UNIVERSIDADE FEDERAL DE MINAS GERAIS (UFMG)

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Programa de Pós-Graduação em Ecologia, Conservação e Manejo da Vida Silvestre

Rangel Eduardo Santos

IMPACTOS DO COMPLEXO HIDRELÉTRICO DO RIO MADEIRA SOBRE A PESCA E OS ECOSSISTEMAS AQUÁTICOS AMAZÔNICOS

Belo Horizonte

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Versão Final

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Orientador: Prof. Dr. Ricardo Motta Pinto-Coelho

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"A Amazônia foi e continua sendo, em larga medida, um mundo natural e social desconhecido, alvo de ações que buscam torná-la uma válvula de escape para os problemas vivenciados em outras regiões do Brasil."

(Daniel Chaves de Brito, 2001)

Resumo

O número de usinas hidrelétricas construídas em ecossistemas amazônicos têm crescido de forma substancial nos últimos anos. Apesar de ser considerada uma fonte de energia limpa, as usinas hidrelétricas causam impactos negativos nos processos ecológicos fundamentais para a manutenção dos serviços ecossistêmicos e conservação da biodiversidade. Nesse contexto, essa tese tem como objetivo identificar e avaliar os impactos ambientais gerados pelas hidrelétricas de Santo Antônio e Jirau sobre a pesca e os ecossistemas aquáticos na bacia do rio Madeira. Para atender este objetivo, essa tese foi estruturada em dois capítulos. No primeiro capítulo, foi investigada a influência do complexo hidrelétrico do rio Madeira sobre o estoque pesqueiro local. Este estudo testou a hipótese de que a instabilidade do pulso de inundação, devido à construção das barragens, causou uma redução significativa nos estoques pesqueiros da bacia. Essa hipótese foi testada utilizados dados correspondentes ao período de janeiro de 2002 a setembro de 2017 de desembarques pesqueiros da colônia de pescadores (Z-31) “Dr. Renato Pereira Gonçalves”, localizada no município de Humaitá, Amazonas. Os dados obtidos foram registrados diariamente contendo: data de partida e chegada das expedições, espécies capturadas e o número de capturas em quilogramas (kg). Nesse estudo, foi constatada queda de 39% da produção média anual e 34% da produção média mensal de pescado após a construção do complexo hidrelétrico do rio Madeira. Os resultados ainda apontam que o declínio do estoque pesqueiro registrado para a colônia de pescadores de Humaitá está principalmente relacionado com o aumento da média da fluviometria do rio Madeira após a construção das hidrelétricas. No segundo capítulo, foram avaliados os impactos gerados pelo complexo hidrelétrico do rio Madeira através da percepção dos pescadores locais (22 Homens e 6 Mulheres) e banco de dados da colônia Z-31. As questões levantadas neste capítulo têm como objetivo identificar e avaliar os impactos das barragens focando em três temas principais: (i) a pesca local; (ii) o peixe e (iii) o ecossistema aquático. Os pescadores locais foram selecionados por meio da abordagem “snowball” para a aplicação de entrevistas semiestruturadas. Todos os pescadores locais confirmaram ter percebido um declínio na produtividade da pesca após o barramento do rio Madeira. As alterações nos peixes também foram percebidas pelos pescadores: exoftalmia (82%), redução do peso/comprimento (25%) e período reprodutivo irregular (14%). Em relação aos impactos percebidos no rio, a mudança no ciclo hidrológico foi o processo mais citado pelos entrevistados (75%). Os resultados dessa tese elucidam diversos impactos ambientais ocasionados pelas implantações de usinas hidrelétricas no rio Madeira, e colocam em evidência o alto risco desses empreendimentos para os ecossistemas aquáticos, atividades de pesca e populações ribeirinhas amazônicas. A esperança é a de que essa tese possa contribuir para prevenir, mitigar ou mesmo compensar de modo justo impactos similares tanto em outras partes da bacia hidrográfica em questão como em outras bacias situadas na região amazônica.

Palavras-chave: Impacto ambiental, Fauna de peixes, Colônia de pescadores, Represamentos, Distúrbios antropogênicos, Pescadores artesanais, Etnoecologia, Comunidades ribeirinhas

Abstract

The number of dams operating in the Brazilian Amazon region has grown at an increasingly rapid rate in recent years. Despite being considered beneficial by providing clean energy, hydroelectric dams' plants have negative impacts on the ecological processes that are fundamental to maintaining ecosystem services and conserving biodiversity in the Amazon. In this context, this thesis aims to identify and evaluate the environmental impacts generated by the Santo Antônio and Jirau dams on the aquatic ecosystems and fisheries activity of the Madeira River basin. To fulfill this objective, this thesis was structured in two chapters. In the first chapter, the influence of the Madeira river hydroelectric complex on the local fishery stocks was evaluated. This study investigated the hypothesis that the instability of the flood pulse caused by the construction of the dams has caused a significant reduction in the fish stocks of the Madeira River. This hypothesis was tested using fishery landings data obtained in fishing colony (Z-31) "Dr. Renato Pereira Gonçalves ", located in the municipality of Humaitá, Amazonas State, from January 2002 to September 2017. The collected data were daily recorded at the colony and include the fishing ground (point), the date of the beginning and the end of each fishing trip, type of fish caught and total catch (kg). This study indicated reductions of 39% in the mean annual catch and 34% in the mean monthly catches. The results also point out that the decline of fisheries recorded for the Humatiá colony is mainly related to the increase of the Madeira River fluviometry average after the construction of the hydroelectric dams. In the second chapter, the impacts generated by the Madeira River hydroelectric complex were evaluated through the perception of local fishers (22 Men and 6 Women) and the fishery database from the Z-31 colony. This study aimed to investigate the environmental impacts generated by the hydroelectric complex in the Madeira River based on the perceptions of local fishers and fishery database, it focuses attention on three main points: (i) local fishery stocks; (ii) the fish and (iii) the aquatic ecosystems. The local fishers were selected through the "snowball" approach for the application of semi-structured interviews. All the fishers confirmed having perceived a decline in fishery productivity following the impounding of the Madeira River. Changes in fishes' conditions were also perceived by the local fishers, including exophthalmia (82%), a reduction in the weight or length of the fish (25%), and irregular breeding season (14%). Regarding impacts on the river, changes in the hydrological cycle were the process most frequently remembered (75%). The results of this thesis elucidate several environmental impacts caused by the implantation of hydroelectric power plants in the Madeira River and highlight the high risk of these enterprises for aquatic ecosystems, fishing activities, and Amazonian riverside populations. It is hoped that this thesis may help to prevent, mitigate or even fairly compensate for similar impacts both in other parts of the concerned river basin and in other basins in the Amazon region.

Keywords: Environmental impact, Fish fauna, Fishing colony, Impoundments, Anthropogenic disturbance, Artisanal fishers, Ethnoecology, Riverside communities

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1.1- Empreendimentos hidrelétricos na Amazônia

Os grandes empreendimentos na região amazônica ganharam impulso com os governos militares na década de 1960. Nesse período, foi lançada a "Operação Amazônia", que tinha como finalidades a ocupação, criação de estruturas produtivas e integração da Amazônia legal (Costa et al. 2017). Esse processo levou a migração em massa de pessoas para a região, seja para trabalharem na implantação dos novos projetos, seja para desbravarem novas fronteiras agropecuárias (Castro e Hébette 1989; Lima e Lozzobon 2005). As primeiras obras realizadas nesse período foram a construção de grandes rodovias, como por exemplo a transamazônica (BR-230), que tinham como objetivo conectar a Amazônia legal com as outras regiões do país (Neto e Nogueira 2017).

Ao mesmo tempo, surgiram os projetos para o desenvolvimento do setor energético na região, dos quais originaram a implantação das primeiras usinas hidrelétricas (UHE) na Amazônia: Coaracy Nunes, no rio Araguari, estado do Amapá (40 MW - inaugurada em 1975) e de Curuá-una, no rio que dá o mesmo nome à hidrelétrica, no estado do Pará (30 MW - inaugurada em 1977) (Moretto et al. 2012). Essas primeiras hidrelétricas inauguradas na região possuíam um menor potencial de impacto, pois a soma de seus reservatórios cobre uma área menor do que 100 km^2 (Junk e Mello 1990). No entanto, a situação mudou a partir da década de 1980, com a inauguração da UHE de Tucuruí (8,370 MW – inaugurada em 1984) no baixo Tocantins, estado do Pará, e de Balbina (250 MW – inaugurada 1989) no rio Uatumã, estado do Amazonas, os quais possuem reservatórios que ocupam uma área de 2.430 km^2 e 2.360 km^2 respetivamente (Moretto et al. 2012).

A decisão do governo brasileiro em desenvolver o setor energético na Amazônia estava principalmente relacionada ao fato da região possuir um alto potencial hidrelétrico (Moretto et al. 2012), já que é considerada a maior bacia hidrográfica do mundo, cobrindo uma área de 6 milhões de km^2 e aproximadamente 1.100 afluentes (Brasil 2019). Além disso, as primeiras hidrelétricas construídas na região foram planejadas em um período com baixo grau de disciplina do uso e ocupação do espaço, principalmente por causa das leis ambientais menos exigentes (Sánchez 2016). Desde então, o número de hidrelétricas em ecossistemas amazônicos tem crescido de forma acentuada (Tundisi, et al. 2014). Ao todo, a região já possui 154 barramentos hidrelétricos, entretanto, esse número pode aumentar consideravelmente com o planejamento de 277 novos empreendimentos para os próximos anos (Castello e Macedo 2016). Somente o setor energético brasileiro inclui a construção de seis novas UHE’s em ecossistemas amazônicos até o ano de 2026 (Brasil 2017).

Atualmente, a construção de grandes empreendimentos hidrelétricos na região amazônica tem sido estratégica e vista como a principal solução para a segurança energética dos países que compartilham essa bacia. Dentre estes países, o Brasil é um dos principais dependentes da energia hídrica, já que aproximadamente 65% da sua energia advém de usinas hidrelétricas implantadas nos seus gradientes fluviais (EPE 2019). De acordo com o Ministério de Minas e Energia, entre os anos de 2016 e 2026, o consumo final de energia no Brasil irá crescer à taxa média de 1,9% por ano (Brasil 2017). O rápido crescimento na taxa de consumo anual de energia e o baixo investimento em outras fontes de energia renováveis (ex. energia eólica, solar) aumentam a pressão dos governantes para a ampliação do setor hidrelétrico na Amazônia e subestimam os impactos desses empreendimentos para a região.

1.2 - Impactos gerados por usinas hidrelétricas

Apesar de ser considerada uma fonte de energia limpa, as hidrelétricas são geradoras de inúmeros impactos ambientais (Pelicice et al. 2017; Figura 1). Diversos estudos confirmam ainda prejuízos sociais, culturais, históricos, econômicos, de saúde e lazer em regiões que receberam implantação de usinas hidrelétricas (Figura 1).

Devido à complexidade e ao grande número de impactos gerados por barramentos hidrelétricos, o gerenciamento de bacias hidrográficas afetadas por esses empreendimentos é extremamente difícil. É possível observar que a maior parte destes impactos estão relacionados entre si e, muitas vezes, um único impacto possui origens diferentes (Figura 1). Isso significa que, na maioria das vezes, para minimizar de forma efetiva um determinado prejuízo ambiental, é necessário atuar em várias vias distintas de impactos. Por exemplo, o barramento hidrelétrico pode causar o declínio da pesca por diferentes vias (Figura 1): (1) bloqueio de rotas migratórias (Anderson et al. 2018); (3) injúrias e mortalidade de peixes na casa de força (McKinstry et al. 2007); (4) mudanças no ciclo hidrológico (Santos et al. 2018); (5) alterações na qualidade físico-química das águas (Junk e Mello 1990; Wera et al. 2019); e (6) mudanças na estrutura trófica dos novos ambientes, principalmente quanto à oferta qualitativa e quantitativa de recursos alimentares essenciais para a produtividade das várzeas (Abelha e Goulart 2004; Hahn e Fugi 2007; Lobo et al. 2019).

Todos esses impactos diminuem a disponibilidade de peixes no rio e consequentemente prejudicam a subsistência das comunidades de pescadores locais. Nesse caso, se houvesse uma única estratégia de gestão que buscasse aumentar o fluxo de peixe entre a montante e a jusante, por exemplo, não causaria de forma efetiva um aumento na disponibilidade de peixes no rio, haja vista que a ictiofauna seria ainda afetada por outras vias de impactos (Figura 1). Caso os gestores não identifiquem todas essas vias de impacto e atuem também sobre elas, minimizar um determinado prejuízo ao ecossistema pode ser extremamente difícil ou até mesmo impraticável. Isso demonstra que a gestão de bacias hidrográficas afetadas por barramentos hidrelétricos é complexa, demorada e de alto custo. A partir desta composição de fatores, identificar e avaliar os impactos gerados por empreendimentos hidrelétricos na Amazônia se torna essencial para a gestão dos ecossistemas locais.

1.3 - O complexo hidrelétrico do rio Madeira

As UHE's de Santo Antônio e Jirau constituem o Complexo Hidrelétrico do Rio Madeira, uma das principais obras do Plano de Aceleração do Crescimento (PAC) dos últimos governos brasileiro (Brasil 2018). Inicialmente foi planejada a construção de uma única barragem na cachoeira de Santo Antônio, a montante do município de Porto Velho, Rondônia (Brasil 1987). Porém, a construção desse reservatório causaria inundações em algumas regiões da Bolívia, por isso o plano foi alterado para a construção de duas hidrelétricas menores, também no estado de Rondônia: Santo Antônio e Jirau (Brasil 1987).

O processo de licenciamento ambiental para a construção das barragens foi extremamente controverso (Tabela 1). Muitos pesquisadores, técnicos ambientais e populares se manifestaram contra as suas construções, alegando que os empreendimentos trariam diversos impactos para a região amazônica (Killeen 2007; Fearnside 2014). Os principais alertas sobre esses impactos foram feitos pelo corpo técnico do Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), o qual apresentou alguns pareceres recomendando um novo estudo de impacto ambiental (EIA) (Deberdt et al. 2007; Franco e Campos 2007; IBAMA 2007 a, b; Tabela 1). De acordo com os técnicos do IBAMA, o EIA carecia de uma série de análises de impactos ambientais na bacia do rio Madeira. Como sinal do descontentamento do governo com a posição da equipe técnica do órgão ambiental, importantes cargos de comando do IBAMA foram substituídos e a nova administração declarou como resolvida uma série de questões pendentes e outorgou a licença prévia para ambas as represas sem um novo EIA (Franco 2007; Neto 2007; Amaral et al. 2013; Tabela 1).

Em últimas tentativas, os técnicos do IBAMA emitiram pareceres se opondo à aprovação da Licença de Instalação das hidrelétricas (IBAMA 2008; IBAMA 2009; Tabela 1). Porém, tanto os apelos populares quanto os pareceres técnicos foram sumariamente rejeitados, e a mesma pessoa que aprovou as licenças prévias como chefe do departamento de licenciamento foi promovida a chefe geral do IBAMA, e nessa função outorgou a licença de instalação para a UHE de Santo Antônio em agosto de 2008 (Franco 2008). Quase um ano depois, no mês de julho de 2009, foi concedida a Licença de Instalação da UHE de Jirau (Franco 2009).

Após a emissão da licença de instalação, em setembro de 2008, a UHE de Santo Antônio começou a ser construída na cachoeira de Santo Antônio, a 7 km a montante do município de Porto Velho, capital do estado de Rondônia. O seu reservatório de 422 km^2 começou a ser enchido no final de 2011, quando a sua primeira comporta foi fechada (SAE 2019). As suas primeiras turbinas começaram a operar em 30 de março de 2012 e, em novembro de 2016, a usina foi concluída com 50 turbinas e a capacidade de 3.568 MW de potência instalada, sendo 2.424 MW de energia assegurada (SAE 2019). A UHE de Jirau começou a ser construída em 2009 a 100 km a montante de Porto Velho, no local denominado Ilha do Padre (ESBR 2019a). O seu reservatório de 361,6 km^2 começou a ser enchido em outubro de 2012 e, quase um ano depois, em setembro de 2013, iniciou a sua operação (ESBR 2019a, b). A usina foi totalmente concluída em dezembro de 2016 com 50 turbinas instaladas e capacidade de 3.750 MW de potência, sendo 2.184 MW assegurados (ESBR 2019a).

O complexo hidrelétrico do rio Madeira foi projetado para minimizar os impactos dos seus barramentos sobre os ecossistemas locais. Para isso, foi estabelecido no seu projeto de construção a implantação das turbinas hidrelétricas do tipo bulbo (Fearnside 2013). Essa tecnologia permitiu a construção de um reservatório menor em comparação com as outras hidrelétricas que utilizam as turbinas do tipo Kaplan ou Francis (ESBR 2019b). O volume reduzido de água nos reservatórios resulta em um rápido tempo de substituição e consequentemente em uma melhor qualidade de água (Fearnside 2014). Essas características foram citadas como altamente positivas, pois os impactos gerados pelas barragens seriam mínimos (ESBR 2019; SAE 2019). No entanto, é notório que essa tecnologia não reduz de forma expressiva os impactos desses empreendimentos, visto que a área alagada é altamente significativa para a biota, assim como para uma infinidade de serviços ecossistêmicos. Mesmo atuando com uma tecnologia que é considerada “fio d'água”, as áreas de florestas inundadas pelas hidrelétricas de Santo Antônio e Jirau chegam a 388 km^2 (SAE, 2012; ESBR, 2019), o que corresponde uma área de 38.800 hectares de floresta de várzea permanentemente inundadas. Para efeito de comparação, essa área corresponderia aproximadamente a 36 mil campos de futebol. A inundação dessa área causou uma perda instantânea de floresta de várzeas, assim como áreas fundamentais para abrigo, reprodução e alimentação da biota local.

A displicência dos órgãos competentes na execução do Estudo de Impacto Ambiental (EIA) e seu respectivo Relatório de Impacto Ambiental (RIMA), demonstra que os inúmeros impactos que esse complexo hidrelétrico poderia gerar à bacia do rio Madeira foram seriamente subestimados. Um dos principais problemas apontados por especialista no EIA-RIMA está relacionado com o fato de que a área de estudo leva em consideração apenas o território nacional (Amazônia legal) e não a bacia hidrográfica como um todo (Tucci 2007). Isso impossibilitou avaliar os impactos ambientais em outras regiões da bacia, como por exemplo, o processo de sedimentação e formação de remansos no território boliviano (Fearnside 2014). Os relatórios também carecem de informações sobre a localização dos povos indígenas que viviam na área afetada, extensão exata das áreas de inundação, ausência de ações eficientes no controle da malária, análise dos impactos do sistema de transmissão, entre outros (Deberdt et al. 2007; Jacob e Astrid 2009). Por fim, o local de construção da UHE Jirau foi alterado para 9,2 km à jusante do ponto originalmente estabelecido (Brasil 2008). Mesmo tendo conhecimento dessa alteração, o IBAMA concedeu a licença de Instalação para a UHE Jirau sem a exigência de um novo EIA, ignorando as mudanças evidentes e os impactos que essa alteração poderia gerar (Brasil 2008).

É possível ainda apontar uma displicência aos quesitos relacionados à pesca, pois os relatórios não contemplam análises de banco de dados das principais colônias de pescadores da bacia, impossibilitando um diagnóstico preciso dos possíveis impactos das hidrelétricas sobre as atividades pesqueiras na bacia do rio Madeira. Além disso, o relatório desconsiderou as consequências do barramento para as populações de peixes nas regiões da Bolívia e do Peru, tampouco demonstrou a real eficiência do sistema de transposição de Peixes das UHE’s Santo Antônio e Jirau (Fearnside 2014). É preciso ressaltar que o sistema de transposição de peixes para a UHE Jirau termina em um grande recipiente de metal. Periodicamente os peixes deste recipiente são transportados por caminhão e soltos à montante da barragem. Nenhum estudo foi realizado para avaliar a eficiência deste sistema de transposição para os peixes da bacia do rio Madeira.

Além disso, é necessário ressaltar que, devido à complexidade dos ecossistemas amazônicos, muitos dos seus processos ecológicos, assim como as inúmeras espécies locais, ainda não foram totalmente estudados. Isso significa que a construção de grandes empreendimentos hidrelétricos em ecossistemas amazônicos pode gerar impactos além daqueles que são previstos no EIA. Estima-se, por exemplo, que inúmeras espécies de peixes amazônicos poderão ainda ser descritas a partir do aprofundamento dos estudos taxonômicos na região (Reis et al. 2003; Winemiller e Willis 2011; Ohara et al. 2015). Esse é um indicativo de que inúmeras espécies endêmicas na bacia do rio Madeira poderão passar por um processo de extinção, sem ao menos serem descritas.

Diante disso, espera-se que o complexo hidrelétrico da bacia rio Madeira esteja causando graves impactos aos ecossistemas amazônicos, não só nas suas áreas de influência no Brasil, mas em outros países que compõem esta bacia, como a Bolívia e Peru. Embora sejam esperados impactos de diversas ordens, buscou-se compreender neste estudo a influência das barragens do rio Madeira sobre as atividades pesqueiras, bem como no funcionamento dos ecossistemas aquáticos da bacia.

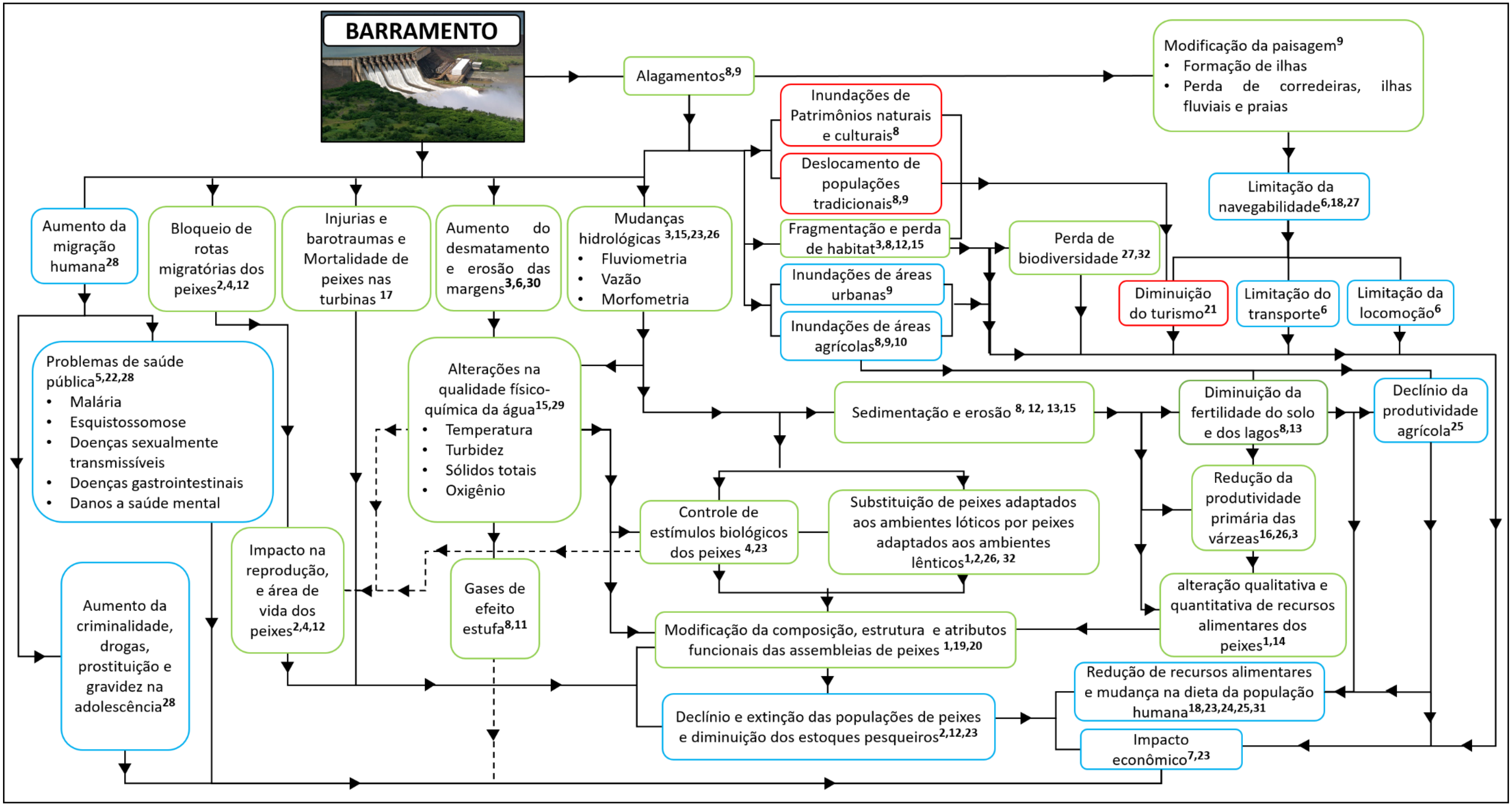

Figura 1 Mapa mental demonstrando os principais impactos gerados por barramentos hidrelétricos. Verde: impactos ambientais; azul: impactos sociais e/ou socioeconômicos e vermelho: impactos socioculturais. As linhas tracejadas representam ligamentos que se cruzam.

Referências do mapa mental (Figura 1)

1- Abelha, M. C. F., e Goulart, E. (2004). Oportunismo trófico de *Geophagus brasiliensis* (Quoy e Gaimard, 1824) (Osteichthyes, Cichlidae) no reservatório de Capivari, Estado do Paraná, Brasil. *Acta Scientiarum*, 26(1): 37-45.

2- Agostinho, S. A., Miranda, L. E., Bini, L. M., Gomes, L. C., e Thomaz, S. M. (1999). Patterns of colonization in Neotropical reservoirs and prognosis on aging. In J. G. Tundisi e M. Straskraba (Eds.), Theoretical reservoir ecology and its applications (pp. 227–265). Rio de Janeiro, Brazil and Leiden, The Netherlands: Backhuys Publishers.

