Predicted impacts of proposed hydroelectric facilities on fish migration routes upstream from the Pantanal wetland (Brazil)

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Abstract
There are 104 hydroelectric facilities proposed to be installed in the watersheds that feed the Pantanal, a vast floodplain wetland located mostly in Brazil. The Pantanal is host to 23 long-distance migratory fish species that ascend upland tributaries to spawn. A Geographic Information System was used to predict the impact of hydroelectric dams on potential migration routes for these species. Both anthropogenic (hydroelectric dams) and natural barriers were included in the analysis. Natural barriers were identified by river slope. Critical river slopes of 10 and 25%, above which fish were predicted to be incapable of ascending, were modeled as natural barriers. Based on this model, we show that between 2 and 14% of rivers in the Pantanal watershed are naturally blocked to fish migration. An additional 5 to 9% of rivers are currently blocked due to 35 existing hydroelectric facilities. If all proposed dams are built, the area flooded by new reservoirs will triple and the river kilometers blocked will double, blocking 25 to 32% of the river system to fish migration. The Taquari and Cuiabá River sub-basins will be the most impacted, each having more than 70% of their rivers blocked. The impact of individual proposed facilities on the loss of migration routes is related to their proximity to existing barriers. Fourteen of the proposed dams are upstream from existing barriers and will therefore not further restrict long-distance fish migration routes while proposed dams are predicted to close an additional 11,000 to 12,000 km of river channels.

KEYWORDS
dams, fish migration, hydrologic fragmentation, Pantanal, small hydropower

1 | INTRODUCTION

More than 3,000 hydroelectric facilities are expected to be built around the world in the coming decades (Zarfl, Lumsdon, Berlekamp, Tydecks, & Tockner, 2015). Evaluation of environmental changes caused by dams requires analysis of multiple criteria, one of which is the quantification of habitat loss resulting from the fragmentation of river systems (Stanford & Ward, 1983). Identifying potential natural barriers for migratory fish routes can help identify which reaches of the river network are accessible to migratory fishes, and hence most vulnerable to blockage by construction of impoundments.
The Pantanal, one of the world’s largest freshwater wetlands (Silva & Abdon, 1998), is renowned for its biodiversity (Junk et al., 2006). This floodplain ecosystem is driven by a seasonal flood pulse that begins in the upper reaches roughly in November and ends in April (Junk et al., 2006; Junk, Bayley, & Sparks, 1989). The area subject to seasonal inundation is 138,000 km² (Silva & Abdon, 1998), flood waters are fed roughly equally by direct rainfall on the floodplains as well as inflows from rivers that mostly originate in the Brazilian Upper Plateau (Planalto) (Oliveira, Hamilton, & Calheiros, 2019).

In Brazil, 149 hydroelectric facilities are currently in the proposed or construction stages; of these, 104 are on rivers that feed the Pantanal (ANEEL, 2018). Existing and proposed hydropower projects are often located where tributaries in the Planalto descend steep slopes before entering the Pantanal. Thirty-five hydroelectric facilities currently exist in the watershed. Most of the existing and proposed facilities are categorized as small hydroelectric facilities (SHPs), defined in Brazil as facilities with an installed capacity between 1 and 30 MW and reservoir areas less than 13 km² (Ely, 2019). Diversion designs that operate in approximate run-of-river mode are most common. Their main ecological impacts may be fragmentation of fish migration routes and localized habitat loss; preliminary studies indicate that the magnitudes of water quality changes are small (Fantin-Cruz, Pedrollo, Girard, Zeilhofer, & Hamilton, 2016).

None of the 35 existing hydroelectric facilities in the Pantanal watershed have installed fish passage systems, the efficacy of which has been questioned for tropical fishes and are likely to prevent fish access to upstream spawning sites (Pelice, & Agostinho, 2008; Resende, 2003). Large migratory fish populations have been shown to be important both for their role in supporting a resilient ecosystem and also for supporting local economies. Agostinho, Gomes, and Pelice (2007) show how anthropogenic fragmentation of river systems in Brazil, especially due to the construction of dams, has resulted in widespread losses of fish migration pathways.

