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Sub-daily flow alterations (hydropeaking) due to reservoir operations in Brazil

Variações de vazão em escala sub-diária (hydropeaking) decorrentes da operação de reservatórios no Brasil

Pedro Frediani Jardim[1] & **Walter Collischonn**[1]

[1] Universidade Federal do Rio Grande do Sul, Porto Alegre, RS, Brasil
E-mails: pedro_fjardim@hotmail.com (PFJ), collischonn@iph.ufrgs.br (WC)

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ABSTRACT

International studies have focused on the hydrological impacts on an hourly or sub-daily scale that hydroelectric plants can cause through hydropeaking operations. However, this topic is still underexplored in Brazil, despite its large number of hydroelectric plants. Thus, to bring it to the Brazilian context, this study initially presents a literature review to characterize hydropeaking, its impacts and proposed mitigating measures, and research conducted in Brazil. Next, it was demonstrated that hydropeaking operations occur throughout the entire national territory, in hydroelectric plants of different sizes, that can cause changes increasing up to 450% of the base flow. Conflicts related to hydropeaking in Brazil are also brought up and, despite their occurrences and records of specific thresholds for their mitigation, this has not been addressed in environmental impact studies for licensing Small Hydropower Plants (SHPs) or legislation. Thus, the present study seeks to bring to light the importance of further research on hydropeaking in Brazil.

Keywords: Characterization; Occurrence; Impacts; EIA-RIMA.

RESUMO

Estudos internacionais têm focado nos impactos hidrológicos em escala horária ou sub-diária que hidrelétricas podem ocasionar por operações de hydropeaking. Contudo, essa temática ainda é pouco estudada no Brasil, apesar do seu grande número de hidrelétricas. Assim, para trazer ao contexto brasileiro, o presente estudo apresenta inicialmente uma revisão da literatura para caracterizar o hydropeaking, seus impactos e medidas mitigadoras propostas, e trabalhos a respeito no Brasil. A seguir, demonstrou-se que operações de hydropeaking ocorrem em todo território nacional por hidrelétricas de diferentes tamanhos, com alterações podendo aumentar 450% a vazão de base. São também trazidos conflitos relacionados ao hydropeaking no Brasil e que, apesar de suas ocorrências e registro de limiares pontuais sua mitigação, esse não vem sendo abordado em estudos de impacto ambiental para licenciamento de PCHs. Assim, o presente estudo busca trazer à luz a importância de maiores pesquisas sobre hydropeaking no Brasil.

Palavras-chave: Caracterização; Ocorrência; Impactos; EIA-RIMA.

INTRODUCTION

The temporal variation on water demand, in its most diverse uses, is rarely synchronized with its natural availability. In general, exactly the opposite occurs, that is, demand increases when availability decreases, generating scarcity (van Loon & van Lanen, 2013). This is the case of water use for irrigation, for example, where the demand is normally greater in periods of low rainfall, when rivers discharges are low (Cai et al., 2003). Other water uses, such as human supply and electricity generation, also face this difficulty.

The usual engineering solution to this problem has been to change the availability of water by regulating the flow in reservoirs. In general, flow regulation methods consist in making the flow more constant over time, or, in other words, operating reservoirs in such a way that the outflow becomes less variable over time than the natural inflow, controlled by the hydrographic basin.

This flow regulation brings great benefits to society, allowing an increase in the availability of water for the most diverse uses in periods of greater scarcity. On the other hand, the reduction of the natural variability of flows causes environmental impacts that can negatively affect society as many nature life cycles rely on the hydrological variability (Poff et al., 1997).

However, despite being able to provoke seasonal changes, the reservoirs operation does not always reduce the temporal variability of flows. There are situations in which exactly the opposite occurs, that is, the operation of the reservoir generates an outflow with greater temporal variability than the natural inflow. This variability normally stems from a need to meet peaks in instantaneous water demands, especially for power generation.

Abrupt changes in river flow caused by the operation of dams and reservoirs have been address as “hydropeaking” in the international literature, a term first used by Jackson et al. (1991). Hydropeaking is characterized by a rapid rise in river flow, with increases in an order of 100%, or even more, in just a few hours, followed by a period of relatively constant flow, for a few hours, and then a sudden reduction in flow, back to the initial magnitude (Carolli et al., 2015). Typically, hydropeaking is repeated daily, resulting in small artificial flood waves that propagate downstream (Hauer et al., 2017, Greimel et al., 2023).

The search for the term “hydropeaking” in titles, abstracts and keywords on the SCOPUS portal shows that, from the 309 articles found between 1990 and 2021, 233 of these were published from 2014 onwards, thus showing that this is a very studied research topic over the last 7 years and in several countries, mainly in Europe (Bejarano et al., 2018; Moreira et al., 2019). Studies in the international technical and scientific literature focus on the possible impacts of this type of operation, since its influence on the local hydrology can extend for more than 400km downstream of the dam depending on the magnitude of the pulses and local geography (Wiele & Smith, 1996), capable of impacting on fauna (Dibble et al., 2015; Mihalicz et al., 2019; Boavida et al., 2020), flora (Bejarano et al., 2017, 2018) and even on the physical environment (Melcher et al., 2017; Trung et al., 2020; Gierszewski et al., 2020; Vericat et al., 2020).

In Brazil, on the other hand, there are relatively few works that address the issue of hydropeaking. Among them, we can mention the work by Braun-Cruz et al. (2021), who propose indicators to assess the sub-daily hydrological impact of the operation of SHPs, Figueiredo et al. (2021), who evaluated the influence of the hydropeaking operation through data from automatic gauges in the Upper Paraguay River Basin, and Almeida et al. (2020), whose objective was to evaluate the impacts of the operation of the Jirau and Santo Antônio dams on the hydrology of the Madeira River. In addition to these, more focused on the hydrological impacts related to hydropeaking in Brazil, there is also the work by Gandini et al. (2014) who evaluated the impact of hourly fluctuations in flow on the diet of fish in the Grande River, a tributary of the Paranaiba River.

Although being few, articles such as those by Figueiredo et al. (2021) and Almeida et al. (2020) demonstrate that, in the Brazilian context, hydropeaking occurrences are observed both from SHPs and LHPs, and even from those considered run-of-river (Ashraf et al., 2018; Greimel et al., 2018). Despite their lower reservoir capacity compared to LHPs, SHPs can also cause hydropeaking waves with potential impacts on the environment and riparian communities.

Despite the few studies on the topic, there is some evidence in the country that water uses that generate hydropeaking result in conflicts with other water uses, especially fishing, tourism, and ecosystem maintenance. Therefore, it is important to deepen the knowledge about this phenomenon, and to create tools to improve the management of these conflicts.

Thus, the objectives of this work are (1) to review the literature on the characterization of hydropeaking, its potential negative impacts and ways of mitigation (2) present examples of hydropeaking occurrence in Brazil; identify cases in Brazil of water use conflict that are related to hydropeaking; and, finally (3) to analyze how hydropeaking has been considered in decision-making processes and in Environmental Impact Studies (EIAs) and Environmental Impact Reports (RIMAs) for water use regulation.

HYDROPEAKING WORLDWIDE

The term “hydropeaking” refers to rapid and recurring fluctuations in river flow and water level, occurring over short periods, typically less than 24 hours. These sub-daily changes in the hydrological regime can keep daily average flows relatively unchanged but introduce flow variations throughout a day that differ from the natural variation pattern (Hayes et al., 2022).

In general, hydropeaking occurs as a result of the operation of hydropower plants, where the flow passing through the turbines is increased or decreased to produce more or less energy (Hayes et al., 2022; Deemer et al., 2022). A hypothetical example of Hydropeaking is illustrated in Figure 1. The green line corresponds to the natural hydrograph that would occur at the dam site, where the flow is relatively constant during the period represented in the figure. The red line corresponds to the flow at location A, immediately downstream of the dam, representing the total outflow from the dam, including the flow passing through the turbines and flow released by other means (spillways, bottom outlets, fish ladders, locks, and diversions). The blue line corresponds to the flow at location B, which could be situated several tens of kilometers downstream from the dam.

