Impact of hydroelectric dams on freshwater ecosystems and mitigation strategies

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Abstract

Hydroelectric power will always be balanced with energy from other renewables. However, hydroelectric power is a renewable energy source. Hydropower dams impede the fragmentation of freshwater ecosystems. These include the fragmentation of freshwater ecosystems, alterations in the reproduction and migratory patterns of some species, and disruptions to the hydrological regime. This study aims to examine the biological impacts of hydropower dams on freshwater ecosystems, including the current negative impacts and proposed mitigation measures. We conducted impact surveys in biological fields and freshwater hydrological systems, and in the cycles of ecosystems. And the Itaipu and its rivers. We portray impacts on ecosystems, sediment removal and deposition, warming, peripheral areas, poor areas, negative areas, and biodiversity. Moreover, in the region, migratory fish species are on the verge of extinction, as surface habitats are lost and other barriers include the regime's migratory flow. Downstream ecosystems depend on the unconfined circulation of sediment and nutrients. Our research serves as a framework for the impact of the proposed biological interventions and the other proposed biological interventions. Our research illustrates the successful fish ladder framework as an active means of mitigating impacts, but it also underscores the need for additional mitigation. To minimize adverse effects on biodiversity and ecosystem services, this research underscores the need to consider biophysical factors in the planning and management of hydroelectric facilities, especially to reduce losses to freshwater ecosystems.

Keywords: Hydroelectric dams, Freshwater ecosystems, Ecological impact, Mitigation strategies, Fish migration, Environmental flow

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Introduction

Freshwater ecosystems sustain life, provide water, and support human activities like agriculture, water supply, and recreation. Further, ecosystems offer numerous other services, such as flood regulation, shelter for diverse aquatic organisms, and nutrient cycling. Most, if not all, ecosystems face human exploitation and activities, including the devastating construction of hydroelectric dams. The construction of hydroelectric dams for flood control and renewable energy has increased sharply globally (Arantes *et al*., 2019). The International Energy Agency (IEA) documents 58,000 hydroelectric dams, and hydroelectric renewable energy continues to rise. These economically active, renewable energy, hydroelectric dams come with significant environmental/'eco' costs, including alteration of the natural flow of rivers, sediment trapping, and river compartmentalization. As a result, there is significant ecosystem fragmentation. The hydrological regime is altered, the flow is rationalized, and the changes to the habitats of aquatic organisms are extreme, all of which are serious problems. Dams also flood terrestrial habitats, creating reservoirs that greatly increase the land area the dam proprietor can exploit. In addition, these habitat modifications enhance sediment retention in the reservoir and disrupt normal sediment transport in the river. These modifications encompass the obstruction of economically and ecologically significant species such as fish stocks, thereby fostering biodiversity loss and the erosion of critical ecosystem services.

The cumulative impacts of hydropower and their individual impacts have been overlooked owing to the construction of multiple dams along the same fluvial system. Despite extensive studies of the impacts of numerous hydropower dams within the same fluvial system, a knowledge gap remains regarding the incremental and ecological impacts of multiple dams (Gracey and Verones, 2016). The impact of the various mitigation strategies implemented so far remains unresolved. This is true irrespective of the type of ecosystem and the configuration of the dam. With the construction of dams being a constant, the impacts of the exploitation of ecosystems and the construction of new mitigation strategies aimed to protect freshwater ecosystems shall become a research priority (Zarfl *et al*., 2019). This work tries to promote the understanding of the ecological impacts and alterations of hydrodynamics, habitat fragmentation, and species assemblage changes of migratory resilience in freshwater systems impaired by hydropower (Trottier *et al*., 2022; Simonov *et al*., 2019). The ecological impacts and disruption of ecosystems are chiefly due to alterations in the flux and sediment transport for ecosystems. This work also aims at the more conventional forms of mitigation of the impacts of dams on freshwater ecosystems, the artificial diversion of environmental flows, fish passage systems, and the restoration of impacted ecosystems (Baumgartner *et al*., 2021). All these methods try to counterbalance the environmental consequences caused by developing hydropower (Ahmad and Hossain, 2020).

Research-oriented and analytical thinking to solve problems is the core purpose of any study. With that in mind, this study is mostly concerned with answering these questions.

