz et al., 2011, 2014; Bravo et al., 2012), and in other environments with significant floodplains (Pontes et al., 2017; Fleischmann et al., 2018) and applied them to assess the magnitude and extension of fluvial regime changes imposed by the operation of Manso dam on rivers within the Pantanal, therefore supplementing previous assessments made by Souza et al. (2009) and Zeilhofer and de Moura (2009). Using computational modeling by combining the MGB large-scale hydrologic model with the SIRIPLAN large-scale wetland model, the effects of Manso dam on the hydrology of the Upper Paraguay River Basin could be identified continuously along the drainage network downstream. With this approach, we could assess hydrologic alteration in any segment of the river network, not only at gauges like on previous studies on the same dam. In addition, confounding climatic variability effects could be isolated since the only difference between the two simulated scenarios is the Manso dam operation. This differentiates the present work from previous studies about the influence of Manso dam operation on the hydrological regime of the Cuiabá river and also the fact that the present research is based on a larger discharge time series than the previous ones. Also, by representing the interaction between river and floodplain through modeling, we were able to better comprehend the impacts that a dam can have on the flow exchange between them and how far those impacts can go, which may be of interest for other locations upstream or in floodplains, not only in the Pantanal or Amazon region, where dams are operating or are intended to be installed.

Therefore, there are two main contributions of our paper. First, we define the magnitude, extent and spatial distribution of changes in the hydrological regime caused by a large dam in the Pantanal, which is a region of globally recognized ecological importance. This definition was made less influenced by other factors than previous studies, such as climate variability, and, therefore, makes it possible to analyze the influence of the dam's operation more clearly. Second, we present an innovative way to analyze changes in hydrological regime by using hydrologic and hydrodynamic models of rivers with extensive floodplains, and with complex drainage patterns. Although the use of distributed hydrological models to assess and quantify the spatial patterns of flow regime alterations along the drainage network of a river basin have been presented before by Ryo et al. (2015), our study extends this approach to the wider and much more complex environment of the Pantanal wetland.

MATERIALS AND METHODS

The South American Pantanal and the Upper Paraguay River basin

The Paraguay river is the major tributary of the Paraná river basin within the Paraná – La Plata river basin, draining an area of about 1.2 million km^2 (Collischonn et al., 2016). The Upper Paraguay region is the 600,000 km^2 basin upstream of the confluence of the Paraguay river with the Apa river, which marks the limits between Brazil and Paraguay (**Figure 1**). The region is within a seasonally dry tropical region, roughly defined by latitudes 14 and 33 South, and longitudes 53 and 60 West, and encompasses parts of three countries (Brazil, Bolivia, and Paraguay).

The landscape in the region is normally divided in two parts: the Planalto (Uplands) above nearly 200 m altitude; and the Pantanal (Wetland) below 200 m altitude. Rivers in the Planalto region are normally incised in bedrock, and flow into the Pantanal where they become alluvial (Assine et al., 2015). The Pantanal is an extensive low-lying region that was probably formed by subsidence followed by infilling with sediments from the Planalto, with 500 m of sediment deposits measured in some places (Assine et al., 2015). Deposition is still occurring, therefore, the Pantanal is a place of changing rivers with active and abandoned alluvial fans, which form a varied system (Assine et al., 2015). Due to this the Pantanal is a mosaic of variable flooded environments, including permanent lakes, water-filled depressions and small lakes that dry out seasonally, temporary flood drainages with sand or short grass and relatively permanent channels that connect flooded areas (Evans et al., 2010; Girard et al., 2010).

In terms of biodiversity, Pantanal is known for its numerous species and a rich diversity of aquatic and terrestrial ecosystems (Agência Nacional das Águas , 2004), being recognized by UNESCO as a World Biosphere Reserve and as a National Heritage by the National Constitution of Brazil. Pantanal presents a unique variety of fishes, although a considerable number have likely not been identified yet (Shimabukuro-Dias et al., 2017). Barletta et al. (2010) state that about 270 fish species have been reported in the Pantanal, while Petrere et al. (2002) cite estimates of 400 fish species. Both artisanal and recreational fisheries are mostly supported by large migratory species, and tourism fishing is gaining more importance in the last decades (Mateus et al., 2004; Barletta et al., 2010). Migratory movements comprise ascending displacements for spawning that can reach 400 km or even more for some species (Hahn et al., 2011; Barzotto and Mateus, 2017). These migrations are in phase with

the rainy season, and the high fish productivity in the region is normally related to the seasonal inundation of floodplains (Barletta et al., 2010).

Over most of the region, rainfall in the six wettest months from October to March accounts for more than 80% of the annual total. Annual average precipitation varies from above 2000 mm in the Northeast of the basin to below 1000 mm in the West, along the border between Brazil and Bolivia (CPRM, 2011). Regularity of climate, with well-defined wet and dry seasons, together with the damping effect of floodplain inundation over the progress of the flood wave, results in a highly predicable flood pulse every year, with a single flood peak occurring in more or less the same time every year. This regular flooding and drying behavior, known as flood pulse, has strong influences on the regions ecological processes (Junk et al., 1989, 2006) and, also, strong consequences on human occupation of the Pantanal. This, together with access difficulties and isolation from major demographic centers hindered economic development and human occupation of the Pantanal. As a consequence, the region still has a very low demographic density and features unique natural landscapes, relatively untouched ecosystems, and traditional cultural practices and is known for its outstanding biological resources making it a priority for Brazilian and international conservation efforts (Junk and de Cunha, 2005; Schulz et al., 2019).

Flood waves formed in the Planalto rivers move relatively quickly to the Pantanal, where large portions of the water spread over the floodplain and deviate from the main channels through divergent drainage networks formed over alluvial fans (Paz et al., 2010; Assine et al., 2015). The overflow of the river channel and consequent floodplain inundation reduces peak discharges to more than one-half along the main rivers that flow into the Pantanal. These effects strongly modify the shape of hydrographs from upstream to downstream, as exemplified by Paz et al. (2010). Peak flows typically occur in February in the northeastern Planalto rivers, concomitantly with rainfall maximums. In the floodplains, on the other hand, flood peaks are delayed due to its slow movement, and typically occur in June, which corresponds to the dry season, in the middle of the Pantanal (Paz et al., 2010). The maximum area subject to inundation in the Pantanal, which include permanent open waters of river channels and lakes, is above 130,000 km^2, while the long-term mean inundation area is around 35,000 km^2, according to Hamilton et al. (2002).

Several studies relate the ecological functioning of the region to the fluvial regime, including floods, low water, timing of floods, and other abiotic variables related to hydrology. For instance, Bailly et al. (2008) stated that floods of the Cuiabá river, one of the most important tributaries of the Paraguay river, have an important role in the recruitment of species and influence spawning success as well as juvenile survival, and that floods are the principal trigger for the reproduction of many species of fishes. The overarching influence of the fluvial regime on the ecosystem was further highlighted in several other studies (Catella and Petrere, 1996; Petrere et al., 2002; Marchese et al., 2005; Costa and Mateus, 2009; Lourenço et al., 2012; Pinho and Marini, 2012; Ziober et al., 2012; Penha et al., 2015, 2017; Súarez and Scanferla, 2016; Wantzen et al., 2016; Barzotto and Mateus,

2017; Pereira and Súarez, 2018; Tondato et al., 2018; Santana et al., 2019).