In Figure 1, it can be observed that the daily average flow, over a 24-hour period, is the same in all three represented

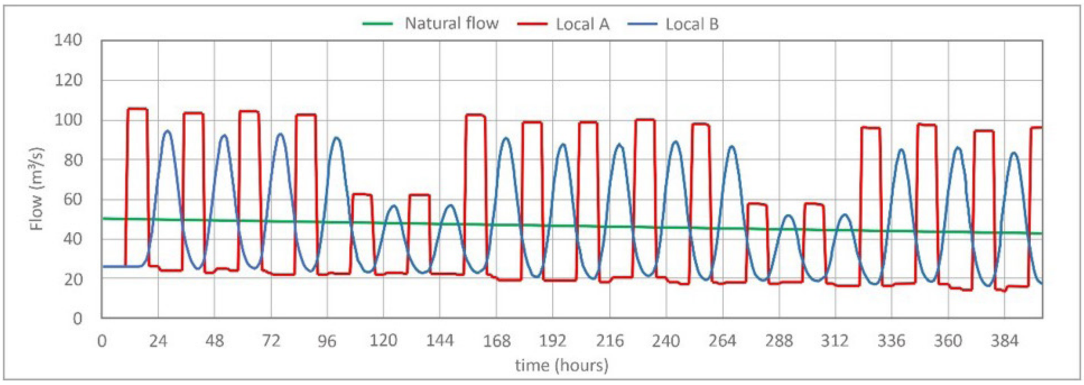

Figure 1. Hypothetical example of change in hydrological regime on a sub-daily time scale (hydropeaking) caused by the operation of a hydroelectric plant: natural flow (green line); flow at a location A, immediately downstream of the plant (red line); flow at a location B, located a few tens of kilometers downstream of the plant (blue line).

hydrographs. However, the flow released by the dam (red line) alternates between low and high values with very rapid transitions between them. This alternating pattern of low and high outflow creates artificial hydropeaking waves, similar to small flood waves, that propagate downstream and can be observed at distances of tens or hundreds of kilometers, depending on the river's characteristics and the watershed (Hayes et al., 2022; Deemer et al., 2022). In the figure, this effect is illustrated by the hydrograph at location B, which is situated several tens of kilometers downstream from location A and the dam.

Generally, the flow oscillations generated by hydropeaking are relatively small, causing low-amplitude hydropeaking waves that remain within the river channel without causing flooding. However, these abrupt oscillations alter flow and other hydrological variables, such as water velocity and depth, more quickly than would be expected if the typical natural hydrological regime were followed in the same river stretch.

Figure 1 also illustrates that the hydropeaking waves caused by hydropeaking are progressively attenuated as they propagate downstream. Additionally, the translation of the hydropeaking wave results in a time lag between the occurrence of flow peaks at the dam site (location A) and downstream points (illustrated by the hydrograph at location B). This lag time depends on the speed of the hydropeaking wave, commonly referred to as the wave celerity (Meyer et al., 2018), and the distance between locations A and B (Greimel et al., 2023).

Hydropeaking causes

The main cause of hydropeaking is the operation of hydropower plants and dams to increase the flow released by the turbines, and consequently, the generation of electrical energy during periods of higher energy demand, and vice versa.

The demand for electrical energy is not constant throughout the 24 hours of the day due to the concentration of human activities during the daytime compared to nighttime, as well as due to environmental, technological, and cultural factors. The hourly variability of energy demand in Brazil is illustrated in Figure 2, prepared for a cold period from July 2nd to July 19th (Figure 2a), and during the summer, from January 15th to the 31st (Figure 2b), both in 2019, based on load curve data provided by the National Electric System Operator (ONS) for the National Interconnected System (SIN) (Brasil, 2023).

It can be observed that the demand is higher during the day and lower at night. During weekends (such as on July 6th, 7th, 13th, and 14th), the demand is also lower, although it still exhibits hourly fluctuations. Also, the demand is significantly higher in the summer period, with high demand for devices such as air conditioning. The difference during week days in this period in relation to weekends is even more evident, possibly due to people spending more time outdoors than during winter.

Among the various sources for energy generation, hydroelectric power plants have been preferred to meet the demand during peak consumption due to their flexibility, allowing for relatively quick increases and decreases in generation, and due to their relatively low generation costs.

Some authors suggest that the trend of operating hydroelectric power plants with large variations in discharged flow over short periods will intensify in the future in response to factors such as hourly energy pricing, decentralization, and deregulation of the electric power sector (Kern et al., 2011; Alonso et al., 2017). Furthermore, the growing inclusion of other intermittent energy sources such as wind or solar in the electric power generation mix may intensify the need to operate hydroelectric power plants with large flow variations over time (Haas et al., 2015).

In hydroelectric power plants with an arrangement involving a relatively long Stretch of Reduced Instream Flow, sub-daily regime alterations can occur even if the total outflow (combined flow from turbines and flow released through bottom and surface outlets) remains constant. This happens due to the difference in the time it takes for water to traverse the two pathways: turbines and stretch of reduced instream flow.

An important observation is that, for a hydropeaking regime to be possible, the reservoir of a hydroelectric power plant does not need to have a very significant active storage capacity. This is because the increase and decrease in flow last for only a few hours. In Brazil, even power plants classified as "run-of-river" may have the conditions to operate using hydropeaking, as per the adopted definition, where this type of hydropower plant is

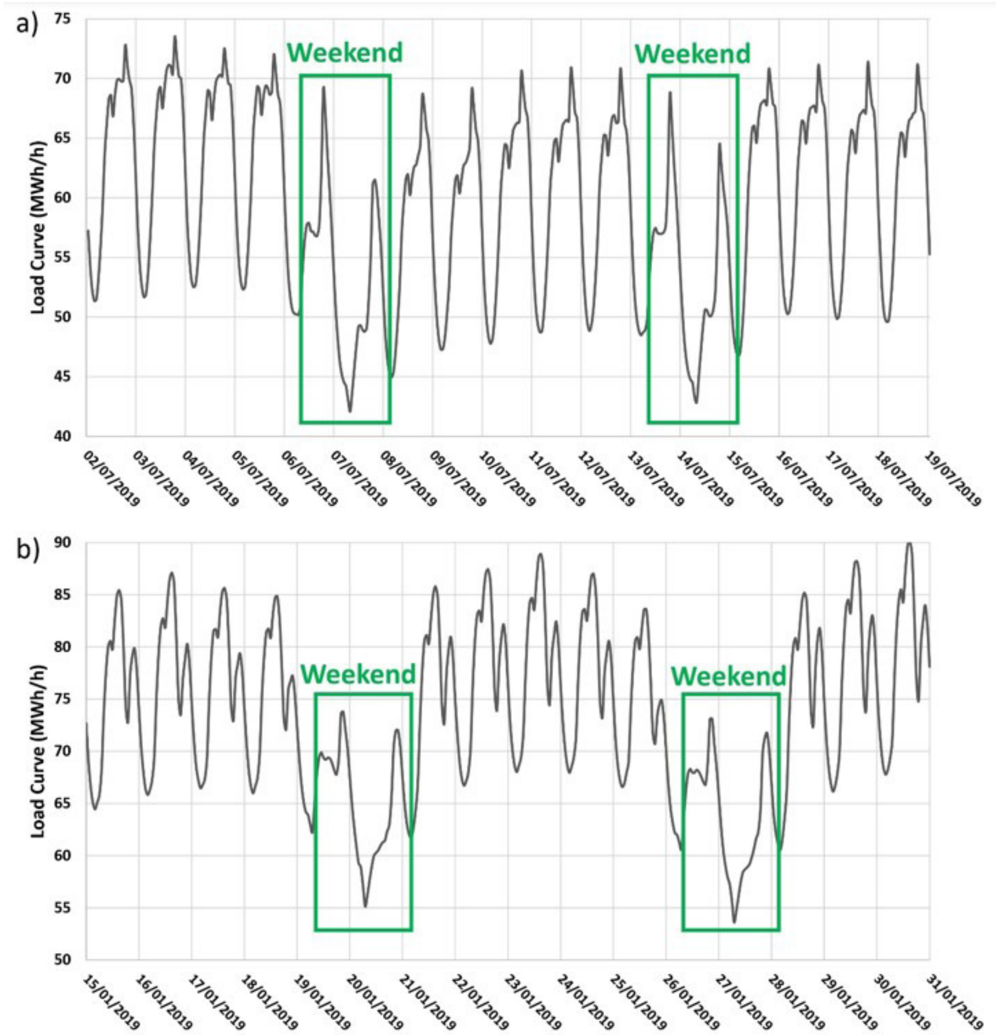

Figure 2. Hourly load curve of the National Interconnected System (SIN), in a cold (a) and warm (b) period of 2019 (hourly data from Brasil, 2023).

characterized by a reservoir with sufficient storage only to provide daily or weekly regulation (Brasil, 2011; Anderson et al., 2015). This implies that power plants classified as "run-of-river" potentially have the capacity to alter the river's flow on time scales ranging from a few hours to a few days (Almeida et al., 2020).

