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Research

Downstream impacts of the Madeira Hydroelectric Complex on *várzea* traditional agriculture and extractivism

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ABSTRACT. Hydropower development in the Amazon has accelerated under public and private incentives, aiming to promote economic growth, environmental conservation, renewable energy, and social equity within a sustainable development agenda. However, recent studies show significant negative impacts on local communities and ecosystems, raising concerns about hydropower's true contribution to sustainability. Despite increasing awareness, research has largely overlooked the downstream effects of hydropower dams. Since the Madeira Hydroelectric Complex became operational, it has introduced sub-daily flow oscillations (hydropeaking) in the Madeira River, Southwest Amazon. Although poorly understood, hydropeaking can disrupt the river's essential flood pulse, which rural riverine communities, known as *ribeirinho*, depend on for traditional flood recession agriculture and extractivism in the whitewater floodplains (*várzea*). These communities have long adapted their livelihoods to seasonal flood dynamics, using both low- and high-gradient *várzea* floodplains, but this downstream flow alteration may be affecting the *várzea* social-ecological system and must be investigated. To investigate hydropeaking's effects, we conducted semi-structured interviews with local experts (n = 51) of four downstream *ribeirinho* communities, along with hydrological and soil analyses. Our findings reveal a shift in agricultural practices, particularly in flood recession agriculture in low-*várzea* areas. Soil analysis corroborates local experts' concern about declining fertility, showing reduced phosphorus content following dam operations. Additionally, the extreme 2014 flood and expanding illegal gold mining have further diminished engagement in extractivist activities. A truly sustainable future for the Madeira River depends on revitalizing *várzea*-based value chains while preserving both ecological integrity and social resilience. We recommend establishing an independent monitoring group composed of *ribeirinho* communities and local scientists to assess downstream impacts on the *várzea* social-ecological system. Furthermore, targeted compensation and mitigation projects should be implemented to promote the sustainable use of *várzea* resources.

Key Words: *Amazon; extractivism; flood recession agriculture; hydropeaking; traditional livelihoods*

INTRODUCTION

Hydropower is Brazil's primary renewable energy source, accounting currently for about 60% of the electrical mix (Energy Research Office (EPE) 2024). Since the 1980s, hydropower development has been boosted, particularly in the Amazon basin, as it possesses immense hydraulic potential (von Sperling 2012). Hydropower development has been accelerated by government and private sector incentives aimed at fostering economic growth, environmental conservation, and social equity under a sustainable development agenda (Fearnside 2015, Moran and Athayde 2019). However, recent years have seen a proliferation of studies highlighting the adverse impacts of hydropower development on local communities' well-being and the ecosystems of the Amazon (Athayde et al. 2019). This has led to growing concerns regarding the role of hydropower in sustainable development in the Amazon (Moran et al. 2018).

Despite this increased awareness, certain types of impacts have received more attention than others. Major research efforts have concentrated on the direct impacts of the large dam construction and surrounding reservoir areas (Dias et al. 2018), including involuntary population resettlement and the repercussions of a large reservoir in ecological processes (Kirchherr et al. 2016, Cernea and Maldonado 2018). However, less scientific attention has been directed toward the downstream socio-ecological impacts of hydropower dams (Richter et al. 2010), especially within tropical regions (Winemiller et al. 2016, Runde et al. 2020). This constitutes a significant knowledge gap, given that the dam operation typically results in hydrological alteration downstream, often crossing jurisdictional boundaries over long distances (Nilsson et al. 2005, Poff and Schmidt 2016). Lost in hydropower development's shadow, the downstream impacts have been overlooked in the Amazon, leading to recurrently underestimated and undercompensated impacts on people and the environment (Mayer et al. 2022*c*, García et al. 2024, Utsunomiya et al. 2024).

In the Amazon, downstream dam regulation is a significant concern due to the intrinsic connection between aquatic ecosystems and the seasonal flow regime, described by Junk et al. (1989) as the flood pulse. The largest Amazonian rivers are characterized by a predictable monomodal flood pulse driven by dry and rainy seasons in their catchment basins (Junk et al. 2014). Along the margins of these rivers occur floodplains, which are crucial habitats for endemic and endangered species adapted to flood pulse (Junk and da Silva 1997, Wittmann et al. 2013). The flood pulse also regulates biochemical cycles within the floodplain (Melack 2016), such as soil and water nutrients (Melack and Forsberg 2001).

Beyond its influence on biota and ecological processes, the flood pulse profoundly defines the livelihoods of rural traditional riverine communities (known as *ribeirinho* in Portuguese), who reside in floodplain areas, especially the biodiverse whitewater floodplain, locally known as *várzea*. The bond between traditional *ribeirinho*'s livelihoods, *várzea*, and flood pulse is so profound that it resonates in their identity, resource utilization,

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movements, and social activities (Harris 1998). For instance, *ribeirinho* communities manage agriculture and extractivism in the *várzea* in synchrony with flood pulse (Junk et al. 2020). In this sense, natural and human elements of the *várzea* are interrelated and inextricably shaped by the flood pulse, functioning as a complex socio-ecological system (Kumar et al. 2023).

In this intertwined socioecological system, downstream dam regulation needs to be seen as an essential factor that pushes into a transitional state, eventually leading to new dynamic equilibria (Berkes and Folke 1998). Different components of the system that depend on the flood pulse adjust to flow regulation at varying rates. For instance, invertebrates and floodplain herbaceous vegetation may reach a new equilibrium within a few years (Baladrón et al. 2023), whereas fish and vegetation composition may continue adjusting for decades (Gandini et al. 2014, Bejarano et al. 2018). As the ecology adapts to the regulated flow, local residents, particularly farmers and extractivists, also adjust their livelihoods, which rely on floodplain resources (Thomas and Adams 1999). These adaptations are further influenced by broader economic and social factors from outside the floodplain, although their impacts are felt locally. However, few studies have explored how social-ecological systems adapt to downstream changes caused by dams, especially in the Amazon.

