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Ruin-of-the-Rivers? A Global Review of Run-of-the-River Dams

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Abstract

The classification of a hydropower scheme as run-of-the-river (or run-of-river; ROR) evokes an image of a low-impact installation; however, examination of eight case studies worldwide shows that substantial negative societal and ecological impacts are tied to them, albeit in somewhat different ways. We conclude that ROR dams not only potentially displace communities, disrupt livelihoods, and degrade environments in surrounding areas, but they also divert water from areas of need, impact aquatic ecology through habitat destruction and disruption of fish migration, emit non-trivial amounts of greenhouse gases over the lifespan of the project, and disrupt streamflow in downstream river sections. While these negative impacts vary on a case-by-case basis, medium and large ROR dams consistently have multiple and cumulative impacts, even when not having appreciable reservoirs. We contend that many impactful dams do not qualify as low-impact ROR projects, despite being defined as such. Such mislabeling is facilitated in part by the ambiguous definition of the term, which risks the ROR concept being used by proponents of impactful structures to downplay their negative effects and thus mislead the public or gain status, including within the Clean Development Mechanism in relation to mitigating climate change.

Keywords: Run-of-the-river, hydropower, dams, EIA, hydropeaking

1. Introduction

While hydropower has benefited parts of society for more than 150 years (e.g. Von Sperling, 2012; Harrison 2019), their dams have often resulted in myriad negative social and environmental impacts (Baxter 1977; Goldsmith and Hilyard 1984; McCully 2001; Scudder 2005; McManamay et al. 2015). Beyond scholarly critiques, many communities have long raised grave concerns about the negative impacts, lending on-the-ground voices to express mounting worries regarding the integrity of ecologies of local riverscapes and livelihood resources (Goldsmith and Hilyard 1984). Dams constructed on international rivers also remain a tense geopolitical conundrum (Hirsch 2016). A current wave of apprehension focuses on the uncertain role hydropower dams can play in decarbonizing the energy production efforts during a period of climatic uncertainty (cf. Carvajal and Li 2019; Harlan 2020; Sasges and Ziegler 2024).

Since the late 20th Century, the dam-building industry has faced significant resistance to new development from a variety of actors, including local communities, activists, ecologists, and international financiers (McCully 2001; Scudder 2005; Shoemaker and Robichaud 2018). Thus, amidst a period of polarization that pitted proponents of hydropower for economic development against those advocating against it due to environmental costs and social justice concerns (Goodland et al. 1993), the industry began reshaping in an attempt to diminish negative public perception, including advocating for somewhat smaller hydropower facilities (HPFs) and also focusing on improving public relations. This approach also paved the way for the construction of new large dams, albeit with reduced reservoir sizes. This partially but incompletely addressed concerns of large-scale human resettlement, the loss of sensitive or productive lands, and the dramatic disruption of environmental flows in rivers and streams (Cernea 1999; Cernea and McDowell 2000; Scudder 2005; Randell 2022).

Many of these structures were labelled "run-of-river" or “run-of-the-river” (ROR) dams and were often promoted as “environmentally friendly” (Jager and Bevelhimer 2007). Unfortunately, much of this infrastructure has not resulted in the benefits claimed by proponents (Venus et al. 2020).

Contrary to the imagery evoked by the term, ROR dams are not designed to preserve the integrity of all types of environmental flows. Nearly three decades ago, Roberts (1995) used the phrasing "ruin-of-the-river" in reference to 12 proposed mainstream dams of 32 to 46 m height on the Mekong River that would have severe consequences on the aquatic resources and livelihoods of local people, as they are all located at critical locations on the mainstream of the river. These high dam facilities were, and still are, promoted as ROR.