3- Arantes C. C., Fitzgerald, D. B., Hoeinghaus D. J, e Winemiller K. O. 2019. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. *Current Opinion in Environmental Sustainability* 37: 28-40.

4- Anderson, E. P., Jenkins, C. N., Sebastian, H., Ocampo-Maldonado, J. Á., Carvajal-Vallejos, F. M., Encalada, A. C., et al. (2018). Fragmentation of Andes to Amazon connectivity by hydropower dams. *Science Advances*, 4(1): 1429–1437.

5- Barbosa, F. E F., Giongo, C. R., e Mendes, J. M. R. (2018). Construção de hidrelétricas e populações atingidas no Brasil: uma revisão sistemática. *Aletheia* 51 (1-2): 165-176

6- Becker, B. K (2012). Reflexões sobre hidrelétricas na Amazônia: água, energia e desenvolvimento. *Boletim do Museu Paraense Emílio Goeldi. Ciências Humanas*, 7(3): 783-790.

7- Castro-Diaz, L., Lopez, M. C., e Moran, E. (2018) Gender-differentiated impacts of the Belo Monte hydroelectric dam on downstream fishers in the Brazilian Amazon. *Human Ecology*, 46:411–422. https://doi.org/10.1007/s10745-018-9992-z

8- CMB - Comissão mundial de barragens. Barragens e desenvolvimento: uma nova tomada de decisoes. Traducão de carlos alfonso maferrairi Londes: Earthscan, 2000.

9- COBRAPE, Relatório de análise do conteúdo dos estudos de impacto ambiental (EIA) e do relatório de impacto ambiental (RIMA) dos aproveitamentos hidrelétricos de Santo Antonio e Jirau, no Rio Madeira, Estado de Rondônia, Porto Velho: Cobrape – Cia, Brasileira de Projetos e Empreendimentos/Ministério Público do Estado de Rondônia, 2006

10- DHESCA, Plataforma Brasileira de Direitos Humanos Econômicos, Sociais Culturais e Ambientais, Violações de Direitos Humanos Ambientais no Complexo Madeira, Relatoria Nacional para o Direito Humano ao Meio Ambiente. Dhesca, Abril de 2008 36p.

11- Fearnside, P. M. (2013). Carbon credit for hydroelectric dams as a source of greenhouse-gas emissions: The example of Brazil's Teles Pires Dam. *Mitigation and Adaptation Strategies for Global Change*, 18(5): 691-699. doi: 10.1007/ s11027-012-9382-6

12- Fearnside, P. M. (2014). Impacts of Brazil's Madeira River dams: Unlearned lessons for hydroelectric development in Amazonia. *Environmental Science & Policy*, 38: 164–172. https://doi.org/10.1016/j.envsci.2013.11.004

13- Fortin, G., Leblanc, M., Schiavone, S., Chouinard, O., e Utzschneider, A. (2014). Local Perceptions, Ruslefac Mapping, and Field Results: The Sediment Budget of Cocagne River, New Brunswick, Canada. *Environmental Management*, 55(1): 113-127.

14- Hahn, N. S., e Fugi, R. (2007). Alimentação de peixes em reservatórios brasileiros: alterações e consequências nos estágios iniciais do represamento. *Oecologia Brasiliensis* 11(4):469-480.

15- Junk, W. J. e Mello, J. A. S. (1990). Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. *Estudos Avançados*, 4(8): 126-143.

16- Lobo, G. S., Wittmann, F., e Piedade, M. T. F. (2019). Response of black-water floodplain (igapó) forests to flood pulse regulation in a dammed Amazonian river. *Forest Ecology and Management*, 434: 110–118.

17- McKinstry, C., Carlson T. J., e Brown, R. S. (2007). Derivation of a mortal injury metric for studies of rapid decompression of depth-acclimated physostomous fish. PNNL-17080. Pacific Northwest National Laboratory, Richland, Washington.

18- Orr, S., Pittock, J., Chapagain, A., e Dumaresq, D. (2012). Dams on the Mekong River : Lost Fish Protein and the Implications for Land and Water Resources. *Global Environmental Change*, 22(4): 925–932. https://doi.org/10.1016/j.gloenvcha.2012.06.002.

19- Penczak, T., Agostinho, A. A., Gomes, L. C., Latini, J. D. (2009). Impacts of a reservoir on fish assemblages of small tributaries of the Corumbá river, Brazil. *River Research and Applications,* 25 (8): 1013–1024. https://doi.org/10.1002/rra.1200

20- Pinto, M. D. S., Dória, C. R. C., e Marques, E. E. (2019). Alterações temporais sobre a estrutura funcional das assembleias de peixes durante onze anos de formação de um reservatório do médio rio Tocantins, Brasil. *Biota Amazônia*, 9 (1): 17-21. doi:http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v9n1p17-21.

21- Rodrigues, W., Nogueira, J. M., e Carvalho, E. (2009). Avaliação Econômica dos Danos Ambientais Causados pela Implantação da Usina Hidrelétrica Luís Eduardo Magalhães: uma Aplicação do Método de Valoração Contingente. *Informe Gepec*, 13(1): 52-63

22- Rovere, E. L. L., Silva, H. V. O., Bulcao, J. A. S., Santos, S., Barcelos, C., Luigi, G., Sousa, D. S., Moura, F. H. S., e Niemeyer, L. F. Mapa de risco epidemiológico de projetos hidrelétricos no Brasil - Produto 1. Rio de Janeiro: LIMA/COPPE/UFRJ, 2009.

23- Santos, R. E., Pinto-Coelho, R. M., Fonseca, F., Simões, N. R., e Zanchi, F. B. (2018). The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin. *Fisheries Management and Ecology*, 5: 380-391. doi - 10.1111/fme.12305

24- Stenberg, R. (2006). Damming the River: A Changing Perspective on Altering Nature. *Renewable and Sustainable Energy Reviews,* 10 (3): 165–197.https://doi.org/10.1016/j.rser.2004.07.004

25- Tilt, B., Braun, Y., e He, D. (2009). Social Impacts of Large Dam Projects: A Comparison of International Case Studies and Implications for Best Practice. *Journal of Environmental Management,* 3: 249–S257. https://doi.org/10.1016/j. jenvman.2008.07.030

26- Timpe, K., e Kaplan, D. (2017). The changing hydrology of a dammed Amazon. *Science Advances*. 3: 1-13. 10.1126/sciadv.1700611

27- Trussart, S., Messier, D., Roquet, V., and Aki, S. (2002). Hydropower Projects: A Review of most Effective Mitigation Measures. *Energy Policy,* 30(14): 1251–1259. https://doi.org/10.1016/S0301-4215(02) 00087-3

28- Von Sperling, E. (2012). Hydropower in Brazil: Overview of Positive and Negative Environmental Aspects. *Energy Procedia*, 18: 110–118. https://doi.org/10.1016/j.egypro.2012.05.023.

29- Wera, F. A., Ling, T. Y., Nyanti, L., Sim, S. F., e Grinang, J. (2019). Effects of opened and closed spillway operations of a large tropical hydroelectric dam on the water quality of the downstream River. *Journal of Chemistry,* 11.https://doi.org/10.1155/2019/6567107

30- Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., et al (2016). Balancing Hydropower and Biodiversity in the Amazon, Congo, and Mekong. *Science* 351 (6269): 128–129. https://doi.org/10.1126/science.aac7082

31- Ziv, G., Baranb, E., Namc, S., Rodríguez-Iturbed, I. And Levina, S. (2012) Trading-off Fish Biodiversity, Food Security, and Hydropower in the Mekong River Basin. *Proc. Natl. Acad. Sci*. 109(15): 5609–5614.

32- Assis, D.A.S., Dias-filho, V.A.; Magalhães, A.L.B.; Brito, M.F.G. (2017). Establishment of the non-native fish Metynnis lippincottianus (Cope 1870) (Characiformes:Serrasalmidae) in lower São Francisco River, northeastern Brazil. Studies on Neotropical Fauna and Environment, 52(1): 1-11.

Tabela 1 Cronologia do processo de implantação e licenciamento ambiental das hidrelétricas Santo Antônio e Jirau.

Ano	**Data**	**Evento**		**Referências**
		UHE Santo Antônio	**UHE Jirau**	
2001-2002	-	Estudos de inventário realizado por Furnas Centrais Elétricas (FURNAS) e Construtora Norberto Odebrecht (CNO)		SAE, 2019 ; ESBR, 2019 b
2002-2005	-	Estudos de viabilidade (Técnica, energética, econômica e ambiental) realizado por FURNAS e CNO.		SAE, 2019 ; ESBR, 2019 b
2006	-	Aceite do estudo de viabilidade e aprovação do EIA/RIMA para as UHE's do rio Madeira		Brasil, 2013
2007	21 de Março	Apresentação de um parecer contra a aprovação da Licença Prévia pelos técnicos do IBAMA		Deberdt, 2007 (IBAMA)
	30 de Março	O chefe do Departamento de Licenciamento, Luiz Felippe Kunz, solicitou algumas informações adicionais, mas rejeitou a necessidade de um novo EIA		Kunz, 2007 (IBAMA)
	12 e 23 de Abril	Apresentação de uma série de perguntas sobre as lacunas remanescentes no EIA pelos técnicos do IBAMA		Franco e Campos, 2007; IBAMA, 2007a, b
	30 de Abril	Substituição de cargos de comando do IBAMA, entre eles o presidente do instituto, o secretário-executivo e o diretor de licenciamento		Amaral et al. 2013
	Maio	FURNAS e CNO entregaram uma resposta para as perguntas do IBAMA sobre as lacunas remanescentes no EIA. Muitas repostas não foram respondidas, pois de acordo com as empresas, o IBAMA estava solicitando informações além daquelas que corresponderiam a procedimentos normais		FURNAS e CNO, 2007
	Julho	O novo diretor do departamento de licenciamento, Roberto Messias Franco, emitiu um parecer reafirmando a rejeição de um novo EIA e declarou como resolvido uma série de questões pendentes		Franco, 2007 (IBAMA)
		Concessão da Licença prévia para as UHE Santo Antônio e Jirau		Neto, 2007 (IBAMA)
	Dezembro	Leilão da UHE Santo Antônio. Consorcio vencedor: Consórcio Madeira Energia	-	SAE, 2019
2008	8 de maio	Técnicos do IBAMA apresenta um parecer se opondo à aprovação da Licença de Instalação da UHE Santo Antônio	Leilão da UHE Jirau. Consorcio vencedor: Energia Sustentável do Brasil S.A.	IBAMA, 2008; ESBR, 2019 b
	20 de maio	O diretor de Licenciamento, Roberto Messias Franco, é promovido a presidente do IBAMA		Amaral et al. 2013
	Agosto	Concessão da Licença de Instalação	-	Franco, 2008 (IBAMA)
	setembro	Início das obras	-	SAE, 2019
2009	Maio	-	Técnicos do IBAMA apresenta um parecer se opondo à aprovação da Licença de Instalação da UHE Jirau	IBAMA, 2009
	-	-	Início das obras	Brasil, 2013
	junho	-	Concessão da Licença de Instalação	Franco, 2009 (IBAMA)
2011	julho	Desvio do rio Madeira	-	SAE, 2019 b
	setembro	Concessão da Licença de Operação	-	Trennepohl, 2011 (IBAMA)
		Início do enchimento do reservatório	Desvio do rio Madeira	SAE, 2019 ; ESBR, 2019 b
2012	julho	Início da operação comercial	-	SAE, 2019
	outubro	-	• Concessão da Licença de Operação • Início do enchimento do reservatório	Volney, 2012 (IBAMA) ESBR, 2019 b
2013	setembro	-	Início da operação comercial	ESBR, 2019 b
2016	-	Conclusão das obras com a 50ª turbinas instaladas		Santos et al. 2018

2 - ESTRUTURA DA TESE

A partir dessa composição de fatores, essa tese tem o objetivo de identificar e avaliar os impactos ambientais gerados pelas hidrelétricas de Santo Antônio e Jirau sobre a pesca e os ecossistemas aquáticos da bacia do rio Madeira. Para atender esse objetivo, esta tese foi estruturada em dois capítulos.

No primeiro capítulo será apresentado um estudo sobre a influência do complexo hidrelétrico do rio Madeira sobre os estoques pesqueiros locais. Esse estudo testou a hipótese de que as instabilidades do pulso de inundação causadas pela construção das barragens de Santo Antônio e Jirau provocaram uma redução significativa nos estoques pesqueiros da bacia do rio Madeira. Este capítulo contempla um extenso e contínuo banco de dados de desembarque pesqueiro, com 16 anos de dados diários registrados à jusante das hidrelétricas. Esses dados permitiram avaliar, de forma sistemática, os impactos das barragens sobre os ecossistemas aquáticos e a atividade pesqueira local.

No segundo capítulo, foram avaliados os impactos gerados pelo complexo hidrelétrico do rio Madeira através da percepção dos pescadores locais e banco de dados da colônia de pescadores Z-31. As questões levantadas neste capítulo têm o objetivo de identificar e avaliar os impactos das barragens focando em três temas principais: (i) a pesca local; (ii) o peixe e (iii) os ecossistemas aquáticos. Esse estudo testou a hipótese de que os informantes da colônia de pescadores locais possuem uma percepção ampla sobre os mecanismos de impactos ambientais gerados pelo complexo hidrelétrico do rio Madeira. Utilizar o conhecimento de pescadores locais permitiu fornecer novos dados sobre os impactos gerados pelas hidrelétricas de Santo Antônio e Jirau e suas consequências para os ecossistemas aquáticos, atividades de pesca e populações ribeirinhas amazônicas.

REFERÊNCIAS

Abelha, M. C. F., e Goulart, E. (2004). Oportunismo trófico de Geophagus brasiliensis (Quoy e Gaimard, 1824) (Osteichthyes, Cichlidae) no reservatório de Capivari, Estado do Paraná, Brasil. Acta Scientiarum, 26(1): 37-45.

Amaral, M., Aranha, A., Barros, C. J., Branford, S., Mota, J., Castro, A., Rabello, T. Amazônia Pública, Agência Pública. 160 p., 2013.

Anderson, E. P., Jenkins, C. N., Sebastian, H., Ocampo-Maldonado, J. Á., Carvajal-Vallejos, F. M., Encalada, A. C., et al. (2018). Fragmentation of Andes to Amazon connectivity by hydropower dams. *Science Advances*, 4(1): 1429–1437. doi: 10.1126/sciadv.aao1642

EPE - Empresa de Pesquisa Energética. (2018). Informações gerencias. Disponível em: http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-377/topico-470/Relat%C3%B3rio%20S%C3%ADntese%20BEN%202019%20Ano%20Base%202018.pdf. Acesso em 11 de novembro de 2019.

Brasil, ELETROBRAS (Centrais Elétricas do Brasil (2013). Relatório Técnico – 8481/2015 Análise e Propostas de Aperfeiçoamentos do Processo de Licenciamento de Empreendimentos Hidrelétricos com vistas a efetivar projetos de Usinas-Plataforma. Disponível em: http://www.mme.gov.br/documents/10584/24216247/Produto+2-36.pdf/5d280074-29ca-4458-9120-d1509089145c. Acesso em 02 de fevereiro de 2019.

Brasil, ELETROBRAS (Centrais Elétricas do Brasil). (1987). Plano 2010: Relatório Geral. Plano Nacional de Energia Elétrica 1987/2010 (dezembro de 1987). Brasília, DF. 269 pp.

Brasil, MMA (Ministério do Meio Ambiente). (2019). Biomas. www.mma.gov.br/biomas/amazônia. Acesso em 07 de fevereiro de 2019.

Brasil, MME (Ministério de Minas e Energia). (2017). Plano Decenal de Expansão de Energia 2026. (pp. 1–271). Ministério de Minas e Energia, Empresa de Pesquisa Energética

(MME/EPE). Brasília, DF, Brasil. 2 vols. http://www.mme.gov.br/documents/10584/0/PDE2026.pdf/474c63d5-a6ae-451c-8155-ce2938fbf896

Brasil, MP (Ministério do planejamento). (2018). Plano de aceleração do crescimento. Disponível em: http://www.pac.gov.br/infraestrutura-energetica/geracao-de-energia-eletrica. Acesso em 07 de fevereiro de 2019.

Brasil, MPF/MPER (Ministério Público Federal e Ministério Público do Estado de Rondônia). (2008). Ação Civil Pública por Ato de Improbidade Administrativa em desfavor de: Roberto Messias Franco, na condição de Presidente Nacional do Instituto do Meio Ambiente e Recursos Renováveis – IBAMA. Disponível em: http://www.mpf.mp.br/pgr/copy_of_pdfs/acao_jirau.pdf

Castello, L. e Macedo, M. N. (2016). Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology*, 22(3): 990-1007. Doi: https://doi.org/10.1111/gcb.13173

Castro, E. M. R. e Hébette, J. Na Trilha dos Grandes Projetos. Modernização e Confronto na Amazônia. orgs. Belém: NAEA/UFPA, 1989.

Costa, A. C., Oliveira, I. C., e Ravena, N. (2017). Vozes institucionais e os discursos de dominação: análise dos grandes projetos hidrelétricos na Amazônia. *Revista FAMECOS - Mídia, Cultura e Tecnologia*, (24)2: 80-101. http://dx.doi.org/10.15448/1980-3729.2017.2.24880

Deberdt, G., Teixeira, I., Lima, L. M. M., Campos, M. B., Choueri, R. B., Koblitz, R., Franco, S. R. e Abreu, V.L.S. 2007. Parecer Técnico No. 014/20007 – FCOHID/CGENE/ DILIC/IBAMA. Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Brasília, DF. 221 p.

ESBR - Energia Sustentável do Brasil (2019a). Dados Técnicos. Disponível em https://www.esbr.com.br/a-usina#dados-tecnicos. Acesso em 07 de fevereiro de 2019.

ESBR - Energia Sustentável do Brasil (2019b). Tecnologia Informações gerencias. Disponível em: http://www.santoantonioenergia.com.br/tecnologia/tecnologiaavancada/. Acesso em 07 de fevereiro de 2019.

Fearnside, P. M (2013). Viewpoint-decision making on Amazon dams: Politics trumps uncertainty in the Madeira river sediments controversy. *Water Alternatives*, 6: 313–325, 2013.

Fearnside, P. M. (2014). Impacts of Brazil's Madeira River dams: Unlearned lessons for hydroelectric development in Amazonia. *Environmental Science & Policy*, 38: 164–172. https://doi.org/10.1016/j.envsci.2013.11.004

Franco, R. M. (2007). Memorando à Coordenação Geral de Infraestrutura de Energia Elétrica-CGENE, Memo No. 379/2007. 04/07/2007. Brasília, DF, Brasil: Diretoria de Licenciamento Ambiental (DILIC), Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

Franco, R.M. 2008. Licença de Instalação 540/2008. 13 de agosto de 2008. Brasília, DF: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

Franco, R.M. 2009. Licença de Instalação No. 621/2009. 03 de junho de 2009. Brasília, DF: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

Franco, S. R., e Campos, M. B. (2007). Parecer Técnico No. 17/2007-COHID/CGENE/DILIC/IBAMA de 12 de abril de 2007. Assunto: Aproveitamentos Hidroelétricos Santo Antônio e Jirau – Rio Madeira. Brasília, DF: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

Hahn, N. S., e Fugi, R. (2007). Alimentação de peixes em reservatórios brasileiros: alterações e consequências nos estágios iniciais do represamento. *Oecologia Brasiliensis*, 11(4):469-480. (12)

IBAMA. (2007a). Parecer Técnico No. 19/2007-COHID/CGENE/DILIC/IBAMA de 23 de abril de 2007. Assunto: Aproveitamentos Hidroelétricos Santo Antônio e Jirau – Rio Madeira. Brasília, DF, Brasil: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

IBAMA. (2007b). Parecer Técnico No. 20/2007-COHID/CGENE/DILIC/IBAMA de 23 de abril de 2007. Assunto: Aproveitamentos Hidroelétricos Santo Antônio e Jirau – Rio Madeira. Brasília, DF, Brasil: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

IBAMA. 2008. Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis. Parecer Técnico No. 45/2008-COHID/ CGENE/DILIC/IBAMA de 08 de maio de 2008. Assunto: Análise da solicitação da emissão da Licença de Instalação do Aproveitamento Hidrelétrico de Santo Antônio. Brasília, DF, Brasil: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

IBAMA. 2009. Parecer Técnico Nº 039/2009 – COHID/CGENE/DILIC/IBAMA de 25 de maio de 2009. Assunto: Análise da solicitação da emissão da Licença de Instalação do Aproveitamento Hidrelétrico de Jirau. Brasília, DF, Brasil: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA). Disponível em: http://www.ibama.gov.br/licenciamento/index.php

Jacob, k. e Astrid, P. R. Grandes represas en América¿ Peor el remedio que la enfermedad? Principales consecuencia ambientales en los derechos humanos y posibles alternativas: México: Asociación Interamericana para la Defensa del Ambiente (AIDA) 2009.

Junk, W. J. e Mello, J. A. S. (1990). Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. *Estudos Avançados*, 4(8): 126-143.

Killeen, T. J. (2007). A Perfect Storm in the Amazon Wilderness: Development and Conservation in the Context of the Initiative for the Integration of the Regional Infrastructure of South America (IIRSA). Conservation International, Arlington, Virginia, E.U.A. 98 p. Disponível em: http://www. conservation.org/publications/pages/perfect_storm.aspx

Lima, D. e Pozzobon, J. (2005). Amazônia socioambiental. Sustentabilidade ecológica e diversidade social. *Estudos Avançados*, 19(45): 45-76. doi: http://dx.doi.org/10.1590/S0103-40142005000200004

Lobo, G. S., Wittmann, F., e Piedade, M. T. F. (2019). Response of black-water floodplain (igapó) forests to flood pulse regulation in a dammed Amazonian river. *Forest Ecology and Management*, 434: 110-118. https://doi.org/10.1016/j.foreco.2018.12.001

McKinstry, C., Carlson T. J., e Brown, R. S. (2007). Derivation of a mortal injury metric for studies of rapid decompression of depth-acclimated physostomous fish. PNNL-17080. Pacific Northwest National Laboratory, Richland, Washington.

Moretto, E. Mateus., Gomes, C. S., Roquetti, D. R., e Jordão, C. O. (2012). Histórico, tendências e perspectivas no planejamento espacial de usinas hidrelétricas brasileiras: a antiga e atual fronteira Amazônica. *Ambiente & sociedade*, 15(3): 141-164.

Neto, B. A. M. (2007). Licença Prévia No. 251/2007. 09 de junho de 2007. Brasília, DF: Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA).

Neto, T. O. e Nogueira, R. J. B. (2017). O debate institucional sobre rodovias na Amazônia: O caso da BR- 319. *Sociedade e Território*, 29:(1), 84 -101. https://doi.org/10.21680/2177-8396.2017v29n1ID9521

Ohara, W. M., Queiroz, L. J., Zuaon, J., Torrente-Villara, G., Vieira, F. G. e Doria C. C (2015). Fish collection of the Universidade Federal de Rondônia: its importance to the knowledge of Amazonian fish diversity. *Acta Scientiarum*, 37(2): 251-258. http://dx.doi.org/10.4025/actascibiolsci.v37i2.26920

Pelicice, F. M., Azevedo-Santos, S. V. M., Vitule, J. R. S., Orsi, M. L., Lima, J. D. P., Magalhães, A. L. B., Pompeu, P. S., Petrere Jr, M., e Agostinho, A. A. (2017). Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries*, 18: 1119–1133. https://doi.org/10.1111/faf.12228

Reis, R. E., Kullander, S. O., Ferraris, C. J. Check list of the freshwater fishes of South and Central America. Porto Alegre, RS, Brasil: EDIPUCRS, 2003. 742pp

SAE - Santo Antônio Energia (2012). Contribuição do Projeto Hidrelétrica Santo Antônio para o Desenvolvimento Sustentável Atendimento à Resolução nº1 de 11 de setembro de 2003 da Comissão Interministerial de Mudança Global do Clima Versão Dezembro, 2012. Disponível em: https://www.mctic.gov.br/mctic/export/sites/institucional/ciencia/SEPED/clima/mecanismo_de_desenvolvimento_limpo/submetidos/aprovados_termos_resolucao_1/publicacoes/434/anexo_resolucao01.pdf

SAE - Santo Antônio Energia. Hidrelétrica Santo Antônio. (2019). Construção. Disponível em: www.santoantonioenergia.com.br/tecnologia/construcao/. Acesso em: Acesso em 07 de fevereiro de 2019.

Sánchez, L. E. Avaliação de impacto ambiental: conceitos e métodos. 1ª Edição. São Paulo: Oficina de Textos, 2006. 495p.

Tucci, C.E.M. 2007. Análise dos estudos ambientais dos empreendimentos do rio Madeira. Fevereiro de 2007, Relatório para o Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Brasília, DF, Brasil.

Tundisi, J. G., Goldemberg, J., Matsumura-Tundisi, T., e Saraiva, A. C. F. (2014). How many more dams in the Amazon? *Energy Policy*, 74: 703-708. https://doi.org/10.1016/j.enpol.2014.07.013

Wera, F. A., Ling, T. Y., Nyanti, L., Sim, S. F., e Grinang, J. (2019). Effects of opened and closed spillway operations of a large tropical hydroelectric dam on the water quality of the downstream River. *Journal of Chemistry*, Article ID 6567107, 11.https://doi.org/10.1155/2019/6567107

Winemiller, K. O., e Willis, S. T. The Vaupes Arch and Casiquiare Canal - Barriers and passages. In: Albert, J. S. e Reis, R. E. (Ed.). Historical biogeography of Neotropical freshwater fishes. London: University of California Press, 2011. p. 225- 242.