There are 23 species of long-distance (>100 km) migratory fish in the Pantanal, including some of the most abundant species and a number that are important for artisanal, commercial, and recreational fisheries (Agostinho, Gomes, Veríssimo, & Okada, 2004; Resende, 2003; Resende et al., 2011). Twelve of these species belong to the characiform order (characins) and 11 belong to the siluriform order (catfishes) (Table 1). While all of these fish species migrate upstream from the Pantanal to reproduce, little is known about their spawning sites.

Understanding the impact of proposed dams on populations of long-distance migratory species requires an understanding of the locations and conditions where migratory species spawn. Similar studies of the impact of proposed dams on migratory fish populations have typically relied on spawning and rearing habitat suitability criteria (Ziv, Baran, Nam, Rodriguez-Iturbe, & Levin, 2012). These criteria typically are established from basin-wide studies of spawning grounds and/or extensive species level knowledge of habitat criteria (Louhi, Mäki-Petäys, & Erkinaro, 2008; Moir, Gibbins, Soulsby, & Youngson, 2005). In comparison to other important basins in Brazil (Agostinho, Pelice, Petry, Gomes, & Júlio, 2007; Castello, 2008) and beyond, significantly fewer studies have been conducted within the PHB. While there have not been any basin-wide studies of spawning sites or ichthyoplankton abundance, there have been a handful of localized studies within the basin. These studies report the presence of ichthyoplankton (Ziober et al., 2012) or actively migrating adults (Loureno et al., 2017; Okazaki et al., 2017; Pereira et al., 2009; Sanches & Galetti, 2012) at between one and eight sites within the PHB but outside of the Pantanal sub-basin. These studies have been conducted in streams ranging from first to fourth order, and represent 35% of the 23 migratory fish species in the basin. The specific studies in the basin are footnoted by species in Table 1. The most comprehensive study available is by Ziober et al. (2012), which sampled eight sites in the headwaters of the Cuiabá River for ichthyoplankton abundances. This study reports the presence of Brycon hilarii (microlepis), Prochilodus lineatus, Salminus brasiliensis, Hemisorubim platyrynchus, Pimelodus maculatus, Pseudoplatystoma corruscans, and Pseudoplatystoma fasciatum. Four of the sites in this study were along the fourth order Cuiabazinho River and four sites were in second and third order tributaries of this mainstem. Eggs for migratory species were found in greater abundance in the mainstem (1–6.5 m depth) but were also present in the smaller tributary sites (0.2–5.5 m depth). The authors conclude that the Cuiabazinho River represents the primary spawning habitat for the long-distance migratory species in their study, with the smaller tributaries providing reduced habitat suitability. While the six localized studies that have been conducted in the basin are not

### Table 1 Long-distance (>100 km) migratory fish species of the Pantanal. Species list compiled from Agostinho et al. (2004) and Resende (2003, 2011). Fish lengths (mm), provided in parentheses, have been compiled from Assumpção et al. (2012), Barros, Moraes Filho, and de Oliveira (2006), Britski et al. (2007), and Vazzoler, Suzuki, Marques, and Lizama (1997). Spawning and ichthyoplankton studies from the basin have been footnoted by species

| Characiformes | Siluriformes |
|--------------|-------------|
| • Brycon hilarii (microlepis) | • Hemisorubim platyrynchus* (500) |
| • Leporinus elongatus (545) | • Oxydoras knerii (700) |
| • Leporinus friderici (400) | • Paulicea lukeni (1000) |
| • Leporinus macrocephalus (600) | • Pimelodus maculatus* (500) |
| • Leporinus obtusidens (500) | • Piniaramus pirinampu (800) |
| • Mylossoma orbignyanum (170–210) | • Pseudoplatystoma corruscans* (1000) |
| • Piranactus mesopotamicusd (500) | • Pseudoplatystoma fasciatum* (1000) |
| • Potamorhina squamoralevis (215) | • Pterodoras granulosus (540) |
| • Prochilodus lineatusa, (400) | • Rhinolepis aspera (400) |
| • Rhineiodon vulpinus (800) | • Sorubim luna (500) |
| • Salminus brasiliensis* (1000) | • Steindachneridion sp (70–110) |
| • Schizodon borelli (300) | |

*aZiober, Bialetzki, and Mateus (2012).
*bSanches and Galetti (2012).
*cOkazaki, Hallerman, de Resende, and Hilsdorf (2017).
*dLoureno, Costa, Rondon, and Mateus (2017).
*eResende et al. (1995).
*fPereira, Foresti, and Oliveira (2009).
sufficient to codify habitat suitability criteria, and therefore we have treated all streams equally, we use these studies to guide the interpretation of our results.