Under this scenario lies the enormous Madeira Hydroelectric Complex (MHC), which has been damming the Madeira River, a large whitewater tributary of the Amazon River. Operation of the MHC causes a sub-daily flow oscillation (hydropeaking) due to the intermittent operation of floodgates associated with energy demand (Almeida et al. 2020). Despite being considered a minor variation in hourly flow, hydropeaking may have significant implications for the social-ecological dynamics, however, there have been no studies to date that investigated how *ribeirinho* communities perceive hydropeaking concerning the impacts and adaptation on the *várzea* agriculture and extractivism activities (Bipa et al. 2024, Jardim and Collischonn 2024). We hypothesize that even subtle fluctuations in water levels can disrupt *várzea* traditional livelihoods, influencing agriculture and extractivism practices, and broader ecological interactions.

To test this hypothesis, we applied an interdisciplinary approach that combined interviews with 51 local experts from four downstream *ribeirinho* communities, daily and hourly hydrological analyses, and an assessment of soil chemical properties before and after the implementation of the MHC. A key aspect of our study was capturing the lived experiences of these communities, highlighting how hydropeaking influences their agricultural and extractivist activities within the *várzea*, a phenomenon largely understudied worldwide (Richter et al. 2010).

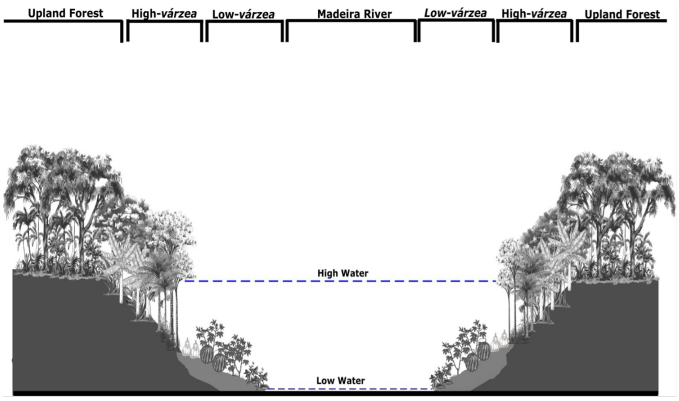
METHODS

Study site

The Madeira River basin spans over 1.4 million km², encompassing parts of Bolivia, Brazil, and Peru. Formed by the confluence of the main tributaries of the Amazonian–Andean region (Beni, Mamoré, and Madre de Dios Rivers), it is recognized as one of the most significant whitewater rivers in the Amazon basin in terms of sediment load (Latrubesse 2008). Naturally, the Madeira River has a flood regime that varies about 10 m between the dry and rainy seasons (Junk et al. 2014). Along the Madeira River occurs the *várzea*, the most biodiverse floodplains (Wittmann et al. 2013), which are divided into low and high topographic gradients according to both scientific and local knowledge (Junk et al. 2012, Souza et al. 2012). The low-*várzea* is flooded annually for more than 3 mos. and covered by mud bars, grassland, or sparse forest vegetation, whereas the high-*várzea* is elevated, covered with dense forest vegetation, agroforestry systems, and flooded for less than 3 mos. during the highest peak.

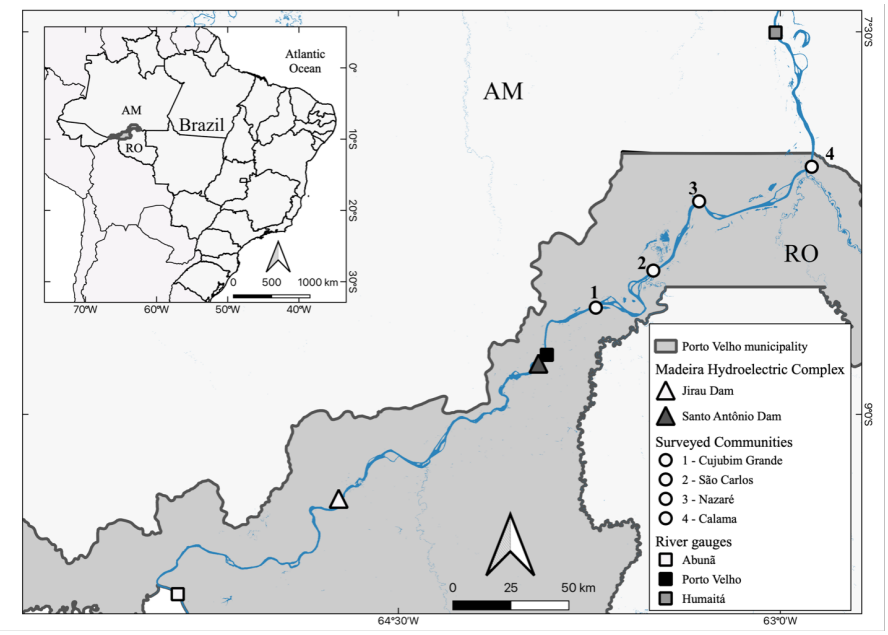
Within the *várzea*, several *ribeirinho* communities live and maintain their unique traditional livelihoods intricately tied to the flood regime rhythm (Harris 1998). They depend on the naturally fertile *várzea* soils for flood recessional agriculture, cultivating short-term crops (less than 90 d to produce), like beans (*Vigna unguiculata*), manioc (*Manihot esculenta*), and watermelon (*Citrullus lanatus*) in the low-*várzea*, especially in river mud bars. In the high-*várzea*, they practice conventional agriculture, planting long-term crops, such as corn (*Zea mays*), squash (*Cucurbita* sp.), and banana (*Musa* sp.). Also, they manage the high-*várzea* by adopting an agroforestry system to harvest essential forest resources, especially açaí (*Euterpe precatoria*) and other native fruits (Souza et al. 2012) (Fig. 1).

