Hydropeaking by Small Hydropower Facilities Affects Flow Regimes on Tributaries to the Pantanal Wetland of Brazil

Juliane Stella M. C. de Figueiredo 1, Ibraim Fantin-Cruz 1,*, Geovanna Mikaelle S. Silva 2, Renato Leandro Beregula 2, Pierre Girard 1, Peter Zeilhofer 1, Eduardo Morgan Uliana 1, Eduardo Beraldo de Morais 1, Hans M. Tritico 3 and Stephen K. Hamilton 4,5

1 Postgraduate Program in Water Resources, Federal University of Mato Grosso, Cuiabá, Brazil, 2 Sanitary and Environmental Engineering Course, Federal University of Mato Grosso, Cuiabá, Brazil, 3 School of Engineering, University of Mount Union, Alliance, OH, United States, 4 W.K. Kellogg Biological Station, Department of Integrative Biology, Michigan State University, East Lansing, MI, United States, 5 Cary Institute of Ecosystem Studies, Millbrook, NY, United States

Hydroelectric facilities often release water at variable rates over the day to match electricity demand, resulting in short-term variability in downstream discharge and water levels. This sub-daily variability, known as hydropeaking, has mostly been studied at large facilities. The ongoing global proliferation of small hydropower (SHP) facilities, which in Brazil are defined as having installed capacities between 5 and 30 MW, raises the question of how these facilities may alter downstream flow regimes by hydropeaking. This study examines the individual and cumulative effects of hydropower facilities on tributaries in the upland watershed of the Pantanal, a vast floodplain wetland system located on the upper Paraguay River, mostly in Brazil. Simultaneous hourly discharge measurements from publicly available reference and downstream gage stations were analyzed for 11 reaches containing 24 hydropower facilities. Most of the facilities are SHPs and half are run-of-river designs, often with diversion channels (headraces). Comparison of daily data over an annual period, summarized by indicators of hydrological alteration (HA) that describe the magnitude, frequency, rate of change, and duration of flows, revealed differences at sub-daily scales attributable to hydropeaking by the hydropower facilities. Results showed statistically significant sub-daily HA in all 11 reaches containing hydropower facilities in all months. Discharge indicators that showed the highest percentage of days with increased variability were the mean rates of rise and fall, amplitude, duration of high pulses, maximum discharge, and number of reversals. Those that showed higher percentages of decreased variability included minimum discharge, number of high pulses, duration of stability, and number of low pulses. There was no correlation between HA values and physical characteristics of rivers or hydropower facilities (including installed capacity), and reaches with multiple facilities did not differ in HA from those with single facilities. This study demonstrates that...
INTRODUCTION

Small hydropower (SHP) facilities are the most common kind of hydroelectric dams being built around the world, and although they are generally viewed as less environmentally harmful than larger dams, there has been little research to support that assertion, particularly in tropical and subtropical regions where most new SHPs are being constructed (Mbaka and Mwaniki, 2015; Couto and Olden, 2018). Reflecting the widespread assumption that SHPs have lower environmental and social impacts than larger dams, many countries have enacted policies that promote SHPs, including less stringent environmental impact assessments. In Brazil and many other countries, multiple SHPs may be distributed in series along river systems, raising concerns about their cumulative effects on rivers and downstream ecosystems (Kibler and Tullos, 2013; Athayde et al., 2019).

Even dams that are small may affect channel morphology, sediment transport, and deposition (Baker et al., 2011; Olden, 2016; Couto and Olden, 2018). Where significant impoundments exist relative to the size of the stream, artificially warm or cold water released downstream can negatively affect the aquatic biota (Zaidel et al., 2021). Dams and weirs associated with SHPs represent physical barriers for migratory species that rely on connected rivers to move upstream to spawn, to access floodplains, and for downstream migrations (Ovidio and Philippart, 2002; Santucci et al., 2005; Pompeu et al., 2012; Couto et al., 2021), and passage through turbines can harm or kill larval and adult fishes, shrimp, and other aquatic animals (Dubois and Gloss, 1993; Benstead et al., 1999).

A well-known effect of larger hydroelectric dams is the release of water at variable rates over the course of the day (i.e., sub-daily) to accommodate variation in electricity demand, and the resultant short-term variability in downstream velocity, discharge, and water levels is known as load following or hydropeaking (Bejarano et al., 2017). The ecological impacts of hydropeaking have mostly been studied at large facilities in North America and Europe, where mitigation measures have been designed to protect against stranding of fishes and maintain minimum flows to avoid desiccation of fish eggs (Moreira et al., 2019).

The ongoing global proliferation of small hydropower (SHP) facilities, which in Brazil are defined as having installed capacities between 5 and 30 MW [Aneel (Agência Nacional De Energia Elétrica), 2016], raises the question of how downstream flow regimes may be altered. Hydrological effects of SHPs are of particular concern in the upland watershed of the Pantanal, a world-renowned floodplain wetland system located mostly in Brazil. While the effects of hydropeaking are unlikely to extend into the floodplains due to longitudinal attenuation (Collischonn et al., 2019), the unnatural sub-daily variability in river flow regimes in reaches downstream of SHP facilities could affect behavior and reproduction of fishes that migrate upstream from the Pantanal (Campos et al., 2020), in addition to resident fishes and other aquatic and riparian organisms.

Existing and proposed hydropower facilities in tributaries to the Pantanal are depicted in Figure 1. As of 2018 there were 47 hydropower facilities in operation (hereafter “current hydropower facilities”), the majority of which are SHPs, with an additional 138 projects under construction, planned, proposed, or identified by the government as prospective sites (hereafter “future hydropower facilities”) (Agência Nacional de Águas, 2018). Most of these SHPs present diversion designs, where a low dam with a small or non-existent reservoir diverts river water into an artificial channel for as much as several km to a powerhouse farther down the river valley (Oliveira et al., 2020). The majority of the river discharge is normally diverted, leaving the natural channel with little as 10% of the discharge. The SHP designs that lack a large reservoir are “run-of-river” facilities inasmuch as they cannot alter discharge except on short time scales (Csiki and Rhoads, 2010; Kaunda et al., 2012). Many of the SHPs are located on lower-order rivers but some are on larger rivers with low elevational gradients.