The objectives of this study are to (a) identify and map the potential natural barriers to fish migration in river systems which feed the Pantanal; (b) identify and map the anthropogenic barriers formed by current and proposed hydroelectric projects; and (c) quantify effects of each proposed project on potential fish migration routes. We set these objectives to aid stake-holders during the decision making process in the face of limited habitat suitability data and impending hydropower development within the basin.

2 | METHODS

2.1 | Study area

The Paraguay River Hydrologic Basin (PHB), also referred to as the Upper Paraguay Basin, includes the Pantanal and its upland watershed. The PHB is approximately 600,000 km² in area and comprises parts of Bolivia, Paraguay, Argentina and Brazil; the Brazilian portion contains 360,000 km² in the states of Mato Grosso and Mato Grosso do Sul (Gonçalves, Mercante, & Santos, 2011). Most hydroelectric development is occurring in the Brazilian portion of the watershed, which is the focus of this paper. There are 11 sub-basins in the Brazilian PHB as delimited by Brazil’s national water agency (Agência Nacional de Águas, ANA) (Figure 1); other than the Pantanal, all of these are referred to as the Planalto.

The climate of the PHB is wet/dry tropical humid, with a mean annual temperature and precipitation ranging between 22.5–26.5°C and 800–1,600 mm, respectively (Gonçalves et al., 2011). The rainy season occurs from October to April and annual rainfall is greater in the Planalto than the Pantanal. The natural vegetation in the Planalto is Cerrado savanna but much of the land has been converted to crops and pasture.

2.2 | Potential natural barriers

The identification and mapping of natural barriers was conducted using the Model Builder Resource in ArcGIS®. The process of identifying the natural barriers began by extracting a river network and flow direction from a digital elevation model (DEM). River slopes at each pixel along the river network were then calculated. Potential natural barriers were identified as areas with slopes exceeding a predefined threshold. These areas were then mapped and exported for further analysis.

FIGURE 1 Location of the Brazilian part of the Paraguay Hydrologic Basin (PHB), including the Pantanal and its 10 upland sub-basins in the Planalto.
barriers were identified based on slope thresholds. If the river slope at a point had a value equal to or greater than the slope threshold, the location was identified and mapped. The most downstream of these barriers along each river network was considered to be the first barrier to upstream fish migration from the Pantanal, and therefore was identified as a "natural barrier." The locations of these potential natural barriers were used to calculate the length of rivers naturally restricted to migration.

2.3 | Digital elevation model (DEM)

For the analysis of river slopes, we employed the DEM produced by the Shuttle Radar Topography Mission (SRTM), processed and made available by the Brazilian National Institute for Space Research (Instituto Nacional de Pesquisas Espaciais—INPE, 2017). The grid size of this DEM is 1 arc-second, which is approximately 30 m resolution (SRTM-GL1).

SRTM data have been used extensively to model large watersheds such as the Amazon River (de Paiva et al., 2013) and the Blue Nile River (Ali, Crosato, Mohamed, Abdalla, & Wright, 2014) which otherwise lack elevation data for the entire extent of the watershed. Within the PHB, the SRTM dataset has been used by Bravo, Allasia, Paz, Collischonn, and Tucci (2011) to model rainfall-runoff processes.

The global altimetric error of the SRTM-GL1 DEM is reported to be less than 6 m (Farr et al., 2007; Rabus, Eineder, Roth, & Bamler, 2003). Bonfietti-Marini et al. (2017) estimated the average altimetric error (considering TOPODATA DEM data) in the Pantanal sub-basin to be 3.64 m. Grohmann (2018) compared the SRTM-GL1 in the PHB against the ASTER GDEM30 and ALOS AW3D30 datasets and found the SRTM dataset to have the least amount of absolute vertical error of any available dataset for the region.

