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Document Version

Final published version

Citation (APA)

Terrazas Villarroel, L. G. (2026). *Ecohydrology of the Beni River-floodplain: Integrating Fishers' Knowledge and Remote Sensing for River Planning and Habitat Conservation*. [Dissertation (TU Delft), Delft University of Technology]. <https://doi.org/10.4233/uuid:963038e9-348c-4757-a591-c6ed24714657>

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Ecohydrology of the Beni River– floodplain:

Integrating Fishers' Knowledge and Remote
Sensing for River Planning and Habitat
Conservation

Lina Gabriela Terrazas Villarroel



**ECOHYDROLOGY OF THE BENI RIVER-FLOODPLAIN:
INTEGRATING FISHERS' KNOWLEDGE AND REMOTE SENSING
FOR RIVER PLANNING AND HABITAT CONSERVATION**

Lina Gabriela Terrazas Villarroel

ECOHYDROLOGY OF THE BENI RIVER-FLOODPLAIN:
INTEGRATING FISHERS' KNOWLEDGE AND REMOTE SENSING
FOR RIVER PLANNING AND HABITAT CONSERVATION

DISSERTATION

for the purpose of obtaining the degree of doctor
at Delft University of Technology
by the authority of the Rector Magnificus Prof.dr.ir. H. Bijl,
chair of the Board for Doctorates
and
in fulfilment of the requirement of the Rector of IHE Delft
Institute for Water Education, Prof.dr. G.P.W. Jewitt,
to be defended in public on
Friday, 23 October 2026 at 15:00 hours

by

Lina Gabriela TERRAZAS VILLARROEL

This dissertation has been approved by the (co)promotors.

Composition of the doctoral committee:

Rector Magnificus TU Delft	chairperson
Rector IHE Delft	vice-chairperson
Prof.dr. M.E. McClain	TU Delft / IHE Delft, promotor
Prof.dr.ir. N.C. van de Giesen	TU Delft, promotor
Dr. J.W. Wenninger	IHE Delft / TU Delft, copromotor
Independent members:	
Prof.dr. T.A. Bogaard	TU Delft
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Dr. E.P. Anderson	Florida International University, USA
Dr. K.B.J. Dunne	TU Delft
Prof.dr.ir. P. van der Zaag	TU Delft / IHE Delft, reserve member

Dr. M. Heredia, Researcher Lecturer, University of San Simón, has significantly contributed towards the supervision of this dissertation.

This research was conducted under the auspices of the Graduate School for Socio-Economic and Natural Sciences of the Environment (SENSE)

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Published by IHE Delft Institute for Water Education
www.un-ihe.org
ISBN 978-90-73445-87-1

To the local communities whose livelihoods remain tied to the fate of the river

ACKNOWLEDGEMENTS

I would like to extend my heartfelt gratitude to every person and institution who contributed to this research.

First and foremost, I acknowledge my supervisory team for their guidance, support, and for creating a constructive environment during this process. I especially thank my main promotor, Prof. Michael McClain, who trusted this project from the beginning, led enriching discussions on ecohydrology, and provided support on multiple aspects. I am also grateful to Assoc. Prof. Jochen Wenninger for contributing through his expertise in hydrology, and for supporting access to complementary funds. My local promotor Dr. Marcelo Heredia has always encouraged me forward and helped to make this work visible in Bolivia. I also thank Prof. Nick van de Giesen for his guidance and feedback at key moments, as well as his support to access complementary funds.

I gratefully acknowledge the Schlumberger Foundation and Faculty for the Future program for providing the main financial support for this PhD. I also thank the World Wide Fund for Nature (WWF) Education for Nature Russell E. Train Fellowship program for supporting the last year in Bolivia. In addition, IHE Delft and the Lamminga Fonds provided valuable support for conference attendance and publications.

Fieldwork was possible thanks to our reliable boat rider Carlos Torres “Pájaro” and his crew, who safely transported me along the river and helped me in many activities. I also appreciate the generosity of every community leader and association representative who shared information. Particularly, I extend my heartfelt gratitude to the fishers who participated in this study, for sharing their time, knowledge, and experiences of the river. Their testimonies provide the conceptual basis for this work, and I hope it contributes to the recognition of their knowledge and respect for their territories.

This work has also received support and collaboration of colleagues and institutions through technical comments from different disciplines. I thank Dr. Arved Schwendel for clarifying geomorphologic process and encouraging me to pursue research in the Beni River. I am also grateful to fish ecologists Dr. Fernando Carvajal and Dr. Paul van Damme for devoting time and attention to commenting my drafts, explaining ideas about fish ecology and, for their willingness to help. I would like to thank my colleagues at IHE Delft and fellow Schlumberger grantees for sharing this experience. Special thanks to Janvière, Balbina, and Ingrid for the many conversations where I found understanding and a sense of familiarity.

Finally, I express my deepest gratitude to my parents and my sister for always encouraging me and being present. I especially thank my grandma, whose support has been essential in my life and will always be remembered.

SUMMARY

River-floodplain systems are one of the most productive types of ecosystems. Their flooding dynamics help sustain diverse aquatic habitats and support the livelihoods of riverine communities. In the Andean–Amazon region, these systems are increasingly threatened by hydropower development and environmental pressures. However, the impact assessment of hydrologic alteration remains limited because understanding about ecohydrology in these systems is insufficient. This thesis addresses this gap by using an integrated approach to characterize ecohydrologic relationships in the Beni River-floodplain in Bolivia. Two complementary sources of knowledge are combined: fishers' knowledge about fish ecology and long-term satellite imagery of oxbow lake dynamics. The identified ecohydrologic relationships are used to evaluate potential impacts of a planned hydropower project on fish ecology and small-scale fisheries.

The analysis of local knowledge is based on semi-structured interviews with fishers. Their testimonies revealed detailed links between hydrologic variability, fish ecology and the fishing practice. Fishers describe how seasonal flooding, connectivity between the main channel and floodplain water bodies, and multiannual variability influence fish migration, feeding behavior, and habitat use. They also relied on hydrologic indicators at multiple spatial and temporal scales to guide fishing practices and anticipate fish availability. This conceptual knowledge provided process-based descriptions and causal links that extend understanding of fish ecology. Moreover, they helped pose new questions about understudied processes.

Remote sensing analysis is focused on the characterization of forty oxbow lakes using long-term satellite imagery. Surface reflectance is used to classify water types and calculate oxbow lake area. Seasonal and multiannual changes in these variables showed that lake dynamics were influenced by hydrologic variability and lake properties such as age and distance from the main channel. In particular, extreme low-flow years revealed notable reductions in lake area. For many lakes, seasonal trends showed higher areas during the rising water period and turbid water types during flooding events. These patterns were interpreted as indicators of overflow from the main channel and hydrologic connectivity. These trends differed among lakes allowing their classification into groups. Lakes that displayed the highest correlation between area change and discharge were interpreted as having the highest level of connectivity with the main channel, while lakes with the lowest correlation are interpreted as having lower connectivity levels. These differentiated connectivity levels determined the availability of the lakes as aquatic habitats for fish, and supported fish migration as described by fishers. Overall, the dynamics and diversity of oxbow lakes highlighted their complex ecological function within the river-floodplain system.

A common spatiotemporal framework is used as the structural basis to integrate the results obtained from these different knowledge sources through shared spatial, temporal, and process-based relationships. The resulting ecohydrologic relationships represented structured links between ecological processes and hydrologic variability. A key process in the system is hydrologic connectivity between oxbow lakes and the main channel, controlling fish migration and enabling the development of their life cycle. To represent this threshold-based connectivity, hydrologic indicators were adjusted to characterize discharge connectivity ranges and assess oxbow lake availability when these thresholds are exceeded. These relationships reflected the spatial heterogeneity and different connectivity levels of oxbow lakes within meandering river-floodplains. Overall, this integrative approach provided an effective framework for defining ecohydrologic relationships and offers a transferable methodology for other dynamic, data-limited systems.

To explore the response of ecohydrologic functions to hydrologic alteration, a proposed hydropower project consisting of a storage dam at the Chepete Strait is simulated using the WEAP (Water Evaluation and Adaptation Planning) model. Two operational scenarios were defined as contrasting boundary conditions. One scenario prioritizes energy generation, while the other represents the most favorable condition for the ecohydrologic functions by aiming to preserve the natural flow regime. The most significant hydrologic alteration was the reduction of peak flows, which occurred even under the ecohydrologically favorable scenario. These results indicated that reservoir operation alone would still limit connectivity to oxbow lakes, reduce habitat availability and disrupt fish migration patterns. Future studies require a comprehensive assessment of multiple environmental and socio-economic impacts to assess integral reservoir operational strategies.

Overall, this thesis demonstrated the value of integrating diverse knowledge sources to advance ecohydrologic understanding in data-scarce regions. The findings highlighted the importance of natural hydrologic variability and connectivity in river-floodplain systems. This approach contributes to participatory water resource management and provides transferable insights for similar river systems.

SAMENVATTING

Rivier-overstromingsvlakten systemen behoren tot de meest productieve ecosystemen. Hun overstromingsdynamiek draagt bij aan het in stand houden van diverse aquatische habitats en ondersteunt het levensonderhoud van riviergemeenschappen. In het Andes-Amazonegebied worden deze systemen in toenemende mate bedreigd door de ontwikkeling van waterkracht en milieudruk. De effectbeoordeling van hydrologische veranderingen blijft echter beperkt, omdat het begrip van de ecohydrologie in deze systemen onvoldoende is. Deze thesis voorziet in deze leemte door gebruik te maken van een geïntegreerde aanpak om de ecohydrologische relaties in de overstromingsvlakte van de Beni-rivier in Bolivia te karakteriseren. Hierbij worden twee complementaire kennisbronnen gecombineerd: de kennis van vissers over de visecologie en langetermijnsatellietbeelden van de dynamiek van hoefijzermere. De geïdentificeerde ecohydrologische relaties worden gebruikt om de potentiële effecten van een gepland waterkrachtproject op de visecologie en de kleinschalige visserij te evalueren.

De analyse van lokale kennis is gebaseerd op semigestructureerde interviews met vissers. Hun getuigenissen leggen gedetailleerde verbanden bloot tussen hydrologische variabiliteit, visecologie en de visserijpraktijk. Vissers beschrijven hoe seizoensgebonden overstromingen, de connectiviteit tussen de hoofdstroomgeul en waterlichamen in de overstromingsvlakte, en meerjarige variabiliteit de vismigratie, het foerageergedrag en het habitatgebruik beïnvloeden. Daarnaast baseerden zij op hydrologische indicatoren op verschillende ruimtelijke en temporele schalen om hun visserijpraktijken te sturen en te anticiperen op de beschikbaarheid van vis. Deze conceptuele kennis leverde processen gebaseerde beschrijvingen en causale verbanden die ons begrip van de visecologie vergroten. Bovendien droegen ze bij aan het formuleren van nieuwe vragen over onderbelichte processen.

De remote sensing-analyse richt zich op het karakteriseren van veertig hoefijzermere met behulp van langetermijnsatellietbeelden. Oppervlaktereflectantie is gebruikt om watertypen te classificeren en het oppervlak van de hoefijzermere te berekenen. Seizoensgebonden en meerjarige veranderingen in deze variabelen toonden aan dat de meerdynamiek werd beïnvloed door hydrologische variabiliteit en meerkenmerken, zoals ouderdom en de afstand tot de hoofdstroomgeul. Met name jaren met extreem lage afvoer lieten een aanzienlijke afname van het meeroppervlak zien. Voor veel meren toonden seizoensgebonden trends grotere oppervlakken tijdens de periode van stijgend water en troebele watertypen tijdens overstromingen. Deze patronen werden geïnterpreteerd als indicatoren van overstroming vanuit de hoofdgeul en van hydrologische connectiviteit. Deze trends verschilden per meer, waardoor ze in groepen

kunnen worden ingedeeld. Meren met de sterkste correlatie tussen oppervlakteverandering en rivierafvoer werden beschouwd als meren met de hoogste mate van connectiviteit met de hoofdgeul, terwijl meren met de laagste correlatie worden geïnterpreteerd als meren met een lager connectiviteitsniveau. Deze gedifferentieerde connectiviteitsniveaus bepaalden de beschikbaarheid van de meren als aquatische habitats voor vissen en ondersteunden de vismigratie zoals beschreven door de vissers. Over het algemeen onderstreepten de dynamiek en de diversiteit van hoefijzmeren hun complexe ecologische functie binnen het rivier-overstromingsvlaktesysteem.

Een gemeenschappelijk ruimtelijk-temporeel kader dient als structurele basis om de resultaten van deze verschillende kennisbronnen te integreren via gedeelde ruimtelijke, temporele en procesgebaseerde relaties. De resulterende ecohydrologische relaties vormen gestructureerde verbanden tussen ecologische processen en hydrologische variabiliteit. Een sleutelproces in het systeem is de hydrologische connectiviteit tussen hoefijzmeren en de hoofdstroomgeul, die de vismigratie reguleert en de voltooiing van hun levenscyclus mogelijk maakt. Om deze op drempelwaarden gebaseerde connectiviteit weer te geven, werden hydrologische indicatoren aangepast om de bereiken van afvoerconnectiviteit te karakteriseren en de beschikbaarheid van hoefijzmeren te beoordelen wanneer deze drempelwaarden worden overschreden. Deze relaties weerspiegelen de ruimtelijke heterogeniteit en de verschillende connectiviteitsniveaus van hoefijzmeren binnen meanderende rivier-overstromingsvlaktes. Over het algemeen biedt deze integratieve benadering een effectief raamwerk voor het definiëren van ecohydrologische relaties en levert het een overdraagbare methodologie op voor andere dynamische, dataschaarse systemen.

Om de respons van ecohydrologische functies op hydrologische veranderingen te onderzoeken, is een voorgesteld waterkrachtproject – bestaande uit een stuwdam in de Chepete-kloof – gesimuleerd met behulp van het WEAP-model (Water Evaluation and Adaptation Planning). Hierbij zijn twee operationele scenario's gedefinieerd als contrasterende randvoorwaarden. In één scenario krijgt energieopwekking prioriteit, terwijl het andere de meest gunstige conditie voor de ecohydrologische functies vertegenwoordigt door te streven naar het behoud van het natuurlijke afvoerregime. De meest significante hydrologische verandering was de afname van piekafvoeren, die zelfs onder het ecohydrologisch gunstige scenario optrad. Deze resultaten wezen uit dat het reservoirbeheer op zichzelf de connectiviteit met hoefijzmeren nog steeds zou beperken, de beschikbaarheid van habitats zou verminderen en vismigratiepatronen zou verstoren. Toekomstige studies vereisen een alomvattende evaluatie van meerdere ecologische en sociaaleconomische effecten om integrale operationele strategieën voor het stuwmeer te beoordelen.

Samenvattend toonde dit proefschrift de waarde aan van het integreren van diverse kennisbronnen om het ecohydrologische begrip in dataschaarse regio's te vergroten. De bevindingen onderstrepen het belang van natuurlijke hydrologische variabiliteit en connectiviteit in rivier-overstromingsvlaktesystemen. Deze benadering draagt bij aan participatief waterbeheer en biedt overdraagbare inzichten voor vergelijkbare riviersystemen.

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1

INTRODUCTION

1.1 BACKGROUND

Large river-floodplain systems are fundamental components of the global environment and essential resources for riverine communities. Their ability to transport vast volumes of water and sediment makes them integral to global hydrologic and biogeochemical cycles (Thoms and Sheldon, 2019). These floodplains are also hot-spots of exceptional biodiversity and productivity, supporting ecosystems that provide key services such as habitat provision, nutrient cycling, and fisheries (Ashworth and Lewin, 2012; Erős et al., 2019; Sparks, 1995). In such systems, the natural flow regime and its seasonal flood pulse are the primary drivers of ecological processes, influencing species presence, productivity, and interactions (Bayley, 1995; Junk et al., 1989, 2020). Floodplains support a wide variety of aquatic habitats that interact dynamically through hydrologic connectivity (Ahmad et al., 2025; Pettit et al., 2017; Ward and Stanford, 1995; Winemiller et al., 2016). Fish rely on this connectivity to migrate, feed, and reproduce, which in turn supports small-scale fisheries (Fullerton et al., 2010; Hurd et al., 2016; Puckridge et al., 1998). For remote riverine communities, these fisheries are the main source of food security and income (Begossi et al., 2019; Hallwass et al., 2020; Mikkola, 2024).

Ecohydrology investigates the interactions between hydrologic processes and ecological responses, helping explain how river systems support biodiversity and ecosystem services (Acreman et al., 2014; Wood et al., 2008; Zalewski, 1998). Key concepts include the natural flow regime, the flood pulse, and hydrologic connectivity. The natural flow regime describes the characteristic flow pattern in an unaltered river, and it is defined by components such as magnitude, frequency, duration, timing, and rate of change (Poff et al., 1997; Richter et al., 1996). These components represent ecological conditions to which species have adapted to preserve healthy ecosystems. In river-floodplains, the flood pulse represents the seasonal flooding pattern that structures aquatic habitat. It can be characterized by ecologically relevant descriptors such as predictability, frequency, and amplitude (Junk et al., 1989; Junk and Wantzen, 2004).

Connectivity among floodplain water bodies controls the exchange of water and sediment, and the interplay between both hydrologic and geomorphologic connectivity determines the status of water bodies as lentic or lotic aquatic habitats (Lewin and Ashworth, 2014). Hydrologic connectivity patterns between water bodies influence fish migration, reproduction, habitat access, and survival, making hydrologic variability a key driver of aquatic ecosystem dynamics (Puckridge et al., 1998).

Andean–Amazon tributaries are among the most biologically and ecologically significant river systems in the world (Melack et al., 2009; Ribas et al., 2025). These rivers cover wide climatic gradients and support diverse floodplain environments, which can be classified based on water quality, flood pulse dynamics, aquatic-terrestrial transitions, and vegetation patterns (Junk et al., 2011a, 2012). In particular, white-water rivers are sustained by nutrient-rich sediments originating in the Andes, which are transported downstream and deposited in extensive floodplains (McClain and Naiman, 2008; Meade, 2007; Melack and Forsberg, 2001). These processes create highly productive ecosystems that support a notable diversity of fish species. Many of these species rely on both longitudinal and lateral connectivity to migrate between habitats for spawning, feeding, and refuge (Caldas et al., 2023; Duponchelle et al., 2021; Sousa et al., 2017). Furthermore, Indigenous and riverine communities have historically depended on these systems for subsistence, with their territories and cultural practices closely linked to the seasonal dynamics of the rivers (Athayde et al., 2025; Sirén and Valbo-Jørgensen, 2022; Victoria-Lacy et al., 2025).

Amazon River-floodplains and habitats are increasingly affected by degradation and fragmentation caused by multiple pressures (Goulding et al., 2019; Tognelli et al., 2019). Deforestation and climate change alter the water balance of the basin and intensify extreme hydrologic events (Anderson et al., 2011; Marengo et al., 2024; Oberdorff et al., 2015). Among these pressures, the construction of large dams stands out as one of the most significant threats to riverine ecosystems (Anderson et al., 2018; Latrubesse et al., 2017; Winemiller et al., 2016). Storage dams alter natural flow regimes by reducing seasonal variability, shortening flood durations, and decreasing the frequency of large floods (Chaudhari and Pokhrel, 2022; Timpe and Kaplan, 2017). These alterations have severe impacts on fish ecology, including blocked migration routes, reduced floodplain habitat availability, and disruption of hydrologic cues synchronized with key life stages (Bunn and Arthington, 2002; Wu et al., 2019). As a result, fisheries decline, affecting the livelihoods and food security of riverine communities (Castro-Diaz et al., 2024; Doria et al., 2018).

Despite the ecological importance of Amazon habitats and the growing pressures they face, understanding of ecohydrologic processes in these systems remains limited. Data scarcity in remote regions restricts the availability of long-term hydrologic and ecological information needed for sustainable planning and impact evaluation. In

addition, commonly used methods to assess hydrologic alterations may fail to represent key processes in dynamic river-floodplains. In this context, alternative sources of information emerge as valuable opportunities to address data gaps. Remote sensing and long-term satellite image datasets allow the characterization of aquatic habitats and temporal dynamics (Mutanga and Kumar, 2019; Sogno et al., 2022). In rivers with high sediment content, surface reflectance can also help understand connectivity and water quality processes (Fassoni-Andrade and Paiva, 2019; Rudorff et al., 2018). At the same time, local ecological knowledge reveals detailed, long-term observations of environmental dynamics and resource use (Jackson et al., 2014; Stephenson et al., 2016). Integrating these complementary knowledge sources can improve the representation of ecohydrologic processes and support management measures suitable to the local context and communities.

1.2 PROBLEM STATEMENT AND MOTIVATION

This study focuses on the Beni River, one of the three largest Andean–Amazon tributaries of the Madeira River. It is characterized by a highly dynamic meandering pattern, strong discharge variability, and high sediment loads. The river flows through Indigenous and riverine communities whose livelihoods largely depend on small-scale fisheries (Bénéfice et al., 2010; CIPTA and WCS, 2010; Luna-Monrroy et al., 2008; Townsend, 2017). One of the most important pressures in this system is a planned hydropower project upstream (Chepete Strait). Potential hydrologic alterations caused by this project may affect floodplain ecosystem processes and food security for river communities.

Previous research in the Beni River basin is limited in space and interdisciplinarity. Studies on fish ecology have primarily focused on species inventories, identification of spawning areas, and correlations with environmental variables (Mariac et al., 2022; Miranda-Chumacero et al., 2015, 2020; Pouilly et al., 2006). Floodplain dynamics have been analyzed mainly from a geomorphological perspective, emphasizing sediment transport and deposition processes along river banks and oxbow lakes (Aalto and Nitttrouer, 2012; Gautier et al., 2007, 2010; Schwendel et al., 2018, 2015). A few regional participatory studies have described fish catches through surveys at Rurrenabaque and nearby landing sites (Argote et al., 2014; Carvajal-Vallejos et al., 2011; Coca-Méndez et al., 2012; Espinoza-Antezana and Van Damme, 2020). However, no studies have addressed the underlying ecohydrologic processes that influence fish availability for fishers in time and space and their habitat use.

As a result, ecohydrologic relationships in the study area are poorly understood. There is limited published and systematic knowledge of how hydrologic variability influences specific species' life stages, how connectivity determines the use of oxbow lakes, or

how these habitats evolve over time in relation to flow variability. Existing hydrologic indicators do not reflect the complex and threshold-based connectivity processes of oxbow lakes. In addition, available data have low spatial resolution and were not collected recently. For instance, long-term hydrologic records are available on a single gauging station along a 500 km reach, and ecological data were obtained at different locations and times. These limitations stress the need for an integral and context-specific approach to study ecohydrologic processes in the Beni River.

A preliminary study of the planned hydropower storage dam at the Chepete Strait has raised concerns about the limited assessment of environmental impacts. That study suggests a minimum flow release of 10% of the mean annual discharge, equivalent to 160 m³/s (Geodata, 2016). Similar assessments are common in data-scarce regions, where environmental flows are estimated using simplified hydrologic methods developed for small single-channel river systems. As a result, impact evaluations misrepresent the ecohydrology of large river-floodplain systems. In addition, an integral study conducted by the University of San Andrés highlighted the limited consideration of impacts downstream of the dam (Comisión Universidad Mayor de San Andrés, 2019). Deficient impact assessment at the planning stage can lead to poor decision-making, inadequate infrastructure design, and insufficient mitigation measures.

Dams can considerably alter the hydrologic and ecological processes that sustain connectivity and aquatic ecosystems in the Amazon. In the Brazilian Amazon, hydrologic alterations caused by dams are evident in the frequency, duration, and rate of change of high- and low-water conditions (Timpe and Kaplan, 2017). Large dams in the Xingu, Madeira and Tocantis subbasins have led to altered downstream flow amplitude by up to 3 orders of magnitude, and future dams could lead to a 10% reduction in flood duration in parts of the Amazon mainstem (Chaudhari and Pokhrel, 2022). At the basin scale, dams have caused important losses of longitudinal connectivity (50-70%), particularly in the Madeira and Marañón basins (Anderson et al., 2025). This is concerning for long-distance migratory fishes, whose migrations are closely associated with seasonal hydrologic conditions (Herrera-R et al., 2024). Thus, maintaining freshwater connectivity corridors such as the Beni River is vital (Caldas et al., 2023).

Along the Madeira River, the effects of the run-of-river Santo Antônio and Jirau dams extend from riverine livelihoods to fish communities and ecological processes. Fishers have reported changes in the river level, an 84% decline in fish catch and a 64% decrease in fishing income after dam construction (Clarke et al., 2026). These impacts are also reflected in notable declines in regional fish migration upstream and downstream (52% and 86%) of key landing ports (de Souza et al., 2025). Also, the functional composition of fishery yields changed, with large and long-distance migratory species among the most affected (Arantes et al., 2022). Species dependent on fast-flowing habitats, structural complexity, flood pulses, or connectivity to complete

their life cycles are also considered more vulnerable to dam impacts (Arantes et al., 2019). These impacts emphasize the consequences of connectivity loss on fish ecology and fisheries in the Amazon.

Beyond hydropower development, the capacity to assess impacts from other pressures on fish ecology and fisheries is also limited. Climate change is expected to intensify extreme events, leading to more frequent and intense droughts and floods. An insufficient understanding of river-floodplain ecohydrology hinders the appropriate prediction of impacts on habitat availability. Similarly, fisheries management strategies require knowledge of ecological responses to hydrologic conditions, habitat preferences, and seasonal dynamics. These limitations halt efforts to adapt fisheries management to environmental change.

The motivation behind this research is the need to improve understanding of ecohydrologic processes in river-floodplain systems under environmental pressures. In the Beni River, low data availability restricts the impact assessment of pressures, and existing hydrologic indicators do not properly represent meandering river-floodplain processes. To address these limitations, this study integrates local ecological knowledge from fishers with remote sensing analyses of floodplain habitats. By combining these sources of information within a spatiotemporal framework, this research aims to identify context-specific ecohydrologic relationships and propose adjusted indicators that better reflect the dynamics of aquatic habitats.

The author's background as a Bolivian engineer specialized in water resources provides personal knowledge of the Beni River context, and professional expertise in hydrology and water-resource planning. This is an independent study intended to provide information relevant to the planning and environmental impact assessment of the proposed dam. This positioning shaped the focus of the research on understanding how natural hydrologic variability may affect relevant ecosystem services. The main audiences include electricity-sector planners, environmental and fisheries institutions, and researchers in ecology and hydrology. Given the early planning stage of the project and preliminary available information, the hydropower scenarios were developed independently for this study as reference boundary conditions, instead of potential operating strategies.

1.3 RESEARCH OBJECTIVES AND QUESTIONS

The main objective of this thesis is to understand and characterize ecohydrologic relationships in the Beni River-floodplain, and to evaluate how potential hydrologic alteration may affect key ecological functions linked to fish and fisheries.

The specific objectives are:

- SO1: Assess the influence of hydrologic variability on fish ecology and fishing practices of Indigenous and riverine communities through the analysis of local knowledge.
- SO2: Characterize the spatiotemporal dynamics of oxbow lakes using remote sensing and evaluate how hydrologic variability influences their connectivity and role as aquatic habitats.
- SO3: Integrate local knowledge and remote sensing analyses to define ecohydrologic relationships and identify hydrologic indicators that represent these processes.
- SO4: Simulate a proposed hydropower project to evaluate contrasting hydrologic alteration levels under two operational scenarios and assess the impacts on ecohydrologic functions.

This thesis addresses the following research questions:

- How does hydrologic variability influence fish ecology and fishing practices in the Beni River-floodplain?
- How do oxbow lake dynamics relate to hydrologic variability and connectivity with the main channel?
- Which hydrologic indicators represent key ecohydrologic processes in a meandering river-floodplain system?
- How would hydropower development alter hydrologic variability and affect fish ecology functions and fisheries?

1.4 THESIS OUTLINE

This thesis is organized into six chapters. Chapter 1 provides the theoretical background, presents the problem statement, and defines the research objectives and questions addressed in this study. Chapter 2 describes the study area and the main environmental and social-ecological aspects of the Beni River. Chapter 3 identifies key fish ecological functions and their link with hydrology through the analysis of fishers' knowledge. Chapter 4 presents a long-term remote sensing analysis of the spatiotemporal dynamics of forty oxbow lakes along a 250 km reach of the Beni River. Chapter 5 integrates local knowledge and remote sensing insights to define ecohydrologic relationships and representative hydrologic indicators. It also explores potential hydrologic alterations by simulating the planned Chepete Dam. Finally, Chapter 6 synthesizes the main findings, discusses their implications, and presents recommendations for future research and river management.

2

THE BENI RIVER-FLOODPLAIN SYSTEM

This chapter introduces the Beni River as the study area, detailing the environmental and social-ecological aspects considered for the analyses. It describes the main climatic, hydrologic, and geomorphologic characteristics of the river-floodplain system, as well as the ecological features that support its high biodiversity. In addition, the chapter presents the importance of fisheries for Indigenous and non-Indigenous communities and introduces the planned hydropower project as one of the main pressures affecting the system. This context represents the basis for the following chapters, which focus on ecohydrologic processes and their implications for river management.

The meandering Beni River originates in the Eastern Andes and flows 840 km through Bolivia's lowlands to its confluence with the Madre de Dios River. As such, it represents the downstream endpoint of a tropical montane river system (Encalada et al., 2019). The analysis presented in Chapter 3 and Chapter 4 covers a 250 km reach downstream of the town of Rurrenabaque (see Figure 2.1). This town is the location of a hydrometric station with long-term data, and the primary fish landing site concentrating small-scale production. Upstream of Rurrenabaque, there is a planned hydropower project that includes a storage dam at the Chepete Strait, which is simulated in Chapter 5.

2.1 HYDROCLIMATE AND GEOMORPHOLOGY

The climate in the region presents a marked seasonal pattern, with the rainy period from November to March and the dry period from June to September. Significant moisture flux from the Atlantic and Amazon rainforest is retained by Andean orography, creating rainfall hotspots (Espinoza et al., 2015, 2020; Molina et al., 2019). This pattern results in highly variable discharge at the piedmont station of Rurrenabaque. At this station, the mean annual value is 2000 m³/s, and the mean monthly discharges vary from 760 m³/s in August to 4700 m³/s in February. A regional hydroclimatic analysis emphasized the high interannual variability, frequent peaks, and low flows that reflect the rapid response of steep sub-basins (Molina-Carpio et al., 2017; Siddiqui et al., 2021). This study indicates that several floods are linked to La Niña conditions with no long-term negative trends during the wet period, in contrast to lowland basins. Additionally, there is an intensification of the dry period associated with shifts in rainfall timing. Among other relevant climatic variables, mean monthly wind speed decreases from January to June (6 to 4 km/h) and increases from July to December (up to 8.3 km/h with the maximum from September).

The Beni River is notable for its high sediment load, with an estimated mean suspended load of 200 million tons/year at the Rurrenabaque station (Vauchel et al., 2017). This transport is associated with high rates of channel migration and meander cutoffs, ranked among the highest of Amazon tributaries (Constantine et al., 2014). Spatial variability of channel migration is mainly influenced by bank heterogeneity, with clay-rich banks acting as hinge points and sandy banks migrating actively (Schwendel et al., 2015). Hydrologic controls on meandering dynamics include the intensity and duration of bankfull flows, which influence erosion and deposition rates (Gautier et al., 2007).

Oxbow lakes formed after meander cutoffs serve as aquatic habitats and sediment basins, and their use increases with greater proximity and connectivity to the main channel. Their life stages depend on the connection channel's capacity to allow overflow and return flow. Sediment deposition in lakes is influenced by the distance from the main

channel and the connectivity angle (Schwendel et al., 2018). Field measurements in one oxbow lake revealed higher sedimentation linked to overflow duration, local rain influence, local erosion, and wind-driven sediment resuspension (Gautier et al., 2010).

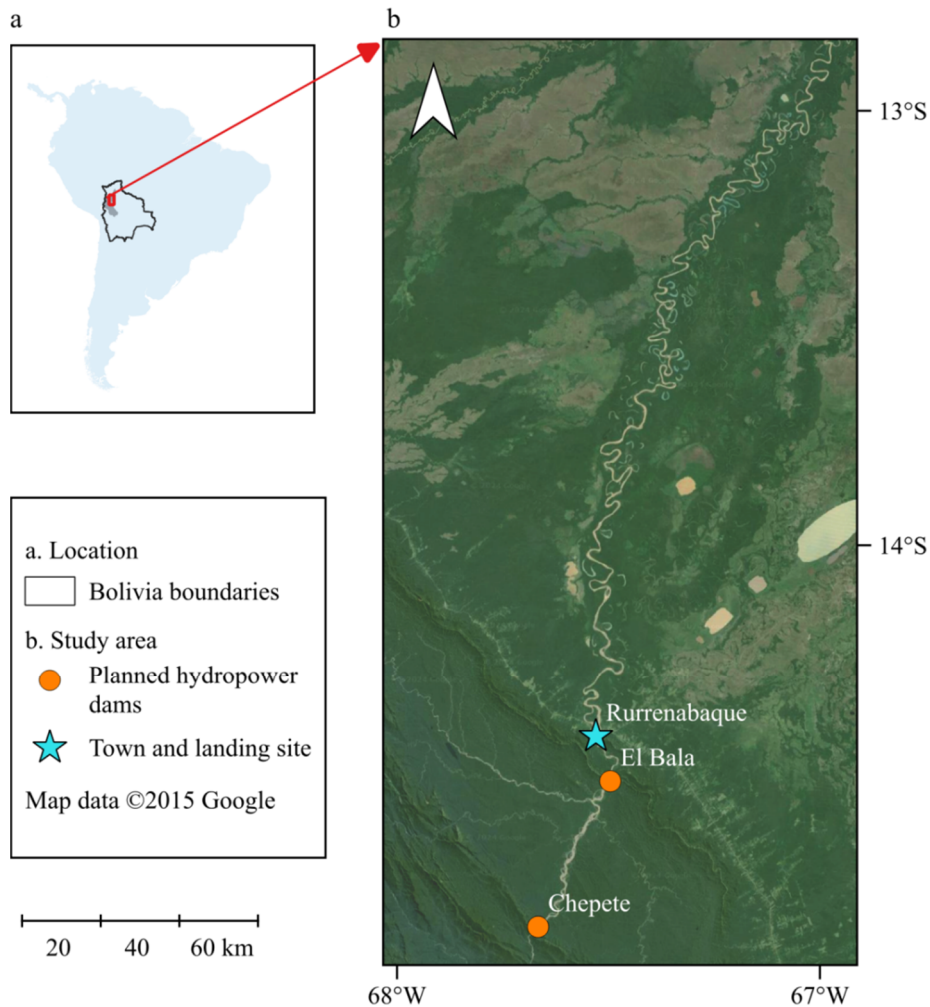


Figure 2.1. a) Location of the study area within South America, b) Satellite image of the Beni River indicating: the area upstream showing the location of planned hydropower dams and the study reach (downstream Rurrenabaque) Map data ©2015 Google

2.2 FISH ECOLOGY AND VEGETATION

The Beni River-floodplain provides essential habitat for fish. In one of the recent inventories of Amazonian fish biodiversity, the Beni basin stands out with 435 verified species (Jézéquel et al., 2020). Recent studies have used metabarcoding approaches upstream and downstream of Rurrenabaque, showing differences in fish compositions between streams and lakes (Mariac et al., 2022). Other studies have identified spawning areas for at least 11 fish species (Miranda-Chumacero et al., 2020). A species-specific

study documented an upstream migration event of juvenile catfish of the genus *Trichomycterus* through a participatory approach involving Indigenous Tacana I observers (Miranda-Chumacero et al., 2015). Previous research has also characterized the distribution and diet of 28 fish species upstream of Rurrenabaque (Pouilly et al., 2006). Although similar studies are available in adjacent basins, comparisons should consider key differences in sediment transport and physicochemical properties that influence fish ecology (Carvajal-Vallejos et al., 2011; Villafán et al., 2020).

Migratory patterns of typical species correspond to the medium-distance, large-bodied group (Duponchelle et al., 2021). *Zungaro zungaro* (bagre) migrates upstream during rising waters for feeding, *Pseudoplatystoma* spp. (pintao, chuncuina) undertake upstream reproductive migrations, and *Piaractus brachipomus* (tambaquí) migrates laterally for feeding and downstream for spawning (Herrera-R et al., 2024).

Non-native species such as *Arapaima gigas* (paiche) have been spotted in the study reach. This species was accidentally introduced before the 1980s from Perú into the Bolivian Madre de Dios basin. Since that time, it has expanded upstream into the Beni floodplain (Miranda-Chumacero et al., 2012; Van Damme et al., 2015). Their migration pattern is classified as a short-distance resident species (Duponchelle et al., 2021).

Riparian vegetation in the Beni River-floodplain is mainly formed by flooded savanna forests that vary with flood duration and soil type (Junk et al., 2011b; Navarro, 2011; Navarro and Maldonado, 2002). Tree species exhibit morphological adaptations that influence seed production, establishment, and survival (Parolin et al., 2016). Fruits and seeds from these species are key food sources for frugivorous fish, which play an important role in seed dispersal. Several studies have described the dietary preferences of key species such as *Colossoma macropomum* (pacú) in the Bolivian Amazon (Maldonado, 2004; Pouilly et al., 2004; Rejas, 2018).

2.3 FISHING PRACTICE AND LIVELIHOODS

Along the study reach downstream of Rurrenabaque, fishing is practiced for both commercial and subsistence purposes by Indigenous and non-Indigenous communities (see Figure 2.2). Fishers include residents of Rurrenabaque, Indigenous Tacana communities from TCO Tacana I (La Paz, represented by Consejo Indígena del Pueblo Tacana CIPTA) and TCO Tacana III (Beni, represented by Organización de Comunidades Indígenas Tacana de Ballivián OCITB), Esse Ejja families, and non-Indigenous riverine communities (unknown ethnicity). Commercial fleets operating further downstream land their catches in Riberalta (~500 km downstream).

More Indigenous territories exist upstream of Rurrenabaque, including the territory of Pueblo Indígena de San José de Uchupiamonas (PI-SJU), but these areas are outside the study's reach and were not included in the analysis.

Rurrenabaque, a town of approximately 21000 inhabitants, is the main commercial fishing port and economic center of the region. Livelihoods depend on commerce, agriculture, livestock, fishing, forestry, and tourism (Instituto Nacional de Estadística, 2025). The ethnicities in Rurrenabaque include white, mestizo, and migrants from the Indigenous highlands (Lopez-Pila, 2014). Most fish catches (80–90%) are sold locally or transported to major cities. Annual landings were estimated at 142 tons in 2008 and approximately 209 tons in 2015. Key species include *Zungaro zungaro*, *Pseudoplatystoma tigrinum*, and *Piaractus brachypomus*, locally known as bagre, surubí, and tambaquí (Espinoza-Antezana and Van Damme, 2020; Van Damme et al., 2011).