CAPÍTULO 1

The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin

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The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin

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Abstract

Despite being considered beneficial by providing a clean and renewable source of energy, the construction of hydroelectric dams has extremely negative implications for Amazonian fisheries. This study investigated the impacts of the Santo Antônio and Jirau hydroelectric dams on the fishery stocks of the Madeira River. This investigation was based on fish catch data from the Z-31 fishing colony, located in the municipality of Humaitá, in Amazonas State, Northern Brazil. Data were collected daily and provided information on the date of return from each trip, the fish species targeted, and the total catch (kg) between January 2002 and September 2017. The results indicated reductions of 39% in the mean annual catch and 34% in the mean monthly catches. These results highlight the high price paid by local fish communities for the development of hydroelectric power in the Amazon basin.

KEYWORDS

biodiversity, environmental impact, fish fauna, fishing colony, fluviometry, impoundments

1 | INTRODUCTION

The Madeira River basin is one of the most important ecosystems for Amazonian fisheries (Doria, Ruffino, Hijazi & Cruz, 2012; Goulding, 1979). The high productivity of the Amazon basin generally is related not only to it being the world's largest hydrographic basin but also the highly dynamic relationship between the terrestrial environment and the aquatic ecosystem, which is a characteristic of fluvial ecosystems located in tropical and equatorial regions (Junk, 2001). In this region, fishing patterns and the quantity and quality of the fish caught are determined primarily by the hydrological cycle, which regulates the formation of shoals and the timing of their migrations (Batista & Petrere, 2003; Junk, Bayley & Sparks, 1989).

The equilibrium between terrestrial and aquatic environments in the Amazon basin is threatened by the construction of hydroelectric dams. The hydroelectric potential of the region's rivers has led to major advance in this sector (Soito & Freitas, 2011), and 100 dams are already in operation within the whole Amazon region, while another 137 are planned or under construction in the countries that make up this region (Lees, Peres, Fearnside, Schneider & Zuanon, 2016; Tundisi, Goldemberg, Matsumura-Tundisi & Saraiva, 2014). Plans for the Brazilian energy sector include the expansion of the hydroelectric potential by 6.8 GW, with 16 new dams, by 2026, with 57% of this potential being provided by dams located in the Amazon basin (MME/EPE, 2017).

Despite being considered beneficial, by providing a clean and renewable source of energy, hydroelectric dams provoke major impacts on the hydrological cycle (Timpe & Kaplan, 2017), causing longitudinal disturbances throughout the course of the river, as predicted by the Ward and Stanford (1995) serial discontinuity concept.

One of the most obvious effects of river damming on the hydrological cycle is the modification of the patterns of river discharge and fluviometry (Junk & Mello, 1990; Winemiller et al., 2016). These impacts may reduce the deposition of nutrients on the floodplain and in marginal lakes (Zahar, Ghorbel & Albergel, 2008) and change the morphological configuration of the river channel, such as the number and intensity of the erosional processes affecting the margins, and the physical–chemical characteristics of the water (Lobato et al., 2015).

The construction and subsequent operation of hydroelectric dams provoke major environmental impacts (e.g., loss of habitats and hydrological shifts), which have highly negative implications for the fundamental ecological processes that maintain the biological diversity of the system and sustain local fish stocks (Agostinho, Pelicice & Gomes, 2008; Bunn & Arthington, 2002; Pelicice et al., 2017). These environmental changes may interrupt fish migration routes, modifying the abundance, composition and trophic configuration of their communities, including an increase in the abundance of some species; whereas the populations of other species may be greatly reduced or even become extinct (Agostinho, Miranda, Bini, Gomes & Thomaz, 1999).

The change from a lotic to a lentic environment also favours the invasion of non-native species, creating a high risk of regional colonization (Assis, Dias-Filho, Magalhães & Brito, 2017). This type of impact is not yet common in Amazon ecosystems. According to Leprieur, Beauchard, Blanchet, Oberdorff and Brosse (2008), hydrological alterations and biological invasions are considered the two largest threats to aquatic native biota.

The Madeira River in northern Brazil is among the ecosystems that have suffered from the construction of hydroelectric dams. The Santo Antônio and Jirau dams were inaugurated on the middle Madeira River in 2012. While these dams were planned to guarantee the energy security of Brazil, their impacts on the local ecosystem and fisheries are still poorly understood, considering that most of the commercial fish species found on the Madeira River are migratory (Barthem et al., 2017). This is a major issue, given that these fish are migratory (e.g., *Mylossoma* spp., *Prochilodus nigricans* Spix and Agassiz, *Semaprochilodus* spp.) and large-bodied catfish (*Brachyplatystoma* spp. and *Pseudoplatystoma* spp.) that undertake long-distance longitudinal migrations, and are among the most threatened by dam construction (Fearnside, 2014). Stocks of most of the species of commercial interest may suffer major fluctuations due to the presence of physical barriers to their migration and the changes in the hydrological regime of the Madeira River.

Given the importance of fisheries in the Amazon region, the impacts of hydroelectric dams on fish stocks may have socio-cultural and economic implications for local communities. Fishing was practiced in the Amazon well before European colonisation, and fish is an essential component of the diet of its riverside and indigenous peoples (Furtado, 2006). In the present day, fish continues to be an essential resource for human communities throughout the region where it is a principal source of both animal protein and income (Cerdeira, Ruffino & Isaac, 1997).

Major development projects will inevitably have some impact on any ecosystem. However, the proliferation of hydroelectric dams in the Amazon region and the acceleration in the construction of these plants, as is the case with Belo Monte Hydroelectric Complex on the Xingu River (Fitzgerald et al., 2018), indicates that their impacts on local fisheries may not only be underestimated, but may exceed the resilience of local ecosystems. In this context, this study investigated the influence of the hydroelectric complex implemented recently on the Madeira River on the local fisheries, using the database available from fisheries located downstream from the dams. This study tested the hypothesis that the instability of the flood pulse caused by the construction of the dams has caused a significant reduction in the fish stocks of the Madeira basin.

2 | METHODS

2.1 | Study area

This study was based on the database of fishery catches landed in the municipality of Humaitá, in the south of the Brazilian state of Amazonas, 675 km south of the state capital, Manaus. The municipality of Humaitá has an area of approximately 34,430 km^2, and around 52,000 inhabitants (IBGE, 2017).

The Madeira River is part of the Amazon basin and is the principal tributary of the right margin of the Amazon. The headwaters of the Madeira are located in the Bolivian Andes, and the river is formed by the confluence of the Beni and Mamoré rivers (Goulding, Barthem & Ferreira, 2003). The Madeira has a total length of 3,240 km, of which 1,425 km are within Brazil, where this river traverses the states of Rondônia and then Amazonas before discharging into the Amazon River near the town of Itacoatiara, metropolitan region of Manaus (Costa, 1998). The mean discharge of this river is 31,200 m^3/s (Guyot, 1993). According to the Köppen classification system, local weather belongs to group A (rainy tropical) and type Am (monsoon rains), with a short dry period, and annual precipitation ranging from 2,250 to 2,750 mm. The mean annual temperature ranges from 24 to 26°C.

The Santo Antônio hydroelectric dam (08°48′ S, 63°56′ W) is 7 km upstream from Porto Velho, capital of the Brazilian state of Rondônia, and 175 km from the municipality of Humaitá, in the state of Amazonas (Figure 1). The construction of this dam began in September 2008, and the reservoir began to fill in early 2011, when the first of the sluice gates was closed. The first turbines began to operate on 30 March 2012, and in November 2016 the power plant was completed with 50 turbines installed with a total production capacity of 3,568 MW. The Jirau hydroelectric dam (09°15′ S, 64°38′ W) is 100 km upstream from Porto Velho and 263 km from Humaitá (Figure 1). In October 2012, the river was dammed to fill the Jirau reservoir. The first turbine began to operate in September 2013, and the power station was completed in December 2016 with 50 turbines and a capacity of 3,750 MW.

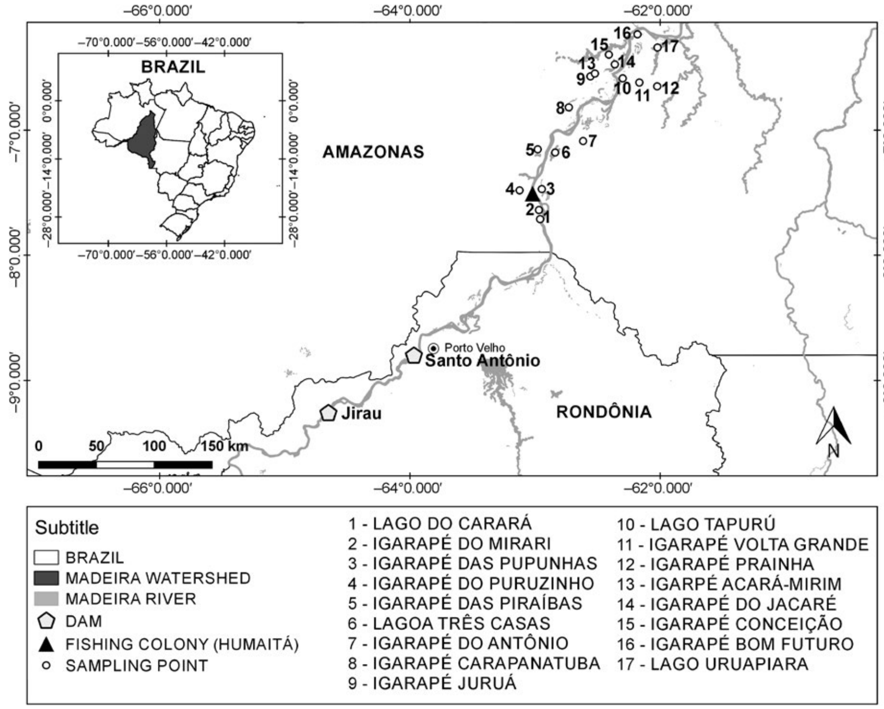

FIGURE 1 Fishing ground of the Z-31 (Dr. Renato Pereira Gonçalves) fishing colony based on the municipality of Humaitá, Amazonas state, Brazil, and the location of the Santo Antônio and Jirau dams on the Madeira River in Rondônia State

2.2 | Sample collection

The influence of the Santo Antônio and Jirau dams on local fishery catches was evaluated through analysis of the productivity database of the "Dr. Renato Pereira Gonçalves" (Z-31) fishing colony, covering the period between January 2002 and September 2017. The catches landed by this colony are taken from 17 fishing grounds located downstream from the dams (Figure 1). A total of 1,655 fishers are registered as members of the Z-31 fishing colony.

Catch data were recorded daily at the colony and include the fishing ground (point), the date of the beginning and the end of each fishing trip, type of fish caught and total catch (kg). All commercial catches obtained in the region are landed at the colony's floating pier for the collection of the catch data. River-level data were obtained from the Humaitá station of the hydrological information system with the Agência Nacional de Águas (www.hidroweb.ana. gov.br).

2.3 | Data analyses

In 2013, the floating pier of the fisher colony was removed from the Madeira River to make way for the construction of flood prevention works by the Humaitá town council. This led to the suspension of data collection between January and October 2013, so the data from 2013 were excluded from the analyses. The data on the catches of the tambaqui, *Colossoma macropomum* (Cuvier), were also excluded from the analyses because many of the specimens landed were raised in fish farms and were thus isolated from the direct effects of the impact of damming of the Madeira.

For the analysis of the impacts of the dams on the fishery catches, the data were divided into "Before" (prior to damming) and "After" (post-damming) samples. As the sluices gates of the Santo Antônio dam were closed completely in July 2011, the data for the period between January 2002 and July 2011 were allocated to the "Before" sample, whereas those from August 2011 to September 2017 were allocated to the "After" sample. The sluice gates of the Jirau dam were shut off completely in October 2012.

The trends in the fishery catches over time were evaluated through a descriptive analysis of the catch history. Mann–Kendall test for the detection of monotonic trends was also applied to determine the trends in fishery production during the "Before" and "After" samples.

Analysis of variance (ANOVA) was used to verify the significance of the variation in fishery catches among the different phases of the hydrological cycle, and between periods (Before and After). Due to temporal dependence of the data, ANOVA was performed with the standardized errors of a model that included the temporal dependence of the data. A serial autocorrelation test was performed with the standardised errors and was not significant.

Impacts of fluviometric changes on fisheries were evaluated through a descriptive analysis of the catch history. Thereafter, a linear regression analysis was run to verify the extent to which the changes in the fluviometry (level) of the Madeira River after damming influenced fishery production. The regression was based on the variation between the periods (before and after) in the mean fishery harvest with the mean variation in fluviometry (river level). The mean monthly variation in fluviometry was calculated based on: $\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$ (I), where $\Delta\overline{FI}_i$ is the mean variation in fluviometry between periods (before and after) in each month *i* (from January to December), $\overline{FI}_{Ai}$ = mean fluviometry after damming of the river in each month *i*, and $\overline{FI}_{Bi}$ = mean fluviometry before damming in each month *i*. The $\Delta\overline{FI}_i$ values were grouped in five, 100-cm classes: −100–0, 0–100, 100–200, 200–300 and 300–400.

TABLE 1 Fish landings at Humaita, Amazonas state from 2002-2017

Year	Total annual catch (kg)	Minimum monthly catch (kg)	Maximum monthly catch (kg)	Mean monthly catch	±Standard deviation (kg)
2002	294,355	8,851	61,239[a]	24,530	14,962
2003	299,300	10,728	44,163	24,942	8,880
2004	247,664	15,679	26,347	20,639	3,411
2005	248,065	14,733	29,802	20,672	4,594
2006	350,269[a]	11,382	56,321[a]	29,189[a]	13,973
2007	314,895	10,635	34,735	26,241	7,625
2008	247,119	11,123	28,214	20,593	6,028
2009	162,353	6,452	25,487	13,529	5,276
2010	238,995	5,910	39,744	19,916	12,084
2011	407,554[a]	12,261	52,274[a]	33,963[a]	14,115
2012	243,165	6,346	36,139	20,264	9,684
2014	158,560	2,174[b]	29,094	13,213	9,388
2015	94,514[b]	1,607[b]	16,625	7,876[b]	4,594
2016	156,379	8,112	19,560	13,032	3,353
2017	101,054[b]	7,424	15,588	11,228[b]	2,230
Total	3,564,241	[c]	[c]	[c]	[c]

[a]"Peaks" in fishery production. [b]Lowest fishery productivity. [c]The total for these variables (min, max, mean, and *SD*) would not clearly express the results for these columns.

Mean variation in fishery production was calculated using: $\Delta\overline{P}_i = \overline{P}_{Ai} - \overline{P}_{Bi}$ (II), where $\Delta\overline{P}_i$ = mean variation in fishery production between periods (before and after) in each month *i*, $\overline{P}_{Ai}$ = mean fishery production after the damming of the river in each month *i*, and $\overline{P}_{Bi}$ = mean fishery production before damming in each month *i*. The result of mean variation in fishery production was regressed on the classes recorded for mean variation in fluviometry. All statistical analyses were run using the software R 2.14.1 (R Core Team 2011) (Sokal & Rohlf, 1995).

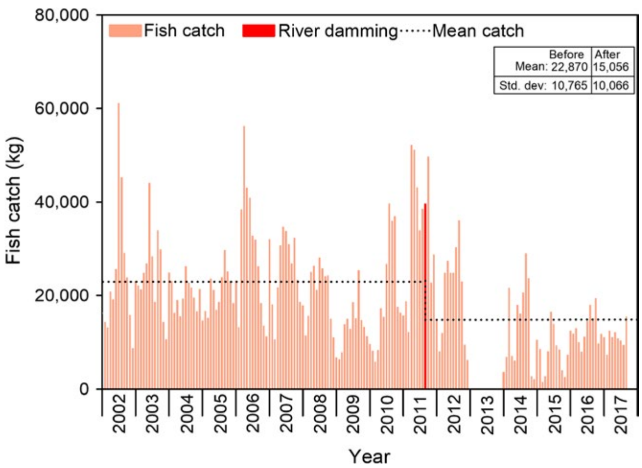

FIGURE 2 Fishery production (kg) landed in the municipality of the municipality of Humaitá, Amazonas state, Brazil, between January 2002 and September 2017. The vertical red line represents the initial damming of the Madeira River (July 2011). Note that the data from 2013 were not included here

3 | RESULTS

3.1 | Analysis of fisheries

During the study period as a whole (January 2002 to September 2017), the total fishery catch was 3,564,241 kg, with an annual mean of 237,616 kg (Table 1). The most productive years were 2011, the year of damming, and 2006 during the Before period. The least productive years were recorded after damming in 2015 and 2017 (Table 1).

The highest monthly fishery production was recorded in July 2002, and the lowest in March 2015 (Figure 2; Table 1). In addition to 2002, peaks in the monthly catches were recorded in April 2006 prior to damming and April 2011 during the damming period (Figure 2, Table 1). No monthly peaks were recorded after damming. The second lowest monthly catch was recorded in December 2014.

Mean monthly fishery productivity before damming was 22,876 kg, while after damming it declined to 15,056 kg (Figure 2), a decline of 34% in the mean monthly production of fish. Considering only years with a full set of monthly records, the mean annual fishery production was 267,001 kg prior to damming (2002–2010) (Table 1) and 163,155 kg for the period after damming (2012–2016). This represents a 39% decline in the annual fishery production, based on the catches landed in the municipality of Humaitá.

Mann–Kendall test did not reveal any significant tendency for any increase or decline in fishery production (Figure 3) prior to

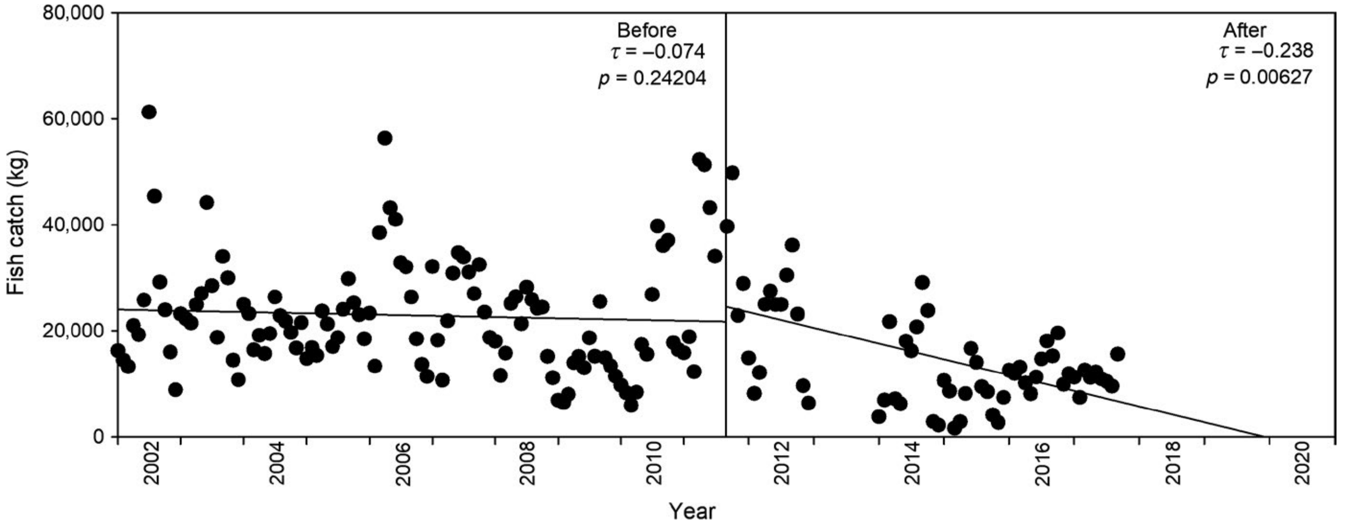

FIGURE 3 Monthly fish catch at Humaitam Amazona state before (2002-2011) and after (2011-2017) of the Medeira River. Tau (use symbol) is Kendall rank correlation

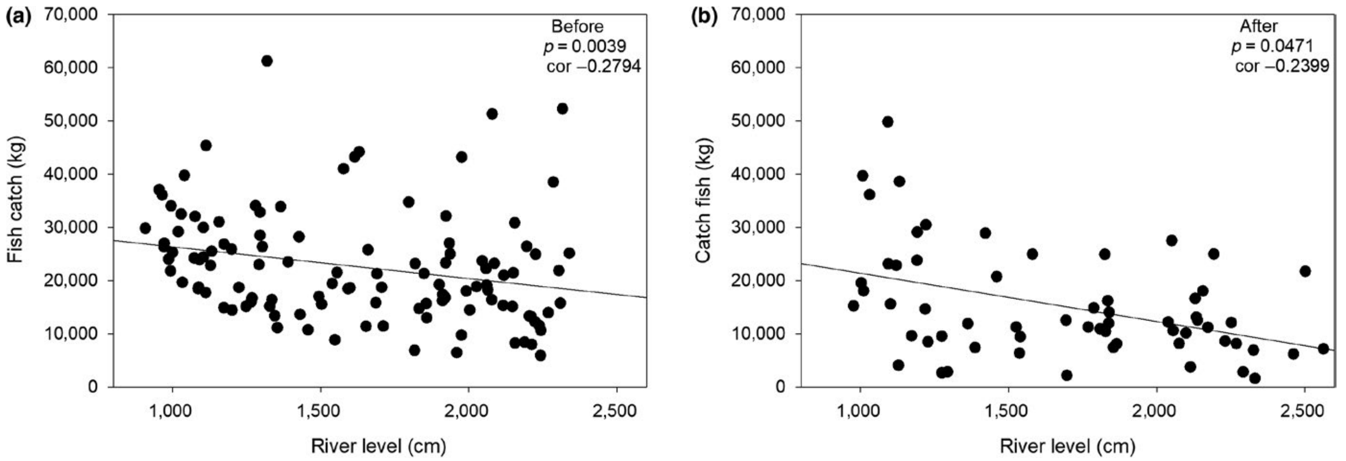

FIGURE 4 Linear regression of the fishery production landed in the municipality of Humaitá, Amazonas state (Brazil) on the level of the Madeira River before (a) and after (b) damming the Madeira River

damming of the river. After damming, however, a significant tendency for declining production was recorded (Figure 3).

3.2 | Influence of the hydrological cycle on fisheries

A significant difference in the mean fishery production among the different phases of the flood pulse was found both before (Figure 4a) and after (Figure 4b) damming of the river (ANOVA: $F = 4.925$, $N = 171$, $df = 3$, $p < 0.001$). A negative (Pearson) correlation was found between fishery production and the river level; that is, fishery productivity tended to be higher when the river was at its lowest levels (Figure 4).

3.3 | Impacts of fluviometric changes on fisheries

Considerable differences were observed in the fluviometric cycle of the Madeira River following damming (Figure 5a) when at least 1 month in a given year exceeded the maximum level recorded historically (prior to damming) for that month. River levels also varied more among years, and there was less homogeneity in the fluviometric patterns following damming of the Madeira River (Figure 5a).

Comparison with the historical means indicated a pronounced increase in the mean variation of river levels between March and October following damming (Figure 5b, Table 2), and greater discrepancies were recorded between May and August during the ebb period when the river level falls after the annual peak. This indicates that after damming the river level remained higher during the ebb period but reached a lower level by November and December (Figure 5b, Table 2). This indicates that the beginning of the flood period was characterised by lower river levels after damming of the Madeira, although the variation levelled off in January and February as the river flooded.

The greatest variation in river levels was observed in July with a mean value of 1,328 cm being recorded before damming and 1,661 cm afterwards (Figure 5b, Table 2). The smallest difference was recorded in January with a mean of 1,881 cm before damming and 1,884 cm afterwards (Figure 5b, Table 2).

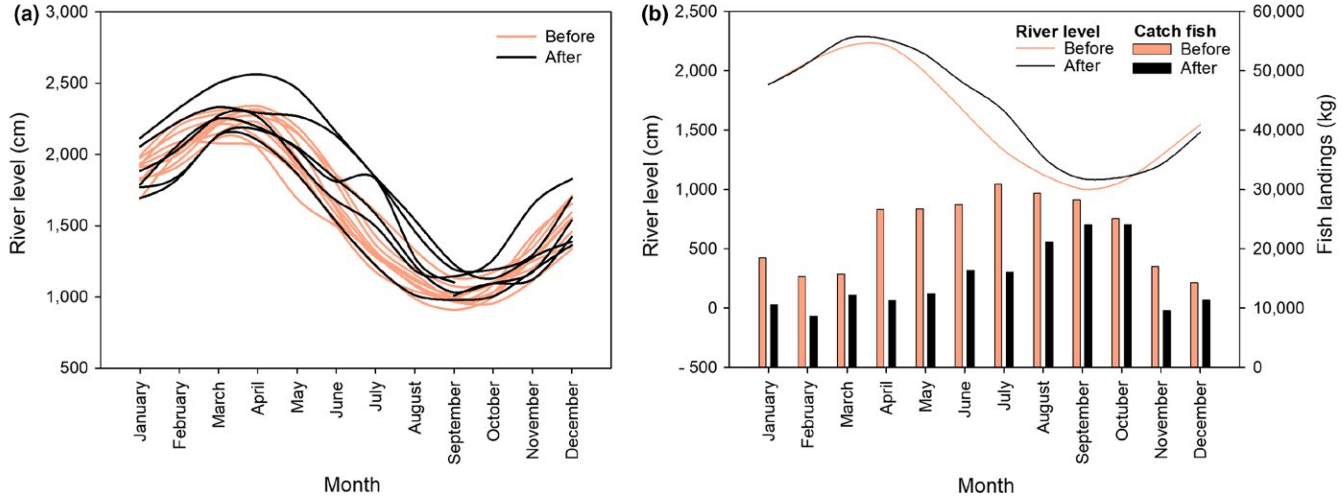

FIGURE 5 Mean monthly river level of the Madeira River (a) and fishery landings at Humaita, Amazonas state before (2002-2011) and after (2014-2017) closing dams on the Madeira River (b)

A reduction in mean catches in all months was found following damming of the Madeira River (Figure 5b, Table 2). The decline in catches was most pronounced between April and July (ebb period), which coincides with the period most affected by the increase in the mean fluviometry of the Madeira River when the variation exceeded 300 cm (Figure 5b, Table 2). Catches were least affected in October, December and March when the variation in the river level did not exceed 100 cm (Table 2). Fishery production declined most in April with a reduction of 15,414 kg (a decrease of 57.8%) and least in October with a reduction of only 1,055 kg (4.2%).