Complementing the rebranding of hydropower dams as ROR is the positioning of hydroelectricity as "green energy" or "climate change friendly energy" (Kahn et al. 2014; Baird and Green 2020). While it may be true that ROR schemes frequently have smaller reservoirs than the early mega-dams, an important consideration pertains to conjuring the idea that all ROR dams are firstly small, and, secondly, that they are socially and environmentally benign. Recent reviews suggest otherwise (cf. Csiki and Rhoads 2010; Anderson et al. 2015; Kibler and Tullos 2013; Kelly-Richards et al. 2017; Hennig and Harlan 2018; Kuriqi et al. 2021).

This paper challenges prevailing narratives by examining case studies that highlight the significant impacts of ROR dams in Europe, Asia, South America, and North America. The eight case studies presented are based on research conducted by one or more of the authors. These dams vary in size, from 10 MW to over 3,000 MW, and are built on diverse systems, from small mountain streams to large continental rivers. Despite these differences in technology and scale, all are labeled as ROR. The lack of standardized design is a central theme of this paper, as is the ambiguity of the term "run-of-the-river," which allows it to be used as a rhetorical device to mislead the public, financers, and government sectors, enabling significant disruption of sensitive riverscapes for profit, often under the guise of development and climate change mitigation. Our goal is not merely to criticize hydropower development but to place our findings within the context of existing research and evaluate whether "run-of-the-river" is a meaningful descriptor for the types of projects that it actually describes.

The paper proceeds as follows. We first briefly present eight case studies of hydropower dams in various parts of the world that developers define as ROR. We then provide a short synthesis of the case studies before briefly reviewing the ROR dam literature related to impacts. We finally provide some concluding remarks.

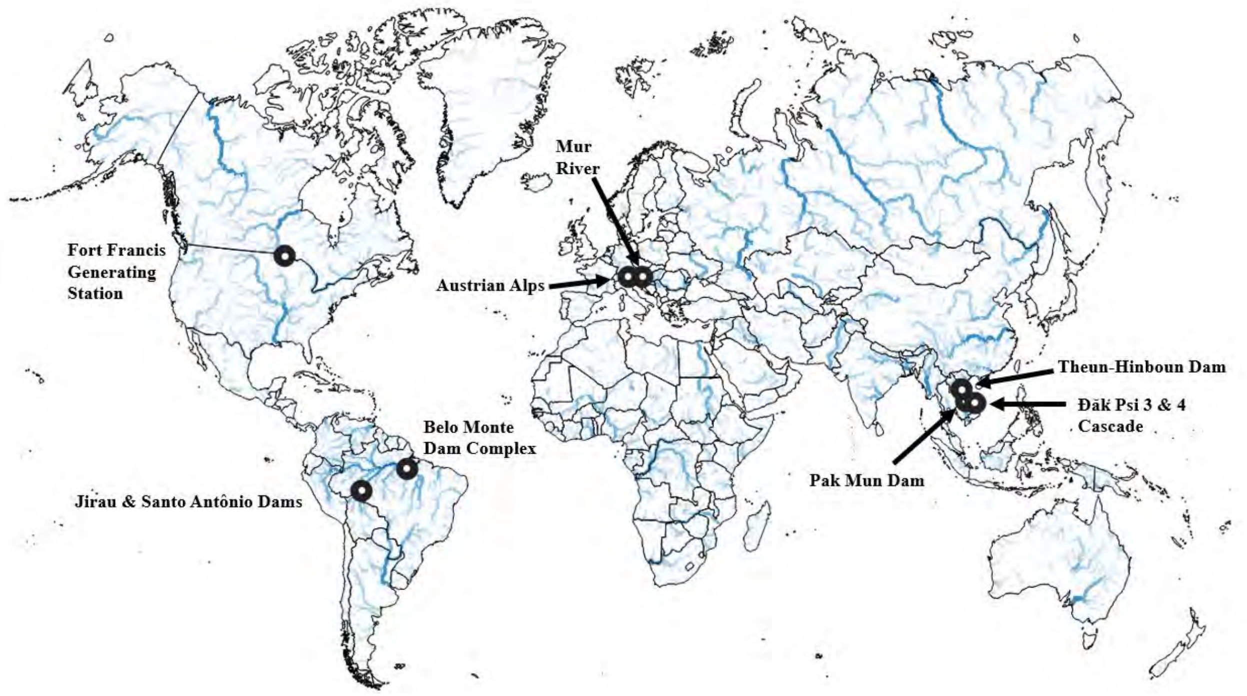

Figure 1. Map of the locations of case studies included in this paper (source: authors)