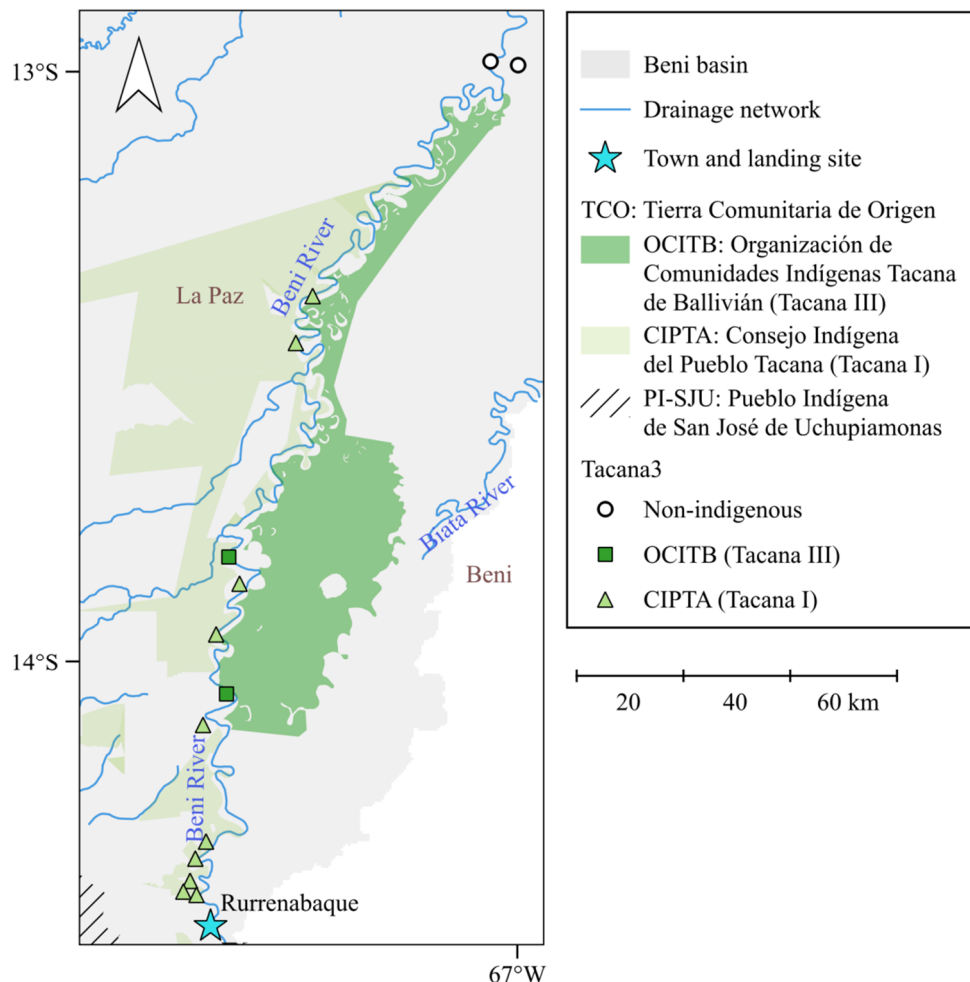


Figure 2.2. Study reach of the Beni River (downstream of Rurrenabaque), indicating Indigenous territories and the location of communities

TCO Tacana I communities have a strong organizational capacity and collaborate with various Non-Governmental Organizations. Their livelihoods depend on fishing, hunting, agriculture, and forest resources (Bauer et al., 2018). A self-monitoring study about the fishing practice of six communities in 2008 estimated approximately 20 tons/year of fish catch, with 65% sold commercially, and the same key species as Rurrenabaque (CIPTA and WCS, 2010). The importance of fisheries increased after an extreme flood in 2014, which destroyed agricultural fields and game resources, but increased fish abundance and supported food security (Townsend, 2017).

The Esse Ejja families are primarily nomadic. While they have small settlements, they have no officially recognized territory. Their livelihoods rely heavily on fishing for subsistence and small-scale commerce (Bénéfice et al., 2010; Tschirhart, 2011).

Information on Indigenous TCO Tacana III communities is scarce, with little documentation on organization or fishing practices. Similarly, there are no studies about the non-Indigenous communities further downstream.

Fishing techniques in the region include different types of nets (malla, tarrafa) used in all water bodies, hook-and-line methods (espinel, lineada) for large species in lentic water bodies, and spears for migratory fish. Subsistence fishing is mainly carried out in small motorized canoes with a capacity of 200 to 500 kg, while commercial fishers use larger boats (cascos) with a storage capacity of 1000 to 2000 kg (Alviz Costa, 2006; Van Damme et al., 2011).

2.4 PLANNED HYDROPOWER DEVELOPMENT

A planned hydropower project in the stage of Final Design poses a significant risk of alteration in the Beni River system. This project consists of a storage dam located in the Chepete Strait and a run-of-river dam in El Bala Strait, as illustrated in Figure 2.1. According to Preliminary Stage documents (Geodata, 2016), the run-of-river dam was evaluated as unfeasible and is not part of the simulation in this study. The Chepete Dam is located 65 km upstream of Rurrenabaque, where the mean annual discharge is estimated as 1600 m³/s. The storage volume at full capacity is 31.4 km³, equivalent to 62% of the mean annual discharge at Chepete. This preliminary document suggests a minimum flow release of 10% of the mean annual discharge (160 m³/s). A report about potential multiple impacts of the dam concludes there is a limited consideration of impacts downstream on the environment and the livelihoods of local communities (Comisión Universidad Mayor de San Andrés, 2019).

3

LOCAL FISHERS' KNOWLEDGE

This chapter addresses SO1 by assessing how natural hydrologic variability influences fish ecology and fishing practices of riverine communities along the Beni River. To this end, this chapter studies the local knowledge of fishers based on the qualitative analysis of 28 semi-structured interviews¹. In their testimonies, fishers described how hydrologic variability, connectivity, and flooding dynamics influence fish migration, habitat use, and fishing practices. Also, fishers' observations highlighted the importance of hydrologic indicators to predict fish availability and guide fishing decisions. Within the broader structure of the thesis, this chapter establishes the essential ecological functions and their relevance for the fisheries and riverine communities. This knowledge is later integrated with remote sensing analyses of floodplain habitats to define ecohydrologic relationships and assess the potential impacts of dam scenarios.

¹ This chapter is adapted from: Terrazas-Villarroel, L.G., Wenninger, J., Heredia-Gómez, M., van de Giesen, N., McClain, M.E., 2026. Exploring ecohydrology through the lens of local fishers in the Bolivian Amazon, *Ecosphere*, 17, e70594, <https://doi.org/10.1002/ecs2.70594>

3.1 INTRODUCTION

In river-floodplain systems, the degree of connectivity among water bodies determines their use (Lewin and Ashworth, 2014). In systems where the principal source of water is overbank flow, the influence on fish ecology of the floodplains is described by the flood pulse concept (Junk et al., 1989, 2020). During extended and predictable flood pulses, fish migrate to floodplains for spawning, feeding, and shelter. As water levels recede, the fish return to the main channel or tributaries (Herrera-R et al., 2024; Melack et al., 2009; Welcomme, 1985). The duration of the flood pulse and retention time in the floodplain reflect tolerances and adaptations to hypoxic conditions in fish and riparian vegetation. In addition to lateral connectivity to the floodplains, longitudinal connectivity is necessary for long-distance migratory fish to reproduce upstream (Duponchelle et al., 2021; Vasconcelos et al., 2021).

Besides fish ecology, hydrologic variability also affects fishing practice. Factors such as the seasonal permanency of water, the accessibility to water bodies, and hydraulic settings are relevant for navigation and inform the selection of the fishing site and gear (Welcomme, 1985). In artisanal fisheries in the Amazon basin, the analysis of catch records showed a close relationship with flood pulse dynamics (Castello et al., 2015; Lima et al., 2017; Sousa et al., 2017). Extreme floods presented a yearly lagged positive correlation with the annual catch, indicating higher reproduction rates in the floodplains, which also matched the growth time and longevity of the fish species (Isaac et al., 2016; Santos et al., 2020). The seasonal variability showed that during low-water periods, the concentration of fish in water bodies facilitated higher catches; while in flood periods, fish dispersed into inaccessible flooded forests (Lauzanne et al., 1990; Santos et al., 2018).

Riverine natural resources are often managed by Indigenous peoples and local communities that contribute to governance through conservation, knowledge co-production, resistance to unsustainable practices, advocacy for environmental justice, and alternative perspectives on people-nature relationships (Brondízio et al., 2021). Traditional knowledge shows a deep ecological understanding reflected in the systematic use of diverse environments. In the Peruvian Amazon, local and Indigenous knowledge systems reflect complex techniques adapted to flooding dynamics, integrating conservation and production through sequences of agriculture, fishing, gathering, and hunting (Hiraoka, 1985; Pinedo-Vasquez et al., 2002). Likewise, local knowledge of soils provides valuable insights for sustainable crop production in floodplains (WinklerPrins and Barrios, 2007).

Similarly, local fishers' knowledge presents potential advantages to inform effective management, including broader spatial and temporal scales, a perspective closer to nature, and their participation in the local socioeconomic context (Collins, 2007;

Stephenson et al., 2016; Taylor and de Loë, 2012). Previous research studies have integrated local and scientific knowledge, validating and extending insights about fish ecology. Their results highlighted new information incorporated into conceptual models of fish life-traits and improved understanding of their linkages with flow variability. The analysis of local knowledge helped to increase the level of confidence in existing theories, assess the validity of spatial extrapolation, and reveal new hypotheses or identify those that need further testing (Finn and Jackson, 2011; Gaspare et al., 2015; Jackson et al., 2014; Nunes et al., 2019; Silvano and Valbo-Jørgensen, 2008).

3.2 METHODS

The semi-structured interview was designed using a topic guide to inquire about the details of fishing practices and their connection to hydrologic variability. The interview sections included general data about fishers, access to resources (planning and fishing techniques), fishing site characteristics, seasonal variability, fish ecology, preferred species, and production (See Section A.1 in Appendix A). The questions were formulated to explore the spatiotemporal variability of these aspects and to investigate potential links with hydrology. The questions focused on the fishers' experiences and permitted new information to emerge, as recommended by O'Keeffe et al. (2016). For this purpose, three levels of inquiry were followed, including descriptive, relational, and cause-and-effect analysis, as described in DePoy and Gitlin (2016).

The aim of participant selection was to interview as many fishers as possible along the study reach, given the time and resources available. Fieldwork was conducted between April and June 2022. The reach from Rurrenabaque to Carmen del Emero was visited on 4 and 5 April 2022. Ten fishers were interviewed: four in communities (Carmen del Emero, San Antonio de Tequeje, Villa Fátima, and Soraide) and six along the main channel. At the time of the visit, a few fishers were at the communities, while others were fishing, hunting, or working in agricultural plots. In particular, San Antonio de Tequeje was nearly abandoned following the severe 2014 flood, which had destroyed homes and fields. Along the main channel, interviews were conducted at commercial fishers' temporary camps, though some camps were empty when crews were fishing farther away in oxbow lakes. Subsistence fishers were also encountered on their boats along the river.

To increase the likelihood of finding participants, further interviews were conducted at the Rurrenabaque landing site (18 interviews in the intervals of 7-12 April, 16-17 May, and 2-16 June). Typically, for each boat, one crew member was designated to respond while others continued their activities. In some cases, fishers declined because they were busy.

In total, 36 fishers were contacted during the study period, 28 of whom agreed to participate. The sample included both commercial and subsistence fishers, representing Tacana I, Tacana III, non-Indigenous communities, and Rurrenabaque. Unfortunately, no Esse Ejiia fishers were interviewed. Subsistence fishers were more difficult to locate, as their livelihoods involve multiple activities beyond fishing. Figure 3.1 shows the location of the origin communities of the interviewed fishers.

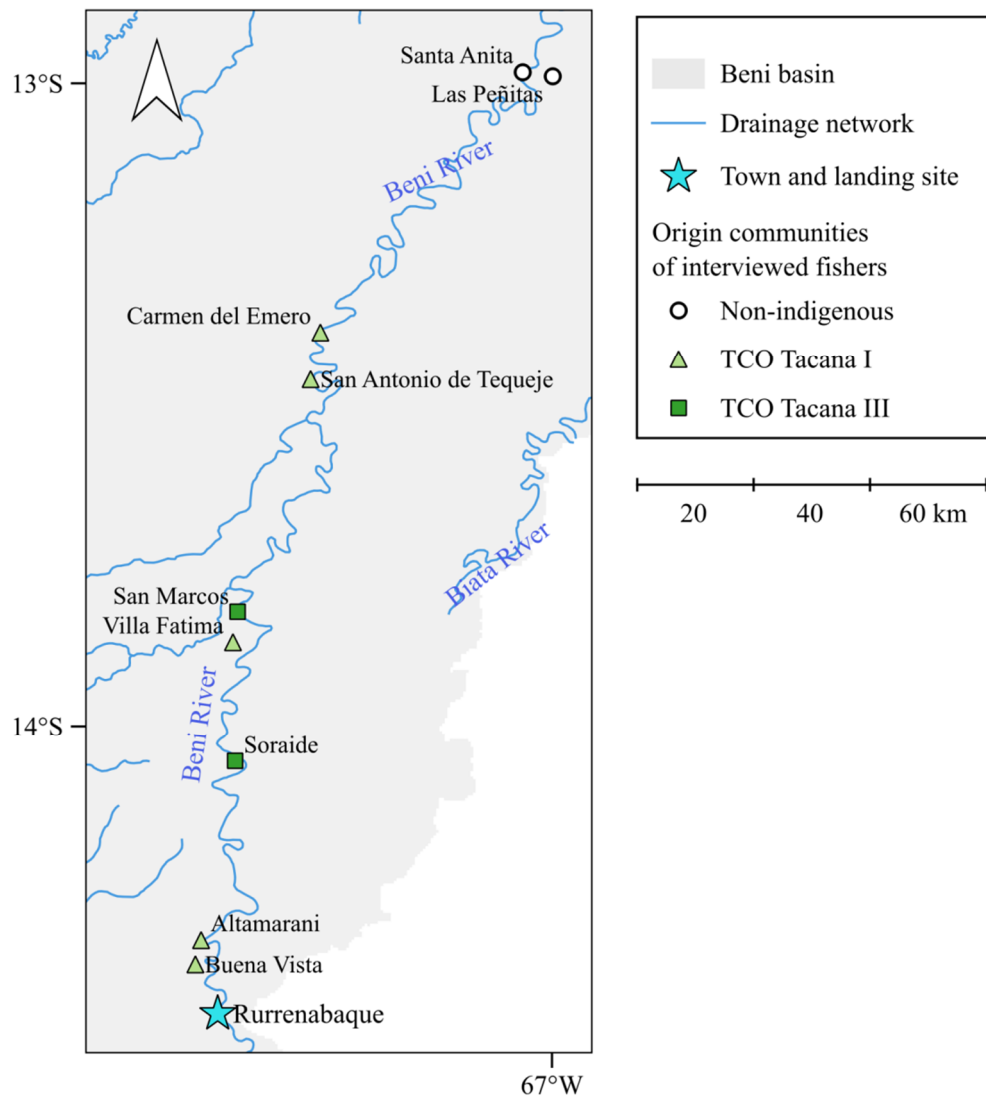


Figure 3.1. Beni River study reach indicating the origin communities of interviewed fishers.

Community visits were conducted with Authorization Request to the leader, and all interviews followed ethical guidelines of informed consent, with approval from the Delft University of Technology Human Research Ethics Committee (Letter of Approval #1994). Responses were anonymized and transcribed.

The data analysis involved a detailed description of the case and its context; it was organized into categories that represented distinct patterns, functions, and processes. The identification of these categories was the result of a coding process in Microsoft Excel, in which responses were linked to specific categories of fish species (general, specific species), temporal (hydrologic periods), and spatial scale (water bodies) (Rädiker and Kuckartz, 2019; Saldaña, 2013). The emergent categories were linked, reflecting their interdependencies. Next, the coded responses were interpreted based on the frequency, specificity, degree of elaboration, and new insights (Chi, 1997; Sijbesma and Postma, 2008). A synthesis table showing the interview questions, assigned code, categories, number of mentions, and association with separate categories (fish species, hydrologic period, water body, and others) is presented in Appendix A: Table A.1.

For example, a response to question P1 (Production long-term change) is “In these years there has been low fish catch, it depends on the flooding”, and it was coded as follows: General fish (fish species), Flooding (hydrologic period), Unspecified (water body), Decline (observation), and Flooding (associated factor/cause).

Fish production is not officially recorded by any institution. However, estimating the recent amounts is helpful to assess the relevance of the fishing practice. For this purpose, we asked for data from the National Agricultural Health and Food Safety Service (Servicio Nacional de Sanidad Agropecuaria e Inocuidad Alimentaria, SENASAG), which provided access to the last year (May 2021 to April 2022) of data of fish transported from Rurrenabaque to the cities. Also, we have inquired with collectors about estimated counts of standard freezing units (300 to 350 kg per unit) for the recent year.

3.3 RESULTS

3.3.1 General aspects of the fishing practice and terminology

Information about the origin territory, age group, and fishing purpose of the 28 fishers is presented in Table 3.1. The participants mainly originate from Indigenous communities (57%) and the town of Rurrenabaque (32%). Most of the interviewees practice fishing full-time for commercial purposes (75%), and the rest for subsistence. The age of the fishers ranged from 23 to 63 years, with 36 years as the mean. Most fishers interviewed were male (86%), but a few women also lead fishing trips mainly for subsistence purposes.

Table 3.1. Characteristics of all interviewed fishers by origin territory or town, age group, and fishing purpose

N	TCO / Town	Age group	Purpose	N	TCO / Town	Age group	Purpose
1	T1	G3	S	15	R	G1	C
2	T1	G3	C	16	T1	G2	C
3	T1	G1	S	17	R	G2	C
4	T1	G3	S	18	N-I	G1	C
5	R	G3	C	19	T1	G2	C
6	T1	G1	C	20	T1	G1	C
7	T3	G1	C	21	N-I	G1	C
8	T3	G2	S	22	T1	G1	C
9	T1	G1	S	23	R	G1	C
10	T1	G1	S	24	R	G2	C
11	R	G1	C	25	R	G1	C
12	T3	G1	C	26	N-I	G1	C
13	T1	G2	C	27	T3	G1	C
14	R	G2	C	28	R	G1	S

N: Participant number; TCO: Origin Community Territories (Indigenous); T1: Tacana I; T3: Tacana III; R: Rurrenabaque; N-I: non-Indigenous; G1: 21-35 years; G2: 36-50 years; G3: 51-65 years; S: subsistence and C: commercial

As a result of the coding process, common terms and categories of space, time, and fish species were identified. Fishers recognize five types of water bodies: the river (main channel), the lakes (oxbow lakes), the clearer western streams, the darker eastern streams, and the rapids (upstream). The temporal periods are mainly associated with river hydrology and flood dynamics: the dry period during which water levels and flooded area are reduced to the minimum (July to October), the period of rising waters that starts with the heavy rains (November to December), the flooding period that initiates when the main channel overflows to and connects the oxbow lakes (January to March) and finally, the period of receding waters during which the oxbow lakes drain back to the main channel and become disconnected (April to June).

In the river system, fishers have unrestricted access to the main channel. However, access to lakes and streams is determined by the territorial jurisdiction of the nearest community upstream on the same river margin. In addition, a closed fishing season is imposed tentatively from November to March for particular species and sizes according

to departmental government regulations (Reglamento para la pesca y comercialización de especies piscícolas en el Departamento del Beni, issued by Servicio Departamental Agropecuario SEDAG Beni, (2016)).

Fishers also distinguish fish species by body cover and size, as presented in Table 3.2. These categories are associated with fishing sites and fish preferences. Body cover was specified by 11 fishers, and the main factors associated were water body and turbidity (4), feeding habits (4), and preference (4). Size type was mentioned by 12 fishers who linked it with fish life traits (5) and water body (4).

Table 3.2. Characteristics of key fish species, including local names, body cover types, and size categories indicated by fishers for key fish species, with corresponding scientific names from the literature

Local name	Body cover	Size	Scientific name
Bagre, chanana	Skin	Large	<i>Zungaro zungaro</i> (Humboldt, 1821) [†]
Dorado	Skin	Medium	<i>Brachyplatystoma rousseauxii</i> (Castelnau, 1855) [‡]
Pacú	Scale	Medium	<i>Colossoma macropomum</i> (Cuvier, 1816) [†]
Paiche	Scale	Large	<i>Arapaima gigas</i> (Schinz, 1822) [†]
Pintao, chuncuina	Skin	Large	<i>Pseudoplatystoma</i> spp. [‡]
Piraíba	Skin	Large	<i>Brachyplatystoma filamentosum</i> (Lichtenstein, 1818) [†]
Piraña	Scale	Small	<i>Serrasalmus</i> spp. [‡]
Ruta	Scale	Medium	<i>Anostomidae</i> spp. [‡]
Surubí	Skin	Large	<i>Pseudoplatystoma</i> spp. [†]
Tambaquí	Scale	Medium	<i>Piaractus brachipomus</i> (Cuvier, 1818) [†]
Tucunaré	Scale	Medium	<i>Cichla pleiozona</i> (Kullander & Ferreira, 2006) [†]
Tujuno	Skin	Small	<i>Leiarius marmoratus</i> (Gill, 1870) [†]
Yatorana	Scale	Small	<i>Brycon cephalus</i> (Günther, 1869) [†]
Jatara	Scale	Medium	<i>Mylossoma duriventre</i> (Cuvier, 1818) [†]
Sábalo	Scale	Small	<i>Prochilodus nigricans</i> (Spix & Agassiz, 1829) [†]
Buchere	Scale	Medium	<i>Hoplosternum littorale</i> (Hancock, 1828) [†]
Carancho	Skin	Small	<i>Pterygoplichthys multiradiatus</i> (Hancock, 1828) [‡]
Llorona	Scale	Small	<i>Curimatidae</i> spp. [‡]
Panete	Scale	Small	<i>Triportheus angulatus</i> (Spix & Agassiz, 1829) [†]
Sardina	Scale	Small	<i>Iguanodectes spilurus</i> (Günther, 1864) [†]
Griso	Skin	Small	<i>Pimelodus blochii</i> (Valenciennes, 1840) [†]
Bentón	Scale	Small	<i>Hoplias malabaricus</i> (Bloch, 1794) [†]
Tachacá	Skin	Small	<i>Pterodoras granulosus</i> (Valenciennes, 1821) [‡]

[†] Sarmiento et al (2014)

[‡] CIPTA and WCS (2010), Froese and Pauly (2024)

Experienced fishers have noticed important changes over the course of their fishing experience, particularly the proliferation of the paiche, a significant decline in the abundance of native species, and shifts in upstream migration patterns, as indicated in the quotes in Table 3.3. They attribute the reduction of native species to various causes. The most frequently mentioned (64%) is the increasing use of gill nets for commercial purposes, followed by the possible consequences of dry years (18%) and predation by paiche (18%). The disruption of migration patterns of pintao and sábalo was also linked to the dams located further downstream in the Madeira River (Brazilian territory). In response to these changes, fishers who practice subsistence have to increase their efforts and visit more remote water bodies.

Table 3.3. Illustrative quotes from fishers about long-term changes in fish ecology and the fishing practice

Frequency of responses (%)	Long-term change	Illustrative quotes
20 (71)	Reduction of fish catch in general (particularly pintao and pacú)	“In general, there is a decrease in fish catches. This year it was low. I do not why that is, maybe the increase of fishers.” “Before, there were small pintaos, now we only find tachacá when we install the gill nets. The fish catch is low because there are too many gill nets.” “In these years there has been low fish catch, it depends on the flooding.” “Now, there are no (native) fish. The paiche is preying on them.”
11 (40)	Increase of paiche	“One year ago the paiche has appeared and proliferated in the lakes.”
6 (21)	Change in migration patterns of sábalo, surubí	“Before 2009, the fish would migrate upstream; we do not see them anymore.” “In the past, the dry period was the best to go fishing because the sábalos used to migrate upstream”...“Now we have to target the fish that migrate from the lakes back to the main channel during receding waters period” “In the past, the sábalos would migrate upstream, now they can't because of the dams downstream. Now they are very small, before they were big.” “We were affected by the dams downstream in Brazil, it has affected dorado and surubí, they do not migrate upstream anymore.”

The target fish species mainly depend on the purpose of production, the temporal variation of demand, and the abundance in the river system. As indicated in the relative frequency of responses in Figure 3.2, when fishing for commercial purposes, fishers target large species such as paiche and skin-covered species such as bagre and surubí. In contrast, native species are preferred for local consumption in the town and communities. The most popular species are pacú (scale-covered body) because of the good flavor and quality of the meat, as well as pintao and surubí (skin-covered body), followed by diverse native species of medium or small-size groups. The recent reduction of some of the larger species has led to an increase in the preference for smaller species.

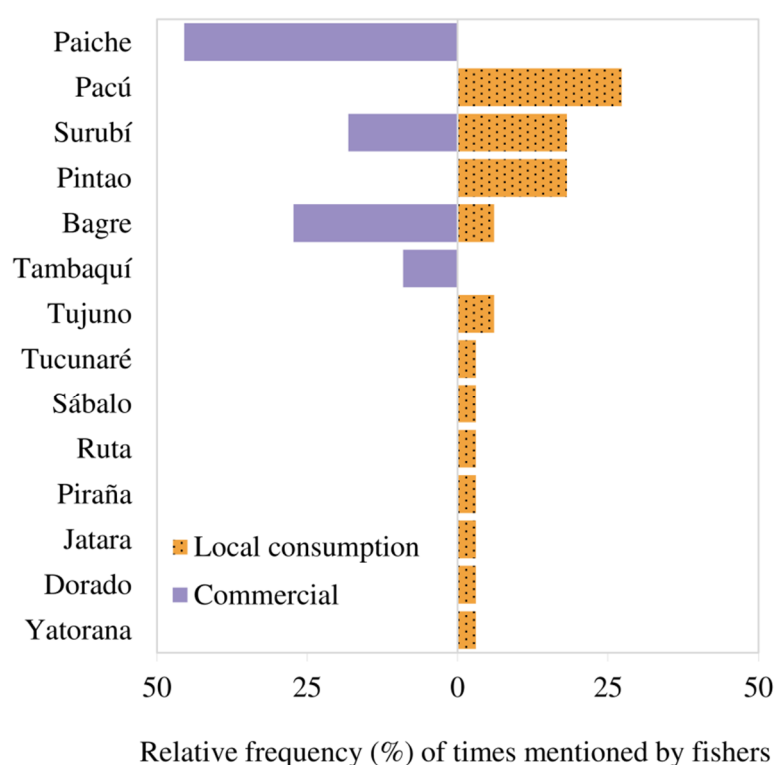


Figure 3.2. Relative frequency (%) of times that fishers mentioned the target fish species for local consumption (32 mentions) or commercial purposes (21 mentions)

Fish production is mainly associated with the abundance of fish in the river system during the different hydrologic periods, the temporal fluctuations in demand, and the fishing restrictions. According to data collected from Senasag, the amount of fish transported from Rurrebabaque to larger Bolivian cities was 294 tons from May 2021 to April 2022, with a maximum in April (43 tons) due to high demand linked to religious traditions and the minimum in January during the flooding and restriction period (19 tons). The collectors estimate that approximately 80% of the fish production is transported to the cities, while the remaining stays in the local markets. Therefore, an

approximate production for this period is 370 tons. On the other hand, the estimations made by collectors and the count of freezer units indicate a production of 284 tons (+/- 47 tons) for the last year.

The fish catch composition is mainly comprised of paiche, followed by pintao, pacú, bagre, surubí, and tambaquí. Paiche is the most important species during the rising and flooding periods, whereas the other species become more available during the receding and dry periods. Fish collectors suggested that paiche constitutes at least half of the monthly production, underscoring the dominance of this species in general.

3.3.2 Hydrologic variability and fishing practice

The selection of water bodies for fishing is primarily based on the seasonal flooding dynamics and fishing restrictions, as indicated in Table 3.4.

Table 3.4. Characteristics of fishing practices during different hydrologic periods, highlighting restrictions, demand level, preferred water bodies and general production level

Fishing practice characteristics	Flooding	Receding	Dry	Rising
Months	Jan, Feb, Mar	Apr, May, Jun	Jul, Aug, Sep, Oct	Nov, Dec
Partial restrictions on native species	Jan, Feb			Nov, Dec
High demand		Apr		
Main fishing water body	Lakes	Main channel,	Main channel, streams, lakes	Main channel
General production	Low	High-Medium	High	Medium

Figure 3.3a presents the hydrograph at Rurrenabaque station, indicating maximum, mean, and minimum daily discharge obtained from the Amazon basin water resources Observation Service of Hydrology and Biogeochemistry of the Amazon basin (HyBAm) database (<https://hybam.obs-mip.fr/>) for the period 1989 to 2016, and Figure 3.3b shows the migration patterns of native species and paiche during each hydrologic period. In the case of native species, fish disperse and migrate to the lakes and shallow flooded depressions or “bajíos”. During this period, only deep open water bodies (1.5 to 4 m)

are accessible, while flooded depressions are covered by forest and access is difficult. Navigation risks also increase during flood waves, further limiting fishers' activities. As water recedes, fish return to the main channel where diverse species initiate their reproductive migration upstream. This movement indicates to the fishers that the main channel is a good fishing site. Afterwards, as the water levels further reduce, the fish concentrate in all water bodies, and the migration activity intensifies in the main channel and streams. Thus, fishers expect high catches in all water bodies. After breeding upstream, the fish migrate downstream during the period of rising waters and continue their growth phase in the lakes or the main channel. In this period, there is no clear fishing preference for a water body, and there are navigation risks in the main channel.

In the case of paiche, the migration patterns are only laterally to lakes where paiche carries out most of its life stages. Thus, the fishers who target this species visit the lakes during most of the year; if there is no connectivity, some will portage boats by land, and during the flooding period, there are low catches because of the fish dispersal in the flooded depressions. The quotes presented in Table 3.5 reflect the perception of these changes.

In addition to seasonal flooding, fishers also consider interannual dynamics and short-duration events to predict the migratory behavior of native species. Occasional connectivity due to intense rainfall can occur throughout the year; falling water levels and return flow to the main channel indicate potential catch there. The interannual flooding variability is taken into account to predict the production of future years, as described in the interview quotes in Table 3.5. In dry years, there is minimal connectivity between most lakes and the main channel; thus, most of the fish that were growing in the lakes remain there. In contrast, in years with extensive and prolonged flooding, such as in 2014, fish were able to take advantage of the abundant resources in the flooded depressions and later migrate upstream in better conditions to reproduce. Thus, fishers anticipated abundant catches in the main channel for that year and even future years. These observations allow fishers to either invest in resources for fishing or to select temporally alternative economic activities.

After the fishers have selected a water body or a section along the main channel, they search for physical signals that suggest the presence of particular fish species or categories as specified in the quotes in Table 3.5. They associate areas with high water levels and slow currents with the presence of medium-sized fish. In the main channel or streams, they search for backwater, swirls and areas with accumulated woody debris. The confluence of a stream and main channel are typical places to find fish, especially during migration periods.

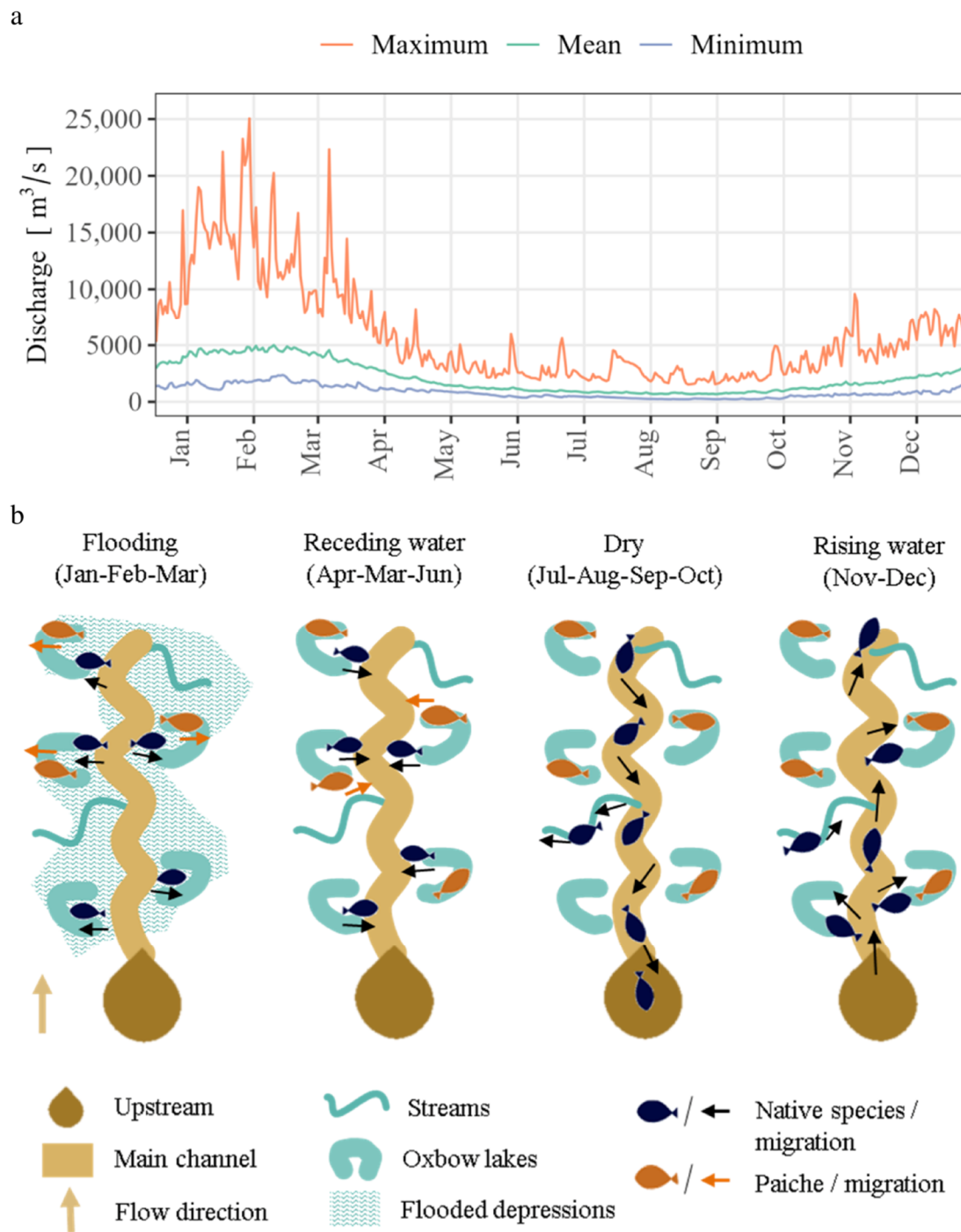


Figure 3.3. a) Hydrograph at Rurrenabaque station indicating maximum, mean, and minimum daily discharge for the period 1989 to 2016, b) Schematic of fishers' description of migration patterns of native fish species and paiche.

Table 3.5. Illustrative quotes from fishers about hydrologic factors that affect fishing practices

Illustrative quotes about seasonal flooding dynamics and water body selection for fishing

“During the flooding period there is low fish catch because the fish are in the bajíos”

“During the flooding period we enter the lakes because it is possible to access from the main channel”

“When the water level reduces, there are plenty of fish going from the lakes and bajíos to the main channel, the fish catches are high”

Illustrative quotes about interannual flooding dynamics and prediction of fish catch

“The fish catches will be low; there was no flooding this year...”

“There has to be a larger inundation so that fish can come out of the lakes to the main channel...”

“There was no flooding; the fish in the lakes have not come out...”

“The flood in 2014 wiped out Villa Fatima, several animals died; but there was abundant fish because the lakes were flooded, and the fish migrated back to the main channel afterwards.”

Illustrative quotes about interpretation of physical aspects in a water body

“We fish near rapid currents; behind the debris... these are strategic locations in the beach where we install the hook and bait.”

“We put the fixed hook and bait in backwater zones, confluences, in the turns of the main channel and streams.”

“The gill nets are mainly installed in the lakes, in a backwater location with low current.”

The choice of fishing gear depends on the target species, flow velocity, and water depth. Gillnets are preferred in slow-flowing lake waters, while hook-and-bait methods are better suited for shallow areas and traps for deeper areas in the main channel. Paiche is mainly caught using hook-and-bait sets or traps in the lakes, whereas native species such as pacú, surubí, and pintao are typically captured in deeper sections of the main channel using both nets and hook-and-bait techniques. Bait selection varies according to the target species and their seasonal feeding habits. For carnivorous fish such as paiche, fishers commonly use species like llorona, sábalo, bentón, buchere, carancho, and panete as bait. Pacú, on the other hand, is caught with fruits, while various worms are generally effective for a wide range of species.

3.3.3 Hydrologic variability and fish ecology

The main habitat characteristics that fishers associate with fish species are preferred water bodies, water depth, substrate, turbidity levels, and vegetation. In general, fishers note that most fish species can be found in most types of water bodies as they constantly move between them, while certain species show a preference for specific types, as indicated in quotes in Table 3.6, and in Table 3.7. Water depth is associated with fish size and characteristics such as feeding habits and morphology. Fishers estimate depth using a leafless shrub called chichío (*Tessaria integrifolia*) of approximately 4 meters maximum. Vertical movement is notable for preying on smaller species during the night, sheltering in deep waters during temperature drops or full moons, as well as for air-breathing, especially observed in paiche.

In the proximity of vegetation, fishers commonly find fish species that feed on fruits or use the aquatic vegetation as shelter and nursery sites for juveniles that feed on algae and the roots of aquatic plants. Fishers identify various fruit tree species along the margins of water bodies, including bibosi, ambaibo, chonta, cedrillo, panejaja, coquino, and chirimoya, with corresponding scientific names *Ficus pertusa*, *Cecropia concolor*, *Spondias mombin*, *Pouteria nemorosa*, *Xylopia ligustrifolia*, and *Annona Cherimola* (Killeen et al., 1993). Aquatic vegetation environments are locally called yomomo, tarope, and cañuela. They may include communities formed by herbaceous and floating plant species such as *Oxycarium cubensis* and *Paspalum repens* (Navarro, 2011).

Fishers associated water turbidity with the occurrence of particular fish groups and species. Scaled fish are commonly found in the clear waters of lakes and western streams. Surubí and pintao are known to seek clear waters during the rising water period. Bagre, however, is the only species that is more associated with turbid waters in the main channel and upstream. Three respondents pointed out that turbidity reflects the contamination levels that affect the quality of the fish meat, which explains their higher preference for fish mainly found in clear water bodies. In addition, ten fishers have observed events of mass mortality, especially of sábalo, following heavy rains in water bodies that contain more organic material. The possible causes they suggest include the drainage of ashes from agricultural activities upstream and the decomposition of vegetation.

*Table 3.6. Illustrative quotes from fishers about fish habitat and fish ecology***Illustrative quotes about habitat**

“In the lakes we find paiche, sábalo, pacú, carancho, surubí. The bagre is found in rapid waters.”

“Paiche is abundant in the lakes, there is also pintao, pacú, tujuno, sábalo, piraña. In the river we find chanana, pintao, tujuno, piraña, tachacá.”

“Pacú and pintao are found in deep waters, the paiche is found at all water depths.”

“The paiche is found in deep and shallow waters. It comes out to breath.”

“Under bibosi tree we find pacú, yatorana and jatara (...). Paiche is found in aquatic vegetation.”

“Paiche lives within yomomo, where there they prey on small fish.”

Illustrative quotes about fish migration

“The sábalo, yatorana, pacú migrate upstream through the main channel.”

“The paiche does not migrate upstream, it is from stagnant waters.”

“Pacús migrate upstream in schools in November. The surubís migrate upstream preying on the sardinas and sábalos.”

“First the sardina and small sábalo migrate upstream. When there is flooding, they migrate earlier in April to June. The large fish migrate upstream preying on the schools of smaller fish.”

Illustrative quotes about fish reproduction and growth

“There is a delay in the reproductive migration of pacús, tambaquis and pintaos. We see them and they do not have eggs yet.”

“Paiche reproduces in the lakes, pacú and pintao in the main channel.”

“Paiche reproduces faster than the other fish species. In March you can see them with the juveniles in the lakes where they grow under the care of the parents, which guard the group from the front and behind.”

Illustrative quotes about feeding habits from bait selection and vegetation in habitat

“Pacú eats bibosi, coquino, chirimoya during the flooding season.”

“The most carnivorous fish are paiche and piraña.”

“For the large skin-covered fish the best bait is carancho, buchere, panete.”

“For paiche and pintao, we use llorona”

“The selection of bait depends on which fish species are migrating upstream through the main channel. For instance, now it is sardina”

Fish migration for reproduction is locally referred to as “arribada”. Large schools of fish are audibly and visibly recognized as they migrate upstream along the main channel.

Most fish lay their eggs in unknown locations further upstream, and the smallest reach more distant locations than the larger species. The fishers note that migration occurs in ascending order of size from April to August, as indicated in Table 3.7, with larger species preying upon smaller ones. The stomach content informs the feeding preference of the larger fish and the bait selection. The timing and size of schools in the main channel are used as predictors of the potential production for the year.

Table 3.7. Summary of the most frequent attributes associated with fish species for habitat and fish ecology

Fish species	Water body			Habitat characteristics				Fish ecology	
	MC	OL	S	Depth	Substrate	Turbidity	AV	Main food	Migration in MC
Paiche		X		Shallow		Clear	Y	Meat	NA
Pacú		X	X	Deep		Clear	Y	Fruits	Fi, Mi
Surubí	X	X		Shallow		Clear			Mi
Pintao	X	X	X	Both		Clear		Meat	Mi, La
Bagre	X			Deep	Clay	Turbid		Meat	La
Tambaquí				Deep				Fruits	La
Tujuno				Shallow					Mi
Jatara		X	X					Fruits	La
Piraña		X	X					Meat	
Sábalo	X	X		Shallow	Mud			Mud	Fi, Mi, La
Tucunaré		X				Clear			
Yatorana								Fruits	Mi, La
Piraíba	X			Deep	Clay				La
Griso				Shallow	Sand				Fi, Mi
Tachacá		X				Clear		Fruits	
Sardina				Shallow					Fi
Panete					Sand			Fruits	Fi, Mi, La

MC: Main channel; OL: Oxbow lake; S: Stream; X: Fish is present; AV: Aquatic vegetation; Y: Yomomo; Fi: First; Mi: Middle; La: Last; NA: Not applicable

Fishers also observe other stages of reproduction and growth. For instance, they observe the eggs drifting through the main channel like oil drops as water levels rise, also in the lakes where hatching occurs, and juveniles' growth during the flooding period, taking advantage of abundant food resources. In regards to the adult care of juveniles, paiche

shows this behavior as two adult fish flank a school of juveniles on the front and behind, protecting it from potential predators. Also, the carnivorous feeding habits of paiche are partially informed by the bait selection.