Considering this strong dependency of the ecosystem on the natural hydrological regime in the Pantanal, it is expected that changes to the hydrological regime can severely impact ecosystem functioning, as reported in several other places in the world (Poff et al., 2010), including rivers in South America. River regime changes by dam operation have already impacted the ecosystem of the nearly located Paraná river basin, where flow regulation reduced the extent and duration of flood events, limiting or frustrating the reproductive processes of several fish species (Agostinho et al., 2004) and impacting fish populations (Agostinho et al., 2004, 2007, 2016).

According to the Brazilian Water Agency (ANA), there are currently 47 hydropower plants operating at the Upper Paraguay river basin, and more than 100 other hydroelectric facilities are currently in the proposed or construction stages (Medinas de Campos et al., 2020). Among the currently operating facilities, Manso dam is the one with the greatest potential of impacts on the hydrological regime of the Pantanal, due to its large reservoir, even though some regime changes have been reported for the relatively smaller Ponte de Pedra (Fantin-Cruz et al., 2015) dam.

The Manso Dam

Manso dam is a multipurpose dam that was conceived mainly for hydropower generation and flood control (Zeilhofer and de Moura, 2009; Paes and Brandão, 2013). The dam is located on the Manso River (**Figure 1**), one of the major rivers that form the Cuiabá River, at a point where drainage area is 9365 km^2, and average discharge is estimated at 170 m^3.s^{-1}. The reservoir has a total volume of 7.3 × 10^9 m^3 with an active storage capacity of 2.95 km^3 in the elevation range between 278 m (minimum operational level) and 287 m (maximum normal operation level), and additional 0.45 km^3 for flood control in the elevation range between 287 and 288.15 m (Paes and Brandão, 2013). The reservoir regulates the flow of the Manso river and of the Cuiabá river downstream. The dam is located almost 300 km upstream of the cities of Cuiabá and Várzea Grande, which are the main targets for flood control. Downstream from the city of Cuiabá, the Cuiabá river drains into the Pantanal, where it connects to lakes and the floodplain through side channels. The confluence of the Cuiabá and Paraguay river is located well within the Pantanal, at about 900 km downstream of the Manso dam.

The reservoir of Manso dam begun to be filled in November 1999, and the dam started operation in November 2000 (Furnas Centrais Elétricas, 2002). The reservoir was scheduled to be filled by the end of 2000 but due to lower than expected precipitation the complete filling only occurred in February 2002, when it reached the maximum level of 287.5 m (Shirashi, 2003).

Hydrological Modeling

We assessed hydrologic alteration caused by Manso dam operation in the Pantanal region using synthetic streamflow time series obtained by a combination of two hydrologic models and the Indicators of Hydrologic Alteration (Richter et al., 1996) metrics.
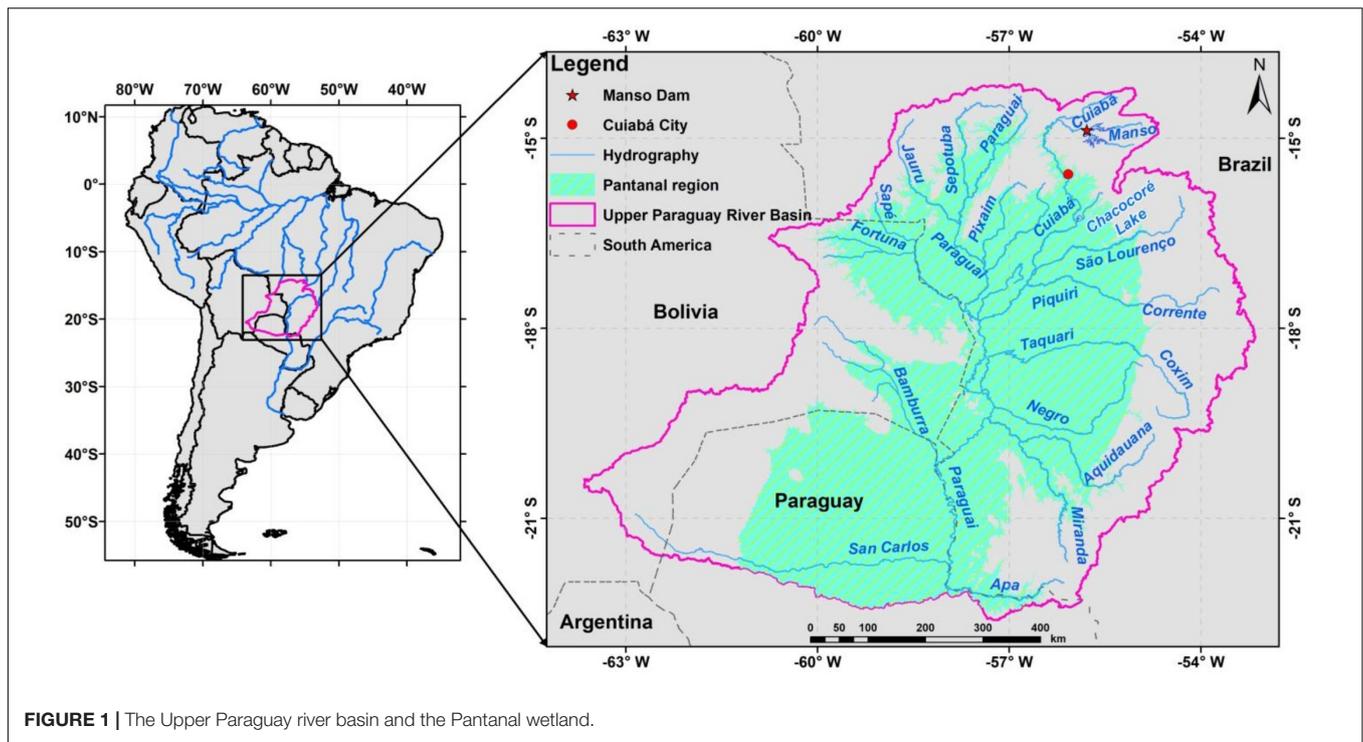
FIGURE 1 | The Upper Paraguay river basin and the Pantanal wetland.

We divided the Upper Paraguay river basin in two regions, following a threshold altitude of 200 m (Assine et al., 2015). In regions above 200 m we applied the MGB large-scale hydrological model (Collischonn et al., 2007), further described in Section "Hydrologic Model of the Upper Basin (Planalto), Input Data, and Scenarios." In regions below 200 m, where the drainage network is not dendritic, and where there are several interconnected lakes, temporary inundated areas and secondary channels, we applied the coupled 1D/2D SIRIPLAN model (Paz et al., 2011), further described in Section "Hydrologic Model of the Lower Basin (Pantanal)." The two modeling sub-regions of the basin are shown in **Figure 2** along with the main river gauges used during the calibration of one model or another.