The current paper uses the SRTM data to develop a river network and evaluate river slopes for potential barriers to fish passage. The accuracy of both of these steps is determined by the relative elevation error between adjacent points along the stream channel rather than the absolute vertical error. Satgé et al. (2015) found that the relative error of the SRTM-GL1 dataset in the Andean Plateau was lower than that for other elevation datasets available for the region. The coefficient of variation of the relative error between adjacent points was largest at low absolute slopes (151% for slopes between 0 and 2%) and decreased as the absolute slopes increased. For absolute slopes between 10 and 20% the coefficient of variation of the relative error was 27.8%, and for absolute slopes greater than 20% was 29.2%. While these errors are substantial, the SRTM-GL1 dataset is currently the most accurate, freely available DEM for the PHB.

2.4 | River slope

A river network was developed from the SRTM data together with a hydrologic network developed and maintained by ANA (Base Hidrográfica Ortocodificada da Bacia do Paraguai). The PHB watershed was delineated in the SRTM dataset by overlaying the ANA network and trimming data not within the watershed outline. An initial stream network was made using the flow direction, length, and stream order tools within the Hydrology Toolset. This initial stream network was then trimmed by stream order to a level that best matched the ANA hydrologic network (Medinas de Campos, 2018). River reach elevation data was exported to a Microsoft Excel® spreadsheet to calculate the river slope as the elevation difference between adjacent cells along the river divided by the distance between the centroids of the two adjacent cells. The river network, along with the river slope, was then re-imported to ArcGIS.

2.5 | Critical slope

Due to the diversity of migratory fish species in the watershed and the fact that many natural barriers are not complete barriers for all hydrologic events it is unlikely that a single slope threshold would be able to accurately capture the existence of all natural barriers. We have instead chosen two slope thresholds; one that identifies natural barriers most of the time but may overestimate the number of natural barriers in the watershed (10%) and one that is at the upper end of known migratory fish climbing abilities but may underestimate the number of barriers in the watershed (25%). By identifying two slope thresholds we provide a range of results intended to bracket the actual thresholds among species and flow conditions. These slope ranges are based on available literature both for species endemic to the PHB and for species beyond the PHB region, as well as on an analysis of the ability of our process to detect known natural barriers.

While systematic studies of swimming capability for the 23 migratory fish species of the PHB are lacking, we do have observational data from two sources that imply that most of these species will be able to swim upriver in slopes approaching 6%. Both observations come from the Paraná River Basin, which borders the PHB to the southeast and is part of the larger Paraguay-Paraná Basin. A fish ladder on the Itaipu Dam, in the Paraná Basin, has a 150 m channel with an average slope of 6.25% (Fontes Júnior, Castro-Santos, Makrakis, Gomes, & Latini, 2012). The average rate of success for passing this section of the fish ladder was reported to be 88% across all migratory species (Makrakis, Miranda, Gomes, Makrakis, & Júnior, 2011). Robust observational data of fish migration in natural streams within the basin would strengthen our understanding of slope thresholds for migratory fish species. A second observational study occurred at the Branca Waterfall on the Verde River, which is a tributary of the Paraná (Silva, Gubiani, Piana, & Delariva, 2016). Fish assemblages were recorded upstream and downstream from this 1.5 m high waterfall. While the waterfall was shown to significantly impact the composition of fish species, most migratory fish species that were observed below the waterfall were also observed (albeit at lower abundances) above the waterfall. This waterfall would appear as a 5% slope in a 30 m DEM. These two regional observations indicate that slopes of 5–6% represent partial but incomplete barriers to local fish migration.
Due to the lack of more detailed information on the ability of migratory fish in the PHB to ascend river gradients, we extended our literature review to include freshwater migratory fish more generally. Noonan, Grant, and Jackson (2012) and Bunt, Castro-Santos, and Haro (2012) have each conducted reviews of fish passage efficiencies at hydroelectric facilities. The steepest fish passage facilities in these reviews had slopes of 15–20%. They show that there is a negative relationship between passage efficiency and slope. For non-salmonids the passage efficiency was nearly zero at 20% slope. In a natural river setting, Adams, Frissell, and Rieman (2000) marked and recaptured brook trout (*Salvelinus fontinalis*) in high gradient rivers where trout had previously been removed. Over the course of a year, brook trout in slopes of 13% were able to migrate 67 m upstream while those in 22% slopes migrated only 14 m upstream. Nagel, Buffington, and Isaak (2006) used a DEM and geographic information system (GIS) model to calculate river slopes to predict fish passage barriers for salmonids on the Middle Fork of the Salmon River of Idaho using a 20% slope threshold to identify natural barriers.