Fig. 1. Illustration of topographic gradients, water column variation, agricultural and extractivism practices, and vegetation in the *várzea* of the Madeira River. Source: Authors.



Since 2013, the MHC, comprising the Jirau and Santo Antônio dams, has been fully operational on the Madeira River. The cascade operation of these two large run-of-river dams has triggered multiple hydrosedimentological changes, making the Madeira River the most environmentally vulnerable basin in the Amazon (Latrubesse et al. 2017). Located approximately 100 km apart, the combined effects of the dams affected downstream flood regime with significant increases in daily and sub-daily flow peaks (i.e., hydropeaking) (Almeida et al. 2020), significantly threatening the natural ecosystem state (Siddiqui et al. 2021). Additionally, the damming of the MHC has led to a decline in downstream sediment load (Li et al. 2020). Despite the *ribeirinho* communities' fundamental connection to the *várzea*, they have had limited participation in environmental assessment reports of the MHC (Mayer et al. 2022*a*), leading to lack of compensation for losses in livelihoods and health (Mayer et al., 2022*b*, 2022*c*, García et al. 2024).

Fig. 2. Study area with river gauges used in hydrological analysis. Surveyed *ribeirinho* communities: Cujubim Grande, São Carlos, Nazaré, and Calama. Source: Prepared by the authors using data from IBGE (boundaries), ANA (gauges and dams), SEDAM-RO (communities), and Pekel et al. 2016 (hydrography).



Shortly after the completion of the MHC, an extreme flood event occurred in 2014. Driven by intense regional rainfall and aggravated by dam operations, the Madeira River reached unprecedented levels (Oliveira et al. 2021). This event resulted in irreparable losses for urban and rural populations along the Madeira River (Novoa Garzon and Silva 2020), and caused severe impacts on the *várzea*'s fauna and flora (Moser et al. 2019, Bobrowiec et al. 2021, Medeiros et al. 2023, Dayrell et al. 2024). This event exemplifies how the flood regime is the fundamental process governing the *várzea*, where the fates of people and nature are governed by the river's rhythm (Jackson et al. 2022).

Hydrological data collection and analysis

Hydrological analyses were conducted using daily flow data (m^3 s^-) from the Madeira River, from 1967 to 2022, to identify hydropeaking events and assess other hydrological anomalies. The data were obtained from the Brazilian National Water Agency (Agência Nacional de Águas e Saneamento Básico (ANA)) database including two of the region's most established and consistent downstream river gauges: the Porto Velho gauge (Code 15400000), located 5 km downstream of the Santo Antônio Dam, and the Humaitá gauge (Code 15300000), approximately 250 km downstream from the same dam. To evaluate hourly flood pulse oscillations, the analysis was restricted to years and river gauges with adequate data coverage (greater than 90% of the year with hourly data) during the MHC's operation period (2013–2019). Hourly data for the pre-dam period were unavailable, and the Humaitá gauge has a large data gap for all time series, therefore, it was no longer considered. The comparison focused on the Porto Velho gauge, representing the impacted downstream area, and the Abunã gauge (Code 15320002), located 5 km upstream of Jirau dam and not impacted (Fig. 2).

The daily flow data of the Madeira River was analyzed using the Indicators of Hydrologic Alteration (IHA) software, version 7.1, developed by the Nature Conservancy (2009). These analyses followed the IHA environmental flow protocol to evaluate the hydrological impacts of anthropogenic activities, focusing on key parameters related to hydropeaking. Daily rise and fall rates (m^3 s^{-1} h^{-1}) and the number of reversals were computed for periods before and after the construction of the MHC. Rise rates were determined by the median of positive differences between consecutive daily flow values, whereas the median of negative differences determined fall rates. Additionally, the number of reversals, defined as abrupt changes from rising to falling flow trends, was calculated for each seasonal flood pulse regime (October to September).

Changes in the seasonal flood pulse of the Madeira River were further assessed by comparing monthly Pardé coefficients for periods before (1967–2012) and after (2013–2022) the construction of the MHC. The Pardé coefficient, the ratio of mean monthly discharge to mean annual discharge, indicates shifts in the seasonal flood pulse regime (Almeida et al. 2020).

Sub-daily flood pulse oscillations were evaluated using the HP1 indicator (m^3 s^{-1} h^{-1}), which quantifies the magnitude of hydropeaking. This indicator is calculated as the difference between sub-daily maximum and minimum hourly flows, normalized by the mean daily flow (Carolli et al. 2015). The non-parametric Wilcox test was employed to assess the statistical significance using R software.

Soil data collection and analysis

The soil's chemical properties were assessed by analyzing samples collected before and after the construction of the MHC. For the pre-construction period, we used data from the "Studies and

Perspectives of Development for Downstream Madeira River 2010–2011" program (Souza et al. 2012). This program was conducted in collaboration with the Institute for Agri-Environmental Studies and Research and Sustainable Organizations (IEPAGRO) and the Santo Antônio Energia, the company responsible for the Santo Antônio Dam operation. The IEPAGRO program collected eight samples in productive areas of the low and high *várzea* of each downstream *ribeirinho* community expected to be impacted by dam regulation. The soil was sampled at 20 cm depth, during September and October 2011, which coincides with the Madeira River low water season. All samples were georeferenced and stored in geodatabases. The samples were analyzed for various soil chemical parameters, including base saturation (Al+H), calcium, magnesium, organic matter, pH, phosphorus, and potassium, following the Brazilian Agricultural Research Corporation (Embrapa) standardized protocol (Embrapa 1997).

For the post-construction period, samples were collected during the low water season as well, in September and October 2023, adopting the same protocols used in 2011 and in the same georeferenced points. These samples were analyzed for the same soil chemical parameters following Embrapa standardized protocols (Embrapa 1997). The differences between soil chemical properties in the surveyed *várzea* were compared using the Student's *t*-test, performed with the Python library scipy.stats.