The MGB model of the upper basin was applied first, and output of this model was introduced as boundary conditions for the SIRIPLAN model, which was applied in sequence, at the nine most important inflow points to the Pantanal, as shown by the gauges in red in **Figure 2**. The blue gauges inside the SIRIPLAN modeling region were used for calibration of this model.
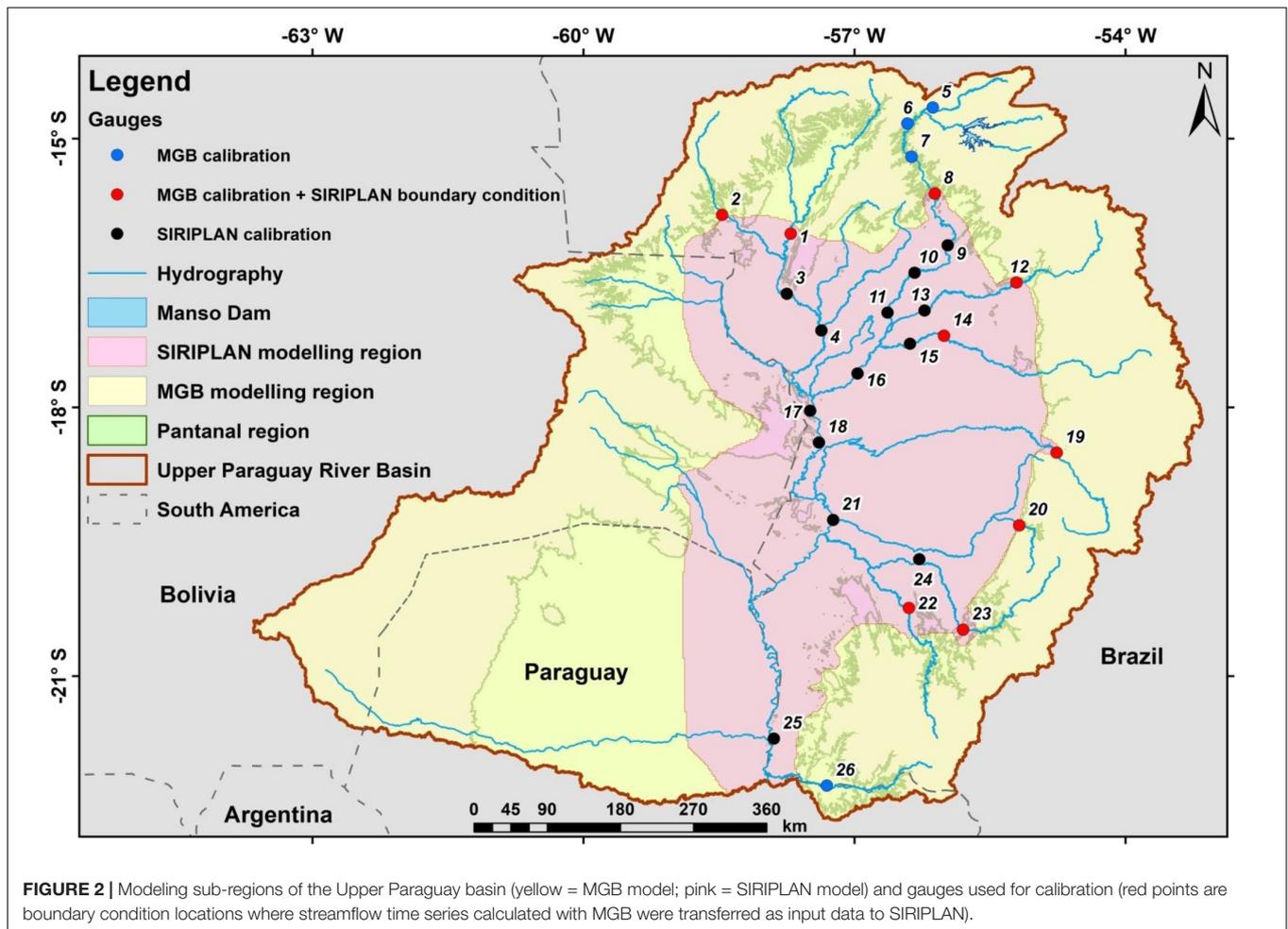
MGB was applied in two scenarios: with and without Manso dam operation, applying methods described in Section "Hydrologic Model of the Upper Basin (Planalto), Input Data, and Scenarios." Results of the MGB model in the two scenarios were then used as boundary conditions (input variables) to the SIRIPLAN model. **Table 1** presents the characteristics of the main river gauges used for calibration and the performance measures Nash-Sutcliffe, used for calibration of maximum flows, Nash-Sutcliffe of the logarithm of the flows, used for calibration of minimum flows, and the volumetric error (BIAS). Further details on the calibration can be found in the work by Paz et al. (2011).

Both MGB and SIRIPLAN are distributed models and provide results of daily streamflow and water stage at river segments of 2 to 10 km covering the whole drainage network of the Upper Paraguay river basin, at least for rivers with drainage area above 20 km^2. Time series covering the period from 01/01/2003 to 31/12/2015, considering the scenarios with and without Manso dam, were then analyzed using the Indicators of Hydrologic Alteration (Richter et al., 1996). These metrics include mean monthly flows, minimum and maximum river discharge values for 1, 3, 7, 30 and 90 days, Julian day of the maximum and minimum flows, as further described in Section "Assessment of Hydrological Change."

Therefore, for each river segment, two different IHA metric values were obtained, one for each scenario. These two values were subsequently compared and the magnitude of change was estimated as a relative departure of the original value for the majority of the metrics, or as an absolute deviation in the case of the Julian day of minimum and maximum flows. This methodology allowed us to obtain results of the spatial variability of dam impact.

Hydrologic Model of the Upper Basin (Planalto), Input Data, and Scenarios

MGB is a semi-distributed, process-based model developed for large-scale to continental regions. It was first presented by Collischonn et al. (2007), and subsequently improved by Paiva et al. (2011); Pontes et al. (2017), and Fleischmann et al. (2018). The model was used before in several large basins of South America, including assessments of climate change impacts in the Amazon (Sorribas et al., 2016); potential impacts of dams on fluvial ecosystems (Forsberg et al., 2017); hydrological reanalysis

FIGURE 2 | Modeling sub-regions of the Upper Paraguay basin (yellow = MGB model; pink = SIRIPLAN model) and gauges used for calibration (red points are boundary condition locations where streamflow time series calculated with MGB were transferred as input data to SIRIPLAN).

(Wongchuig et al., 2019); water management scenarios in transboundary river basins (Gorgoglione et al., 2019); streamflow forecasting (Fan et al., 2015); and continental hydrological modeling for South America (Siqueira et al., 2018).