Table 3.8 presents a spatiotemporal synthesis of the qualitative insights from fishers and their link to quantifiable and measurable hydrologic variables. These ecohydrologic relationships represent the ecological functions linked to hydrologic indicators that allow the evaluation of alteration scenarios, including natural extreme events and human alterations.

Table 3.8. Indicators of hydrologic variability that influence fishing practices

Temporal scale	Spatial scale and observations of hydrologic variability	Influence on fishing practice	Influence on fish ecology
Multiannual	River system: connectivity; duration of flooding; flooding extent	Expectation of catch levels for next year, invest in resources	Paiche: explore and occupy new lakes Native species: optimize reproductive migration strategies for survival
Seasonal	Water body: water level changes; flooding extent	Select water body; prepare resources for fishing; prepare additional resources for small boat transport	Paiche: shelter in available flooded depressions Native species: reproductive migration upstream
Weekly/daily	Connectivity areas: flow from lake to main channel; confluence of stream and main channel Water body: flow velocity in main channel Fishing location: water depth; flow velocity; flow direction	Schedule fishing trip; selection of specific fishing location; selection of suitable fishing technique; assess navigability risk	Paiche: local migration Native species: signal for lateral migration; vertical migration; response to hypoxia

3.4 DISCUSSION

In this chapter, the analysis of fishers' knowledge has significantly contributed to understand how hydrology influences fish ecology and the fishing practice along the Beni River (SO1). Fishers' observations revealed key species migration patterns, feeding habits, and life stages that are linked to hydrologic variability and connectivity. These observations also inform fishing decisions and provide insights into potential consequences of hydrologic alteration, including reduced connectivity and fish

availability. The findings highlight the value of incorporating fishers' knowledge into river planning, environmental assessment, and river-floodplain management.

The increasing importance of fishing in the Beni River is evident in the estimated rise (+40%) in fish production from 209 tons in 2015 (Espinoza-Antezana and Van Damme, 2020) to 294 tons estimated for 2022 (using data from Senasag). The identification of the most valuable fish species reflects trends previously observed in downstream communities, particularly the rise in paiche catches (Coca-Méndez et al., 2012; Macnaughton et al., 2015). In addition, the decline in native species is concerning because of their high preference for local consumption. Although native species and paiche show very distinctive life traits, their abundance and access to habitats depend largely on flooding dynamics, as well as connectivity, as depicted in Figure 3.3b and Table 3.8. Thus, fishers' knowledge highlights the importance of maintaining hydrologic connectivity in meandering rivers.

The influence of hydrologic variability on the fishing practice is evidenced in the use of various indicators to predict fish catches seasonally and for future years. The selection of water bodies based on hydrologic periods and fish migration patterns coincides with documented strategies in the Mamoré and Madeira rivers (Isaac et al., 2016; Lauzanne et al., 1990). Quantitative studies indicate similar trends of expected catches of native species, with high fish catch during the dry period and low during the flooding period (Lauzanne et al., 1990; Zacarkim et al., 2015). In the Madeira River, water level changes and flooded areas were also used to predict fish catch and inform the number of fishing trips (Santos et al., 2018, 2020). The relationship between annual fish yields and flooding dynamics was analyzed through correlation studies, showing that high and low waters in a given year affect yields two or three years later, with higher fish biomass and fishing effort (Castello et al., 2015; Isaac et al., 2016). This coincides with fishers' expectations of higher catch after humid years and lower catch after dry years. Similarly, the extent of flooding was highly correlated with fish production in the Lower Amazon (Doria et al., 2018; Isaac et al., 1996). While dry years in the Beni River have been linked to lower catches, studies in Negro River near Manaus report more severe drought effects, including fish mortality, species loss, and smaller catch sizes (Camacho Guerreiro et al., 2016). These findings highlight the potential ecological and livelihood disruptions as a consequence of hydrologic alterations.

3.4.1 Comparative insights from local and scientific knowledge

The proliferation of paiche partially explains the estimated increase in recent fish production. The expansion of this species was facilitated by hydrologic connectivity to lakes with adequate temperature and rare anoxic events, as well as high reproduction rates and parental care, also observed by the fishers (Carvajal-Vallejos et al., 2011; Coca-Méndez et al., 2012). The migration patterns between the lakes and flooded

depressions coincide with those studied in the Juruá floodplains and in the Japura floodplains (Campos-Silva et al., 2019; Castello, 2008). Although primarily carnivorous, paiche has displayed omnivorous traits in the Madre de Dios floodplains (Villafán et al., 2020), indicating that feeding habits depend on the local and temporal availability of resources. In this study, the fishers mentioned diverse species used as bait for paiche (small species) and preying sites near aquatic vegetation. While paiche is an introduced species to the Beni River, it has become a dominant preferred species among commercial fishers that requires sustainable management.

The fishers closely observe how native fish migration patterns are linked to hydrologic variability, emphasizing the upstream migration and eggs drifting downstream. In tropical systems, the seasonal reproduction patterns are considered an adaptation to the flood pulse timing, which allows both adults and juveniles to benefit from the food resources and shelter in the floodplains (Goulding, 1980; Junk, 1997; McConnell and Lowe-McConnell, 1987; Welcomme, 1985). Beyond supporting widely recognized ecological concepts, fishers' knowledge also contributes with new evidence of habitats. Fishers' knowledge about the sequence (ascending size) and timing of fish species during the upstream migration along the Beni main channel has parallels with migration patterns described by Indigenous fishers in the Caquetá River and in the Yahuaraca Lakes in the Colombian Amazon (Rodríguez-Fernández, 1992; Victoria-Lacy, 2025). These patterns should be further evaluated to find links with hydrologic connectivity and fish abundance.

Sábalo (*Prochilodus nigricans*) is highlighted as one of the most important native species for fishers, with observed disruptions in their migration patterns and mass mortality attributed to changes in water quality. This species was known to migrate in large shoals upstream along the main channel on two occasions during the receding waters and dry period, similar to observations in the Central Amazon (Petrere Jr., 1978). The initial migration of juveniles aims to switch food sources and evade hypoxia, while the second migration of adult fish synchronizes with hydrologic signals for reproduction purposes (Fernandes, 1997). Sábalo is particularly vulnerable to hydrologic changes because it has a short reproductive period, and it requires a minimum growth level prior to leaving the floodplains (Barros et al., 2021; de Magalhães Lopes et al., 2018). One of the responses to hydrologic changes is the mechanism of "skipped breeding", in which only part of the adult population migrates for reproduction, and the rest remains in the floodplains to increase their chances of survival (de Magalhães Lopes et al., 2018). These studies can partially explain the observations of the fishers and the association of lower flooding during dry years.

Relevant species such as pacú and *Pseudoplatystoma* spp. (surubí and pintao) are also in decline. A possible cause was linked to predation by paiche and also reported in downstream fisheries (Macnaughton et al., 2015; Miranda-Chumacero et al., 2012; Van

Damme et al., 2015). The descriptions of habitat preferences of pacú coincide with studies that indicate the use of aquatic vegetation as nursery zones in lakes, and proximity to forest trees to feed on fruits, and shelter in deep areas in the main channel (Córdova, et al., 2012; Silva et al., 2000). In regards to *Pseudoplatystoma* spp., they are predators during the reproductive migration along the main channel. This aligns with regional studies that found faster growth rates during the receding waters, while in the dry period; predation is low due to high densities and competition (Armas et al., 2022; Loubens and Panfili, 2000). These observations highlight the need to investigate trophic dynamics and propose measures to protect declining fish species.

3.4.2 Fishers' and local knowledge about dam development

Hydropower development in the Amazon has deeply affected riverine ecosystems and local livelihoods. Local knowledge studies on the impact of the Belo Monte Dam (Xingu River) revealed major disruptions to fisheries and vegetation. Fishers reported declining catches, altered practices, and loss of income, demanding operational changes to protect spawning sites (Assunção et al., 2024; Juruna et al., 2025). Similar impacts were described by fishers within the impact area of the Tucuruí Dam (Tocantins River), including the abandonment of fishing sites, change of techniques, increased effort, as well as reduced income and food security (Lima et al., 2024; Santos and Pelicice, 2023). On the Madeira River, the Jirau and Santo Antônio dams caused declines in catch per unit effort, loss of migratory species, lower income, and fish consumption (Arantes et al., 2022, 2023; de Souza et al., 2025). These cases expose the continued marginalization of small-scale fishers in hydropower planning (Doria et al., 2018), and the overlapping distributional, procedural, and recognition injustices faced by downstream communities (Castro-Díaz et al., 2024).

In this study, the identified ecohydrologic relationships help us point out various potential impacts of the planned Chepete Dam on the natural hydrologic regime. At the seasonal scale, flood-pulse attenuation could reduce lateral connectivity between the main channel and oxbow lakes, limiting adult native fish from migrating upstream to spawn and restricting juvenile access to feeding and nursery habitats during rising waters. Prolonged disconnection of oxbow lakes could lead to drying or water quality degradation, exacerbated by reduced sediment and nutrient inflows from the main channel. The dam would also block longitudinal migrations of species that spawn further upstream. Although nearby streams might offer alternative habitats, their suitability would vary by species. Reduced habitat availability for paiche could increase overfishing risks, while declining fish abundance might push commercial fishers toward timber extraction and threaten the food security of subsistence fishers, increasing pressure on hunting and crops. The evaluation of these impacts at the planning stage could help to reduce impacts and evaluate alternative scenarios.

Fishers' and local ecological knowledge have a key role in assessing and mitigating dam impacts (Baird et al., 2021). In the Tapajós River, fishers' observations about fish habitat preference, connectivity, and migratory species informed how a dam could affect the fishing practice and threaten their livelihoods (Runde et al., 2020). Studies in other regions show how local knowledge can extend ecohydrologic understanding and inform environmental flow assessments (Finn and Jackson, 2011; Jackson, 2017). Thus, incorporating local knowledge into hydropower planning is not only a matter of stakeholder inclusion but a practical need for planning more just, adaptive, and ecologically sustainable water management strategies.

3.4.3 Fishers' and local knowledge about hydrologic variability and river-floodplain processes

Fishers also described key river-floodplain processes and long-term hydrologic trends. They identified drivers of lateral connectivity between the main channel and oxbow lakes, including overbank flow, intense local rainfall, and stream inflow. Also, their perception of reduced flooding over time is consistent with a reported decline of about 100 m³/s per year in the Beni River (Laureanti et al., 2024). Similarly, in clear-water rivers, fishers have reported drier conditions in the Tocantins, more frequent floods in the Trombetas, and variable trends in the Tapajós. They also associated poor water quality with pollution, as well as dams, mining, and deforestation (Nunes et al., 2019). Collectively, these insights show how local knowledge can contribute to detect and understand hydrologic and environmental change.

Integrating diverse knowledge sources and analytical tools is needed to further understand the Beni River's floodplain processes. In this dynamic meandering system where main channel migration continually forms and erodes oxbow lakes, remote sensing can help characterize individual oxbow lakes, their connectivity patterns with the main channel, and changes in water quality (Terrazas-Villarroel et al., 2026b). These insights can inform hydrologic models simulating dam operations and different scenarios of hydrologic alterations. Combining local knowledge, remote sensing, and hydrologic modeling allows for a comprehensive assessment of multiple environmental pressures and supports adaptive habitat conservation.

3.4.4 Limitations

Our analysis of fishers' knowledge using a qualitative approach implemented with semi-structured interviews has provided in-depth insights and flexibility. Despite its value, we acknowledge limitations in data collection and analysis. The limited sample size restricted extensive frequency analysis, with responses mainly reflecting different fish species and lower frequencies. The content of the interviews is constrained by the fishers' experience, age, fishing purpose, target species, and specific fishing locations.

In this study, 60% of participants were young adults (21-35 years), while only 14% were older adults (51-65 years), which indicates that long-term trends represented a smaller time interval for the younger fishers. In the preliminary analysis, a couple of instances of species terminology conflict were discarded. Some of these limitations can be addressed in further qualitative studies organized per fish species or type of fisher.

3.5 CONCLUSIONS

In conclusion, the analysis of local knowledge has revealed important changes in valuable species and emphasized their reliance on hydrologic variability, connectivity, and flooding dynamics for various life stages. The fishers use this information to predict fish catches and strategically plan their fishing activity. We have extended the information about reproductive migration by highlighting the fishers' detailed observations of the sequence and timing of shoals of different species, as well as variable fish feeding habits. The continuous observation of these life-traits revealed temporal trends also linked to hydrologic variability that should be further studied. The potential hydrologic alteration caused by a hydropower dam would lead to reduced connectivity and a potential decline in fish abundance, which in turn would negatively affect the subsistence and livelihoods of fishers. In summary, this study highlights the need to incorporate local and fishers' knowledge into hydropower planning, environmental assessments, and river-floodplain studies. This would help to recognize and safeguard the dependence links between local and Indigenous communities with river dynamics.

4

MONITORING OXBOW LAKES USING REMOTE SENSING

This chapter addresses SO2 by analyzing spatiotemporal dynamics of oxbow lakes and evaluating how hydrologic variability influences their role as aquatic habitats. For this purpose, this chapter presents a long-term remote sensing analysis (1999-2022) of forty oxbow lakes along a 250 km reach of the Beni River². These lakes serve as critical aquatic habitats for fish and are also used as fishing locations. Their role is highly influenced by hydrologic connectivity and flooding dynamics. The high sediment load of the river enabled the classification of water types based on their optical properties, allowing surface reflectance to be used as a proxy of turbidity. Landsat 7 imagery was accessed through the Google Earth Engine platform and used to evaluate oxbow lake area and water type dynamics at the monthly and annual temporal scales. These dynamics were analyzed in relation to lake properties and discharge variability to interpret patterns of hydrologic connectivity. Within the broader thesis, this chapter provides a quantitative evaluation of the spatiotemporal dynamics of aquatic habitats, which is later integrated with fishers' knowledge to define ecohydrologic relationships and evaluate potential impacts of hydrologic alteration under dam scenarios.

² This chapter is adapted from: Terrazas-Villarroel, Lina G., Wenninger, J., Heredia-Gómez, M., van de Giesen, N., McClain, M.E., 2026. Monitoring Oxbow Lakes with Remote Sensing: Insights into Turbidity, Connectivity, and Fish Habitat. *Remote Sensing* 18, 474. <https://doi.org/10.3390/rs18030474>

4.1 INTRODUCTION

In large river-floodplains where the main channel transports substantial sediment loads, water surface reflectance represents water quality and connectivity processes relevant to ecological functions (Alcântara and Edward, 2020; Park and Latrubesse, 2014; Rudorff et al., 2018). Water turbidity associated with suspended sediment reflects key characteristics linked to fish habitat preferences (Borghezan et al., 2021). In addition, hydrologic connectivity among water bodies is vital for aquatic habitat availability (Junk et al., 1989, 2020). Long-term satellite records and platforms such as Google Earth Engine help characterize water surface reflectance, turbidity, and flooded area over time and space (Gorelick et al., 2017; Mutanga and Kumar, 2019; Sogno et al., 2022). Analyzing these dynamics provides insights into habitat characteristics, while understanding their relationship with hydrologic variability helps evaluate the potential impact of hydrologic alterations.

Meandering channels are the most common pattern in systems where the main channel dominates connectivity (Crosato, 2008; Hooke, 2013; Lewin and Ashworth, 2014). Their aquatic habitat structure includes the main channel, oxbow lakes, connection channels, and internal drainages. The formation of cutoffs and oxbow lakes is influenced by slope, vegetation density, and bank erodibility (Dunne and Aalto, 2013). Following cutoff, oxbow lakes evolve through typical life stages, from initial plug bar formation to progressive sedimentary infilling and eventual near-complete infill (Saucier, 1994; Wren et al., 2008). Lake responses to flood pulses have been linked to characteristics such as lake age, orientation angle, and distance from the main channel (Gautier et al., 2010; Hudson et al., 2012; Paulino et al., 2023). To evaluate connectivity, previous studies have integrated oxbow lake life stages with the flood pulse concept, emphasizing functional differences among these stages (Hudson et al., 2012).

Seasonal changes in water turbidity, driven by suspended sediment, may also influence fish habitat preferences and behavior. Reduced light availability affects fish sensory responses, altering predator-prey interactions and modifying prey abundance (Borghezan et al., 2021; Tejerina-Garro et al., 1998). In addition, water bodies with higher turbidity have been associated with a greater presence of detritivorous fish species (Santana et al., 2015). Studies in Amazon systems have shown that water type and turbidity are associated with differences in fish assemblage composition and, for some species, habitat selection (Bogotá-Gregory et al., 2020; Borges et al., 2023).

Water turbidity in meandering rivers can be represented by surface reflectance, especially in rivers with high sediment loads (Maurice-Bourgoin et al., 2007; Park and Latrubesse, 2014; Rudorff et al., 2018). Relationships between water optical properties and physicochemical parameters have been widely used to classify water types in different regions (Gholizadeh et al., 2016; Spyarakos et al., 2018). Optical water types

identified in Brazilian waters reflect dominant limnological traits associated with turbidity, trophic status, and organic matter (Martinez et al., 2015; da Silva et al., 2021b). An increase in suspended particles is often linked to the change of spectra in the green to near-infrared bands (Valerio et al., 2021). In turn, sediment settling enhances light penetration and photosynthetic activity, increasing chlorophyll levels. Together, these optical responses provide proxies that reflect sediment dynamics and hydrologic conditions in river-floodplain environments.

Remote sensing has become a key tool for monitoring river-floodplain waters due to its spatiotemporal coverage of optical properties. Several studies have characterized channel-floodplain dynamics by monitoring water type transitions that reveal areas of dilution, sedimentation, flow reversal, backwater effects, and wind-driven resuspension (Barbosa, 2006; Fassoni-Andrade and Paiva, 2019; Maciel et al., 2021; Park and Latrubesse, 2014; da Silva et al., 2021a; Valerio et al., 2021). The classification of water types is often performed using machine learning methods (Aggarwal, 2015). Among these, the widely used random forest classifier consists of an ensemble of decision trees that introduce randomness in their building process (Breiman, 2001). These classifiers have been used to assess hydrologic connectivity in floodplain lakes, classify land cover and water areas in wetlands, and distinguish water types based on water quality parameters (Maciel et al., 2021; Paulino et al., 2023). A key advantage of decision tree classifiers is their flexibility in handling different feature subsets and decision rules, balancing accuracy and efficiency (Safavian and Landgrebe, 1991). Random forest classifiers also allow the estimation of feature importance while maintaining high predictive performance (Maciel et al., 2021).

Previous studies in the Amazon basin have assessed the hydrologic connectivity of oxbow lakes using optical image classification (Paulino et al., 2023; Terborgh et al., 2018). However, reliance on high-resolution commercial imagery limits transferability and long-term analysis. A recent study in the Beni River evaluated oxbow lake hydrologic dynamics using remotely sensed area changes and rainfall patterns (Ahmed, 2024), but did not incorporate river discharge data or water optical proxies that are particularly relevant in turbid systems. Field-based studies in other regions have provided insights into physico-chemical processes within individual oxbow lakes (Hudson et al., 2012; Wang et al., 2020); however, their specificity and cost limit their application to multi-lake assessments. In this chapter, we address these limitations by applying a multitemporal, satellite-based analysis that combines lake area dynamics, water optical types, and river hydrologic variability to infer hydrologic connectivity and habitat availability in a turbid river-floodplain system. This approach enables a comparative, long-term assessment of oxbow lake dynamics and their ecological relevance in a data-scarce region.

4.2 AVAILABLE DATA

The study area covers a 250 km reach downstream of the town of Rurrenabaque (see Figure 4.1), which is the primary fish landing site concentrating on small-scale production. The main focus is on key fishing locations within this reach, including the main channel and forty oxbow lakes, as indicated by local fishers (see Chapter 3). Other water bodies include flooded depressions (locally known as *bajíos*) and larger lakes (e.g. Lake Moa). During the flooding period, *bajíos* connect to the main channel and oxbow lakes, providing temporary habitat for fish as observed by local fishers (see Chapter 3). However, these environments are not accessible fishing sites, and their large shallow areas remain inundated for shorter periods compared to oxbow lakes. Thus, they were not included in this analysis.

The selection of the satellite data sensor was based on its suitability to represent the Beni River system. The Landsat 7 and the Enhanced Thematic Mapper Plus (ETM+) sensor was selected because it acquires satellite images with 6 reflective bands, 30 m spatial resolution, 15-day revisit frequency, and data available from 1999 until 2023. This period is the longest compared to Landsat 5, Landsat 8, and Sentinel 2. The data were accessed through the Google Earth Engine (GEE) catalog, specifically Level 2, Collection 2, Tier 1, courtesy of the U.S. Geological Survey. This dataset contains ready-to-use atmospherically corrected surface reflectance created using the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) algorithm (Schmidt et al., 2013). Additionally, images accessed through Google Earth Pro's timeline were used to visually analyze patterns at higher spatial resolution.

Image filtering and preprocessing were performed in GEE, applying first a 40% cloud coverage threshold to the entire image and later a 20% limit within each oxbow lake polygon to mask clouds. Thus, the number of images varies among lakes, especially when local or sparse clouds only affect a group of lakes. Then, for each lake, the calculated area (after land cover classification) was screened for values outside the 10th and 90th percentiles. These images were inspected for residual clouds, haze, or cloud shadows and removed from the analysis of that lake. The monthly distribution of valid satellite images for each of the 40 lakes is indicated in Figure 4.2a. Finally, the areas in lakes affected by Scan Line Corrector-off (SLC-off) striping were corrected using a morphological mean filter applied to each band; with a square kernel of radius equal to 3 and 3 iterations (see more detailed analysis in Terrazas-Villarroel et al. 2026b). The resulting images were used for further analysis.

Additionally, historical imagery from Google Earth Pro was used to identify lake formation years. Also, the analysis of wind-driven effects was performed using high-resolution imagery from ©2020 Maxar Technologies (see more detailed analysis in Terrazas-Villarroel et al. 2026b).

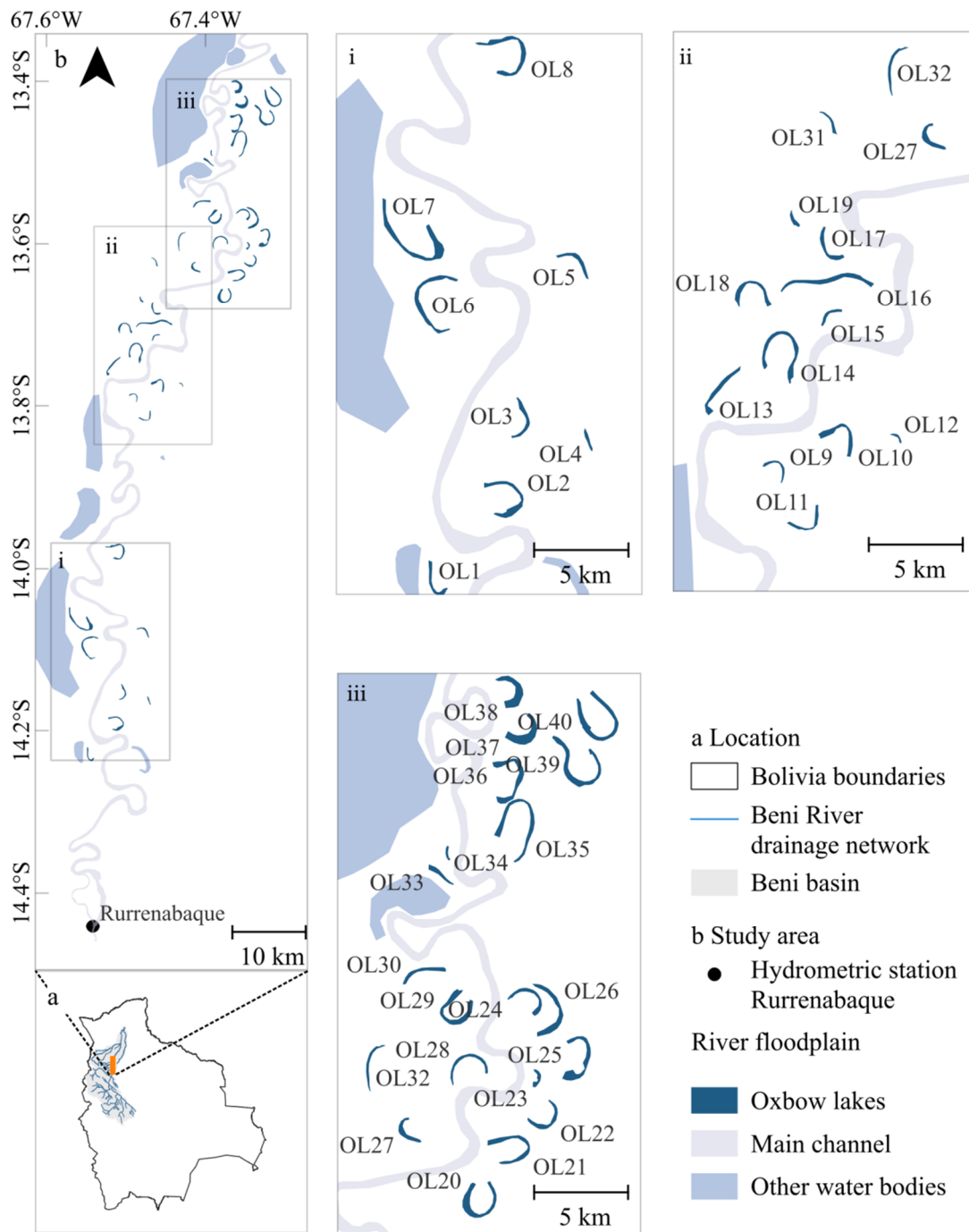


Figure 4.1. a) Location of study area, b) Study reach of the Beni River indicating the location of the hydrometric station Rurrenabaque, oxbow lakes, and water bodies detailed in areas i, ii, and iii.

The hydrologic records at the Rurrenabaque station were obtained from HyBAM (<https://hybam.obs-mip.fr/>, accessed in early 2022; note that the new platform may provide different access) with observed water levels and calculated discharge from 1989

to 2016. The analysis period was set to coincide with the availability of satellite images from 1999 onward. Water levels were not monitored from October 2016 to 2019, resulting in a data gap for this period. Water level measurements from October 2019 to October 2022 (provided by Servicio Nacional de Meteorología e Hidrología) were used to estimate discharge using adjusted rating curves (Chávez-Flores, 2020). Figure 4.2b presents the boxplot of monthly discharge at the Rurrenabaque station. The year was separated into two periods: October-March with low availability of satellite data and mainly wet conditions, and April-September with high availability of satellite data and primarily dry conditions. The hydrologic year was set to match these months. Figure 4.2c illustrates the daily hydrograph at Rurrenabaque station for the period 1999 to 2022, indicating the capture time of satellite images during these periods.

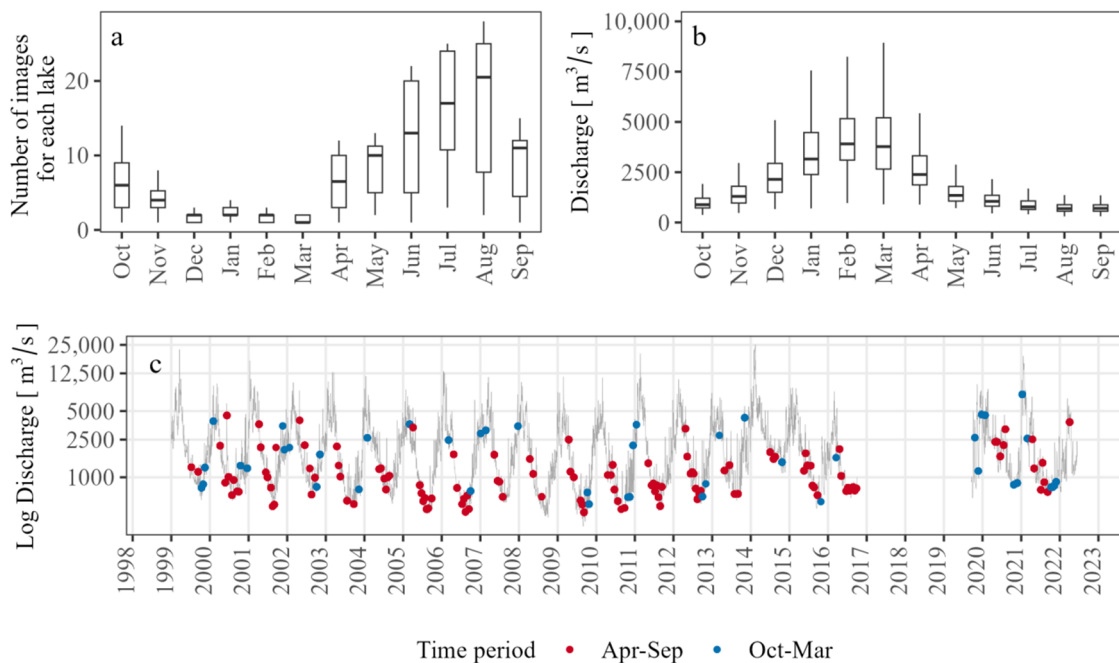


Figure 4.2. a) Boxplot of image count per month per lake, b) Boxplot of monthly discharge [m^3/s] at Rurrenabaque station in the Beni River, c) Daily discharge showing the timing of satellite images: red (April-September), blue (October-March).

4.3 METHODOLOGY

4.3.1 Workflow and conceptualization

Figure 4.3 presents the workflow of this study, indicating how remote sensing analysis of surface reflectance was used to inform habitat characteristics and availability for fish.

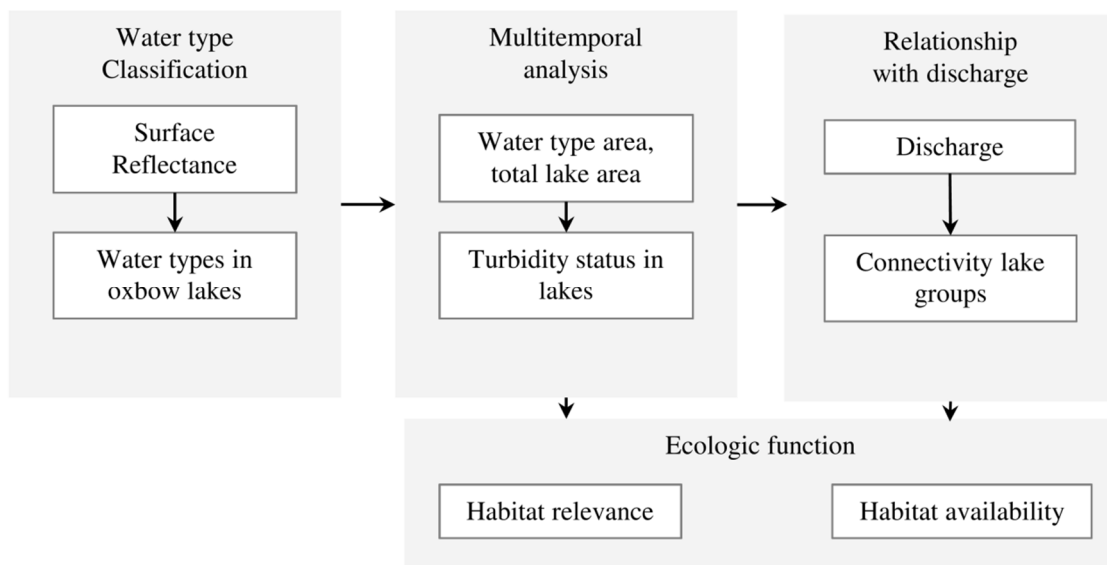


Figure 4.3. Workflow of analysis

4.3.2 Classification of water types

The water type classification aims to distinguish turbid from clear water in the oxbow lakes, which we interpret as reflecting changes in suspended sediment. The land cover and water types listed in Table 4.1 represent the dominant classes in the study area. We selected an image from the receding-water period (4 April 2022) because it contains a balanced combination of exposed sand, clear water, and turbid water, capturing spectral variability that is absent during peak flood or extreme dry conditions. Using an image with a broad set of spectral responses provides a robust basis for defining a representative classification scheme for oxbow lakes (see additional analysis of the spectral variability in this image in Terrazas-Villarroel et al. 2026b).

Class separation was guided by commonly used spectral indices. Vegetation was identified using the Normalized Difference Vegetation Index (NDVI) (Berveglieri et al., 2021; Rouse et al., 1974), exposed sand using the Normalized Sand Index (NSI) (Secu et al., 2022), and water bodies were first separated by hydromorphological setting (lotic main channel from lentic oxbow lakes). Water in the main channel showed a stronger influence of the Near Infrared (NIR) band, while within oxbow lakes, a red-band gradient helped distinguish turbid from dark water. Intermediate water types were further separated using the Green/Red band ratio, which is sensitive to chlorophyll production (Ha et al., 2017) as light availability increases when sediment settles (Kirk, 2011; Moore et al., 2014; da Silva et al., 2021a).

Table 4.1. Spectral indices and thresholds to separate land and water types in the image of 4 April 2022

Type	Spectral indices and thresholds
Vegetation	$NDVI = \frac{NIR - Red}{NIR + Red}$, $NDVI > 0.6$
Exposed sand	$NSI = \frac{Green + Red}{\log SWIR1}$, $0.5 < NSI < 0.75$
Turbid water in main channel (WTO)	$0.1 < Red < 0.15$ and $0.1 < NIR < 0.15$
Very turbid water in oxbow lake (WTA)	$Red > 0.15$
Turbid water in oxbow lake (WTB)	$Green / Red < 1$
Water in oxbow lake with chlorophyll	$Green / Red > 1$
Dark water in oxbow lake (WTD)	$Green < 0.05$

NDVI: Normalized Difference Vegetation Index; NSI: Normalized Sand Index; NIR: Near infrared; SWIR1: Short-wave infrared

Figure 4.4 shows the mean surface reflectance values for each water type. The water types in oxbow lakes (WTA, WTB, WTC, and WTD) presented a gradual decrease of surface reflectance across all bands. WTO in the main channel indicated lower surface reflectance than WTA but resembled WTB in the blue and green bands, while presenting higher values in the red and near-infrared.

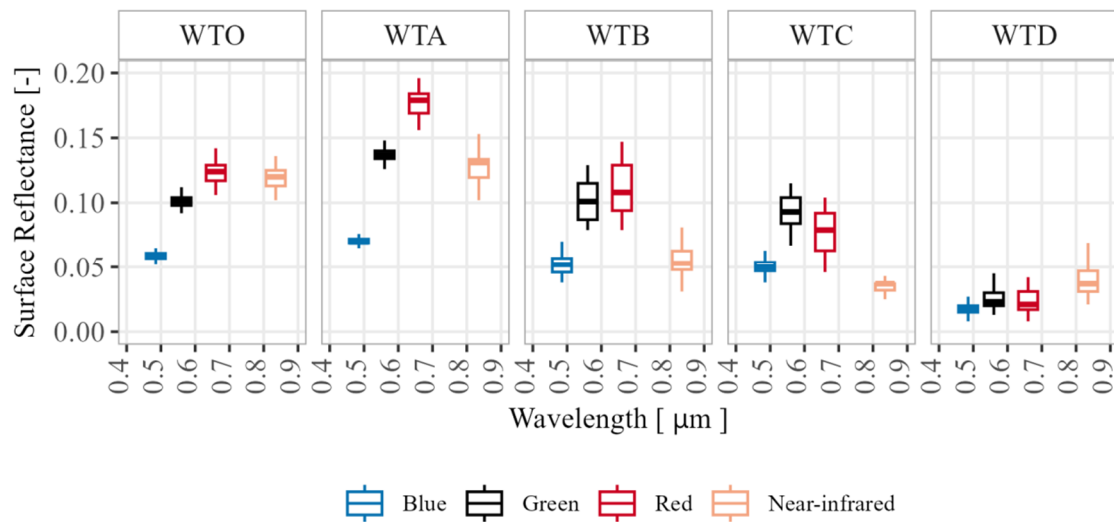


Figure 4.4. Mean surface reflectance of the water types in the blue, green, red, and near-infrared bands

The classification was conducted in GEE using the Landsat 7 ETM+ image for 4 April 2022. For each class, an average of 208 points was identified as training and validation points. The training sample contained 65% of the points, while 35% were used for validation. A random forest algorithm was employed for the classification. This ensemble learning method is based on decision trees that incorporate randomness in their construction (Aggarwal, 2015; Breiman, 2001). This process involves the random selection of training data subsets for each class and the definition of conditional rules using input variables, in this case, the surface reflectance of each band. These rules start with a root node and split into branches until they reach a leaf node, which represents the optimized probability of the sample belonging to the class. The parameters of the algorithm are the number of trees and the number of variables to consider at each split. They control the structure and randomness level of the forest. The former was set to 50, and the latter was set to the square root of the number of variables. The prediction capacity of the random forest is the mean response from the regression trees. The internal classification consistency for the selected image was assessed with a confusion matrix and overall accuracy metrics. Additionally, the feature importance of each variable (surface reflectance in each band) was evaluated.

4.3.3 Multitemporal analysis approach

The classifier tree derived from the water type classification was applied to the preprocessed collection of images from 1999 to 2022. Afterwards, the area of each water type and total area were calculated for each oxbow lake throughout the analysis period. In order to allow for comparison among lakes, an area-weighted measure of turbid water types (turbidity status) was calculated for each lake as the percentage of the summed area of turbid water types (WTO, WTA, WTB) relative to the total water area of the lake. The turbidity status was separated into quartiles to categorize the dominant water type of each lake, with 0-24% representing low turbidity, 25-49% moderate low, 50-74% moderate high, and 75-100% high turbidity.

To compare the behavior of similar lakes, both qualitative and quantitative indicators were used to characterize them. Lakes that were modified as a result of the migration of the main channel into their area were identified, along with the year of alteration. Lake age was categorized into three groups based on the formation year identified through the historical imagery in Google Earth Pro: old (before 1999), middle-aged (1999-2013), and recent (after 2014). Dynamic characteristics, such as the distance from the closest plug bar to the continuously migrating main channel (along the direction of the connecting channel), were distinguished for the years 1999 and 2020 as close (<1300 m), medium (1300-2600 m), or far (>2600 m), and the change between those years as closer or farther. The recent lake area, calculated as the mean value over three years (2019-2022), was categorized into three size intervals: <1, 1-2, and >2 km². The relative

frequency (%) of the turbidity status for each lake was aggregated over the study period, allowing lakes to be classified as primarily turbid lakes (frequency of low turbidity status lower than 33%), mainly clear lakes (dark and green, frequency of low turbidity status higher than 67%), or intermediate.

The multiannual analysis of lake area and turbidity status was divided into the two data periods (dry and humid). For the turbidity status, the most frequent status for each time step (month or year) was identified, and its relative frequency (%) was calculated across all lakes for the same time step. For the area analysis, the mean monthly difference (%) relative to the mean annual area was calculated for each lake and later averaged across all lakes. The annual area difference (%) was calculated relative to the recent area, and the variability was aggregated across all lakes. Finally, the dynamics of both variables in time, the timing of changes, and trends were associated with lake characteristics.

4.3.4 Evaluation of the relationship with discharge

The relationship between discharge at the Rurrenabaque station and the variables in the oxbow lakes was evaluated through various steps. First, the mean monthly and annual variability of discharge, lake area, and turbidity status were compared to identify multitemporal trends and interpret interlinked processes. Then, water types during an extreme hydrologic year were described to identify the causes of turbidity changes. For each lake, the relationship between area changes and discharge was evaluated in scatter plots, and similar patterns were used to group lakes. Finally, these patterns allowed an interpretation of the dominant hydrologic processes that cause area changes, and the identification of lakes in which overflow from the main channel is more relevant.