To verify the accuracy of our chosen natural barrier thresholds, we identified likely natural barriers throughout the PHB by examining named waterfalls in Google Earth Pro®. Through a combination of site visits and Google Earth imagery we confirmed that 34 of these waterfalls had drops of at least 2 m. We then calculated the maximum slope in our river network DEM within 500 m of each waterfall. Figure 2 shows that 91% of the waterfall reaches had maximum calculated slopes greater than or equal to 0.10 (ratio of vertical drop to distance, $dz/dx$). Similarly, approximately 35% of the waterfalls had a maximum calculated slope greater than 0.25 (Figure 2). Information about the magnitude of slope errors is available in the Digital Elevation Model Section.

### 2.6 Anthropogenic barriers

Both SHPs and large hydroelectric plants (LHPs) were considered as anthropogenic barriers. The location, flooded area and installed capacity of the existing and proposed hydroelectric facilities were obtained from the website of the Brazilian electrical energy agency (Agência Nacional de Energia Elétrica—ANEEL, 2018). At the time the database was collected from ANEEL, it consisted of all the hydroelectric facilities registered with the agency prior to May 31, 2018. The locations of the hydroelectric dams were mapped onto the river network. These points were defined to be anthropogenic river barriers, above which river reaches were considered inaccessible to potential fish migration.

In order to evaluate the loss of potential routes for migrating fish by anthropogenic barriers, three perspectives were analyzed:

1. the current state of the watershed: The migratory routes that have already been lost by the installation of existing hydroelectric facilities were quantified;
2. a proposed future scenario: The potential future loss of migration routes by the installation of all proposed and operating facilities in the watershed; and
3. an individualized scenario: The potential future loss of migration routes by the isolated construction of each new proposed hydroelectric facility. The sum of potential migratory routes blocked by a particular hydroelectric facility (km), the proportion of potential migratory routes blocked in its sub-basin (km/km), and the ratio of the potential maximum power produced (i.e., the installed capacity) to potential routes blocked by each hydroelectric facility (efficiency index; MW/km) were used as indicators of impact. The indicators were calculated for the proposed hydroelectric facilities and were compared against the “current” state in which existing dams are included in the watershed but other proposed dams were not included. The ratio of the potential power produced to the potential migratory routes blocked is a measure of the efficiency with which power is produced with respect to the impact on fish migration.

### 3 RESULTS

#### 3.1 Characteristics and distribution of hydroelectric facilities

The PHB has 35 hydroelectric facilities in operation (Figure 3). Of these, 29 are categorized by the Brazilian government as SHPs and 7 are LHPs. In total, the total installed capacity of these existing facilities is 1,105 MW. Of the 11 sub-basins, 5 currently have hydroelectric power facilities. The Paraguay sub-basin has the largest number of existing projects (15), with a total installed capacity of 413 MW (Table 2).

An additional 104 hydroelectric facilities are proposed for the PHB (Figure 3). Of these proposed facilities, 101 are SHPs and 3 are...
FIGURE 3  Location of existing and proposed hydroelectric facilities in the PHB. PHB, Paraguay River Hydrologic Basin [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2  Existing and proposed hydroelectric facilities in the PHB. #: number of hydroelectric projects; ΣP: sum of the installed capacity of facilities in the watershed (MW); ΣA: sum of the reservoir area created by hydroelectric facilities (km²)