In its most recent version, MGB divides the river basin in relatively small unit-catchments. This unit-catchments are defined based on the contribution areas that drains to river segments, which are divided with constant length (Siqueira et al., 2016). Within each unit-catchment, Hydrological Response Units (HRU's) are defined based on soil type and land use, and for each one the water and energy budget is computed through the soil-vegetation system, as described by Collischonn et al. (2007). Surface, subsurface and groundwater outflows from water balance are routed to the main river of the unit catchment using linear reservoirs, while flow propagation through drainage networks is computed using either the Muskingum-Cunge method or 1D hydrodynamic equations (Pontes et al., 2017). To access the influence of dams and reservoir operation within MGB it can be done by introducing internal boundary conditions at the dam location, and forcing the model with observed reservoir outflow data, or by specifying reservoir operation rules (Fleischmann et al., 2019).

In order to do so for the Manso Dam case the model was calibrated using precipitation and river discharge data obtained mainly from the National Water Agency (ANA) in Brazil. We used data from 153 precipitation gauges and a total of 42 streamflow gauges distributed over the whole Upper Paraguay river basin to calibrate the model, focusing on the Planalto region. The main gauges are presented in **Figure 2**. Rainfall information outside Brazil was obtained from the Multi-Source Weighted-Ensemble Precipitation (MSWEP) product, that is based mainly on satellite precipitation estimates.

Operational data of the Manso dam were also obtained from ANA, including observed outflow time series and naturalized time series from 01/01/2001 to 31/12/2015. Naturalized streamflow is an information routinely estimated for the main hydropower reservoirs in Brazil by ANA and ONS (Operador Nacional do Sistema) (Agência Nacional da Água, 2011) and corresponds to streamflow that would be observed at the dam site if there was no flow regulation by reservoirs and no water abstractions upstream.

After model calibration and verification MGB was applied in two scenarios during the period from 01/01/1985 to 31/12/2015. In the first scenario, intended to represent the natural condition, we used naturalized streamflow at the dam site as input to the

TABLE 1 | Characteristics of the main river gauges presented in **Figure 2**, used during calibration of the MGB and SIRIPLAN models, and the performance measures obtained.

Gaude ID	Gauge Code	Gauge name	Drainage area (km^2)	River	Nash	Nash-log	BIAS (%)
1	66070004	Cáceres	32400	Paraguai	0.816	0.851	2.0
2	66072000	Porto Esperidião	5660	Jauru	0.402	0.502	−13.6
3	66090000	Descalvados	47100	Paraguai	0.910	0.920	−5.0
4	66120000	Porto Conceição	64000	Paraguai	0.630	0.620	7.6
5	66160000	Quebó	4260	Cuiabá	0.601	0.789	−25.1
6	66250001	Rosário Oeste	16000	Cuiabá	0.709	0.784	−6.5
7	66255000	Acorizal	19700	Cuiabá	0.758	0.825	−3.8
8	66260001	Cuiabá	23500	Cuiabá	0.748	0.821	−5.5
9	66280000	Barão de Melgaço	28900	Cuiabá	0.940	0.970	−5.8
10	66340000	Porto Cercado	36900	Cuiabá	0.910	0.920	−4.6
11	66360000	São João	38500	Cuiabá	0.820	0.840	−8.8
12	66460000	Acima do Córrego Grande	23000	São Lourenço	0.588	0.823	−1.0
13	66470000	São José do Boriréu	24100	São Lourenço	0.920	0.940	4.9
14	66600000	São Jerônimo	23300	Piquiri	0.581	0.665	−6.8
15	66650000	São José do Piquiri	30000	Piquiri	0.750	0.820	8.9
16	66750000	Porto Alegre	103000	Cuiabá	0.820	0.850	8.3
17	66800000	Amolar	234000	Paraguai	0.670	0.720	6.3
18	66810000	São Francisco	243000	Paraguai	0.700	0.730	−2.0
19	66870000	Coxim	27600	Taquari	0.326	0.531	−7.3
20	66886000	Perto da Bocaina	2840	Negro	−1.034	−0.124	32.9
21	66895000	Porto da Manga	327000	Paraguai	0.820	0.760	2.5
22	66910000	Miranda	15000	Miranda	0.273	0.579	15.7
23	66945000	Aquidauana	15700	Aquidauana	−0.403	0.491	19.4
24	66950000	Porto Ciriaco	17200	Aquidauana	0.760	0.830	−3.5
25	67100000	Porto Murtinho	576000	Paraguai	0.610	0.650	−6.1
26	67170000	São Carlos	10200	Apa	0.484	0.620	11.0

hydrological model. In the second scenario, intended to represent the impact condition, we used observed reservoir outflow time series as input to the hydrological model. In those two scenarios the rainfall-runoff processes upstream of the Manso dam have been turned off, since the dam was represented as a boundary condition. However, in the remaining area of the basin, the rainfall-runoff and flood routing processes have been ordinarily represented by the model.

Hydrologic Model of the Lower Basin (Pantanal)

Outputs from the hydrological model described in Section "Hydrologic Model of the Upper Basin (Planalto), Input Data, and Scenarios" were introduced as inputs for the hydrologic hydrodynamic model of the Pantanal wetland, called SIRIPLAN (Paz et al., 2011, 2014). SIRIPLAN is composed by a 1D hydrodynamic model based on a solution of the full Saint Venant equations for river networks (Tucci, 1978) coupled to a 2D raster-based inundation model, similar to the LISFLOOD-FP model (Bates et al., 2010).

The 1D model simulates the flow routing along the river drainage system, considering cross sections restricted to the main channels. The raster-based model simulates the water accumulation and the 2D propagation of inundation over the floodplains. A water exchange scheme is used to simulate channel outflows to the floodplain and from the floodplain

back into the channel (Paz et al., 2011). Additionally, the vertical processes of precipitation, evapotranspiration and infiltration in the floodplain are simulated in the 2D part of SIRIPLAN, following the methods described by Paz et al. (2014).

SIRIPLAN was previously applied in the same region by Paz et al. (2011, 2014). A total of 3965 km of main river channels and 219,514 km^2 of floodplains were represented by the model. Rivers were discretized in 2 km long computational reaches, and floodplains were divided in 46,741 square-grid elements of 0.02 × 0.02 degrees (approximately 2 × 2 km). The model was calibrated by comparing discharge hydrographs and water level time series at several gauging stations on the rivers Paraguay, Cuiabá, and other tributaries, and satisfactorily reproduced the hydrological regime in most of the basin. SIRIPLAN is arguably the most detailed and accurate hydrologic-hydrodynamic model that has been applied to the whole Pantanal.

In addition to daily river discharge and water level time series along the main rivers and over the floodplain, SIRIPLAN's outputs include the amount of water that is delivered from the rivers to the floodplains, and backward. This feature is particularly interesting in the present context of evaluating the hydrological changes due to the operation of an upstream located dam, since hydrological changes may be not limited to river discharges, but possibly include river-floodplain interaction.

TABLE 2 | Indicators of Hydrologic Alteration (IHA) flow regime descriptors (from Richter et al., 1996).