4.3.5 Interpretation of ecological functions

The availability and relevance of oxbow lakes as aquatic habitats were evaluated based on the aspects highlighted in the analysis of fishers' knowledge in (Terrazas-Villarroel et al., 2026a). In regards to fish habitat preference, fishers indicated that water clarity is associated with fish body cover, which also reflects the meat quality. The preferred scaled fish are commonly found in clear waters, in contrast to skin-covered fish that are mainly present in turbid waters.

Figure 4.5 presents fishers' descriptions of fish migration patterns of native species and non-native *Arapaima gigas* (locally known as paiche). The year is divided into four periods: dry (July to October), rising waters (November to December), flooding (January to March), and receding waters (April to June). During the dry period, native fish species carry out their upstream reproduction migration along the main channel. As water levels rise, eggs drift, and juvenile fish migrate downstream, where connectivity from the main channel to the oxbow lakes allows them access to grow in these water

bodies. During the flooding period, fish disperse into more distant oxbow lakes and flooded depressions. As water levels recede in the main channel, return flow from the oxbow to the main channel cues fish to begin their upstream migration again.

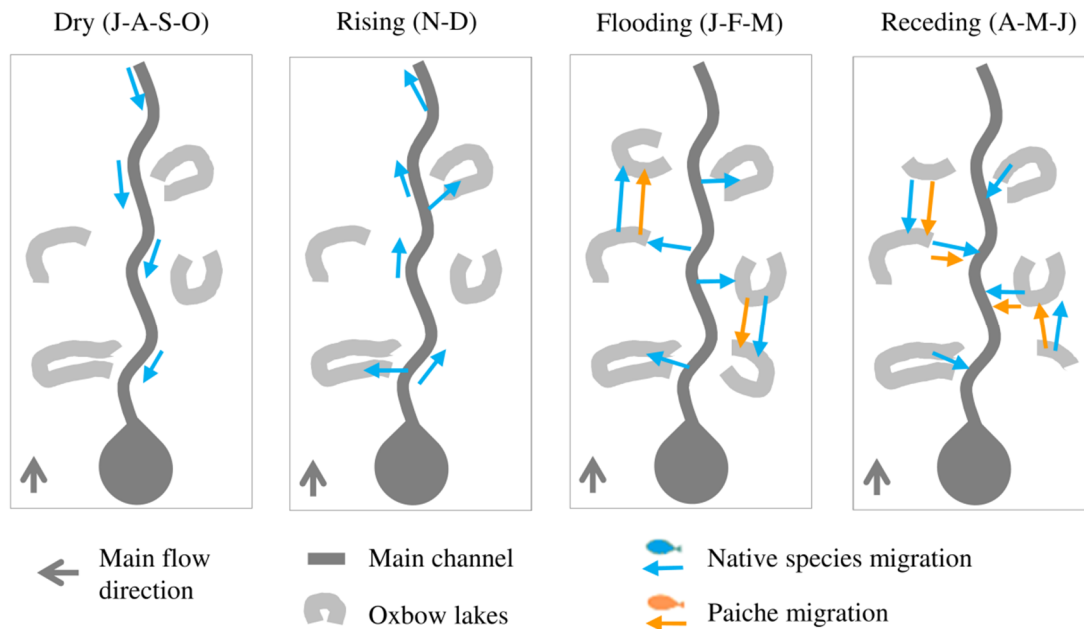


Figure 4.5. Conceptual model of Beni River connectivity and fish migration patterns of native species and the non-native paiche across hydrologic periods as described by the fishers (adapted from Chapter 3).

In contrast to the native fish species, fishers stated that the paiche primarily migrates between the main channel, oxbow lakes, and flooded depressions (bajíos) during the flooding and receding periods, completing most of its life stages in the oxbow lakes. For this species, the extent of flooding, both interannually and seasonally, is key to exploring new lakes, accessing food resources, and shelter in flooded depressions.

The selected satellite and hydrologic datasets allow the representation of physical habitat features that influence the ecological function of oxbow lakes. For instance, a seasonal increase in flooded area and shift to a turbid water type would reflect an increase in water input caused by overflow from the main channel (hydrologic connectivity), which enables fish access to oxbow lake habitats for refuge and food resources. In addition, the satellite-based classification of clear and turbid water types allows us to associate oxbow lakes and their most frequent water type with fish species based on their water type preferences. Furthermore, the water level variability in the main channel indicates periods of potential hydrologic connectivity or disconnection.

4.4 RESULTS

4.4.1 Water type classification results

Figure 4.6a presents the Landsat 7 ETM+ image (4 April 2022) in area iii, while Figure 4.6b shows the classified water types in each lake. Feature importance analysis identified near-infrared reflectance (31%) and the red band (20%) as the most relevant classification variables. The internal consistency check showed high agreement (99%) for the selected image, noting that both training and validation samples belong to the same date.

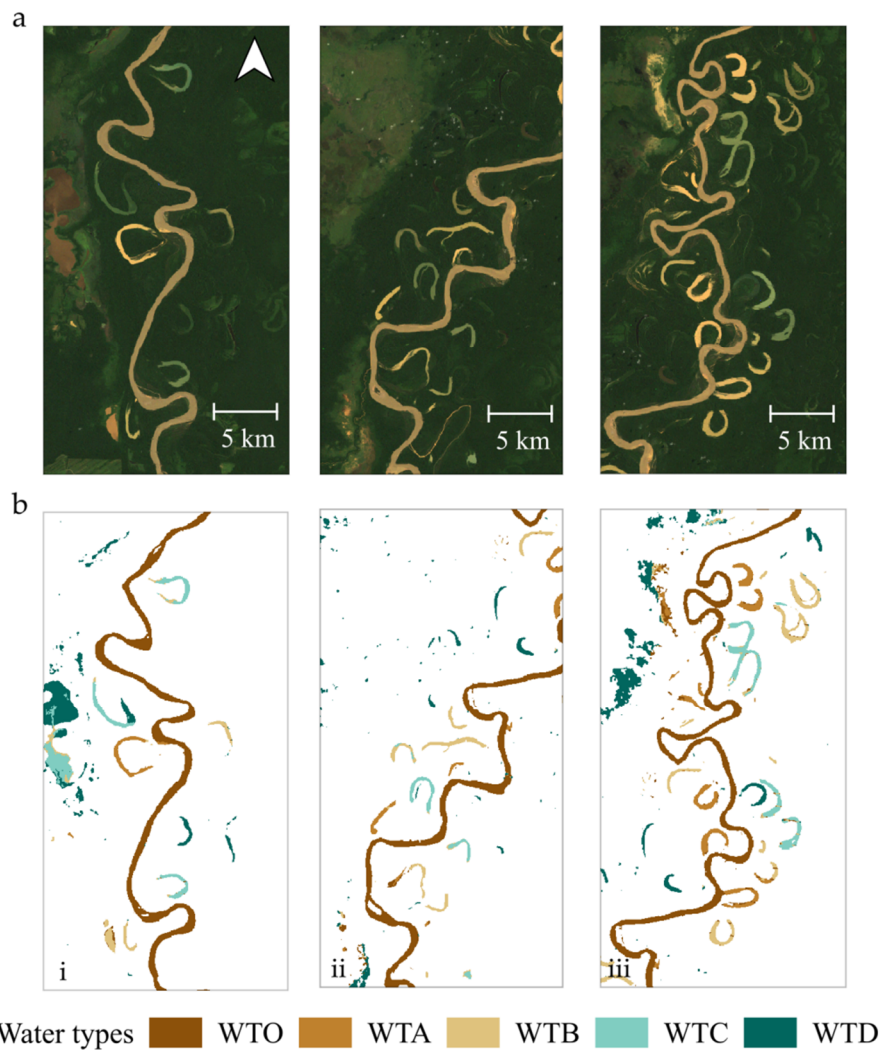


Figure 4.6. a) Red, green, blue (RGB) composite of Landsat 7 ETM+ image of 4 April 2022 in areas (i–iii), and b) classified image of water types in areas (i–iii).

4.4.2 Multitemporal patterns of lake area and water types

Table B.1 in Appendix B presents all lake properties, and Figure 4.7 illustrates important aspects: a) satellite data availability (1999–2022), b) mean recent lake area (2019–2022), and c) turbidity status frequency % (1999–2022). Most oxbow lakes (23 of 40) were formed before 1999, with additional formations in 2001, 2005, 2008, and 2012–2018. Nine of these recently formed lakes were altered by main channel migration (AMC) into their area (2011 and 2019). Among the fifteen smallest lakes (<1 km²), a few remained far from the main channel (6), while others suffered alterations (6). Nine lakes, mostly old (7) and distant to the main channel (2), present a more frequent low turbidity status (clear). In contrast, ten lakes are primarily categorized as high turbidity (turbid), displaying formation or alteration post-2012 (6). No clear relationship exists between turbidity status and the recent lake area.

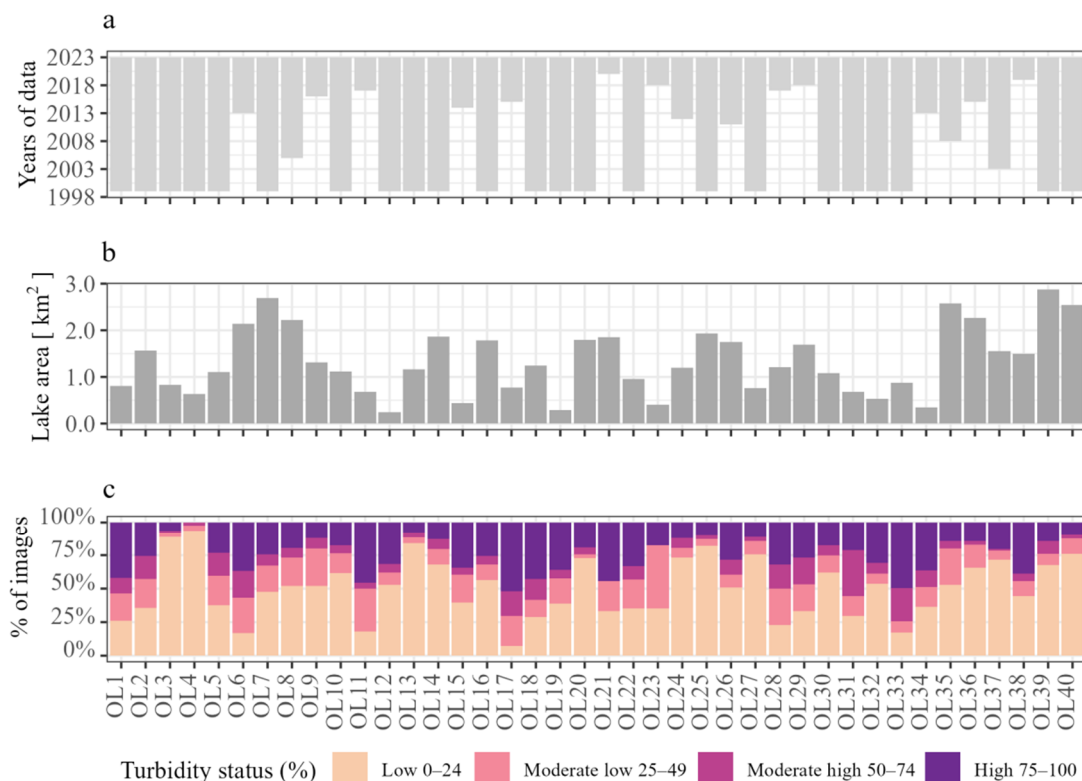


Figure 4.7. a) Satellite data availability for each lake (1999 to 2022), b) Mean recent lake area (2019–2022), c) Turbidity status frequency (%) for each lake (1999 to 2022).

Figure 4.8a presents the most frequent monthly turbidity status for each lake. Low turbidity status is predominant in most lakes at the beginning of the dry period. This status is reached at different timings and persists for distinct months. Notably, 12 recently formed lakes (or altered) show late transition (June–July) and only 2 months of clear water status. The shift to intermediate turbidity status begins in August, September,

and October for 15, 8, and 6 lakes. There are also four lakes (OL17, OL21, OL1, OL6) that consistently exhibit high turbidity year-round.

Figure 4.8b presents the annual turbidity frequency (%) across all lakes for the dry period (based on 101 valid images for at least 15 lakes compared to 18 images during the wet period). There were insufficient images for 1999, 2008, 2014, and 2022. Low turbidity prevailed (25-52% of images) in 2007, 2009-2010, 2013, and 2018. In contrast, high turbidity status was more common (25-30% of images) in 2000-2003, 2006, 2011, 2015-2016, and 2019-2021.

These multitemporal results indicate that turbidity dynamics are strongly seasonal and suggest a link to lake age and alteration with the main channel.

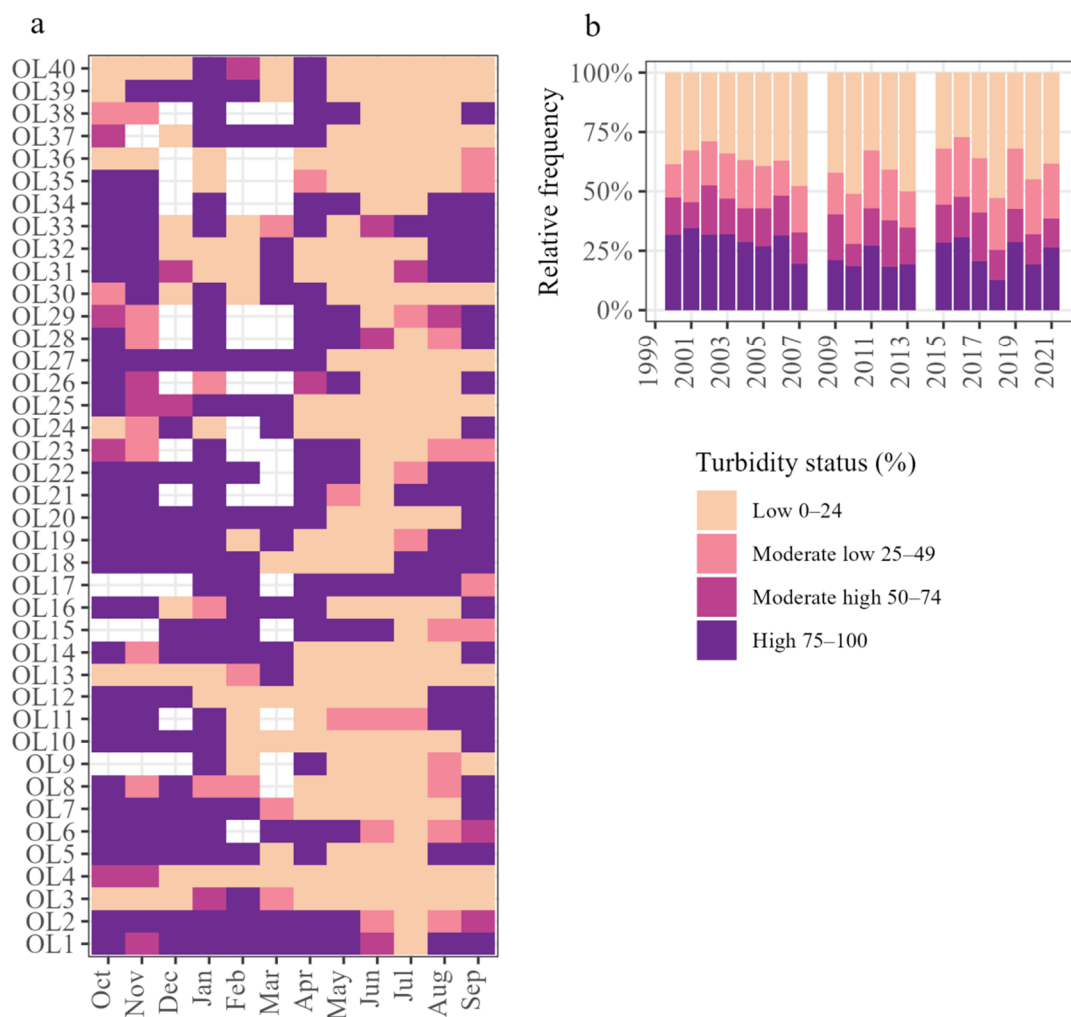


Figure 4.8. a) Most frequent monthly turbidity status, and for the dry period (April–September), b) Multiannual turbidity status frequency (%) across all lakes.

Figure 4.9a illustrates the mean monthly area difference (%) compared to the annual mean for each lake. Most lakes exceed the mean from January to July, showing mixed values during January-March due to limited satellite imagery. In contrast, a majority of lakes present small differences below the mean from August to December. Lake area variability is low, medium and, high for 21, 13, and 6 lakes (mainly turbid OL6, OL9, OL28, OL31, OL32, and OL33).

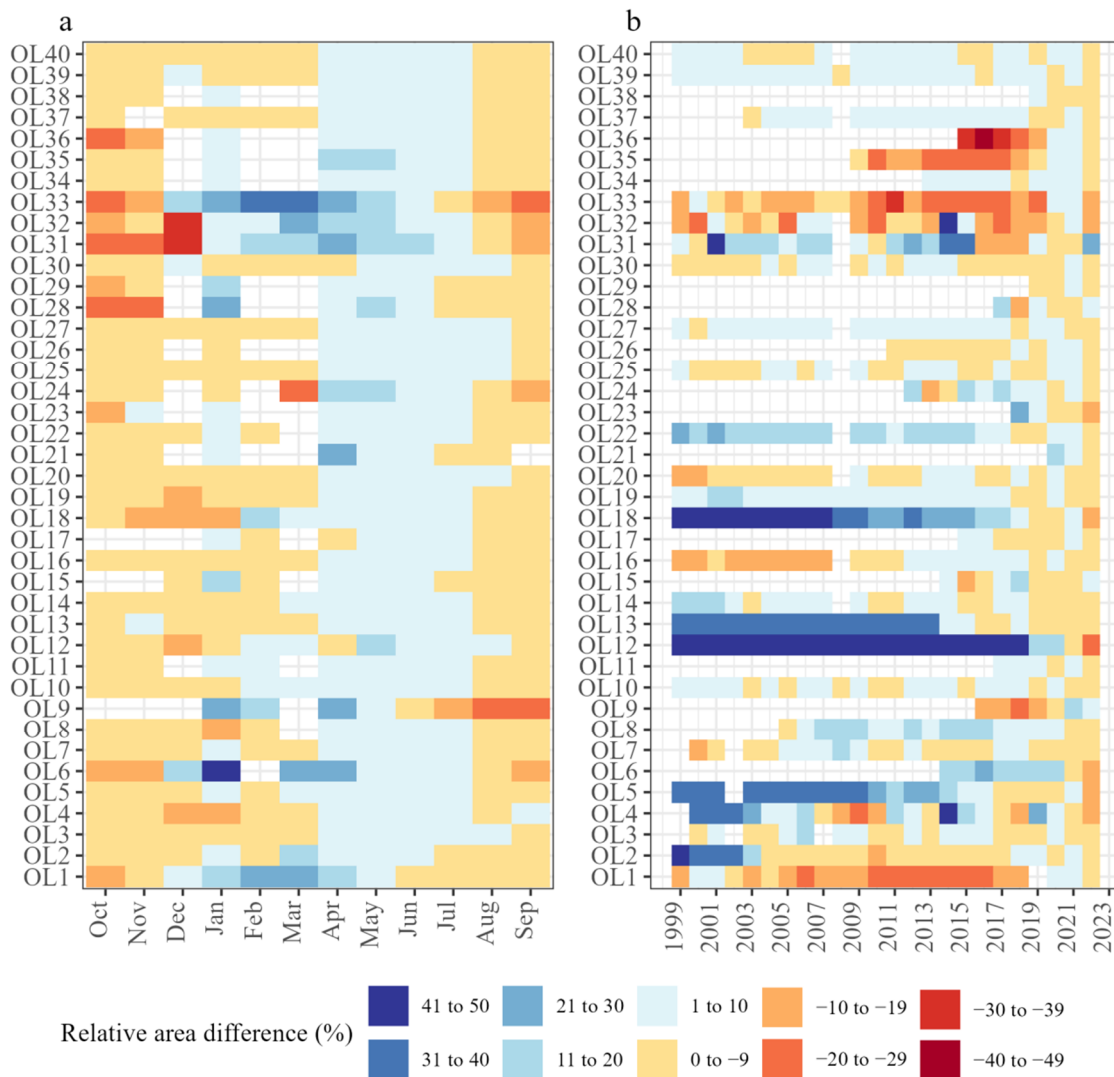


Figure 4.9. a) Mean monthly area difference (%) compared to the annual mean, b) mean annual difference (%) relative to the recent area (2019–2022).

For multiannual trends, only dry-period data were used. Figure 4.9b presents the mean annual difference (%) relative to the recent area (2019–2022), indicating different trends: decreasing (positive difference for 11 lakes), increasing (negative difference for 5), mixed high variability (8), or stable (15). Eleven lakes decreased in area (notably OL5, OL12, OL13, and OL18), presenting old age (8) and medium to far distance to the main

channel. In contrast, five lakes (OL1, OL16, OL33, OL35, and OL36) slightly expanded, displaying medium to high turbidity.

4.4.3 Discharge relationship with lake area and water types

The multitemporal comparison of discharge, lake area, and turbidity status is presented in Figure 4.10. The mean monthly lake area difference (Figure 4.10b) presents a break in February due to limited satellite imagery. The increase in lake area coincides with the rising discharge (Figure 4.10a) and remains above the mean until June, indicating the role of lakes as water storage.

Figure 4.10c shows that low turbidity status frequency (%) peaks in June-July, but high turbidity status sharply increases in September and persists into the rising and flooding periods, despite lake area continuously reducing until October.

Annual discharge variability (Figure 4.10d) is mainly coherent with mean annual lake area differences (%) with the recent area (Figure 4.10e, calculated with dry period data). Coincident lows occur in 2000, 2010, and 2016; while highs coincide in 2001 and the extreme year 2014. Figure 4.10f shows that annual turbidity status frequency (%) across all lakes is predominantly high during the wet period (45-75%), which considerably exceeds dry-period values (Figure 4.8b). Notably, high turbidity years include 2000, 2003, 2006, 2015- 2016, 2019, and 2021, while lower values appear in 2005, 2010, and 2018, only coinciding with discharge lows in 2005 and 2010. This comparison is limited due to data gaps (2008-2009, 2014, and 2018) and the complex processes that affect lake behavior.

The transition of dominant water types was analyzed for the extreme hydrologic year 2020-2021. Figure 4.11a shows the hydrograph, indicating two satellite images: one during flooding (7500 m³/s) and another at the end of the dry period (900 m³/s). A middle-reach area was selected for analysis. Figure 4.11c illustrates the satellite and classified images, and Figure 4.11b displays the dominant water type per date and oxbow lake. During flooding, the dominant WTA indicates high turbidity associated with high discharge for all visible lakes. In contrast, at the end of the dry period, five lakes transition to clear WTC and dark WTD, while four lakes display turbid WTB, especially near the point bars.

Figure 4.11d illustrates a similar spatial variability in OL8 and OL29 using a high-resolution image from November 2020 (accessed from Google Earth Pro, ©2020 Maxar Technologies) and the corresponding satellite and classified images. The high-resolution image reveals a trace of suspended sediment originating from point bars, likely due to wind action, extended evaluation of this driver is presented in Terrazas-Villarroel et al. (2026b). These results emphasize the influence of wind at the beginning of rising waters and highlight the multiple drivers of turbidity dynamics in the oxbow lakes.

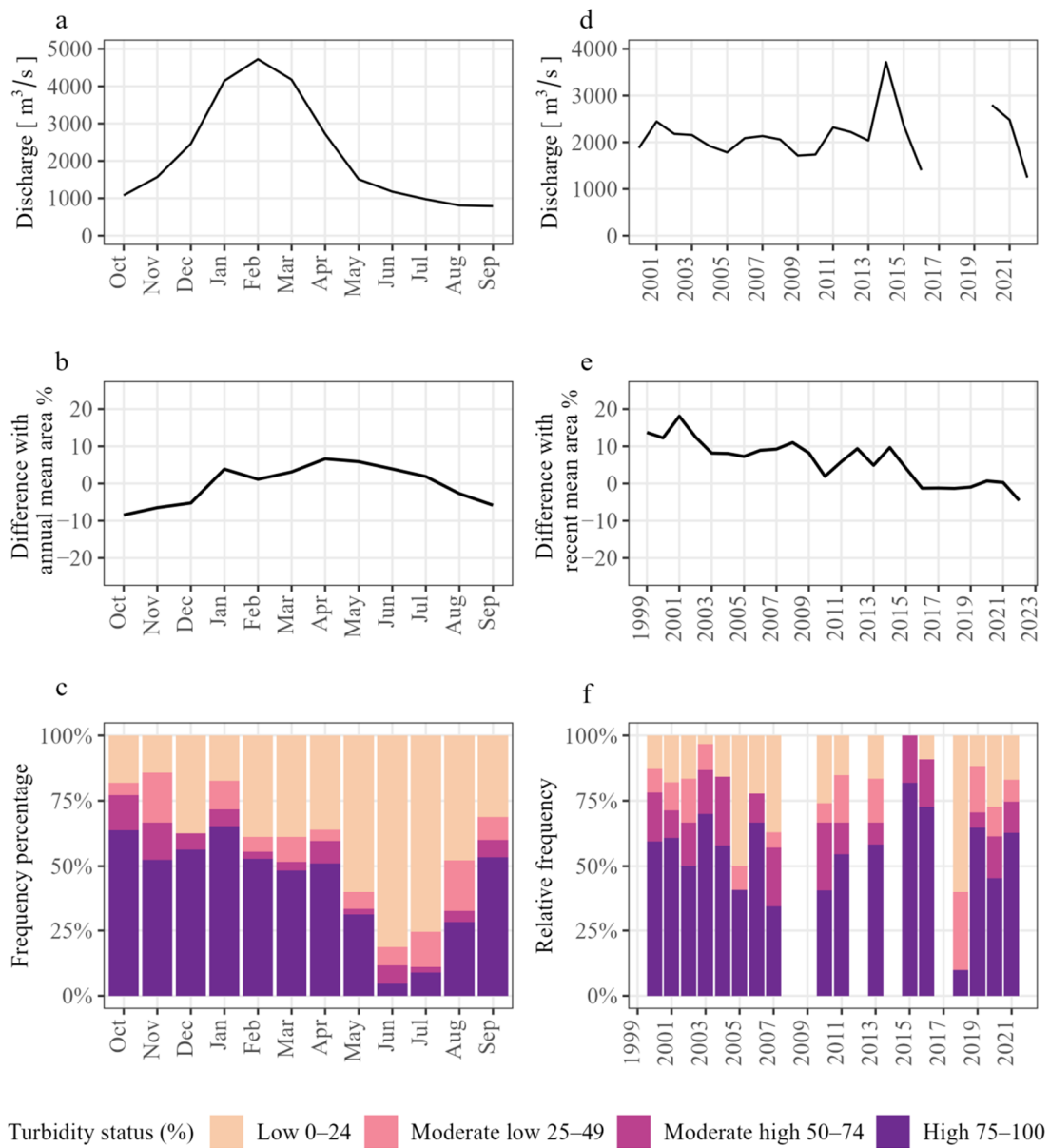


Figure 4.10. a) Mean monthly discharge at Rurrenabaque, b) Mean monthly area difference (%) with mean annual across all lakes, c) Monthly turbidity status frequency (%) across all lakes, d) Mean annual discharge at Rurrenabaque, e) Mean annual difference (%) with recent area across all lakes, f) Multiannual turbidity status frequency (%) across all lakes in the wet period (October–March).

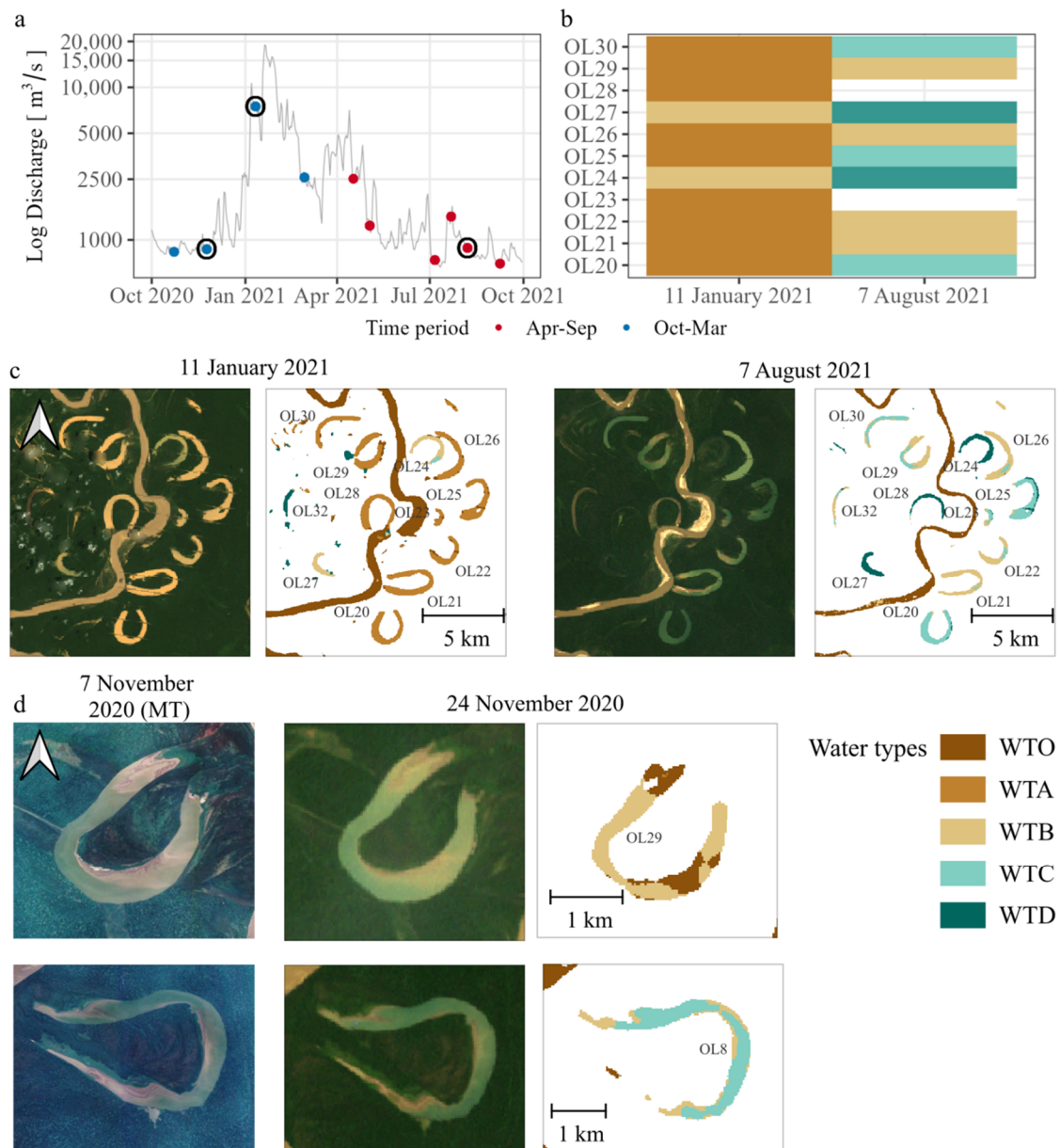


Figure 4.11. a) Hydrograph for 2020–2021, indicating satellite images in wet and dry periods. For selected dates 11 January 2021 and 7 August 2021 (marked by the two rightmost black circles): b) Tile plot of dominant water type in each lake, and c) satellite (Landsat-7) and classified images. d) High-resolution satellite image (accessed from Google Earth Pro, ©2020 Maxar Technologies) for 7 November 2020 and lakes OL29 and OL8, satellite (Landsat-7), and classified image for 24 November 2020 (indicated by the leftmost black circle).

Figure 4.12 presents the relationship between discharge at Rurrenabaque (y-axis, logarithmic scale) and lake area difference from the annual mean (x-axis, %), with dot colors indicating dominant water types.

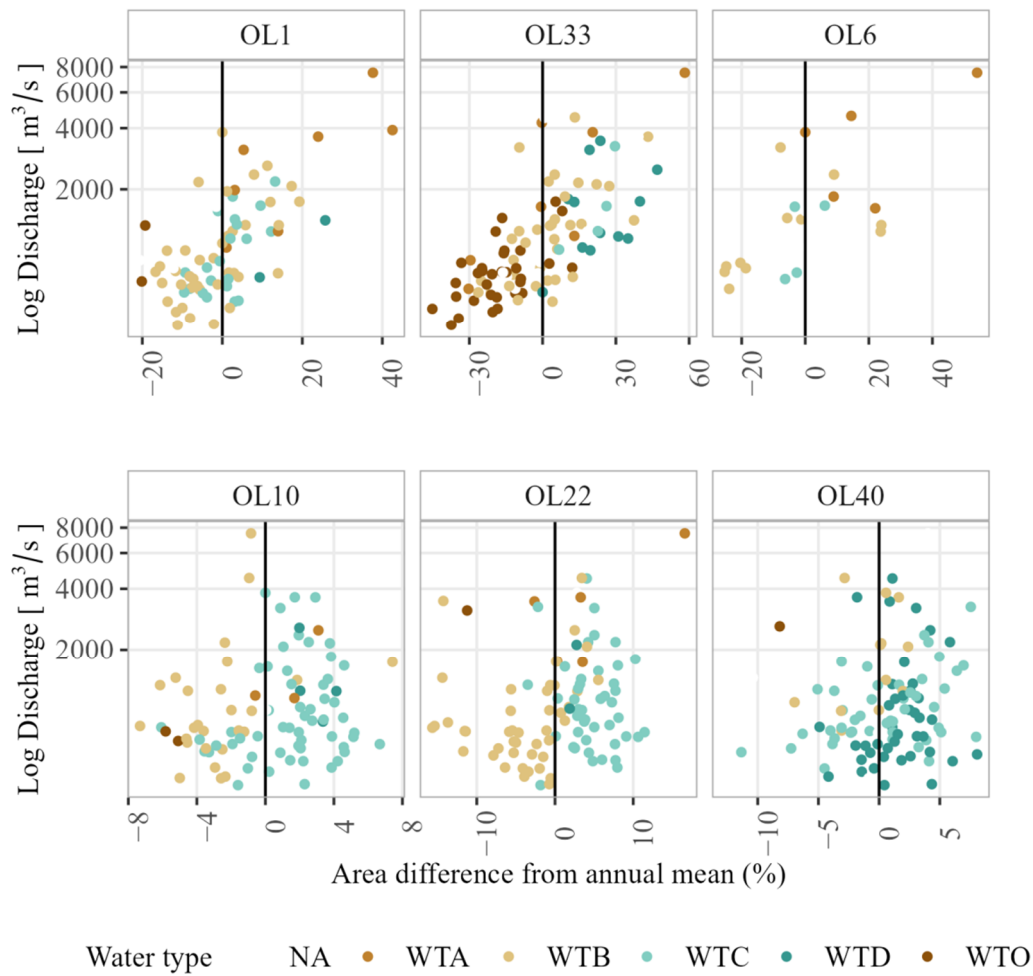


Figure 4.12. Scatter plot of area difference from annual mean (%) versus discharge (logarithmic scale), with dominant water type indicated by color for selected lakes. The black vertical lines indicate the zero value in the x axis.

Table B.1 (Appendix B) presents the Pearson correlation coefficients for each lake and their statistical significance, assessed using a two-sided t-test (p-value and sample size). The correlation coefficients were used to categorize lakes into three groups:

- Group 1 (>0.4): fourteen lakes show a scattered log-linear increase (e.g. OL1, OL6, and OL33), with ten revealing a range of discharge values linked to the area above the mean. Most of these lakes (8) are recently formed, close to the main channel, and predominantly turbid;
- Group 2 (>0.1 and ≤ 0.4): thirteen lakes that exhibit a distinct separation of turbid and clear water types, corresponding to areas below and above the annual mean, respectively (e.g. OL10, OL22);

- Group 3 (≤ 0.1): thirteen lakes predominantly older, clear-water with minimal area changes (e.g. OL40) that have the least direct influence from main channel overflow.

The categorization of recent lakes may change over time in response to river dynamics, particularly the migration of the main channel relative to lake position. Thus, the correlation analysis should be updated in future assessments.

4.4.4 Relevance of oxbow lakes as fish habitat

The relevance of oxbow lakes as fish habitat was evaluated based on characteristics in Table B.1, Appendix B. The total lake area is 53 km², with 22% categorized as turbid, mainly in recent oxbow lakes close to the main channel, 56% intermediate, and 22% categorized as clear waters, mostly found in old lakes. These distinctions can be useful to design experimental studies to assess specific-species water type preferences along the Beni River, and compare with fishers' observations that associated turbid waters with skin-covered fish, and clear water types with scaled fish (Terrazas-Villarreal et al., 2026a).

Habitat availability to fish species migrating from and to the river was derived from assumptions about surface hydrologic connectivity based on relationships between area changes, water type, and discharge. The total available habitat area of oxbow lakes is 49 km², distributed as 13.7 km² in Group 1 (28%), 15.2 km² in Group 2 (31%), and 20.1 km² in Group 3 (41%). Group 1 lakes display the highest correlation with discharge and have a direct influence on overflow during most of the year. In contrast, Group 3 lakes have the least frequent connectivity only during bankfull discharge, as evidenced by the changes in water type in Figure 11. Group 2 lakes represent an intermediate scenario in which the lack of discharge correlation and the presence of clear water, while exceeding the mean annual area, may indicate overflow with lower suspended sediment after settling along the connection channel. In addition, the occurrence of turbid water types below the mean area is associated with wind-driven resuspension during the dry and rising periods.

For native fish species, Group 1 lakes are relevant as early and late connectivity provide additional migration opportunities. For instance, juvenile species born early can access these habitats during the rising period, and species that reproduce late or undertake a second reproductive migration (e.g. *Prochilodus nigricans* as observed by the fishers along this Beni River reach, see Chapter 3 Section 3.3.3) can access them during the receding period. For *Arapaima gigas*, which primarily inhabits oxbow lakes, Group 3 lakes serve as important refuges, as their primary medium distance from the main channel reduces accessibility and minimizes the risk of alteration from channel migration, providing a more geomorphologically stable habitat.

In summary, the three lake groups reflect distinct patterns in area variability, water type trends, and relationship with discharge. These trends provide a quantitative basis to differentiate their hydrologic behavior and ecological function

4.5 DISCUSSION

This chapter has addressed SO₂ by analyzing spatiotemporal dynamics of oxbow lakes and by evaluating how hydrologic variability influences their role as aquatic habitats. The main results showed that water type and lake area dynamics are associated with different lake properties, reflecting different trajectories of lake evolution. Lake groups distinguish recent lakes near the main channel with more frequent connectivity than older lakes, which mainly connect during bankfull discharge. These patterns highlight the importance of natural flooding dynamics for habitat availability and river-floodplain ecological functions.

The variability in surface reflectance among water types is consistent with regional classifications, with high relevance of red and near-infrared reflectance for turbid waters (Gholizadeh et al., 2016; Montanher et al., 2014). Higher surface reflectance of turbid water WTA compared to WTO results from higher scatter from finer sediment particles in the surface layer of the main channel that are transported to the lakes (Bhargava and Mariam, 1991; Kwon et al., 2023; Novo et al., 1989). In addition, shallower depths of oxbow lakes compared to the main channel contribute to higher surface reflectance from the bottom (Zhang et al., 2018).

Most oxbow lakes showed an intermediate turbidity (proxy) category, followed by clear and turbid, evenly distributed (Figure 4.7). Turbidity was mainly associated with lake age and distance from the main channel (Figure 4.8 and Table B.1), similar to a previous study (Güntzel et al., 2020). The analysis of discharge, lake area, turbidity status, and wind speed at the seasonal and event time-scale (Figure 4.10 and Figure 4.11) suggested that monthly turbidity changes were driven by hydrologic connectivity during the flooding period and by wind causing sediment resuspension in the dry period. Lakes with less frequent connectivity are likely to experience stronger wind-driven effects. The role of other processes, like rainfall erosion, requires further exploration (Gautier et al., 2010).

Multiannual lake area changes primarily follow typical oxbow lake life stages (Figure 4.10), with sedimentation at point bars narrowing the inner bank and reducing the lake area (Toonen et al., 2012). These sedimentation rates depend on hydrologic connectivity and lake geometry, with frequent flooding and higher rates in the early stages (Hudson et al., 2012; Wren et al., 2008) and lower rates as the main channel migrates away, which extends the connection channel and reduces its sediment conveyance efficiency until the lake area stabilizes (Citterio and Piégay, 2009; Gautier et al., 2007; Schwendel

et al., 2018). These area trends are similar to recent regional observations (Ahmed, 2024). A few lakes, however, experienced erosion due to main channel alteration (Figure 4.9 and Table B.1). In these cases, overbank flow through the lake prevented sediment deposition and induced erosion, increasing the lake area.