| Sub-basins       | Existing | Proposed |
|------------------|----------|----------|
|                  | #        | ΣP       | ΣA     | #        | ΣP       | ΣA     |
| Paraguay         | 15       | 412      | 149    | 41       | 364      | 200    |
| São Lourenço     | 9        | 123      | 45     | 10       | 106      | 5      |
| Cuiabá           | 7        | 256      | 428    | 12       | 178      | 31     |
| Itiquira         | 4        | 301      | 19     | 7        | 61       | 23     |
| Taquari          | 1        | 13       | 1      | 29       | 404      | 155    |
| Negro            | –        | –        | –      | 4        | 23       | 3      |
| APA              | –        | –        | –      | 1        | 5        | 0.23   |
| Miranda          | –        | –        | –      | –        | –        | –      |
| Aquidauana       | –        | –        | –      | –        | –        | –      |
| Nabileque        | –        | –        | –      | –        | –        | –      |
| Pantanal         | –        | –        | –      | –        | –        | –      |
| Total            | 35       | 893      | 215    | 104      | 1,142    | 417    |

Note: Data are provided by ANEEL (2018).
Abbreviation: PHB, Paraguay River Hydrologic Basin.
LHPs. These proposed facilities would total 1,141 MW of additional installed capacity. Compared to the current state, the number of projects will quadruple, while the reservoir area will triple and the power production will double. The sub-basins with the largest number of proposed projects are the Paraguay with 41 projects, followed by the Taquari with 29 (Table 2).

### 3.2 Natural barriers

Six of the 35 existing hydroelectric facilities had already been constructed and filled at the time the SRTM data were collected (February 2000). Because of their existence, and the steep drop in elevation associated with each dam, these facilities were originally flagged as natural barriers. Two of these facilities, Juba I and Juba II, were constructed just downstream from large waterfalls that acted as natural barriers to fish migration. Natural barrier classification at these two dams was therefore maintained. The other four facilities (Manso, Casca II, Casca III, Upper Paraguay, and Poxoréu) were not built in the vicinity of waterfalls (ECOA, 2015). The natural barrier designation at each of these dams was therefore removed.

Natural barriers are likely to block fish migration to 14% of the channel length of PHB Rivers based on the lower slope threshold of 10%. This value is reduced to 2% with the upper slope threshold of 25%. Natural barriers were typically identified in two distinct settings—headwater streams and rivers passing through the transition zone from the Planalto to the Pantanal floodplain (Figure 4).

For the less restrictive slope threshold of 10%, the Itiquira sub-basin had the highest proportion of rivers naturally blocked to migration (61%) followed by the São Lourenço sub-basin (37%, Figure 5). When the slope threshold is 25%, the São Lourenço sub-basin had the highest proportion of rivers naturally blocked (6%), followed by the Paraguay sub-basin (5%, Figure 5). The range of naturally blocked rivers is relatively small in sub-basins with low topographic relief (e.g., Pantanal), moderate for sub-basins with well-defined escarpments between the upper and lower plains (e.g., Paraguay), and largest for sub-basins where the transition region has slopes greater than 10% but less than 25% (e.g., Itiquira). This process predicts the existence of natural barriers in the PHB, many of which have not previously been reported.
3.3 | Current and future scenarios

The existing 35 hydroelectric facilities in the PHB have blocked an additional 5.3 to 9.4% of the potential routes to fish migration, depending on the threshold used for natural barriers (Figure 6a,c).

The Cuiabá (25–29% blocked), São Lourenço (19–32% blocked), and Paraguay (13–15% blocked) sub-basins are currently among the...
most impacted in the watershed (Figure 7a). Depending on the slope threshold used to predict fish passage barriers, the Itiquira sub-basin is currently between 0 and 56% blocked by dams. The wide range is due to the fact that the four existing hydroelectric dams are upstream from a 10% slope barrier, while 25% slopes are nearly non-existent in this sub-basin.

If all proposed hydroelectric facilities are built, 18 to 23% of potential fish migration routes will be blocked by dams within the PHB (Figure 6b,d). If only the rivers in the Planalto are considered, 30 to 37% of these rivers will be blocked to fish migration. This represents a 150 to 240% increase in rivers blocked to fish migration due to proposed dams compared to the current state. The sub-basins with the highest losses would be the Taquari with 77–80% blocked, followed by the Cuiabá with 75–79% (Figure 7b). The sub-basins that would have the greatest additional losses due to the proposed facilities would be the Taquari with the potential blockage changing from 0% currently to 79% if all proposed dams are built, the Cuiabá (from 27 to 76%), and the Negro (from 0 to 24%).