Hydropeaking characterization

Different authors have been studying ways to characterize and identify hydropeaking hydrographs (Baker et al., 2004; Zimmerman et al., 2010; Zolezzi et al., 2009, 2011; Meile et al., 2011; Bevelhimer et al., 2015; Carolli et al., 2015; Greimel et al., 2016; Alonso et al., 2017; Bejarano et al., 2017; Braun-Cruz et al., 2021), including some automated methods to do so (Sauterleute & Charmasson, 2014; Li & Pasternack, 2021).

Most of the proposed methodologies have in common the evaluation of the magnitude of hydropeaking waves, the rates of rise and recession of the hydrograph or level graphs, and the duration of these events. Figure 3, adapted from Greimel et al. (2016), presents some of the key points characterizing waves resulting

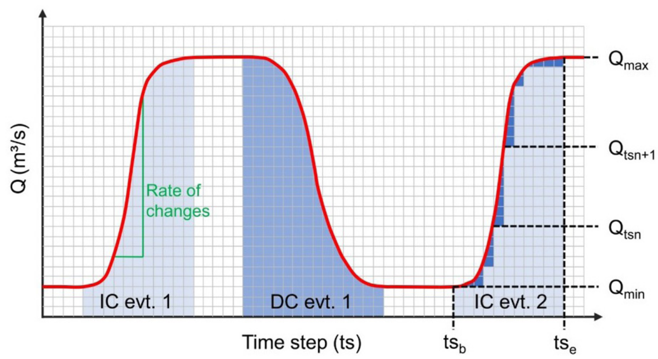

Figure 3. Hypothetical example of a hydrograph with sub-daily oscillations (hydropeaking) highlighting periods of rise (IC) and recession (DC) of the flow, the maximum (Qmax) and minimum (Qmin) values and the rates of variation (adapted from Greimel et al., 2016).

from hydropeaking operations. Meanwhile, Table 1 presents five parameters, like the ones proposed by Richter et al. (1996) for

Table 1. Event-based hydropeaking intensity characterization parameters.

Nr	Parameter	Definition	Unit
1	Maximum flow fluctuation rate	$Max(abs((Q_{tsn+1})-(Q_{tsn})))/(ts_{n+1-}\ ts_n)$	m^3/s^2
2	Mean flow fluctuation rate	Amplitude/duration	m^3/s^2
3	Amplitude	$Q_{max} - Q_{min}$	m^3/s
4	Flow ratio	Q_{max} / Q_{min}	
5	Duration	$t_{Se} - t_{Sb}$	s

Adapted from Greimel et al. (2018).

analyzing hydrological alteration, that can be used to characterize the intensity of hydropeaking based on the observation of hydrographs.

Hydropeaking impacts

The scientific literature has shown that hydropeaking-induced alterations in hydrological regimes have impacts on the environment, including both biotic and abiotic aspects, as well as on other water uses. However, unlike the discussion surrounding the impacts of hydrological regime alterations over longer time scales, which has been ongoing for several decades (Richter et al., 1996; Poff et al., 1997; Bunn & Arthington, 2002), the recognition of potential problems associated with sub-daily scale hydrological regime alterations is relatively recent.

One of the categories of organisms most directly affected by hydropeaking is the ichthyofauna (Resh et al., 1988; Hunter, 1992; Young et al., 2011; Bozeman et al., 2023; Hayes et al., 2022). Among the impacts on fish resulting from hydropeaking described in the literature, one can mention: low survival of eggs and larvae in river reaches subjected to hydropeaking (Casas-Mulet et al., 2015; Lagarde et al., 2018); slow growth of fish (Flodmark et al., 2004; Finch et al., 2015); reduced abundance (Hunter, 1992; Young et al., 2011; Freeman et al., 2001; Korman & Campana, 2009) biomass (Hayes et al., 2021) and primary production (Deemer et al., 2022); stranding of fish during the descending flow phase of hydropeaking (Hunter, 1992, Saltveit et al., 2001; Nagrodski et al., 2012, Larrieu et al., 2021); deterioration of habitats (Vehanen et al., 2005; Boavida et al., 2015); and behavioral changes (Young et al., 2011; Vollset et al., 2016; Capra et al., 2017; Costa et al., 2019; Vehanen et al., 2020).

In addition to the effects on fish, other organisms can also be negatively affected by sudden and high-magnitude fluctuations in flows and water levels, such as insects and plants. The physical environment itself can also undergo changes due to the constant flow variations. Examples of impacts on these organisms include: high transport of macroinvertebrates (Carolli et al., 2012; Bruno et al., 2016; Mihalicz et al., 2019; Salmaso et al., 2021); reduced presence of beetles (Looy et al., 2007) and macrophytes (Mjelde et al., 2013); impacts on insect reproduction and the food chain (Kennedy et al., 2016); impacts on aquatic and riparian plants (Bejarano et al., 2017, 2020; Liu & Xu, 2022); changes in river channels due to erosion alterations (Gierszewski et al., 2020); sediment generation and transport (Vericat et al., 2020); and abrupt changes in water temperature, known as thermopeaking (Toffolon et al., 2010).

Therefore, it is evident that there are various negative effects associated with both biotic and abiotic aspects. These effects can, in turn, directly impact riparian populations, affecting activities such as fishing, as well as indirect uses such as tourism. In Brazil, unfortunately there are not many scientific studies directly dealing with the impacts caused by hydropeaking, such as the one on impacts on neotropical fish community by Gandini et al. (2014) in the Grande River, but rather some addressing its existence (e.g. Almeida et al., 2020; Figueiredo et al., 2021). Even so, there are correlated reports of impacts on fauna and riverside communities, as will be presented later in this work.

Hydropeaking control and mitigation

Since the impacts of hydropeaking can lead to significant harm to fauna and flora, consequently affecting the populations that rely on and depend on the exploitation of natural river resources, many authors have been studying and proposing measures to reduce the negative effects of hydropeaking downstream of reservoirs (Charmasson & Zinke, 2011).

Greimel et al. (2018) categorizes mitigation measures into two main groups: direct and indirect measures. According to the author, direct measures can be subdivided into operational measures for power plants, such as increasing base flow and reducing the ramping rates, amplitudes, and frequencies of flood pulses during specific periods (as proposed by Hayes et al., 2019, 2022), and structural measures, such as diverting hydropeaking flows into secondary channels or to other power plants. Indirect measures can be subdivided into creating habitat refuges by expanding river channels and reconnecting tributaries, and improving habitat measures, including channel restructuring and increasing the duration of flooded areas.

Proposals involving the use of alternative forms of energy storage to reduce the amplitude of fluctuations caused by sub-daily dam operations have also been studied, such as the use of batteries (Anindito et al., 2019), in line with the increasing production of electric and hybrid vehicles (Román et al., 2019). This measure would be particularly interesting for use in Brazil due to its large vehicle fleet and the predominantly hydroelectric energy production, as noted by Román et al. (2019).

Regarding structural measures, some studies include the proposal of using retention basins or underground volumes (caverns) to dampen hydropeaking waves and reduce the rate of flow variation caused by hydropeaking. These would be among the few structural measures to be implemented with a feasible cost-benefit ratio for mitigating the effects of hydropeaking (Person et al., 2014; Tonolla et al., 2017).

As an alternative to the construction of new structures exclusively for hydropeaking mitigation, the joint operation of hydroelectric plants in series along a river (cascading plants) can be planned to reduce flow fluctuations at upstream plants (Premstaller et al., 2017). In this type of solution, the dam located further downstream along the river would have the function of restoring flow patterns to a condition closer to the natural regime. Operationally, the last plant (from upstream to downstream) in a sequence of plants would have stricter restrictions on maximum flow rate changes and could not operate to meet peak energy demand. These restrictions could potentially reduce energy generation capacity and the income earned by this last plant, but the costs associated with this reduction in revenue could be shared with the upstream developments, similar to what was presented by Marques & Tilmant (2018).

Moreira et al. (2019) conducted a review of legislation and thresholds adopted for hydropeaking mitigation, taking into account ecological criteria. It was observed that only Switzerland and Austria had legal regulations regarding limits for hydropeaking operations. Other countries such as Norway and the USA have legislation that may require mitigation measures to be implemented for hydropeaking. The authors also suggest that thresholds, such as rates of river level rise and recession, should be defined based on key species and the specific morphological characteristics of each river.