Main IHA groups	Descriptors of river regime
Group 1. Magnitude of monthly water conditions	Mean discharge for each calendar month (12 descriptors)
Group 2. Magnitude and duration of annual extremes	1-day-minimum flow
	1-day-maximum flow
	3-day-minimum flow
	3-day-maximum flow
	7-day-minimum flow
	7-day-maximum flow
	30-day-minimum flow
	30-day-maximum flow
	90-day-minimum flow
	90-day-maximum flow
Group 3. Timing of annual extremes	Date of 1-day maximum flow
	Date of 1-day-minimum flow
Group 4. Frequency and duration of high and low pulses	Annual number of high pulses
	Annual number of low pulses
	Mean duration of high pulses (days)
	Mean duration of low pulses (days)
Group 5. Rate and frequency of change in conditions	Mean daily flow increase
	Mean daily flow decrease
	Number of reversals

Assessment of Hydrological Change

For the assessment of hydrological change, we examined results from the natural and altered hydrological scenarios using the 28 out of the 32 descriptors of river regime proposed by Richter et al. (1996) in their Indicators of Hydrologic Alteration (IHA) methodology. The IHA descriptors are biologically relevant hydrological indices that cover flow magnitude, frequency, duration, timing, and rate of change believed to be essential to ecosystem health (Poff et al., 1997), and are given in **Table 2**. Among the 32 IHA descriptors, we observed that the four metrics related to high and low flow pulses were hypersensitive to small changes in the hydrographs due to the way the low flow and high flow thresholds are defined, so we skipped all those four descriptors of group 4 (**Table 2**).

All the 28 metrics of groups 1, 2, 3, and 5 were obtained for every year along the simulation period (from 2003 to 2015) for the two scenarios (with and without dam operation), and its average value (mean of the 12 simulation years) in the two scenarios were compared to assess the magnitude of change, following equations 1 (for groups 1, 2, and 5) or Eq. 2 (for group 3).

$$A = \frac{X_D - X_0}{X_0} \tag{1}$$

$$A = \frac{J_D - J_0}{\left(\frac{365}{2}\right)} \tag{2}$$

were X_0 is the value of the descriptor in the reference scenario (no dam operation); X_D is the value of the descriptor in the altered scenario (with dam operation); J_0 is the Julian day of the maximum or minimum in the reference scenario; J_D is the Julian day of the maximum or minimum in the altered scenario.

We understand that applying Eq. 1 to changes in timing would lead to the wrong conclusion that a 20 days change in events typically occurring earlier during the hydrological year (lower Julian day values) represents a larger relative change than a 20 days change (delay or anticipation) occurring later in the hydrological year. Therefore, we used Eq. 2 to calculate relative change in minimum and maximum dates, as a substitute of Eq. 1, because we understand that a 20 day change should represent the same relative change, independently of the date in the reference scenario (J_0), and that the worst change in timing would be a delay or anticipation of half year (or 365/2 = 182.5 days), and this should be equivalent to 100% change.

Besides, to calculate average Julian dates we used circular statistics. Circular statistics is a subfield of statistics, devoted to the development of statistical techniques for data on an angular scale, for which there is no designated zero, and the designation of high and low values is arbitrary, such as the direction of wind, the time of the day, or the day of the year, as in statistics of group 3 (Berens, 2009).

Finally, we compared results of the 28 descriptors at all river computational elements of the model downstream of the dam, resulting in 857 points where the IHA descriptors were compared. In order to present the results in a synthesized way and also in the form of maps, the averages of the alteration of all the descriptors within the same group were performed for each simulated model element.
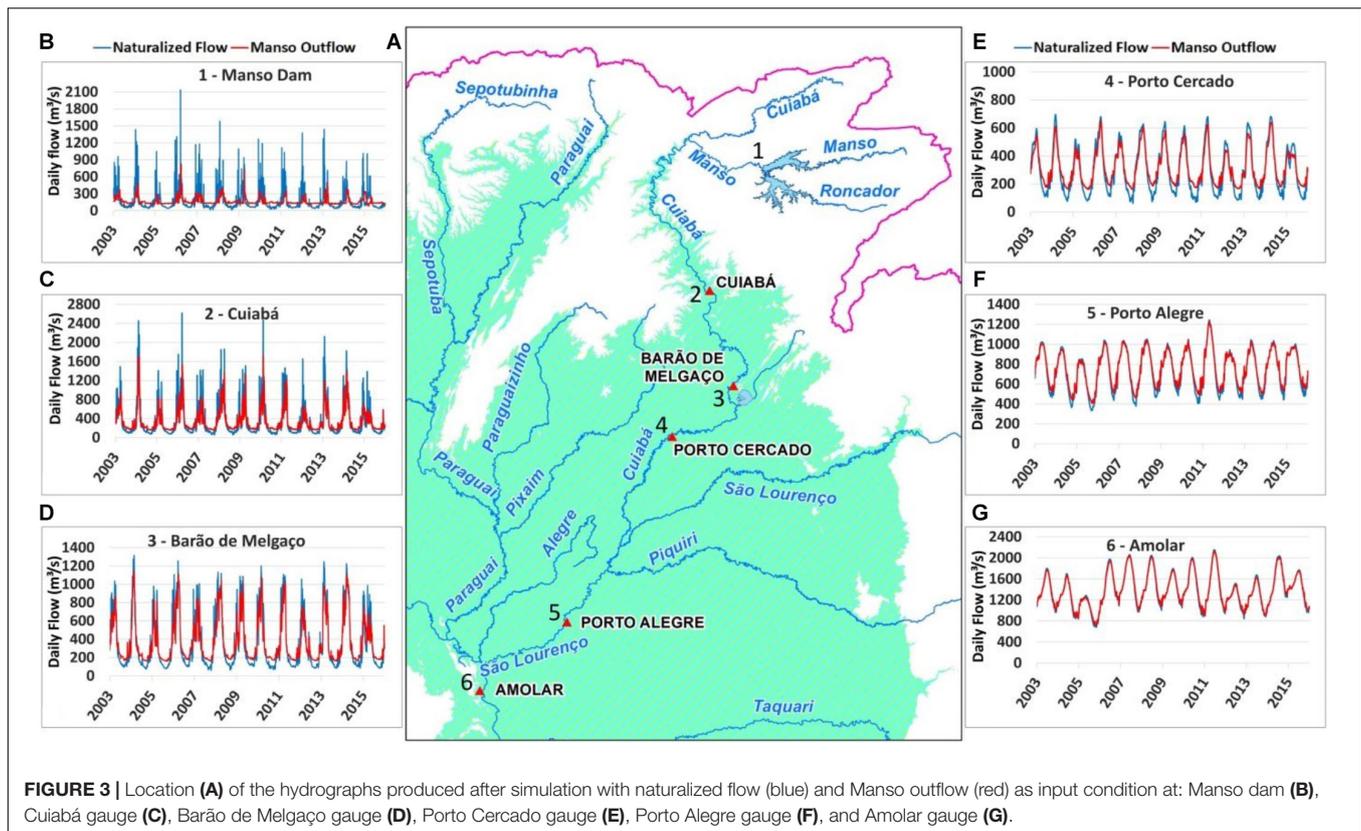
RESULTS

River discharge time series were calculated at river reaches 2 to 10 km long over the whole Upper Paraguay river basin during the period from 2003 to 2015, considering two scenarios: with and without dam operation. In the first scenario, intended to represent the natural or reference condition, we used naturalized streamflow at the dam site as input to the hydrological model. In the second scenario, intended to represent the impact condition, we used observed reservoir outflow time series as input to the hydrological model.