Lake area changes are coherent with mean annual discharge trends (Figure 4.10), especially during low-flow years. Monthly lake area changes correlated well with discharge (Group 1) for recent lakes close to the main channel, while no correlation was found (Group 3) for older lakes located at a medium distance from the main channel (Figure 4.12). These patterns are coherent with previous studies evaluating relationships among lake age, distance from the main channel, and discharge (Hudson et al., 2012; Terborgh et al., 2018). For that reason, lake categorizations based on similar correlation analysis should be periodically reassessed as river dynamics evolve.

Hydrologic connectivity was represented by diverse processes and their interaction with lake properties, with turbidity changes highlighting notable sediment input during hydrologic events exceeding bankful discharge ($>6000 \text{ m}^3/\text{s}$ (Gautier et al., 2010) as shown in Figure 4.11). The influence of smaller events could be masked with wind-driven sediment resuspension. Monthly lake area and water type patterns suggest low-sediment water input likely causes hydrologic connectivity (Figure 4.12), potentially linked with lower discharge peaks, sediment settling along connection channels, or backwater effects. Additional water sources, such as rainfall, may extend connectivity duration (Mertes, 1997). The influence of each driver and flow direction depends on the hydrologic period. For instance, during the rising water period, a discharge threshold in the main channel is associated with connectivity, while during the receding period, thresholds of lake area or rainfall may represent connectivity to the main channel. Further studies are needed to improve understanding of the interactions among these drivers, particularly for lakes in groups 2 and 3.

At the regional Amazon scale, differences in water types and their associated physicochemical properties have shown to influence fish community composition and fish species distribution (Bogotá-Gregory et al., 2020; Borges et al., 2023). Along the Beni River system, oxbow lakes exhibited distinct water types, ranging from clear to turbid conditions. This categorization may provide a useful basis for defining fish sampling sites and assessing if water types are associated with differences in fish composition within the system. Such results can be compared with fishers' observations, who associated turbid waters with skin-covered fish and clear water types with scaled fish (Terrazas-Villarroel et al., 2026a).

Habitat availability was assessed considering the connectivity-based lake groups with Group 1 lakes providing the highest duration and Group 3 lakes acting as key refuges, and Group 2 lakes as intermediate (Figure 4.12). Thus, these three lake groups serve as functionally distinct fish habitats with varied hydrologic connectivity, which highlights

the complementary role of diverse oxbow lakes in supporting fish species with different life traits in the Beni River system. Other studies have evaluated the role of connectivity, turbidity levels, and lake characteristics as indicators of fish assemblages (Goetz et al., 2015; Miranda, 2005; Osorio et al., 2011), highlighting higher fish richness associated with higher connectivity levels (Virgilio et al., 2020). Further studies are needed to evaluate whether these relationships are representative of the Beni River.

These ecohydrologic insights can inform river management practices. The observed influence of hydrologic variability on habitat availability (through surface connectivity) highlights the importance of preserving natural flood dynamics in the river. These dependence links should be considered when evaluating potential hydrologic alterations, such as hydropower development. Flow regulation by dams typically dampens the seasonal hydrograph by reducing peak flows and increasing discharge in the dry period. These changes would lead to reduced flooded area and differentiated loss of oxbow lake habitats, as high (discharge) connectivity thresholds are no longer surpassed. Group 1 and 2 lakes, which rely on frequent and moderate connectivity, would experience fewer connectivity events. In contrast, Group 3 lakes that mainly connect during bankfull conditions would be vulnerable to permanent disconnection. These changes would block migratory routes of native species and diminish the extent of paiche habitat. Therefore, management strategies should incorporate connectivity thresholds of oxbow lakes to preserve hydrologic connectivity and mitigate habitat loss.

In general, habitat conservation strategies should ensure annual connectivity to all lakes and prevent lake infill in those with decreasing areas. Also, designating protected oxbow lakes based on species preferences can help maintain balanced trophic dynamics. Overall, the different turbidity and connectivity dynamics among oxbow lakes highlight their diversity and complexity as aquatic habitats for fish and their importance in preserving the ecological integrity of the river system.

Satellite data limitations include seasonal gaps during the flooding period (December–March), leading to underestimation of the frequency of turbid water types linked to hydrologic connectivity, as well as lower estimates of mean annual lake area and its correlation with discharge. In addition, the 15-day interval between satellite images hides short-duration events, resulting in missed short-term connectivity during the rising and receding periods. The 30 m resolution of Landsat 7 ETM+ also limits detection of narrow connection channels and fine scale area changes, leading to underestimated lake area variability. Overall, these limitations produce conservative estimates of connectivity. Nevertheless, the main seasonal patterns and relative differences among lakes are expected to remain robust, as they are derived from multitemporal observations.

Analyses limitations of water type classification may mistype transitional pixels (such as wet sand during receding waters or dark vegetated water). Also, the discharge

analysis omits flood wave travel and water mixing times (hours to days), which may result in satellite images capturing lagged hydrologic conditions. In addition, the interpretation of connectivity relying on the sediment-rich character of Andean–Amazon tributaries is site-specific. Therefore, relationships between turbidity proxies and connectivity may not be transferred to clear-water systems or algae-dominated lakes. Lastly, the complex interaction of hydrologic connectivity drivers requires further evaluation through field validation.

Our study provides innovative insights into oxbow lake dynamics by integrating remote sensing and hydrologic data to assess connectivity, turbidity, and habitat availability. The integration of lake area and turbidity as indicators of hydrologic connectivity and their relevance to fish habitat offers a novel approach for evaluating aquatic ecosystems. The study highlights the separation of processes driving turbidity changes, such as overbank flow and wind-driven sediment resuspension, which are often difficult to distinguish. In addition, the classification of lakes into connectivity-based groups (1, 2, and 3) provides a new framework for understanding their ecological roles, particularly in supporting fish migration and refuge habitats. The study also distinguishes the atypical behavior of oxbow lakes altered by a highly dynamic main channel, extending the knowledge of oxbow lake evolution. These findings contribute to conservation strategies by emphasizing the need for targeted habitat protection based on connectivity and turbidity dynamics, ensuring sustainable fish habitat and ecosystem integrity.

4.6 CONCLUSIONS

This study highlights the complex dynamics of oxbow lakes in the Beni River, as reflected by relationships among lake properties, hydrologic processes, and sediment-related proxies. Turbidity levels are associated with lake age, distance from the main channel, and inferred connectivity. These patterns are also consistent with wind-driven resuspension processes. Seasonal and long-term lake area changes reflect different patterns of lake evolution, influenced by differences in connectivity, sedimentation, and alteration by the main channel. The identified lake groups distinguish recent lakes near the main channel that experience frequent connectivity from older lakes that mainly connect during bankful discharge. These ecohydrologic insights suggest higher habitat availability during flooding conditions and highlight the importance of natural flooding dynamics. Overall, understanding the diversity of oxbow lake dynamics provides valuable ecohydrologic insights for river-floodplain management and the preservation of ecological functions in these systems.

5

ECOHYDROLOGIC RELATIONSHIPS AND DAM SCENARIOS

This chapter addresses two specific objectives of this thesis (SO3 and SO4). First, it focuses on SO3 by defining ecohydrologic relationships through the integration of fishers' local knowledge with the characterization of oxbow lake habitats derived from remote sensing analysis. Hydrologic indicators were adapted to represent key processes such as hydrologic connectivity in meandering river-floodplains. Then, SO4 is considered by simulating a proposed hydropower project to evaluate contrasting boundary conditions of hydrologic alteration using preliminary data. The purpose of the operation scenarios is to evaluate the response of ecohydrologic functions to distinct levels of hydrologic alteration. These impacts were evaluated for the historical period under two contrasting scenarios: one prioritizing energy production and another prioritizing the preservation of a natural flow regime. The results of hydrologic alteration are therefore interpreted as bounds of potential alteration.

This chapter aims to inform project planning by demonstrating how an integrative approach of multiple knowledge sources can inform ecohydrologic relationships and indicators. These relationships can provide the basis of future flow requirements and impact assessments in data-scarce regions.

5.1 INTRODUCTION

Ecohydrology studies the mutual interactions between hydrologic processes and ecosystems, including the wide variety of services they provide (McClain et al., 2012). This interdisciplinary field helps us understand how river systems support biological diversity and ecosystem services. A key concept in river-floodplain ecohydrology is the flood pulse, which represents the temporal flooding pattern that structures aquatic habitat. It can be characterized by ecologically relevant descriptors such as predictability, frequency, and amplitude (Junk et al., 1989, 2012). In large rivers, multiple components of hydrologic variability interact and influence fish ecology in different ways (Puckridge et al., 1998). For instance, the timing of flood pulses is linked with reproductive stages, while flooding duration affects the development of early life stages. Flow magnitude and frequency regulate habitat access, dispersal opportunities, and colonizing ability. Predictability describes how consistently floods occur with similar seasonal patterns, allowing fish to rely on them and adapt their life cycles accordingly. Multiannual variability shapes community assemblage structure, and prolonged dry periods are often associated with habitat loss and increased mortality. In addition, indicators representative of altered flow conditions can help diagnose or predict ecological outcomes (Bunn and Arthington, 2002; Richter et al., 1996).

Because many ecohydrologic relationships are derived from site-specific studies, they reflect interactions between specific biota, habitat structures, flow regimes and ecological processes that can vary among environmental contexts (Bruckerhoff et al., 2019; Freeman et al., 2022; Lamouroux et al., 2017; Palmer and Ruhi, 2019; White et al., 2022). Consequently, their transferability to other settings, such as tropical meandering rivers and oxbow lake systems, is limited (Hudson et al., 2012; Puckridge et al., 1998). This constraint is reinforced by the practical challenges of conducting experimental studies in large river-floodplains, especially in remote regions. These challenging conditions call for the use of complementary approaches and knowledge sources that enable a contextual representation of river-floodplain processes (Taylor and de Loë, 2012; Wheeler and Root-Bernstein, 2020). For instance, long-term satellite imagery helps to characterize the temporal dynamics and spatial heterogeneity of these systems, overcoming the logistical challenges of field studies (Barbosa, 2006; Fassoni-Andrade and Paiva, 2019). Similarly, the analysis of local knowledge presents a user expert interpretation of ecological processes that may not be captured through field experiments. In addition, local knowledge increases the relevance of research for local communities (Collins, 2007; Stephenson et al., 2016).

Dams modify river-floodplain connectivity by altering natural flow regimes, disrupting sediment transport, and fragmenting aquatic habitats (Forsberg et al., 2017; Wang et al., 2014). These changes reduce the frequency, duration, and extent of lateral connectivity and floodplain inundation, degrading habitat quality and undermining the

multifunctionality of the system (Erős and Bányai, 2020). In meandering river systems, flood regulation by dams can deactivate floodplains, lead to sediment starvation and bank erosion downstream, hinder the formation of oxbow lake plugs, and limit their functionality as aquatic habitats (Marren et al., 2014). Among the most critical ecological impacts is the disruption of fish life cycles, including the blockage of migratory paths, the loss of floodplain habitats for different life stages, and the disturbance of hydrologic cues that synchronize with spawning, feeding, and recruitment cycles (Bunn and Arthington, 2002; Mims and Olden, 2013; Wu et al., 2019). These changes affect fisheries, causing a decline in productivity, reduced size of fish, and interference in breeding patterns (Santos, 2015; Santos et al., 2018).

5.2 METHODOLOGY

5.2.1 Ecohydrologic relationships

The integration process refers to the development of a common ecohydrologic framework linking multiple knowledge sources through common spatial, temporal, and process-based relationships. One source is the knowledge of local fishers about fish ecology (Chapter 3), characterized as experiential, location specific and qualitative. Fishers' knowledge is derived from long-term continuous observations and close interaction with both the river and the fish. The other source is the scientific and quantitative knowledge derived from empirical observations (Chapter 4). These data include long-term hydrometric measurements at a single point and multi-temporal satellite imagery. The remote sensing analysis characterized the habitat dynamics of oxbow lakes and hydrologic variability. Both components were organized according to their relevance to specific fish species or groups, common hydrologic periods, and water bodies. These relationships were later represented using hydrologic statistical indicators. The resulting ecohydrologic relationships therefore represent structured links between ecological processes and hydrologic variability.

In order to represent the qualitative data in a quantitative way, the relevance and suitability of existing hydrologic indicators from the literature were evaluated, focusing on those related to the flood pulse concept, large river systems, and flow regime alterations (e.g. Junk et al., 2011, 1989; Puckridge et al., 1998; Richter et al., 1997). These indicators were adjusted to properly represent the ecohydrologic dynamics in a meandering river with oxbow lakes. Table 5.1 and Table 5.2 list these multiannual and seasonal indicators, and the adjusted versions used in this study to characterize peak flows, low flows, and seasonal variability.

Table 5.1. List of multiannual hydrologic statistical indicators linked to ecological functions relevant to river-floodplain systems

Multiannual hydrologic component	Descriptor	Statistical indicator unit	Ecological function	Adjusted indicator for this study unit
Flood pulse	Magnitude	PEAK m ³ /s (*)	Colonizing ability	Five categories of discharge m ³ /s
Flood pulse	Duration	G4MDHP days (**)	Life stage development	Number of days above the lower limit of five discharge categories days
Flood pulse	Frequency	G5NHP events/year (**)	Species richness Conversion of lotic to lentic habitat (***)	Multiannual distribution of peaks in five categories events/year
High flows (extreme)	Magnitude Timing	- G2AMaXD m ³ /s (**) - G3JXDma Julian day (**)	Influences fish reproductive cycles	- Discharge peak over threshold (POT) magnitude m ³ /s (§) - No adjustment
Low flows (extreme)	Magnitude Duration Timing	- G2AMiXD m ³ /s (**) - G3JXDMi Julian day (**) - G4MDLP days (**)	Mortality	- No adjustment - No adjustment - Multiannual variability of continuous duration of low flow period (<Q _{50dry}) days

(*) Puckridge et al. (1998); (**) Richter et al. (1996); (***) Bunn and Arthington (2002); (§) Willems (2009); PEAK: Variability of all peak discharges; G4MDHP: Group 4 Mean duration of high pulses within each year; G5NHP: Group 5 No. of high pulses each year; G2AMaXD: Group 2 Annual maxima x-day means; G3JXDma: Group 3 Julian date of each annual 1-day maximum; G2AMiXD: Group 2 Annual minima x-day means; G3JXDMi: Group 3 Julian date of each annual 1-day minimum; G4MDLP: Group 4 Mean duration of low pulses within each year; Q50dry: Mean Q50 during the dry period

Because the habitat availability of oxbow lakes depends on exceeding connectivity discharge thresholds, peak flows were classified into five categories with lower limits of 2000 m³/s, 4000 m³/s, 6000 m³/s (bankfull level), 8000 m³/s, and 10000 m³/s. Instead of separating individual flood pulses, peak flows were extracted using a multiple criteria method (Willems, 2009), with an inter-event time of at least 5 days, an inter-event

discharge lower than 90% of the peak flow, and a minimum peak height of 2000 m³/s. To represent connectivity duration, the number of days exceeding the lower threshold of each category was calculated per month and year, replacing the use of mean peak flow duration.

For extreme low-flow events, the threshold was defined as the mean Q_{50} during the dry period (Q_{50dry}). This value was assumed to represent no-connectivity conditions, making it a suitable indicator of conditions of lake area reduction. The longest annual time span with discharge below this threshold was included as an adjusted indicator.

For the quantitative data obtained from the remote sensing analysis, indicators that represent oxbow lake area changes and water type were presented in Chapter 4, as well as preliminary discharge ranges of connectivity and the connected lake areas.

Table 5.2. List of seasonal hydrologic statistical indicators linked to ecological functions relevant to river-floodplain systems

Seasonal hydrologic component	Descriptor	Statistical indicator unit	Ecological function	Adjusted indicator for this study unit
Monthly flows	Magnitude Timing Variability	Mean value m ³ /s (**)	Fish populations Life history responses Favor exotic fish species	- No adjustment
Flood pulse	Variability Timing	PSEA (*)	Reproductive cycles Cues for spawning and migration (***)	- Monthly distribution of five categories of peak events/month - Number of days above the lower limit of five discharge categories days

(*) Puckridge et al. (1998); (**) Richter et al. (1996); (***) Bunn and Arthington (2002); PSEA: Inverse of the monthly variability in the number of pulse peaks

5.2.2 Model simulation

WEAP is a widely used modeling integrated tool developed by the Stockholm Environment Institute to simulate water resource systems under various management scenarios (Sieber and Purkey, 2015). This modeling tool allows for flexible spatial and temporal configurations, using a node-link framework to represent key components

such as catchments, rivers, reservoirs, demand sites, and other water infrastructure. In Bolivia, WEAP has been widely implemented. One of the largest projects was the development of the National Water Balance (1980-2016), which was later updated through 2022 to assess national water availability and potential impacts of future climate scenarios (Ministerio de Medio Ambiente y Agua, 2017). In addition, Master Catchment Plans have been prepared for various regions, with the main focus on water demands and service coverage (Balderrama Durán and Lima Quispe, 2021; Pérez and Balderrama Durán, 2022; Stockholm Environment Institute, 2018). Smaller-scale studies have also employed this model to evaluate specific projects, with emphasis on hydropower potential, equality in water distribution, and resource availability (Medina, 2021; Terrazas V. et al., 2020).

The capacity of WEAP for scenario-based planning makes it a valuable tool for evaluating hydropower development, assessing hydrologic alterations, and incorporating water flow needs for ecological functions. The model has been implemented in various river catchments worldwide to support hydropower planning and impact analysis (Amjath-Babu et al., 2019; Sun et al., 2022; Zhang et al., 2017). One of WEAP's key advantages is its capability to integrate multiple water demands, enabling users to explore trade-offs among competing uses. It supports the simulation of different operational rules, using a priority-based system for demand satisfaction. Although it is not designed for real-time dam operations, it is well-suited for strategic planning and long-term assessments. Given these advantages and its widespread use in Bolivia, WEAP is an appropriate and accessible choice for planners, policymakers, and researchers involved in hydropower scenario evaluation.

In this study, WEAP was configured to assess the isolated effect of reservoir operation, allowing the evaluation of hypothetical alterations to the historical natural flow regime under two operational scenarios. An additional configuration that simulates catchment hydrology calibrated at the Rurrenabaque station is presented in Appendix C. This unaltered catchment model provides a basis for future evaluation of potential hydrologic alterations under alternative scenarios.

The isolated reservoir configuration includes elements such as the Beni River, the Chepete reservoir, and the downstream Rurrenabaque station with observed discharge. The inflow to the Chepete reservoir was estimated by proportionally scaling the observed series at Rurrenabaque with the area fraction of Chepete (79% of the drainage area at Rurrenabaque). Downstream of the reservoir, an additional river headflow was defined as the difference between the discharge at Rurrenabaque and the estimated Chepete inflow. The hydrologic alteration was evaluated at Rurrenabaque by comparing simulated and observed series.

Dam characteristics (Table 5.3) were derived from the Preliminary Feasibility study (Geodata, 2016). A common measure of flow alteration is the degree of regulation

(DOR) presented by (Lehner et al., 2011). This index is defined as the fraction of the river's mean annual flow volume that can be retained within the reservoir (Top of Conservation minus Top of Inactive). Based on an estimated mean annual discharge of 1600 m³/s at Chepete, the calculated DOR is 0.58, which suggests a potentially medium to high hydrologic alteration downstream.

Considering the preliminary stage of the dam and that only fish ecohydrologic functions are assessed in this study, the operational scenarios were intentionally defined as contrasting boundary conditions instead of operational recommendations. The objective is to evaluate the response of ecohydrologic functions to referential levels of hydrologic alteration. For a comprehensive evaluation of operational trade-offs, additional environmental and socio-economic functions need to be incorporated.

Two scenarios were defined to represent upper and lower bounds of hydrologic alteration: one prioritizing hydropower production (S1) and another prioritizing a flow requirement (S2). This flow requirement was defined as the estimated natural flow regime at Chepete, representing the lowest possible level of hydrologic alteration under the most favorable flow conditions for fish ecohydrology. As such, S2 is presented as a referential boundary condition representing the alteration caused solely by the presence and operation of the reservoir. Two reservoir parameters (hydropower priority, reservoir priority) and two flow requirement parameters (water use priority and minimum flow requirement) were modified for both scenarios as indicated in the data column. Then, hydrologic alterations under each scenario were evaluated using the indicators relevant to the ecohydrologic function, and both hydropower generation and reservoir storage variability were compared.

Table 5.3. List of parameters for the Chepete reservoir and flow requirements, including values for scenarios S1 and S2

Chepete reservoir				
Section	Variable/parameter	Unit	Value	Detail
Physical	Storage capacity	10 ⁶ m ³	37780	(+) Extraordinary maximum level
Physical	Volume Elevation Curve	10 ⁶ m ³ , m	0,0; 2160,48.85; 5530,71; 13000,100; 31430,140; 37780,150	(+)

5. Ecohydrologic relationships and dam scenarios

Physical	Net Evaporation (Evaporation minus Precipitation)	mm	Daily	Station data
Physical	Loss to Groundwater	10^6 m^3	0	Default
Operation	Top of conservation	10^6 m^3	31430	Default (Normal operational level)
Operation	Top of buffer	10^6 m^3	Top of inactive	Default (Dead level)
Operation	Top of inactive	10^6 m^3	2160	(+) Dead level
Operation	Buffer coefficient (Fraction of water in buffer zone available each day for release 0-1)	-	1	No buffer zone
Hydropower	Maximum turbine flow	m^3/s	2600	(+)
Hydropower	Tailwater elevation	Masl	231.87	(+)
Hydropower	Plant factor	%	92.4	(+)
Hydropower	Generating efficiency	%	94	(+)
Hydropower	Hydropower priority	-	S1:1; S2:2	Scenario-based
Hydropower	Energy demand per day	10^3 GWH	0.043	(+) $15.47 \cdot 10^3$ GWH/year
Priority	Priority (Reservoir- filling)	-	S1:1; S2:2	Scenario-based
Priority	Buffer priority	-	0	No buffer zone
Flow requirement downstream of the Chepete reservoir				
Section	Variable	Unit	Value	Detail
Water use	Minimum flow requirement	m^3/s	S1:0; S2: Natural flow regime at Chepete	Scenario-based
Water use	Priority	-	S1:99; S2:1	Scenario-based

(+): Preliminary feasibility study (Geodata, 2016)

5.3 RESULTS

5.3.1 Ecohydrologic relationships

Ecohydrologic relationships were defined by integrating ecological functions identified through local knowledge and remote sensing analysis with hydrologic indicators within a common spatiotemporal framework.

Multiannual relationships are labeled MA_Sy and MA_OL:

- MA_Sy: native fish species abundance in the river system during years of extreme hydrologic conditions (droughts or floods) as mentioned by fishers (particularly sábalo during dry years)
- MA_OL: For general fish, availability of aquatic habitat within oxbow lakes during dry years as observed through remote sensing analysis (see Chapter 4, Figure 4.9)

Seasonal relationships describe hydrologic connectivity between the main channel, oxbow lakes, and flooded depressions (S_CoRe, S_CoRi, and S_CoFlo). They are linked to discharge ranges that define connectivity thresholds. Among the identified processes, hydrologic connectivity is the dominant driver shaping ecological dynamics in the river-floodplain system.

Seasonal relationships that represent processes in a single water body include S_MCMi, which describes the upstream reproductive migration sequence and predation activity in the main channel. Also, S_OLHa reflects habitat availability in oxbow lakes during the dry period, when shifts in water quality may affect fish tolerance thresholds. S_OLA and S_OLWT represent the distinct seasonal area and water type patterns of each oxbow lake as described in Chapter 4.

- S_CoRe: Lateral migration of native fish species from oxbow lakes to the main channel during the receding period to start reproductive migration, as mentioned by fishers. It occurs when discharge exceeds connectivity thresholds.
- S_CoRi: Lateral migration of native fish species from the main channel to oxbow lakes during the rising period to access feeding resources and refuge as indicated by fishers. It occurs when discharge exceeds connectivity thresholds.
- S_CoFlo: Lateral migration of general fish from oxbow lakes and main channel to flooded depressions during the flooding period to access feeding resources and refuge, as indicated by fishers. It occurs when discharge exceeds connectivity thresholds.
- S_MCMi: Upstream longitudinal migration of native fish species along the main channel for reproductive purposes during the receding and dry periods. This

movement follows a certain sequence and timing that depends on connectivity with oxbow lakes.

- S_OLHa: For general fish, the availability of aquatic habitat within oxbow lakes during the dry period influenced by seasonal discharge patterns
- S_OLA: For general fish, changes in oxbow lake area throughout the year influenced by their relationship with discharge (see Chapter 4, Figure 4.9, Figure 4.12)
- S_OLWT: For general fish, changes in oxbow lake water type throughout the year influenced by sediment input from the main channel and connectivity patterns (see Chapter 4, Figure 4.8).

Table 5.4 and Table 5.5 present the elements linked in each multiannual and seasonal ecohydrologic relationship, including the ecological function, the hydrologic component or period, and the corresponding descriptor and statistical indicator.

Table 5.4. Summary of multiannual ecohydrologic relationships relevant for fish ecology in the Beni River, along with hydrologic statistical indicators

Code	Fish species	Water body	Ecological function	Hydrologic component	Descriptor	Statistical indicator
MA_Sy	NS	All	Abundance: decrease / increase (LK)	Dry years / extreme flooding	Extreme low flow and flooding indicators	G2AMiXD m ³ /s, Duration low flow (Q _{50dry}) days, G2AMaX m ³ /s, G3JXDMi Julian day, G3JXDMa Julian day, Number of peaks in five Q categories days
MA_OL	G	OL	Habitat availability: lake area (RS)	Dry years	Multiannual lake area variability	Minimum lake area km ² (Chapter 4)

NS: Native species (e.g. sábalo); G: General species; OL: Oxbow lake; LK: Local knowledge; RS: Remote sensing; G2AMiXD: Group 2 Annual minima 1-day means; Q_{50dry}: Low flow period; G2AMaX: Group 2 Annual maxima 1-day means; G3JXDMi: Group 3 Julian day of each annual 1-day minimum; G3JXDMa: Group 3 Julian day of each annual 1-day maximum.

Table 5.5. Summary of seasonal ecohydrologic relationships relevant for fish ecology in the Beni River, along with hydrologic statistical indicators

Code	Fish species	Water body	Ecological function (from LK or RS)	Hydrologic period	Descriptor	Statistical indicator
S_Co Re	NS	OL and MC	LaMi: start reproductive migration (LK)	Receding period (connectivity from OL to MC)	Peak flows categories	Peak flow frequency, duration above lower limit of discharge categories days
S_Co Ri	NS	OL	LaMi: feeding and refuge for juveniles (LK)	Rising period (connectivity from MC to OL)	Peak flows categories	Peak flow frequency, duration above lower limit of discharge categories days
S_Co Flo	All	OL, MC and FD	LaMi (LK)	Flooding period (connectivity from MC and OL to FD)	Peak flows categories	Peak flow frequency, duration above lower limit of discharge categories days
S_MC Mi	NS	MC	UpMi: sequence (LK)	Receding, dry period	Peak flow categories sequence	Peak flow timing sequence
S_OL Ha	All	OL	Habitat availability (LK)	Dry period	Monthly discharge variability	Mean monthly discharge m ³ /s
S_OL A	G	OL	Habitat: changes in lake area (RS)	All periods	Monthly lake area variability	Mean monthly lake area km ² (Chapter 4) versus discharge m ³ /s
S_OL WT	G	OL	Habitat: changes in water type (RS)	All periods	Peak flow categories	Dominant monthly water type (Chapter 4)

NS: Native species (e.g. sábalo); P: paiche; G: General species; MC: Main channel; OL: Oxbow lake; FD: Flooded depressions; LaMi: lateral migration; UpMi: Upstream migration; LK: Local knowledge; RS: Remote sensing

Figure 5.1 illustrates seasonal ecohydrologic relationships that describe connectivity and fish migration during different hydrologic periods marked in a hydrograph (S_CoRe, S_CoRi, S_CoFlo). Below the hydrograph, the main water bodies are distinguished, as well as the presence of native species, paiche or all fish during each period.

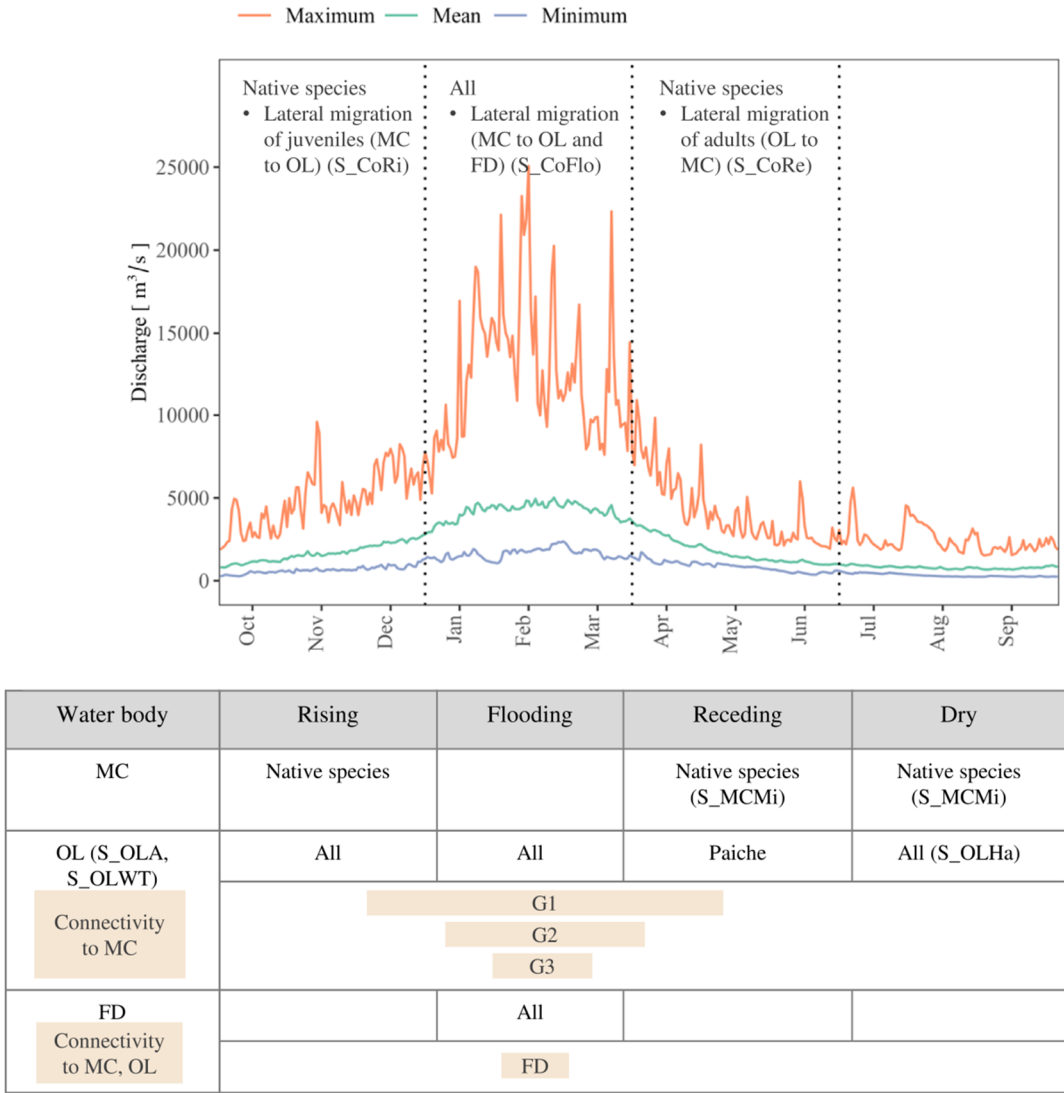


Figure 5.1. Diagram of seasonal ecohydrologic relationships indicating hydrograph variability, periods, water bodies, and relevant fish species. Shaded boxes represent connectivity windows between the main channel and groups of oxbow lakes: G1 (mostly close oxbow lakes), G2, G3 (mostly distant oxbow lakes), and flooded depressions. MC: Main channel, OL: Oxbow lake, FD: Flooded depressions (see text for detailed descriptions of codes)

Single water-body functions are also indicated in Figure 5.1, including migration along the main channel during the receding and dry periods (S_MCMi) and habitat availability in oxbow lakes during the dry period (S_OLHa). Lateral connectivity with the main channel is differentiated among the three oxbow lake groups identified in Chapter 4 (G1, G2, G3), as well as flooded depressions or bajíos, which provide habitat for fish during the flooding period (see fishers' descriptions in Chapter 3). In addition, remote sensing relationships representing seasonal variability in oxbow lake area and water type throughout the year are indicated (S_OLA and S_OLWT).

A numerical estimation of the recent relationship (2019-2022) between discharge and connected oxbow lake area is presented in Table 5.6 (adapted from Chapter 4). The table summarizes the aggregated oxbow lake area by connectivity range and the cumulative connected oxbow lake area corresponding to increasing discharge limits (upper bounds of each category).

Table 5.6. Sum of oxbow lake areas by connectivity range (columns 1 and 2) and cumulative connected area for each discharge upper bound (columns 3 and 4) (see Appendix B)

Connectivity range m³/s	Sum of lake areas by connectivity range km²	Upper bound of category m³/s	Cumulative lake area connected for discharge upper bound km²
2000≤Q<4000	23.7	4000	23.7
4000≤Q<6000	15.7	6000	39.4
6000≤Q<8000	6.7	8000	46.2
8000≤Q<10000	5.3	10000	51.5
10000≤Q	0.8	10000≤Q	52.3

The multiannual variability of hydrologic indicators was selected to represent the ecohydrologic relationship MA_Sy that describes the perceived abundance of fish and the influence of extreme hydrologic events. Figure 5.2 illustrates that dry indicators exhibit moderate interannual variability in low-flow conditions. The 1-day minimum discharge ranged from 227 m³/s in dry years to 820 m³/s in wet years, with a slight upward trend over time (Figure 5.2a). Annual minima typically occurred between early August and late October (Figure 5.2b), shifting later in recent decades, consistent with a delayed rainfall season. Days below the dry threshold (< 675 m³/s) ranged from zero in wet years to over 75 during extreme droughts, notably in 1991–1992 and 1994 (Figure 5.2c).

Extreme flow indicators exhibit marked variability, with the 1-day maximum ranging from 5103 m³/s in dry years to 25060 m³/s in extreme years, with an upward trend

suggesting more frequent or intense peaks (Figure 5.2a). Annual maxima generally occurred between mid-January and late March, except in 2014 when it was observed in late December (Figure 5.2b).

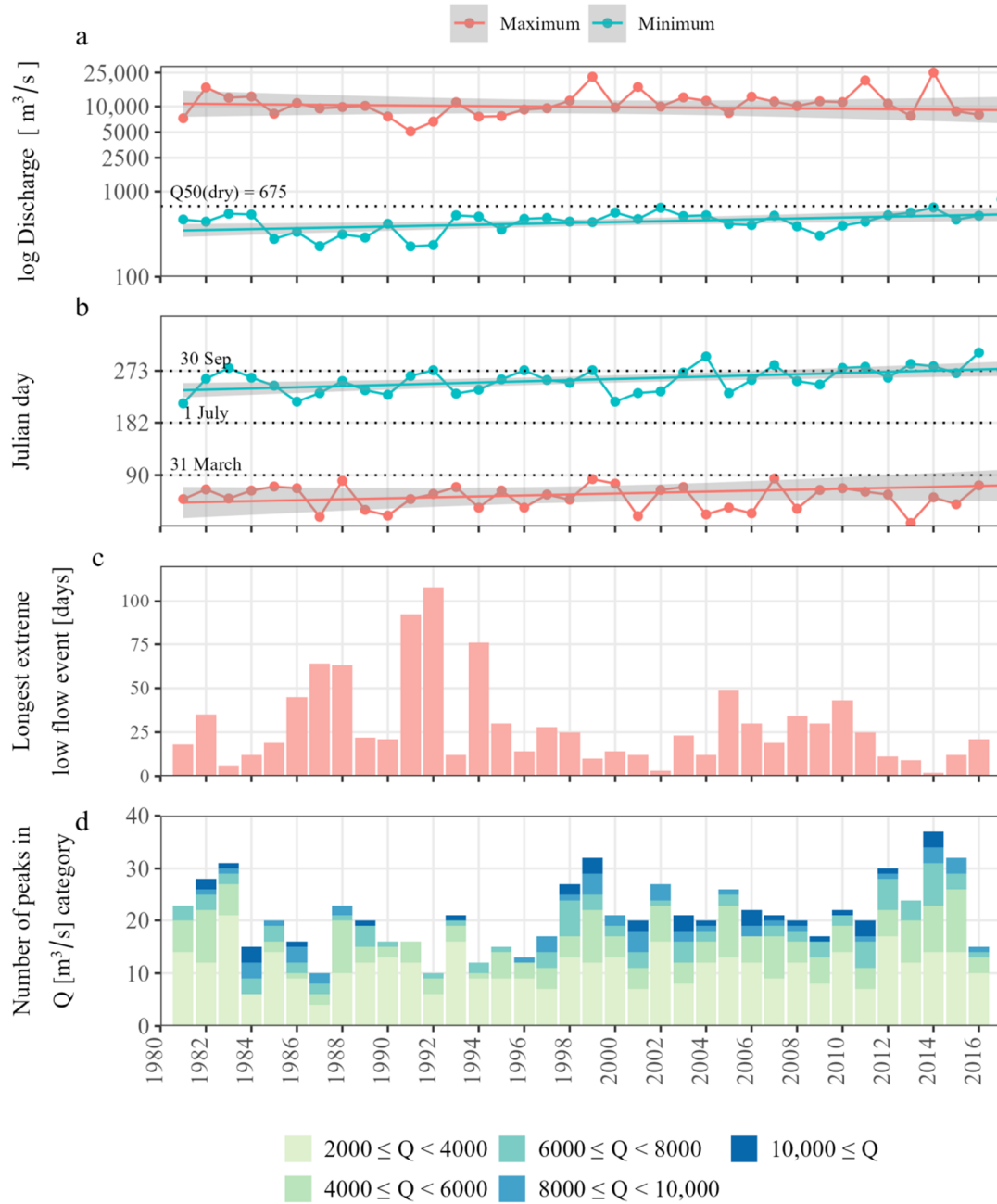


Figure 5.2. Multiannual variability of hydrologic indicators for multiannual ecohydrologic relationship MA_Sy: a) Magnitude of 1-day minimum and 1-day maximum, b) Timing of 1-day minimum and maximum, c) Longest extreme low flow event (below $Q_{50}(\text{dry})$), d) Number of peaks in discharge (Q) categories

Figure 5.2d shows the multiannual distribution of peaks in five discharge categories, and Table 5.7 summarizes the corresponding statistics. The mean annual number of peaks declines with increasing discharge magnitude, from 11.3 ± 3.5 in the lowest category ($2000\text{--}4000 \text{ m}^3/\text{s}$) to 0.9 ± 1.1 in the highest category ($\geq 10000 \text{ m}^3/\text{s}$). Table 5.7 also reports the mean annual number of days exceeding the lower limit of each category. On average, discharge surpasses $4000 \text{ m}^3/\text{s}$ for 44 ± 22 days per year, resulting in connectivity of an aggregated oxbow lake area of 23.7 km^2 (area indicated in Table 5.6). In contrast, when discharge exceeds $10000 \text{ m}^3/\text{s}$, the total sum of lake areas (52 km^2) is connected for only 2 ± 4 days per year. Although these area-discharge relationships are preliminary, they highlight the importance of high peaks for river-floodplain connectivity.

Table 5.7. Multiannual summary statistics of hydrologic indicators for the multiannual ecohydrologic relationship MA_Sy: number of peak flows (#POT) and number of days exceeding the lower limit of five discharge categories for the period 1981-2015

Category	$2000 \leq Q < 4000$		$4000 \leq Q < 6000$		$6000 \leq Q < 8000$		$8000 \leq Q < 10000$		$10000 \leq Q$	
Summary statistics	#POT	Days	#POT	Days	#POT	Days	#POT	Days	#POT	Days
Total	406	4854	180	1589	92	520	48	179	34	73
Mean	11.3	135	5.0	44	2.6	14	1.3	5	0.9	2
Max	21	250	12	101	8	50	4	24	3	18
Min	4	68	0	10	0	0	0	0	0	0
Sd	3.5	33	2.9	22	1.8	12	1.2	6	1.1	4

Sd: Standard Deviation

Monthly distribution of peak flows and timing for five discharge categories (see Figure 5.3) represents the seasonal ecohydrologic relationships that describe connectivity (S_Co_Re, S_Co_Ri, S_Co_Flo).