Interview data collection and analysis

The interviews were conducted in four downstream non-indigenous rural riverine (*ribeirinho*) communities outside protected areas in Porto Velho, Rondônia State, Brazil: Cujubim Grande, São Carlos, Nazaré, and Calama (Fig. 2), which have a combined total population of 2,743 residents (Instituto Brasileiro de Geografia e Estatística (IBGE) 2024). From September 2022 to November 2023, we identified interviewees using a non-probabilistic "snowball" sampling method, an appropriate method for research with remote and dispersed groups (Russell 2005). The participants selected were local experts, defined for this study as community members recognized by their peers for their long-term practical knowledge of *várzea* agriculture and extractivism. A key inclusion criterion was at least 10 yrs of continuous residence downstream, including the period prior to the construction of the MHC.

Semi-structured interviews were conducted with these selected participants to explore their perceptions of *várzea* agricultural and extractivism practices in the context of hydropeaking. Participants were asked about their agricultural and extractivism practices in both low-*várzea* and high-várzea. For extractivism, they were questioned about resource use, such as edible fruits, medicinal products, oils, palm hearts, resins, tannins, textile fibers, and timber.

The interviews further explored any abnormal changes in the Madeira River's daily flooding, and how these changes may have impacted their agricultural and extractivism activities over the past decade. Participants were asked to suggest and discuss possible causes when changes were noted.

Interviews were conducted using the ArcGIS Survey123 on tablets, with audio recording, and took place in the participants' homes or work environments. Before the interviews, participants were informed about the study's objectives and provided consent, ensuring anonymity and the option to withdraw at any time. This study was approved by the Human Research Ethics Committee at the University of Campinas (CEP authorization number: 61440222.9.0000.8142).

Interviews were transcribed to be analyzed in the Python "pandas" and "spacy" libraries. We implemented a content analysis approach to identify the most frequently mentioned terms across all interviews, focusing on the perceptions of local experts from *ribeirinho* communities regarding hydropeaking occurrence and the adaptation strategies in agriculture and extractivism within the *várzea*.

RESULTS

Hydrological data

The mean monthly Pardé coefficient comparison between pre-dam and post-dam periods shows that Madeira River still preserves a seasonal flood pulse regime, validated with Porto Velho and Humaitá gauges flow data (Fig. 3).

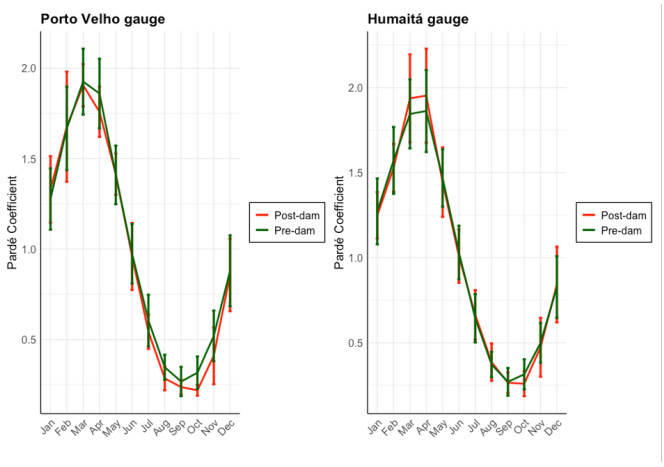
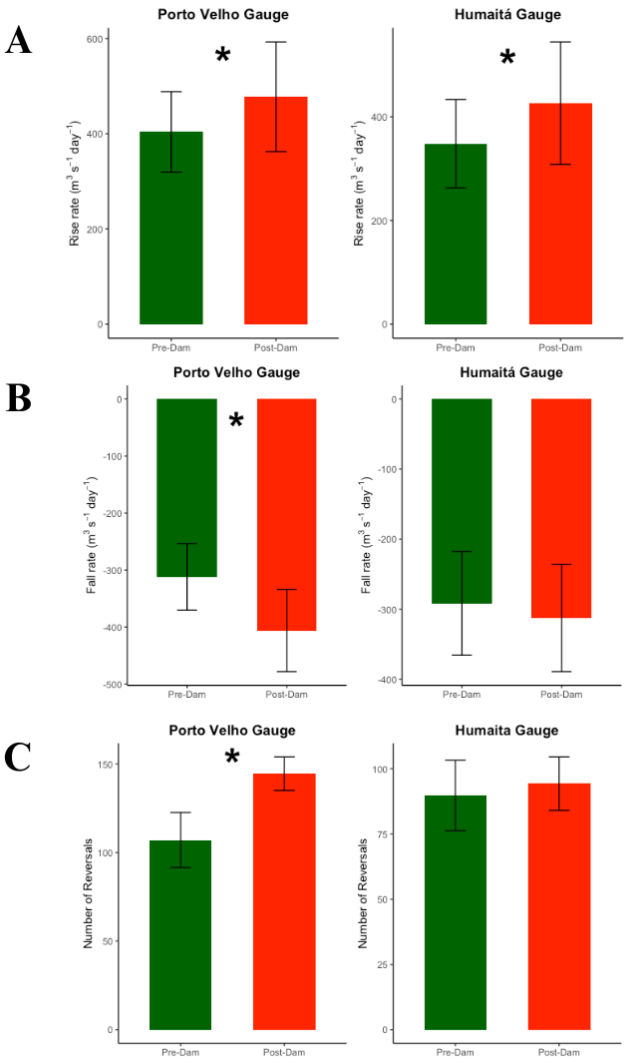


Fig. 3. Mean monthly Pardé coefficients (± standard deviation) for the Madeira River, a normalized indicator average monthly flow divided by the annual average flow, comparing pre-dam (1967–2012) and post-dam (2013–2022) at the Porto Velho and Humaitá gauges, from 1967 to 2022.