2. Case Studies

2.1 FISH MIGRATION DISRUPTION: Pak Mun Dam, Thailand

The Pak Mun Dam in northeastern Thailand exemplifies how medium-sized ROR dams can cause significant environmental and social harm, particularly when situated in locations that obstruct critical seasonal fish migrations (Roberts 1995). In 1967, Thailand's National Energy Office proposed the Pak Mun Dam on the Mun River, a major Mekong tributary in Ubon Ratchathani Province. Initially planned with a large reservoir requiring mass resettlement, it was later redesigned as a smaller ROR dam to reduce displacement. Construction began in 1990 and finished in 1994. The 17 m high dam has a 136 MW capacity, but actual energy output has been lower than expected (Missingham 2003; Foran and Manorom 2009).

Despite its downsizing, the Pak Mun Dam has still caused significant impacts on people forced to resettle due to the creation of the dam’s 60 km^2 reservoir. However, the project’s most significant impacts, including in relation to the number of people negatively impacted, have been on seasonal fish migrations between the mainstream Mekong River and the Mun River Basin. Many species migrate up and down the Mekong River during different seasons (Baird et al. 2003; Baran et al. 2005), and the Pak Mun Dam has heavily disrupted many fish migrations that previous migrated upstream from the dam (WCD 2000). Also affected were tributaries of the Mun River that were not originally assessed as affected, and therefore, those impacted have never been compensated (Baird et al. 2020).

The Pak Mun dam's negative impacts on wild capture fisheries have been so severe that since its construction, considerable effort has been devoted to advocating for either opening the dam’s gates at certain times of the year or throughout the year to enable fish migration (Foran and Manorom, 2009). Women have been at the forefront of this resistance, adapting older cultural rituals and developing new ones to maintain their opposition to the project (Soukhaphon and Baird 2024). Additionally, the fish ladder added to the dam was poorly designed and has proven ineffective (Roberts 2001).

At one point, the Pak Mun Dam likely stood as the most devastating dam for fisheries ever constructed in the Mekong River Basin, despite being a ROR dam (WCD, 2000). More recently, Ziv et al. (2012) estimated that another highly contentious ROR dam, the Lower Sesan 2 dam in northeastern Cambodia, would become the most damaging dam to fish ecology and fisheries in the Mekong Basin. This project is situated along a crucial migratory fish passage. These two projects highlight that ROR dams can be devastating when it comes to obstructing vital fish migrations.

2.2 BIODIVERSITY: Danube Salmon

Three proposed small-scale (<10 MW) ROR hydropower projects planned for the Mur River in Central Europe are a grave threat for Danube salmon (*Hucho hucho*), the world's largest salmonid species, which is endemic of the Danube River basin (Holčík et al. 1988) and is symbolic of the region's ecological heritage. In recent decades the salmon have faced extensive habitat loss and hydropower-related impacts (Schmutz et al. 2002). Once widespread, this flagship species is now one of the most threatened species in the catchment (Freyhof and Kottelat 2008) and is protected under European conservation law (Annex II and V of the EU Habitats Directive - 92/43/EEC). Recent assessments in Bavaria, Germany, and Austria (Schmutz et al. 2023) revealed that merely 0.7% of its original 7,500 river kilometers habitat range still hosts very good populations, with most rivers showing only moderate to poor population status, reflecting fragmented habitats and dwindling reproduction rates (Schmutz et al. 2023). This situation underscores the urgency of safeguarding the Danube salmon.