Figure 5.3 illustrates that in the category $6000\text{--}8000 \text{ m}^3/\text{s}$ (above bankfull level), the number of peaks was most often exceeded in March, with isolated occurrences in December. The highest peaks ($\geq 10000 \text{ m}^3/\text{s}$) occurred primarily during the flooding period. Table 5.8 summarizes the mean monthly number of peak flows and the number of days per month exceeding the lower limit of each discharge category. On average, peaks in the categories above $4000 \text{ m}^3/\text{s}$ primarily occur between November and April, resulting in a connected oxbow lake area of 24 km^2 , while oxbow lakes requiring higher connectivity ranges are connected mainly during the flooding period. This pattern suggests that the connectivity ranges may require refinement, as some lakes would be

expected to remain connected with the main channel for longer time, particularly during the receding and rising periods.

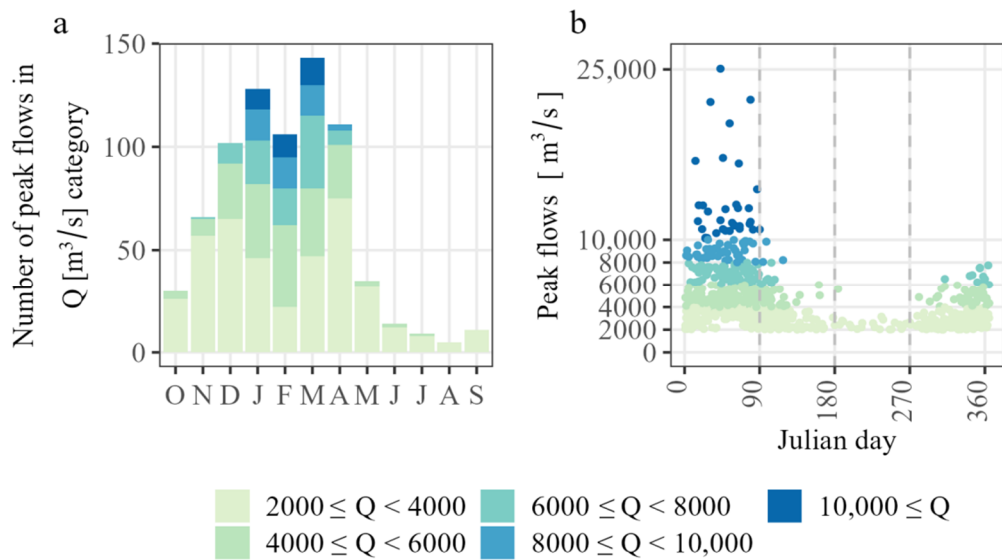


Figure 5.3. Seasonal distribution of indicators of seasonal ecohydrologic relationships of connectivity S_{Co_Re} , S_{Co_Ri} , S_{Co_Flo} : a) Number of peak flows and b) Timing of peak flows, in each discharge (Q) category

Table 5.8. Seasonal distribution of indicators of ecohydrologic relationships S_{Co_Re} , S_{Co_Ri} , S_{Co_Flo} : Number of peak flows (#POT) and number of days exceeding the lower limit of each discharge (Q) category for the period 1981-2016

Category	2000≤Q<4000		4000≤Q<6000		6000≤Q<8000		8000≤Q<10000		10000≤Q	
Month	#POT	Days	#POT	Days	#POT	Days	#POT	Days	#POT	Days
J	46	995	36	380	21	135	15	45	10	17
F	22	985	40	489	18	165	15	72	11	34
M	47	1025	33	494	35	185	15	58	13	22
A	75	675	26	103	7	18	3	4	0	0
M	32	128	3	5	0	0	0	0	0	0
J	12	52	2	3	0	0	0	0	0	0
J	8	23	1	3	0	0	0	0	0	0
A	5	17	0	0	0	0	0	0	0	0
S	11	21	0	0	0	0	0	0	0	0
O	26	77	4	5	0	0	0	0	0	0
N	57	256	8	20	1	1	0	0	0	0
D	65	600	27	87	10	16	0	0	0	0
Sum	406	4854	180	1589	92	520	48	179	34	73
Mean	33.8	404.5	15.0	132.4	7.7	43.3	4.0	14.9	2.8	6.1
Max	75	1025	40	494	35	185	15	72	13	34
Min	5	17	0	0	0	0	0	0	0	0
Sd	23.8	421.6	15.9	199.0	11.4	72.4	6.7	26.8	5.2	11.6

Sd: Standard Deviation

The ecohydrologic function S_{OLHa} , specific to oxbow lakes, represents habitat availability during the dry period, and it is further interpreted together with hydrologic alteration results in Sections 5.3.2 and 5.3.3.

The remote sensing ecohydrologic function focused on monthly oxbow lake area variability S_{OLA} is represented by the oxbow lake groups identified in Chapter 4. These groups exhibit different levels of connectivity: G1 (lakes mostly close to the main channel), and G2 and G3 (lakes mostly distant to main channels).

The multiannual area variability relationship MA_{OL} and the seasonal water type relationship S_{OLWT} show distinct trends among lakes and are influenced by additional processes beyond hydrologic connectivity. Thus, these relationships are preliminary represented using the lake area and water type trends identified in Chapter 4, and they are not further extended here.

The single water-body ecohydrologic relationship S_{MCMi} requires a more detailed characterization of connectivity thresholds, as it represents the simultaneous connectivity status of forty oxbow lakes during the receding and dry periods. The temporal evolution of connectivity across oxbow lakes also contributes to the observed size-related sequence of fish migration. Smaller fish would migrate earlier from oxbow lakes that disconnect sooner, while larger species would migrate later from lakes that remain connected for longer periods. However, fish migration from downstream lakes, streams, and other floodplain water bodies would also influence the sequence of species observed in the main channel. Thus, further investigation is required to better characterize these processes and their spatial variability.

5.3.2 Model simulation results

The simulation results for the period 1983-2015, considering dam operation under two contrasting boundary scenarios, are presented in Figure 5.4 and Table 5.9.

Under Scenario 1, reservoir storage reaches the Top of Conservation level in most years and remains above 60% of that level at its minimum (Figure 5.4a), resulting in low interannual variability. In contrast, storage under the referential Scenario 2 is considerably lower, with mean monthly volumes 58-66% below those of Scenario 1 (Table 5.9). Water releases reduce storage to the Inactive level, reaching near-empty conditions in several years.

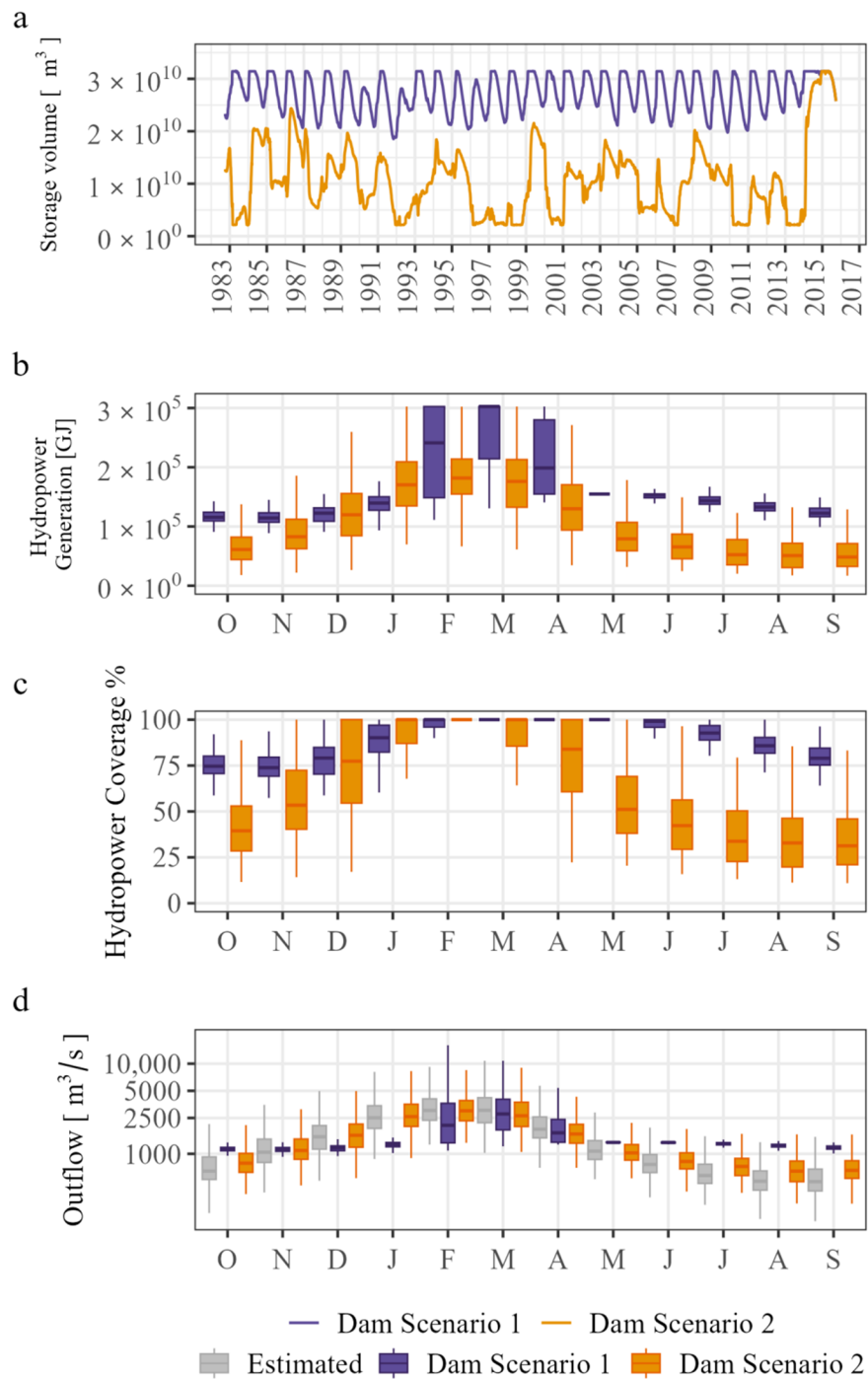


Figure 5.4. Hydropower generation results for dam Scenario 1 and Scenario 2 for 1983-2015: a) Time series of Reservoir storage volume, b) Monthly boxplot of hydropower generation, c) Monthly boxplot of hydropower coverage, d) Monthly boxplot of estimated flow at Chepete and outflow of reservoir for two scenarios

Hydropower generation and coverage differ largely between scenarios (Figure 5.4b,c). In Scenario 1, energy coverage ranges from approximately 60% during the dry period to

nearly 100% during the flooding period. In contrast, Scenario 2 presents relative differences that range from 57% lower energy coverage during the dry months to 5% higher in January (Table 5.9).

Downstream hydrologic alteration at Chepete was assessed by comparing the estimated natural discharge with the reservoir outflows (Figure 5.4d). Relative differences (Table 5.9) indicate that under Scenario 1, mean monthly discharge reduces by 44% in January and increases by 121% in August. In Scenario 2, representing the most favorable conditions for the ecohydrologic functions, hydrologic alterations are smaller but still reach a maximum reduction of 14% in April and an increase of 27% in August. These increases in mean monthly discharge during the dry period, represented by ecohydrologic relationship S_OLHa, suggest that oxbow lake habitat availability may become less critical, especially for oxbow lakes with lower connectivity thresholds as they would remain connected to the main channel.

Table 5.9. Monthly relative differences between Scenario 2 and Scenario 1 for 1983-2015: mean storage volume, mean hydropower generation, and mean energy coverage (Columns 1–3), together with estimated natural discharge at Chepete (Column 4) and relative differences with each simulated outflow for Scenarios 1 and 2 (Columns 5-6)

Month	Mean Storage volume difference (%) Sc2 vs Sc1	Mean Hydropower generation difference (%) Sc2 vs Sc1	Mean Energy coverage difference (%) Sc2 vs Sc1	Estimated mean natural discharge m³/s	Outflow difference (%) Sc1 vs estimated	Outflow difference (%) Sc2 vs estimated
J	-63	14	5	2878	-44	6
F	-66	-18	-1	3573	-21	-7
M	-65	-32	-7	3419	-8	-9
A	-64	-37	-21	2172	-7	-14
M	-63	-47	-45	1227	16	-11
J	-61	-53	-53	862	56	3
J	-60	-57	-57	669	94	15
A	-59	-57	-57	558	121	27
S	-58	-53	-53	583	102	25
O	-58	-43	-43	768	48	14
N	-58	-21	-23	1212	-7	3
D	-59	0	-5	1704	-30	4
Mean	-61	-34	-30	1636	27	5
Sd	3	23	24	1115	56	14

Sc1: Scenario 1, Sc2: Scenario 2, Sd: Standard deviation

Extended hydrologic alteration was assessed at Rurrenabaque by comparing monthly series, peak flows, and extreme flow magnitude and timing. These indicators represent the seasonal connectivity relationships (S_Co_Re, S_Co_Ri, S_Co_Flo), and their ecological impacts are interpreted in Section 5.3.3.

Figure 5.5 and Table 5.10 present the monthly changes under both scenarios. For Scenario 1, the mean monthly discharge decreases by 33% in January and increases by 95% in August. Scenario 2 shows smaller alterations, with a maximum reduction of 13% in April and an increase of 23% in August. Scenario 1 exhibits considerably lower seasonal variability, as illustrated in Figure 5.5a. In general, these alterations are slightly smaller than those estimated upstream at Chepete because of the unregulated additional runoff from the intermediate drainage area.

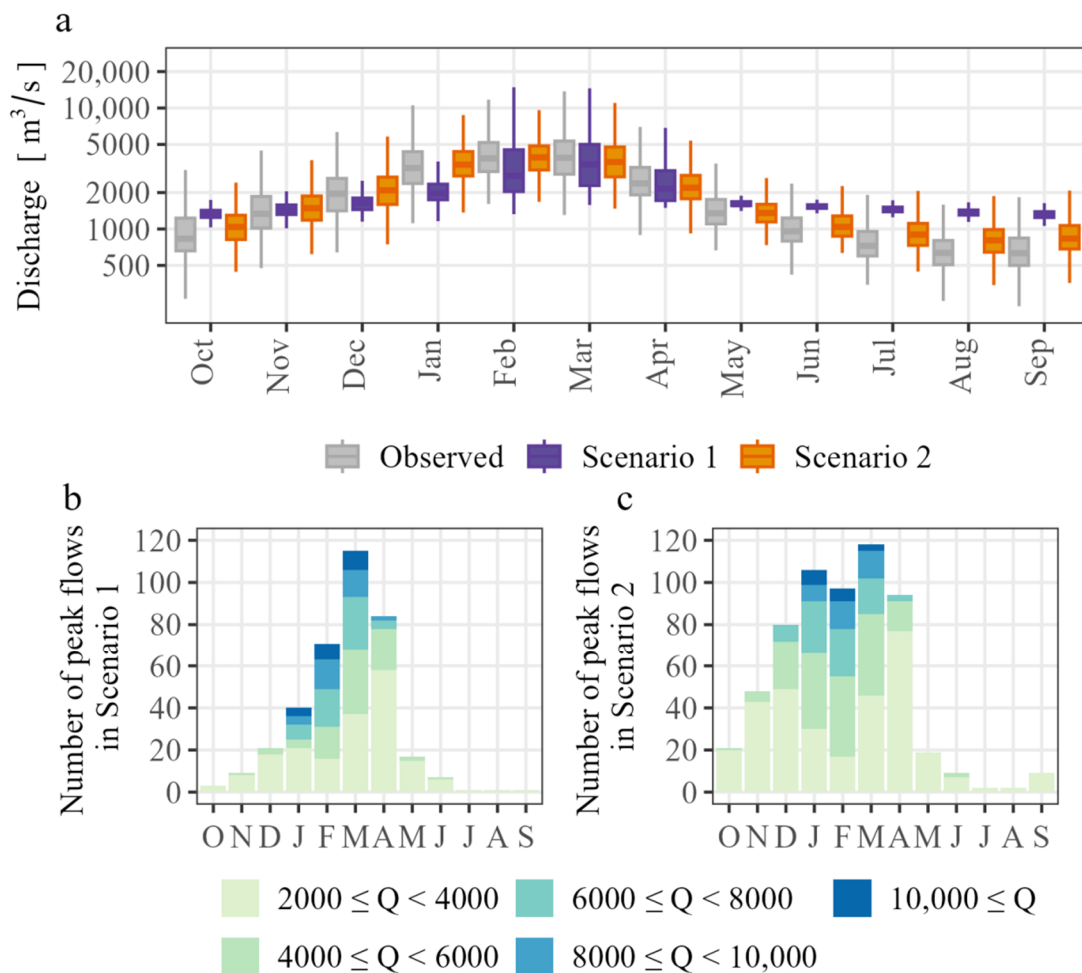


Figure 5.5. Hydrologic alteration at Rurrenabaque for Scenarios 1 and 2 for 1983-2015: a) Monthly distribution of discharge at Rurrenabaque in natural and altered conditions, Monthly distribution of peaks in five discharge (Q) categories for b) Scenario 1 and c) Scenario 2

Table 5.10. Monthly relative differences between observed discharge at Rurrenabaque and Scenarios 1 and 2 for 1983-2015

Month	Mean monthly discharge m ³ /s		
	Obs	Δ Sc1 (%)	Δ Sc2 (%)
J	3606	-33	6
F	4481	-17	-6
M	4324	-8	-9
A	2745	-7	-13
M	1550	11	-9
J	1093	43	3
J	848	74	13
A	710	95	23
S	743	80	21
O	967	40	15
N	1535	-4	4
D	2142	-21	5

Obs: observed indicator, Δ : Relative difference, Sc1: Scenario 1, Sc2: Scenario 2

Changes in the number of POT events differ between scenarios (Figure 5.5b, Figure 5.5c and Table 5.11). Scenario 1 shows reductions in POT events in all discharge categories and months, with the most marked decreases occurring during the dry and rising periods (categories with lower bounds of 2000, 4000, and 6000 m³/s). Scenario 2 also presents overall reductions; however, during the flooding period, the number of peaks increases for the intermediate categories (lower bounds of 4000 and 6000 m³/s). For the lowest category (lower bound of 2000 m³/s), small increases are also observed in specific months of the receding and rising periods (April and October).

The monthly distribution of days exceeding the lower bound of each discharge category (Table 5.12) shows patterns similar to those observed for peak flows. In Scenario 1, the duration of oxbow lake connectivity during the rising period is seriously reduced for the area that connects at 2000-4000 m³/s (23.7 km² from Table 5.6), as well as for the area that connects at 4000-6000 m³/s (an additional 16 km²). In the dry period, the lakes that connect at 2000-4000 m³/s also experience considerably fewer connectivity opportunities. In Scenario 2, reductions in connectivity duration are smaller than in Scenario 1. Moreover, the number of connected days during the flooding period increases for lakes connected at 6000-8000 m³/s.

Table 5.11. Relative differences between mean numbers of peaks per month for each discharge (Q) category observed at Rurrenabaque and Scenarios 1 and 2 for 1983-2015

Category	2000≤Q<4000			4000≤Q<6000			6000≤Q<8000			8000≤Q<10000			10000≤Q		
Month	#P	ΔSc	ΔSc	#P	ΔSc	ΔSc	#P	ΔSc	ΔSc	#P	ΔSc	ΔSc	#P	ΔSc	ΔSc
	O	1	2	O	1	2	O	1	2	O	1	2	O	1	2
	T	(%)	(%)	T	(%)	(%)	T	(%)	(%)	T	(%)	(%)	T	(%)	(%)
J	47	-55	-36	35	-89	3	21	-67	19	14	-71	-43	12	-67	-42
F	21	-24	-19	38	-61	0	21	-14	10	17	-18	-24	11	-27	-45
M	45	-18	2	31	0	26	33	-24	-48	15	-13	-13	11	-18	-73
A	71	-18	8	28	-29	-50	7	-43	-57	3	-33	-100	0	0	0
M	34	-56	-44	4	-50	-100	0	0	0	0	0	0	0	0	0
J	14	-57	-50	2	-50	0	0	0	0	0	0	0	0	0	0
J	11	-91	-82	2	-100	-100	0	0	0	0	0	0	0	0	0
A	6	-83	-67	0	0	0	0	0	0	0	0	0	0	0	0
S	11	-91	-18	0	0	0	0	0	0	0	0	0	0	0	0
O	19	-84	5	5	-100	-80	0	0	0	0	0	0	0	0	0
N	52	-85	-17	7	-86	-29	1	-100	-100	1	0	0	0	0	0
D	63	-71	-22	26	-88	-12	9	-100	-11	1	0	0	0	0	0
Mean	33	-61	-28	15	-54	-29	8	-29	-16	4	-11	-15	3	-9	-13
Sd	22	28	28	15	39	44	11	39	35	7	22	30	5	20	25
Max	71	-18	8	38	0	26	33	0	19	17	0	0	12	0	0
Min	6	-91	-82	0	-100	-100	0	-100	-100	0	-71	-100	0	-67	-73

Q: discharge m³/s, #POT: number of peak flows, Δ: Relative difference, Sc1: Scenario 1, Sc2: Scenario 2, Sd: standard deviation

Table 5.12. Relative differences between mean numbers of days per month above discharge (Q) limits observed at Rurrenabaque and Scenarios 1 and 2 for 1983-2015

Cat.	2000 ≤ Q			4000 ≤ Q			6000 ≤ Q			8000 ≤ Q			10000 ≤ Q		
Month	# D	ΔSc 1 (%)	ΔSc 2 (%)	# D	ΔSc 1 (%)	ΔSc 2 (%)	# D	ΔSc 1 (%)	ΔSc 2 (%)	# D	ΔSc 1 (%)	ΔSc 2 (%)	# D	ΔSc 1 (%)	ΔSc 2 (%)
J	923	-47	8	311	-73	11	101	-51	2	29	-34	3	13	-46	-15
F	907	-19	1	441	-28	5	166	-30	-30	74	-24	-53	31	-10	-74
M	976	-10	3	496	-14	-17	182	-9	-33	63	-21	-49	22	-32	-73
A	707	-17	-11	136	-27	-59	30	-43	-83	4	0	-100	1	-100	-100
M	173	-34	-57	15	-67	-100	1	-100	-100	1	-100	-100	0	0	0
J	58	-50	-69	3	-67	-67	0	0	0	0	0	0	0	0	0
J	28	-39	-79	3	-100	-67	0	0	0	0	0	0	0	0	0
A	15	-80	-67	0	0	0	0	0	0	0	0	0	0	0	0
S	16	-75	-50	0	0	0	0	0	0	0	0	0	0	0	0
O	39	-77	-10	1	-100	-100	0	0	0	0	0	0	0	0	0
N	212	-89	-7	17	-100	-65	1	-100	-100	0	0	0	0	0	0
D	499	-77	18	58	-86	-16	9	-100	-44	0	0	0	0	0	0
Mean	379	-51	-27	123	-55	-40	41	-36	-32	14	-15	-25	6	-16	-22
Sd	397	28	35	185	39	41	69	42	41	27	29	40	11	31	37
Max	976	-10	18	496	0	11	182	0	2	74	0	3	31	0	0
Min	15	-89	-79	0	-100	-100	0	-100	-100	0	-100	-100	0	-100	-100

Cat: Category; Q: discharge m³/s, #D: Number of days; NΔ: Relative difference, Sc1: Scenario 1, Sc2: Scenario 2, Sd: standard deviation

Table 5.13 summarizes the changes in mean multiannual flow indicators under both scenarios. These indicators represent the multiannual relationship MA_Sy, and their ecological impacts are interpreted in Section 5.3.3.

In Scenario 1, the mean annual 1-day minimum discharge is 1.6 times higher and occurs 25 days later than under natural conditions. For the annual 1-day maximum discharge, both scenarios show a small reduction of approximately 15%, with negligible shifts in timing. In addition, because of the dampening of the hydrograph, the number of days below the low flow threshold reduced from an average of 26 days per year to zero in Scenario 1 and 10 days in Scenario 2.

Table 5.13. Multiannual long-term differences between observed discharge indicators at Rurrenabaque and Scenarios 1 and 2 for: Mean 1-day minimum and 1-day maximum magnitude (relative difference %), and 1-day minimum and 1-day maximum Julian day (absolute difference in days)

Multiannual indicator	Obs	Difference unit	ΔSc1	ΔSc2
Mean 1-day minimum discharge	452	%	161	43
Mean 1-day maximum discharge	11242	%	-16	-15
Mean 1-day minimum Julian day	258	Days	25	4
Mean 1-day maximum Julian day	51	Days	5	-1
Mean duration of low flow	26	Days	0	10

Obs: observed indicator, Δ: Difference, Sc1: Scenario 1, Sc2: Scenario 2

5.3.3 Impacts on ecological functions

Hydrologic alteration is expected to modify key ecohydrologic functions of the river. The multiannual variability of flooding linked to fish abundance (MA_Sy) is reduced under both scenarios. The overall reduction in large flood peaks limits the extent of connected floodplain areas (oxbow lakes and flooded depressions). The decline in habitat availability and access to food resources reduces fish survival, growth, and recruitment.

In contrast, the multiannual variability of oxbow lake areas (MA_OL) that connect at lower discharge ranges would face a lower risk of drying because of higher minimum discharges, especially under Scenario 1. This change may reduce the risk of fish mortality during extreme dry periods.

Seasonal functions characterized by mean monthly discharge variability (S_OLHa) show notable alteration in Scenario 1, with lower discharge during the flooding period and a considerable increase during the dry period. The resulting change in oxbow lake area variability (S_OLA) follows two patterns: lakes that connect at lower discharge thresholds reflect higher area during the dry period, whereas lakes that require higher discharge thresholds have lower area throughout the year.

Seasonal connectivity functions (S_CoRe, S_CoRi, and S_CoFlo) depend on meeting specific discharge thresholds. Opportunities for native species to initiate upstream reproductive migration during the receding period (S_CoRe) decrease notably under both scenarios, especially for lakes with higher connectivity thresholds. For lakes with lower connectivity thresholds, Scenario 2 provides slightly more opportunities. These alterations are likely to limit reproduction and cause population decline.

Connectivity between the main channel and oxbow lakes during the rising period (S_CoRi) is essential for juvenile access to feeding and nursery habitats. Reduced peak flows during this period are particularly critical in Scenario 1, while Scenario 2 shows smaller reductions for the lowest connectivity ranges. Reduced access is expected to diminish juvenile survival due to increased predation risk, food limitation, and slower growth. This habitat loss would ultimately limit recruitment and fish stocks.

Paiche, as well as native species, require connectivity among floodplain water bodies to expand their habitat beyond oxbow lakes and access additional food resources (S_CoFlo). Large depressions typically connect at higher discharge ranges; thus, reduced peak flows may limit paiche reproduction and growth. At the same time, the stronger negative impacts on native species may benefit paiche populations and reinforce their dominance in the river system.

The individual relationships between discharge and oxbow lakes (S_OLA and S_OLWT) would also be altered, especially under Scenario 1. Under natural conditions, oxbow lakes display distinct patterns of connectivity that satisfy ecological functions in a complementary way within the system. Hydrologic alteration would increase the relative importance of lakes with low connectivity thresholds, while accelerating drying and water quality deterioration in lakes that connect at higher discharges.

Finally, the upstream migration function (S_MCMi) would be heavily impacted by dam-induced longitudinal disconnection. This barrier would halt or reduce reproductive migration and oblige fish to seek alternate spawning areas. In addition, the altered connectivity patterns would affect the species composition in the main channel, changing the sequential order of migration and predation dynamics.

5.4 DISCUSSION

This chapter addresses two specific objectives of this thesis (SO3 and SO4). First, it focused on SO3 by evaluating ecohydrologic relationships in a river-floodplain system with oxbow lakes through knowledge integration. Fishers' knowledge provided insights into long-term trends, habitat preferences of key species, and the importance of both longitudinal and lateral fish migrations. These perspectives were essential to understand dynamics that cannot be reflected with short-term experimental data, similar to other knowledge integration studies (Finn and Jackson, 2011; Jackson et al., 2014; Nunes et al., 2019; Silvano and Valbo-Jørgensen, 2008). Remote sensing analysis complemented this by characterizing oxbow lakes and their connectivity patterns, which determine their role as key aquatic habitats. Both qualitative and remote sensing analysis have shown the value of integrating alternative data sources to improve understanding of ecohydrology.

The representation of links between ecological functions and hydrology required the adjustment of commonly used hydrologic indicators. The extraction and categorization of peak flows was intended to correspond with the grouping of oxbow lakes based on connectivity ranges. The multitemporal variability of both peaks and the number of days above threshold can be used to develop flow recommendations relevant to habitat needs. These recommendations should account for year types (dry, normal, wet), timing of peak flows (early, late), and seasonal distribution. Under natural conditions, the identification of these ecologically relevant flows can improve forecasts of habitat availability, inform sustainable management of oxbow lakes, and implement fish conservation strategies.

This chapter also addressed SO4, by simulating a proposed hydropower project and evaluating two contrasting operational scenarios, one prioritizing hydropower (Scenario 1) and a referential scenario favorable to ecohydrologic functions (Scenario 2). Mean monthly energy generation for Scenario 2 was 34% lower than under Scenario 1. Seasonal variability showed that Scenario 1 generated more energy throughout the year, especially during the dry period, while Scenario 2 produced slightly more energy only in January (+14%). The resulting hydrologic alterations at Rurrenabaque were important. Scenario 1 reduced mean monthly flows during the rising and flooding periods, and all peak flow categories throughout the year, while Scenario 2 preserved some seasonal variability and peak flows in the low discharge categories. These results highlight that even Scenario 2, which aims to maintain the natural flow regime and represents the alteration caused solely by reservoir operation, still produces shifts in peak flow distribution and reduced hydrologic connectivity.

Potential hydrologic alterations are expected to negatively affect key ecohydrologic functions. Reductions in peak flows are especially disruptive for oxbow lakes with high

connectivity thresholds (e.g. $\geq 4000 \text{ m}^3/\text{s}$ that corresponds to 28 km^2 or 54% of total lake area), which rely on infrequent flood events to maintain ecological function. A decrease in the frequency and duration of lateral connectivity events would lead to habitat fragmentation and disruption of migration patterns (Castello, 2008; Fernandes, 1997; Herrera-R et al., 2024).

Native species would have fewer opportunities to migrate upstream along unregulated streams, altering the species sequence and composition within the main channel. In addition, there would be limited access to nursery habitats in oxbow lakes for juveniles. For both paiche and native species, the reduced flooded area would limit access to feeding resources and shelter. Also, changes in peak timing may disrupt species-specific cues to migrate, altering their life cycles. Similar to other dams in the region, the potential reduction of fish abundance in the river system may hinder livelihood resources and food security for Indigenous and riverine communities (Agostinho et al., 2008; Arantes et al., 2022; Santos et al., 2018; Wu et al., 2019).

Our results emphasize the importance of incorporating context-specific ecohydrologic relationships and appropriate hydrologic metrics to inform ecological flow requirements for fish. The findings highlight key relationships between fish ecology and oxbow lake habitat availability. In particular, they demonstrate the important role of hydrologic connectivity and seasonal variability in sustaining habitat diversity and fish migration within the river-floodplain system. Finally, study limitations and scope should be considered when interpreting the findings. Ecohydrologic relationships that are influenced by other drivers besides hydrologic variability, such as multiannual area and seasonal water type changes, need further studies and were preliminary characterized here. In regards to data availability, dam information is preliminary and does not specify operational constraints. Thus, the evaluated scenarios are indicative as they represent reference conditions of hydrologic alteration and ecohydrologic response. In addition, the impacts assessed here focus on fish ecohydrology, which is only one component of the river system. Additional environmental and socio-economic functions, including channel pattern dynamics, sediment and nutrient transport, and biogeochemical processes, need to be considered for impact assessment and operational trade-offs (Dai and Liu, 2013; Latrubesse et al., 2017; Maavara et al., 2020). Future environmental flow assessments should also account for dynamic hydroclimatic conditions that better represent future natural flow variability (Horne et al., 2019; Poff, 2018).

5.5 CONCLUSION

In summary, this study integrated local fishers' knowledge and remote sensing analysis to characterize ecohydrologic relationships in the Beni River-floodplain and to evaluate referencial impacts of the proposed Chepete Dam on fish ecohydrology. The results

show that hydrologic alteration, particularly reductions in peak flows, would likely disrupt key connectivity processes that sustain oxbow lake habitats and fish populations. Comparison of referential and contrasting operational scenarios revealed alteration levels linked to hydropower generation and the maintenance of natural flow dynamics. The largest ecological disruptions would affect oxbow lakes that depend on high flow events. These findings support the need to explicitly incorporate peak flow variability and connectivity requirements into flow requirements and reservoir operation planning. Although the analysis is based on preliminary dam information and focuses only on fish ecohydrology functions, it provides an initial basis to guide multiple impact assessments aimed at balancing energy production with the protection of river-floodplain ecosystems and dependent communities.

6

CONCLUSIONS AND FUTURE PERSPECTIVES

6.1 CONCLUSIONS

This thesis addressed the limited understanding of ecohydrologic processes in large, data-scarce river-floodplain systems under increasing environmental pressures. In particular, it focused on the Beni River, where hydrologic variability, connectivity, fish ecology, and fisheries are closely interlinked.

The most important addressed gaps include the lack of interdisciplinary studies and data, as well as the limited suitability of commonly used tools to represent processes in meandering rivers. To address data scarcity, this study relied on meaningful and representative information sources. Fishers' knowledge provided a firsthand qualitative understanding of hydrology, fish ecology, and fishing practices. These insights effectively linked river dynamics with fish availability and livelihoods. In parallel, long-term satellite imagery enabled the characterization of the spatiotemporal dynamics of oxbow lakes. The interdisciplinary gap was addressed through a knowledge integration approach based on a common spatiotemporal framework. In addition, suitable and representative ecohydrologic indicators were identified by focusing on connectivity dynamics between the main channel and oxbow lakes. Overall, the study responds to the need for methods capable of representing the complexity, heterogeneity, and threshold-based dynamics of meandering river-floodplain systems.

Analysis of expert fisher knowledge demonstrated that hydrologic variability is a major factor influencing ecological processes in the Beni River, especially through connectivity and flooding dynamics. Local knowledge revealed detailed relationships between flow conditions and fish life traits, including migration timing, feeding patterns, and habitat use. These observations highlight the dependence of key species on seasonal

connectivity between the main channel and oxbow lakes and other floodplain water bodies. Fishers also use hydrologic indicators at multiple spatial and temporal scales to anticipate fish availability and guide their fishing activities. This conceptual knowledge provided process descriptions and causal links that extend the understanding of fish ecology in the region.

Remote sensing analysis enabled the characterization of the complexity and diversity of oxbow lake dynamics. The availability of long-term satellite imagery and surface reflectance data allowed the assessment of temporal changes in water type (clear or turbid) and lake area. These dynamics were linked to key lake properties such as age and distance from the main channel. Seasonal changes in water type show the influence of hydrologic connectivity during the flooding period, as well as wind-driven sediment resuspension during the dry season. Long-term trends in lake area mainly show a typical decreasing pattern, while other lake areas increase due to main channel erosion. The influence of multiannual discharge variability on lake area is evident during extreme low-flow years. Seasonal relationships between lake area and discharge vary among lakes. Correlation between these variables allowed differentiation of lakes into three groups. Higher correlations were evidenced for recently formed lakes (Group 1), no correlation was observed for older and more isolated lakes (Group 3), while intermediate values corresponded to lakes with intermediate properties (Group 2). These patterns were interpreted as differences in connectivity frequency, with Group 1 lakes connecting more frequently and Group 3 lakes only during high discharge events. The total area of each lake group represents the (long-term) relative availability of aquatic habitats for fish based on their connectivity levels. Overall, these findings highlight the importance of seasonal flooding and its interaction with long-term geomorphological processes that influence the role of oxbow lakes as habitats.

The integration of these knowledge sources within a common spatiotemporal framework was the basis for identifying key ecohydrologic relationships and their hydrologic indicators. Typically used indicators were adjusted, and new ones were proposed to better represent the dynamic and threshold-based nature of connectivity. In particular, discharge indicators defined as connectivity ranges help evaluate the availability of oxbow lake areas when connectivity thresholds are met. These quantitative relationships reflect the diversity and multifunctionality of oxbow lake habitats within the river-floodplain, as described by fishers. Overall, this integrative approach proved effective in defining ecohydrologic relationships and provides a potentially transferable framework for other dynamic data-scarce systems.

The evaluation of the planned hydropower project at the Chepete Strait showed important hydrologic alterations, particularly reductions in peak flows. These changes are likely to reduce connectivity with oxbow lake habitats and negatively affect fish stocks. Scenario analysis defined the boundaries of potential alterations under two

contrasting operational strategies: one prioritizing hydropower generation and the other aiming to maintain the natural flow regime. Both scenarios produced hydrologic alteration, emphasizing that even the most favorable conditions of reservoir operation affect oxbow lakes with higher connectivity thresholds. The resulting impacts on ecohydrologic functions indicate important reductions in fish habitat, disruption to migration patterns, and potential declines in fish stocks. These findings demonstrate that evaluating hydrologic alteration in relation to site-specific ecohydrology improves impact assessment on fish ecology and fisheries.

Beyond the Beni River case study, this thesis highlights the importance of ecohydrologic assessments adjusted to the dominant processes of specific river-floodplain systems. The findings demonstrate that the use of common hydrologic indicators and simplified environmental flow methods may fail to represent connectivity flow requirements in meandering rivers. In this context, the integration of alternative knowledge sources largely enhanced process representation. Overall, this research contributes to the development of participatory and context-specific approaches for environmental studies in river systems exposed to increasing pressures.

6.2 LIMITATIONS

The types of knowledge integrated in the framework introduce specific limitations and sources of uncertainty that should be considered when interpreting the results.

The local knowledge analysis is based on semi-structured interviews designed to capture process understanding through descriptive, relational and cause-and-effect questions. Consequently, the findings reflect the experiences and perceptions of fishers with different fishing purposes, target species, fishing locations and skills. The predominance of young adult participants limits the temporal span of long-term ecological observations. Also, the limited sample size restricts quantitative comparisons among fish species and hydrologic conditions. In addition, the interview design was constrained by the thematic scope defined by the researcher, which may have limited the enquiry of site-specific ecohydrologic processes that remain unexplored in literature. Despite these limitations, the interviews provided detailed process-based knowledge that is often overlooked through conventional field-based methods.

The remote sensing analysis also presents methodological constraints associated with the temporal and spatial resolution of satellite imagery. Seasonal cloud cover reduces image availability during the flooding period when hydrologic connectivity is most active, resulting in conservative estimates of turbid water types linked to connectivity and seasonal lake area increase. Likewise, the time interval imagery collection limits the detection of short-duration connectivity events during rising and receding water periods, while the spatial resolution of Landsat imagery restricts the analysis of narrow

connection channels and small-scale lake area dynamics. These limitations produce conservative interpretations of connectivity levels. Additional uncertainties originate from the misclassification of specific transitional water types. Moreover, the interpretation of connectivity based on clear and turbid water type proxies may not be transferable to clear-water floodplain systems. Finally, the absence of field measurements prevents the calibration of relationships between suspended sediment concentrations and satellite-derived surface reflectance, restricting the derivation of absolute site-specific relationships.

While ecohydrologic relationships describing connectivity were effectively represented, other single water body processes remain partially characterized. In particular, further investigation is needed about the sequential reproductive migration of fish along the main channel, and its relation to the simultaneous connectivity conditions of multiple oxbow lakes. Such complex dynamics demand higher-resolution spatial and temporal observations. Similarly, the influence of other drivers beyond hydrologic variability requires further analysis in remote sensing relationships, including long-term lake area patterns and seasonal water type dynamics. These unresolved questions highlight that ecohydrologic indicators are context-specific representations of dominant system processes and need adaptation to different floodplain environments.

Finally, the hydropower impact assessment is restricted by the preliminary stage of the project data and by the thematic focus of the study. The evaluated operational scenarios are therefore intended as reference boundary conditions instead of recommendation strategies. Moreover, the assessment focuses specifically on fish ecohydrology, while other important environmental and socio-economic functions should be included, but remain outside the scope of this study. For instance, hydrologic relationships that represent processes of sediment transport, channel morphology, nutrient dynamics, floodplain vegetation, and broader livelihood dependence links should be incorporated. Future comprehensive environmental flow assessments should also integrate hydroclimatic forecasts capable of representing non-stationary future flow regimes.