In light of the ongoing construction and planning of future SHPs in the Pantanal watershed, there is an urgent need to understand how numerous SHPs on the tributaries may, in aggregate, alter the transport of water, sediments, and nutrients from the uplands into the Pantanal, and as well produce enough barriers to the upstream migration of fishes from the Pantanal to impede their reproduction and reduce their populations. In recognition of these needs, the present study is part of a multidisciplinary research program that has examined many dimensions of the issues surrounding hydroelectric facilities in the tributaries of the Pantanal, including hydrology (this study), sediment transport (Fantin-Cruz et al., 2020), water quality (Oliveira et al., 2020; Fantin da Cruz et al., 2021), and fish and fisheries (Campos et al., 2020; Ely et al., 2020). In this study, evidence for hydropeaking is evaluated based on discharge patterns in river gages downstream of 11 reaches containing a total of 24 hydropower facilities compared to simultaneous measurements at reference gages not influenced by the facilities. Comparison of hourly data, summarized by indicators of hydrological alteration, reveals differences at sub-daily scales that may be attributable to the hydropower facilities and aspects of their design. Accordingly, relationships between the observed hydrological alterations and the hydraulic and

**Keywords:** hydroelectricity, dams, load following, tropical, hydrology, index of hydrological alteration
hydrological characteristics of rivers and hydropower facilities were also examined. These included installed potential, mean discharge, watershed area, reservoir area, hydraulic residence time, diverted natural channel length, and dam design. The paper ends with recommendations on further research to better understand how hydropoeaking by small hydropower facilities may affect the aquatic biota of downstream reaches.

MATERIALS AND METHODS

Study Site

This study examines rivers in the Brazilian portion of the uplands in the Upper Paraguay River basin that drain to the Pantanal wetland. The Pantanal lies mostly within Brazil, and drains southward via the Paraguay River. The uplands (150–1,400 m a.s.l.), which represent 59% of the basin area and lie mainly to the east and north of the Pantanal, include sloping terrain favoring rapid runoff and high sediment production. The Pantanal floodplains (80–150 m a.s.l.) are subject to extensive seasonal inundation by overflow of river inflows originating in the uplands as well as delayed drainage of local rainfall (Hamilton et al., 1996). According to the Köppen-Geiger climate classification, the climate of the region is tropical savanna, with average annual precipitation in the uplands ranging from 1,200 to 1,800 mm. About 80% of the annual rainfall occurs in the rainy season from October to April (Gonçalves et al., 2011).

The native vegetation in the uplands is Cerrado savanna, but extensive areas are now converted to cropland (29% of the upland watershed area analyzed in this study) or pasture (22%). Human population density in the rural municipalities is low with mostly <10 inhabitants km$^{-2}$. Cuiabá city and its environs, situated along the Cuiabá River <50 km upstream of the Pantanal, is the largest urban area, which together with three other medium-sized cities located in the uplands has about 1,260,000 inhabitants.
| Multiple (cascade) or isolated facility | Facility          | River   | Installed potential (MW) | Mean discharge (m³/s) | Watershed area (km²) | Reservoir area (km²) | Hydraulic residence time (days) | Diverted natural channel (km) | Design | Reference gage station | Downstream gage station | Year |
|---------------------------------------|-------------------|---------|--------------------------|-----------------------|----------------------|----------------------|-------------------------------|-------------------------------|--------|----------------------|------------------------|------|
| Cascade Jauru                         | Antônio Brennand  | Jauru   | 21.96                    | 46.5                  | 1,590                | 0.05                 | 0.1                           | 0.99                          | RoR    | 66071355             | 66071470               | 2018 |
| Ombreiras                             | Jauru             | 26      | 60                       | 2,207                 | 2.91                 | 9.5                  | 0                            | 9.5                          | RoR    |                      |                        |      |
| Jauru                                 | Jauru             | 121.5   | 85.4                     | 2,620                 | 2.62                 | 2.7                  | 0.95                         |                               | Conv   |                      |                        |      |
| Indiavai                              | Jauru             | 28      | 70.1                     | 2,320                 | 0.22                 | 0.3                  | 0                            |                               | RoR    |                      |                        |      |
| Salto                                 | Jauru             | 19      | 79.9                     | 2,657                 | 1.06                 | 0.5                  | 0.66                         |                               | Conv   |                      |                        |      |
| Figueiró-polis                        | Jauru             | 19.4    | 102                      | 2,960                 | 7.44                 | 4                    | -                            |                               | Conv   |                      |                        |      |
| Cascade Juba                          | Juba I            | Juba    | 42                       | 55.2                  | 1,550                | 0.82                 | 1                            | 3.6                          | RoR    |                      | 66051000 | 66052000 | 2018 |
| Juba II                               | Juba              | 42      | 61.25                    | 1,808                 | 2.5                  | 1.8                  | 2.4                          | 2.5                          | n/a    |                      |                        |      |
| Graça Brennand                        | Juba              | 27.4    | 77.9                     | 1,974                 | 5.92                 | 9.6                  | 0                            |                               | RoR    |                      |                        |      |
| Pampeana                              | Juba              | 28      | 80                       | 2,503                 | 4.17                 | 5.8                  | 1.2                          |                               | RoR    |                      |                        |      |
| Cascade Ponte de Pedra                | Eng. José Gelásio da Rocha | Ponte de Pedra | 24.4 | 26.9 | 1,680 | 0.27 | 0.9 | 6.6 | Conv | * | * | 2018 |
| Rondonó-polis                         | Ponte de Pedra    | 26.6    | 28.62                    | 1,733                 | 0.02                 | 0.1                  | 2                            |                               | Conv   |                      |                        |      |
| Cascade Santana                       | Diamante          | Rio Santana | 4.23 | 12.92 | 560 | 0.49 | 0.7 | 0 | Conv | 66005400 | 66005960 | 2018 |
| Santana I                             | Rio Santana       | 14.8    | -                        | 804                   | 1.17                 | -                    | -                            | n/a                          |       |                      |                        |      |
| Cascade Tenente Amaral                | Sucupira          | Saia Branca | 4.5  | 11.02 | 356 | 0.07 | 0.3 | 1.5 | Conv | 66390090 | 66386000 | 2018 |
| Pequi                                 | Saia Branca       | 6       | 10.22                    | 327                   | 0.02                 | 0                    | 2.6                          |                               | Conv   |                      |                        |      |
| Cambará                               | Tenente Amaral    | 3.6     | 9.97                     | 332                   | 0                    | 0                    | 1.3                          |                               | Conv   |                      |                        |      |
| Embaúba                               | Tenente Amaral    | 4.5     | 10.02                    | 320                   | 0.09                 | 0.3                  | 1.7                          |                               | Conv   |                      |                        |      |
| Isolated                              | Maracanã          | Córrego Maracanã | 10.5 | 4.49 | 148.2 | 0.38 | 1.4 | 2.7 | Conv | 66051000 | 66025500 | 2017 |
| Isolated                              | São Tadeu I       | Arcá-Mirim | 18  | 6.31 | 256 | 0.46 | 0.1 | 2.8 | RoR | 66162000 | 66260110 | 2017 |
| Isolated                              | São Lourenço      | São Lourenço | 29.9 | 108 | 5,775 | 1,290 | 10.8 | 0 | RoR | 66450010 | 66403900 | 2018 |
| Isolated                              | Santa Gabriela    | Correntes | 24  | 54.2 | 3,132 | 0.43 | 0.1 | 2.2 | RoR | 66483600 | 66485400 | 2018 |
| Isolated                              | Itiquira          | Itiquira | 96.6 | 72.9 | 5,137 | 2.1 | 0.8 | 11 | Conv | 66522000 | 66525100 | 2018 |
| Isolated                              | Ponte de Pedra    | Correntes | 176.1 | 80.7 | 4,000 | 14.5 | 15.9 | 12.7 | RoR | 66483600 | 66493000 | 2018 |