In Austria, the last bastions of Danube salmon persist in three (sub-) catchments: the Mur, Gail, and Pielach Rivers. These fish, known for their migratory behavior and preference for gravelly substrates, are critically dependent on free-flowing rivers. Notably, the few remaining (very) good Danube salmon populations in Austria are mainly located in rivers with longer free-flowing sections (>50 km), defined as river sections without dams, impoundments, and flow alterations (water abstraction, hydropeaking), such as the Mur and Gail Rivers (Figure 2). In addition, Danube salmon stocks in the mainstem Danube and lower Mur River suffer from increased summer temperatures. These pressures have led to severe declines in Danube salmon stocks in Austrian rivers (Schmutz et al., 2023), which have been further compounded by losses in prey species such as European grayling (*Thymallus thymallus*) (Hayes et al. 2021), nase (*Chondrostoma nasus*), and barbel (*Barbus barbus*) (Hayes et al. 2022a).

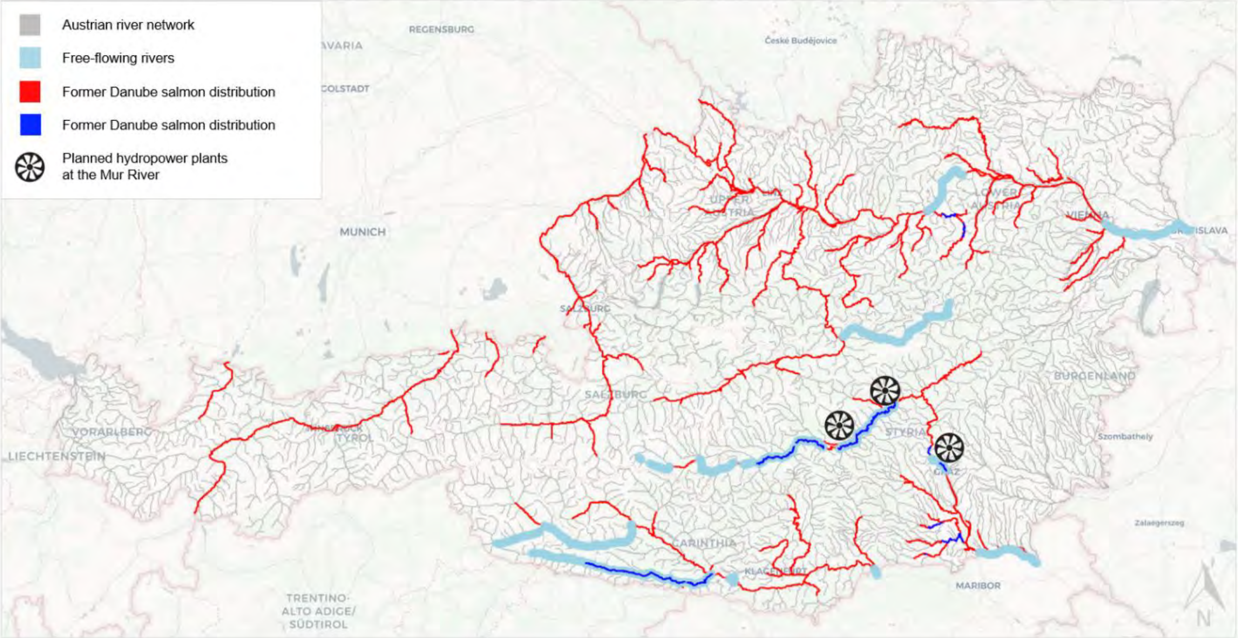

Figure 2. Former and present distribution of Danube salmon in Austria, remaining rivers with free-flowing river sections (>50 km), and the planned hydropower plants at the Mur River (data source: Schmutz et al., 2023).

Despite generating a mere 0.3% (120 GWh) of Austria's annual hydropower output, the three proposed ROR projects pose a significant risk to the last upper Danube River stretches harboring robust Danube salmon populations. Alarmingly, some of these projects are situated within Natura 2000 protected areas. Despite environmental campaigns against them, politicians have largely supported their development plans are largely supported by politicians, and Europe's emergency council regulation (EC 2022/2577) has also supported them in their push for more renewable energy.