1) What are the ways in which the hydrological regime, sediment transport, and habitat connectivity of freshwater systems are modified by hydroelectric dams?
2) What are the most significant ecological consequences of these changes concerning the composition and distribution of species?
3) What is the effectiveness of the mitigation measures currently in use? What is the extent of the negative impacts they account for, and what improvements are needed for greater effectiveness?

This study focuses on the problems and the negative consequences of hydroelectric power development and tries to find the least damaging consequences of hydropower development, the more of it is attainable.

Materials and Methods

The Amazon River, along with its hydraulic reservoirs, flows through South America. The construction and operation of hydroelectric dams along the Amazon River and its tributaries impact the entire region concerned. The Amazon basin, characterized by a tropical climate, receives large amounts of rainfall. Seasonal and inter-annual variability of temperature and precipitation affects the hydrology and ecology of the river basin. Still, in terms of hydro-systems, the Amazon River basin is unique due to the many ecosystem services it provides. The river basin and its river support numerous recreational activities, provide services and resources from commercial multi-species fisheries, and offer a wide range of freshwater and recreational services. The remarkable freshwater biodiversity of the river basin is complemented by the migratory fish, which enhance local biodiversity and commercial fisheries. The wetlands, riparian flooding, and geomorphologic features like river terraces, floodplains, and wetlands help mitigate climate extremes. The research is focused on the upper Amazon River in the vicinity of the constructed and operational dams. This research is both an appreciation of the comparative context upstream and downstream of the dams and an assessment of the impact of hydroelectric development on photic freshwater ecosystems.

The study draws examples from two hydroelectric dams, namely the Itaipu Dam and the Balbina Dam. They are of different sizes and have different operational characteristics because of the Itaipu Dam's construction period and operationalization date (1971 and operationalization in 1984). By 2023, it will have been operational for 40 years. In contrast, the Balbina Dam was operationalized in 1987 and has been in operation for 35 years. Both dams serve the same purpose of flood control and electricity generation. Operationally, they employ peak load regulation and seasonal flow control. They also differ in size, with Itaipu Dam's reservoir volume being 1350 km² and Balbina Dam's being 250 km². Each employs flood control and intermittently discharged water release techniques of 2-3 of the assumed six regional impacts of downstream hydrograph variability and aquatic systems. These operational patterns are predictive of the adverse basin flow regime and ecological consequences. These are downstream habitat fragmentation and the control of water from the flood reserve (Ravshanova *et al*., 2024; Ouyang *et al*., 2021).

The effects of the dams were also examined in relation to the hydrological regime by collecting flow and sediment data, and water levels from both upstream and downstream from the dam (Ahmad *et al*., 2021). For hydrologic flow data, the Brazilian National Water Agency, as well as some irrelevant local hydrological monitoring stations, were used for the years 2000 to 2020. For sediment load measurements, sediment traps were used in combination with the suspended sediment concentration. For the water levels, monitoring was conducted at defined locations, including the Xingu River location, which is located near the Itaipu Dam, and at the Rio Uatumã location close to the Balbina Dam. Ecological data were also gathered through field surveys focusing on the assemblages of fish, communities of macroinvertebrates, and the riparian vegetation. For the fish portion, surveys were conducted using a combination of electrofishing and gill netting, while for the other surveys, multiple data collection stations were set up along the river, both upstream and downstream of the dams, to support comprehensive species identification and population estimation.

Multiple kick sampling techniques were used to evaluate macroinvertebrate communities. Surveys documented the distribution and invasiveness of riparian and aquatic plants while assessing riparian vegetation nearby. Water quality parameters—including temperature, dissolved Oxygen, pH, turbidity, nitrogen, and phosphorus—were collected from monitoring sites and analyzed in the lab. Data loggers recorded temperature and dissolved Oxygen continuously. Geomorphological assessments focused on riverbed surveys and obstacles posed by dams, examining channel configuration, vegetation density, slope, sedimentation, habitat availability for macrobenthos, water velocity, substrate type, and barriers to fish passage. To assess the ecological effects of hydroelectric dams, the study evaluated eco-variables considering spatial (upstream, downstream) and temporal (pre- and post-construction) aspects. It analyzed species richness, evenness, and community structures using SPSS and R, while hydrological parameters were examined through ANOVA. Long-term effects of operational scenarios on freshwater ecosystems were simulated using the SWAT model, calibrated with historical and field data (Soomro *et al*., 2024). Mitigation measures were reviewed through literature, expert consultations, and case studies, focusing on strategies like fish passage and habitat restoration. Expert discussions provided insights into the effectiveness of these measures and their impact on biodiversity and ecological functions in dam-affected rivers (Figure 1).