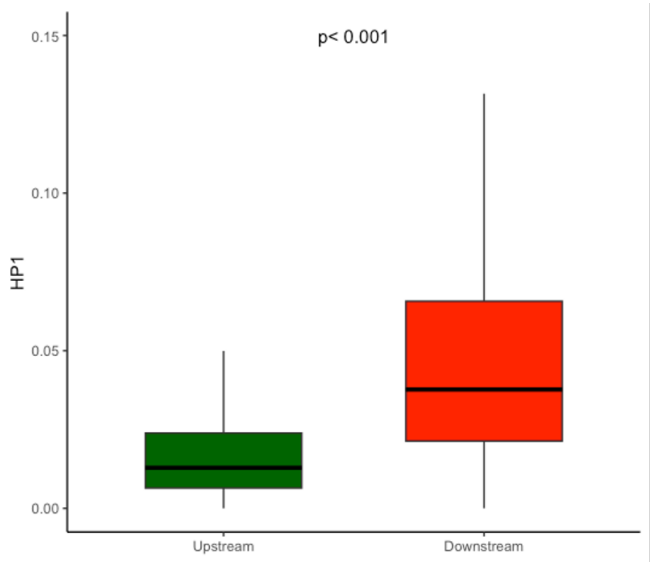
The flow rise rate ($m^3 s^{-1} day^{-1}$) showed a marked difference between the pre-dam (1967–2012) and post-dam (2013–2022) periods. Both river gauges recorded a significant increase in the rise rate following the dam's operation (Porto Velho gauge, $p < 0.001$; Humaitá gauge, $p < 0.05$). Daily flow analysis revealed a 21.4% increase at the Porto Velho gauge and a 26.9% increase at the Humaitá gauge (Fig. 4*a*). The flow fall rate ($m^3 s^{-1} day^{-1}$) showed a significant increase of 33.1% at the Porto Velho gauge between the pre-dam and post-dam periods ($p < 0.001$). At the Humaitá gauge, there was a 6.2% increase in the fall rate, but it was not statistically significant (Fig. 4*b*). Daily flow analyses showed a 35.6% increase in flow reversals. The comparison between pre-dam and post-dam impact showed a 35.6% increase in the number of flow reversals at Porto Velho Station ($p < 0.001$). The Humaitá gauge showed a 5% increase in reversals (Fig. 4*c*).

Fig. 4. Indicators of short-term flood pulse variability based on flow daily data (m3 s–1 day–1) from 1967 to 2022. Plots show pre-dam (1967–2012) and post-dam (2013–2022) mean (± standard deviation) for (a) flow rise rates, (b) flow fall rates, and (c) the number of flow reversals at gauges located 5 km (Porto Velho) and 250 km (Humaitá) downstream of the dam. Asterisks reveal significant differences between the pre and post-dam periods (Wilcox test, $p < 0.05$).



The comparison between Abunã and Porto Velho gauges hourly flow shows a significant downstream sub-daily flood pulse oscillation ($p < 0.001$), as the hydropeaking indicator (HP1) has a greater mean and standard deviation in the impacted region (Fig. 5).

Fig. 5. Dimensionless hydropeaking indicator (HP1) for the Madeira River using hourly flow data from the Abunã gauge (green, upstream, non-impacted) and the Porto Velho gauge (red, < 5 km downstream of Santo Antônio dam, impacted). The indicator shows the hourly rate of flow change, calculated as the difference between maximum and minimum flow divided by the daily mean. The Wilcoxon test revealed a significant difference between impacted and non-impacted regions ($p < 0.001$).



Soil data

The soil chemical comparison between 2011 and 2023 from Cujubim Grande, São Carlos, Nazaré, and Calama revealed slight acidification and a general decline in fertility, with reductions in calcium, magnesium, phosphorus, and potassium levels. Despite these trends, only the decrease in phosphorus was statistically significant ($p < 0.018$), observed only in the low-*várzea* soils across all communities. Other parameters, such as base saturation (Al+H) and organic matter, showed less pronounced variations (Table 1).

Survey data

Agriculture and extractivism in the várzea

A total of 51 local experts from four downstream *ribeirinho* communities were interviewed, one adult (over 18 yrs old) per family unit. Of these, 85% were male, with an average age of 58, and most had completed primary education. The interviews revealed that the importance of the *várzea* to local livelihoods has persisted after the establishment of the MHC. Ninety-six percent of respondents considered the *várzea* very important for their traditional livelihood. Local experts stated that low-*várzea*, especially river mud bars, are very important for the flood recessional agriculture of beans, manioc, and watermelon. The high-*várzea* are mostly used to plant bananas and sometimes squash, and harvest açaí, as exemplified by a *ribeirinho* from the Nazaré community:

> *We plant beans and manioc on the river's mud bars, and we grow long-term crops on the higher ground in the* várzea. *We plant bananas on the higher ground, and we also grow squash and harvest native açaí.*

For our purposes, respondents were asked if they perceived hydropeaking in the Madeira River in recent years. Eighty-five percent perceived hydropeaking. Among the respondents who perceived hydropeaking, the majority pointed to the MHC as the

Table 1. Soil chemical parameters for 2011 and 2023 samples of each *várzea* topographic gradient (low and high *várzea*) in the *ribeirinho* communities located downstream of the Madeira Hydroelectric Complex, Porto Velho, Brazil.