This case study underscores the critical need to scrutinize ROR hydropower expansion, considering the ongoing biodiversity crisis and the imperative to safeguard this irreplaceable species for future generations, particularly given the limited energy benefits provided by these relatively small-scale projects.

2.3 HYDROPEAKING: Austria-wide survey

This case study explores the large-scale potential of ROR hydropower to cause sub-daily flow fluctuations (Almeida et al. 2020), a phenomenon commonly associated with storage hydropower (i.e., hydropeaking), and which cause severe impacts on river ecosystems (Hayes et al. 2022b; Schmutz et al. 2015). To this aim, sites situated within Austrian mountain rivers (Hayes et al. 2021) were categorized into three groups based on their peaking frequency (Figure 3a): low (<0.2 daily peaks), medium (0.2–2.1 daily peaks), and high (>2.26 daily peaks). River sections experiencing medium to high levels of flow fluctuation frequency were predominantly found near peak-operating hydropower plants (Figure 3b). Intriguingly, some negatively affected sites were discovered close to ROR hydropower plants, even when no peak-operating storage dam was present in the upstream catchment, lending evidence that ROR facilities can contribute to sub-daily flow fluctuations. However, this is not always the case, as evidenced by sites classified under the 'low' category (Figure 3c).

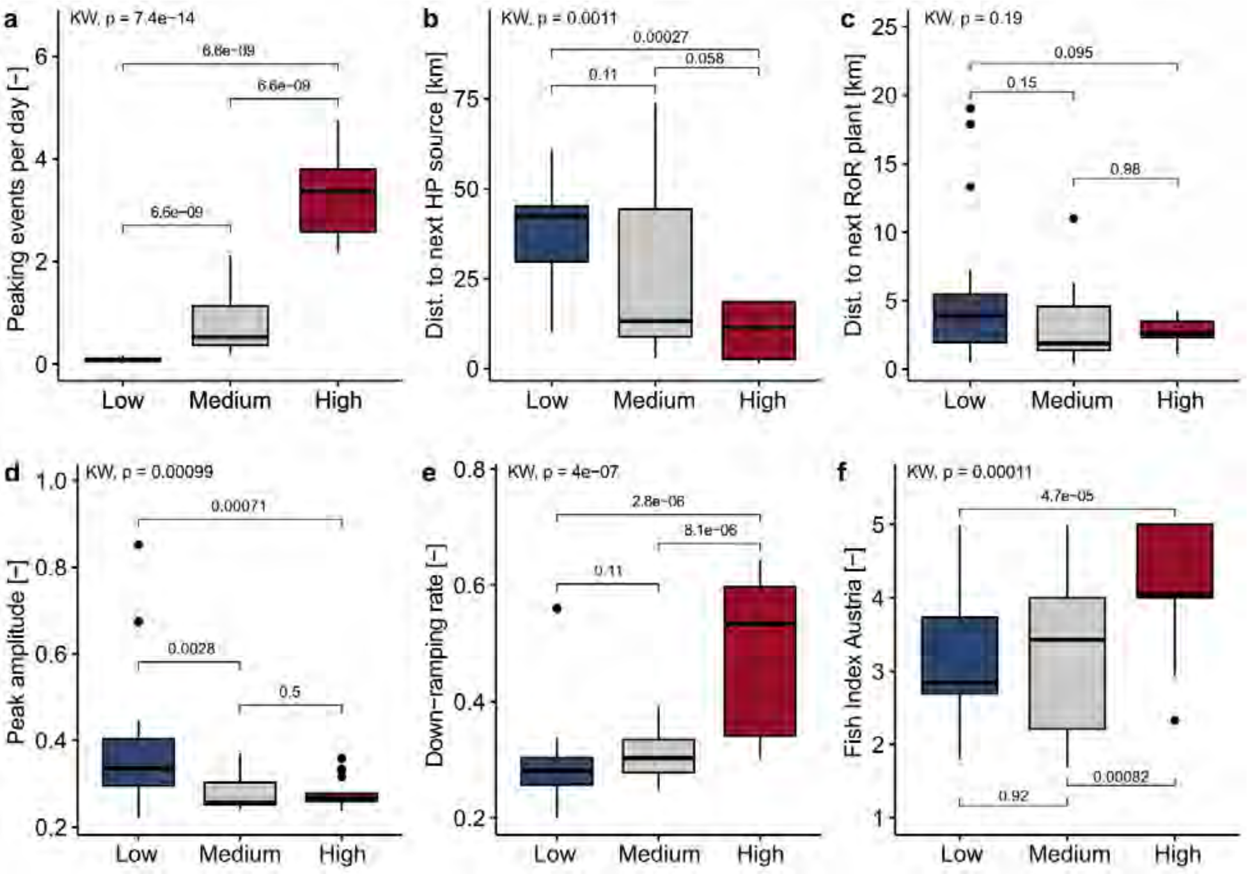

Figure 3. Hydro-ecological effects of artificial flow fluctuations at Austrian fish sampling sites (n=69; Hayes et al., 2021). This figure categorizes the sites into 'low', 'medium', and 'high' groups based on (a) the peaking frequency terciles. Panels (b) and (c) illustrate the proximity of each site to the nearest hydropeaking (HP) or ROR power plant, respectively. Panels (d) and (e) present ecologically relevant flow fluctuation metrics (amplitude and down-ramping rate), each normalized against the long-term mean annual maximum flow event (Greimel et al., 2016; Greimel, 2022). Panel (f) depicts the response of the 'Fish Index Austria', a fish-based measure of ecological integrity (1 being best, 5 worst). Group differences were determined with the Kruskal-Wallis (KW) test, followed by pairwise comparisons with the Mann-Whitney U test.