Hydrologic Alteration Along the Main River

In order to evaluate the changes between the two scenarios, hydrographs where plotted at six locations downstream of the dam (**Figure 3**). The results show that just downstream of the dam, the regulation effect of Manso dam operation clearly reduced high flows and increased low flows (**Figure 3B**). Low flows are increased from about 60 m^3.s^{-1} to circa 130 m^3.s^{-1}, while maximum flows are reduced from up to 2,100 m^3.s^{-1} to below 900 m^3.s^{-1} at all times. The timing of maximum flows was also altered, with maximum flows occurring 3 to 17 days later in the scenario with dam operation.

By Cuiabá city, nearly 300 km downstream of the dam, and also the point where the Cuiabá river leaves the upper region

FIGURE 3 | Location **(A)** of the hydrographs produced after simulation with naturalized flow (blue) and Manso outflow (red) as input condition at: Manso dam **(B)**, Cuiabá gauge **(C)**, Barão de Melgaço gauge **(D)**, Porto Cercado gauge **(E)**, Porto Alegre gauge **(F)**, and Amolar gauge **(G)**.

and flows into the Pantanal, the same pattern of alteration is still clearly visible (**Figure 3C**). Low flows are increased from about 93 to 170 $m^3.s^{-1}$, while maximum flows are reduced from the range 1,390–2,617 $m^3.s^{-1}$ to below 1,723 $m^3.s^{-1}$ at all times and can be as low as 650 $m^3.s^{-1}$. The timing of maximum flows was also altered, with maximum flows occurring 2 to 5 days later in the scenario with dam operation.

At Barão de Melgaço, approximately 420 km downstream of the dam, the hydrograph shows that changes in low flows are still clearly visible with an increase from about 90 $m^3.s^{-1}$ in the scenario without dam operation to about 165 $m^3.s^{-1}$ in the scenario with dam operation (**Figure 3D**). Changes in maximum flows, on the other hand, are less marked. This occurs because maximum flows are naturally decreased while the flood wave moves from Cuiabá to Barão de Melgaço, due to river outflowing to the floodplains, mainly through distributary channels. Maximum river discharges at Barão de Melgaço are in the range of 980 to 1,315 $m^3.s^{-1}$ in the scenario without dam operation and drop to about 750 and 1,140 $m^3.s^{-1}$ at the same events in the scenario with dam operation. Changes in the timing of maximum flows at Barão de Melgaço due to dam operation are lower than 5 days.

Circa 550 km downstream of the dam, at Porto Cercado, and already well within the Pantanal, changes in low flows are still clearly visible, while changes in maximum flows are slightly perceived. At this location, changes in timing of maximum flows are practically absent (**Figure 3E**). The same behavior is observed at Porto Alegre (**Figure 3F**), located 825 km downstream of the

dam. At this point, dissemblance between the hydrographs are only clearly perceptible at low flows but, even so, with small differences. Finally, at Amolar, after the confluence with the Paraguay river, there is practically no difference between the hydrographs for both scenarios (**Figure 3G**).

It is clear in all IHA groups that changes are higher just downstream of the dam, and progressively decrease downstream, as the Cuiabá river flows into the Pantanal (**Figure 4**). This is due probably to both the entry of large tributaries into the impacted network, as is the case of the São Lourenço river already within the Pantanal, and due to river-floodplain interaction. It is noticeable at **Table 3**, which summarizes the results found regarding IHA statistics for the locations previously analyzed (**Figure 3**), that in January (wet season) average flows decrease more than 44% just downstream of the dam (point 1), more than 22% at Cuiabá (2) and more than 13% at Barão do Melgaço (3). August/September (dry season) average flows increase more than 140% at the dam (1), and more than 70% as far as Porto Cercado (point 4), located more than 500 km downstream of the dam.

Minimum flows increase substantially due to dam operation as far as Porto Cercado (point 4), and are still present as far as Amolar (point 6), on the Paraguay river. Changes in timing of both minimum and maximum flows are large just downstream of the dam (point 1), but decrease rapidly with distance downstream. Rates of change decrease at all six points downstream of the dam, with greater values close to the dam, and lower values as the Cuiabá river enters the Pantanal. Nevertheless, decreases of the rates of change larger than 5% are still present at

TABLE 3 | Summary of relative changes in average IHA descriptors at reference points.

Changes in parameters of the indicators of hydrologic alteration		Location					
		Manso dam	**Cuiabá**	**Barão do Melgaço**	**Porto Cercado**	**Porto Alegre**	**Amolar**
Group 1. Magnitude of monthly water conditions	Mean January flow	−44.6%	−22.7%	−13.7%	−6.5%	0.9%	0.5%
	Mean February flow	−43.3%	−19.9%	−13.5%	−8.3%	−0.7%	−0.2%
	Mean March flow	−26.8%	−12.1%	−10.4%	−8.8%	−1.1%	−0.2%
	Mean April flow	−0.6%	−1.4%	−6.7%	−8.2%	−1.7%	−0.6%
	Mean May flow	47.2%	23.1%	7.5%	−1.7%	−1.9%	−1.5%
	Mean June flow	73.8%	39.2%	26.4%	10.7%	−0.7%	−1.7%
	Mean July flow	115.7%	61.5%	47.0%	29.9%	2.0%	−1.1%
	Mean August flow	146.0%	79.9%	71.4%	56.7%	7.7%	0.8%
	Mean September flow	124.2%	75.2%	78.0%	71.2%	13.8%	3.3%
	Mean October flow	69.5%	42.1%	52.7%	53.0%	12.4%	4.0%
	Mean November flow	16.1%	9.7%	20.8%	21.4%	7.7%	3.2%
	Mean December flow	−27.1%	−13.8%	−8.1%	1.8%	4.7%	2.3%
Group 2. Magnitude and duration of annual extremes	1-day-minimum flow	196.5%	111.4%	108.0%	100.2%	16.8%	3.5%
	1-day-maximum flow	−66.1%	−34.3%	−13.7%	−9.0%	−1.7%	−1.8%
	3-day-minimum flow	209.4%	111.4%	107.0%	99.2%	16.7%	3.5%
	3-day-maximum flow	−59.5%	−31.8%	−13.3%	−9.0%	−1.7%	−1.8%
	7-day-minimum flow	196.5%	106.8%	103.2%	95.5%	16.4%	3.4%
	7-day-maximum flow	−48.9%	−26.1%	−12.3%	−8.9%	−1.7%	−1.8%
	30-day-minimum flow	155.4%	85.5%	83.1%	76.3%	14.4%	3.1%
	30-day-maximum flow	−37.1%	−18.9%	−11.4%	−8.8%	−1.8%	−1.8%
	90-day-minimum flow	125.8%	73.0%	70.6%	62.8%	12.0%	3.0%
	90-day-maximum flow	−34.6%	−16.8%	−11.3%	−8.5%	−1.5%	−1.5%
Group 3. Timing of annual extremes	Date of 1-day maximum flow	−65.8%	−1.6%	−0.5%	1.1%	3.3%	1.1%
	Date of 1-day-minimum flow	18.6%	−1.6%	2.7%	−1.6%	−2.7%	0.0%
Group 5. Rate and frequency of change in conditions	Mean daily flow increase	−78.4%	−45.0%	−32.2%	−33.2%	−4.7%	−5.8%
	Mean daily flow decrease	−81.8%	−51.4%	−34.6%	−34.7%	−11.8%	−7.6%
	Number of reversals	18.1%	14.8%	8.9%	10.1%	0.2%	0.1%