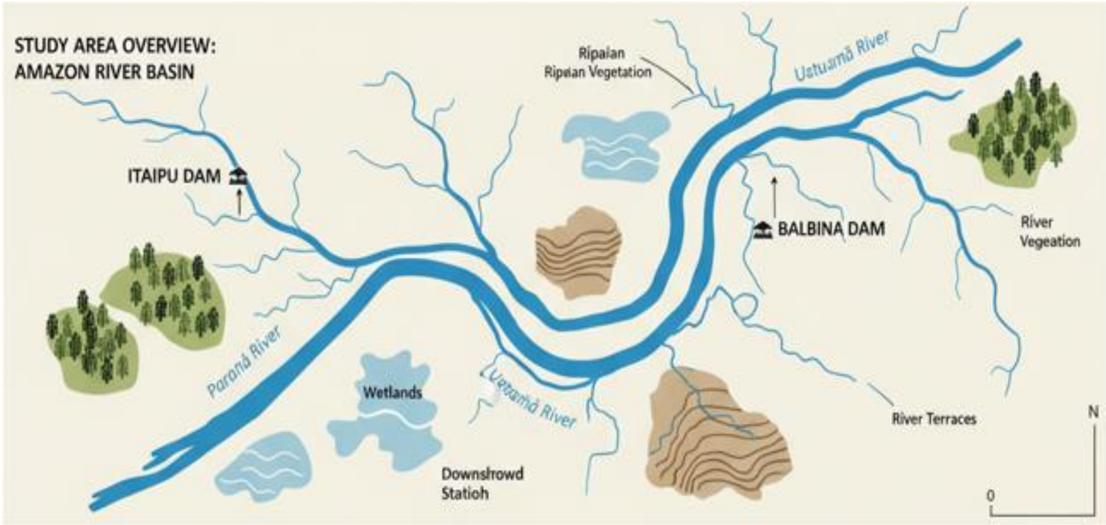

Figure 1: Study area overview: amazon river basin.

Results

The construction and operation of hydroelectric dams have altered the hydrological patterns of the Amazon River and its tributaries. Flow gauging during periods of dam operation shows decreased seasonal flow variability. In particular, the area downstream of the Itaipu and Balbina Dams saw lower peak flows during the rainy season, up to 20% of the peak discharge. Explosive sediment trapping has allowed the reservoirs to grow, since the dams hold 60% of the sediment load and thus limit sediment transport downstream. This sediment retention has caused aggradation of the downstream riverbed, thus increasing the already reduced availability of sediment of the aggraded riverbed. There were extreme and contradictory fluctuations of the water level at the Balbina Reservoir, which, along with the more than three-meter seasonal changes in water levels, affected the riparian vegetation and floodplain ecosystems. Figure 2 represents the flow regime changes upstream and downstream of the Itaipu Dam.