Design indicates run-of-river (RoR) or conventional (Conv) where conventional indicates capability to regulate discharge (n/a = facilities did not provide this information). Station numbers are from the Sistema Nacional de Informações sobre Recursos Hídricos do Brasil. Year refers to the period of analysis of hydrological data.

* Information provided by the hydropower company.
FIGURE 2 | Hydrographs showing examples of hydrological alteration by small hydropower (SHP) facilities during the 2018 calendar year (2017 for Maracanã) and in representative months of that year during the season of lower discharge. Red lines show discharge downstream of the hydropower facilities and blue lines show the reference discharge station. All discharge data are standardized to the mean annual discharge to facilitate comparisons among rivers. (A,B) Cascade Jauru on the Jauru River in Mato Grosso State; (C,D) SHP Maracanã on the Córrego Maracanã (a tributary of the Sepotuba River); (E,F) SHP Santa Gabriela on the Correntes River; and (G,H) Cascade Juba on the Juba River.
TABLE 2 | Indicators of hydrological alteration at the sub-daily scale.

| Component of the flow regime | Parameter (Abbreviation) | Units | Description |
|------------------------------|--------------------------|-------|-------------|
| Magnitude                    | Minimum discharge (Qmin) | –     | Daily median discharge standardized to the annual mean of minimum hourly discharge |
|                              | Maximum discharge (Qmax) | –     | Daily median discharge standardized to the annual mean of maximum hourly discharge |
|                              | Amplitude (Qamp)         | –     | Daily median discharge standardized to the annual mean of the difference between maximum and minimum hourly discharges |
| Frequency of pulses          | Number of high pulses (Nhp) | Nhp/day | Median daily number of times that the discharge is above the 3rd quartile at the reference site |
|                              | Number of low pulses (Nlp) | Nlp/day | Median daily number of times that the discharge is below the 1st quartile at the reference site |
| Rate of change               | Mean rate of rise (RrQ)  | –     | Mean rate of daily rise in discharge |
|                              | Mean rate of fall (RfQ)  | –     | Mean rate of daily fall in discharge |
|                              | Number of reversals (Nrev) | Nrev/day | Median daily number of times that the sign of change in discharge reversed over the day |
| Duration                     | Duration of stable discharge (Dsta) | Hours/day | Median daily duration of stable discharge |
|                              | Duration of high pulses (Dhp) | Hours/day | Median daily duration of high pulses |
|                              | Duration of low pulses (Dlp) | Hours/day | Median daily duration of low pulses |

Study Reaches, Data Sources, and Processing

The study region has data for 108 gaging stations with sub-daily measurements, of which 80 have rating curves to estimate discharge from stage and the remainder recorded only stage with no discharge measurements, and were installed at dams. Of the 80 stations with discharge data, 40 had sufficiently complete records for our analysis (i.e., gaps amounting to <20% of the year) and met our quality checks (Figure 1). These stations permitted upstream-downstream comparisons for the 24 hydropower facilities whose characteristics are shown in Table 1. Six of the 24 hydropower facilities were bounded by gaging stations, whereas the other 18 are sequentially arranged within 5 reaches, in which case we call them “cascades,” and thus we evaluate 11 reaches in this study. The watersheds above the 24 hydropower facilities range in area from 148 to 5,775 km², and the rivers range in long-term mean discharge from 4.5 to 108 m³ s⁻¹.