### 3.4 | Individualized scenario

Three of the top four proposed facilities that will result in the largest losses are in the Cuiabá sub-basin (SHP Guapira II: 6,200–6,700 km of lost routes; Iratambé I: 5,100–5,600 km; and Iratambé II: 4,700–5,100 km). The Sucuri hydroelectric facility is in the Taquari sub-basin and is predicted to block 4,800 to 5,300 km of potential migratory fish routes (Figure 8a). The Guapira II SHP is predicted to block 66% of the migration routes in its sub-basin (Paraguay sub-basin) and is predicted to block 4,800 to 5,300 km of potential migratory fish routes (Figure 8a). The Sucuri hydroelectric facility is in the Taquari sub-basin and is predicted to block 66% of the migration routes in its sub-basin (Paraguay sub-basin), followed by the Iratambé I and II SHP facilities, which will block 55% and 50% of the migration routes, respectively, of the Cuiabá sub-basin (Figure 8b). The proposed facilities that will result in the least power produced per kilometer blocked are the Biguá SHP (0.0005 MW/km), Saíra SHP (0.0037 MW/km), and Guapira II SHP (0.0039–0.0042 MW/km) (Figure 8c).

### 4 | DISCUSSION

With the number of dams in the watershed expected to quadruple, the impact on the reproductive success of migratory fish species in the Pantanal has the potential to be significant. The relative impact of these dams will, in part, depend on their proximity to other migration barriers. In this paper we investigate the impact of proposed dams with respect to both natural and anthropogenic barriers.

This paper provides the first prediction of natural barriers within the PHB through the use of river slope. Because very little is known about the swimming capabilities of the 23 migratory fish species in the watershed, we have identified both a lower and an upper critical slope threshold. By identifying lower and upper bounds to what is likely to pose a natural barrier to fish migration, we are able to report a range between which results are likely to fall.

For most sub-basins and proposed hydroelectric facilities, the range in results is not strongly dependent on the exact value of the critical slope threshold chosen. However for some sub-basins, such as the Itiquira, the choice of threshold is more important. The percentage of naturally blocked rivers in the Itiquira sub-basin, based on the two alternative critical slope thresholds, is predicted to be between 2 and 61%. This broad range in results is in contrast to sub-basins such as the Paraguay where a narrower range, from 5 to 16% blocked, is predicted.

The wide range of predicted impacts in the Itiquira sub-basin highlights the need for additional research into the swimming capabilities of local fish species, field research verifying the locations of natural barriers in the watershed, and the need for additional parameters to be used when predicting the location of natural barriers in the
watershed. For example, anecdotal evidence exists for the presence of a velocity barrier on the main channel of the Itiquira River at 17°04'21"S/54°50'29"W where a deep narrow channel with low slope but high velocities follows the edge of an escarpment. Anglers report a difference in catch composition upstream from this reach, rarely catching large-bodied migratory species.

If all proposed dams are built, the percentage of potential migration routes blocked by dams is expected to double. The impacts are predicted to be particularly pronounced in the Taquari and Cuiabá sub-basins where more than 70% of the rivers will be blocked. The four dams that will block the most river kilometers are also within the Taquari and Cuiabá sub-basins. Combined, these four dams (Guapira II, Iratambé I and II, and Sucuri) are predicted to block between 11,000 and 12,000 km of migration routes. To put this number into perspective, Sheer and Steel (2006) inventoried all barriers to fish passage in the Willamette and Lower Columbia River Basins (United States), where anadromous salmonid fish populations have been drastically reduced, in part due to damming, and estimate that across 1,400 barriers 15,000 km of river are currently blocked. The outsized impact of these four proposed dams in the Taquari and Cuiabá rivers on fish migrations in their sub-basins should be considered when determining whether to approve construction at these locations. Alternatively, there are 14 proposed facilities upstream from existing barriers that are not expected to further impact available migration routes for long-distance migratory species in the watershed. These 14 dams may still have migratory impacts on local species.
Environmental impact analyses of proposed hydroelectric facilities typically rely on estimates of predicted costs compared to benefits. The efficiency index proposed in this paper is a ratio of the benefits (megawatts of power produced) to one particular form of costs (kilometers of fish migration routes blocked) and has been calculated for each proposed dam on an individual basis. The proposed facilities with the lowest efficiency index are the Biguá, Sairá, and Guapíra II. The Guapíra II is particularly noteworthy since it is also predicted to block the most migration routes (6,200–6,700 km), and block the largest percentage of rivers within any sub-basin (66%). A basin-wide approach that models the impact of alternative scenarios of hydropower development would allow decision-makers to optimize the cost to benefit ratio of the overall portfolio of hydropower facilities.