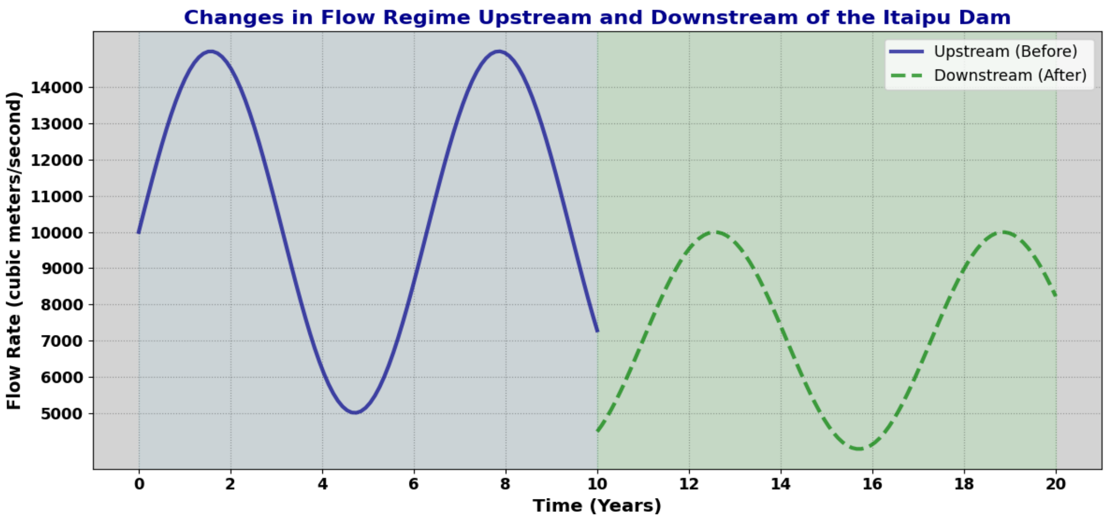

Figure 2: Changes in flow regime upstream and downstream.

Some major upstream and downstream shifts in the river's course occur due to the geomorphological dynamics of the floodplains and riverbeds. Constant upstream flooding of wetland habitats and the resultant loss of critical floodplains for some migratory species are consequences of the Itaipu Dam. Downstream floodplains also experienced loss of floodplain connectivity and consequent geomorphological transformation. The altered hydrological conditions did not allow for the floodplain to be inundated during the wet season. Moreover, the increased sediment deficit has resulted in narrowing of the river channel, excessive bank erosion, disconnection of terraces, which once supported the river by transferring important sediment and nutrients, and severe sediment deficit. The sum of these consequences has geomorphologically fragmented these riverine habitats and disrupted the geospatial ecology of many species that rely on seasonal floods for reproduction.

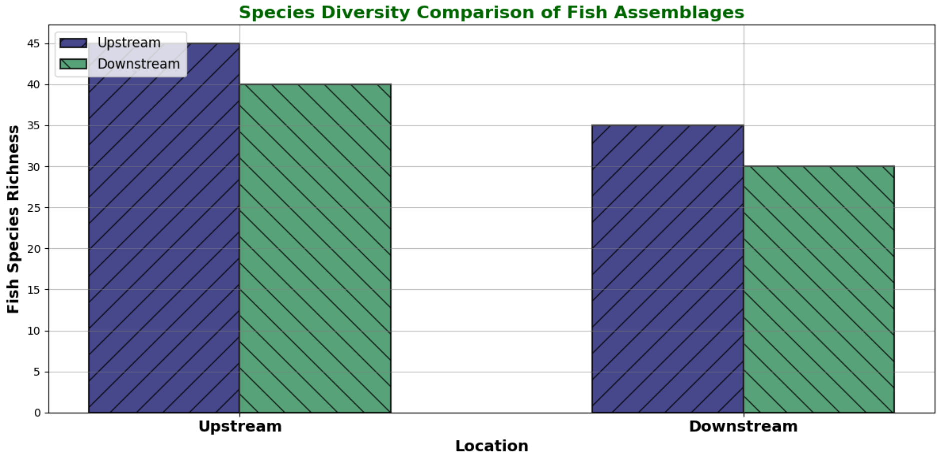

Figure 3: Species diversity comparison of fish assemblages upstream and downstream.

The building of the dams in the region changed the local freshwater fish populations, as dams changed the migratory patterns of the fish, the makeup of the fish communities, and the riparian macroinvertebrate communities and vegetation. Fish migration became almost impossible as prochilodus and catfish species holding migratory patterns were blocked from the Itaipu Dam. Fish species richness downstream was 30% of what it was upstream, and migratory fish of the species cascudo and tambaqui were completely absent from the Balbina Dam downstream, which is illustrated in Figure 3. There was a downstream loss of macroinvertebrate richness, as the index of Shannon-Wiener diversity 15%, as the community composition changed. Probably, as the sediment and water flow alterations increased, the detritivore populations were lost, as the scrapers and collector-gatherers increased, as shown in Table 1.

Table 1: Macroinvertebrate diversity indices at various study sites.

Site	Shannon-Wiener Index
Upstream of Itaipu	3.5
Downstream of Itaipu	2.8
Upstream of Balbina	3.2
Downstream of Balbina	2.6
Upstream of Amazon	3.7
Downstream of Amazon	3.0

The riparian vegetation downstream from Itaipu Dam and its associated floodplains suffered a 20% reduction in vegetation cover in the riparian zones, flood-tolerant species predominated, and invasive species of vegetation increased. Minor, also exotic flood-tolerant species, became dominant in disturbed areas.