Most of these hydropower facilities can be considered small, although five have installed capacities above the Brazilian government’s regulatory definition of small hydropower as <30 MW installed capacity, and two of those exceed 100 MW. Two of those that exceed 30 MW (Juba I and II, 42 MW each) have dams and reservoirs similar in size to the SHPs. One of the SHPs (São Lourenço, 29 MW) creates a reservoir comparable in size to larger facilities such as the largest one studied here, Ponte de Pedra (176 MW). Thus, installed capacity is an imperfect indicator of the potential environmental effects of these facilities (Couto and Olden, 2018). Hence, we analyze the SHPs and larger facilities together in this study to examine similarities and differences in their downstream hydrological effects.

All facilities have dams that form reservoirs, which range in area from 0.01 to 14.5 km², in volume from 0.035 to 111 hm³, and in hydraulic residence time from 0.1 to 15.9 days. Twelve of the 24 are run-of-river designs, nine have the capacity to regulate discharge (labeled as conventional in Table 1), and information on design was unavailable for the other three. Most (17) of the facilities divert water from the natural channel into headraces for distances ranging from 0.66 to 12.7 km.

Figure 1 shows the distribution of existing and future hydropower facilities as well as available river gage stations considered in this study. Discharge data were downloaded from a public portal called the Sistema Nacional de Informações sobre Recursos Hídricos do Brasil (http://www.snirh.gov.br/hidrotelemetria). We used only stations with high-frequency measurements (i.e., every hour or more often). Discharge time series were screened for gaps, defined as either zero discharge (none of these rivers are intermittent) or missing date, time, and/or discharge data within the temporal sequence. For cases with missing discharge data, the sequential dates and times were added to enable us to estimate the percentage of missing data. Each discharge time series was inspected for outliers that were obviously unrealistic, as well as for abrupt changes that might reflect equipment problems, and in these cases the suspect data were replaced with gaps. For further analysis we selected only time series with gaps amounting to <20% of the total times, and gaps were excluded from statistical summaries. We analyzed data from 2018 where possible, though in some cases we had to use data from 2017 because data gaps in 2018 amounted to >20%.

We analyzed discharge time series where stations existed both upstream and downstream of one or more hydropower facilities, which in many cases were measurements made by the hydropower companies as required for environmental compliance. Only stations with discharge data, as opposed to just water level as is often measured at the dams, were selected. Hereafter we use the term reference in place of upstream because not all cases presented a gaging station immediately upstream of the hydropower facility. In some cases we had to use a reference station well upstream, but not downstream of other hydroelectric facilities, and in one case we
had to use a station on a downstream tributary with similar watershed features and discharge (the Vermelho River below the SHP São Lourenço). Discharge data were standardized to the mean annual discharge to facilitate comparisons across river reaches of different discharge rates (Bejarano et al., 2017). This standardization assumes that there is a fixed proportionality between flows at the reference site and downstream flows in a particular river reach.

**Indicators of Flow Regime Alteration**

We calculated sub-daily flow regime metrics from discharge data at 1-h intervals, based on the methods of Greimel et al. (2016), Timpe and Kaplan (2017), and Bejarano et al. (2017). These methods adapt the widely used Indicators of Hydrological Alteration approach (IHA; Richter et al., 1996) to produce sub-daily Indicators of Hydrological Alteration including 11 indicators that describe the magnitude, frequency, rate of change, and duration of flows. The indicators were calculated at daily time scales based on pairwise comparisons of temporally matched data from the reference site and downstream of hydropower facilities (Table 2).

For a particular hydrological indicator, the difference between the reference site and downstream of the hydropower facility was considered significant in a particular month only when the monthlong series of daily values showed statistically significant differences based on the non-parametric Mann-Whitney U-test ($\alpha \leq 0.05$).

For each of the indicators in Table 2 that showed significant differences between the reference and downstream sites in a particular month, we evaluated the hydrological alteration (HA) attributable to the hydropower facilities following the method described by Timpe and Kaplan (2017):

$$HA\% = \left(\frac{M_{\text{down}} - M_{\text{ref}}}{M_{\text{down}}}\right) \times 100$$  (1)

where $HA$ is the median percent alteration in the indicator, $M_{\text{down}}$ is the median daily value of the indicator downstream of the hydropower facility, and $M_{\text{ref}}$ is the median daily value of...
FIGURE 4 | Percentage change in sub-daily indicators of hydrological alteration for each study reach by month, showing only cases where there was a statistically significant difference (Mann-Whitney test) between the upstream reference site and the downstream site.
FIGURE 5 | Overall hydrological alteration (HA overall) across all indicators and months for each hydropower facility (in the five reaches containing more than one facility, the labels show the name of the facility that is closest to the downstream gaging station).

the indicator at the reference site. Equation (1) was computed at daily intervals, from which monthly medians of HA were determined. Significant positive values of HA indicate an increase in the indicator from the reference site to downstream, negative values indicate a decrease, and in some cases the medians of the distributions were equal but the Mann-Whitney test indicated significant differences in the distributions of daily values around the median.

To facilitate HA comparisons among reaches with hydropower facilities, we calculated the overall HA across all indicators and months for each hydropower facility (Timpe and Kaplan, 2017). We summed the absolute values of the monthly HA values that were statistically significant, then divided that sum by the total number of months with data (including months that did not show significant differences between the reference and downstream sites in a particular month, effectively counting them as zero HA values).

We evaluated the effects of hydraulic and hydrological characteristics at each hydropower facility (Table 1) on the monthly HA values as well as the overall HA using the Spearman’s rank correlation coefficient ($\alpha \leq 0.05$). Where more than one hydropower facility existed between the upstream and downstream gage stations, we examined correlations by two alternative approaches—using just the characteristics of the most downstream hydropower facility or using the sum of characteristics of all of the facilities in the reach (except in the case of discharge). The Mann-Whitney test was then employed to determine whether the number of indicators with significant HA values as well as the sub-daily HA values differed between those two approaches ($\alpha \leq 0.05$).