6.3 FUTURE PERSPECTIVES

6.3.1 Regional studies

Recent studies in the region continue to improve understanding of floodplain ecohydrology and the response of aquatic ecosystems to ongoing environmental pressures. An Amazon basin study showed that richness patterns of frugivorous fish are strongly influenced by floodplain characteristics such as forest extent, tree species richness, and flood duration (Correa et al., 2025). In turn, frugivorous fish are critical to

forest regeneration as they act as seed dispersal agents. Both functions are highly dependent on connectivity and access to hydrologically functional environments.

Climate change is also becoming an important focus of ecohydrologic research in the region. A recent study evaluated the future habitat suitability for *Piaractus brachipomus* using ecological niche models that incorporate both bioclimatic and hydrologic variables (de Oliveira et al., 2026). Results suggest moderate reductions in suitable habitats and emphasize the importance of maintaining water quality, hydrologic variability, and river connectivity. The severe Amazon drought of 2023 caused major reductions in floodplain habitat availability and diversity. Studies in the Rio Negro and Rio Solimões showed that aquatic habitats became smaller and more isolated, while fish experienced high water temperatures and reduced dissolved oxygen, especially in floodplain lakes and shallow environments (Johannsson et al., 2026). Similar concerns have motivated research in the Paraná River, where ecohydrologic criteria were developed to characterize fish responses to extreme drought conditions, including floodplain connectivity and habitat availability for reproductive and nursery stages (Espínola et al., 2024). These criteria are later used to implement fisheries management strategies under extreme drought conditions.

The participation of local communities is well established and increasingly important in ecohydrologic research. Recent collaborative studies with fishers in the Tapajós, Trombetas, and Tocantins rivers showed the value of fishers' ecological knowledge to characterize spatial patterns of fish habitat use across Amazon floodplains (Silvano et al., 2026). These participatory approaches provide continuous and locally relevant environmental observations that are highly valuable for conservation.

Similar approaches in the Beni River could extend the assessment of critical drought conditions in different oxbow lakes and their effects on specific species. In addition, fishers' knowledge can be further studied through participatory monitoring of fish catches and water quality assessments in specific oxbow lakes.

6.3.2 Remote sensing

Remote sensing techniques have been widely applied to analyze channel migration processes and perform wetland mapping in dynamic floodplain environments (Nagel et al., 2023; Yuan et al., 2025). Studies increasingly use hybrid approaches that combine optical imagery and Synthetic Aperture Radar (SAR) data to distinguish spectrally similar environments such as marshes, swamps, and seasonally inundated grasslands. These incorporations help overcome common limitations associated with cloud cover, temporal gaps, and spatial resolution, allowing a more comprehensive characterization of wetland hydrology and vegetation dynamics.

Future studies focused on smaller floodplain water bodies, such as oxbow lakes, would particularly benefit from satellite imagery with higher spatial and temporal resolution. Recent constellations of microsatellites provide opportunities for this type of analysis. For example, the PlanetScope Dove-R and SuperDove sensors provide imagery with approximately 3 m spatial resolution and a daily revisit frequency (Roy et al., 2021). These datasets have already been used to assess oxbow lake connectivity in the Juruá River-floodplain and to monitor small wetland dynamics in Arctic environments (Mullen et al., 2023; Paulino et al., 2023). Similarly, the RADARSAT Constellation Mission, launched in 2019, can monitor water extent at approximately 5 m spatial resolution with revisit periods of about four days (Cote et al., 2021). These datasets would improve the detection of short-duration connectivity events and allow more detailed correlations with daily hydrologic records.

Future progress will also depend on improvements in cloud-based geospatial platforms such as Google Earth Engine. This platform already enables large-scale multitemporal analyses of wetlands and floodplain dynamics. Expanding access to recent high-resolution satellite datasets would enable the analysis of small and dynamic water bodies. At the same time, improvements in cloud computing capacity, including processing speed, memory, and storage, are necessary to support long-term trend analysis and detailed hydrologic analysis (Sharnagat et al., 2025). These developments could largely enhance future ecohydrologic studies in complex river-floodplain systems.

6.3.3 River-floodplain connectivity

Recent studies in river-floodplain environments increasingly focus on the assessment and quantification of lateral hydrologic connectivity. Geomorphic features contained in these environments differ in forms, elevations, and spatial arrangements that strongly influence their flooding dynamics and habitat availability. For example, studies in the Nuwejaars River-floodplain in South Africa combined high-resolution topography with surface reflectance from satellite imagery to characterize these geomorphic features and assess their flood frequency (Askew et al., 2025). In the Lower Mississippi River, hydrologic connectivity has been characterized using remotely-sensed surface water occurrence, stream order, and lake–channel intersections (Ahmad et al., 2025). In the Savannah River-floodplain, conceptual models were used to represent changing connectivity conditions among the river channel, oxbow lakes, and floodplain habitats (Wilbanks and Batzer, 2026). The larger scale of floodplain environment processes allows satellite imagery with medium spatial resolution to represent flooding processes, while high-resolution topographic data enables a precise assessment of flooding dynamics. Similar approaches could help characterize the flooding dynamics of oxbow lakes and flooded depressions in the Beni River-floodplain.

Several studies have specifically quantified oxbow lake connectivity using diverse approaches. In the Lower Rio Grande, hydrodynamic models and high-resolution topographic data were combined to simulate connectivity under different discharge return periods (Davila, 2022). In the Baihe River Basin in China, field observations (flow velocity) and historical satellite imagery were used to categorize the connectivity status of oxbow lakes with the main channel as lotic, semi-lotic, and lentic (Hou et al., 2026). Other approaches incorporated statistical tools to evaluate oxbow lake connectivity. A study conducted in the Zoige Basin used Sentinel-2 imagery to calculate lake areas and developed probability-based indices to quantify levels of hydrologic connectivity (Guo et al., 2023). Another study developed a statistical model to characterize the probability distribution of daily water level changes, and an empirical model linking water level changes and exchange flow. These tools were used to assess the impacts of the Three Gorges Dam on the connectivity between the Yangtze River and oxbow lakes (Liu et al., 2025). The applicability of these methodologies should be analyzed for the Beni River, as it may contribute to improving the characterization of oxbow lake connectivity.

Appendix A

A. FISHERS' KNOWLEDGE

A.1. INTERVIEW AND SYNTHESIS

Semi-structured interview - English version

General data

G1: Name

G2: Age

G3: Gender

G4: Community

G5: Are you member of a fishing organization?

G6: Since when do you fish? How did you learn to fish?

Seasonal variability – fishing trips

S1: How does the fishing activity vary during the year? Which factors affect this variation?

S2: How often do you make fishing trips? How long do your fishing trips last? What affects this duration?

Fishing Technique

T1: Which fishing techniques do you use? Which factors influence this choice?

T2: Which aspects do you consider in selection of bait?

Fishing site characteristics

FT1: What types of fishing sites can you identify?

FT2: What are the characteristics of each fishing site? (Vegetation, substrate, water depth/velocity, turbidity, etc.).

FT3: How do you estimate/assess these characteristics?

FT4: How does each of these characteristics affect fish?

FT5: How does each of these characteristics affect the fishing practice?

FT6: How do you select the fishing site? What are the factors that influence this selection?

Target species

TS1: Which aspects influence your selection of target species?

Fish ecology

FE1: For which species do you observe evidence of reproduction stages?

FE2: For which species do you observe evidence of migration patterns?

FE3: For which species do you observe evidence of feeding habits?

FE4: For which species do you observe evidence of growth?

FE5: Have you caught ill/death fish? What could be the reason?

Production

P1: Which changes in fish catches have you observed in the last years? (abundance, diversity) What are the possible causes?

P2: Which aspects of fish catch can you predict for the next years?

P3: When do you expect catch to be high or low? How do you anticipate this?

Entrevista semi-estructurada - Spanish version

Datos generales

G1: Nombre

G2: Edad

G3: Género

G4: Comunidad

G5: Es usted miembro de alguna organización de pescadores?

G6: Desde cuándo pesca? Como aprendió a pescar?

Variabilidad estacional – Viajes de pesca

S1: Como varia la actividad pesquera durante el año? Que factores afectan esta dinámica?

S2: Con qué frecuencia pesca? Cuanto tiempo duran sus viajes de pesca? Que afecta esta duración?

Técnicas de pesca

T1: Que técnicas de pesca utiliza? Que factores influncian esta selección?

T2: Que aspectos considera en la selección de la carnada?

Características de sitios de pesca

FT1: Que tipos de sitios de pesca puede identificar?

FT2: Cuáles son las características de los sitio de pesca? (vegetación, sustrato, profundidad de agua, velocidad de agua, turbidez, etc.)

FT3: Como estima/evalúa estas características?

FT4: Como afectan estas características a los peces?

FT5: Como afectan estas características a la actividad pesquera?

FT6: Como selecciona el lugar de pesca? Que factores influncian su selección?

Especie preferida

TS1: Qué aspectos influncian su preferencia por una especie?

Ecología de peces

FE1: Para que especies observa evidencias de estados de reproducción?

FE2: Para que especies observa evidencias de patrones de migración?

FE3: Para que especies observa evidencias de hábitos de alimentación?

FE4: Para que especies observa evidencias de crecimiento?

FE5: Ha atrapado peces enfermos/muertos? Cuál puede ser la causa?

Producción

P1: Que cambios en la pesca ha observado en los últimos años? (abundancia, diversidad, comportamiento) Cuales son las posibles causas?

P2: Cuáles son los aspectos de la pesca que puede predecir para los siguientes años?

P3: Cuando se espera alta o baja producción pesquera? Como estima este indicador?

Table A.1. Synthesis indicating the corresponding interview question with code, categories, mentions by fishers (all mentions, mentions associated with general fish, mentions associated with specific fish species), association with factors (hydrologic period, water body and others), result section. Sample size (28)

Interview		Code	Categories	Mentions by fishers			Association (mentions)			Results section
Section	Question label			All	General fish species	Specific type or fish species	Hydrologic period *	Water body+	Other factors	
Seasonal variability	S1, S2	Hydrologic period	F, Re, D, Ri	28	24	21 (1 type, 14 fish species)	F (21), Re (20), D (18), Ri (16)	MC (17), OL (15), S (4)	-	Section 3.4.1
Fishing technique	T1	Fishing technique	Nets, hookand bait types, traps	17	11	11 (11 fish species)	F (2), D (2)	MC (6), OL (6), S (2)	Water depth (2)	Section 3.4.2
Fishing technique	T2	Bait	Meat, fruit, others	24	17	17 (11 species)	-	-	Performance (4), size (2)	Section 3.4.3
Fishing site characteristics	FT1	Habitat - water body	MC, OL, S, U	27	3	26 (2 types, 16 fish species)	-	All (13), MC (11), OL (19), S (7)	-	Section 3.4.3
Fishing site characteristics	FT2, FT3, FT4	Vegetation	Trees	28	6	24 (15 fish species)	-	MC (1), OL (7), S (1)	Feeding habits (15), 16 Fruit species	Section 3.4.3
Fishing site characteristics	FT2, FT3, FT4	Vegetation	Aquatic vegetation	13	4	9 (9 fish species)	-	OL (5)	Communities/species (3)	Section 3.4.3
Fishing site characteristics	FT2, FT3, FT4	Water depth	Shallow, deep, surface	18	13	12 (12 fish species)	-	MC(2), OL (8)	Time of day (4), site selection (7), Temperature (2), Feeding habits (2), breathing (3)	Section 3.4.3

* Hydrologic period categories are F: flooding; Re: receding; D: dry; Ri: rising; + Water body / habitat categories are MC: main channel; OL: oxbow lake; S: stream; U: upstream

Table A.1. Continued

Interview		Code	Categories	Mentions by fishers			Association (mentions)			Results section
Section	Question label			All	General fish species	Specific type or fish species	Hydrologic period *	Water body+	Other factors	
Fishing site characteristics	FT2, FT3, FT4	Substrate	Sand, clay, mud	3	-	3 (6 fish species)	-		-	Section 3.4.3
Fishing site characteristics	FT2, FT3, FT4	Turbidity	Clear, turbid	8	7	3 (7 fish species)	Re (1), D(1), Ri(2)	MC(3), OL(4), S(5)	-	Section 3.4.3
Fishing site characteristics	FT5, FT6	Site selection	MC, OL, S	28	26	18 (2 types, 7 fish species)	-	MC (14), OL (15), S (7)	Fishing techniques (14)	Section 3.4.2
Target species	TS1	Preferred species	Subsistence, commerce	21	-	21 (14 fish species)	-	-	-	Section 3.4.1
Fish ecology	FE1	Reproduction		17	3	16 (1 type, 7 species)	D (2), Ri (4), F (5)	-	-	Section 3.4.3
Fish ecology	FE2	Fish Migration	Lateral, longitudinal	21	6	18 (15 fish species)	F (2), Re (13), D (2), Ri (3)	U (13)	Lateral (7), longitudinal (16)	Section 3.4.3
Fish ecology	FE3	Feeding habits	Meat, fruit, others	13	1	13 (2 types, 14 fish species)	-	-	-	Section 3.4.3

* Hydrologic period categories are F: flooding; Re: receding; D: dry; Ri: rising; + Water body / habitat categories are MC: main channel; OL: oxbow lake; S: stream; U: upstream

Table A.1. Continued

Interview		Code	Categories	Mentions by fishers			Association (mentions)			Results section
Section	Question label			All	General fish species	Specific type or fish species	Hydrologic period *	Water body+	Other factors	
Fish ecology	FE4	Growth	-	10	2	8 (1 type, 4 species)	-	-	-	Section 3.4.3
Fish ecology	FE5	Disease	-	15	10	7 (1 type, 8 fish species)	Ri (7)	OL (7), S (5)	Mortality (10), Small (4)	Section 3.4.3
Production	P1	Long-term change	-	25	15	19 (11 fish species)	-	-	Declining trend native species (20), increase in paiche (11), migration patterns (6)	Section 3.4.1
Production	P2, P3	Prediction	-	15	14	-	F (14)	-	Flooding (14), No reduction (2)	Section 3.4.2
Emergent	No	Skin type	Skin, scale	11	-	17 fish species	-	MC(3), OL(2), S(2)	Feeding habits (3), use as bait (3), species preference (4)	Section 3.4.1
Emergent	No	Size type	Small, medium, large	12	-	14 fish species	-	MC(2), OL(3), S(1)	Fish life traits (7)	Section 3.4.1

* Hydrologic period categories are F: flooding; Re: receding; D: dry; Ri: rising; + Water body / habitat categories are MC: main channel; OL: oxbow lake; S: stream; U: upstream

Appendix B

B. OXBOW LAKES

B.1. OXBOW LAKE PROPERTIES

Table B.1 presents oxbow lake properties.

Table B.1. Oxbow lake properties

Lake	Year o (*)	Altered	Age	Distance	Recent Area [km ²]	Turbidity category	AAT (+)	Low TS (~)	Low TS Dur. (^)	High TS (!)	MAV (#)	QPC (-)	WPC (-)
OL1	1999	NA	Old	Medium	0.69	Turbid	Increase	Jul	1	Aug	Medium	0.61 ¹ , 1x10 ⁻⁹ , 84	0.5
OL2	1999	NA	Old	Medium	1.64	Intermediate	Decrease	May	3	Aug	Low	0.48 ¹ , 2x10 ⁻⁵ , 73	0.7
OL3	1999	NA	Old	Medium	0.81	Clear	Constant	Apr	9	N	Low	-0.09 ³ , 4x10 ⁻¹ , 71	0.9
OL4	1999	NA	Old	Far	0.63	Clear	Mixed	Apr	10	N	Medium	-0.07 ³ , 5x10 ⁻¹ , 91	0.9
OL5	1999	NA	Old	Medium	1.34	Intermediate	Decrease	May	3	Aug	Low	0.06 ³ , 6x10 ⁻¹ , 86	0.8
OL6	2013	NA	Middle	Close	2.19	Turbid	Decrease	Jul	1	Aug	High	0.67 ¹ , 2x10 ⁻⁴ , 26	-
OL7	1999	NA	Old	Medium	2.66	Intermediate	Constant	Apr	4	Aug	Low	0.10 ³ , 3x10 ⁻¹ , 91	0.8
OL8	2005	NA	Middle	Medium	2.28	Intermediate	Decrease	Apr	4	Aug	Low	0.08 ³ , 5x10 ⁻¹ , 73	0.8
OL9	2016	NA	Recent	Close	1.3	Intermediate	Mixed	Jun	2	Aug	High	0.62 ¹ , 1x10 ⁻² , 15	-
OL10	1999	NA	Old	Close	1.1	Intermediate	Constant	Apr	5	Sep	Low	0.20 ² , 5x10 ⁻² , 96	0.7
OL11	2017	NA	Recent	Medium	0.67	Turbid	Constant	Apr	1	May	Low	0.47 ¹ , 5x10 ⁻² , 18	-
OL12	1999	NA	Old	Far	0.41	Intermediate	Decrease	Apr	4	Aug	Medium	0.17 ² , 1x10 ⁻¹ , 94	0.9
OL13	1999	NA	Old	Medium	1.39	Clear	Decrease	Apr	9	N	Low	-0.16 ³ , 1x10 ⁻¹ , 97	-0.9

(*) Year o: First year of data; AMC: Altered by main channel; (+) AAT: Annual lake area trend

(~) Low TS: Month in which low turbidity status starts more frequently; (^) Low TS Duration: More frequent duration of low turbidity status in months

(!) High TS: Month in which high turbidity status starts more frequently; (#) MAV: Monthly lake area variability

QPC: Pearson correlation between log Discharge and Area difference with annual mean (%), group in superscript, p-value, and sample size

WPC: Pearson correlation between mean monthly Turbidity Status and wind speed for the period 2010-2016

Table B.1. Continued

Lake	Year o (*)	Altered	Age	Distance	Recent Area [km ²]	Turbidity category	AAT (+)	Low TS (~)	Low TS Dur. (^)	High TS (!)	MAV (#)	QPC (-)	WPC (-)
OL14	1999	NA	Old	Medium	1.88	Intermediate	Decrease	Apr	5	Sep	Low	0.18 ² , 8x10 ⁻² , 97	0.7
OL15	2014	AMC	Recent	Close	0.44	Intermediate	Mixed	Jun	2	Aug	Medium	0.29 ² , 2x10 ⁻¹ , 22	-
OL16	1999	NA	Old	Medium	1.65	Intermediate	Increase	May	4	Sep	Low	0.03 ³ , 8x10 ⁻¹ , 96	0
OL17	2015	AMC	Recent	Close	0.8	Turbid	Constant	NA	N	N	Low	0.48 ¹ , 7x10 ⁻² , 15	-
OL18	1999	NA	Old	Far	1.61	Turbid	Decrease	Apr	3	Jul	Medium	0.11 ² , 3x10 ⁻¹ , 94	0.9
OL19	1999	NA	Old	Far	0.3	Intermediate	Decrease	Apr	3	Jul	Low	0.16 ² , 1x10 ⁻¹ , 94	0.9
OL20	1999	NA	Old	Medium	1.72	Clear	Increase	Jun	4	Oct	Low	0.07 ³ , 6x10 ⁻¹ , 64	0
OL21	2020	AMC	Recent	Close	1.77	Turbid	Decrease	Jun	1	Jul	Medium	0.48 ¹ , 7x10 ⁻² , 15	NA
OL22	1999	NA	Old	Medium	1.05	Intermediate	Decrease	Jun	2	Aug	Medium	0.21 ² , 4x10 ⁻² , 98	0.7
OL23	2018	AMC	Recent	Close	0.42	Turbid	Mixed	Jun	2	Aug	Medium	0.34 ² , 2x10 ⁻¹ , 14	NA
OL24	2012	NA	Middle	Medium	1.18	Clear	Mixed	Apr	5	Sep	Medium	0.37 ² , 3x10 ⁻² , 36	0.3
OL25	1999	NA	Old	Medium	1.87	Clear	Constant	Apr	6	Oct	Low	0.08 ³ , 5x10 ⁻¹ , 102	0.3
OL26	2011	AMC	Middle	Medium	1.68	Intermediate	Constant	Jun	3	Sep	Low	0.11 ² , 4x10 ⁻¹ , 50	0.1

(*) Year o: First year of data; AMC: Altered by main channel; (+) AAT: Annual lake area trend

(~) Low TS: Month in which low turbidity status starts more frequently; (^) Low TS Duration: More frequent duration of low turbidity status in months

(!) High TS: Month in which high turbidity status starts more frequently; (#) MAV: Monthly lake area variability

QPC: Pearson correlation between log Discharge and Area difference with annual mean (%), group in superscript, p-value, and sample size

WPC: Pearson correlation between mean monthly Turbidity Status and wind speed for the period 2010-2016

Table B.1. Continued

Lake	Year o (*)	Altered	Age	Distance	Recent Area [km ²]	Turbidity category	AAT (+)	Low TS (~)	Low TS Dur. (^)	High TS (!)	MAV (#)	QPC (-)	WPC (-)
OL27	1999	NA	Old	Far	0.76	Clear	Constant	May	5	Oct	Medium	0.08 ³ , 4x10 ⁻¹ , 105	0.7
OL28	2017	NA	Recent	Close	1.17	Turbid	Mixed	Jun	2	Aug	High	0.70 ¹ , 8x10 ⁻³ , 13	NA
OL29	2018	NA	Recent	Close	1.68	Intermediate	Constant	Jun	2	Aug	Low	0.56 ¹ , 5x10 ⁻² , 13	NA
OL30	1999	NA	Old	Close	1.06	Intermediate	Constant	May	5	Oct	Low	-0.06 ³ , 5x10 ⁻¹ , 110	-0.1
OL31	1999	NA	Old	Far	0.72	Turbid	Mixed	May	2	Jul	High	0.43 ¹ , 5x10 ⁻⁶ , 104	0.9
OL32	1999	NA	Old	Far	0.46	Intermediate	Mixed	Apr	4	Aug	High	0.54 ¹ , 2x10 ⁻⁹ , 108	0.9
OL33	1999	NA	Old	Close	0.7	Turbid	Increase	May	1	Jun	High	0.66 ¹ , 2x10 ⁻¹⁵ , 111	0.8
OL34	2013	AMC	Middle	Close	0.34	Intermediate	Constant	Jun	2	Aug	Medium	0.31 ² , 7x10 ⁻² , 36	0.2
OL35	2008	NA	Middle	Medium	2.2	Intermediate	Increase	May	4	Sep	Medium	0.49 ¹ , 2x10 ⁻⁴ , 54	-0.2
OL36	2015	NA	Recent	Close	1.82	Intermediate	Increase	Apr	5	Sep	Medium	0.25 ² , 2x10 ⁻¹ , 28	NA
OL37	2003	AMC	Middle	Close	1.59	Clear	Constant	May	5	Oct	Low	0.05 ³ , 6x10 ⁻¹ , 83	-0.1
OL38	2019	AMC	Recent	Close	1.5	Intermediate	Constant	Jun	3	Sep	Low	0.51 ¹ , 4x10 ⁻² , 16	NA
OL39	1999	NA	Old	Far	2.89	Intermediate	Constant	May	5	Oct	Low	0.19 ² , 4x10 ⁻² , 114	0.4
OL40	1999	NA	Old	Far	2.52	Clear	Constant	May	8	N	Low	0.10 ³ , 3x10 ⁻¹ , 111	-0.3

(*) Year o: First year of data; AMC: Altered by main channel; (+) AAT: Annual lake area trend

(~) Low TS: Month in which low turbidity status starts more frequently; (^) Low TS Duration: More frequent duration of low turbidity status in months

(!) High TS: Month in which high turbidity status starts more frequently; (#) MAV: Monthly lake area variability

QPC: Pearson correlation between log Discharge and Area difference with annual mean (%), group in superscript, p-value, and sample size

WPC: Pearson correlation between mean monthly Turbidity Status and wind speed for the period 2010-2016

B.2. RECENT CONNECTIVITY RANGES

This section presents a preliminary analysis to estimate hydrologic connectivity ranges for each oxbow lake. This evaluation includes both optical and radar datasets available through Google Earth Engine.

B.2.1. Datasets and identification criteria

Table B.2 summarizes the main characteristics of the satellite image collections and the implementation of the water classification process. The analysis period corresponds to the most recent discharge data available from the Rurrenabaque hydrometric station (1 October 2019 to 13 March 2022).

For the optical datasets Landsat 8 and Sentinel 2, the cloud image filter was applied as described Chapter 4. No additional lake-specific quality control was performed; thus, area estimates affected by sparse clouds or shadows may represent outliers. The predefinition of water types (WTO, WTA, WTB, WTC, WTD) and lake area calculation were implemented as detailed in the main text. For each collection, a different image was used to train a classifier tree of six comparable bands and then applied over the analysis period.

For the radar dataset a backscatter threshold lower than -16 was applied to classify water pixels over the collection and a filter was used to reduce speckle.

The suitability of the datasets was assessed based on the availability of images throughout the analysis period.

Table B.2. Summary of satellite image collections obtained from Google Earth Engine for the period 1 October 2019 to 13 March 2022

Collection	Training image	Classifier tree bands / water threshold	Availability for analysis period	Spatial resolution / Time interval	Time period
Landsat 5 ETM	-	Same tree for Landsat 7 Blue, Green,	No	30 m / 16 day	1999-2012
Landsat 7 ETM+	04 April 2022	Red, NIR, SWIR 1, SWIR2	Yes	30 m / 16 day	1999-2022
Landsat 8 OLI	11 May 2021	Blue, Green, Red, NIR, SWIR 1, SWIR2	Yes	30 m / 16 day	2013-2025
Landsat 9 OLI	20 April 2022	Blue, Green, Red, NIR, SWIR 1, SWIR2	Insufficient	30 m / 16 day	2021-2025
Sentinel 2	03 April 2022	Blue, Red, Green, NIR 1, SWIR 1, SWIR2	Yes	10-20 m / 5 day	2017-2025
Sentinel 1 SAR	-	VV<-16 decibels	Yes	10 m / 6 day	2014-2025

ETM: Enhanced Thematic Mapper; OLI: Operational Land Imager; SAR: Synthetic Aperture Radar; VV: Vertical transmit/Vertical receive; NIR: Near-Infrared; SWIR: Shortwave infrared

Table B.3 lists the discharge peaks during the analysis period ($> 2000 \text{ m}^3/\text{s}$) classified into five discharge categories. These categories were also interpreted as hydrologic connectivity ranges.

Table B.3. Summary table of discharge (Q) peaks considered during the analysis period (1 October 2019 to 13 March 2022)

Hydrologic year	Period	Date	Peak m ³ /s	Discharge category m ³ /s
2020	Flooding	22-Feb-20	8541	8000≤Q<10000
2020	Recession	8-Apr-20	4598	4000≤Q<6000
2020	Recession	3-May-20	4521	4000≤Q<6000
2020	Recession	23-May-20	2465	2000≤Q<4000
2020	Recession	3-Jun-20	2431	2000≤Q<4000
2020	Recession	23-Jun-20	3194	2000≤Q<4000
2020	Dry	1-Jul-20	3256	2000≤Q<4000
2020	Dry	25-Jul-20	4546	4000≤Q<6000
2020	Dry	15-Aug-20	2075	2000≤Q<4000
2020	Dry	20-Aug-20	2482	2000≤Q<4000
2021	Rising	11-Dec-20	2060	2000≤Q<4000
2021	Rising	31-Dec-20	2749	2000≤Q<4000
2021	Flooding	7-Jan-21	10623	10000≤Q
2021	Recession	13-Apr-21	7082	6000≤Q<8000
2021	Recession	26-Apr-21	4173	4000≤Q<6000
2021	Recession	7-May-21	2482	2000≤Q<4000
2021	Recession	29-Jun-21	2000	2000≤Q<4000
2022	Rising	14-Nov-21	2330	2000≤Q<4000
2022	Rising	25-Dec-21	2712	2000≤Q<4000
2022	Flooding	28-Feb-22	2380	2000≤Q<4000

Periods of hydrologic connectivity caused by main channel overflow were identified by comparing temporal variations in lake areas with the occurrence of discharge peaks. The interpretation of connectivity was based on the following assumptions:

- Sudden increases in lake area indicate connectivity
- Consecutive increases in lake area indicate connectivity
- Consecutive decreases in lake area at constant or faster rates indicate no connectivity
- Consecutive decreases in lake area at slower rates indicate connectivity

Because the main focus of this analysis was on internal temporal trends, differences among satellite collections were not evaluated.

B.2.2. Representative oxbow lakes

Three examples of the interpretation are shown for lakes with different long-term area trends. OL4 reflects a continuous declining trend (Figure B.1), OL18 presents seasonal lake area variability (Figure B.2), and OL22 shows a stable pattern of lake area (Figure B.3).

Lake OL4

Figure B.1a shows the lake area derived from each satellite collection, and Figure B.1b presents the discharge series at Rurrenabaque hydrometric station.

Sentinel-1 results are slightly lower than the optical sensors, but its higher temporal resolution (including both ascending and descending orbits) better captures short-term area changes. For instance, there are periods of sudden increase, followed by no change and decline during March to August 2020. This pattern coincides with the occurrence of major peaks during the 2020 flooding period, followed by a receding period with peaks in the 4000-6000 m³/s category (August 2020).

In 2021, the rate of decreases slows after a May 2021 small peak (slightly above 2000 m³/s), which would indicate a lower connectivity threshold. However, this trend is not coherent with the area reductions in 2020 while similar small peaks occur. An alternative explanation is that the lake reached a minimum area regulated by groundwater.

Thus, the August 2020 peak (4000-6000 m³/s) seems to be the lowest associated with no area decline and it is identified as a connectivity range.

Lake OL18

Figure B.2a presents the lake area time series and Figure B.2b the discharge record. The lake presents similar seasonal variability in L7, L8 and S1, while S2 slightly overestimates the area. Sentinel-2 shows faster area reduction rates, but its temporal patterns are consistent with Sentinel-1. The higher frequency Sentinel-1 observations allow clearer identification of change rates.

Remarkably, large peaks during the rising period of hydrologic year 2020 do not correspond to area increases; only the March 2020 flooding peak produces an abrupt expansion. The area then remains relatively constant and presents a slight reduction before June 2020. Afterwards, an increase (only visible in Sentinel-1) appears linked to peaks in June and August 2021, suggesting connectivity ranges of 2000-4000 m³/s.

A sharp area reduction and later gap in Sentinel-1 images coincides with a low flow period, possibly indicating no water pixels classified. After the 2021 flooding period, the area declines rapidly until May and then stabilizes during a period with peaks in the 2000-4000 m³/s range. Thus, this is the identified range of connectivity for lake OL18.

Lake OL22

Figure B.3a shows lake area estimates and Figure B.3b the discharge record at Rurrenabaque. Collections Landsat 7 and Sentinel-2 display similar seasonal variability, whereas Sentinel-1 indicates an almost constant area, except for an abrupt decrease and recovery around the 2021 flood peaks.

The near-constant Sentinel-1 pattern may reflect sustained groundwater recharge that counteracts evaporation losses. However, Sentinel-2 reveals additional variability that supports alternative interpretations. After scattered area values likely affected by clouds during the flooding period, the lake exhibits a near constant area period (May-June 2020), followed by gradual decline (August-December 2020).

The 2020 receding-dry period barely surpasses 2000 m³/s, whereas 2021 peaks reach 2000-6000 m³/s. The stable area observed in 2020 is therefore coherent with a connectivity range of approximately 2000-4000 m³/s.

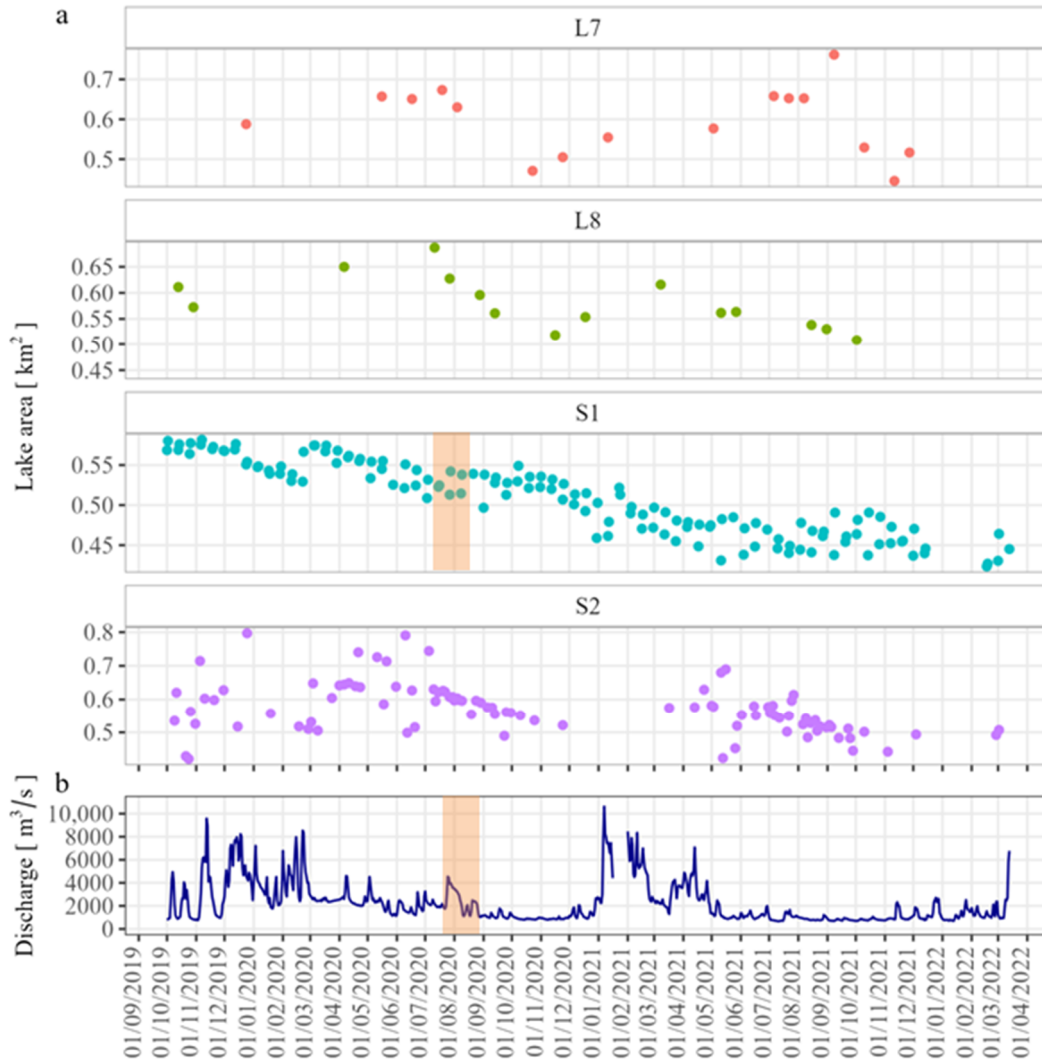


Figure B.1 a) Time series of calculated area for lake OL4 for different satellite collections (L7: Landsat 7 ETM+, L8: Landsat 8 OLI, S1: Sentinel-1 SAR, S2: Sentinel-2), b) Discharge at the Rurrenabaque hydrometric station (extreme 2021 event is not fully visible, horizontal grid lines indicate discharge categories, orange shading marks identified connectivity period in range 4000-6000 m^3/s).

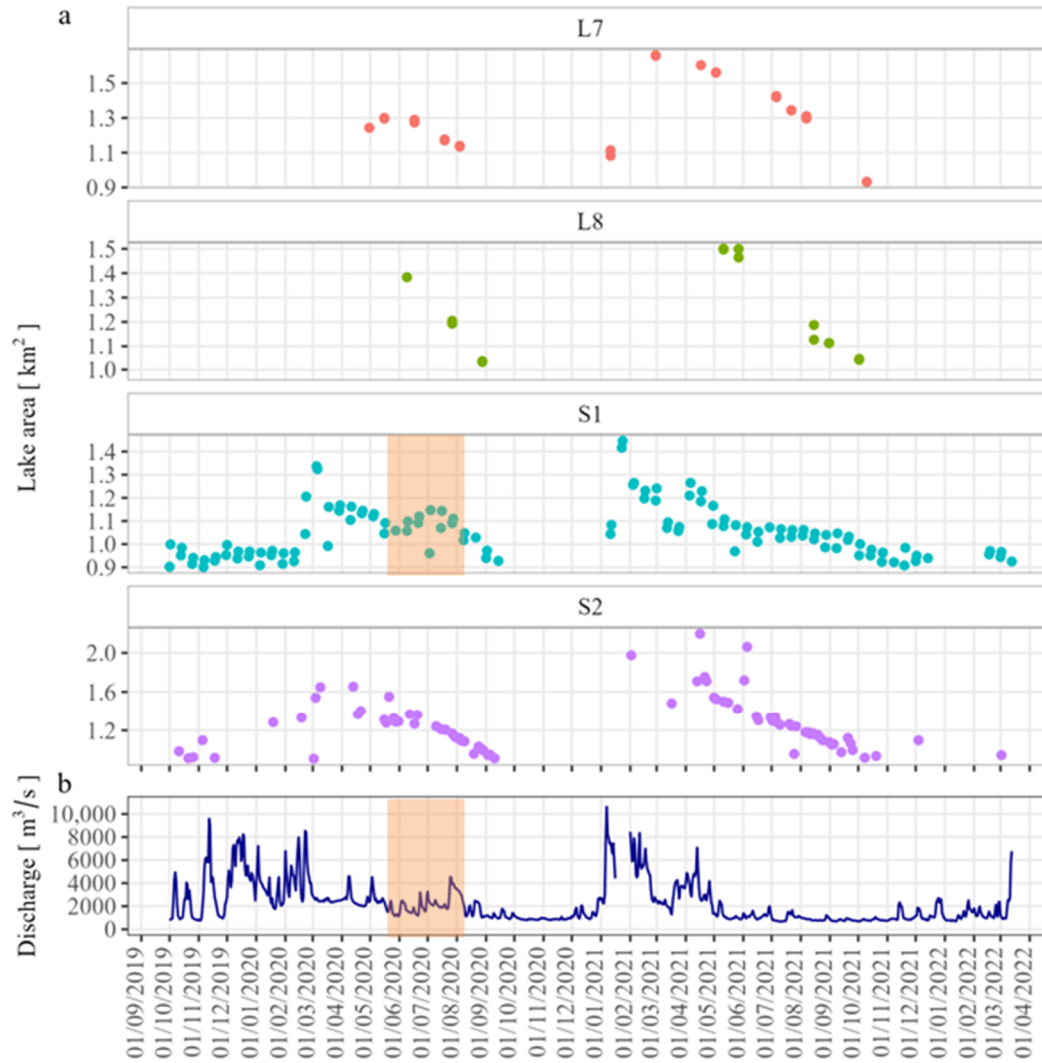


Figure B.2 a) Time series of calculated area for lake OL18 for different satellite collections (L7: Landsat 7 ETM+, L8: Landsat 8 OLI, S1: Sentinel 1 SAR, S2: Sentinel 2); b) Discharge at the Rurrenabaque hydrometric station (extreme 2021 event is not fully visible, horizontal grid lines indicate discharge categories, orange shading marks identified connectivity period in range 2000-4000 m^3/s).