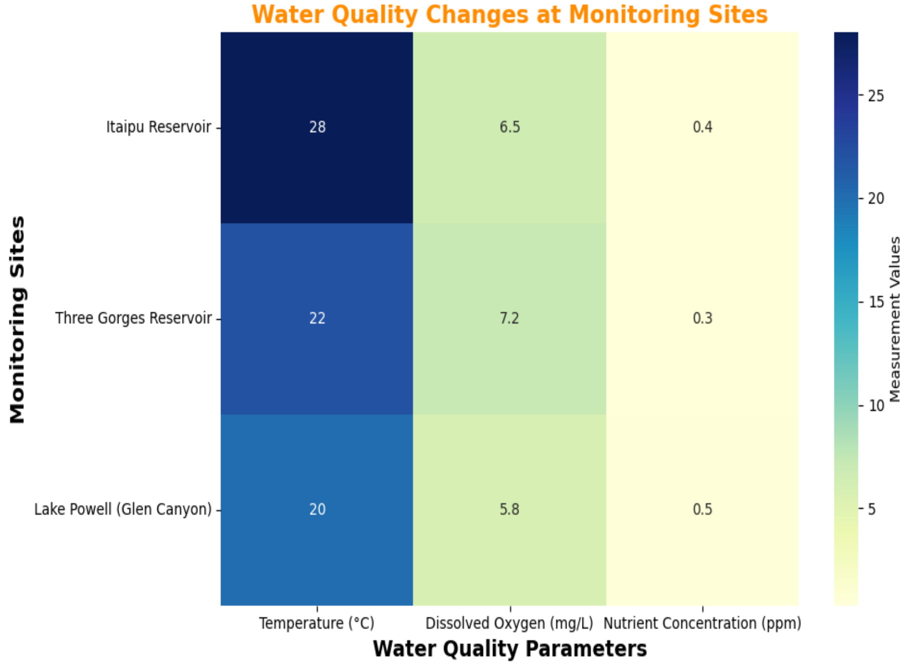

Figure 4: Water quality changes at monitoring sites.

Recent operational assessments concentrated on water quality variables that exposed significant discrepancies. Water temperature at the dams downstream has increased by 2-3°C on average, more so during the dry season when the reservoirs' water temperature is significantly higher than that of the natural river. There was a marked oxygen (DO) deficit downstream. Oxygen (DO) concentrations were 30% lower than upstream in the shallower layers of the reservoirs, and in the deeper layers, which were also more hypoxic. Greater nutrient (particularly N and P) concentrations in the reservoirs were the cause of localized eutrophication, resulting in algal blooms and subsequent hypoxic conditions. These changes in water quality made the biota distress more problematic, particularly the more temperature and oxygen-sensitive species. Figure 4 shows the changes in water quality variables at the monitoring sites before and after the dams were constructed.

Adjustments to environmental flows within operational regulation of damming went hand-in-hand with attempts at restoration of flow mimicry. This was most obvious when flow releases at the Itaipu Dam coincided with the most critical breeding periods of large, migratory fish that breed during the environmental flows of the Rio Paraná downstream. Short-term downstream fish populations that were observed were, however, more the result of inadequate spawning habitats and sediment retention. The fish ladder at the Balbina Dam also illustrated poorly designed fish passage facilities, although the fish ladder was meant to facilitate fish spawning runs. The system, however, seems to have done very little to assist the larger tambaqui, while most of the downstream fish runs were made up of small, non-migratory fish. Attempts at restoration of habitats, especially the replanting of riparian and floodplain vegetation where sediment was retained, were the most effective of the three and aided in the re-establishment of several native species. The fragmented nature of the landscape still poses some of the most formidable challenges, particularly within the sediment harvest and retention system. Table 2 displays the changes in water quality before and after the dam was constructed.

Table 2: Water quality changes at monitoring sites before and after dam construction.