RESULTS

Hydrological Alteration at Sub-daily Time Scales

Example hydrographs comparing reference and downstream stations for reaches with particularly marked HA show clear sub-daily variation imposed by the facilities (Figure 2). This variation occurs with a visible diel periodicity below the Santa Gabriela (Figures 2E,F) and Maracanã (Figures 2C,D) hydropower facilities, but is more irregular below the multiple facilities in the Jauru (Figures 2A,B) and Juba cascades (Figures 2G,H). These examples comparing hydrographs above and below reaches with the highest overall HA values reveal variable diel patterns of alteration ranging from irregular with high and low pulses of brief duration (Jauru and Juba cascades) to relatively regular with higher and lower periods lasting longer (SHP Maracanã and SHP Santa Gabriela), and these examples provide an indication of the magnitude of sub-daily variation that can be induced by the hydropower facilities (Figure 2). The magnitude of discharge variability would likely be accompanied...
by significant changes in the wetted area of channels downstream of these facilities, particularly during low discharge periods.

Analysis of 11 indicators of hydrological alteration in 11 reaches containing a total of 24 hydropower facilities, most of which are SHPs, provides clear evidence of sub-daily variability that can be attributed to hydropeaking by dam operations (Figures 3, 4). Almost all of the indicators showed significant differences between gages at reference sites and gages downstream of the reaches in most months over the year of analysis. The greatest alterations involved the rates of change (rises and falls) in discharge and the magnitudes of minimum flows (often lower) and maximum flows (often higher). The duration of stable periods decreased in most cases. The hydrological alteration was most marked at the height of the dry season (Aug–Oct) but was apparent in all months. There were more than twice as many significantly positive values of monthly HA (and thus increased variability) than negative ones (49 vs. 22% overall) (Figure 3A). Discharge indicators that showed the highest percentage of increases (positive HA values) were the mean rates of rise and fall in discharge, with 91 and 89% showing significant alterations, respectively. Indicators that were least often significant include the numbers of high and low discharge pulses (58 and 51%, respectively) (Figure 3C). The highest percentages of statistically significant sub-daily hydrological alterations occurred during months of lower discharge and particularly from August through October, although the percentages exceeded 50% in all months (Figure 3D). The full temporal resolution of the data summarized in Figure 3 is depicted in Figure 4.

Among the 11 reaches, the overall HA varied by >4-fold among the reaches analyzed (Figure 5). The greatest overall HA occurred in the Jauru River reach containing the six hydropower facilities (Jauru Cascade in Table 1: 423%), followed by the Maracanã (302%), Santa Gabriela (229%) and Juba Cascade (181%) reaches. The overall HA did not vary in rank order of installed capacity; the lowest overall HA values were found for two of the larger facilities in terms of installed capacity (Itiquira and SHP São Lourenço), whereas the highest overall HA was found for the Jauru cascade containing six facilities with one particularly large one.

Relationships Between Hydrological Alteration and Characteristics of Rivers and Facilities
The physical characteristics of rivers and facilities in the 11 reaches (Table 1) were not significantly correlated with the number of indicators that changed significantly between upstream and downstream (Figure 3A), nor with the monthly HA values (Figures 3C, 4) (statistical results not shown). In addition, comparison between reaches containing more than one hydropower facility with those containing a single facility showed no significant differences in either the percentage of significant indicators of hydrological alteration (Figure 6A) or the overall HA (Figure 6B), and therefore no evidence for cumulative impacts.

DISCUSSION
Our results are consistent with earlier studies that evaluated hydrological alterations by subsets of these hydropower facilities. Timpe and Kaplan (2017) analyzed indicators of hydrological alteration at multiannual time scales below 33 hydropower facilities, 16 of which were SHPs, across the Amazon and Upper
Paraguay River basins, including several of the facilities we analyze here as well as the much larger reservoir created by the Manso Dam (212 MW) on the Cuiabá River. Although lowland hydropower facilities with the largest dams and reservoirs induced the greatest alterations, Timpe and Kaplan noted that for reaches containing single facilities that were either large dams or SHPs, the SHPs induced alterations similar in magnitude to the large dams when scaled to installed capacity (i.e., % HA per MW). Ely et al. (2020), in a multyear analysis of indicators of hydrological alteration, found that high and low pulse counts as well as the number of reversals were the most frequent dam-induced impacts in the Upper Paraguay River basin.

Other studies have examined individual hydropower facilities in the upper Paraguay River basin. Braun-Cruz et al. (2021) reported evidence of hydropoeaking by the Itiquira hydropower facility on the Itiquira River, which was included in the present study. The downstream hydrological effects of the much larger Manso Dam were recently evaluated in detail by Jardim et al. (2020). Fantin-Cruz et al. (2015) analyzed IHA at multiannual time scales attributable to the Ponte de Pedra hydropower facility, also one of our study sites and our largest facility in terms of installed capacity (176 MW). Seven indicators were significantly altered by Ponte de Pedra—magnitude of lowest monthly flow, minimum flows of 1, 3, and 7 days, maximum flow of 90 days, and counts of high and low pulses—and the reservoir released higher flows during the dry season.

Sub-daily hydrological alterations attributable to hydropoeaking have been documented below hydropower facilities elsewhere throughout the world (Bejarano et al., 2017), though only in a few studies of modern SHPs (e.g., Lu et al., 2018; Xiao et al., 2019). Hydrological alterations by SHPs tend to occur over short time scales as the number of active turbines is increased during high demand in the day and reduced at night, particularly below run-of-river facilities with relatively small reservoir volumes that depend on managing discharge to meet short-term variation in electricity demand (Bevelhimer et al., 2015). Many of these SHPs are diversion designs in which most of the discharge is directed into a headrace leading to the powerhouse, and thus fluctuations in discharge through the turbines may cause opposite fluctuations in the diverted portion of the natural channel. In contrast, large dams and reservoirs tend to dampen seasonal variation in outflow discharge, releasing more water during the dry season and attenuating short-term discharge peaks resulting from precipitation or snowmelt (Magilligan and Nislow, 2005).