Because habitat suitability criteria aren’t available for the migratory fish species of the PHB we have treated all streams in the basin equally. As basin-wide studies of spawning habitat become available, those data can be incorporated into this model to strengthen the predictions of dam impacts. For now, the six peer-reviewed studies of spawning habitat in the basin indicate that spawning habitat occurs in first through fourth order streams and many of the species are widely distributed across the PHB sub-basins (Resende, 2003). Most reported spawning activity appears to happen in third and fourth order streams (Lourenço et al., 2017; Resende et al., 1995; Ziobor et al., 2012), while the hydropower facilities in this basin are typically on fourth order and larger streams. The limited amount of spawning site data makes firm predictions premature but early data indicate that the proposed hydropower facilities will typically be downstream from spawning sites and that the greatest impact may be to the loss of fourth order stream spawning sites in the basin. As more data become available, and the this preliminary indication that fourth order streams are the primary spawning site for many migratory fish species, third order and smaller streams could then be cropped from future analyses.

While proposed dams upstream from existing barriers have been assumed to have no additional impact on the availability of migration routes within the watershed, there are numerous other factors to consider when determining total ecological impact. One consideration is that this analysis presumes that existing barriers created by dams are permanent even though the design life of SHPs is typically only a few decades. A second point to consider is that while this paper has focused on the proposed dams’ impacts on fish migration, it is likely that the presence of dams will impact hydrology and sediment transport functions within the watershed. Existing studies within the basin indicate that the nearly run of the river dams do not substantially alter the long temporal scale (weekly or monthly) hydrology but may influence the sub-daily hydrology (de Paes et al., 2019; Fantin-Cruz et al., 2016; Zeilhofer & de Moura, 2009). Given that most spawning happens at night, the sub-daily adjustments may still impact spawning behavior downstream from the proposed dams (Ziobor et al., 2012). Because spawning often happens in high turbidity waters, presumably to reduce predation, dams which trap fine sediment may reduce population level reproductive success. Since fish passage facilities are not likely to sustain migratory populations the choice of dam locations should be done wisely and the potential for success of fish passage facilities should be considered on a project by project basis.

5 | CONCLUSIONS

The percentage of rivers blocked to fish migration in the PHB is predicted to double should all proposed dams be built, leaving 25–32% of the rivers blocked to migration. If only the rivers in the upland Planalto surrounding the Pantanal wetland are considered, 30 to 37% of these rivers will be blocked to fish migration. The impacts of proposed hydroelectric facilities vary by sub-basin and location relative to existing barriers. The most impacted sub-basins will be the Cuiabá and Taquari, in which more than 70% of rivers would be blocked to migration. The Guapíra II facility alone is expected to block access to more than 6,000 km of river, whereas there are 14 proposed facilities that will not further restrict migration pathways for long-distance migratory species.

The Pantanal wetland is internationally recognized for its biodiversity, while its 23 long-distance migratory fish species provide important ecological and social benefits. The 104 proposed dams in the watershed have the potential to generate up to 1,100 MW of electricity that will help sustain the growing Brazilian economy. Nevertheless, a basin-wide cost to benefit analysis that includes predicted impacts on migratory fish will help decision-makers choose among alternative portfolios of hydropower development to minimize environmental impacts while meeting power generation goals.

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DATA AVAILABILITY STATEMENT

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

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