The highest mean fishery production was recorded in July and August (ebb period) prior to damming of the river (Figure 5b, Table 2). Following damming, mean production was highest in September and October in the dry season; December was the least productive month in the period prior to damming, although February was the least productive month following damming (Figure 5b, Table 2).

Linear regression was used to compare mean variation in river levels ($\Delta\overline{FI}_i$) with that in fishery production ($\Delta\overline{P}_i$) between the before and after damming periods (Table 3). A negative trend was found; that is, the greatest losses in production were recorded in the classes that had the greatest increase in river levels following damming of the Madeira River (Figure 6). According to the regression, for each 100 cm increase in the mean variation of the level of the river after damming, there was a decrease in the catch of approximately 2.864 kg of fish, a reduction of 12.5% for each increase in class (Figure 6).

The 300–400 class had the greatest effect on the catches (Figure 6, Table 3). By contrast, the reduction in the mean river level (−100–0 class) had the least effect on fishery production. Considering the overall loss in fishery production (48,896 kg) recorded (Table 3), 30% was concentrated in the 300–400 class, and only 12% in the −100–0 class. The regression indicated that, independently of any variation in the level of the river, damming alone was responsible for a reduction of 2,305 kg (10.1%) in the mean fishery production (Figure 6).

4 | DISCUSSION

4.1 | Declining fisheries

Following damming of the Madeira River, mean monthly catches landed at Humaitá decreased 34%, and mean annual fishery production declined 39%. The regression analysis revealed a tendency for decreasing fishery production following damming. A similar decline in fishery production has been recorded in other aquatic ecosystems of the Amazon region impacted by hydroelectric dams. Following the construction of Tucuruí dam on the Tocantins River, Brazil, for example, Santana, Bentesm, Homma, Oliveira and Oliveira (2014) found that the contribution of the downstream fisheries to the total local production decreased from 44% to 25%. Forty years after damming of the Tocantins River, the situation remains unfavourable, and the downstream fisheries are unable to satisfy the demand for fish of the resident population. Hallwass, Lopes, Juras and Silvano (2013) also reported a decrease in fish abundance and a possible local extinction of a commercial fish species (*Semaprochilodus bram*) after the Tocantins River dam.

Besides the Amazon region, the impacts of hydroelectric dams on the fish fauna and the decline of important commercial species have also been found in other aquatic ecosystems around the world (e.g., Agostinho et al., 2008; Assis et al., 2017; Dugan et al., 2010; Neraas & Spruell, 2001; Stone, 2016; Zhong & Power, 1996). For instance, a study of the effects of the Tallowa dam on the Shoalhaven River (south-east Australia) found a reduction in the abundance of four species of migratory fish and possibly the extinction of another ten species (Gehrke, Gillgian & Barwick, 2002). Other relevant studies using modelling of future scenarios verified that the construction of a hydroelectric dam in the Mekong River could lead to a fish production

TABLE 2 Monthly river levels and fishery production landed in Humaitá, Amazonas (Brazil), before (January 2002–July 2011) and after (August 2011–September 2017) damming of the Madeira River, with the variation between the periods (Before and After)

			January	February	March	April	May	June	July	August	September	October	November	December
River level (cm)	Before	Min	1,686	1,921	2,077	2,045	169	1,494	1,174	987	908	955	1,112	1,335
		Max	1,991	2,237	2,309	2,339	2,195	1,858	1,599	1,328	1,132	1,173	143	1,711
		Total	18,813	20,714	22,067	22,152	19,844	16,522	13,281	10,116	9,028	9,575	11,551	13,911
		Mean	1,881	2,071	2,207	2,215	1,984	1,652	1,328	1,124	1,003	1,064	1,283	1,546
		Standard deviation	92	103	73	108	159	137	118	93	66	66	97	140
	After	Min	1,694	1,838	2,134	2,099	1,865	1,526	1,219	1,011	977	1,003	1,121	1,363
		Max	2,114	2,327	2,502	2,563	2,462	2,156	184	154	1,228	1,191	1,294	1,697
		Total	9,421	10,326	11,358	1,132	10,686	9,446	8,303	7,639	6,538	551	6,043	7,406
		Mean	1,884	2,065	2,272	2,264	2,137	1,889	1,661	1,273	109	1,102	1,209	1,481
		±Standard deviation	188	219	153	181	231	261	270	199	103	68	73	138
		Variation in the mean	3	−6	65	49	153	237	333	149	87	38	−75	−64
Fish catch (kg)	Before	Min	6,866	6,452	591	8,408	15,116	12,992	18,631	1,517	21,794	14,896	13,369	8,851
		Max	32,102	2,321	38,489	56,321	51,289	44,163	61,239	45,352	36,064	37,042	23,482	21,518
		Total	184,958	153,299	157,420	266,665	267,362	275,141	309,187	254,752	253,852	2,261	153,473	128,582
		Mean	18,496	1,533	15,742	26,667	26,736	27,514	30,919	28,306	28,206	25,122	17,053	14,287
		Standard deviation	7,538	5,582	9,139	15,481	12,116	12,152	11,985	9,755	4,588	7,074	3,778	4,507
	After	Min	3,753	6,903	1,607	2,812	6,197	10,907	10,425	9,434	8,488	4,076	2,654	2,174
		Max	14,844	11,954	21,713	24,974	27,488	24,929	24,958	38,596	39,664	49,781	22,846	28,894
		Total	52,963	43,073	61,075	56,261	62,144	81,742	80,276	126,808	144,211	120,33	47,846	56,721
		Mean	10,593	8,615	12,215	11,252	12,429	16,348	16,055	21,135	24,035	24,066	9,569	11,344
		Standard deviation	4,154	198	7,135	8,331	8,697	5,748	5,409	11,602	12,703	16,448	8,209	10,402
		Variation in the mean	−7,903	−6,715	−3,527	−15,414	−14,307	−11,166	−14,864	−7,171	−4,171	−1,055	−7,483	−2,942

TABLE 3 Results of equations I ($\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$) and II ($\Delta\overline{P}_i = \overline{P}_{Ai} - \overline{P}_{Bi}$)

Class of mean variation in river level (cm)	Mean fishery production (kg)		Variation mean do catch fishery (kg)	
($\Delta\overline{FI}_i = \overline{FI}_{Ai} - \overline{FI}_{Bi}$)	Before ($\overline{P}_{Bi}$)	After ($\overline{P}_{Ai}$)	$\Delta\overline{P}_i$	Overall loss (%)
−100–0	15.556	9.843	−5.714	−12
0–100	22.846	16.432	−6.414	−13
100–200	27.521	16.782	−10.739	−22
200–300	27.514	16.348	−11.166	−23
300–400	30.919	16.055	−14.864	−30
Total	124.357	75.460	−48.896	−100

loss up to 4%, which is equivalent to an annual decrease of approximately 25,300 t (Ziv, Baran, Nam, Rodríguez-Iturbe & Levin, 2012).

The construction of hydroelectric dams in Amazonian ecosystems represents a major risk for the local fish fauna, especially considering that fishery productivity in this region reflects the enormous diversity of fish species found in the Amazon basin. Approximately 920 fish species are estimated to occur in the Madeira River basin, around a third of all the known fish diversity of the Amazon region (Ohara et al., 2013), which is the highest of any hydrographic basin anywhere in the world (Queiroz et al., 2013).

The decline in catches recorded in the present study may have a negative direct impact on the economy of the local fishing communities. In the Amazon region, fisheries play an important role in the creation of jobs and the generation of income, as well as supplying both national and foreign markets (Almeida, Lorenzen & McGrath, 2004). Tundisi et al. (2014) estimated that the fishery production of the Amazon region contributes US$200 million/year to the region's economy and supports a workforce of 200,000 commercial fishers. Assuming a mean price of US$3.30 per kg for the principal fish species (e.g., *C. macropomum*, *Cichla ocellaris*, *P. nigricans*) exploited by commercial fisheries in the Amazon region (Lima, Almeida, Teixeira & Melo, 2016), the decline in the fishery production in the municipality of Humaitá would represent a mean loss of approximately

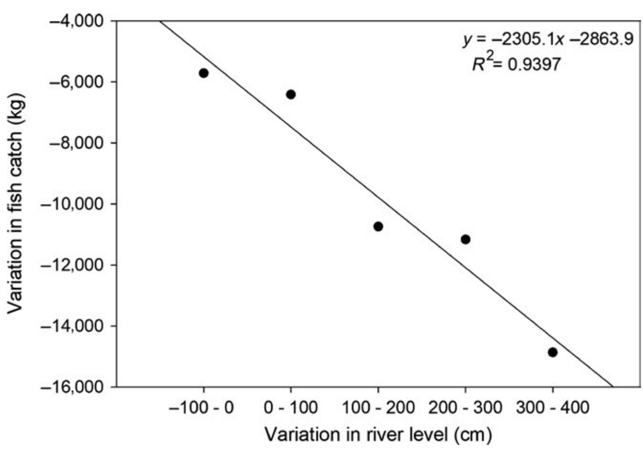

FIGURE 6 Linear regression of the mean variation in the river level on the difference mean fishery production before and after damming

US$342,000 of income per year. In this case, the construction of the Santo Antônio and Jirau dams has already cost the fishers of the Humaitá colony more than one and one half million dollars in lost revenue. These values would be even higher if the impacts on the secondary economic sectors related to the fisheries are considered, such as ice factories and suppliers of fishing equipment (i.e., gill nets), boats, outboard engines, outboard oil/fuel and provisions.

In addition to the impacts on the economic sector, the decline in fishery resources on the Madeira River may also affect the subsistence of local families. In the Amazon region, the *per capita* consumption of fish is among the highest in the world, with an estimated mean consumption of 369 g per person per day or 135 kg/year (Cerdeira et al., 1997). On the Brazilian sector of the Madeira River alone, six major fishing colonies at Guajará-Mirim, Porto Velho, Humaitá, Manicoré, Borba and Nova Olinda do Norte are likely to have their consumption of fish affected (Boschio, 1992; Cardoso & Freitas, 2007; Doria et al., 2012; Santos, 1987). In other words, the 39% reduction in the annual supply of fish on the Madeira River observed in the present study will not only affect the production of the region's commercial fisheries but will also alter the diet of the local human populations that depend on fish for their animal protein needs.

The social impacts brought by hydroelectric development lead to a reflection about the future of fishers who lose their livelihoods based on fishing. The lack of income sources and food insecurity may result in marginalisation (Kirchherr & Charles, 2016), and it could aggravate social conflicts in the Amazon region. According to the World Dams Commission (WCD, 2000), the probability of successful adaptation by fishing communities in the face of dam-affected ecosystem degradation is low. This scenario may increase illegal practices as an easier way of obtaining income, such as drug trafficking, illegal hunting, illegal logging and biopiracy. Bui and Schreinemachers (2011) found that after the construction of the Son la hydroelectric dam in north-eastern Vietnam, the resettled fishermen had to complement their family income by collecting forest products, increasing pressure on forest resources.

It is also important to highlight other impacts that may be generated by declining fisheries in ecosystem services that are rarely taken into account, such as cultural and recreational services, disease control (e.g., schistosomiasis and malaria) and transport of nutrients, carbon and minerals (Holmlund & Hammer, 1999). Another worrying issue is the reduction of populations of frugivorous species (e.g., *Brycon* spp., *C. macropomum*, *Piaractus brachypomus*, *Triportheus* spp.), which have an important ecological function in seed dispersal (Costa-Pereira & Galetti, 2015). The tambaqui (*C. macropomum)*, for example, disperses the seeds of at least 76 plant species (Correa, Costa-Pereira, Fleming, Goulding & Anderson, 2015) and can disperse them kilometres away from their place of origin (Anderson et al., 2018). According to Valiente-Banuet et al. (2015), the disruption of seed dispersal mutualisms directly affects plant reproductive success and threatens biodiversity of the forests.

Hydroelectric dams are a relatively recent feature on the Madeira River, and the long-term effects of these dams must be analysed systematically. However, considering the importance of fisheries in the Amazon region, many authors have warned of the potential impacts of dams on the local fish fauna (e.g., Anderson et al., 2018; Cella-Ribeiro et al., 2015; Duponchelle et al., 2016). One of the main problems discussed by the authors is related to blockage of fish migration. According to Anderson et al. (2018), newly built dams on the Madeira River can modify the habitat for these species and create insurmountable barriers to their movement along the river corridors. They further stated that these impacts will be worsened by future climate change. Fearnside (2014) reported that 1 year after the construction of the Santo Antônio dam, most migratory catfish (e.g., *Brachyplatystoma* spp.) were no longer seen passing through the dam's fish ladders. The reduced volume of water in the ladder is apparently insufficient to attract the fish towards its entrance, and these fish instinctively follow the river's principal current. These reported facts are worrisome because blocking migratory routes can affect the reproductive biology and life cycles of migratory fish species (Agostinho, Gomes, Veríssimo & Okada, 2004; Winemiller et al., 2016) and thereby compromise the fish stock viability in the region.

This evidence indicates that the reduction in fish stocks at Humaitá may be, at least partly, related to blocking of migratory routes on the Madeira River. According to the linear regression, independently of any variation in the level of the river, damming alone was responsible for a reduction of approximately 10% in the mean fishery production. Although there are other dam impacts that may be related to the decline of the fishing (disregarding the hydrological changes). It is likely to affirm that part of the fall is exclusively related to the migratory routes blocking. This conclusion is reinforced by the majority of commercial fish species of the Madeira River being long-distance longitudinal migrators, such as some characiformes (e.g., *Brycon* spp., *Prochilodus* spp. *and Semaprochilodus* spp.) (Araujo-Lima & Ruffino, 2003) and siluriforms (e.g., *B. rousseauxii*, *B. platynemum*, *B. juruense and B. vaillantii*) (Barthem et al., 2017). If Santo Antônio and Jirau dams are reducing migration rates on the Madeira River, as suggested by Fearnside (2014), the populations of important species for commercial fishery production may be declining, which would account for the observed reduction in fishery landings at the Humaitá fishing colony.

Given the ample area of dispersal of the commercial fish species found on the Madeira River, blocking the migration routes by the dams may also have impacts on the fisheries in other parts of the Amazon basin. Fearnside (2014) pointed out that the newly constructed dams may reduce the fishery stocks not only in Brazil, but also in Bolivia and Peru. The spawning grounds of the goliath catfishes (*Brachyplatystoma* spp.), for example, lie upstream from the Santo Antônio and Jirau dams, whereas they complete their life cycle downstream, undergoing migrations of up to 3,000 km (Barthem et al., 2017). Given the importance of these catfish as a fishery resource throughout the Amazon basin, any reduction in their populations will cause social and ecological impacts far beyond the limits of the Madeira basin (Barthem et al., 2017).

4.2 | Influence of the hydrological cycle on fisheries

The present study results indicate a seasonal pattern with productivity tending to increase as river levels decrease. This reflects the migratory behaviour of the species targeted by the region's commercial fisheries. During the flood, most of fish species migrate to the forests to utilise flooded areas to get shelter, food and breeding opportunities (Junk, Soares & Saint-Paul, 1997). In this period, the fish are widely dispersed and it hampers fishing efforts (Cardoso & Freitas, 2007; Doria et al., 2012; Goulding, 1979) resulting in decreases in fishing colony landings. As the river level begins to lower (ebb), the migratory species begin to form shoals and begin their dispersal migration (Barthem & Goulding, 2007). In this period, the fishermen utilise the movement of the shoals to catch them. At low water, many lakes become extremely shallow and many fish seek refuge in the remaining bodies of water forming major concentrations of individuals, which facilitate their capture by local fishers (Alcântara et al., 2015).

4.3 | Impacts of fluviometric changes on fisheries

The present study results indicate that the intensity of the region's fisheries is primarily determined by the hydrological cycle, which regulates the concentration of fish in the water (Isaac & Barthem, 1995). Consequently, the stability of the flood pulse is fundamental to the maintenance of fishery resources in the Amazon basin, and the results of the present study indicate that the dams on the Madeira River have substantial impacts on the dynamics of the flood pulse on this river. This flood pulse instability may be one of the principal factors determining the decline in fishery catches in the region. Analysis of the catch history indicated that the greatest decline in production was during the periods most affected by the increase in the mean level of the river. This result was corroborated by the linear equation analysis, which identified that for each 100 cm of increase in the river level mean after damming there was a decrease in catch of approximately 12.5% of the fishery production. This result indicates that the post-dam hydrological changes altered the ideal conditions for fishing productivity in the region. These changes in fishery dynamics may thus be related to the variation in river levels between periods (Before vs After) and may be related to two principal processes: (a) a reduction in the concentration of fish during periods of higher river levels, which hinders the capture of fish and limits fishery efforts (Goulding, 1979);

and (b) a decrease in the number of fishing trips during periods of high river level to avoid economic losses from the costs of unsuccessful excursions.

In addition to affecting the dynamics of fishery activities, a number of studies have shown that instability in the hydrological cycle generated by the construction of hydroelectric dams may alter the structure and composition of the local fish communities (Agostinho, Gomes & Zalewski, 2001; Fernandes et al., 2009; Fitzgerald et al., 2018). This may be related to the impacts on the essential ecological processes that guarantee the maintenance of fishery stocks. In particular, changes in the hydrological cycle may affect the connectivity between terrestrial and aquatic networks, which is fundamental to the maintenance of biodiversity and its intrinsic evolutionary processes (Tundisi & Matsumura-Tundisi, 2008). This is worrying because, in the coming decades, the trend of species disappearance will be significant.

The results of the present study indicate that the increase in river levels caused by damming of the river caused a delay in the ebb period. In this case, the dispersal of the migratory species that depend on falling river levels to initiate their migrations (Ribeiro & Petrere, 1990) will also be delayed, which may reduce the possibility of their capture during this period. This indicates that the Santo Antônio and Jirau dams may alter the periods of migration and spawning of the fish of the Madeira River. Dams may influence the migratory behaviour of fish by interrupting essential hydrological signals, which the species have responded to systematically over periods of many thousands of years (Anderson et al., 2018). This may account for monthly peak fishery catches shifting from July/August, in the ebb period, to September/October (low water) after damming and indicates a delay of 2 months in the migration of the fish of the Madeira River. This would also account for the reduced loss of productivity in October, with catches being sustained by late migrations.

5 | CONCLUSIONS

The results of this study indicate that the dams constructed on the Madeira River have two distinct types of impact on the region's fisheries. The first type of impact is related to the direct effects of the changes in the environment on the local fish communities, such as the blocking of migratory routes. The second type of impact is linked to the influence of environmental changes on the dynamics of fishery activities, such as a reduction in capture success. The influence of the Santo Antônio and Jirau dams on the decline in the fisheries of the Madeira basin highlights the high price paid by local populations for the environmental impacts caused by the development of the hydroelectric potential of the Amazon basin. This emphasises the need for consistent and impartial environmental management strategies that guarantee the mitigation of these impacts or compensate for the damage caused to the commercial fishers and the local fish diversity.

Finally, it is recommended that:

1. The fish catch be continuously monitored through the creation of a database of the main Madeira river fishing colonies both upstream and downstream of the dams. These data will able to support future evaluations of the basin's fisheries.
2. A technological program development be established for fish reproduction in the basin to enable the repopulation of species affected by hydroelectric dams.
3. Both the concessionaires responsible for the dams and the government agencies invest in the diversification and strengthening of local livelihoods and repair known social problems.
4. The fisheries management be considered with greater importance in the environmental licensing processes to reduce the socio-environmental impacts caused by the construction of new hydroelectric plants.

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REFERENCES

Agostinho, A. A., Gomes, L. C., Veríssimo, S., & Okada, E. K. (2004). Flood regime, dam regulation and fish in Upper Paraná River: Effects on assemblage attributes, reproduction and recruitment. *Reviews in Fish Biology and Fisheries*, *14*(1), 11–19.

Agostinho, A. A., Gomes, L. C., & Zalewski, M. (2001). The importance of floodplains for the dynamics of fish communities of the upper river Paraná. *Ecohydrology and Hydrobiology*, *1*(1), 209–217.

Agostinho, S. A., Miranda, L. E., Bini, L. M., Gomes, L. C., & Thomaz, S. M. (1999). Patterns of colonization in Neotropical reservoirs and prognosis on aging. In J. G. Tundisi & M. Straskraba (Eds.), *Theoretical reservoir ecology and its applications* (pp. 227–265). Rio de Janeiro, Brazil and Leiden, The Netherlands: Backhuys Publishers.

Agostinho, A. A., Pelicice, F. M., & Gomes, L. C. (2008). Dams and the fish fauna of the Neotropical region: Impacts and management related to diversity and fisheries. *Brazilian Journal Biology*, *68*(4), 1119–1132.

Alcântara, N. C., Gonçalves, G. S., Braga, T. M. P., Santos, S. M., Araújo, R. L., Lima, J. P., … Oliveira, A. T. (2015). Avaliação do desembarque pesqueiro (2009-2010) no município de Juruá, Amazonas, Brasil. *Biota Amazônia*, *5*(10), 37–42.

Almeida, O. T., Lorenzen, K., & McGrath, D. G. (2004). Commercial fishing sector in the regional economy of the Brazilian Amazon. In R. Welcomme & T. Peter (Orgs.), *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries* (pp. 15–24). FAO-Regional Office for Asia and the Pacific/Publicación RAP, vol 2. Bangkok, Thailand: Editora.

Anderson, E. P., Jekins, C. N., Sebastian, H., Ocampo-Maldonado, J. Á., Carvajal-Vallejos, F. M., Encalada, A. C., ... Tedesco, P. A. (2018). Fragmentation of Andes-to-Amazon connectivity by hydropower dams. *Science Advances*, *4*(1), 1429–1437.

Araujo-Lima, C. A. R. M., & Ruffino, M. L. (2003). Migratory fishes of the Brazilian Amazon. In J. Carolsfeld, B. Harvey, C. Ross, & A. Baer (Eds.), *Migratory fishes of South America: Biology, fisheries and conservation status* (pp. 235–307). Ottawa, ON: International Development and Research Centre, World Fisheries Trust.

Assis, D. A. S., Dias-Filho, V. A., Magalhães, A. L. B., & Brito, M. F. G. (2017). Establishment of the non-native fish *Metynnis lippincottianus* (Cope 1870) (Characiformes: Serrasalmidae) in lower São Francisco River, northeastern Brazil. *Studies on Neotropical Fauna and Environment*, *52*(3), 228–238.

Barthem, R. B., & Goulding, M. (2007). *Um ecossistema inesperado: A Amazônia revelada pela pesca*. Belém, Brazil: Amazon Conservation Association (ACA), Sociedade Civil Mamirauá. 241 pp.

Barthem, R. B., Goulding, M., Leite, R. G., Cañas, C., Forsberg, B., Venticinque, E., ... Mercado, A. (2017). Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae and migrating juveniles. *Scientific Reports*, *7*, 41784.

Batista, V. S., & Petrere, Jr, M. M. (2003). Characterization of the commercial fish production landed at Manaus, Amazonas State, Brazil. *Acta Amazonica*, *33*(1), 53–66.

Boschio, A. A. P. (1992). Produção pesqueira em Porto Velho, Rondônia (1984-89) - Alguns aspectos ecológicos das espécies comercialmente relevantes. *Acta Amazonica*, *22*(1), 163–172.

Bui, T. M. H., & Schreinemachers, P. (2011). Resettling farm households in northwestern Vietnam: Livelihood change and adaptation. *International Journal of Water Resources Development*, *27*(4), 769–785.

Bunn, S. E., & Arthington, A. H. (2002). Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. *Environmental Management*, *30*, 492–507.

Cardoso, R. S., & Freitas, C. E. C. (2007). Desembarque e esforço de pesca da frota pesqueira comercial de Manicoré (médio rio Madeira), Amazonas, Brasil. *Acta Amazonica*, *37*(4), 605–612.

Cella-Ribeiro, A., Assakawa, L. F., Torrente-Vilara, G., Zuanon, J., Leite, R. G., Doria, C., & Duponchelle, F. (2015). Temporal and spatial distribution of young *Brachyplatystoma spp.* (Siluriformes: Pimelodidae) along the rapids stretch of the Madeira River (Brazil) before the construction of two hydroelectric dams. *Journal of Fish Biology*, *86*, 1429–1437.

Cerdeira, R. G. P., Ruffino, M. L., & Isaac, V. J. (1997). Consumo de pescado e outros alimentos pela população ribeirinha do lago grande de Monte Alegre, PA. Brasil. *Acta Amazonica*, *27*(3), 13–228.

Correa, S. B., Costa-Pereira, R., Fleming, T., Goulding, M., & Anderson, J. T. (2015). Neotropical fish–fruit interactions: Eco-evolutionary dynamics and conservation. *Biological Reviews of the Cambridge Philosophical Society*, *90*, 1263–1278.

Costa, L. S. S. (1998). *As hidrovias interiores no Brasil*. Rio de Janeiro, Brazil: Serviço de Documentaçao da Marinha, Coleçao Amigos do Livro Naval. 125 pp.

Costa-Pereira, R. V., & Galetti, M. (2015). Frugivore downsizing and the collapse of seed dispersal by fish. *Biological Conservation*, *191*, 809–811.

Doria, C. R. C., Ruffino, M. L., Hijazi, N. C., & Cruz, R. L. (2012). A pesca comercial na bacia do rio Madeira no estado de Rondônia, Amazônia brasileira. *Acta Amazônica*, *42*(1), 29–40.