Chemical parameters	Cujubim Grande				São Carlos				Nazaré				Calama			
	Low-*várzea*		High-*várzea*		Low-*várzea*		High-*várzea*		Low-*várzea*		High-*várzea*		Low-*várzea*		High-*várzea*	
	2011	2023	2011	2023	2011	2023	2011	2023	2011	2023	2011	2023	2011	2023	2011	2023
pH	5.4	5.2	5.7	5.1	5.5	5.3	6.7	4.7	6.2	6	5.4	5.3	5.6	5.9	4.2	5.1
P (mg/dm³)	45	15	30	21	86	18	80	84	79	50	75	21	83	27	3	21
K (mmcolc/dm³)	2	1.1	1.2	1.9	1.9	1.3	2	0.4	3.6	0.6	3	0.8	2.3	0.6	0.7	1.9
Ca (mmcolc/dm³)	51	40	48.8	17	72.4	17	60.5	18	15.5	18	18.9	17	63.8	15	2.2	17
Mg (mmcolc/dm³)	27	16	24.2	7	31.2	8	34.2	3	5.1	4	6.4	14	24.8	5	1.8	7
Al+H (mmcolc/dm³)	36.3	17	16.5	14	16.5	13	8.3	11	54.5	8	75.9	12	14.9	9	113.9	14
MO (g/kg)	3	7	9.9	4	6.2	6	7.6	3	14.3	2	16.4	3	6.2	7	39.1	4
V (%)	61	77	77	69	86	67	92	66	53	74	45	73	86	70	4	65

driver of this phenomenon (77.8%), 2.75% indicated illegal mining, 2.75% climate change, and 16.7% don't know the reason. Regarding the predictability of the Madeira River flood rhythm, 89% of respondents stated that hydropeaking jeopardizes their capacity to predict daily flood levels. A *ribeirinho* from the São Carlos community who has been living in the region for 40 yrs reported that several bioindicators have changed with the hydropeaking, such as the inhambu bird (*Crypturellus* sp.) and river dolphin (*Sotalia fluviatilis*) behavior that used to be a signal of rising river water:

> *The river is not normal. In the morning, it's full, but by the afternoon, it dries up. We know that when the inhambu bird starts calling at night, the river will rise. We also know that when the dolphins start moving too fast, the river will rise. It used to be like that, but now it's all messed up. The river can rise a meter from six in the evening until dawn. Then, during the day, it can drop by a meter and a half. We've lost our ability to predict the river.*

Seventy-five percent of respondents indicated that hydropeaking negatively impacts their agricultural practices. The most frequent agricultural activities in *várzea* cited by respondents that decreased after hydropeaking occurrence were beans (14), manioc (9), and watermelon (12), all mostly located in the low-*várzea*. This, in turn, led to the interruption of flood recessional agricultural practices that was described by a *ribeirinho* from Cujubim Grande:

> *Nowadays, you can't plant crops along the river's mud bars like you used to. It's too risky. You plant beans or anything else today, and by tomorrow it's all flooded.*

Several respondents mentioned adapting their agricultural effort from the low-*várzea* to higher ground to avoid hydropeaking, frequently noting (16 mentions) increased banana production in high-*várzea*. Another issue created by the hydropeaking that motivated the focus in agriculture on high-*várzea*, is a misinterpretation of the natural reversal of the river flow, an abrupt change from rising to falling flow trends locally known as *repiquete*, which serves as an environmental signal of the beginning of the flooding season. According to a *ribeirinho* from the Calama community, the similarity of hydropeaking with *repiquete* confuses them:

> *Before these dams, we were familiar with the signs of the flood and drought seasons. In October, we knew the first repiquete would come, with the water rising once and then receding. In early November, there would be a second repiquete. From late November to December, it would rain, and the water would start rising steadily. But it's different now, it's out of season. When it's not expected, the water rises a little and then dries up, because they're releasing water from the dams. It's not affecting the high-várzea*, but we used to plant on the river's very productive mud bars. Now, we have to plant higher up.

The *ribeirinho* local experts were asked if they perceived any change in the *várzea* soil fertility since the beginning of hydropeaking occurrences. Sixty-six percent of the respondents noted a decrease in soil fertility, 28% indicated no change, and 6% responded that they didn't know. The deterioration of soil fertility was noted by a *ribeirinho* from the São Carlos community:

> *The river is shallower now, depending on the outflow from the dams. The dams traps mud, so it no longer settles on the bars, making them more sandy. There's only sand on the banks now, and the soil is weaker for cropping.*

According to the interviews, extractivism was not significantly impacted by hydropeaking, with açaí harvesting being cited three times as impacted, and araça-boi (*Eugenia stipitata*), bacaba (*Oenocarpus bacaba*), and cacao (*Theobroma cacao*) each cited only once. Aside from hydropeaking, several respondents declared that the extreme 2014 flood was a major event that caused disinterest in extractivism due to huge losses (being cited by 28 respondents), including displacing residents and diminishing açaí palms, as stated by another *ribeirinho* from São Carlos community:

> *Here in São Carlos, a lot of people left because of the 2014 flood. The only ones who stayed were those who were pioneers here. I lost everything during the 2014 flood —my house and my crops, including around 1,500 açaí plants.*

During fieldwork, numerous illegal rafts and dredges extracting gold from the riverbed and banks were commonly observed. Despite the risks associated with this illegal activity, many *ribeirinho* community residents have shifted their labor efforts away from *várzea* recession agriculture and extractivism to gold dredging, transforming the agricultural landscape documented by IEPAGRO in 2011 to a marked mining-induced erosion in 2023 (Fig. 6*a*, *b*). Although interviewees acknowledged that gold

Fig. 6. (a) Bean, manioc, and squash plantations managed by *riberinhos* in the low *várzea* of the Nazaré community, September 2011. Photo by J. Gil taken during Institute for Agri-Environmental Studies and Research and Sustainable Organizations (IEPAGRO) fieldwork. (b) Illegal gold mining platforms on the Madeira River contrasted with a squash plantation in the high-*várzea* during the interviews (October 2023). Photo by S. Mandai.



dredging is illegal, some stated that it is the only economic alternative for them and their family members who live downstream from the MHC. As described by a ribeirinho from the Nazaré community:

> *I'm not against ending illegal mining, but it needs to be done differently. We need to bring everyone together and provide economic alternatives that were lost after the dams. I'm tired of seeing the news frame us as criminals, when for us, this is the only way to sustain our families' livelihoods.*

DISCUSSION

We found that local experts from the four surveyed *ribeirinho* communities perceive the occurrence of hydropeaking, which aligns with data analysis from river gauges, demonstrating agreement between information sources. They recognize the specific impacts of hydropeaking, differentiating its effects on their traditional *várzea* flood recessional agriculture and extractivism based on topographic gradients. The low-*várzea* gradient was identified as being more severely impacted, particularly affecting the flood recessional cultivation of beans, manioc, and watermelon on the river's mud bars. Additionally, *ribeirinho* local experts reported challenges in practicing agriculture in the low-*várzea* due to poor soil fertility, which was corroborated by soil analysis showing deficient phosphorus content. According to local experts, they have shifted their agricultural practices to the high-*várzea* gradient, away from the direct impacts of hydropeaking. However, this agricultural adaptation has not been reflected in extractivism. The interviewed local experts reported a decline in *várzea* extractivist activities, primarily due to consequences of the extreme 2014 flood event, which caused significant socio-ecological losses for communities along the Madeira River, as well as the emergence of alternative economic opportunities, such as gold mining.

Our extended hydrological analysis corroborates the findings of Almeida et al. (2020), demonstrating that the operation of the MHC has significantly increased short-term flood pulse oscillations (hydropeaking). This impact is most pronounced near the complex, with attenuation observed further downstream, likely due to the influence of the channel, floodplain, and tributaries such as the Jamari and Ji-Paraná Rivers (Greimel et al. 2018). Despite this attenuation, distant downstream communities, such as Nazaré and Calama, still perceive hydropeaking as a disruptive force in their traditional livelihoods. Hydropeaking has also altered other aspects of local livelihoods. As highlighted by Santos et al. 2020, fishers in Humaitá, a city located 250 km downstream, reported declines in productivity due to the unpredictable flood pulse post-damming. Although hydropeaking is a subtler phenomenon compared with the impact of older Amazonian dams (Schöngart et al. 2021), it significantly alters how Amazonian traditional livelihoods interact with floodplains and rivers, as observed in this case and others, such as the Arara people from the Xingu River (Utsunomiya et al. 2024). Therefore, hydropeaking must be addressed by decision makers as a direct impact of the MHC that requires appropriate compensation.

We found a new aspect of hydropeaking's impact on traditional *ribeirinho*'s livelihoods according to local experts. Undoubtedly, the main hydropeaking impact perceived by local experts is predicting flood timing to practice flood recessional agriculture in the low-*várzea*. As noted by previous studies, flood recessional agriculture is risky when the flood regime becomes unpredictable (Coomes et al. 2016). For instance, early floods, similar to hydropeaking, cause substantial agricultural losses in the Peruvian Amazon (Langill and Abizaid 2020). In the case of the Madeira River, the persistent hydropeaking led to a significant decline in the efforts of local communities to develop flood recessional agriculture, dropping the traditional production of beans and manioc in river mud bars, both of which are rooted in ancient indigenous heritage (Watling et al. 2018). This disruption has driven *ribeirinho* community members to adapt, particularly anchoring their production effort in banana monoculture in the high-*várzea* areas. Such a focus on higher ground could potentially trigger a forest transition process in the high-*várzea* and upland areas due to limited access to flood recessional agriculture areas (Coomes et al. 2022).

This study presents the first soil chemical assessment of agricultural *várzea* areas following the damming of the Madeira River, revealing a decline in soil phosphorus content in the low-*várzea*, consistent with local experts' perceptions. The observed reduction in phosphorus in low-*várzea* soils is validated by water data (Almeida et al. 2015). Finer and Jenkins (2012) have raised concerns about the impact of damming the Madeira River on sediment load, as sediment trapping is a documented phenomenon in reservoirs worldwide (Dethier et al. 2022). Phosphorus depletion poses a significant threat to the entire social-ecological system, as phosphorus is a critical limiting macronutrient in the Amazon (Malhi et al. 2021). For instance, high productivity of *várzea* flood recessional agriculture is naturally sustained by nutrient-rich sediments deposited by the Madeira River, originating from the Andes (McClain and Naiman 2008). Therefore, declining phosphorus in the low-*várzea* soil is another key driver for the agricultural shift to higher ground, as local experts confirmed. In the case of *várzea* agriculture, phosphorus content depletion is especially concerning given the local logistical challenges of supplying phosphorus from outside the natural cycle (Morello et al. 2018). Moreover, phosphorus fertilization has been shown to increase

phytoplankton biomass and productivity in central Amazon whitewater lakes and *várzea* (Melack and Forsberg 2001). In this sense, the decline in phosphorus may also be contributing to decreasing commercial fish yields in the Madeira River (Santos et al. 2018), as many fish species consumed in the Amazon rely on food chains that begin with phytoplankton (Forsberg et al. 1993).

Surprisingly, extractivism was not frequently mentioned by interviewees as important to their livelihood, despite its potential to create sustainable chains for native products (Abramovay et al. 2021). A significant factor contributing to the disinterest in *várzea* extractivism was the substantial losses experienced during the extreme 2014 flood, which destroyed productive areas and residences (Novoa Garzon 2019). This event killed numerous *várzea* tree and herbaceous species (Oliveira et al. 2021, Medeiros et al. 2023), thereby likely reducing the availability of extractive resources (Evangelista-Vale et al. 2021).