HYDROPEAKING IN BRAZIL

Although hydropeaking has been a subject of research in the international literature for several decades, it has only recently begun to be addressed in Brazil.

The first published studies related to the impact of hourly dam operations in Brazil aimed to correlate the effect of flow peaks from the Itutinga Dam on the Grande River with the drift of benthonic macroinvertebrates (Castro et al., 2013a) and invertebrates (Castro et al., 2013b). The authors were able to correlate variations in the density and taxonomic composition of drift with flow fluctuations caused by the dam. Regarding the Itutinga Dam, Gandini et al. (2014) pointed out that the hydropeaking operation of the hydroelectric plant possibly affects the diet of downstream ichthyofauna.

In terms of local hydrological effects, most of the published works until now have focused on alterations caused by large dams, using metrics such as the Indicators of Hydrological Alteration (IHA - Richter et al., 1997) to assess the degree of modification of different parameters of the natural river hydrograph (e.g., Santos & Souza, 2015; Timpe & Kaplan, 2017; Vasco et al., 2019; Jardim et al., 2020).

The first work found in searches on the Scopus portal that deals with sub-daily hydrological alterations in the hydrological signature of rivers was published by Almeida et al. (2020). In this work, the authors aimed to demonstrate whether the operations of the Jirau and Santo Antônio Hydropower Plants, located on the Madeira River, cause sub-daily scale alterations in the downstream propagated hydrographs. The authors confirmed that the operations carried out by the dams, even if considered run-of-river, significantly alter the variability of flows, both on a daily and sub-daily scale.

Braun-Cruz et al. (2021) also analyzed the influence of the Itiquira Dam, located on the Itiquira River, by proposing and evaluating 17 hydrological indicators. The results showed that during dry periods, the effects of the hydropeaking operations of the hydropower plant were more noticeable and had a greater impact on the river's flow regime.

Figueiredo et al. (2021) used observed data from 11 sections measured by automatic gauges downstream of 24 hydropower plants in the Upper Paraguay River Basin to assess the hydrological alterations caused by hydropeaking. The indicators adopted indicated that all the sections studied had sub-daily scale hydrological alterations to some extent, even though most of them were small hydropower plants (SHPs), and half of them operated as run-of-river.

In summary, it is evident that, despite the potential for observation through measurements at automatic gauges, with hourly and sub-hourly measurements, there are still relatively few studies conducted in Brazil that seek to characterize the impacts produced by hydropeaking operations.

The occurrence of hydropeaking at river gauges in Brazil

To obtain a preliminary estimate of the extent of hydropeaking in Brazil, a assessment was conducted based on the data available from automatic gauges, in the Brazilian telemetry database called Hidroweb. The process began by identifying all hydrometric gauges in the Hidroweb database whose names started with the abbreviations CGH (hydropower generating central), PCH (small hydropower plants) or UHE (large hydropower plant) and ended with the suffix "Jusante" (meaning downstream), such as "UHE Itutinga Jusante" or "PCH Contestado Jusante". This resulted in 529 automatic gauges that met these criteria, with a higher concentration in the Southern, Southeastern, and Central-Western regions, as illustrated in Figure 4a.

These 529 automatic gauges were then individually and manually analyzed for visual clear signs of hydropeaking in its hydrographs, such as abrupt variations in water level or flow, as well as oscillations with a periodicity of 24 hours or one week. This analysis revealed clear signs of hydropeaking in 233 automatic gauges, while 79 out of the 529 gauges showed no signs of hydropeaking. In the remaining 217 gauges, assessment was not possible due to the poor quality of the data. It is important to note that all these gauges had temporal resolution between 15 minutes and one hour, as with daily resolution the variations caused by hydropeaking may not be visible or underestimated.

Excluding the hydrometric stations without data or with low-quality data from the analysis, the sample suggests that hydropeaking occurs at 64% of the locations downstream of hydropower dams in Brazil.

Figure 4b illustrates the distribution of automatic gauges where fluctuations in flow resulting from the operation of upstream developments could be identified. It is evident that, similar to the distribution of dams in Brazil, the occurrence of hydropeaking is widespread in the country's rivers.

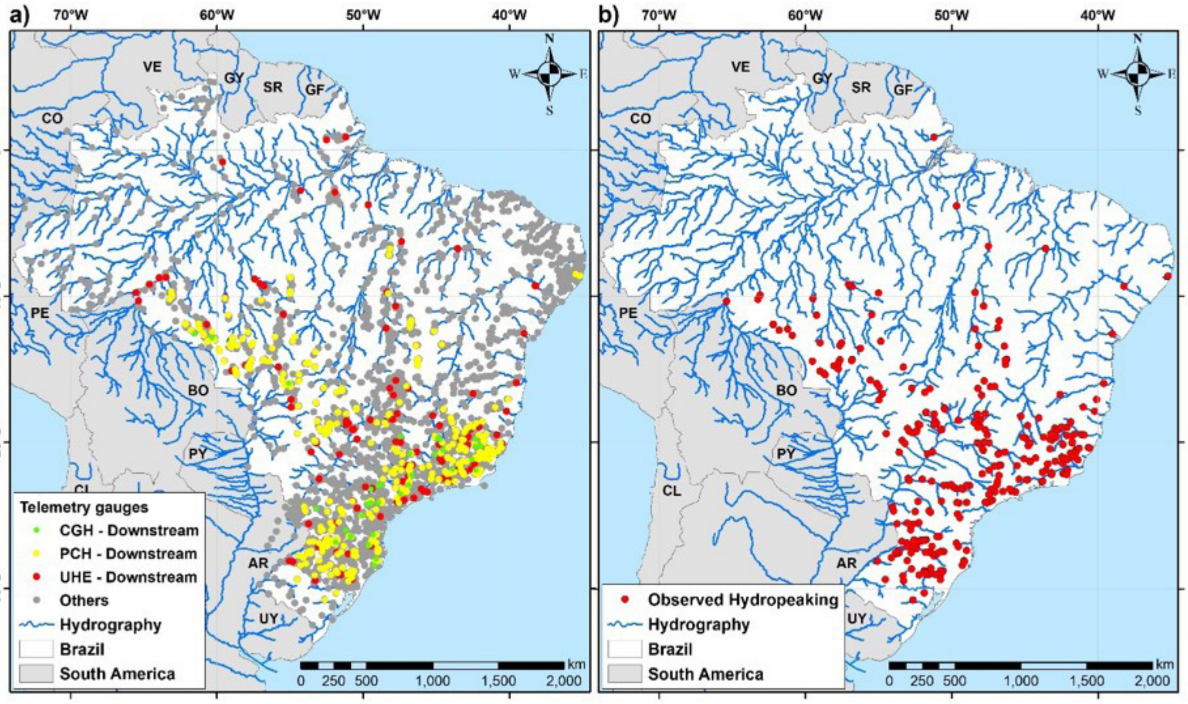

Figure 4. Base with automatic gauges in Brazil, highlighting those with the word "Downstream" in their nomenclature (a) and those where the occurrence of hydropeaking was identified (b).

Examples of hydropeaking at river gauges in Brazil

Modifications in the hydrological regime at sub-daily time scales, such as those caused by hydropeaking operations, are not discernible in conventional hydrological data time series collected at daily intervals. These time series tend to filter out flow fluctuations by providing a single value as the flow for each day. Therefore, to correctly identify flow fluctuations resulting from hydropeaking operations, it is necessary to analyze data at hourly or finer time intervals (Greimel et al., 2016).

To illustrate the hydropeaking process and the alterations in the hydrological regime at sub-daily time scales generated by reservoir operations, several river sections with hydrometric gauges offering time series of hydrological data at hourly intervals or finer were identified in the ANA's telemetry database.

The examples of river sections affected by hydropeaking presented here include: 1) the Pardo River (MS) downstream of the Assis Chateaubriand hydropower plant; 2) the Grande River (MG) downstream of the Itutinga hydropower plant; 3) the Juba River (MT); 4) the Iguaçu River (PR); 5) and the Pomba River (MG). Figure 5 shows the locations of the automatic gauge clusters presented below and Table 2 their main attributes. These particular sites were selected because of their distribution across Brazil, the quality of the data and, in some cases, the existence of other automatic gauges downstream from the dams that could show the magnitude and attenuation of the hydropeaking waves a few kilometers ahead, without the influence of other dams downstream, and even unaffected gauges upstream for comparison with the rivers natural flow regime.