Dugan, P. J., Barlow, C., Agostinho, A. A., Baran, E., Cada, G. F., Chen, D., ... Winemiller, K. O. (2010). Fish migration, dams, and loss of ecosystem services in the Mekong. *Ambio*, *39*, 2677–2698.

Duponchelle, F., Pouilly, M., Pécheyran, C., Hauser, M., Renno, J. F., Panfili, J., ... Baras, E. (2016). Trans-Amazonian natal homing in giant catfish. *Journal of Applied Ecology*, *53*, 1511–1520.

Fearnside, P. M. (2014). Impacts of Brazil's Madeira River dams: Unlearned lessons for hydroelectric development in Amazonia. *Environmental Science & Policy.*, *38*, 164–172.

Fernandes, R., Agostinho, A. A., Ferreira, E. A., Pavanelli, C. S., Suzuki, H. I., Lima, D. P., & Gomes, L. C. (2009). Effects of the hydrological regime on the ichthyofauna of riverine environments of the Upper Paraná River floodplain. *Brazilian Journal of Biology*, *69*(2), 669–680.

Fitzgerald, D. B., Perez, M. H. S., Sousa, L. M., Gonçalves, A. P., Py-Daniel, L. R., Lujan, N. K., ... Lundberg, J. G. (2018). Diversity and community structure of rapids-dwelling fishes of the Xingu River: Implications for conservation amid large-scale hydroelectric development. *Biological Conservation*, *222*, 104–112.

Furtado, L. G. (2006). Origens pluriétnicas no cotidiano da pesca na Amazônia: Contribuições para projeto de estudo pluridisciplinar. *O Boletim do Museu Paraense Emílio Goeldi*, *1*(2), 1981–8122.

Gehrke, P. C., Gillgian, D. M., & Barwick, M. (2002). Changes in fish communities of the Shoalhaven River 20 years after construction of Tallowa dam, Australia. *River Research and Applications*, *18*, 265–286.

Goulding, M. (1979). *Ecologia da pesca do rio Madeira*. Manaus, Brazil: INPA, CNPQ-INPA. 172 pp.

Goulding, M., Barthem, R., & Ferreira, E. (2003). *The Smithsonian Atlas of the Amazon*. London, UK: Smithsonian Books.

Guyot, J. L. (1993). Hydrogéochimie des fleuves de l'Amazonie bolivienne, ORSTOM, Collection Etudes et Thèses, Paris.

Hallwass, G., Lopes, P. F., Juras, A. A., & Silvano, R. A. M. (2013). Fishers' knowledge identifies environmental changes and fish abundance trends in impounded tropical rivers. *Ecology Applications*, *23*(2), 392–407.

Holmlund, C. M., & Hammer, M. (1999). Ecosystem services generated by fish populations. *Ecological Economics*, *29*(2), 253–268.

IBGE (2017). Instituto Brasileiro de Geografia e Estatística. Retrieved from http://www.cidades.ibge.gov.br/xtras/perfil.php?lang=_EN&codmun=130170&search=amazonas|humaita

Isaac, V. J., & Barthem, R. B. (1995). Os recursos pesqueiros da Amazônia brasileira. *O Boletim do Museu Paraense Emílio Goeldi*, *11*, 295–339.

Junk, W. J. (2001). The flood pulse concept of large rivers: Learning from the tropics. *Verhandlungen des Internationalen Verein Limnologie*, *27*, 3950–3953.

Junk, W. J., Bayley, P. B., & Sparks, R. E. (1989). The flood pulse concept in river floodplain systems. *Canadian Journal of Fisheries and Aquatic Science*, *106*, 110–127.

Junk, W. J., & Mello, J. A. S. (1990). Impactos ecológicos das represas hidrelétricas na bacia amazônica brasileira. *Estudos Avançados*, *4*, 126–143.

Junk, W. J., Soares, M. G. M., & Saint-Paul, U. (1997). The fish. In W. J. Junk (Ed.), *The central Amazon floodplain: Ecology of a pulsing system* (pp. 385–408, 1st ed.). Berlin, Germany: Springer-Verlag.

Kirchherr, J., & Charles, K. (2016). The social impacts of dams: A new framework for scholarly analysis. *Environmental Impact Assessment Review*, *60*, 99–114.

Lees, A. C., Peres, C. A., Fearnside, P. M., Schneider, M., & Zuanon, J. A. S. (2016). Hydropower and the future of Amazonian biodiversity. *Biodiversity and Conservation*, *25*, 451–466.

Leprieur, F., Beauchard, O., Blanchet, S., Oberdorff, T., & Brosse, S. (2008). Fish invasions in the world's river systems: When natural processes are blurred by human activities. *PLoS Biology.*, *6*(12), 404–410.

Lima, P. K. F., Almeida, I. C., Teixeira, J. A., & Melo, R. A. (2016). A comercialização do pescado no município de Santarém, Pará. *Revista Brasileira de Engenharia de Pesca*, *9*(2), 1–9.

Lobato, T., Hauser-Davis, R., Oliveira, T., Silveira, A., Silva, H., Tavares, M., & Saraiva, A. C. F. (2015). Construction of a novel water quality index and quality indicator for reservoir water quality evaluation: A case study in the Amazon region. *Journal of Hydrology*, *522*, 683.

MME/EPE (2017). Ministério de Minas e Energia/Empresa de Pesquisa Energética. Plano Decenal de Expansão de Energia 2026 (pp. 1–271). Retrieved from http://www.mme.gov.br/documents/10584/0/PDE2026.pdf/474c63d5-a6ae-451c-8155-ce2938fbf896

Neraas, L. P., & Spruell, P. (2001). Fragmentation of riverine Fragmentation of riverine systems: The genetic effects of dams on bull trout (*Salvelinus confluentus*) in the Clark Fork River system. *Molecular Ecology*, *10*(5), 1153–1164.

Ohara, W. M., Queiroz, L. J., Zuanon, J. A., Torrente-vilara, G., Vieira, F. G., Pires, T., & Doria, C. R. (2013). O rio com a maior diversidade de peixes do mundo. In XX Encontro Brasileiro de Ictiologia 2013. Maringá, Brazil: Universidade Estadual de Maringá.

Pelicice, F. M., Azevedo-Santos, S. V. M., Vitule, J. R. S., Orsi, M. L., Lima, J. D. P., Magalhães, A. L. B., … Agostinho, A. A. (2017). Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries*, *18*, 1119–1133.

Queiroz, L. J., Torrente-vilara, G., Ohara, W. M., Pires, T. H. S., Zuanon, J., & Doria, C. R. C. (2013). *Peixes do Rio Madeira*, vol. 3, 1st ed. São Paulo, Brazil: Dialeto. 1163 pp.

R Core Team (2011). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Retrieved from http://www.R-project.org/

Ribeiro, M. C. L., & Petrere, Jr, M. (1990). Fisheries ecology and management of the Jaraqui (*Semaprochildus taenirus*, *S. insignis*) in the Central Amazonian. *Regulated Rivers and Mangement*, *5*, 195–215.

Santana, A. C., Bentesm, E. S., Homma, A. K. O., Oliveira, F. A., & Oliveira, C. M. (2014). Influência da barragem de Tucuruí no desempenho da pesca artesanal, estado do Pará. *Revista de Economia e Sociologia Rural*, *52*(2), 249–266.

Santos, G. M. (1987). Composição do pescado e situação da pesca no Estado de Rondônia. *Acta Amazonica*, *16*(17), 43–84.

Soito, J. K. S., & Freitas, M. A. V. (2011). Amazon and the expansion of hydropower in Brazil: Vulnerability, impacts and possibilities for adaptation to global climate change. *Renewable & Sustainable Energy Review*, *15*, 3165–3177.

Sokal, R. R., & Rohlf, F. J. (1995). *Biometry: The principles and practice of statistics in biological research*. New York, NY: W. H. Freeman.

Stone, R. (2016). Dam-building threatens Mekong fisheries. *Science*, *354*, 1084–1085.

Timpe, K., & Kaplan, D. (2017). The changing hydrology of a dammed Amazon. *Science Advances*, *3*, 1–13.

Tundisi, J. G., Goldemberg, J., Matsumura-Tundisi, T., & Saraiva, A. C. F. (2014). How many more dams in the Amazon? *Energy Policy*, *74*, 703–708.

Tundisi, J. G., & Matsumura-Tundisi, T. (2008). *Limnologia*. São Paulo, Brazil: Oficina de Textos. 631 pp.

Valiente-Banuet, A., Aizen, M. A., Alcántara, J. M., Arroyo, J., Cocucci, A., Galetti, M., … Zamora, R. (2015). Beyond species loss: The extinction of ecological interactions in a changing world. *Functional Ecology*, *29*, 299–307.

Ward, J. V., & Stanford, J. A. (1995). Ecological connectivity in alluvial river ecosystems and its disruption by flow regulation. *Regulated Rivers*, *11*, 105–119.

WCD (World Commission on Dams) (2000). *Dams and development: A new framework for decision-making*. London, UK: Earthscan.

Winemiller, K. O., McIntyre, P. B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., … Sáenz, L. (2016). Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science*, *351*(6269), 128–129.

Zahar, Y., Ghorbel, A., & Albergel, J. (2008). Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity ownstream of the Sidi Salem dam (Tunisia). *Journal of Hydrology*, *351*(3–4), 318–330.

Zhong, Y., & Power, G. (1996). Environmental impacts of hydroelectric projects on fish resources in China. *Regulated Rivers: Research and Management*, *12*, 81–98. https://doi.org/10.1002/(SICI)1099-1646(199601)12:1<81:AID-RRR378>3.0.CO;2-9

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., & Levin, S. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences of the United States of America*, *109*, 5609–5614.

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CAPÍTULO 2

Damming Amazon rivers: Environmental impacts of hydroelectric dams on Brazil’s Madeira River according to local fishers’ perception

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Damming Amazon rivers: Environmental impacts of hydroelectric dams on Brazil's Madeira River according to local fishers` perception

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Damming Amazon Rivers: Environmental impacts of hydroelectric dams on Brazil's Madeira River according to local fishers perception

ABSTRACT

The present study aimed to investigate the environmental impacts generated by the hydroelectric complex in the Madeira River, Brazilian Amazon, based on the perceptions of local fishers and fishery database, it focus attention on three main impacts: (i) on local fishery stocks; (ii) on the fish; and (iii) on the aquatic ecosystems. The local fishers were selected through the "snowball" approach for the application of semi-structured interviews. All the local fishers confirmed having perceived a decline in fishery productivity following the impounding of the Madeira River. Changes in the condition of the fish were also perceived by the local fishers, including exophthalmia (82%), a reduction in the weight or length of the fish (25%), and irregular breeding patterns (14%). In the case of impacts on the river, changes in the hydrological cycle were the process remembered most frequently (75%). The results elucidated a range of environmental impacts caused by the hydroelectric dams of the Madeira River.

Keywords: Anthropogenic disturbance, Artisanal fishers**,** Ethnobiology, Human Ecology, Reservoirs, Riverside communities

Introduction

Despite being considered a source of clean energy, hydroelectric power stations have profound negative impacts on the fundamental ecological processes that sustain the biological diversity of aquatic ecosystems (Athayde et al. 2019). One of the principal impacts caused by these hydroelectric projects is the modification of the hydrological cycle of the river (Timpe and Kaplan 2017). Dams may also reduce the availability of nutrients in the floodplain (Zahar et al. 2008), alter the physicochemical characteristics of the water, and modify the morphology of river channels (Lobato et al. 2015).

Another type of impact resulting from the construction of hydroelectric dams is the blocking of fish migration routes. Dams may create insurmountable barriers to the movement of these organisms along fluvial corridors, affecting their reproduction patterns, and changing their whole life cycle (Nunes et al. 2015; Winemiller et al. 2016). The interruption of migration routes may also affect the composition, abundance and the functional attributes of the local fish assemblages (Agostinho et al. 1999; Pinto et al. 2019). This process is especially preoccupying in the Amazon Basin, where many commercially-important fish species, such as the catfishes (*Brachyplatystoma* spp. and *Pseudoplatystoma* spp.) undertake systematic long-distance migrations over the course of their life cycle (Barthem et al. 2017; Anderson et al. 2018).

In addition to their negative impacts on fish populations, hydroelectric dams also affect the human populations that depend on fishery resources (Alho et al. 2015). Approximately 40.3 million people, worldwide, depend on artisanal fisheries for their livelihood, and this activity provides high quality food for many of the planet’s most vulnerable populations, thus combatting poverty, hunger, malnutrition, and inequality (FAO 2018). In the Amazon region alone, fisheries generate an input of US$200 million per year and support a workforce of 200,000 fishers (Tundisi et al.

2014). In addition, the per capita fish consumption of Amazonian populations is among the highest in the world and is considered to be both the main source of protein and income for many local communities (Doria et al. 2016).

The Madeira River Basin is one of the Amazonian ecosystems that has most suffered from the implantation of hydroelectric dams (Latrubesse et al. 2017). As one of the principal tributaries of the Amazon River, the Madeira River plays a fundamentally important role in the region's fisheries, with more than 1,000 species recorded up to now (Ohara et al. 2015), including a large number of recently-described taxa (Bifi et al. 2019). At least 57 of the fish species recorded in the Madeira Basin are commercially important for the region's fishing communities (Doria et al. 2012). Six major fishing ports are located on the Brazilian stretch of the Madeira River, and more than 40 local communities practice traditional fishing activities (Doria and Lima 2015). It seems likely that most, if not all these communities will suffer irreversible, long-term impacts from the hydroelectric dams.

Given this, the identification and evaluation of the impacts due to hydroelectric complex of the Madeira River will be fundamental to the management of the region's fisheries and its aquatic ecosystems. The analysis of the perceptions of local human populations is an important practical tool for this type of evaluation (Hanazaki et al. 2003). Throughout history, humans have congregated at the margins of watercourses, which have provided them with important ecosystem services (Moulton and Souza 2006). This relationship has resulted in the accumulation of knowledge on environmental processes, and the impacts suffered by aquatic ecosystems over the years (Silvano and Begossi 2009). This knowledge can be of enormous relevance for the environmental management of these ecosystems (Collier et al. 2015).

The present study used the knowledge of local fishers to evaluate the impacts of the Madeira River hydroelectric complex. The local fishers' knowledge has been inestimable and extremely useful source of data on the biology and ecology of the local fish species, the fluctuations in the abundance of commercial stocks, and environmental impacts (Silvano et al. 2008). From this perspective, the present study aimed to investigate the environmental impacts generated by the hydroelectric complex in the Madeira River based on the perceptions of local fishers and fishery database, focusing attention on three main impacts: (i) on local fishery stocks; (ii) on the fish; and (iii) on the aquatic ecosystems. It is hoped that fishers' perceptions provide new information which may mitigate or prevent similar impacts in other hydrographic basins affected by hydroelectric dams.

Materials and Methods

Study area

The study focused on the municipality of Humaitá, located in the southern extreme of the Brazilian state of Amazonas, approximately 675 km southwest of the state capital, Manaus (Fig. 1). The municipality of Humaitá has an area of 34 430 km^2, located on the margin of the Madeira River, with estimated population to 54 000 inhabitants (IBGE 2010).

The source of the Madeira River is located in the Bolivian Andes, where it is formed by the confluence of the Beni and Mamoré rivers (Goulding et al. 2003). The Madeira River has a total length of 3240 km, of which, 1425 km are within Brazil, where the river runs through the states of Rondônia and Amazonas before discharging into the Amazon River near the town of Itacoatiara (Costa 1998). The local climate is classified as A (tropical rainy) and Am (monsoon rains) in the Köppen system, with a short dry season, annual precipitation of 2250-2750 mm, and mean annual temperatures of between 24 °C and 26 °C.

The Santo Antônio hydroelectric dam (08°48′ S, 63°56′ W) is 175 km upstream from Humaitá city and 7 km upstream from Porto Velho city, the capital of Rondônia State. The Jirau hydroelectric dam (09°15′ S, 64°38′ W) is further upstream, 263 km from Humaitá and 100 km from Porto Velho (Fig. 1).

Humaitá Fishing Colony

Under Brazilian federal legislation (Law 1,699 of July 13th, 2008), fishing colonies are recognized as professional class entities for artisanal fishers, that is, for individuals that make their livelihood predominantly from fishing. The statute of the Humaitá colony (colony Z-31) was established on January 15th, 2002. The catches of the members of this colony are landed on a floating pier on the left margin of the Madeira River. The catches are then sold in the municipal market of the town of Humaitá or to middlemen. Approximately 1,655 fishers are currently affiliated with the Humaitá fishing colony (Santos et al. 2018).

The local fishers use a variety of vessels, including rowboats, motorized canoes, and fishing boat of up to 13 m in length (Lima et al. 2016). Gillnets and cast-nets are the principal types of equipment used to fishing, although some fishers also use hook and line, trawls or dragnets, harpoons, and arrows. More than half (54%) of the interviewees reported living in the periphery of the town of Humaitá, while the other 46% live in the rural zone. All interviewees consider themselves to be artisanal fishers and approximately 65% of them use the fish both for commercialization and for own consumption. The gain from the fish commercialization represents between 50% to 100% of family income in the riverside communities of the Madeira River (Doria et al. 2015).

Ethnobiological data

Local fishers were accessed using a non-probabilistic “snowball” approach, which consists of the identification of the local “experts” on the topic under investigation. In this approach, each informant identifies one or more experts until no additional individuals are indicated, thus completed the sample within the target group (Patton 2001). Once all the local fishers had been identified, the objectives of the study were explained, and each local fishers was asked to sign a free and informed consent form. This authorized legally their participation in the study, based on the recommendations of resolution 466/12 of the Brazilian National Health Council (Brasil 2012). The participants’ names are not provided here, in order to protect their identities. This study was approved by the Research Ethics Committee of the Federal University of Minas Gerais (UFMG), under process number CAAE: 80160217.8.0000.5149.

Semi-structured interviews were applied in July 2017 to 28 local fishers (22 men and six women) of the Z-31 colony, also known as the Dr. Renato Pereira Gonçalves fishing colony. At the time of the study, the interviewees were between 35 and 61 years old, with an average age of 52 years. The basic selection criterion was having lived in the study area since before the construction of the Santo Antônio and Jirau dams, with at least 20 years of fishery experience. The questions presented in the interview were intended to decipher the perceptions of the local fishers with regard to the impacts caused by the dams, focusing on three principal impacts: (i) on local fishery stocks; (ii) on the fish; and (iii) on the aquatic ecosystems. To facilitate the interviews and the data analysis, the local fishers were asked to refer only to the changes perceived by them over the past 20 years (1997-2017).

To assess the perceptions of the local fishers on the impacts caused by the impoundment of the Madeira River, the interviewees were asked whether, in the past 20 years, they had perceived:

(i) unusual changes (i.e., an increase or decrease) in fishery production, (ii) changes in the characteristics (e.g., their appearance, biology or behavior) of the fish, and (iii) unusual changes in the characteristics of the aquatic ecosystems (tributaries, lakes, margins, etc.) of the Madeira River. Whenever the answer was positive, the interviewee was asked to define "in which year" or "from which year onward" the change was noticed, and what the "possible cause" of these changes may have been. When the interviewee referred to one or more fish, the interviewer asked "which species" were involved. Finally, the interviewee was asked to describe in detail the situation (regarding the fishery, fish or river) in the periods before and after the impoundment.

The fish species cited in the interviews and recorded in the database were identified taxonomically using a checklist (Medeiros et al. 2014). For this, the interviewees were shown a catalog of photographs of the fish species found in the Madeira River and asked to list the species they knew and their local names. This catalog contained 202 photographs of fish species published in the regional inventories of Queiroz et al. (2013). These photographs were shown to the local fishers in predetermined random order (with the same order being used in all cases).

Fishery data

To evaluate and confirm the perceptions of the local fishers on the impacts of the hydroelectric complex of the Madeira River on its fish and fisheries, the results of the interviews were compared with the local fishery data. These data were obtained from the database available at the Z-31 colony in Humaitá. All catches landed at the colony from 17 fishing grounds located downstream of the dams have been recorded between January 2002 and September 2017 (Fig. 1). The data were recorded daily, and include information on the date of each fishing trip, the type of fish caught, and the catch volume (kg).

Data analysis

The information compiled in the interviews were analyzed using a collective subject technique (Lefevre 2005), which involves the identification of key expressions, that are used to group common themes and the central idea of the "collective discourse". Following the semi-structured interviews, the impacts perceived by the local fishers following the construction of the Madeira River hydroelectric complex were tabulated and allocated to categories. Impacts on fisheries were divided into two categories: (i) decline in fishery productivity and (ii) "peak" in fishery production in the flood season of 2014. The impacts perceived on the fish were assigned into three categories: (i) exophthalmia (lesions in the eyes), (ii) reduction in the size (length/weight) of the fish, and (iii) fish containing mature ova outside the normal breeding season. Impacts on the river were also divided into three categories: (i) irregular flood pulse; (ii) muddy water, and (iii) erosion on the river margins. The relative and absolute frequencies of the different categories were quantified for analysis. Only the perceptions mentioned by at least 10% of the interviewees were considered for analysis.

To compare the perceptions of the local fishers with the fishery data, the information on the catches landed at the Humaitá colony was divided into "Before" and "After" categories, based on the first complete impoundment of the Madeira River (Santo Antônio Dam) in July 2011. All the fishery data collected between January 2002 and July 2011 were thus allocated to the "Before" category, while those collected between August 2011 and September 2017 (except 2013) were assigned to the "After" category. In 2013, the floating pier of the fishing colony was removed from the Madeira River to make way for the construction of flood prevention works by the Humaitá town council. This led to the suspension of data collection between January and October 2013, so the data from 2013 were excluded from the analyses. The sluice gates of the Jirau Dam were shut off completely in October, 2012.

All the fish species referred to by the interviewees were included in the comparative analysis of the fishers' perceptions and the data on the catches landed at the Humaitá colony. This analysis included all the species mentioned by the interviewees, as well as the species that were not mentioned, but were among the 20 most abundant species in the fishery data. In this case, only one fish, the babão (*Brachyplatystoma platynemum*) was among the 20 species most landed by the fishers of the Humaitá colony, but was not cited in the interviews.

RESULTS AND DISCUSSION

Fish most caught

A total of 20 ethnospecies were cited by the local fishers as being the most caught at the Z-31 colony (Table 1). This relatively large number of commercial species indicates that the local fishery production is multispecific, that is, the targeting of an ample diversity of species to supply both the community and the local markets (Rufino et al. 1998). Multispecies fisheries are typical of tropical environments (Hallwass et al. 2011), given its diversity of habitats and high species richness.

The pacu (*Mylossoma* spp.) and the curimatã (*Prochilodus nigricans*) were considered to be the most productive fish by the local fishers, each being cited in 79% of the interviews (Table 1). This was corroborated by the fishery data, with the highest production being recorded for the pacu, followed by the curimatã, in all the periods analyzed (Table 1). This is consistent with the findings of fishery studies in the Amazon Basin, where the bulk of the production is provided by migratory characiforms (Gonçalves and Batista 2008). These findings are thus as expected, given that these species (pacu and curimatã) are not only extremely important fishery resources, but are also widely appreciated and consumed by the riverside populations of the Amazon region (Soares et al 2007). Souza et al. (2015) recorded a similar pattern in the municipality of Iranduba, in the Brazilian state of Amazonas, where the pacu (*Mylossoma* spp., M*yleus* spp., M*etynnis* sp.) and the curimatã (*P. nigricans*) were considered to be the fish most landed by local fishers.

Impacts of the dams on local fisheries

Decline in catches

All the local fishers confirmed having perceived a decline in fishery productivity following the damming of the Madeira River (Fig. 2a). One of the local fishers reported that in areas in which 200–300 kg of fish were caught typically prior to the impoundment, no more than 50 kg is caught in the present day, representing a decline in productivity of approximately 75–83% (Table 2). One other local fisher, responsible for recording catches at the fishing colony, reported that the number of landings has declined noticeably since the construction of the dams, and that even during months that were historically the most productive, there are days that the pier remains empty, with no fish being landed (Fig. 3a, Table 2). Fearnside (2014) recorded a similar scenario at a number of communities in the Madeira River, where fish disappeared following the impoundment of the river. Rainey and Rainey (2016) also found a similar situation in the community of Vila São Sebastião, in the municipality of Porto Velho, where residents reported a reduction in catches in areas adjacent to the community.

Based on the perceptions of the local fishers, the production of 15 ethnospecies declined following the impoundment (Table 1). Many studies have shown that impoundments for hydroelectric projects may provoke a reduction in fish populations due to a number of different types of impact, such as the blocking of migration routes (Perkin and Gido 2012; Mahlum et al. 2014), injuries to the fish in the turbines (McKinstry et al. 2007), shifts in the flood pulse (Santos, et al. 2018), changes in the physical-chemical properties of the water (Preece and Jones 2002; Olden and Naiman 2010), and alterations in the trophic structure of the impounded ecosystem (Agostinho et al. 2016; Oliveira et al. 2018). All these factors may have contributed to the decline in fishery production in the Madeira Basin. It is important to note here that the fishery data from the Madeira River reflect the dependence of local fisheries on migratory species, including *Mylossoma* spp.; *P. nigricans*; *Semaprochilodus insignis*; *Pseudoplatystoma* spp., which are among the fish that are most vulnerable to impoundments (Agostinho et al. 2016).

The pacu was the fish most referred in the interviews, appearing in 25% of the cases. A similar pattern was observed in the mean total catch, with the greatest reduction in the biomass landed at the fishing colony (-2316 kg) was recorded for the pacu. Fishers of the Araguaia-Tocantins Basin also reported a decline in production of the pacu following the impoundment of the Tocantins River (Hallwass et al. 2013). This accentuated reduction in the catches of the pacu may be linked to the fact that the modification of the hydrological cycle of impounded rivers generally leads to a reduction in the survival of the larvae in their spawning areas (Agostinho et al. 2004), a process that may have led to a decline in the abundance of these fish in the Madeira River.