Amolar (point 6), which is on the river Paraguay, and is nearly 900 km downstream of the dam. Finally, the number of flow reversal increases as far as Porto Cercado (point 4).

Figure 4 shows how Manso dam operation changes the average descriptors from IHA along the rivers of the Upper Paraguay basin. These maps suggest that the effects of Manso dam operation are practically dissipated downstream of the points where the Cuiabá river meets the São Lourenço and Piquiri rivers.

Changes in River-Floodplain Interaction

To investigate how Manso dam operation affects the river-floodplain interaction we investigated hydrographs of the outflows from the river to the floodplain. The river-floodplain exchange flow rates simulated in both scenarios were obtained from SIRIPLAN model, with and without the operation of the dam. We selected the approximately 140 km reach between Cuiabá (point 2) and Barão do Melgaço (point 3), which was described by Paz et al. (2014) as a reach where the river mainly loses water to the floodplain, and summed all outflows from

the river to the floodplain, resulting in hydrographs of river-floodplain interaction over the entire 140 km reach. River-floodplain interaction is highest during the wet season, and to illustrate this interaction we selected two outflow events that occurred in January/February: one for a relatively wet year (2010) and one for a relatively dry year (2012).

Along the reach between Cuiabá and Barão do Melgaço, from 22 February to 07 March 2010 in both scenarios (with and without Manso dam operation) the peak outflow from the river to the floodplain is above 1200 $m^3.s^{-1}$ in the reference scenario (no dam operation) while it is lower than 700 $m^3.s^{-1}$ in the altered scenario (**Figure 5A**). Hydrograph volume is also lower in the altered scenario by nearly 40%, meaning that river-floodplain interaction is weaker. Meanwhile, from 25 January to February 1st 2012 the outflow peak in the scenario without Manso is close to 600 $m^3.s^{-1}$, while in the altered scenario (with Manso dam operation) there is no outflow from river to floodplain at all (**Figure 5B**).

The same pattern shown in the two described events occur every year, with outflow hydrographs being reduced
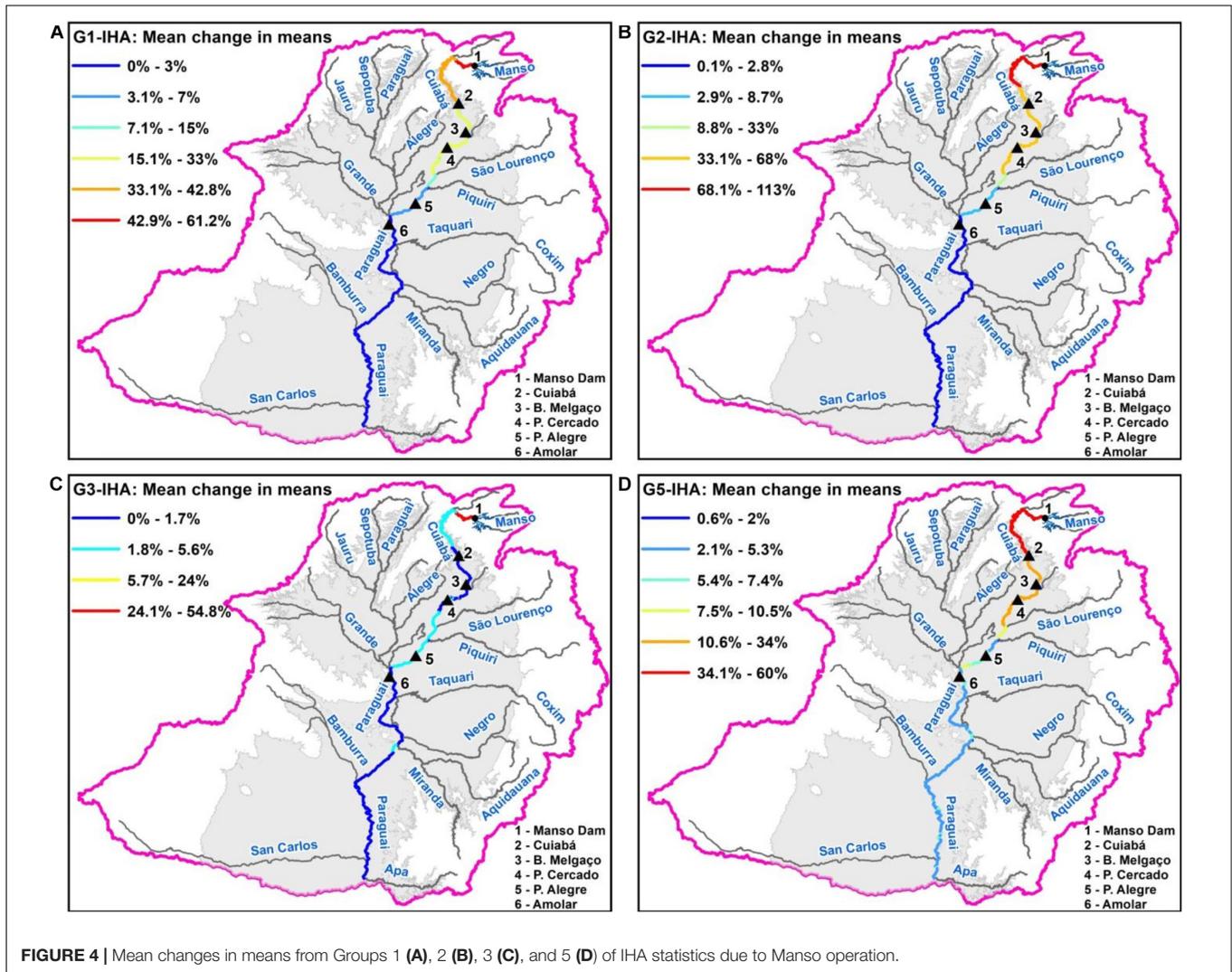
FIGURE 4 | Mean changes in means from Groups 1 **(A)**, 2 **(B)**, 3 **(C)**, and 5 **(D)** of IHA statistics due to Manso operation.
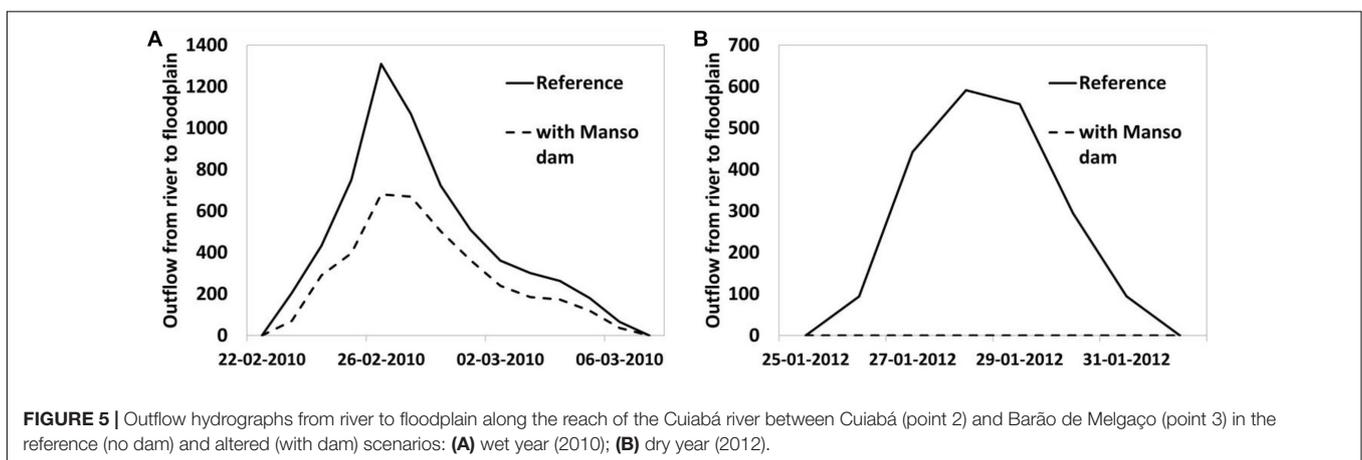