For each case presented, the hydrographs are shown in a manner that the full magnitude of the hydropeaking can be

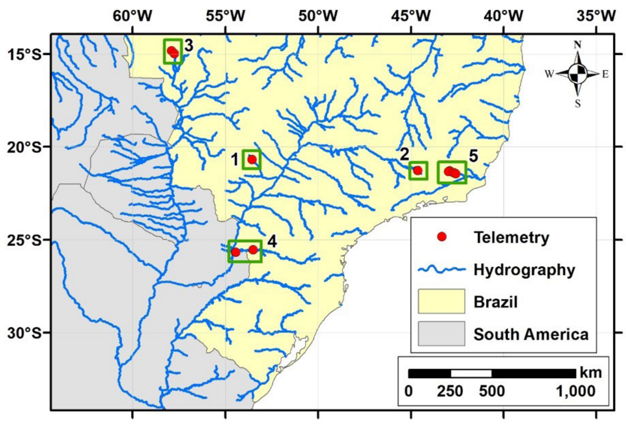

Figure 5. Location of automatic gauges used to exemplify hydropeaking operations observed in Brazil.

seen, and the time period selected englobe some of biggest hydropeaking waves registered. This choice was made to show the difference between base and peak flow that each dam could generate.

Hydropeaking at Pardo River (MS)

The Pardo River is a tributary of the Paraná River located entirely within the state of Mato Grosso do Sul, Brazil. The basin covers a total area of just over 33,000 km² and has few hydropower plants, one of which is called Assis Chateaubriand, situated in an place with approximately 10,000 km² of drainage area.

Table 2. Main characteristics of the automatic gauges presented.

Name	Code	River	State	Drainage area (km^2)	Lat. (º)	Long. (º)	Data
UHE Assis Chateaubriand Jusante	63921000	Pardo	Mato Grosso do Sul (MS)	10300	-20.681	-53.556	30 min
UHE Itutinga Jusante	61065090	Grande	Minas Gerais (MG)	6255	-21.284	-44.634	1 h
PCH Pampeana Jusante	66052900	Juba	Mato Grosso (MT)	1970	-14.826	-57.903	1 h
PCH Graça Brennand Jusante	66053200	Juba	Mato Grosso (MT)	139	-14.976	-57.746	1 h
UHE Juba I Montante	66051000	Juba	Mato Grosso (MT)	817	-14.711	-58.103	1 h
UHE Itaipu Salto Caxias	65975002	Iguaçu	Paraná (PR)	58000	-25.542	-53.510	15 min
UHE Itaipu Hotel Cataratas	65992500	Iguaçu	Paraná (PR)	67100	-25.683	-54.441	15 min
PCH Ivan Botelho III Jusante	58732000	Pomba	Minas Gerais (MG)	2300	-21.301	-42.908	1 h
Cataguases	58770000	Pomba	Minas Gerais (MG)	5880	-21.389	-42.696	15 min
UHE Barra do Braúna Montante	58787000	Pomba	Minas Gerais (MG)	6782	-21.450	-42.579	1 h

Figure 6 presents the observed hydrograph at the automatic gauge "UHE Assis Chateaubriand Jusante". This gauge is located approximately 1.5 km downstream from the large hydropower facility. As seen in the figure, there is a clear influence of the operation of the upstream dam, with characteristic hydropeaking rises and recessions.

The amplitude of the hydropeaking illustrated in the figure varies between 21 m^3/s on the 23rd and 76 m^3/s on the 26th. The lowest flow values occur around noon, at approximately 100 m^3/s, while the highest flow values occur in the early evening/late afternoon, around 18:00 hours when they can exceed 160 m^3/s. The maximum flow observed in the series is up to 85% greater than the base flow on the same day, and the maximum flow rate change is 21.5 m^3/s in one hour.

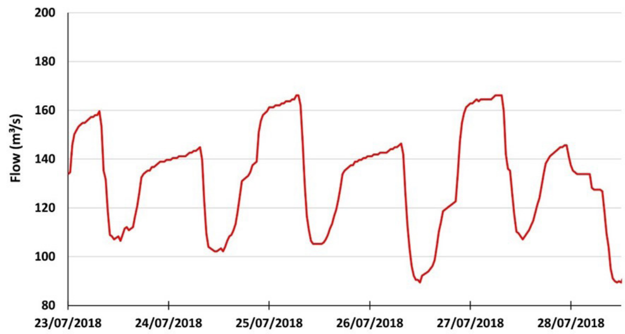

Figure 6. Hydrogram observed at automatic gauge 63921000, located on the Pardo River downstream of the Assis Chateaubriand LHP.

Hydropeaking at Grande River (MG)

The Itutinga LHP, located on the Grande River in Minas Gerais, Brazil, has discharge and naturalized flow data available with a daily time interval on the Reservoir Monitoring System (SAR) portal. Additionally, just over 1 km downstream from the LHP, there is a automatic gauge called "UHE Itutinga Jusante".

Figure 7 presents three hydrographs related to Itutinga dam. The hydrograph defined by the black line corresponds to the natural flow, which is the flow that would occur in the Grande River at the site of the power plant if there were no water uses and reservoirs upstream. The hydrograph defined by the red line corresponds to the outflow in a daily time interval, obtained from the SAR data. The hydrograph defined by the blue line corresponds to the observed flow at the UHE Itutinga Jusante automatic gauge, which measures flow at an hourly time interval.

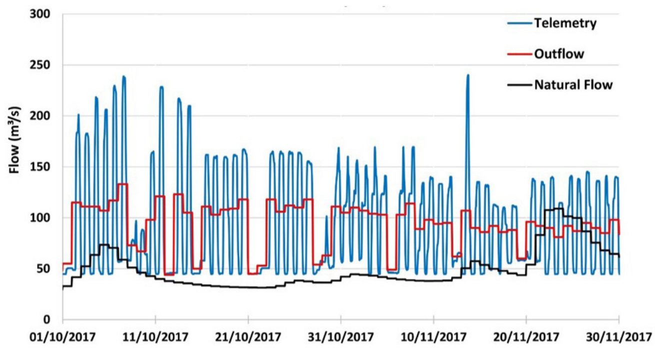

Figure 7. Naturalized daily flows (black) and outflows from HPP Itutinga (red) obtained from SAR and those observed at the UHE Itutinga Jusante automatic gauge (blue).

The image clearly shows the hydrological alterations induced on the natural flow due to the dam's operation. While the naturalized flow exhibits few variations during the presented period, the hydrographs of the outflow and observed flow at the automatic gauge display abrupt fluctuations with significant rises and falls in intervals of less than 4 hours.

Figure 6 also highlights the significant difference between analyzing daily data compared to sub-daily data. While the observations from the automatic gauge show abrupt flow variations on practically every day, the daily data from SAR only reveal these changes when at least one day without fluctuations occurs, mainly at the beginning of Mondays or the start of weekends. Not surprisingly, the days when hourly fluctuations do not occur are on Saturdays and Sundays when energy demand is lower, and the power plant stores water. Thus, an analysis using only daily discharges would lead to the belief that flow variations occur weekly, potentially concealing sub-daily hydropeaking. Furthermore, daily data underestimate the flow peaks reached during hydropeaking operations, not exceeding 130 m^3/s. In contrast, the automatic gauge data show flow peaks of nearly 250 m^3/s.

Exclusive observation of data from the UHE Itutinga Jusante automatic gauge during weekdays shows that, in the analyzed period, the base flow remains at approximately 45 m^3/s. It stays at this value between 01:00 and 09:00 hours each day, during which time the power plants aim to fill their reservoirs. At around 09:00 in the morning, the power plant starts increasing the outflow to meet the rising energy demand, reaching values of up to 240 m^3/s, which is an increase of over 5 times the base flow. The peak flow is reached in approximately 3 hours and remains at that level for up to 10 hours before returning to the base flow, also within 3 hours. This cycle repeats daily, with some variations, characterizing hydropeaking.

Hydropeaking at Juba River (MT)

The Juba River is a tributary of the Sepotuba River, which, in turn, is one of the most important tributaries of the Paraguay River in Mato Grosso, Brazil. In this river, there is a sequence consisting of 4 hydroelectric dams: LHP Juba I (42 MW), LHP Juba II (42 MW), SHP Graça Brennand (27.4 MW), and SHP Pampeana (28 MW). Just downstream from the SHP Pampeana, approximately 1 km from the dam, there is the automatic gauge "PCH Pampeana Jusante". Further downstream, approximately 40 km from the dam, there is the gauge "PCH Graça Brennand Jusante". Between these two gauges, there are no hydroelectric plants with reservoirs; only a few units operate with natural flow and natural falls. There is also a automatic gauge on the Juba River located 4.7 km upstream from LHP Juba I, called "UHE Juba I Montante". This gauge does not have upstream dams capable of altering flow regimes.