The ecological implications of hydropoeaking for downstream ecosystems are little known for tropical rivers (Jumani et al., 2018), but have been studied in temperate zones with negative impacts increasingly demonstrated for riparian and aquatic plants (Bejarano et al., 2018), macroinvertebrates (Kennedy et al., 2016; Leitner et al., 2017; Schulting et al., 2019), and especially for fishes (Vollset et al., 2016; Boavida et al., 2017; Costa et al., 2019; Rocaspana et al., 2019; Vehanen et al., 2019). As a result of increasing awareness of these impacts, abrupt changes in water level and velocity associated with hydropoeaking have received increasing regulatory attention (Hauer et al., 2017, Hayes et al., 2019, Moreira et al., 2019), particularly in rivers supporting important fisheries. In the case of the Itiquira hydropower facility in the upper Paraguay River, Braun-Cruz et al. (2021) provided circumstantial evidence that a fish kill involving stranding was linked to hydropoeaking by the dam operations.

In conclusion, we have demonstrated that many SHPs, as well as somewhat larger hydropower facilities, cause hydrological alterations on sub-daily time scales attributable to hydropoeaking to meet varying energy demand. In our data set, these hydrological alterations were not correlated with characteristics of the river reaches or the facilities. In addition to those variables, prediction of hydrological alterations caused by hydropoeaking would likely require information on operating procedures at each facility, which was not available to us.

Considering the rapid expansion of small hydropower development in tropical environments (Couto and Olden, 2018), there is an urgent need to understand whether the ecological impacts of hydropoeaking documented in temperate biomes also apply to these systems. This will be challenging because life cycles and behavior of the aquatic biota in tropical rivers in relation to river hydrology are less well-understood, and even migration routes of fishes that support socioeconomically valuable fisheries are incompletely known (Campos et al., 2020). It is obvious that the aquatic biota will likely be harmed by abrupt decreases in water levels causing stranding of fishes and other aquatic animals as well as the temporary emergence of aquatic substrata that would otherwise remain underwater. However, changes in depth and wetted area of the river channel as a result of hydropoeaking depend on channel morphology (Moreira et al., 2019), information that is lacking for the rivers we study here, as it is for most other regions of the world where SHPs are proliferating. If negative impacts are revealed, research will be needed on the costs vs. benefits of mitigation of these changes by altering dam operations, as for example those proposed for the SHP Ponte de Pedra by Fantin-Cruz et al. (2015). In addition to mitigating impacts of existing SHPs, planning for new SHP locations and designs needs to consider how the resultant hydrological modifications may negatively affect migratory fishes and other aquatic animals, not only by producing barriers and directing most of the flow through turbines, but also altering downstream hydrology. Such planning should be conducted at the scale of entire river basins to minimize negative impacts on migratory populations (Couto and Olden, 2018; Lange et al., 2018; Couto et al., 2021).

**DATA AVAILABILITY STATEMENT**

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

**AUTHOR CONTRIBUTIONS**

This study was conceived and carried out by IF-C, PG, PZ, and SH. IF-C, GS, and RB developed the computational routine for the high frequency time series analysis. Field work and data analysis were conducted by IF-C, JF, EU, EM, and HT. The paper...
ACKNOWLEDGMENTS

We are grateful for support in field activities and access to secondary data provided by the State Secretariats for the Environment of Mato Grosso (SEMA-MT) and Mato Grosso do Sul (IMASUL), the Prosecutor’s Office of the State of Mato Grosso (MP-MT), the Brazilian Association for Clean Energy generation (ABRAGEL), and the Union of Construction, Generation, Transmission and Distribution of Electrical Energy and Gas in the State of Mato Grosso (SINDENERGIA). We also appreciate field assistance by Valdeci Oliveira, Josias Campos, Adriano Dias, and Luiz Amaro.

REFERENCES

Agência Nacional de Águas (2018). *Conjuntura dos Recursos Hídricos no Brasil 2018: Informe anual*. Available online at: http://arquivos.ana.gov.br/portal/publicacao/Conjuntura2018.pdf (accessed 3 June, 2020).

Aneel (Agência Nacional De Energia Elétrica) (2016). *Resolução Normativa N 745, 22 de Novembro de 2016. Brasil: Ministério de Minas e Energia*. 228-27.

Athayde, S., Duarte, C. G., Gallardo, A. L. C. F., Moretto, E. M., Sangoi, L. A., and Dibo, A. P. A., et al. (2019). Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon. *Energy Policy* 132, 265–271. doi: 10.1016/j.enpol.2019.05.003

Baker, D. W., Bledsoe, B. P., Albano, C. M., and Poff, N. L. (2011). Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain streams. *River Res. Appl.* 27, 388–401. doi: 10.1002/tra.1376

Bejarano, M. D., Jansson, R., and Nilsson, C. (2018). The effects of hydropoeaking on riverine plants: a review. *Biol. Rev.* 93, 658–667. doi: 10.1111/brv.12362

Bejarano, M. D., Sordo-Ward, A., Alonso, C., and Nilsson, C. (2017). Characterizing effects of hydropower plants on sub-daily flow regimes. *J. Hydrol.* 550, 186–200. doi: 10.1016/j.jhydrol.2017.04.023

Benstead, J. P., March, J. G., Pringle, C. M., and Scatena, F. N. (1999). Effects of a low-head dam and water abstraction on migratory tropical stream biota. *Ecol. Appl.* 9, 656–668. doi: 10.1890/1051-0761(1999)009[0656:EOALHD]2.0.CO;2

Bevelhimer, M. A., McManamy, R. A., and O’Connor, B. (2015). Characterizing sub-daily flow regimes: implications of hydrologic resolution on ecohydrology studies. *River Res. Appl.* 31, 867–879. doi: 10.1002/tra.2781