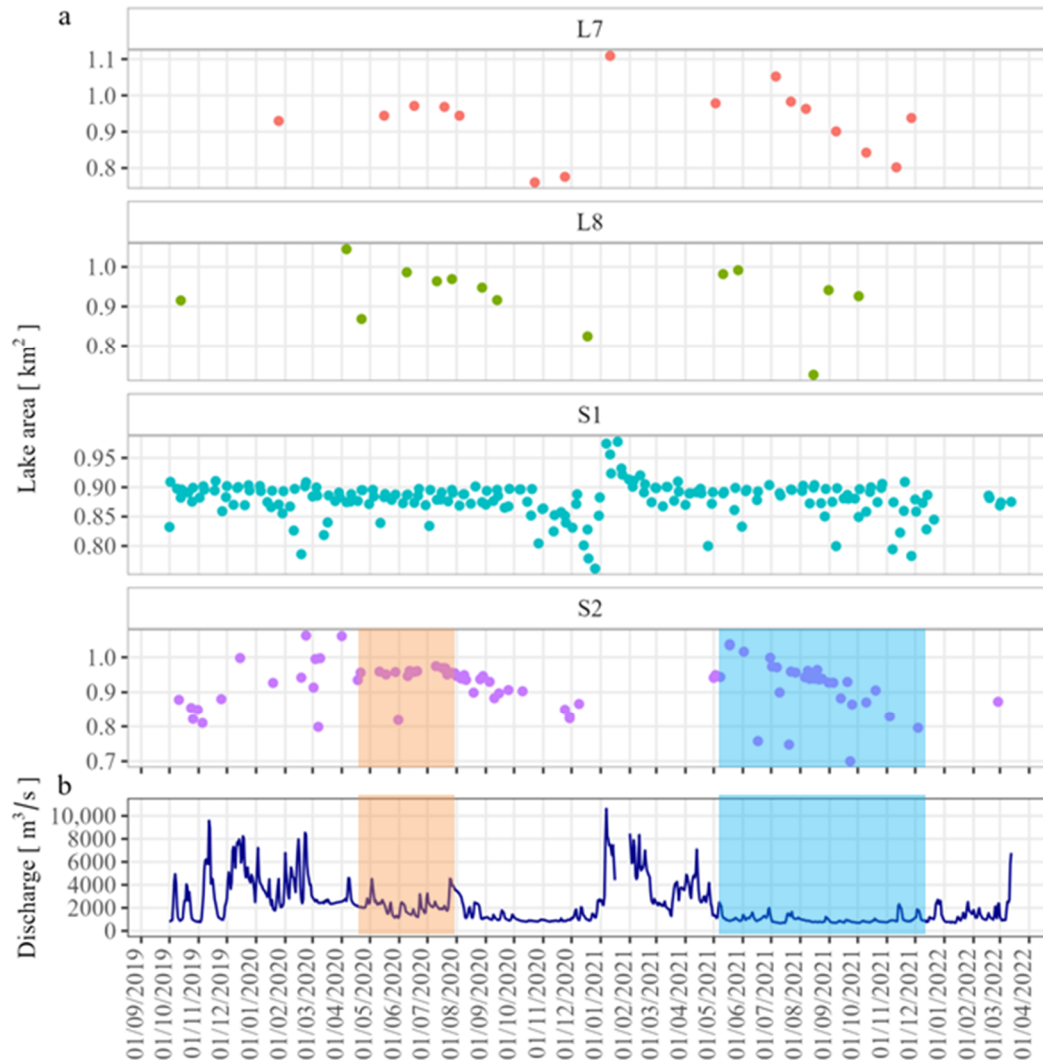


Figure B.3 a) Time series of calculated area for lake OL22 for different satellite image collections (L7: Landsat 7 ETM+, L8: Landsat 8 OLI, S1: Sentinel 1 SAR, S2: Sentinel 2); b) Discharge at the Rurrenabaque hydrometric station (extreme 2021 event is not fully visible, horizontal grid lines indicate discharge categories, orange shading marks identified connectivity period in range 2000-4000 m^3/s and blue shading indicates no connectivity period).

B.2.3. Estimated connectivity ranges

Based on the identification criteria and following an analysis similar to the example lakes, connectivity ranges were estimated for the forty oxbow lakes as summarized in Table B.4. It is important to note that identified connectivity ranges do not necessarily represent the minimum connectivity ranges, but rather the range for which the defined criteria (lake area patterns) were evident during the analysis period.

Table B.4 Summary of oxbow lake connectivity periods indicating discharge (Q) ranges of connectivity for recent period (1 October 2019 to 13 March 2022)

Lake	Recent area* km ²	Area variability for study period	Considered collections	Period of connectivity	Peak category / Connectivity range m ³ /s
OL1	0.76	Constant	L8, S1, S2	Feb-20	8000≤Q<10000
OL2	1.54	Constant	S2	Apr-21	6000≤Q<8000
OL3	0.81	Seasonal variability	L7, L8, S2	No date	10000≤Q
OL4	0.61	Continuous decline	S1	Aug-20	4000≤Q<6000
OL5	1.12	Constant	S1	Feb-20	8000≤Q<10000
OL6	2.00	Seasonal variability	S1	Dec-21	2000≤Q<4000
OL7	2.68	Constant	S1, S2, L7	Feb-20	8000≤Q<10000
OL8	2.14	Constant, decline	S1, S2, L7	Apr-21	2000≤Q<4000
OL9	1.35	Seasonal variability	S2	Apr-21	6000≤Q<8000
OL10	1.10	Seasonal variability	L7, S2	Aug-20	4000≤Q<6000
OL11	0.68	Constant	S1, S2	Aug-20	4000≤Q<6000
OL12	0.23	Continuous decline	S1,S2	Apr-20	2000≤Q<4000
OL13	1.17	Constant	S1,S2	Apr-20	2000≤Q<4000
OL14	1.84	Seasonal variability	L7, L8, S2	Aug-20	4000≤Q<6000
OL15	0.45	Constant	S1, S2	Jul-20	2000≤Q<4000
OL16	1.73	Constant	L7, L8, S2	Aug-20	4000≤Q<6000
OL17	0.79	Constant	S2	Apr-21	6000≤Q<8000
OL18	1.29	Seasonal variability	L7, S1, S2	Jul-20	2000≤Q<4000
OL19	0.30	Constant	L7, S2	Aug-20	4000≤Q<6000
OL20	1.76	Constant	S2, L7	Aug-20	4000≤Q<6000

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OL21	1.64	Constant, decline	S1	Jun-21	2000≤Q<4000
OL22	0.94	Constant, decline	L7, S1, S2	Jun-21	2000≤Q<4000
OL23	0.41	Constant	S1, S2	Aug-20	4000≤Q<6000
OL24	1.14	Constant, decline	L7, L8	Jun-21	2000≤Q<4000
OL25	1.89	Constant	L7, S2	Aug-20	4000≤Q<6000
OL26	1.71	Constant	L7, L8, S2	Jun-21	2000≤Q<4000
OL27	0.75	Constant	S2	Jun-21	2000≤Q<4000
OL28	1.13	Seasonal variability	S1, S2, L7	Jun-21	2000≤Q<4000
OL29	1.72	Seasonal variability	S1, S2	Aug-20	4000≤Q<6000
OL30	1.08	Constant	S2	Jun-21	2000≤Q<4000
OL31	0.75	Constant, decline	S1	Feb-20	8000≤Q<10000
OL32	0.52	Constant	L7, S1, S2	Jun-21	2000≤Q<4000
OL33	0.82	Constant	L7, L8, S1, S2	Aug-20	4000≤Q<6000
OL34	0.34	Seasonal variability	L7, S2	Aug-20	4000≤Q<6000
OL35	2.50	Constant, increase	S1, S2	Jun-21	2000≤Q<4000
OL36	2.17	Constant, increase	S1, S2	Jun-21	2000≤Q<4000
OL37	1.54	Constant, decline	S2	Apr-21	6000≤Q<8000
OL38	1.51	Constant, decline	S2, L7	Apr-21	6000≤Q<8000
OL39	2.83	Seasonal variability	S2, L7	Jun-21	2000≤Q<4000
OL40	2.53	Seasonal variability	S2, L7	Aug-20	4000≤Q<6000

(*) Mean area calculated for hydrologic years 2019-2022

Table B.5 aggregates oxbow lake areas by connectivity range and provides the cumulative connected area as a function of increasing discharge upper bounds (also shown in Figure B.4).

Table B.5 Sum of oxbow lake areas by connectivity range (columns 1 and 2) and cumulative connected area for each discharge (Q) upper bound (columns 3 and 4)

Connectivity range m^3/s	Sum of lake areas by connectivity range km^2	Upper bound of category m^3/s	Cumulative lake area connected for discharge upper bound km^2
$2000 \leq Q < 4000$	23.7	4000	23.7
$4000 \leq Q < 6000$	15.7	6000	39.4
$6000 \leq Q < 8000$	6.7	8000	46.2
$8000 \leq Q < 10000$	5.3	10000	51.5
$10000 \leq Q$	0.8	$10000 \leq Q$	52.3

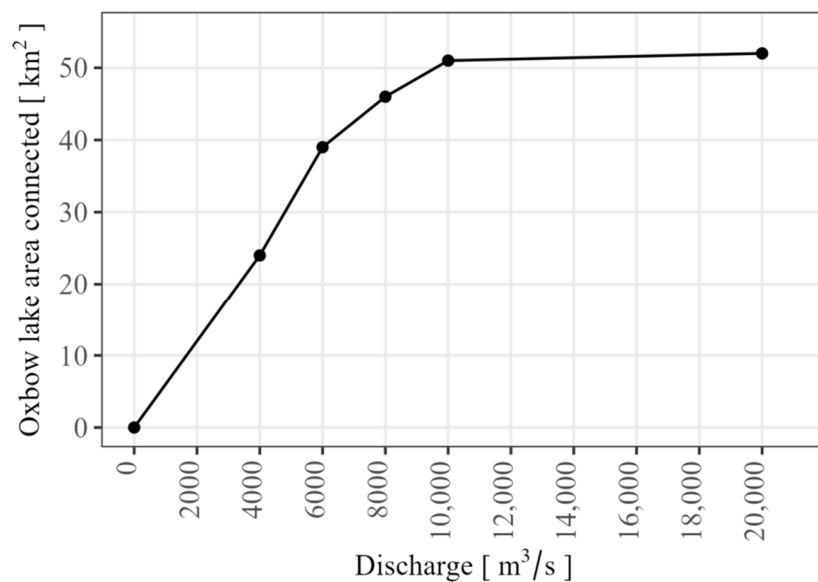


Figure B.4 Cumulative area of oxbow lakes connected to the main channel versus discharge (Q) upper bound of connectivity ranges (last category of $10000 \leq Q$ was assumed equal to an extreme value of $20000 \text{ m}^3/\text{s}$)

B.2.4. Conclusion

This multi-sensor analysis allowed the preliminary identification of discharge connectivity ranges of oxbow lakes. While Sentinel-1 provides higher temporal resolution for detecting short-term dynamics, optical datasets properly represent seasonal variability and contribute to comparison and validation. The identified connectivity ranges should be further evaluated through field work and additional image collections with higher temporal frequency. In addition, image preprocessing and water type classification require additional analysis to reduce uncertainty. Notwithstanding, these results provide an initial basis to associate discharge variability with oxbow lake connectivity, which can inform further ecohydrologic analysis.

Appendix C

C. HYDROLOGIC MODEL

C.1. BENI BASIN WEAP MODEL

This Appendix presents an additional WEAP configuration designed to simulate catchment hydrologic processes using the Soil Moisture Method. This setup was developed to calibrate the model at the hydrometric station of Rurrenabaque, and serves as a foundation for future scenario-based analyses.

C.1.1. Soil Moisture Method

The model setup covers the upper Beni River basin, extending downstream to the Rurrenabaque hydrometric station and covers the historical period from 1980 to 2016 using a daily time step. The rainfall-runoff process is simulated using the Soil Moisture Method, schematized in Figure C.1. It relies on empirical functions to simulate catchment processes such as evaporation, surface runoff, infiltration, interflow, percolation, baseflow and deep percolation (Sieber and Purkey 2015). This method represents the catchment unit with two soil layers. The upper layer simulates the water retained near the surface that is transformed into interflow or percolation, while the lower layer represents baseflow and groundwater recharge.

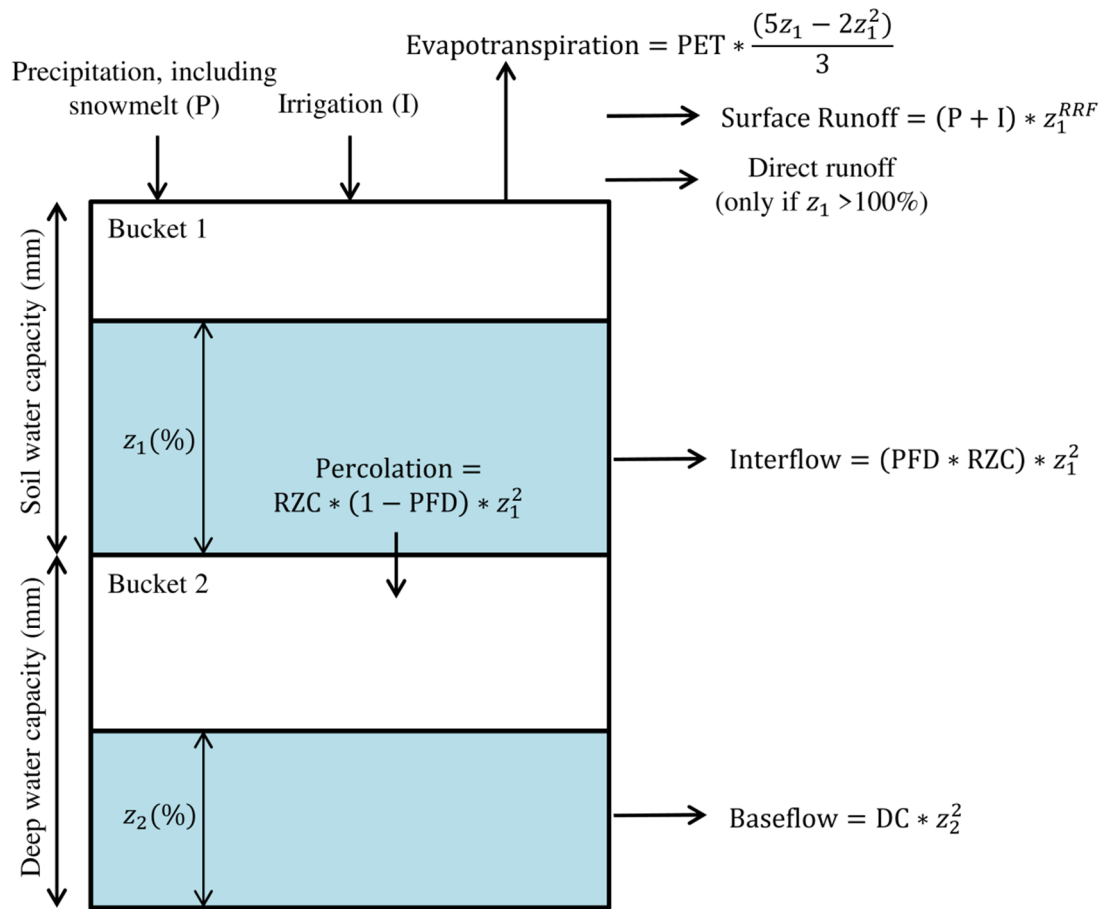


Figure C.1 Conceptual model of the Soil moisture Method in the WEAP model, where PET: Reference potential evapotranspiration, RRF: Runoff resistance factor, RZC: Root zone conductivity, PFD: Preferred flow direction, z_1 : Relative soil water storage at the root zone, and z_2 : Relative water storage at the deeper layer (adapted from Sieber and Purkey (2015))

The water balance for a catchment fractional land cover area (j of N) is calculated with Equation C-1:

$$Rd_j \frac{dz_{1,j}}{dt} = P_e(t) - PET(t)k_{c,j}(t) \left(\frac{5z_{1,j} - 2z_{1,j}^2}{3} \right) - P_e(t)z_{1,j}^{RRF_j} - f_j k_{s,j} z_{1,j}^2 - (1 - f_j)k_{s,j} z_{1,j}^2 \quad C-1$$

Where:

$z_{1,j}$: relative soil water storage at the root zone,

Rd_j : soil holding capacity of fractional land cover area j mm,

$\frac{dz_{1,j}}{dt}$: storage change in the first layer,

$P_e(t)$: effective precipitation, including snow melt mm,

$PET(t)$: reference potential evapotranspiration mm/day,

$k_{c,j}(t)$: crop coefficient for fractional land cover area j,

$P_e(t)z_{1,j}^{RRF_j}$: surface runoff,

RRF_j : runoff resistance factor for fractional land cover area j,

$f_j k_{s,j} z_{1,j}^2$: interflow from the first soil layer for fractional land cover area j,

f_j : preferential flow direction that divides horizontal and vertical $(1 - f_j)$ flows for fractional land cover area j

$k_{s,j}$: root zone saturated hydraulic conductivity for fractional land cover area j mm/time,

$(1 - f_j)k_{s,j} z_{1,j}^2$: deep percolation

The storage change in the bottom layer is calculated with Equation C-2:

$$S_{max} \frac{dz_2}{dt} = \left[\sum_{j=1}^N (1 - f_j)k_{s,j} z_{1,j}^2 \right] - k_{s2} z_2^2 \quad C-2$$

Where:

S_{max} : deep percolation from the upper layer storage,

$\frac{dz_2}{dt}$: storage change in the second layer

k_{s2} : saturated hydraulic conductivity of the lower storage mm/time

Table C.1 presents the input data and their respective sources. Spatial daily precipitation data were obtained from the CHIRPS v.2 model (Climate Hazards Group InfraRed Precipitation with Station data), which combines satellite imagery, infrared-based precipitation estimates, and in-situ rain gauge data (Funk et al. 2015). Previous evaluations in Bolivian regions have shown that CHIRPS performs better than other

satellite-based precipitation products (Gutierrez et al. 2024; Paca et al. 2020; Saavedra and Ureña 2022). Spatial mean temperature was estimated using station data as input for the Gridded Meteorological Ensemble Tool (GMET), which creates a continuous and gridded ensemble incorporating uncertainty estimates, historical variability and elevation (Newman et al. 2015). The resulting dataset was validated in previous studies (Ministerio de Medio Ambiente y Agua 2017) showing good performance in the region.

Additional climate variables including humidity, wind speed and sunshine hours were obtained from the Servicio Nacional de Meteorología e Hidrología of Bolivia (SENAMHI). The most reliable stations were selected for the analysis. Sunshine hours were converted to cloudiness fraction following the methods described in Allen et al. (1998) and Doorembos and Pruitt (1977). For these three variables, spatial data were interpolated using Thiessen polygons.

Land cover data were obtained from the European Spatial Agency Climate Change Initiative – Land Cover (ESA CCI-LC) (Land Cover Climate Change Initiative, 2017). Since land cover changes during most of the study period were minimal, the year 2000 was selected as representative for the model. In the upper Beni catchment (upstream of Rurrenabaque), the dominant land cover is forest (74%), followed by grassland (12%), shrubland (9%) and agriculture/bare land (5%). Soil texture data were accessed from the Harmonized World Soil Database (HWSD v1.2) (Fischer et al. 2008), with Sandy Clay Loam as the most common texture (98%) and clay (2%). Topographic data were obtained from previous studies (Ministerio de Medio Ambiente y Agua 2017) that used Shuttle Radar Topographic Mission (SRTM 30+) to calculate slope, with steep as the dominant slope class in the study area. Hydrologic records at the Rurrenabaque station were accessed from the Amazon basin water resources observation service HyBAm database (<https://hybam.obs-mip.fr/>), which includes observed water levels and calculated discharge values from 1989 to 2016.

Table C.1 Input data at a daily time step for the Soil Moisture Method.

Section	Variable	Unit	Source
Catchment/Climate	Precipitation	mm	CHIRPS v.2
Catchment/Climate	Temperature	degC	Station data and GMET
Catchment/Climate	Humidity	%	Station data
Catchment/Climate	Wind	m/s	Station data
Catchment/Climate	Cloudiness fraction	-	Station data
River/Streamflow Gauge	Streamflow data	m ³ /s	HyBAm
Catchment/ Land use combined with soil texture	Area	km ²	ESA CCI-LC and HWSD v1.2

The model was calibrated at the Rurrenabaque hydrometric station using a daily time step for the period (2001-2005). Calibration was performed by iteratively adjusting the parameters of the Soil Moisture Method until simulated outputs properly represent observed data. The tool “WEAP Calibration and Ensemble with R tool” (Moncada 2020) was used to support parameter evaluation. The process started with the default parameters as a baseline. The optimal parameter set was selected based on the maximization of Nash–Sutcliffe Efficiency (NSE), which was the objective function during calibration. NSE evaluates model performance by comparing the variance of simulation errors to the variance of observed data.

Additional model performance evaluation included the calculation of Percent Bias (PBIAS), which quantifies the tendency of the model to overestimate or underestimate discharge. PBIAS was computed as the percentage ratio of the cumulative difference between simulated and observed discharge to the cumulative observed discharge. Model performance was further assessed through comparisons of the seasonal distribution of peak flows, the duration of low flow periods, and the magnitude and timing of annual maximum and minimum discharges.

After calibration, the model performance (NSE) was evaluated over the long-term period from 1999 to 2016 to assess its performance for each year representing the validation period.

C.1.2. Calibrated model and evaluation

Table C.2 presents the Soil Moisture Model parameters calibrated to simulate rainfall–runoff processes in the upper Beni River catchment for 2001-2005. Parameter sensitivity is illustrated in Figure C.2, which shows the change in NSE resulting from incremental adjustments applied only to the dominant land-soil unit (forest and sandy clay loam). Parameter changes included crop coefficient k_c (0.7-1), deep water capacity DWC (1200-1600 mm), runoff resistance factor RRF (0.8-1.2), root zone conductivity $k_{s,1}$ (100-300 mm/day), deep conductivity $k_{s,2}$ (100-300 mm/day), preferred flow direction f (0.3-0.5) and soil water capacity SWC (300-500 mm). Boxplots indicate that RRF is the most sensitive parameter, leading to the largest NSE improvement, followed by $k_{s,1}$ and $k_{s,2}$. In contrast, increasing k_c , DWC and f reduced NSE. These results highlight the role of RRF representing peak flows and $k_{s,1}$ in modeling interflow.

Table C.2 List of calibrated parameters for the Soil Moisture Model

Section	Parameter	Units	Default	Calibrated value
Land Use	Crop coefficient	-	1	0.75
Land Use	Soil water capacity (first layer)	mm	1000	Sandy clay loam, Forest: 500 Grassland: 200 Shrubland: 200 Agriculture: 300 Other/Bare: 100 Clay, Forest:800
Land Use	Deep water capacity (second layer)	mm	1000	1200
Land Use	Runoff resistance factor		2	Forest: 1 Grassland: 0.8 Shrubland: 0.8 Agriculture: 0.6 Other/Bare: 0.6
Land Use	Root zone conductivity	mm/day	20	Sandy clay loam, Forest: 300 Grassland: 150 Shrubland: 200 Agriculture: 150 Other/Bare: 50 Clay, Forest: 150
Land Use	Deep conductivity	mm/day	20	300
Land Use	Preferred flow direction	-	0.15	Steep: 0.3
Other	Lag	day	-	1

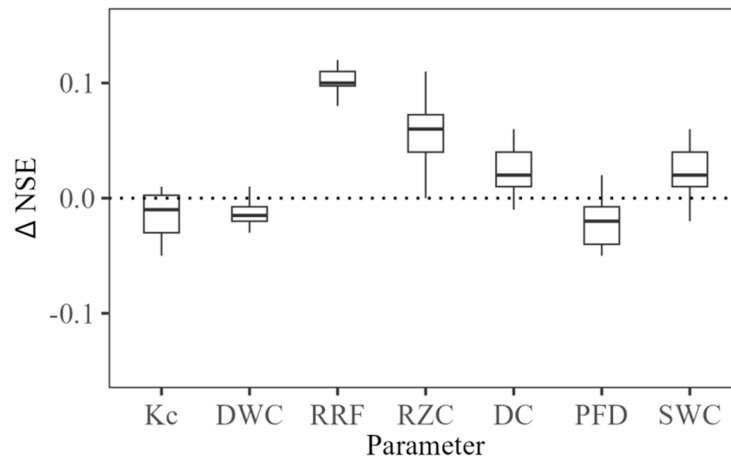


Figure C.2 Boxplot showing the change in NSE corresponding to changes in the Soil Moisture Method parameters for the dominant land-soil unit (forest and sandy clay loam)

Figure C.3 shows the performance evaluation for the calibration period 2001-2005 at Rurrenabaque. The model achieved an NSE of 0.74 and PBIAS of 7.4% indicating a good performance with small overestimation of runoff based on general performance ratings (Moriassi et al. 2007). Daily discharge comparison (Figure C.3a) also indicates the timing of extracted peak flows for both observed and simulated series. Comparisons of mean monthly discharge show that the model matches the seasonal dynamics of the observed series closely (Figure C.3b).

The 1-day minimum timing and magnitude are mainly well represented, with exceptions in 2004, when the minimum occurred two months early (Figure C.3c,d). The underestimated 1-day maximum mostly coincides in timing, except for 2003 (earlier) and 2002 (later) (Figure C.3c,d).

The monthly distribution of observed peaks shows peaks above 6000 m³/s concentrated between January and April (Figure C.4a). In contrast, the simulated series underestimates the number of peaks, especially in February and March and in the categories with upper limit higher than 8000 m³/s (Figure C.4b). Peak flow comparison (Figure C.4c) shows the model adequately captures the magnitude and timing of most peaks below 6000 m³/s, but underestimates larger flood events. Overall, calibration results indicate the model is an acceptable basis for scenario simulations, taking into account the underestimation of extreme events.

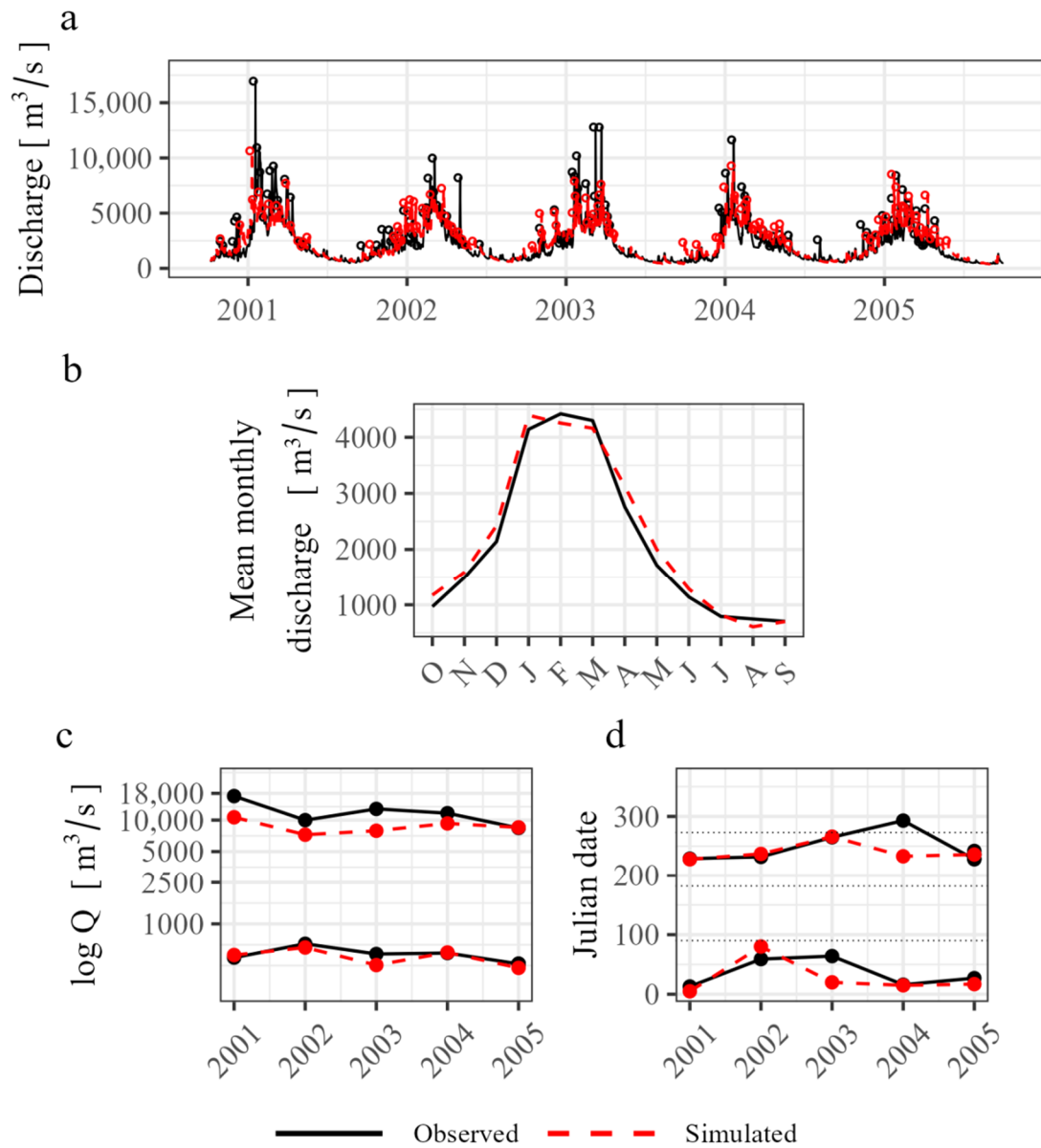


Figure C.3 Performance evaluation of discharge (Q) for the calibration period 2001-2005: a) Daily discharge, b) Mean monthly discharge, c) Magnitude of 1-day minimum and 1-day maximum, d) Timing of 1-day minimum and 1-day maximum

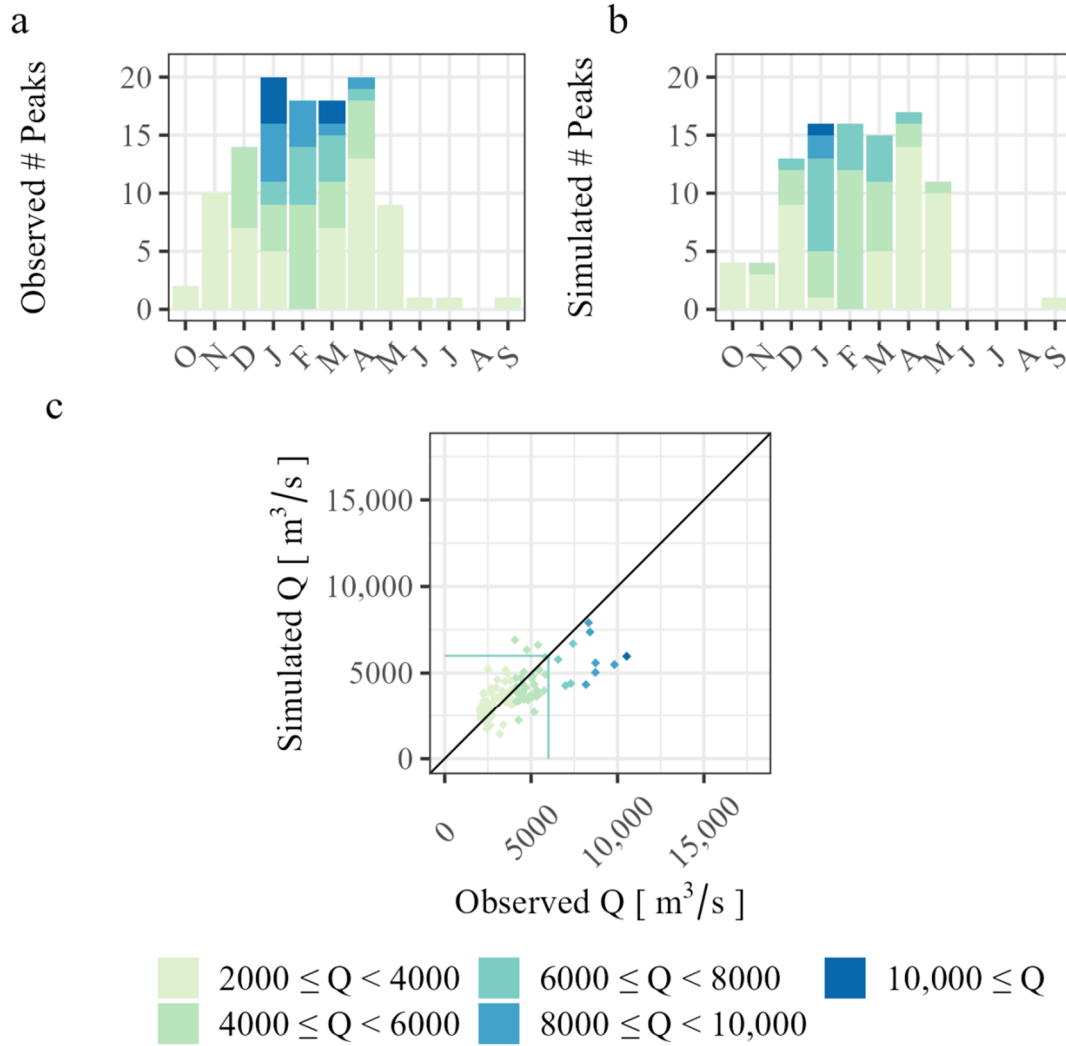


Figure C.4 Performance evaluation of peak flows for the calibration period 2001-2005: Monthly distribution of number # of peak flows within five discharge (Q) categories for: a) Observed and b) Simulated, and c) Scatter plot of peak flows

Figure C.5 presents the model performance for each year during the period 1980-2016. The mean NSE is 0.66, indicating fair agreement between simulated and observed discharge. From 1981-1992, NSE ranged from 0.2 (1991) to 0.76 (1984), reflecting high interannual variability. During 1990-1992, the model overestimated discharge during rising and receding periods, and overestimated peaks in 1992. From 1993-2016, NSE values improved, except during extreme flood years such as 2014.

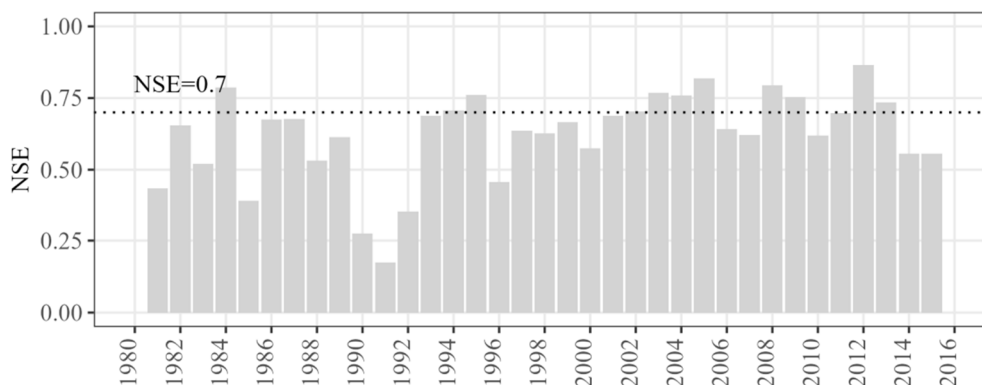


Figure C.5 Annual values of NSE for the 1981-2016 period

C.1.3. Summary

The WEAP model effectively represented the hydrology of the Beni River with acceptable calibration results (NSE=0.74 for 2001–2005). However, peak flows above 6000 m³/s were underestimated. This limitation may be partially attributed to a common issue in rainfall hot-spot regions, where extreme events are not often captured by station networks and satellite-based data (Espinoza et al. 2015; Molina-Carpio et al. 2019). Future improvements should include testing additional precipitation datasets and implementing correction methods specifically designed for extremes events.

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LIST OF ACRONYMS

CIPTA	Consejo Indígena del Pueblo Tacana
ETM+	Enhanced Thematic Mapper Plus
GEE	Google Earth Engine
HyBAm	Hydrology and Biogeochemistry of the Amazon basin
LEDAPS	Landsat Ecosystem Disturbance Adaptive Processing System
NDVI	Normalized Difference Vegetation Index
NIR	Near-Infrared
NSE	Nash–Sutcliffe Efficiency
NSI	Normalized Sand Index
OCITB	Organización de Comunidades Indígenas Tacana de Ballivián
PBIAS	Percent Bias
POT	Peak Over Threshold
SEDAG	Servicio Departamental Agropecuario
SENAMHI	Servicio Nacional de Meteorología e Hidrología
SENASAG	Servicio Nacional de Sanidad Agropecuaria e Inocuidad Alimentaria
SLC-off	Scan Line Corrector-off
SWIR	Shortwave infrared
TCO	Tierra Comunitaria de Origen
TS	Turbidity Status

WCS	Wildlife Conservation Society
WEAP	Water Evaluation and Adaptation Planning
WWF	World Wide Fund for Nature

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ABOUT THE AUTHOR



Lina Terrazas is a Water Resources engineer from Bolivia who has specialized in ecohydrology of river-floodplain systems.

She obtained a degree in Civil Engineering from the Universidad Mayor de San Simón, graduating with Academic Excellence distinction. Her early professional experience in water-related projects motivated her to pursue a specialization. In 2015, she completed a Master's degree in Water Resources Engineering (cum laude) from KU Leuven and Vrije Universiteit Brussel. In this program, she developed a strong background in hydrologic modeling,

which she later applied in projects at the Laboratory of Hydraulics at Universidad Mayor de San Simón, including water balance in the Amazon basin, climate change analysis, and climate forecasting systems. This technical experience and her training in integrated planning encouraged Lina to explore how to include social and ecological aspects in water projects.

Her familiarity with the Beni River and the increasing pressure from hydropower development motivated her to propose a research PhD project focused on potential hydrologic alterations on ecological functions. In a data-limited region, she adopted an integrative approach that combines local fishers' knowledge and remote sensing. Her research emphasizes the value of complementary sources of knowledge in understanding the complexity of river systems. Her findings include the identification of key ecohydrologic relationships and corresponding hydrologic indicators. These results represent key river-floodplain processes such as connectivity among water bodies, and allow for the evaluation of potential impacts under different dam operation scenarios. Her research aims to inform and guide hydropower planning with a stronger focus on ecological functions and the livelihoods of people who rely on them.

Her research interests include ecohydrology, remote sensing applications, qualitative analysis of local knowledge, and environmental impact assessment. Lina has a strong focus on interdisciplinary approaches that link science, people and management. In addition, she has previously engaged in teaching activities and plans to continue sharing her expertise in research and ecohydrology. Her main motivation is to increase understanding of complex environmental processes, and contribute to more sustainable and socially relevant water management.

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SENSE PhD Courses

- o Environmental research in context (2021)
- o Research in context activity: 'Proposal of evaluation of mercury concentration in fish tissues in fish catches in the Beni River' (2025)
- o Fire in the landscape: introduction to biophysical aspects (2021)
- o Decolonising Science, IHE Delft (2023)

Other PhD and Advanced MSc Courses

- o PhD Start-up, TU Delft (2021)
- o River and Floodplain Rehabilitation, IHE Delft (2021)
- o Scientific writing and skill development, IHE Delft (2021)
- o Effective Negotiation: win-win communication, TU Delft (2021)
- o Using creativity to maximize your productivity in your PhD, TU Delft (2021)
- o Analysis of Interviews and other Unstructured Data, TU Delft (2022)
- o Data visualizations, TU Delft (2022)
- o Analytic storytelling, TU Delft (2022)
- o Creative tools for scientific writing, TU Delft (2022)
- o Exploring a research career outside academia, TU Delft (2022)
- o Looking for work in The Netherlands, TU Delft (2024)

External training at a foreign research institute

- o Training with drone (2022)

Oral Presentations

- o *Environmental flow methods*. Virtual workshop Procesos de Evaluación de impacto socioambiental y monitoreo en proyectos de desarrollo: avances, necesidades y desafíos metodológicos y de implementación, 26 March 2021, Online
- o *Retos en la determinación de caudales ambientales*. Webinar on Difusión de Investigación LHUMSS, 8 July 2021, Online
- o *A qualitative study of fishers' perceptions of hydrologic variability in the Beni River*. IHE Delft PhD Symposium 2023, 19 October 2023, Delft, The Netherlands
- o *Conocimiento local sobre la ecohidrología del Río Beni en la Amazonía Boliviana*". XXXI Congreso Latinoamericano de Hidráulica, 2 October 2024, Medellín, Colombia

Rivers and their floodplains are among the most productive ecosystems on Earth, sustaining rich aquatic life and supporting the livelihoods of riverine communities. Andean-Amazon river systems, such as the Beni River in Bolivia, face growing pressure from hydropower development and other environmental changes. Yet, the ecohydrologic processes that sustain them remain poorly understood, and limited data hinder impact assessments. This book presents an innovative approach to address these challenges by combining two sources of knowledge: the expert knowledge of local fishers and decades of satellite observations of floodplain lakes. Fishers described how seasonal floods, river connectivity, and hydrologic variability influence fish migration, habitats, and fisheries.

Satellite imagery revealed how forty oxbow lakes change in area and water turbidity over time, providing new insights into their connectivity with the main channel and their role as fish habitat.

By integrating these perspectives within a common spatiotemporal framework, this study developed ecohydrologic relationships that represent the functioning of meandering river systems. The simulation of a planned hydropower project showed that hydrologic alteration could reduce habitat connectivity and affect fish populations. The presented methodology is transferable to other data-scarce river systems and provides practical insights for sustainable river planning in the Amazon and beyond.