Monitoring Site	Temperature (°C)	Dissolved Oxygen (mg/L)	Nutrient Concentration (ppm)
Itaipu Reservoir (Before)	28	6.5	0.4
Itaipu Reservoir (After)	27	6.2	0.45
Three Gorges (Before)	22	7.2	0.3
Three Gorges (After)	21	6.9	0.35
Lake Powell (Before)	20	5.8	0.5
Lake Powell (After)	19	5.5	0.55

Discussion

Adverse ecological consequences have arisen from the construction and operation of the Balbina and Itaipu Dams, notably through alterations in habitat morphology and hydrology. The dams have led to reduced seasonal flow variability, sediment trapping, and degradation of riverbeds, adversely affecting aquatic habitats. Documented effects include decreased diversity of migratory fish and macroinvertebrate communities, as well as the loss of disconnected floodplains critical for fish spawning. The study highlights a 30% decrease in species richness downstream of the Balbina Dam and aligns with existing literature on hydroelectric dams' impact on migratory species extinctions. Additionally, changes in macroinvertebrate groups mirror those of other dam-altered systems, indicating disruptions in sediment availability and flow regime, which ultimately affect food webs and trophic support.

The studies indicate that changes in water flow significantly impact ecosystem functioning, biodiversity, and services such as water filtration and fisheries. The loss of wetlands upstream and altered species compositions downstream disrupt local food webs and degrade water quality, impacting species like tambaqui and prochilodus, which are crucial for local communities. These concerns highlight the need for integrated management strategies for dams. Current ecosystem services plans, like the environmental flow releases from Itaipu dam, show variable success, and larger migratory species struggle with fish passage structures, often designed only for smaller fish. Significant habitat fragmentation remains a pressing issue, especially with the Balbina Dam, necessitating a cross-sector approach for effective restoration. Hydropower managers could enhance strategies by mimicking natural river flows and constructing adequate fish passage structures (Garrett *et al*., 2023). Moreover, Environmental Impact Assessments should consider long-term hydrological and ecological changes and adopt ecosystem-based adaptive management practices. The challenges of restoring biodiversity and ecosystem services in hydropower management emphasize the need for comprehensive data and broader studies across diverse dam types in the Amazon basin (Kuriqi *et al*., 2021).

Potential future research endeavors may focus on assembling data across a broader spectrum regionally, as well as incorporating additional dams and diverse ecosystems. These endeavors may also focus on longer time spans in order to address the cumulative and prolonged effects of the development of hydropower (Vaidya *et al*., 2021). Future research has identified several important, yet still neglected, areas of investigation. For instance, assessments focusing on the cumulative impacts of several dams within the same river system on the riparian ecosystem would be invaluable in contributing to the understanding of some of the system’s impacts (Widén *et al*., 2022). Furthermore, the ineffectiveness of several mitigation measures, particularly those associated with the management of environmental flow and fish passage, has also led to a reluctance to incorporate further hydropower development (Nezhad and Ghodousi, 2016; Hase and Seidel, 2021). Integrating and interlinking ecological monitoring and hydrological models to the relevant time scales would enhance the design and management 'firewalls' of the mitigation measures to achieve a more balanced compromise between energy production and ecosystem conservation. The preservation of ecological requirements of the river, in combination with the management of anthropogenic requirements of the river, will be crucial for the development of climate-adaptive sustainable hydropower (Coelho *et al*., 2024; Santos *et al*., 2025).

Conclusions

This research addresses the ecological consequences of Balbina and Itaipu Dams on the Amazon River basin. The primary findings evidence serious and negative consequences, such as hydrological alterations, including loss of seasonal water flow patterns, loss of sediment, and the moderation of water control systems. Such moderation inevitably disrupts and controls systems of water with varying levels, and temporarily controls systems of water with varying levels, thus causing moderate to severe clogging and leading to the loss of biodiversity. Habitat fragmentation and loss of floodplain connectivity result in the loss of migratory passage of fish and of macroinvertebrates. The water temperature, the loss of dissolved Oxygen, and the increase of various water-soluble nutrients comprise the water quality, which only adds to the stress within the living aquatic organisms. Proposed mitigation measures, such as the release of environmental flow, construction of fish passage structures, and habitat restoration, are minimal because of the absence of natural flooding and the inadequate construction of the proposed measures, like the fish passage structures. The construction of fish ladders has proven to be inadequate in improving passage for the economically important fish species, tambaqui. A clear message of this study, therefore, is to promote the construction and utilization of hydropower systems that are integrated and that aim to conserve natural ecological systems. The hydropower operators and the environmental planners' adaptive management and planning approaches consider the local communities and will rely on ecosystem-based planning for future systems that will preserve the health of the planet.

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