The decline in interest in agroextractivist practices in the *várzea* has been further exacerbated by the gold mining boom along the Madeira River. In recent years, many *ribeirinho* community members whose livelihoods were based on agriculture, extractivism, fishing, and hunting have turned to illegally extracting gold to increase their profits (Pestana et al. 2022). Despite mining being a fundamental economic activity in the Madeira River (Martins et al. 2022), it threatens local resilience due to its numerous impacts on the ecosystem and social structure of the traditional communities (Froese et al. 2022). With limited sustainable economic alternatives available, they are increasingly being pushed toward illicit activities that compromise the integrity of the regional social-ecological system (Marcovitch and Val 2024). Addressing this challenge requires urgent efforts to develop viable, sustainable livelihood options that align with the ecological and cultural realities of the region (Zerbini et al. 2024). Without such conservation interventions, the cycle of environmental degradation and social-economic vulnerability will only deepen, further endangering both the biodiversity and the *ribeirinho* well-being.

CONCLUSION

Our research explored the perceptions of local experts from *ribeirinho* communities regarding the downstream impacts caused by the MHC, combined with hydrological and edaphic data. Taking advantage of an interdisciplinary approach, our findings show that local experts have not only perceived these impacts but have also adapted their agricultural and extractivist practices within the *várzea*. To our knowledge, we provided the first evidence that the damming of the Madeira River is altering the phosphorus content of low-*várzea* soils. Although our study, based on a comparison of two periods, has limitations in confirming continuous soil chemical changes, it strongly indicates the need for continued monitoring of *várzea* soils and associated social-ecological impacts.

Over the past decade, the downstream changes caused by the MHC have eroded existing resource base and traditional practices in the *várzea*. Without innovation or adequate support, agriculture has become limited to the high-*várzea* areas. At same time, low-*várzea* exhibited the higher downstream impact, diminishing flood recessional agriculture due to hydropeaking impact and phosphorus soil loss. Additionally, the extreme 2014 flood, in addition to "gold fever", put pressure on people to find some other means of labor and subsistence, decreasing interest in *várzea* extractivism and agriculture.

Although the findings from our 51 local experts' interviews cannot be statistically generalized to the entire downstream population of Porto Velho, they are critically important, as these *ribeirinho* community members have experience with *várzea* agriculture and extractivism both before and after the operation of the MHC. Moreover, local knowledge of experts reflects deep social-ecological links that are often invisible to the general population (Wantzen 2024), being of great value to downstream dam assessment, as some impact can be perceived only by those who observe nature processes intimately and daily (Baird et al. 2021). For generations, *ribeirinho* communities have relied on *várzea* agriculture, extractivism, and fishing as their main economic activities. However, recent years have been particularly challenging, pushing them to limited viable economic alternatives. In this context, documenting local expert perceptions alongside empirical assessments, such as soil and hydrological analyses, is essential to capture the downstream impacts of large dams on these often-overlooked communities. This is particularly relevant for run-of-river dams, frequently promoted as sustainable energy solutions with minimal downstream consequences.

Despite the conventional assumption that run-of-river dams cause only subtle flow variations, our findings demonstrate that hydropeaking promotes profound social-ecological consequences on the *várzea* system of the Madeira River. Given these impacts, it is imperative to involve *ribeirinho* communities in conservation initiatives and research efforts, ensuring close monitoring of downstream effects. The active participation of local communities in impact monitoring has proven successful in the case of the Belo Monte Dam, one of the most controversial hydropower projects in the Amazon, and aligns with conditions observed in the Madeira River. Along the Xingu River, *ribeirinho* communities and indigenous people have collaborated with local researchers to independently assess Belo Monte's downstream effects, providing a counterpoint to the periodic social-environmental assessments conducted by the energy company, showing an often underestimated extent of social-ecological consequences (Quaresma et al. 2025).

Similarly, in the Madeira River, the companies responsible for the hydroelectric complex, Jirau Energia and Santo Antônio Energia, have conducted hydrobiochemical monitoring in the downstream region. However, their assessments have consistently overlooked the downstream impacts on the *várzea* social-ecological system. In this context, our findings strongly recommend that *ribeirinho* communities of the Madeira River adopt an independent monitoring protocol inspired by the Xingu River experience. To implement such a monitoring system, we propose establishing partnerships with research institutions (e.g., Federal University of Rondônia - UNIR, and the National Institute for Amazonian Research - INPA), agroextractivist cooperatives, and local NGOs. Through these collaborations, *ribeirinho* residents could be trained by scientists to apply diverse monitoring methods that integrate local knowledge with scientific knowledge. The downstream region of the MHC is a particularly suitable setting for this collaborative monitoring system, as it could be built based on previous initiatives, such as the ForestFisher project, which supported participatory monitoring of artisanal fishing (Biodiversa+ 2024).

Decision makers must recognize the unique vulnerabilities of *ribeirinho* communities living downstream of the Madeira

Hydroelectric Complex and implement mitigation actions that restore hydrological conditions as closely as possible to natural flow patterns. Access to water is a fundamental right, not a commodity, and downstream communities must have real-time access to river flow information to adapt their livelihoods accordingly. A truly sustainable future for the Madeira River depends on revitalizing *várzea*-based value chains, preserving both ecological integrity and social resilience while preventing harmful activities such as illegal mining. In this sense, the sustainability of the Madeira River's *várzea* social-ecological system requires integrating scientific assessments with local knowledge, prioritizing community-led solutions.

Author Contributions:

Conceptualization: GSL, RB, and EM. Fieldwork: GSL and JOG. Data analysis: GSL. Writing – original draft: GSL, RB, and EM. Writing – review and editing: GSL, RB, and EM. All of the authors contributed to and discussed further analyses and commented on various versions of the manuscript.

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Data Availability:

The data and code that support the findings of this study are openly available in the University of Campinas (Brazil) repository named Repositorio de Dados de Pesquisas da UNICAMP (REDU) at https://doi.org/10.25824/redu/1WTNAC. The data set consists of responses from anonymous semi-structured interviews, soil data, and R, Google Earth Engine, and Colab scripts. Ethical approval for this research study was granted by University of Campinas Ethical Committee (CEP: 61440222.9.0000.8142).

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