Boavida, I., Harby, A., Clarke, K. D., and Heggenes, J. (2017). Move or stay: habitat use and movements by Atlantic salmon parr (Salmo salar) during induced rapid flow variations. *Hydrobiologia* 785, 261–275. doi: 10.1007/s10750-016-2931-3

Braun-Cruz, C. C., Triticó, H. M., Bregula, R. L., Girard, P., Zeilhofer, P., Ribeiro, L. S., et al. (2021). Evaluation of hydrological alterations at the sub-daily scale caused by a small hydroelectric facility. *Water* 13:206. doi: 10.3390/w13020206

Campos, M. M., Triticó, H. M., Girard, P., Zeilhofer, P., Hamilton, S. K., and Fantin-Cruz, I. (2020). Predicted impacts of proposed hydroelectric facilities on fish migration routes upstream from the Pantanal wetland (Brazil). *River Res. Appl.* 36, 1–13. doi: 10.1002/tra.3588

Collischonn, W., Paz, A. R., Melo, M. M. M., and Jardim, P. F. (2019). *Potenciais impactos de barragens sobre o regime hidrologico nos rios da RH Paraguai*. Elaboração de Estudos de Avaliação dos Efeitos da Implantação de Empreendimentos Hidrelétricos na Região Hidrográfica do Rio Paraguai. Agência Nacional de Águas, Brasília (DF). Available online at: https://www.ana.gov.br/gestao-da-agua/planejamento-dos-recursos-hidricos/plano-de-recursos-hidricos-rio-paraguai/grupo-de acompanhamento/19a-reuniao-do-gap-1/relatorio-de-andamento_hidrologia_parte1-1.pdf (accessed 3 June, 2020).

Costa, M. J., Fuentes-Perez, J. F., Boavida, I., Tuhtan, J. A., and Pinheiro, A. N. (2019). Fish under pressure: examining behavioural responses of Iberian barbel under simulated hydropoeaking with instream structures. *PLoS ONE* 1:e021115. doi: 10.1371/journal.pone.021115

Couto, T. B. A., Messager, M. L., and Olden, J. D. (2021). Safeguarding migratory fish via strategic planning of future small hydropower in Brazil. *Nat. Sustain.* doi: 10.1038/s41893-020-00665-4 Available online at: https://www.nature.com/articles/s41893-020-00665-4

Couto, T. B. A., and Olden, J. D. (2018). Global proliferation of small hydropower plants – science and policy. *Front. Ecol. Environ.* 16:1746. doi: 10.1002/fee.1746

Csiki, S., and Rhoads, B. L. (2010). Hydraulic and geomorphological effects of run-of-river dams. *Prog. Phys. Geogr.* 34, 755–780. doi: 10.1177/0309133310369435

DuBois, R. B., and Gloss, S. P. (1993). Mortality of juvenile American shad and striped bass passed through Oosberger crossflow turbines at a small-scale hydroelectric site. *N. Am. J. Fish. Mgmt.* 13, 178–185. doi: 10.1575/1548-8675(1993)013[0178:MOJAS]2.3.CO;2

Ely, P., Fantin-Cruz, L., Triticó, H. M., Girard, P., and Kaplan, D. (2020). Dam-induced hydrologic alterations in the rivers feeding the Pantanal. *Front. Environ. Sci.* 8:579031. doi: 10.3389/fenvsci.2020.579031

Fantin da Cruz, R., Hamilton, S. K., Triticó, H. M., Fantin-Cruz, I., Mainmore de Figueiredo, D., and Zeilhofer, P. (2021). Water quality impacts of small hydroelectric power plants in a tributary to the Pantanal floodplain, Brazil. *River Res. Appl.* 37, 448–461. doi: 10.1002/tra.3766

Fantin-Cruz, I., Oliveira, M. D., Campos, J. A., Campos, M. M., Ribeiro, L. S., Mingoti, R., et al. (2020). Further development of small hydropower will significantly reduce sediment transport to the Pantanal Wetland of Brazil. *Front. Environ. Sci.* 8:577748. doi: 10.3389/fenvsci.2020.577748

Fantin-Cruz, I., Pedrollo, O., Girard, P., Zeilhofer, P., and Hamilton, S. K. (2015). Effects of a diversion hydropower facility on the hydrological regime of the Corrientes River, a tributary to the Pantanal floodplain, Brazil. *J. Hydrol.* 531, 810–820. doi: 10.1016/j.jhydrol.2015.10.045

Gonçalves, H. C., Mercante, M. A., and Santos, E. T. (2011). Hydrological cycle. *Braz. J. Biol.* 71, 241–253. doi: 10.1590/S1519-69842011000200003

Greimel, F., Zeiringer, V., Holler, N., Grün, B., and Godina, R. (2016). A method to detect and characterize sub-daily flow fluctuations. *Hydrod. Proc.* 30, 2063–2078. doi: 10.1002/hyp.10773

Hamilton, S. K., Sippel, S. J., and Melack, J. M. (1996). Inundation patterns in the Pantanal Wetland of South America determined from passive microwave remote sensing. *Arch. Hydrobiol.* 137, 1–23.