Figure 8 presents the hydrographs of these three automatic gauges at the beginning of August 2016. It is noticeable that at the 66051000 gauge, the flow remains relatively constant, with values around 20 m^3/s. In the other two locations, the average flow approaches 40 m^3/s, which is due to the additional flow brought by tributaries in the intermediate reach. However, what stands out the most is the alteration of the flow regime, which showed abrupt oscillations repeated in daily cycles in the period. At gauge 66052900, the one closest to SHP Pampeana, the base flow is approximately 27 m^3/s, while during peak operation, it reaches 47 m^3/s, an increase of 74%.

The effect is still clearly noticeable at the "PCH Graça Brennand Jusante" automatic gauge, located 40 km downstream from SHP Pampeana. However, the amplitude of the oscillation is naturally attenuated. At this location, the base flow is approximately 38 m^3/s, and the peak flow is close to 45 m^3/s, an increase of 18%. The ramping rate of the hydrograph is also much smoother compared to that observed immediately downstream of the power plant. It is also possible to observe the translation effect of the hydropeaking wave, which takes approximately 10 hours to travel along the 40 km stretch.

Hydropeaking at Iguaçu River (PR)

The Iguaçu River is a tributary of the Paraná River with a drainage area of approximately 67.5 thousand km^2 at its outlet. It is globally famous for the Iguaçu Falls, a set of approximately 275 waterfalls, and is considered a World Heritage Site by UNESCO.

Approximately 190 km upstream from the Iguaçu Falls, there is a large hydroelectric power plant called Salto Caxias. This plant has an installed capacity of 1.24 GW, a maximum water volume of 3573 hm^3, and a minimum volume of 3300 hm^3, with a free drop of 66.4 meters and a maximum flooded area of 141 km^2. More recently, in 2019, the Baixo Iguaçu hydroelectric power plant, with 350 MW of installed capacity, began operating 29 km downstream from Salto Caxias.

Figure 9 presents the hydrograph observed at the automatic gauge "UHE Itaipu Salto Caxias", located immediately downstream from the Salto Caxias hydroelectric power plant, and the automatic gauge "UHE Itaipu Hotel Cataratas", located 191 km downstream from Salto Caxias. The period shown is before the construction of the Baixo Iguaçu hydroelectric plant to illustrate the extent of the hydropeaking wave discharged from Salto Caxias without the influence of the second dam.

From the hydrograph of the gauge near the dam, it is evident that it has a significant impact on the river's flow. While the base flow is close to 400 m^3/s, during peak periods it can reach 2300 m^3/s in the presented period. On June 4, 2012, for example, this increase, approximately 6 times the base flow (426 m^3/s), occurred at 07:00, peaked at 2242 m^3/s at 10:45, and remained at that level until 24:00, returning to the base value at 04:00 the

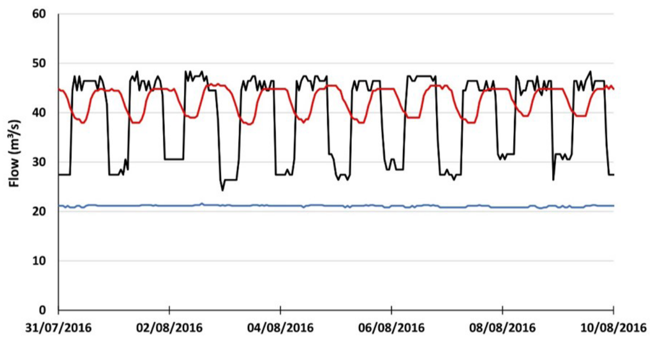

Figure 8. Hydrographs observed at automatic gauge 6605100 (blue), located on the Juba River upstream of the existing dams, and at gauge 66052900 (black) and 66053200 (red) located downstream of the dams.

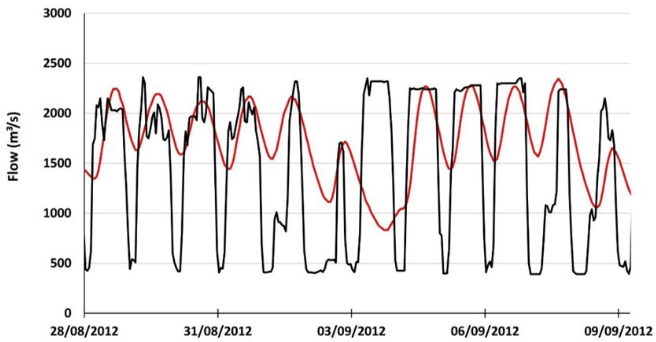

Figure 9. Hydrographs observed at automatic gauges UHE Itaipu Salto Caxias (black) and UHE Itaipu Hotel Cataratas (red), located on the Iguaçu River.

next day. The rate of ascent of the hydrograph in this case was 484 $m^3/s/h$.

Due to the large amplitude of the peak, even at a distance of 191 km from the power plant, at the "Hotel Cataratas" automatic gauge, the effect of the reservoir operation is still evident. In this location, peak flows occur approximately 24 hours after the peak flow releases from the power plant, and the rates of rise and recession are less intense, reaching around 100 $m^3/s/h$ in some cases.

Hydropeaking at Pomba River (MG)

The Pomba River in Minas Gerais, Brazil, is a tributary of the Paraíba do Sul River and is marked by the presence of several reservoirs along its main course. In the upper portion, there is a cascade of four small hydroelectric dams, listed from upstream to downstream: Ivan Botelho I (24.3 MW), Ivan Botelho II (12.4 MW), Zé Tunin (8 MW), and Ivan Botelho III (24.4 MW).

Just downstream of the last dam is the automatic gauge "PCH Ivan Botelho III Jusante". Approximately 42 km downstream, the "Cataguases" gauge operates, and 29 km further downstream is the "UHE Barra do Braúna Montante" gauge. The drainage areas upstream of these gauges are approximately 2200 km^2, 5900 km^2, and 6700 km^2, respectively. Figure 10 presents the observed hydrographs.

In the most upstream gauge, it can be observed that the flow oscillates daily between approximately 15 m^3/s and 38 m^3/s, an increase of 153%, with the variation occurring in just two hours, and the peak lasting for more than 15 hours each day. As shown in the figure, the effects are still noticeable at the downstream automatic gauges. Even with an increase in drainage area by 2.5 times, the amplitude of flow variation is approximately 15 m^3/s at the Cataguases gauge, with a rise rate of 2.84 $m^3/s/h$.

Even 71 km downstream, with a drainage area three times larger than that of the dam, the effects are still noticeable at the "UHE Barra Do Braúna Montante" automatic gauge, although much attenuated. The difference between base flow and peak flow at this location reaches 10 m^3/s and is achieved over 11 hours. The travel time of the hydropeaking wave during the presented period was 11 hours to the Cataguases gauge and 24 hours to the UHE Barra do Braúna Montante gauge.

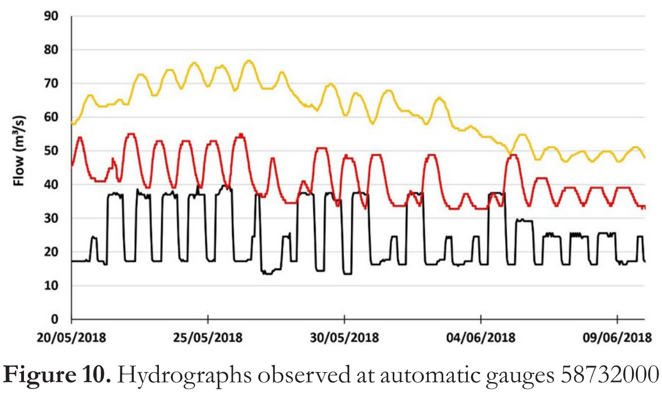

Figure 10. Hydrographs observed at automatic gauges 58732000 (black), 58770000 (red) and 58787000 (yellow), located on the Pomba River.

Water use conflicts related to hydropeaking in Brazil

Despite the limited attention to the topic of hydropeaking in Brazil to date, there are a few recorded cases and reports available on the internet about the impacts of flow fluctuations caused by hydroelectric developments on various water uses. In this section, we present two cases of conflicts related to the operation of hydroelectric plants on an hourly scale with completely different motivations. First, we discuss conflicts related to fishing and riparian communities in the Jauru River basin, followed by conflicts related to tourism on the Uruguay River.