The data indicate that the local fishers of the Humaitá fishing colony have a clear perception of the decline in the production of the pacu, although their perception was less sensitive for other species that suffered an even greater proportional decline in catches, such as the mapará (*Hypophthalmus* spp.) and branquinha, *Potamorhina latir* and *P. altamazonica* (Table 1). In addition, all species that recorded an increase in fish production in the colony's fishery database were not cited in the interviews. This may be related to the fact that local fishers generally provide more details on the most abundant and most exploited species, in particular those with the highest commercial value (Silvano and Begossi 2002). The pacu, in particular, is a prominent fishery target throughout the Amazon Basin (Batista and Petrere 2003), which probably enhanced the perceptions of the local fishers, even though some other species had declined more, in relative terms.

The low frequency of catches of some species may have been the main factor that negatively influenced the perception of local fishers. The mapará, for example, suffered the largest decline in relative frequency in the fishery database, but was largely ignored by local fishers in the interviews. While the mean catch of the mapará declined 87%, it represented only 0.31% of the total catch recorded (Table 1). In addition, species that recorded a significant increase in fishery production, such as Mandi (Pimelodus sp.), were not also remembered by local fishers in the interviews. The increase in fishery production observed for Mandi was 320%, however, its capture represents only 0.06% of all fishery production in Humaitá Colony (Table 1). This pattern can also be observed for the other species that have registered increased fishery production. These results indicate that the low frequency of capture of landed species may have influenced the perception of local fishers regarding the hierarchy of species that were more or less impacted.

Such minor inconsistencies between the perception of the local fishers and the biological data do not necessarily detract from the value of the semi-structured interviews, given that the relationship formed between the researchers and the traditional communities provides an opportunity for the accumulation of knowledge and the collection of new data (Silvano and Valbo-Jørgensen 2008; Daw et al. 2011). In the present study, for example, while the hierarchy of the species most impacted was not defined exactly, it was possible to confirm the negative influence of the impoundment on the fishery stocks (i.e., decline in stocks), as well as identifying the taxonomic groups potentially most affected.

The decline in fishery production reported by the local fishers and confirmed by the fishery data from Humaitá can have a negative impact on the economy of the local communities. In the

Amazon region, fisheries are an important source of income and employment, and supply both national and international markets (Almeida et al. 2004). Santos et al. (2018), for example, estimated that the hydroelectric complex of the Madeira River represents a loss of approximately US$342 000 per annum for fishing activity in Humaitá. In addition to economic losses, the decline of fisheries on the Madeira River may affect the subsistence of local families. The per capita consumption of fish in the Amazon is among the highest in the world, reaching 440 g/day in some regions (Cerdeira et al. 1997; Doria et al. 2016). This implies that the impact of the dams will also modify the diets of local riverside populations that depend on fish as a source of animal protein.

"Peak" of fishery production during the flood of 2014

More than half (54%) of the local fishers reported that the flood of 2014 resulted in a period of atypically high fishery productivity at Humaitá (Fig. 2a, Table 2). The flood of 2014 was considered to be the greatest ever recorded on the Madeira River, reaching a historic peak of 19.74 m on March 30th, 2 m higher than the previous record, in 1997 (Brasil 2014). Rainey and Rainey (2016) recorded a similar situation in Porto Velho, where local fishers reported a major increase in the availability of fish in 2014. Some studies have recorded peaks in fishery productivity in years with atypical floods, such as 2014 (as well as 1993 and 1997) on the Madeira River (Doria et al. 2015; Lima et al. 2017; Ayla et al. 2018). These peaks in fishery productivity recorded during exceptional floods may have been associated primarily with the higher river levels recorded in the preceding years (Lima et al. 2017). Welcomme and Halls (2004) concluded that higher flooding periods lead to an increase in the availability of nutrients, refuges and breeding grounds, which may favor the reproduction of stocks in subsequent years.

However, the more experienced local fishers interviewed in the present study were unanimous in saying that the atypical peak in fishery production during these historic floods is more closely related to the unique features of these events than river levels during the preceding period. In particular, the local fishers explained that the historic floods inundate floodplain lakes that are not normally reached by the rising waters during typical years, enabling large numbers of fish to migrate from these lakes to the river:

> **Fisher:** "*When the flood is normal, the river is not connected to all of the lakes, so the fish can't get to the river, and they stay in the lake for about five years. But during big floods, like in 2014, the water fills all this floodplain, and all the lakes and várzea (floodplain). So the fish that have been living in the lakes for a long time, like the jatuarana (Brycon spp.), who lives in clean water, can get to the river. This is why we caught so many jatuarana in 2014, because they passed here in front of town, and we just caught them.*"

This explanation is supported by other observations from the local fishers, who reported that characiform fish, such as the jatuarana/matrinxã (*Brycon amazonicus, B. melanopterus, B. falcatus*) and the tambaqui (*Colossoma macropomum*), were the most caught during the 2014 flood, with an average citation of 43% and 11% respectively (Table 1). Characiforms are known to dominate the fish faunas of floodplain lakes (Freitas and Garcez 2004), and the increase in their production in 2014 may have been related to the inundation of these lakes, which may not have been reached by the waters of the less intense floods of the previous, more typical years.

Franca et al. (2015) and Marengo and Espinoza (2016) found that the exceptional 2014 flood event was not related directly to the impacts of the hydroelectric complex of the Madeira River, but rather to the exceptional rainfall recorded in central-northern Bolivia and southeastern Peru, where the principal affluents of the Madeira are found.

However, the local fishers did report that the 2014 flood impacted local fisheries in a manner not observed in the historic floods that occurred prior to the construction of the dams. In particular, the local fishers reported that following other atypical flood events, like that of 1997, the peak in fishery production was followed by a decline in the next year, although stocks recovered during subsequent years. Following the peak in productivity associated with the 2014 flood, however, the local fishers reported that many of the species that declined in the subsequent year were unable to recuperate their stocks (Table 2). This indicates that the impoundment of Amazonian rivers may aggravate the impacts of major flood events on the region's fisheries. It is important to note here that most fish populations found in ecosystems impacted by dams are more than usually vulnerable to environmental changes, due to the blocking of migration routes (Anderson et al. 2018), for example, and the modification of the hydrological cycle (Santos et al. 2018). In other words, the increase in fishery productivity during extreme floods results in the depletion of fish stocks already left vulnerable by the impacts of the impoundment. This may reduce the numbers of juveniles available for recruitment to the subsequent generations, which places the species at risk of local extinction.

From this perspective, the environmental impacts of the impoundments, together with natural stochastic events, may result in an increase in the vulnerability of many Amazonian fish species. This may, in part, account for the accentuated decline in the production of some fish, such as the jatuarana/matrinxã (68%), which was the species reported in the interviews as the most productive during the historic flood (Table 1). Overall, this evidence indicates that the local fish fauna has yet to adapt to the environmental changes imposed by the hydroelectric dams.

Although the local fishers identified a marked increase in fish production in the 2014 flood, this result was not observed in the work by Santo et al. 2018. This result may be related to the fact that this increase in fishery production may have occurred in a very short period of time (less than a week), and therefore the month's cumulative production did not peak in historical fishery production. . In addition, it should be noted that although some species increased their fishery production in 2014, the most productive species in the community declined, and this made it impossible to observe the peak fishery production that was cited by the local fishers.

Impacts of the dams in the fishes

Exophthalmia

The appearance of abnormalities in the eyes (exophthalmia) was the change in the fish most cited (82%) in the interviews (Fig. 2b; Table 2). In fish, exophthalmia has been recorded in ecosystems impacted by hydroelectric dams, and is generally associated with the passage of the fish through the hydraulic turbines, which may cause physical trauma related to the variation in the pressure in the fish’s body, a process known as barotrauma (Stephenson et al. 2010; Brown et al. 2014). This occurs when the fish pass through the turbines and suffer rapid decompression, for less than one second, before returning to the surface pressure (Brown et al. 2012). In addition to exophthalmia, the passage through the turbines may cause other types of barotrauma, such as the rupture of the swim bladder, emboli and hemorrhaging (Colotelo et al. 2012).

Exophthalmia in fish may also be associated with parasitic infections (bacteria, fungi, viruses and worms), which may damage the eyes and cause necrotic material to be exuded through the ulcerated cornea (Eiras et al. 2010). However, it seems unlikely that the lesions observed in the fish from the Madeira River are caused by parasitosis, given that infection-related exophthalmia is more typical in farmed fish kept at high densities and water of low quality. By confining fish stocks together at high densities, fish farming may provoke chronic stress, making the fish more vulnerable to infection (Jerônimo et al. 2010). In their natural environment, by contrast, fish are often infected by a number of different parasites, but typically do not present any obvious symptoms (Pavanelli et al. 2002).

While ocular lesions have been observed by local fishers ever since the inauguration of the hydroelectric dams, there has not yet been any specific study of the appearance of exophthalmia in the fish from the Madeira River. The first fish with this condition were caught by the local fishers in 2012, soon after the impoundment of the river (Table 2). The local fishers reported that fish with this condition have been caught continuously since this time, up until the date of the interviews (July 2017). This appears to support the hypothesis that the exophthalmia observed in the fish is in fact associated with their passage through the turbines (i.e., barotrauma), and indicates that some species may be impeded from to access the fish ladders adequately, being attracted instead to the area of the turbines. Fearnside (2014) discusses this possibility, and concluded that the reduced volume of water in the fish ladder at the Santo Antônio Dam is insufficient to attract fish toward its entrance, leaving them to follow the principal flow of the river.

Fish ladders have long been used for migratory species, such as salmon, but due to the enormous diversity of Amazonian fish, systematic studies of the most effective types of transposition mechanisms have not conducted for the majority of the species (Fearnside 2014). This may account for the apparent ineffectiveness of the fish ladders for some characiform species, such as the pacu, curimatã, and the piau (*Schizodon fasciatus*, *Leporinus* spp.), which were the main species observed with exophthalmia by the local fishers (Table 1). The occurrence of these lesions in the fish may also explain to the decline in catches reported by the local fishers and recorded in the fishery database (Table 1), given that barotrauma typically results in the eventual mortality of the animal (McKinstry et al. 2007).

Reduction in the weight/length of the fish

Some of the local fishers (25%) reported that, following the construction of the dams, “scrawny” or “small” fish were caught frequently (Fig. 2b, Table 2). The growth and weight gain of an individual organism is determined by a complex of environmental factors, in particular, the quantity and quality of the nutrients available in the environment (Dourado and Benedito-Cecilio 2005). In the Madeira Basin, the quality and availability of nutrients on the floodplain is related directly to the hydrochemical characteristics of its waters, which contain high concentrations of suspended solids and nutrients derived from its Andean drainage (Barthem and Fabré 2004). This favors the primary production of the floodplain, which support a complex trophic network (Bayley 1989).

However, by regulating the flow of the river and retaining nutrients within the reservoir, hydroelectric dams may limit the input of organic matter downstream from the impoundment, restricting the diversity and abundance of feeding resources, and the primary productivity of the floodplain environment (Hahn and Fugi 2007). Alterations in the timing of the seasonal flood pulse in impounded ecosystems may also provoke behavioral shifts and the adaptation of the fish’s physiology to the availability of nutrients (Vismara et al. 2004). It thus seems likely that the presence of “scrawny” or “small” fish is related directly to the impacts of the Santo Antônio and Jirau dams on the quality and/or availability of feeding resources downstream from this impoundment, as well as to a general reduction in the primary productivity of the floodplain.

This finding is even more preoccupying in the specific case of the Humaitá fishing colony, given that the species considered by the local fishers to have been the most affected are the pacu and the curimatã, which contributed to the greatest catch volume, according to the fishery data (Table 1). The greater impact observed in the pacu may, in part, be related to their omnivorous feeding behavior, and their dependence on a regular hydrological cycle and the seasonal flooding of the floodplain forests to guarantee access to an adequate diet. Claro et al. (2004), for example, found that the principal source of energy of the pacu is allochthonous items, such as the fruit, seeds, and terrestrial invertebrates typically found in flooded forests.

The reduction in the body size and/or weight of the fish will have an important impact on fisheries in the Amazon region. Larger fish are generally considered to be more valuable by fishers and consumers, given that they represent a richer source of nutrients (greater biomass) and comparatively demand less processing time to be consumed (fewer or larger spines), tending to be thus more easily marketed (Begossi et al. 2012). A reduction in body mass is also expected to affect the condition factor of the fish, with negative consequences for the reproduction of the basin's fish fauna (Vazzoler 1996).

Irregular reproductive season

Some of the local fishers (14%) also reported that the construction of the hydroelectric dams on the Madeira River resulted in the capture of females containing mature ova during periods outside the reproductive season (Fig. 2b, Table 2). This unseasonal breeding may be related to changes in the hydrological cycle of the Madeira River following its impoundment. The reproductive migrations of Amazonian fish are closely synchronized with the hydrological cycle of the region's rivers (Arantes et al. 2019), and any alteration of this cycle will obviously have a significant impact on migration patterns and, ultimately, population structure (Agostinho 1999). Santos et al. (2018) observed a two-month delay in the migration period of the fish of the Madeira River, resulting from the shift in the hydrological cycle, which would be consistent with the delay in the reproductive cycle of some species observed by local fishers.

The principal fishes impacted in this case were pacu, sardinha (*Triportheus auritus*, *T. angulatus*), and curimatã (Table 1). The possible changes in the breeding season observed in these species (females containing mature ova between May and July) reflect a delay in comparison with the legal close season for the Madeira River (Brazilian federal law 11,959 of 2009). This period is timed to prohibit the fishing of certain fish species during the reproduction season, to guarantee the preservation of the species. In Amazonas State, the close season is established by the State Environment Council (CEMAAM), and is normally between Novembers and March. The increase in the numbers of mature females captured by the local fishers two to four months after the close season (Table 2) may be related to the impoundment of the Madeira River and has negative consequences for fishery management in the Amazon Basin and for maintaining the diversity of local fish.

Impacts of the dams on the river

Irregular hydrological cycle

Changes in the hydrological cycle were the impact on the river most remembered (75%) by the local fishers during the interviews (Fig. 2c, Table 2). The local fishers believe that this change is related primarily to sudden variations in the level of the river, known locally as “repiquetes”, which are more frequent and intense than they were prior to the impoundment of the river (Table 2). Some fishers also reported that the river is now constantly flooded, and that the low water periods are now less intense than they were prior to the construction of the dams (Table 2).

Agostinho et al. (2004) found that changes in the hydrological patterns of inland aquatic ecosystems are one of the principal impacts caused by the construction of hydroelectric dams, throughout the world, given that major daily variations in the discharge of water are necessary to maximize the generation of electricity. A number of other studies in the Madeira Basin (e.g. Doria et al. 2014; Silva and Paula 2018) have obtained similar results. Santos et al. (2018), for example, found that, following the impoundment of the Madeira River, the level of the river remained high during the ebb period, reaching its lowest levels during what would normally be the rising water periods. According to the study the river levels also varied more between years, and there was less homogeneity in the fluviometric patterns following damming of the Madeira River. The fishers from the area of Ponta do Abunã also observed that the regular cycle in the level of the river had changed following the construction of the Jirau Dam, and that this change was considered to be the principal cause of the scarcity of fish in the region (Silva and Paula 2018).

In the present study, the local fishers were unanimous on the negative effects of the loss of predictability of river flow, claiming that this affects most fishing trips, given that, when they go to fishing during a period of "low" water, they are surprised by a sudden increase in the level of the river, after which, the fish "disappear" (Table 2). As fishery productivity is closely related to the hydrological cycle in the Amazon Basin, changes in this cycle caused by the impoundment of rivers have been one of the principal factors in the decline in catches across the region (Winemiller et al. 2016; Timpe and Kaplan 2017). Santos et al. (2018), for example, concluded that part of the decline (39%) in catches landed at the Humaitá fishing colony is related to the increase in the mean level of the river following impoundment, based on (i) a reduction in the concentration of fish, which hampers catches and limits fishery efforts (Goulding 1979), and (ii) a reduction in the number of fishing trips during periods of more intense flow, as a means of reducing costs.

In addition to causing a decline in fishery production, the local fishers reported that the increased variability in the level of the river has resulted in other losses. Major fishing trips require the purchase of ice, fuel, provisions, and the contracting of additional personnel. However, the imbalance of the river level often results in investment lost, as catches are almost invariably insufficient to cover costs (Table 2), a similar scenario was also recorded by Santos et al. (2018).

Muddy waters

More than half (54%) of the local fishers reported that, following the impoundment, the water of the Madeira River had become "muddier" than normal (Fig. 2c, Table 2). However, no other study of the perceptions of riverside communities on the Madeira River has recorded any similar response.

It seems likely that the perception of the local fishers interviewed in the present study was related directly to the increase in the erosion of the margins of the Madeira River following the impoundment, as reported by the local fishers themselves (Table 2). This conclusion was reinforced by the fact that the local fishers reported that the muddy water was observed primarily during periods of "repiquete", when water is discharged by the dam. High levels of river discharge may cause an increase in erosive processes, and lead to an increase in the quantity of particulate matter suspended in the water, and thus, its turbidity, which may have led the local fishers to believe that the water is muddier than normal (Medeiros et al. 2015).

The sediment load may have a negative impact on an aquatic ecosystem, given that the high turbidity caused by suspended solids may hamper the penetration of sunlight, reducing the potential for photosynthesis, and leading to a reduction in the oxygenation of the water and the primary productivity of the river (Wetzel 2001). This may have negative implications for the maintenance of ecological processes and the biological diversity of aquatic ecosystems. Given this, the negative effects of the Jirau and Santo Antônio dams on the quality of the water of the watercourses and lakes of the Madeira Basin entails risks for both local diversity and the management of the region's fishery stocks.

Erosion of the river margins

Some (18%) of the local fishers also mentioned that the number of erosions of the margins of the river had increased following the impoundment (Fig. 2c, 3b, Table 2). Major erosion events have been recorded following the impoundment of the Madeira River, including the damage or destruction of 300 houses by the erosion on the waterfront of the city of Porto Velho in 2012 (Fearnside 2014). At the community of Vila São Sebastião, in the municipality of Porto Velho, local residents confirmed an increase in the number of landslides following the impoundment of the Madeira River, with larger numbers of trees being ripped out of the river margins (Rainey and Rainey 2016).

An increase in erosion downstream from the dams had been predicted by experts prior to the construction of the hydroelectric complex. The environmental impact study required for the approval of the Santo Antônio and Jirau schemes (FURNAS and CNO, 2005) concluded that, prior to the construction of the dams, the sedimentation of the margins, bed, and floodplain of the Madeira River were prevailing over erosive processes. However, Tundisi and Tundisi (2006) predicted that this equilibrium would be annulled by the impoundment of the river, given that the reservoir would favor the deposition of sediments upstream from the dam and would support erosive processes downstream, since the deposited sediment load would not be transferred downstream.

Other hydrological alterations of the Madeira River may have contributed to an increase in erosive processes on its margins (Fearnside 2014), given that the channeling of its flow through the spillway altered the currents downstream from the dam, forcing more water toward urban areas. This is confirmed by the residents of the town of Vila São Sebastião, who confirmed that the river is faster-flowing and more turbulent than it was prior to the impoundment, and that this turbulence often damages the boats and dugouts canoe moored at the front of their houses (Rainey and Rainey 2016).

CONCLUSIONS

The perceptions of local fishers confirmed that a range of environmental impacts have been generated by the construction of the hydroelectric complex on the Madeira River. It is hoped that these findings will contribute to the development of more effective management strategies for the hydrographic basins affected by hydroelectric dams. As the stocks of some fishery target species are decreasing as a consequence of these impacts, it will be necessary to establish a fish breeding program to ensure the long-term maintenance of their populations. The perceptions of the local fishers on the appearance of exophthalmia in the fish reinforce the need for a more systematic analysis of the efficiency of the transposition systems of the Santo Antônio and Jirau dams. The observation of impacts on the breeding patterns of the local fish fauna also emphasizes the need for the re-evaluation of the timing of the close season for the species most affected by the impoundment, in particular the migratory characiform species that are targeted by local fisheries.

The perceptions of the local fishers on the aquatic ecosystem and fishery activities no longer reflect the natural processes of the river, but rather, the manner in which the dams control the flood pulse. In addition to modifying the way in which the local fishers perceive and relate to the river, the impacts of the dams on the flood pulse of the Madeira River have had a negative effect on the region’s fisheries, which are the principal source of income and subsistence for innumerable local families. In particular, the findings of this study emphasize the need for the implementation of an effective system of management to avoid the enormous oscillations in river levels caused by the operation of the dams, not only seasonally, but also on a daily basis. While this may reduce the output of electricity of the dams, it would results in an important gain in ecosystem services.

Overall, it is clear that the expansion of the hydroelectric network in the Amazon Basin will extend the impacts observed in the present study throughout the basin. Clearly, any reduction in the number of hydroelectric schemes in the region should be seen as a fundamentally important investment to guarantee the future of the region, in economic, social, and ecological terms. Further research will also be essential to minimize the negative impacts of impoundments in the region, as well as developing more sustainable models of power production, that will guarantee a better balance between the region's energy demands and the ecosystem services that support such a large proportion of its population.

Figure captions

Fig. 1 Fishing grounds of the Z-31 (Dr. Renato Pereira Gonçalves) fishing colony, which operates out of the municipality of Humaitá, in Amazonas State, Brazil, and the location of the Santo Antônio and Jirau dams on the Madeira River in Rondônia State. The catches landed by this fishing colony were obtained at 17 fishing grounds located downstream from the dams.

Fig. 2 Relative frequency of citations of the different environmental impacts perceived by the local fishers from the Z-31 fishing colony in Humaitá following the construction of the Madeira River hydroelectric complex: **a** impacts perceived in fisheries; **b** impacts perceived on the fish, and **c** impacts perceived on the river.

Fig. 3 Environmental impacts generated by the hydroelectric complex in the Madeira River**. a** Floating landing pier at the Z-31 fishing colony in Humaitá at the time of the interviews (July, 2017). Note that on this day, in one of the months that is typically among the most productive in this area, the pier is completely empty. It is also possible to observe sale of bananas by one of the local fishers to minimize the fishery financial losses. **b** Erosion of the left margin of the Madeira

River in the municipality of Humaitá at the time of the interviews (July, 2017). Note that the soil and some roots are exposed

Conflict of Interest

The authors declare that they have no conflict of interest.

References

Agostinho, A.A., L. C. Gomes, L.C.N. Santos, J.C.G. Ortega, and F.M. Pelicice. 2016. Fish assemblages in Neotropical reservoirs: Colonization patterns, impacts and management. *Fisheries Research* 173: 26–36. https://doi.org/10.1016/j.fishres.2015.04.006

Agostinho, A.A., L. C. Gomes, S. Veríssimo, and E.K. Okada. 2004. Flood regime, dam regulation and fish in the Upper Paraná River: Effects on assemblage attributes, reproduction and recruitment. *Reviews in Fish Biology and Fisheries* 14: 11–19. doi:10.1007/s11160-004-3551-y.

Agostinho, S.A., L.E. Miranda, L.M. Bini, L. C. Gomes, and S.M. Thomaz. 1999. Patterns of colonization in Neotropical reservoirs and prognosis on aging. In J. G. Tundisi & M. Straskraba (Eds.), Theoretical reservoir ecology and its applications (pp. 227–265). Rio de Janeiro, Brazil and Leiden, The Netherlands: Backhuys Publisher

Alho, C.J.R., R.E. Reis, and P.P.U. Aquino. 2015. Amazonian freshwater habitats experiencing environmental and socioeconomic threats affecting subsistence fisheries. *Ambio* 44: 412–425. doi:10.1007/s13280-014-0610-z.

Almeida, O.T., K. Lorenzen, and D.T. McGrath. 2004. The fisheries sector in the Amazon regional economy. In*: Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries* Volume II. Welcomme R. and T. Petr, Eds., FAO

Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2004/17, pp. 15-24

Anderson, E., C. Jenkins, and S. Heilpern. 2018. Fragmentation of Andes- to- Amazon connectivity by hydropower dams. Science Advances 4. https://doi.org/10.1126/sciadv.aao1642

Arantes C.C., D.B. Fitzgerald, D.J. Hoeinghaus, and k.O. Winemiller. 2019. Impacts of hydroelectric dams on fishes and fisheries in tropical rivers through the lens of functional traits. *Current Opinion in Environmental Sustainability* 37: 28-40. https://doi.org/10.1016/j.cosust.2019.04.009

Athayde, S., M. Mathews, S. Bohlman, W. Brasil, C.R. Doria, J. Dutka-Gianelli, P.M. Fearnside, B. Loiselle, et al. 2019. Mapping research on hydropower and sustainability in the Brazilian Amazon: advances, gaps in knowledge and future directions. *Current Opinion in Environmental Sustainability* 37: 50-69. https://doi.org/10.1016/j.cosust.2019.06.004

Ayla, D.M., M.A.L. Lima, M. Hauser, and C.R.C. Doria. 2018. Jatuarana fishing dynamics *Brycon amazonicus* (Spix & Agassiz, 1829) of the upper and middle Madeira River Basin. *Acta Scientiarum* 40:1-11. http://dx.doi.org/10.4025/actascibiolsci.v40i1.34591

Barthem, R.B., and N.N. Fabré. 2004. Biologia e diversidade dos recursos pesqueiros da Amazônia, p. 17-62. In: Ruffino, M.L. (coord.). A pesca e os recursos pesqueiros na Amazônia brasileira. Ibama/Provárzea, Manaus, Brasil, 268 pp.