Hauer, C., Holzapfel, P., Leitner, P., and Graf, W. (2017). Longitudinal assessment of hydropoeaking impacts on various scales for an improved process understanding and the design of mitigation measures. *Sci. Total Environ.* 575, 1503–1514. doi: 10.1016/j.scitotenv.2016.10.031

Hayes, D. S., Moreira, I., Boavida, I., Haslauer, M., Unfer, G., Zeiringer, B., et al. (2019). Life stage-specific hydropoeaking flow rules. *Sustainability* 11:1547. doi: 10.3390/su11061547

Jardim, P. M., Melo, M. M. M., Ribeiro, L. C., Collischonn, W., and Paz, A. R. (2020). A modeling assessment of large-scale hydrologic alteration in South American Pantanal due to upstream dam operation. *Front. Environ. Sci.* 8:567450. doi: 10.3389/fenvsci.2020.567450

Jumani, S., Rao, S., Kelkar, N., Machado, S., Krishnaswamy, J., and Vaidyanathan, S. (2018). Fish community responses to stream flow alterations and habitat modifications by small hydropower projects in the Western Ghats...
biodiversity hotspot, India. *Aquat. Conserv. Mar. Freshw. Ecosyst.* 28, 979–993. doi: 10.1002/qcc.2904

Kaunda, C. S., Kimambo, C. Z., and Nielsen, T. K. (2012). Hydropower in the context of sustainable energy supply: a review of technologies and challenges. *ISRN Renew. Energy* 2012, 1–15. doi: 10.5402/2012/730631

Kennedy, T. A., Muehlabauer, J. D., Yackulic, C. B., Lytle, D. A., Miller, S. W., Dibble, K. L., et al. (2016). Flow management for hydropower extirpates aquatic insects, undermining river food webs. *Biosciences* 66, 561–575. doi: 10.1093/biowissenschafti/biw059

Kibler, K. M., and Tullos, D. D. (2013). Cumulative biophysical impact of small and large hydropower development in Nu River, China. *Water Resour. Res.* 49, 3104–3118. doi: 10.1002/wrcr.20243

Lange, K., Meier, P., Trautwein, C., Schmid, M., Robinson, C. T., Weber, C., et al. (2013). Cumulative biophysical impact of small dam construction on hydrological alterations in the Jiulong River basin downstream effects of small impoundments on stream habitat conditions and macroinvertebrates. *Environ. Rev.* 23, 257–262. doi: 10.1139/er-20-14-0080

Moreira, M., Hayes, D. S., Boavida, I., Schletterer, M., Schmutz, S., and Pinheiro, A. (2019). Ecologically-based criteria for hydropowering mitigation. A review. *Sci. Total Environ.* 657, 508–1522. doi: 10.1016/j.scitotenv.2018.10.011

Olden, J. D. (2016). “Challenges and opportunities for fish conservation in dam-impacted waters,” in *Conservation of Freshwater Fishes*, eds G. P. Closs, M. Krkosek, and J. D. Olden (Cambridge: Cambridge University Press), 107–148.

Oliveira, M. D., Fantin-Cruz, I., Campos, J. A., Campos, M. M., Mingoti, R., Souza, M. L., et al. (2020). Further development of small hydropower may alter nutrient transport to the Pantanal Wetland of Brazil. *Front. Environ. Sci.* 8:577793. doi: 10.3389/fenvs.2020.577793

Ovidio, M., and Philippart, J. C. (2002). The impact of small physical obstacles on upstream movements of six species of fish: synthesis of a 5-year telemetry study in the River Meuse basin. *Hydrobiologia* 483, 55–69. doi: 10.1023/A:1021398605520

Pompeu, P. S., Agostinho, A. A., and Pelicice, F. M. (2012). Existing and future challenges: the concept of successful fish passage in South America. *River Res. Appl.* 28, 304–312. doi: 10.1002/rra.1557

Richter, B. D., Baumgartner, J. F., Powell, J., and Braun, D. (1996). A method for assessing hydrologic alteration with ecosystems. *Cons. Biol.* 10, 1163–1174. doi: 10.1046/j.1523-1739.1996.10041163.x

Rocaspana, R., Aparicio, E., Palau-Ibars, A., Guillem, R., and Alcaraz, C. (2019). Hydropeaking effects on movement patterns of brown trout (*Salmo trutta L.*). *River Res. Appl.* 35, 646–655. doi: 10.1002/rra.3432

Santucci, V. J. Jr., Gephard, S. R., and Pescitelli, S. M. (2005). Effects of multiple low-head dams on fish, macroinvertebrates, habitat, and water quality in the Fox River, Illinois. *N. Am. J. Fish. Mgmt.* 25, 975–992. doi: 10.1577/M03-216.1

Schulting, L., Feld, C. K., Zeiringer, B., Hudek, H., and Graf, W. (2019). Macroinvertebrate drift response to hydropoeaking: an experimental approach to assessing the effect of varying ramping velocities. *Ecohydrology* 12:12. doi: 10.1002/eco.2032

Timpe, K., and Kaplan, D. (2017). The changing hydrology of a damned Amazon. *Sci. Adv.* 3, 1–13. doi: 10.1126/sciadv.1700611

Vehanen, T., Louhi, P., Huusko, A., Mäki-Petäys, A., Meer, O., Orell, P., et al. (2019). Behaviour of upstream migrating adult salmon (*Salmo salar L.*) in the tailrace channels of hydropoeaking hydropower plants. *Fish. Manag. Ecol.* 27, 41–51. doi: 10.1111/fme.12383

Vollset, K. W., Skoglund, H., Wiers, T., and Barlaup, B. T. (2016). Effects of hydropoeaking on the spawning behaviour of Atlantic salmon *Salmo salar* and brown trout *Salmo trutta*. *J. Fish Biol.* 88, 2236–2250. doi: 10.1111/jfb.12985

Xiao, X., Chen, X., Zhang, L., Lai, R., and Liu, J. (2019). Impacts of small cascaded hydropower plants on river discharge in a basin in Southern China. *Hydrolog. Proc.* 33, 1420–1433. doi: 10.1002/hyp.13410

Zaidel, P. A., Roy, A. H., Houle, K. M., Lambert, B., Letcher, B. H., Nislow, K. H., et al. (2021). Impacts of small dams on stream temperature. *Ecol. Indicators* 120:106878. doi: 10.1016/j.ecolind.2020.106878

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

Copyright © 2021 Figueiredo, Fantin-Cruz, Silva, Beregula, Girard, Zeilhofer, Uliana, Monais, Tritico and Hamilton. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.