Conflicts related to hydropeaking on the Jauru River

The Jauru River, in the state of Mato Grosso, has a series of hydroelectric plants that operate with hydropeaking, meaning they release flow with rapid fluctuations on a sub-daily time scale, which are not typically present in the natural hydrological regime, as demonstrated by Paes et al. (2019) and Figueiredo et al. (2021).

In this region, there have been documented conflicts between hydropeaking operations and other water uses by riparian communities downstream. In a survey conducted in 2018, fishermen in the Jauru River reported experiencing significant fluctuations in river levels over short periods of time, and these variations were related to a decrease in fish abundance and the appearance of sandbanks (Ecologia e Ação, 2018).

Furthermore, in 2015, then-councilor Sandro Ronaldo Ferreira reported that the systematic opening and closing of the sluice gates of the Small Hydroelectric Plants (PCHs) along the river caused erosion, collapses, and other environmental problems, especially during the dry season (Mato Grosso, 2015). He also mentioned at the time,

> The river has a low level in the morning, with an increase during the day, causing many environmental problems. A clear example is the situation of fishermen who leave early in the morning to work and cannot return home due to sandbanks that appear. This fluctuation has also led to the disappearance of many fish species. (Mato Grosso, 2015).

These conflicts led the Mato Grosso State Court to order, in 2020, the preparation of environmental studies within two years by seven companies responsible for the Small Hydroelectric Plants and the Jauru Large Hydroelectric Plant (UHE Jauru) to assess the existing impacts. According to the state prosecutor's office, impacts such as biodiversity loss and navigation problems directly affect the Porto Esperidião Fishermen's Colony (Olhar Jurídico, 2020).

Despite conflicts, new SHPs are planned for construction in the basins of the Cuiabá and Jauru rivers (Ecologia e Ação, 2021), such as Estivadinho 3 (9.9 MW), Mutum I (4 MW), Juba IV (7.4 MW), Mantovilis (5.2 MW), and Jubinha III (4.08 MW). For example, Estivadinho 3 on the Jauru River has received its preliminary license authorization from the State Council of the Environment (Consema). Also located in the Upper Paraguay River Basin, in August 2023, the Supreme Federal Court allowed the construction of SHPs along the Cuiabá River, overturning a Mato Grosso State law that prevented the installation of new hydroelectric plants on that river (Olhar Jurídico, 2023). In the same month, they invalidated state norms that exempted environmental impact studies for dams with reservoirs up to 13 km^2.

Conflicts related to hydropeaking on the Uruguay River

Another impact of hydropeaking, in this case related to tourism, occurs on the Uruguay River at the tourist attraction known as Salto do Yucumã (RS). This location is renowned for having one of the longest longitudinal waterfalls on the planet, stretching over 1800 meters (Porto Alegre, 2019). The falls, which can reach up to 12 meters in height, are visited by tourists but can be completely submerged depending on the flow in the Uruguay River.

Located 160 km upstream from Salto do Yucumã, the Foz do Chapecó Hydroelectric Plant (UHE Foz do Chapecó) operates with hydropeaking flow variations. According to Technical Note No. 001/2019-DIPLA/DRH (Porto Alegre, 2019), before the construction of UHE Foz do Chapecó, it was believed that its operation would not affect the visibility of Salto do Yucumã. However, after the start of operation, there was a loss of local visibility during periods when the falls would normally be visible, leading to a conflict between water uses for energy generation and tourism. As a result, operating rules were established by Resolution No. 49/2018 of the National Water Agency (Brasil, 2018). Among the restrictions imposed to ensure the visibility of Salto do Yucumã during weekends, the resolution states:

> Article 1: Establish that, during periods of low flows into the reservoir of the Foz do Chapecó Hydroelectric Plant, its discharge should be maintained equal to or less than 1,000 m^3/s from 12:00 pm on Friday until 12:00 pm on Sunday of each week. (Brasil, 2018).

However, according to Technical Note No. 001/2019-DIPLA/DRH, compliance with Resolution No. 49/2018 does not guarantee the visibility of the falls at Salto do Yucumã even when the established regulations are followed. It recommends a reevaluation of the maximum outflows from the Foz do Chapecó Hydroelectric Plant during the period from 12:00 pm on Friday until 12:00 pm on Sunday of each week.

Hydropeaking in planning and management in Brazil

As demonstrated, despite its widespread occurrence and the existence of related conflicts, the hydropeaking issue remains relatively underexplored in scientific studies in Brazil. Similarly, in the field of water resources planning and management, concern for hydropeaking is in its early stages, with few countries on the vanguard, such as Austria and Switzerland (Moreira et al., 2019).

In this section, we analyze how hydropeaking has been addressed in environmental impact studies of projects in the water resources sector and the attempts to mitigate its impacts through operational restrictions in certain hydropower projects.

Hydropeaking approach in Environmental Impact Studies and Reports on Environmental Impact (EIA-RIMAs)

To investigate how the potential impacts of sub-daily operational rules are being addressed in EIA-RIMAs, which are required for the issuance of licenses for the installation of hydropower projects, EIAs and RIMAs were gathered from various Small Hydropower Plants (SHPs) in Brazil. This approach was taken to verify if the usual idea that SHPs and run-of-the-river dams do not have significant impact on the flow regime was applied in these studies, despite that even these smaller plants have the capacity to operate under hydropeaking conditions as previously demonstrated.

In total, studies of 9 SHPs were collected, for the following dams:

- PCH-Tombo (MG) – EIA (Limiar Engenharia Ambiental, 2002)
- PCH Plena Energia 1 (PR) – RIMA (Soma Consultoria Ambiental, 2002)
- PCH Ponte Branca (SP) – EIA/RIMA (PB Produção de Energia Elétrica Ltda, 2006)
- PCH Santa Luzia Alto (SC) – RIMA (Terra Consultoria em Engenharia e Meio Ambiente, 2007)
- PCH Cavernoso II (PR) – EIA/RIMA (Companhia Paranaense de Energia, 2009)
- PCHs Santana, Figueira Branca e Niágara (SP) – EIA/RIMA (Santos, 2010)
- PCH Tupitinga (SC) – RIMA (Vital Engenharia e Meio Ambiente, 2015)
- PCH Assombrado (SC) – RIMA (RTK Engenharia, 2016)
- PCH Antônio Dias (MG) – EIA/RIMA (Azurit Engenharia Ltda, 2018)

The analysis of potential impacts outlined in these studies revealed that none of them considered impacts arising from sub-daily or even daily operations of these small hydropower plants. All the impacts described on the biota were related to reservoir formation or the microclimate generated by SHP operations or were relate to reduced flow in low flow segments.

In these studies, it was assumed that SHPs would not have the capacity to significantly alter the natural river flow, as demonstrated by this excerpt from the EIA-RIMA of the Ponte Branca SHP:

> In general, smaller plants with small flooded areas do not substantially alter the hydrological regime, as accumulation reservoirs do, and have a lower limnological impact on local populations, acting more effectively in interrupting possible migratory routes and/or habitat fragmentation. Based on these considerations and previous study results, it is expected that the construction of the Ponte Branca

SHP will not contribute to the disappearance of natural animal populations. (PB Produção de Energia Elétrica Ltda, 2006).

Therefore, it can be concluded that the impacts of sub-daily scale flow alterations are not being taken into account in the licensing processes for SHPs in Brazil, despite their negative effects being observed and efforts to mitigate them through operational restrictions.

Operating restrictions followed by the Brazilian National Electric System Operator

Regarding the regulation of outflow discharges from dams, the "Inventory of Hydroelectric Operational Restrictions" was developed by the Brazilian National Electric System Operator in 2016 (Brasil, 2016). This document outlines a series of limitations concerning outflow discharges from various hydropower projects across the country. These restrictions take into account diverse characteristics that justify the regulations, such as impacts on riverside communities and the fauna that some dams can or were generating. Some of the justifications for the restrictions established by operational entities explicitly cite the impacts that variations in outflow discharges can have on fish, fishing activities, and navigation.

Among the established regulations related to variations in outflow discharges, some notable cases that include rapid flow alterations or flow thresholds are:

- LHP São Simão – Paranaíba River

Restriction 4 – During the spawning season: The minimum discharge to be released by a generating unit must be 296 m^3/s for the protection of ichthyofauna. During this period, variations in power generation require continuous monitoring by power plant personnel to assess and prevent potential environmental impacts resulting from these variations. The behavior of ichthyofauna has been the subject of ongoing studies.