Barthem, R.B., M. Goulding, R.G. Leite, C. Cañas, B. Forsberg, E. Venticinque, P. Petry, M.L. de B. Ribeiro, J. Chictaya, and A. Mercado. 2017. Mercado, Goliath catfish spawning in the far western Amazon confirmed by the distribution of mature adults, drifting larvae and migrating juveniles. *Scientific Reports* 7:1-13. https://doi.org/10.1038/srep41784

Batista, V. S., and M. Petrere. 2003. Characterization of the commercial fish production landed at Manaus, Amazonas State, Brazil. *Acta Amazonica* 33: 53-66. http://dx.doi.org/10.1590/1809-4392200331066

Bayley, P.B. 1989. Aquatic environments in the Amazon Basin, with an analysis of carbon sources, fish production and and yield. *Special Publication of the Canadian Journal of Fisheries and Aquatic Sciences.* 106: 309- 408.

Begossi, A., S.V. Salivonchyk, N. Hanazaki, I.V. Martins, and F. Bueloni. 2012. Fishers (Paraty, RJ) and fish manipulation time: a variable associated to the choice for consumption and sale. *Brazilian Journal of Biology* 72: 973-975. http://dx.doi.org/10.1590/S1519-69842012000500030.

Bifi, A.G., R.R. Oliveira, and L.R. Py-Daniel. 2019. A new species of Ancistrus Kner, 1854 (Siluriformes: Loricariidae) from rio Madeira basin, Amazonas State, Brazil. *Neotropical Ichthyology* 17. http://dx.doi.org/10.1590/1982-0224-20180135

Brasil, MME (Ministério de Minas e Energia). 2017. Plano Decenal de Expansão de Energia 2026. Ministério de Minas e Energia, Empresa de Pesquisa Energética (MME/EPE). Brasília, DF, Brasil. 2 vols. http://www.mme.gov.br/documents/10584/0/%20PDE2026.pdf/474c63d5-a6ae-451c-8155-ce2938fbf896 Accessed 19 Mar 2019.

Brasil. CGU (Controladoria Geral da União). 2014. Secretaria Federal de Controle Interno, Relatório de Fiscalização nº 201408699. Diagnóstico situacional dos efeitos da cheia do Rio Madeira em Porto Velho, Rondônia. https://auditoria.cgu.gov.br/download/7129.pdf Accessed 15 Mar 2019.

Brasil. CNS (Conselho Nacional de Saúde). 2012. Resolução CNS 466 de 12 de dezembro de 2012. Ministério da Saúde. http://conselho.saude.gov.br/resolucoes/2012/Reso466.pdf Accessed 17 sep 2018.

Brown, R.S., A.H. Colotelo, and B.D. Pflugrath. 2014. Understanding Barotrauma in Fish Passing Hydro Structures: A Global Strategy for Sustainable Development of Water Resources. *Fisheries* 39:108-122. doi: 10.1080/03632415.2014.883570

Brown, R.S., B.D. Pflugrath, A.H. Colotelo, C.J. Brauner, T.J. Carlson, Z.D. Deng, and A.G. Seaburg .2012. Pathways of barotrauma in juvenile salmonids exposed to simulated hydroturbine passage: Boyle’s law vs. Henry’s law. *Fisheries Research* 121: 43–50. https://doi.org/10.1016/j.fishres.2012.01.006

Castello, L., and M.N. Macedo. 2015. Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology* 22: 990–1007. https://doi.org/10.1111/gcb.13173

Cerdeira, R.G.P., M.L. Ruffino, and V.J. Isaac. 1997. Consumo de pescado e outros alimentos pela população ribeirinha do Lago Grande de Monte Alegre, PA. Brasil. *Acta Amazonica* 27: 213–228. http://dx.doi.org/10.1590/1809-43921997273228

Claro Jr, L., E. Ferreira, J. Zuanon, and C.R.M. Araujo-Lima. 2004. Effects of flooded forest in the diet of three fish species in floodplain lakes of Central Amazon, Brazil. *Acta Amazonica* 34: 133–137.

Collier, C.A., M.S. de Almeida Neto, G.M.A. Aretakis, R.E. Santos, T.H. de Oliveira, J.S. Mourão, W. Severi, and A.C.A. El-Deir. 2015. Integrated approach to the understanding of the degradation of an urban river: Local perceptions, environmental parameters and geoprocessing. *Journal of Ethnobiology and Ethnomedicine* 11. doi:10.1186/s13002-015-0054-y.

Colotelo, A.H., B.D. Pflugrath, R.S. Brown, C.J. Brauner, R.P. Mueller, T.J. Carlson, Z.D. Deng, M.L. Ahmann, et al. 2012. The effect of rapid and sustained decompression on barotrauma in juvenile brook lamprey and Pacific lamprey: Implications for passage at hydroelectric facilities. *Fisheries Research* 129–130:17–20. https://doi.org/10.1016/j.fishres.2012.06.001

Costa, L.S.S. 1998. As hidrovias interiores no Brasil. Rio de Janeiro, Brazil: Serviço de Documentaçao da Marinha, Coleção Amigos do Livro Naval. 125 pp.

Daw, T.M., J. Robinson, and N.A.J. Graham. 2011. Perceptions of trends in Seychelles artisanal trap fisheries: Comparing catch monitoring, underwater visual census and fishers' knowledge. *Environmental Conservation* 38: 75–88. https://doi.org/10.1017/S0376892910000901

Doria, C.R.C., and M.A.L. Lima. 2015. Histórico do projeto e metodologia de obtenção dos dados. In *Rio Madeira: Seus Peixes e sua Pesca*, 1-11. Porto Velho, RO: Rima.

Doria, C.R.C., L.F. Machado, S.T. Brasil de Souza, and M.A.L. Lima. 2016. A pesca em comunidades ribeirinhas na região do médio rio Madeira, Rondônia. *Novos Cadernos NAEA* 19: 163–188. http://dx.doi.org/10.5801/ncn.v19i3.2499

Doria, C.R. da C., M.A.L. Lima, A.R. do Santos, S.T. Brasil de Souza, M.O.D.A.R. Simão, and A. R. Carvalho. 2014. O uso do conhecimento ecológico tradicional de pescadores no diagnóstico dos recursos pesqueiros em áreas de implantação de grandes empreendimentos. *Desenvolvimento e Meio Ambiente* 30: 89–108. doi:10.5380/dma.v30i0.34196.

Dourado, E.C.S. and E. Benedito-Cecilio. 2005. Ecologia energética de peixes: influência de fatores abióticos e bióticos. Maringá, EDUEM. 53p.

Eiras, J., R., G. Takemoto, E.A.M. Pavanelli. 2010. Clichetec, and undefined. 2010. *Diversidade dos parasitas de peixes de água doce do Brasil*.

FAO. 2018. The State of World Fisheries and Aquaculture 2018 - Meeting the sustainable development goals. Rome. Licence: CC BY-NC-SA 3.0 IGO

Fearnside, P.M. 2014. Impacts of Brazil's Madeira River Dams: Unlearned lessons for hydroelectric development in Amazonia. *Environmental Science and Policy* 38: 164–172. https://doi.org/10.1016/j.envsci.2013.11.004

Franca, R., E.E.D. Justina, and S.F. Sampaio. 2015. Análise climatológica e hidrológica da cheia do rio Madeira em Porto Velho-Rondônia no ano de 2014. *Terra Plural* 9:74-90. doi: 10.5212/TerraPlural.v.9i2.0005

Freitas, C.E.C., and R.C.S. Garcez. 2004. Fish communities of natural channels between floodplain lakes and Solimões-Amazonas River (Amazon-Brazil). *Acta Limnologica Brasiliensia* 16: 273-280.

FURNAS (Furnas Centrais Elétricas S.A.) and CNO (Construtora Noberto Odebrecht S.A.) & Leme Engenharia. 2005b. EIA- Estudo de Impacto Ambiental Aproveitamentos Hidrelétricos Santo Antônio e Jirau, Rio Madeira-RO. 6315-RT-G90-001. FURNAS, CNO & Leme Engenharia, Rio de Janeiro, RJ. 8 Vols.

Gonçalves, C., and V. da S. Batista. 2008. Avaliação do desembarque pesqueiro efetuado em Manacapuru, Amazonas, Brasil. *Acta Amazonica* 38: 135–144. http://dx.doi.org/10.1590/S0044-59672008000100015

Goulding, M. 1979. Ecologia da pesca do rio Madeira. Manaus, Brazil: INPA, CNPQ-INPA. 172 pp.

Goulding, M., R., Barthem, and Ferreira, E. 2003. The Smithsonian Atlas of the Amazon. London, UK: Smithsonian Books.

Hahn, N.S., and R. Fugi. 2009. Alimentação de peixes em reservatórios brasileiros: alterações e conseqüências nos estágios iniciais do represamento. *Oecologia Brasiliensis* 11: 469–480. doi:10.4257/oeco.2007.1104.01.

Hallwass, G., P.F. Lopes, A. A. Juras, and R. A. M. Silvano. 2011. Fishing effort and catch composition of Urban market and rural villages in Brazilian Amazon. *Environmental Management* 47: 188–200. doi:10.1007/s00267-010-9584-1.

Hallwass, G., P.F. Lopes, A. A. Juras, and R. A. M. Silvano. 2013. Fishers' knowledge identifies environmental changes and fish abundance trends in impounded tropical rivers. *Ecological Applications* 23: 392–407. https://doi.org/10.1890/12-0429.1

Hanazaki, N., D. F. Herbst, M. S. Marques, and I. Vandebroek. 2013. Evidence of the shifting baseline syndrome in ethnobotanical research. *Journal of Ethnobiology and Ethnomedicine* 9: 1–11. doi:10.1186/1746-4269-9-75.

IBGE. 2010. Instituto Brasileiro de Geografia e Estatística. https://cidades.ibge.gov.br/brasil/am/humaita/panorama Accessed 15 Aug 2018.

Jerônimo, G.T., G.M. Speck, and M.L. Martins. 2010. First report of *Enterogyrus cichlidarum* Paperna 1963 (Monogenoidea: Ancyrocephalidae) on Nile Tilapia *Oreochromis niloticus* cultured in Brazil. *Neotropical Helminthology* 4: 75-80.

Latrubesse, E.M., E. Y. Arima, T. Dunne, E. Park, V.R. Baker, F.M. D'Horta, C. Wight, F. Wittmann, et al. 2017. Damming the rivers of the Amazon basin. *Nature* 546: 363–369. https://doi.org/10.1038/nature22333

Lees, A.C., C.A. Peres, P.M. Fearnside, M. Schneider, and J.A.S. Zuanon. 2016. Hydropower and the future of Amazonian biodiversity. *Biodiversity and Conservation* 25: 451–466. doi:10.1007/s10531-016-1072-3.

Lefevre, F., and A.M.C. Lefevre. 2005. Depoimentos e discursos: uma proposta de análise em pesquisa social. *Série Pesquisa* 12. Liber Livro.

Lima, M.A.L., C.E. de C. Freitas, S.M. de Moraes, and C.R.C. Doria. 2016. Pesca artesanal no município de Humaitá, médio rio Madeira, Amazonas, Brasil. *Boletim do Instituto de Pesca* 42: 924–935. doi:10.20950/1678-2305.2016v42n4p924

Lima, M.A.L., D. Kaplan, and C.R.C. Doria. 2017. Hydrological controls of fisheries production in a major Amazonian tributary. *Ecohydrology*, 10: 1-19. doi: 10.1002/eco.1899

Lobato, T., R. Hauser-Davis, T. Oliveira, A. Silveira, H. Silva, M. Tavares, and A. C. F. Saraiva. 2015. Construction of a novel water quality index and quality indicator for reservoir water quality evaluation: A case study in the Amazon region. *Journal of Hydrology* 522: 674-683. https://doi.org/10.1016/j.jhydrol.2015.01.021

Mahlum, S., D. Kehler, D. Cote, Y. F. Wiersma, and L. Stanfield. 2014. Assessing the biological relevance of aquatic connectivity to stream fish communities. *Canadian Journal of Fisheries and Aquatic Sciences* 71: 1852-1863, https://doi.org/10.1139/cjfas-2013-0646

Marengo, J.A., and J.C. Espinoza. 2016. Extreme seasonal droughts and floods in Amazonia: Causes, trends and impacts. *International Journal of Climatology* 36: 1033–1050. https://doi.org/10.1002/joc.4420

McKinstry, C., T.J. Carlson, and R.S. Brown. 2007. Derivation of a mortal injury metric for studies of rapid decompression of depth-acclimated physostomous fish. PNNL-17080. Pacific Northwest National Laboratory, Richland, Washington.

Medeiros, P.M., A.L.S. Almeida, R.F.P. Lucena, F.J.B. Souto, and U.P. Albuquerque. 2014. Use of Visual Stimuli in Ethnobiological Research. In: *Methods and Techniques in Ethnobiology* *and Ethnoecology*. Albuquerque U. P., L. V. F. C. Cunha, R. F. P. Lucena and R. R. N. Alves. Springer New York Heidelberg Dordrecht London; p. 87–98.

Medeiros, P.R.P., G.H.C. Segundo, and E.M.M. Magalhães. 2015. Comportamento da turbidez e material em suspensão, em um rio com vazão regularizada por sistema de barragens em cascata: Rio São Francisco (NE, Brasil). *Geochimica Brasiliensis* 29: 35-44. doi: 10.5327/Z0102-9800201500010004

Moulton T.P., and M.L. Souza. 2006. Conservação com base em bacias hidrográficas. In: *Biologia da Conservação*. Bergallo H. G., C. F. D. Rocha, M. A. S. Alves, M. V. Sluys. editors. Rio de Janeiro: Universidade do Estado do Rio de Janeiro, pp. 45–52.

Nunes, D.M.F., A.L.B. Magalhães, A.A. Weber, R.Z. Gomes, F.T. Normando, K.B. Santiago, E. Rizzo, and N. Bazzoli. 2015. Influence of a large dam and importance of an undammed tributary on the reproductive ecology of the threatened fish matrinxã Brycon orthotaenia Günther, 1864 (Characiformes: Bryconidae) in southeastern Brazil. *Neotropical Ichthyology* 13: 317–324. http://dx.doi.org/10.1590/1982-0224-20140084

Ohara, W.M., L.J. de Queiroz, J. Zuanon, G. Torrente-Vilara, F.G. Vieira, and C.D.C. Doria. 2015. Fish collection of the Universidade Federal de Rondônia: its importance to the knowledge of Amazonian fish diversity. *Acta Scientiarum. Biological Sciences* 37: 251-258. doi:10.4025/actascibiolsci.v37i2.26920.

Olden, J.D. and R.J. Naiman. 2010. Incorporando regimes térmicos em avaliações de fluxos ambientais: modificando operações de barragens para restaurar a integridade do ecossistema de água doce. *Freshwater Biology* 55: 86-107.

Oliveira, A.G, M.T. Baumgartner, L.C. Gomes, R.M. Dias, and A.A. Agostinho. 2018. Long-term effects of flow regulation by dams simplify fish functional diversity. Freshwater Biology 63:293-305. https://doi.org/10.1111/fwb.13064

Patton, M. Q. 2001. Qualitative research and evaluation methods. London: Sage Publications.

Pavanelli, G.C., J.C. Eiras, and R. M. Takemoto. Doenças de peixes: profilaxia, diagnóstico e tratamento. Maringá: Ed. UEM, 2ª Ed., 305p., 2002.

Pelicice, F. M., V. M. Azevedo-Santos, J. R. S. Vitule, M. L. Orsi, D. P. Lima Junior, A. L. B. Magalhães, P. S. Pompeu, M. Petrere, et al. 2017. Neotropical freshwater fishes imperilled by unsustainable policies. *Fish and Fisheries* 18: 1119–1133. https://doi.org/10.1111/faf.12228

Perkin, J., and K. B. Gido. 2012. Fragmentation alters stream fish community structure in dendritic ecological networks. *Ecological Applications* 22, 2176–2187. https://doi.org/10.1890/12-0318.1

Pinto, M.D.S., C.R.C. Dória, and E.E. Marques. 2019. Alterações temporais sobre a estrutura funcional das assembleias de peixes durante onze anos de formação de um reservatório do médio rio Tocantins, Brasil. *Biota Amazônia* 9: 17–21. http://dx.doi.org/10.18561/2179-5746/biotaamazonia.v9n1p17-21

Preece, R.M., and H.A. Jones. 2002. The effect of Keepit Dam on the temperature regime of the Namoi River, Australia. *River Research and Applications*, 18:397-414. http://dx.doi.org/10.1002/rra.686

Queiroz, L.J., G. Torrente-vilara, W.M. Ohara, T.H.S. Pires, J. Zuanon, and C.R.C. Doria. 2013. Peixes do Rio Madeira, vol. 1,2,3 st ed. São Paulo, Brazil: Dialeto, pp. 1163.

Rainey S.J., and M.C.A. Rainey. 2016. Perspectivas ribeirinha sobre os impactos da construção de usinas hidrelétricas no rio Madeira em Rondônia. *Confins* 29. https://journals.openedition.org/confins/11621

Ruffino, M., V.J. Isaac and A. Milstein. 1998. Fisheries ecology in the Lower Amazon: a typical artisanal practice in the tropics. *Ecotropica*, 4: 99-114.

Santos, R.E., R.M. Pinto-Coelho, R. Fonseca, N. R. Simões, and F. B. Zanchi. 2018. The decline of fisheries on the Madeira River, Brazil: The high cost of the hydroelectric dams in the Amazon Basin. *Fisheries Management and Ecology* 25: 380–391. https://doi.org/10.1111/fme.12305

Silva, F.M., and E.A. Paula. 2018. Usinas hidrelétricas sob os véus da "sustentabilidade": o pescador artesanal da Ponta do Abunã e a Usina Hidrelétrica de Jirau, em Rondônia. *Novos Cadernos NAEA* 21:159-178. doi: 10.5801/ncn.v21i1.3497

Silvano R.A.M., and A. Begossi. 2009. What do people think about pollution? Contributions of Human Ecology to the study of river pollution with a focus on Brazil. In: River Pollution Research Progress. Gallo M. N., M. H. Ferrari. editors. 1a ed. New York: Nova Publishers Inc. 283–296.

Silvano, R.A.M., A.L. Silva, M. Ceroni, and A. Begossi. 2008. Contributions of ethnobiology to the conservation of tropical rivers and streams. Aquatic Conservation: Marine and Freshwater Ecosystems 18: 241–260. https://doi.org/10.1002/aqc.825

Silvano, R.A.M., and A. Begossi. 2002. Ethnoichthyology and fish conservation in the Piracicaba River (Brazil). *Journal of Ethnobiology* 22:285-306.

Silvano, R.A.M., and J. Valbo-Jørgensen. 2008. Beyond fishermen´s tales: contributions of fishers´local ecological knowledge to fish ecology and fisheries management. Environment, Development and Sustainability 10: 657-675. http://dx.doi.org/10.1007/s10668-008-9149-0

Soares, M.G.M., E. L. Costa, F. K. Siqueira-Souza, H. D. B. Anjos, K. C. Yamamoto, and C. E. Freitas. Peixes de lagos do Médio rio Solimões. Manaus: EDUA, p.176, 2007.

Souza, L.A., C. Edwar, D. C. Freitas, and R. G. Costa. 2015. relação entre guildas de peixes, ambientes e petrechos de pesca baseado no conhecimento tradicional de pescadores da Amazônia central. *Boletim do Instituto de Pesca* 41: 633–644.

Stephenson, J.R., A.J. Gingerich, R.S. Brown, B.D. Pflugrath, Z. Deng, T.J. Carlson, M.J. Langeslay, M.L. Ahmann, et al. 2010. Assessing barotrauma in neutrally and negatively buoyant juvenile salmonids exposed to simulated hydro-turbine passage using a mobile aquatic barotrauma laboratory. *Fisheries Research* 106: 271–278. doi:10.1016/j.fishres.2010.08.006.

Timpe, K., and D. Kaplan. 2017. The changing hydrology of a dammed Amazon. *Science* 11:1-13. doi: 10.1126/sciadv.1700611

Tundisi, J.G. and Matsumura-Tundisi, T. (2006). Parecer Técnico sobre Limnologia, Qualidade das Águas e Sedimentologia, Part B. Vol. 1, Parecer 4, In: Pareceres Técnicos dos Especialistas Setoriais—Aspectos Físicos/Bióticos. Relatório de Análise do Conteúdo dos Estudos de Impacto Ambiental (EIA) e do Relatório de Impacto Ambiental (RIMA) dos Aproveitamentos Hidrelétricos de Santo Antônio e Jirau no, Rio Madeira, Estado de Rondônia. p. 1-50, Porto Velho, Rondônia: Ministério Público do Estado de Rondônia. 2 Vols.

Tundisi, J.G., J. Goldemberg, T. Matsumura-Tundisi, and A.C.F. Saraiva. 2014. How many more dams in the Amazon. Energy Policy 74: 703–708. https://doi.org/10.1016/j.enpol.2014.07.013

Vazzoler, A.E.A.M. 1996. Biologia da reprodução de peixes teleósteos: teoria e prática. Eduem, Maringá, Paraná, Brasil.

Vismara, M.R., E. Benedito-Cecilio, A.C. Esper, and A. De Faria. 2004. Efeito da maturação gonadal sobre o conteúdo calórico e condição geral de peixes da planície de inundação do alto rio Paraná. Acta Scientiarum. Biological Sciences Maringá 26: 189–199. doi. 10.4025/actascibiolsci.v26i2.1635

Welcomme, R.L. and Halls, A.S. 2004. Dependence of tropical river fisheries on flow. In: Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries. Volume II. RAP Publication 2004/16. Food and Agriculture Organization of the United Nations (FAO), Bangkok, pp. 267-283.

Wetzel R.G. Limnology. 2001. 3. ed. Philadelphia, W.B. Sandres, 743 p

Winemiller, K.O., P.B. McIntyre, L. Castello, E. Fluet-Chouinard, T. Giarrizzo, S. Nam, I.G. Baird, W. Darwall, et al. 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* 351:128-129. doi:10.1126/science.aac7082.

Zahar, Y., A. Ghorbel, and J. Albergel. 2008. Impacts of large dams on downstream flow conditions of rivers: Aggradation and reduction of the Medjerda channel capacity downstream of the Sidi Salem dam (Tunisia). *Journal of Hydrology* 351: 318–330. https://doi.org/10.1016/j.jhydrol.2007.12.019

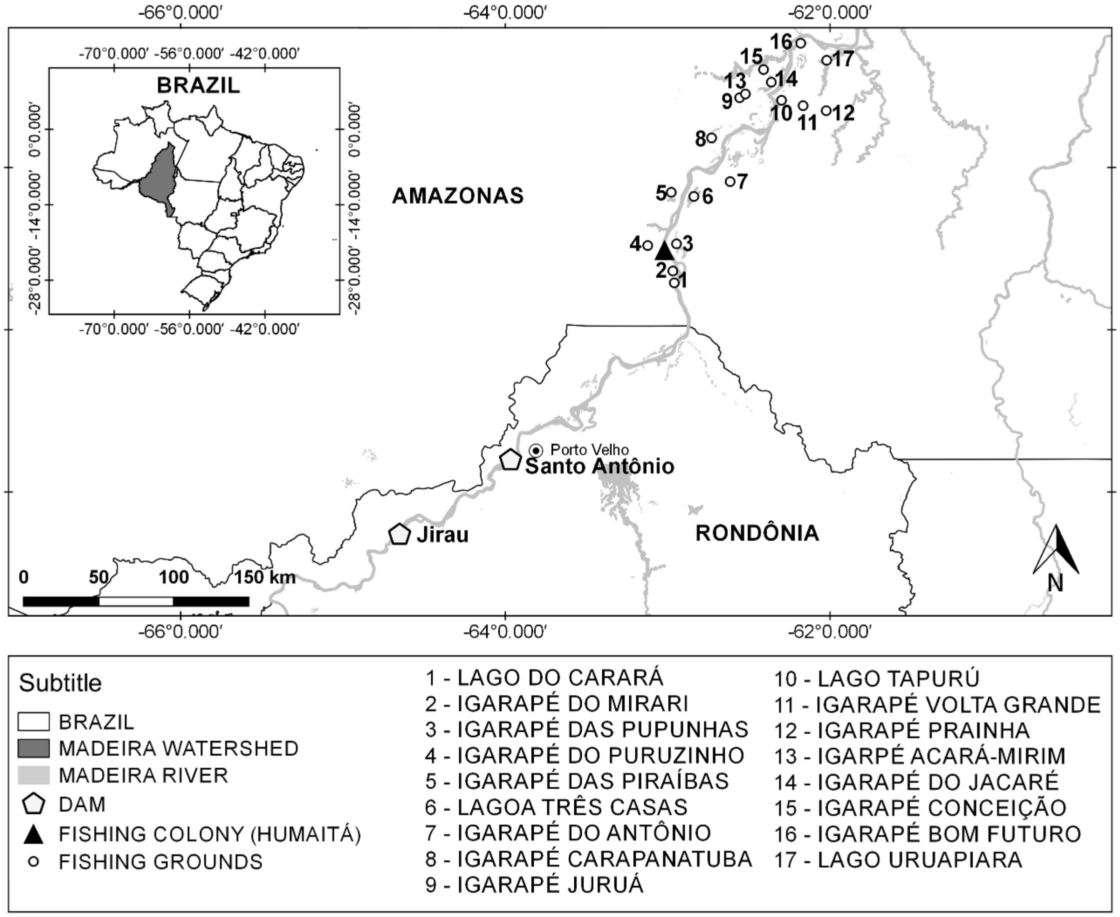

Fig. 1 Fishing grounds of the Z-31 (Dr. Renato Pereira Gonçalves) fishing colony, which operates out of the municipality of Humaitá, in Amazonas State, Brazil, and the location of the Santo Antônio and Jirau dams on the Madeira River in Rondônia State. The catches landed by this fishing colony were obtained at 17 fishing grounds located downstream from the dams.