FIGURE 5 | Outflow hydrographs from river to floodplain along the reach of the Cuiabá river between Cuiabá (point 2) and Barão de Melgaço (point 3) in the reference (no dam) and altered (with dam) scenarios: **(A)** wet year (2010); **(B)** dry year (2012).

by the dam operation. Average peak outflows during the years 2003 to 2015 are 64% lower in the altered scenario than in the reference scenario. This result suggests that despite high flows along the main river within the Pantanal

(downstream of Cuiabá) are relatively less altered by Manso dam operation, the river-floodplain interaction seems to be severely impacted, at least along the reach between Cuiabá and Barão de Melgaço. The intensity of river-floodplain

interaction in the form of outflows from the river to the floodplain seems to be lessened along an important 140 km reach, and, therefore, river-floodplain connectivity, including the flux of sediments, nutrients, fish eggs and larvae may be weakened.

DISCUSSION

Our results show that, as expected, Manso dam has a regulation effect and decreases high flows and increases low flows. The decrease in high flows is somewhat limited to the region upstream of the Pantanal floodplain, while the increase in low flows extends well into the Pantanal. Despite the attenuation of the effects from Manso dam operation while discharge dislocates from the dam toward the Pantanal, noticeable changes can extend more than 500 km downstream of the dam. The Cuiabá river discharge within the Pantanal is more impacted by dam operation during low flows than during high flows, suggesting that the outflow from the Cuiabá to the Pantanal during floods may also be strongly affected by dam operation.

Timing of maximum and minimum flows is less affected by dam operation, except for the river reach immediately downstream of the dam. In comparison to the work by Souza et al. (2009) the present work indicates that changes in 1-day-minimum flow and 1-day-maximum flow go further than those authors indicated. Also, differently from Zeilhofer and de Moura (2009), who noticed an average flow decreases at Cuiabá gauge on the months of November (10%) and December (30%) in the period from 2002 to 2005 due to Manso operation, our findings, which englobes a different and wider period, indicate at the same location an increase of 9.7% of average flow in November and a decrease of 13.8% in December. Overall, our results are in accordance with the analysis provided by Timpe and Kaplan (2017), who analyzed the impact of Manso dam on the Manso river itself, at the Fazenda Raizama gauge. However, we found a much higher impact of Manso dam operation on minimum and maximum flows (112% in average) that those authors (40%), which may be related to the methodology and the time period used.

Regarding river-floodplain interaction in the region where the Cuiabá river flows into the Pantanal, it was strongly affected by Manso dam operation. By lowering maximum flows of the Cuiabá river, dam operation decreases the magnitude of overflows from the river to the floodplain, reducing the lateral connectivity of water. Similar observations were pointed out by Graf (2006) in the Marias River (United States) where floodplain areas were deactivated due to the operation of the Tiber Dam. To avoid this type of impact, an operating rule could be studied for the Manso dam that would mutually optimize urban flood reduction, power generation and maintaining connectivity between the river and the floodplain, especially in times where these connections are most important for fauna. At the same time, other measures to contain floods could be evaluated in the urban centers most affected by floods in the Cuiabá River in order to allow the powerplant to release more flow. These

kinds of approaches have already start to be done in locations such the São Francisco river, in Brazil, where changes in river regime caused by flow regulation by dams since the 70s resulted in impacts on fishes (Pompeu and Godinho, 2006; Santos et al., 2012). Current initiatives are trying to minimize these impacts by changing operation rules of the main reservoir to give way to supplementary water releases during downstream floods (Godinho et al., 2007).

Our findings improve the assessment of spatial patterns of hydrologic alteration, giving more confidence in the assessment of magnitude and spatial extension of the effects of Manso dam in the Pantanal region. By using a model-based approach we avoided the confounding effects of climatic variability, extended the period of analysis, and improved the analysis of the spatial variability of hydrologic alteration over the river network, because the assessment of results was not restricted to river gauges. This approach and the models used could improve the assessment of hydrological changes due to dams operation in other locations, specially complex river systems with wetlands where there are planned dams or where impacts have already been noticed such as the ones caused by the Ponte de Pedra Dam (Fantin-Cruz et al., 2015), also located in the Pantanal, or the Balbina Dam (Fearnside, 1989; da Rocha et al., 2019), located in the Amazon Basin.

DATA AVAILABILITY STATEMENT

Publicly available datasets were analyzed in this study. This data can be found here: https://www.ana.gov.br/sar0/MedicaoSin, http://www.snirh.gov.br/hidroweb/, and https://drive.google.com/drive/folders/1Z-PmTJ9MYNlzkkfhQkYaMjJ8MQdb1nMQ?usp=sharing.

AUTHOR CONTRIBUTIONS

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