- LHP Xingó – São Francisco River

Maximum outflow rate variation: In order to reduce fluctuations in outflow discharges to minimize impacts on riverbanks, the greatest allowable variation in outflow during the day is 800 m^3/s between the maximum and minimum values, with a minimum 10-hour interval, ensuring a maximum hourly fluctuation of 300 m^3/s.

- LHP Itapebi – Jequitinhonha River

The rate of variation in the outflow discharge from the Itapebi Hydropower Plant should not exceed 130 m^3/s. This variation should be adjusted at intervals of a minimum of 30 minutes, with the aim of preventing and minimizing the impacts of potential fluctuations on downstream users, especially riverside populations and fishermen.

- LHP Itiquira I and II – Itiquira River

Restriction 2 – environmental flow of 40 m^3/s: During the dry season, when the inflow is less than 80 m^3/s, the variation in outflow discharge should not exceed 10 m^3/s, with a minimum 2-hour interval for a new variation, until reaching the minimum flow of 40 m^3/s. The 10 m^3/s variation corresponds to the total dispatch at Itiquira I and Itiquira II, equivalent to 20 MW. The reason for this restriction is that, immediately downstream of the Itiquira II Hydropower Plant, the wetlands of Mato Grosso's Pantanal begin, and the marginal lagoons of the Itiquira River should not experience significant abrupt level changes to avoid harming the ichthyofauna and fishing activities in the region.

- LHP Itutinga – Grande River

Flow rate variation downstream: The reduction in released flow discharge down to 300 m^3/s should be carried out gradually in increments of 70 m^3/s, which is approximately equivalent to the opening of 2 gates by 25 cm each. For values lower than 300 m^3/s, until complete closure, the reduction should be 35 m^3/s (± 25 cm) every 1 hour until full closure.

- LHP Salto Caxias – Iguaçu River

Minimum flow – 200 m^3/s, however, for natural flow rates lower than this value, the minimum flow rate will vary based on the observed natural flow. In the stretch of the Iguaçu River between the Salto Caxias Hydropower Plant (Gov. José Richa) and its confluence with the Paraná River, there are predominant rocky basalt outcrops with sections of rapids. During low flows, shallow pools form, leading to the trapping of fish and the emergence of exposed riverbed sections. These exposed areas can quickly become inundated by any increase in flow rates resulting from the operation of the power plant, potentially posing risks to local residents who venture into these areas.

The location of these LHPs with operational restrictions is presented in Figure 11. It is evident, therefore, that the hourly variations in outflow discharges from hydropower plants in Brazil have already been a matter of concern for regulatory agencies, which aim to mitigate the impacts of hydropeaking operations through operational restrictions. However, these measures are typically implemented only after the installation of the hydropower projects and in cases where environmental and social impacts have been observed.

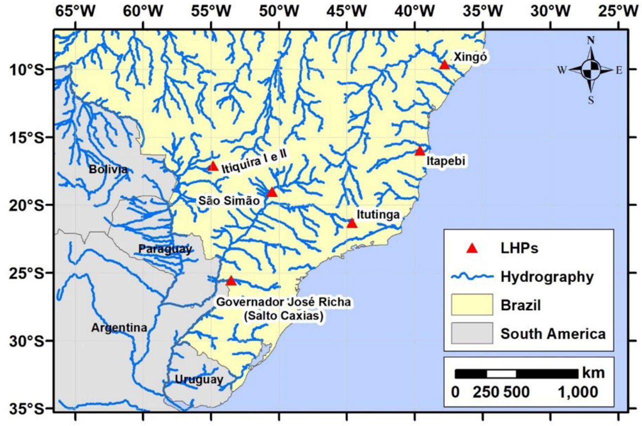

Figure 11. Location of LHPs with operation restrictions regarding rapid flow alteration and thresholds.

More importantly, the record, although sometimes empirical, of thresholds and rates of variation that must be followed in different Brazilian rivers can support decision-making for environments or faunas with similar characteristics, even given the Brazilian territorial and hydrological magnitude, in addition Due to the great biotic diversity, certain thresholds for one river may not be suitable for another. Even so, it could be required that River Basin Plans or other territorial management studies address such values to subsidize the operation of existing or future projects to mitigate impacts resulting from hydropeaking, as countries like Switzerland and Austria do. country level (Moreira et al., 2019), but focusing on Brazilian characteristics.

DISCUSSION AND PROSPECTS

Despite the significant increase in related studies conducted in the past seven years worldwide, impacts resulting from hydropeaking operations have been described in the international literature since the early 1990s (Bejarano et al., 2018). The observed effects can negatively affect numerous fish and insect species, thereby compromising the entire local food chain. Plants, sediments, and water temperature itself can be impacted by the abrupt changes in flow rates and levels caused by dams to meet peak energy demand throughout the day.

This study provided evidence of hydropeaking across the entire territory of Brazil, and the amplitudes of flood pulses released by dams can even be visually identified through the extensive network of automatic gauges available. Hydropeaking operations were observed in both large hydropower plants, such as Salto Caxias and Foz do Chapecó, as well as in small hydropower plants. When analyzing automatic gauges located downstream of the dams, it was noted that sub-daily hydrological changes can, in some cases, be perceptible at distances ranging from tens to hundreds of kilometers downstream of the dam sites.

Regarding the magnitude of impacts caused by SHPs and LHPs, it was observed that both had the ability to significantly and rapidly alter the base flow. However, due to their typical location in smaller rivers, the hydropeaking waves induced by SHPs quickly attenuated upon encountering other tributaries (e.g., Pomba and Juba Rivers). In contrast, for LHPs, the waves can propagate over tens or hundreds of kilometers in a still very noticeable manner (e.g., Uruguay and Iguaçu Rivers). Nevertheless, the large number of SHPs and its proximity to sensible locations (e.g. Jauru and Cuiabá rivers) make their impact very significant in the Brazilian context.

Different reports of impacts resulting from hydropeaking on fauna and fishing activities were found, including observations at tourist locations such as Salto do Yucumã on the Uruguay River, between Brazil and Argentina. The operational restrictions adopted by ONS also describe impacts associated with flow and level variations, seeking to mitigate these effects by establishing limits on the amplitudes and rates of increase of peak flow.

However, despite strong evidence of the existence of hydropeaking and associated impacts, there are still few scientific studies in Brazil that address the topic. In addition to the scarcity of scientific research, none of the EIA-RIMAs reviewed in this study mentioned potential hydrological, biotic, or abiotic impacts resulting from the operations of SHPs. The studies analyzed here, in general, are based on the premise that SHPs do not have the capacity to significantly alter the hydrological regime when, in reality, both SHPs and other "run-of-river" projects can alter flow regimes on a sub-daily time scale (Greimel et al., 2016; Almeida et al., 2020).

In general, studies on hydropeaking are still in their early stages in Brazil, with only a few scientific publications on the subject in the national territory. Although there are reports of conflicts caused by this type of operation, the lack of technical literature hinders the quantification or provision of support for management measures to mitigate its effects or compel the incorporation of its theme into environmental impact studies.

However, for some dams, there are rates and thresholds that their operations must adhere to in order to mitigate negative effects downstream, demonstrating that there is technical capacity to expand the analysis to the scale of the hydrographic basin. Regulatory bodies and managers could start to demand the inclusion of studies that assess the environmental and social sensitivity to different rates of ascent and magnitudes of hydropeaking waves, considering the specificities of each environment. Unfortunately, this still seems distant from the Brazilian perspective given the current reality.

Nevertheless, with the case studies, documents, and research findings collected, it is hoped that this study draws attention to the issue of hydropeaking in Brazil and how this type of operation can affect Brazilian rivers in the present and future, potentially leading to conflicts over water use. It is expected that future research can help identify impacted areas and propose mitigation measures that take into account the unique characteristics of Brazil's fauna and flora, as well as the different river morphologies and dam arrangements present in the country. The Brazilian hydrological and ecological diversity, as well as its large distribution and arrangements of dams, could be a great starting point when studying how different mitigation approaches could be implemented to better suite each environment.

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Authors contributions

Pedro Frediani Jardim: Conceived the study, gathered and analyzed the data, wrote the manuscript, prepared the figures and discussed the findings.

Walter Collischonn: Conceived the study, revised, wrote and discussed the findings.

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