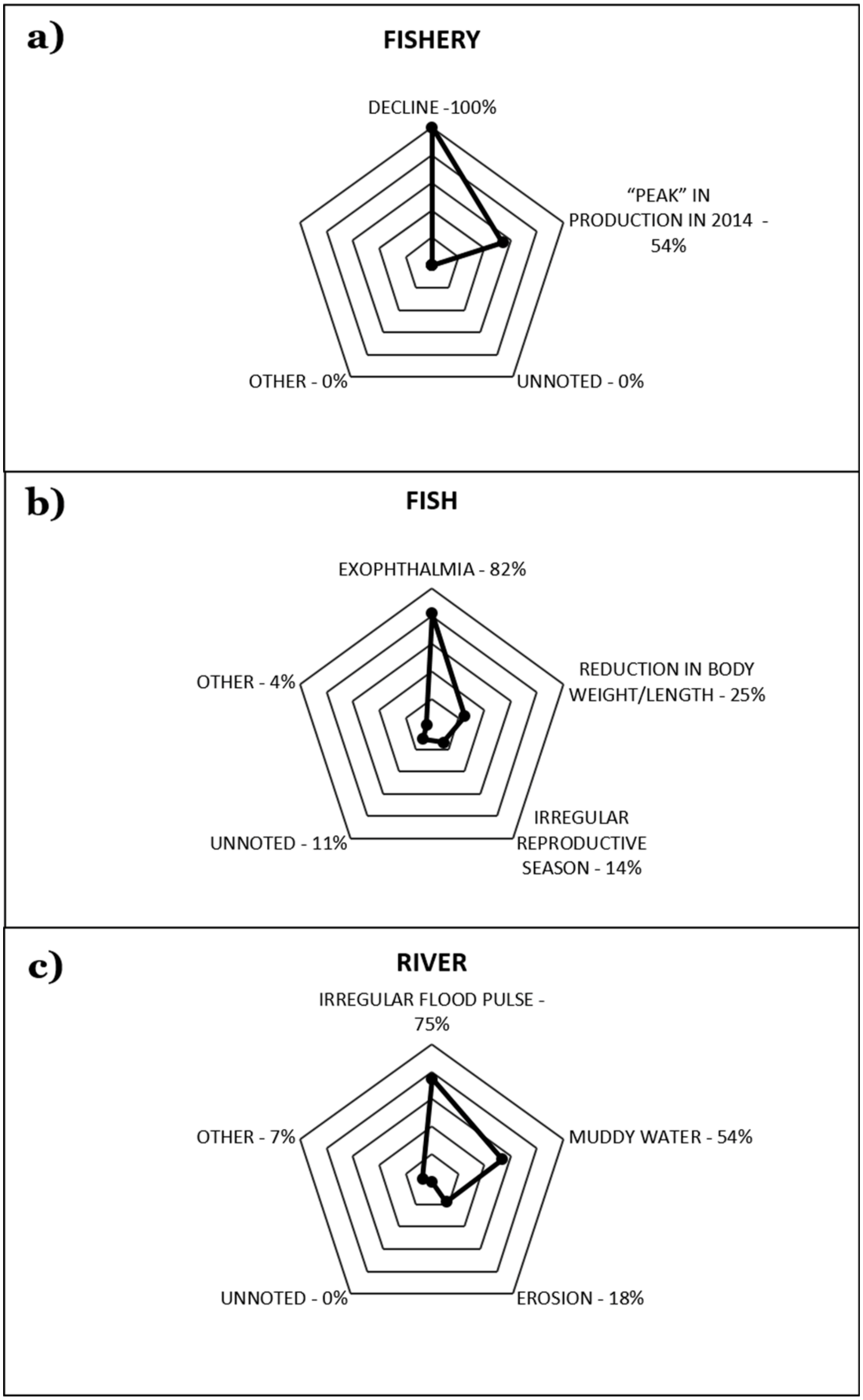

Fig. 2 Relative frequency of citations of the different environmental impacts perceived by the local fishers from the Z-31 fishing colony in Humaitá following the construction of the Madeira River hydroelectric complex: **a** impacts perceived in fisheries; **b** impacts perceived in the fish, and **c** impacts perceived in the river.

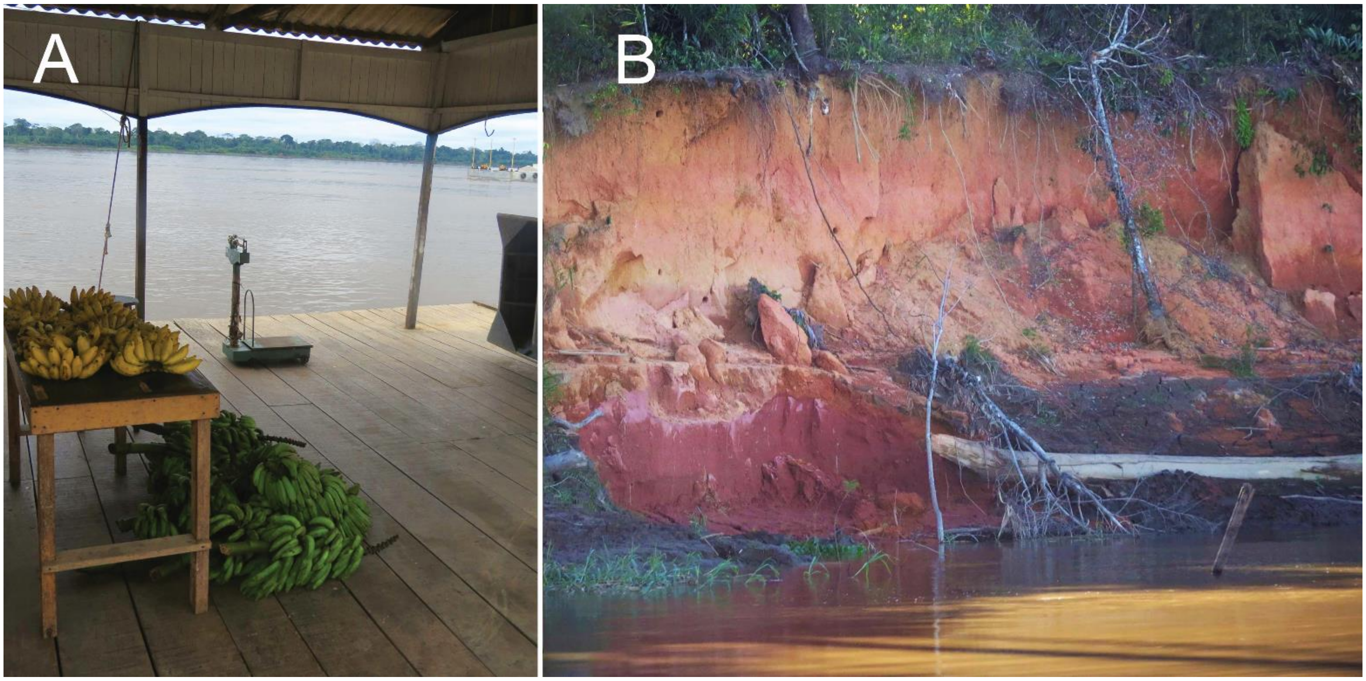

Fig. 3 Environmental impacts generated by the hydroelectric complex in the Madeira River**. a** Floating landing pier at the Z-31 fishing colony in Humaitá at the time of the interviews (July, 2017). Note that on this day, in one of the months that is typically among the most productive in this area, the pier is completely empty. It is also possible to observe sale of bananas by one of the fishers to minimize the fishery financial losses. **b** Erosion of the left margin of the Madeira River in the municipality of Humaitá at the time of the interviews (July, 2017). Note that the soil and some roots are exposed

Table 1 Perceptions of the local fishers interviewed at the Z-31 fishing colony in Humaitá, northern Brazil, with regard to the impacts on local fish and fisheries, and historical data on the fish catch at the fishery colony.

Fish				Impact - Fishery				Impact - Fish						Fish catch				
Common name	Species	Most caught		Decline		"Peak" in production in the flood of 2014		Exophthalmia		Legth/weight		Reproduction		Sum (t)	Monthly mean (kg)		Variation in the monthly mean (kg)	
		Af	Rf (%)	Af	Rf (%)	Af	Rf (%)	Af	Rf (%)	Af	Rf (%)	Af	Rf (%)	Total	Before	After	Av	Rv (%)
Acará	*Astronotus crassipinnis, Aequidens tetramerus, Satanoperca acuticeps*	3	11	0	0	1	4	0	0	0	0	0	0	43	226	300	74	33
Aruanã	*Osteoglossum bicirrhosum*	2	7	1	4	0	0	0	0	0	0	0	0	76	522	294	-228	-44
Babão	*Brachyplatystoma platynemum*	0	0	0	0	0	0	0	0	0	0	0	0	27	121	219	98	81
Bodó	*Hypostomus* sp. *Pseudorinelepis genibarbis*	1	4	0	0	0	0	0	0	0	0	1	4	67	415	340	-75	-18
Branquinha	*Potamorhina latior, P. altamazonica*	7	25	0	0	0	0	0	0	0	0	1	4	378	2905[a]	914	-1991[b]	-69[b]
Curimatã	*Prochilodus nigricans*	22	79*	4	14	2	7	10	36*	3	11*	2	7*	491[a]	3316[a]	2016[a]	-1300	-39
Dourada	*Brachyplatystoma rousseauxii*	2	7	2	7	0	0	1	4	0	0	0	0	69	414	377	-37	-9
Filhote/Piraíba	*Brachyplatystoma filamentosum*	1	4	4	14	0	0	0	0	0	0	0	0	33	195	195	0	0
Jaraqui	*Semaprochilodus insignis, S. taeniurus*	5	18	1	4	1	4	0	0	1	4	0	0	392[a]	2749	1420	-1329	-48
Jatuarana/Matrinxã	*Brycon amazonicus, B. melanopterus, B. falcatus*	8	29	4	14	12	43*	0	0	0	0	0	0	304	2331	737	-1594[b]	-68[b]
Mandi	*Pimelodus* sp.	0	0	0	0	0	0	3	11	1	4	0	0	2	5	21	16	320
Mapará	*Hypophthalmus* spp.	1	4	1	4	1	4	0	0	0	0	0	0	11	89	12	-77	-87[b]
Pacu	*Mylossoma* spp.	22	79*	7	25*	2	7	11	39*	5	18*	2	7*	763[a]	5256[a]	2940[a]	-2316[b]	-44
Piau	*Schizodon fasciatus, Leporinus* spp.	5	18	0	0	0	0	7	25*	2	7	0	0	60	342	368	26	7
Pintado/Surubim	*Pseudoplatystoma* spp.	12	43*	4	14	0	0	0	0	0	0	0	0	214	1175	1369	194	17
Piranha	*Serrasalmus* sp., *Pygocentrus nattereri*	3	11	0	0	0	0	0	0	0	0	0	0	30	147	217	70	47
Pirapitinga	*Piaractus brachypomus*	1	4	2	7	1	4	0	0	0	0	0	0	52	383	150	-233	-61
Pirarara	*Phractocephalus hemioliopterus*	3	11	1	4	0	0	0	0	0	0	0	0	70	387	439	52	13
Sardinha	*Triportheus auritus, T. angulatus*	10	36	4	14	0	0	6	21	0	0	2	7*	127	733	747	14	2
Tambaquí	*Colossoma macropomum*	5	18	4	14	3	11*	0	0	0	0	0	0	138	875	673	-202	-23
Tamoatá	*Hoplosternum littorale*	2	7	1	4	0	0	0	0	0	0	0	0	78	353	631	278	79
Traíra	*Hoplias malabaricus*	0	0	0	0	1	4	0	0	0	0	0	0	19	114	108	-6	-5
Tucunaré	*Cichla* spp.	2	7	1	4	0	0	0	0	0	0	0	0	70	490	253	-237	-48

Af: Absolute frequency, Rf (%): Relative frequency; Av: absolute variation, Rv (%): Relative variation. *fish cited most frequently; [a] fish most caught; [b] most accentuated decline in fishery production.

Tabela 2. Selected comments from the local fishers of the Z-31 fishery cooperative, in the municipality of Humaitá, on the impacts perceived in the fishery, the fish, and the river.

Theme/topic	Comment
Fishery	
Decline	"Since 2012 fishing is more difficult, where we used to catch 200–300 kg of fish per trip, I now catch only 50 kg"
	"After they built the dams, our catches decreased so much, look at this pier, completely empty. I pass my days fixing my nets and selling bananas, to make a little money, because, if I were to depend on fishing, I wouldn't have any money at all."
	"Before they built the dam, I could easily sustain my daughter in the dry season, but now, there are no more fish in the river."
"Peak" in fishery production in the flood of 2014	"During the big flood of 2014, I caught so many fish, that they were beginning to rot."
	"In 2014, I caught so many jatuarana that I had to give them away to my neighbors because no-one wanted to buy them. But afterwards, the fish were even more scarce."
	"Our catches had been declining since 2012, but after the peak in 2014, the fish disappeared completely. I never saw some types of fish again."
Fish	
Exophthalmia	"Right after they built the dam, the pacu and the piau got bug-eyed."
	"In 2017, I began catching fish with enormous eyes, full of pus. When they got trapped in the nets, their eyes dropped out!"
	"I've seen some fish, in particular the sardinha and the curimatã, with bug eyes since 2012. It looks like they've got an eye tumor."
Reduction in the body weight/length	"Before the dam, I always caught nice plump pacu, but now, they're all thin."
	"After the dam, the curimatã and the jaraqui are all small."
Irregular reproduction season	"Now (after the dam) we catch fish with roe in July."
	"The fish is coming with roe now. I saw fish with roe in May"
River	
Irregular flood pulse	"In the old days, the river was more predictable, but now, we don't know when the water will rise or fall. It's difficult to fish now, because the dam controls the river."
	"The river is varying a lot, and the fish have disappeared. Last week, there was a strong variation in water ["repiquete"] and my catch was so small, the only money I received was just enough to pay my crew, there was nothing left for me. I lost almost all the ice I had bought."
	"When the river level begins to fall, we begin to catch a lot of fish. But then they release water from the dam, and the fish disappear. There is no more dry season for us to fish."
Muddy waters	"When the dam releases water, there is this flood ("repiquete"), and the river water gets all muddy."
	"The water is muddier now, and it is so muddy that people have stopped drinking the river water."
Erosion	"We have been having a lot of landslides since they built the dams."
	"The riverbank is collapsing a lot now; some parts of the river have even become wider."

SEMI-STRUCTURED INTERVIEWS

Interviewee data

1- Name:

2- Age:

3- Gender: ( ) Male ( ) Female

4- Community/Neighborhood:

5- How long have you been living in your community/neighborhood?

6- How many years of fishing experience?

7- Is the interviewee affiliated with the fishing colony Z-31?

8- What are your purposes on fishing?

( ) Commercialisation ( ) Own consumption ( ) Recreation

9- Where are the fishing grounds?

10- What are the fishing equipment?

Icebreaker questions

11- How do you feel when you are fishing? Tell me a little about your fishing activity

Fish most caught

11- What are the most caught fish?

Perceived impacts of the dams on local fisheries

12- Have you noticed any unusual changes on Madeira River fishery production (i.e., an increase or decrease) in the last 20 years?

In which year/from which year was this change noted?

What could be some possible causes for these changes?

What fish species have been affected by this change?

Impacts of the dams perceived in the fish

13- Have you noticed any unusual changes in the Madeira River fishes (e.g., their appearance, biology or behavior) in the last 20 years?

In which year/from which year was this change noted?

What could be some possible causes for these changes?

What fish species have been affected by this change?

Impacts of the hydroelectric dams on the river

14- Have you noticed any unusual changes in the Madeira River (tributaries, lakes, margins etc) in the last 20 years?

In which year/from which year was this change noted?

What could be some possible causes for these changes?

Influence of hydroelectric dams

15- Describe in detail the situation of the river, fishes and fishery production in the periods before and after damming. What are the main changes between the two periods?

16- How do you see fishing activity in the future?

Fish checklist

Show the photos of Madeira River fish species to interviewees

17- Which fishes from this list do you recognize? What is their common name?

TERMO DE CONSENTIMENTO LIVRE E ESCLARECIDO

(Elaborado de acordo com a Resolução nº 466/12, do Conselho Nacional de Saúde)

Convido (amos) V.Sa. a participar da pesquisa "Impactos do complexo hidrelétrico do rio Madeira sobre a pesca e os ecossistemas aquáticos amazônicos" sob responsabilidade do pesquisador Rangel Eduardo Santos, que tem por objetivo avaliar a percepção dos pescadores quanto as modificação ambientas recentes ocasionadas pela construção do complexo hidrelétrico do rio Madeira, bem como, compreender como essas mudanças afetaram a produção pesqueira, a cultura local e os fatores socioeconômico dos pescadores artesanais. Para a realização deste trabalho serão utilizados os seguintes métodos: entrevistas, conversas, gravações e fotografias. Esclarecemos ainda que após a conclusão da pesquisa todo material a ela relacionado, de forma gravada, filmada ou equivalente será destruído, não restando nada que venha a comprometer o anonimato de sua participação agora ou futuramente. Quanto aos riscos e desconfortos, o maior risco é o de entrevistado se sentir-se constrangido. Caso você venha a sentir algo dentro desses padrões, comunicar imediatamente ao pesquisador para que se pare imediatamente a pesquisa. Os benefícios esperados com o resultado desta pesquisa são que com base nas informações oferecidas, será possível, no futuro, o desenvolvimento de ações que visem gerir de forma sustentável os estoques pesqueiros do rio Madeira. O (A) senhor (a) terá os seguintes direitos: a garantia de esclarecimento e resposta a qualquer pergunta; a liberdade de abandonar a pesquisa a qualquer momento, sem prejuízo para si ou para seu tratamento (se for o caso); a garantia de privacidade à sua identidade e do sigilo de suas informações. Nos casos de dúvidas e esclarecimentos o (a) senhor (a) deve procurar o pesquisador Rangel Eduardo Santos na Universidade Federal de Minas Gerais, Programa de Pós-Graduação em Ecologia, Conservação e Manejo de Vida Silvestre, Instituto de Ciências Biológica, Av.Antônio Carlos, 6627, Pampulha, Belo Horizonte. E-mail: rangel_es@msn.com, ou pelo telefone (31) 995517725. Caso suas dúvidas não sejam resolvidas pelos pesquisadores ou seus direitos sejam negados, favor recorrer ao Comitê de Ética em Pesquisa da Universidade Federal de Minas Gerais, localizado à Av. Antônio Carlos, 6627, Pampulha, Belo Horizonte- MG, ou pelo telefone (31) 3409-4592, ou através do e-mail coep@prpq.ufmg.br

Consentimento Livre e Esclarecido

Eu____, após ter recebido todos os esclarecimentos e ciente dos meus direitos, concordo em participar desta pesquisa, bem como autorizo a divulgação e a publicação de toda informação por mim transmitida em publicações e eventos de caráter científico. Desta forma, assino este termo, juntamente com o pesquisador, em duas vias de igual teor, ficando uma via sob meu poder e outra em poder do (s) pesquisador (a) (es). Local: Data: ____/____/____

Assinatura do Sujeito (ou responsável) Assinatura do Pesquisador

3 - CONSIDERAÇÕES FINAIS

No presente estudo foram identificados diversos impactos gerados pelas hidrelétricas Santo Antônio e Jirau implantadas no rio Madeira. Tanto os dados de desembarque pesqueiro quanto as entrevistas semiestruturadas evidenciaram o declínio da pesca no rio Madeira, principalmente para as espécies amazônicas de alto valor comercial, como o pacu (*Mylossoma* spp.) e o curimatã (*Prochilodus nigrican*s). É possível concluir que as hidrelétricas estão impactando negativamente a pesca da bacia por duas principais vias de impactos. A primeira está relacionada com os impactos diretos das mudanças ambientais sobre a ictiofauna, como por exemplo, o bloqueio de rotas migratórias que causam diversos impactos sobre a estrutura das populações dos peixes locais. A segunda forma está relacionada com as mudanças ambientais que afetam a dinâmica das atividades pesqueiras, como a alteração da fluviometria, que causou a redução do sucesso de captura dos peixes na região. O banco de dados de desembarque pesqueiro possibilitou ainda estimar um importante impacto econômico para as famílias de pescadores após a implantação das hidrelétricas no rio Madeira. A falta de renda e a insegurança alimentar poderão resultar em marginalização e agravar os conflitos sociais na região.

A percepção dos pescadores locais foi uma ferramenta eficaz para o fornecimento de dados para estratégias de manejo mais efetivas dos ecossistemas impactados por barramentos hidrelétricos na Amazônia. O complexo hidrelétrico do rio Madeira mudou o modo como os pescadores veem e se relacionam com o rio. A percepção dos pescadores locais sobre a atividade pesqueira, por exemplo, já não é mais relacionada com os padrões naturais do rio Madeira, mas com a maneira com que as hidrelétricas controlam as suas cheias. Além das mudanças sobre os ecossistemas aquáticos e atividade de pesca, os pescadores ainda evidenciaram importantes alterações sobre a biologia dos peixes da bacia. É possível afirmar que esses impactos colocam em evidência o alto risco dos empreendimentos hidrelétrico para os serviços ecossistêmicos (i.e pesca), a biodiversidade local bem como para a subsistência das famílias ribeirinhas amazônicas.

A partir desses fatores, é imprescindível que os impactos negativos do desenvolvimento do setor hidrelétrico sejam seriamente considerados tanto no processo de licenciamento ambiental quanto na administração das atividades hidrelétricas após a sua implantação. Para isso, é importante o desenvolvimento de novos planos de gestão para as bacias impactadas por barramentos hidrelétricos na Amazônia. Embora seja consenso de que as hidrelétricas são fontes de diversos impactos ambientais, pouco foi feito para adaptar o gerenciamento ambiental dos ecossistemas amazônicos aos novos ambientes impostos pelas hidrelétricas. Esse é um problema notório para bacia do rio Madeira, que possui o mesmo plano de gestão utilizado antes da construção das hidrelétricas. Impactos sobre o período reprodutivo dos peixes, por exemplo, revelam a necessidade de se reajustar o período de defeso dos peixes da bacia, principalmente para as espécies de grande interesse comercial como o pacu (*Mylossoma* spp.), curimatã (*Prochilodus nigrican*s) e a sardinha (*Triportheus auritus*, *T. angulatus*). A exoftalmia nos peixes ainda demonstra a necessidade de estudos mais aprofundados para avaliar a eficiência do sistema de transposição das UHEs Santo Antonio e Jirau. A presença da exoftalmia nos peixes percebidas pelos pescadores ainda não havia sido registrada na bacia do rio Madeira, demonstrando assim uma informação essencial para futuros planos de gestão dos estoques pesqueiros da região.

Além disso, é extremamente necessário mudar o pensamento sobre a gestão das barragens em bacias hidrográficas brasileiras afetadas pelos empreendimentos hidrelétricos. Em ecossistemas amazônicos barrados, a vazão dos rios poderia ser gerida pelas hidrelétricas não somente visando a geração de energia hídrica, mas também buscando minimizar as grandes oscilações interanuais e diárias da fluviometria. Embora esse tipo de gestão possa diminuir o rendimento energético, ela proporciona um ganho importante dos serviços ambientais.

Por último, é possível concluir que a expansão de hidrelétricas na Amazônia poderá ampliar os impactos destes empreendimentos em toda a extensão da bacia, os quais afetarão uma região de megadiversidade e causarão profundas perdas de serviços ambientais tanto para os ecossistemas neotropicais quanto para o planeta. Além disso diversas espécies ainda não descobertas pela ciência poderão ser extintas nos ecossistemas aquáticos amazônicos. Neste contexto, reduzir o número de empreendimentos hidrelétricos na Amazônia deve ser visto como um sólido investimento econômico, social e ecológico para o futuro. É essencial ainda que pesquisas sejam desenvolvidas com objetivo de minimizar os impactos negativos das hidrelétricas nessa região, assim como possam propor modelos alternativos e mais sustentáveis buscando o equilíbrio entre a geração de energia e os benefícios ecossistêmicos.

3.1 – Recomendações

Medidas emergenciais são recomendadas para prevenir, mitigar ou mesmo compensar de modo justo os impactos dos empreendimentos hidrelétricos tanto na bacia do rio Madeira como em outras bacias situadas na região amazônica.

1- Monitoramento da pesca amazônica através da criação de um banco de dados integrado e *on-line* das principais colônias de pescadores. Esse banco de dados deve conter informações de colônias localizadas tanto na Amazônia legal, quanto em outros países que compartilham a bacia. Esses dados poderão fornecer a real extensão dos impactos do barramento sobre a pesca, bem como apoiar futuras avaliações dos estoques pesqueiros em toda bacia amazônica;

2- Adequação do período de defeso para as espécies de peixes que tiveram a reprodução afetada pelos barramentos hidrelétricos;

3- Estabelecimento de um programa tecnológico para a reprodução e repovoamento dos peixes afetados pelas barragens;

4- Fortalecimento de políticas que visem desenvolver estudos científicos para minorar a razão de perda de serviços ecossistêmicos em relação aos benefícios da geração de energia hídrica;

5- Desenvolvimento de pesquisas tecnológicas que possam propor novas alternativas sustentáveis para compor o modelo energético amazônico;

6- Criação de leis ambientais que obriguem as hidrelétricas a minimizar as grandes oscilações diárias e interanuais da fluviometria do rio Madeira;

7- Criação de programas sociais para diversificar e fortalecer os meios de subsistências das comunidades impactadas por barramentos. Essas iniciativas são fundamentais para minimizarem os problemas socioeconômicos ocasionados pelas hidrelétricas;

8- Desenvolvimento de uma aquicultura sustentável nas regiões mais afetadas pelas UHEs onde provavelmente os impactos observados são irreversíveis. Espécies nativas de interesse comercial como o pacu, curimatã e o tambaqui são exemplos de peixes que poderão compor a produção aquícola sustentável nas regiões mais atingidas.