Sites characterized by having a low peaking frequency experienced events with the highest amplitudes compared to those in the medium and high frequency groups. These significant flow fluctuations predominantly constitute natural floods. Conversely, the peak amplitudes observed in the medium and high frequency groups are significantly lower (Figure 3d), which is likely due to the maximum turbine flow of the hydropower plants and a corresponding limitation of the artificial flow fluctuation amplitude. Sites experiencing medium to high event frequencies are distinguished by rapid down-ramping rates (Figure 3e), which can have significant ecological impacts, including fish stranding (Hayes et al. 2022b; Moreira et al. 2019). These hydrological pressures result in a decline in ecological integrity, as evidenced by the scores from the multi-metric ‘Fish Index Austria’, indicating step-wise degradation (Figure 3f).

This study on Austrian rivers reveals that ROR hydropower installations often produce a high frequency of sub-daily flow fluctuation events, like traditional hydropower plants with large storage. Others have indicated that ROR installations can cause such flow variations, for example, due to delayed reactions of the power plant flow control, low flow stoppages, system start-ups, powerhouse breakdowns, intake malfunctions, cycling operations, and forebay oscillations (Greimel et al. 2016; Hunter 1992). While these artificial fluctuations have a smaller amplitude than natural floods, they occur frequently and exhibit a fast down-ramping intensity, thus causing significant negative impacts on river ecology.

2.4 TRANSBASIN WATER TRANSFER: Theun-Hinboun Dam, Laos

The Theun-Hinboun Dam in Central Laos illustrates how some projects are classified as ROR despite having nothing to do with maintaining natural flow regimes. The Theun-Hinboun Hydropower Project, which is located in Bolikhamxay and Khammouane Provinces in the Lao People’s Democratic Republic (Lao PDR), originally had a 220 MW installed capacity when it started operations in 1998. In 2012 the project was expanded to 500 MW capacity. The dam was developed in partnership between the Lao government, Thailand’s MDX Lao Public Company, and Nordic Hydropower AB, with considerable loans to the Lao PDR government from the Asian Development Bank.

The dam was built based on a 30-year “build–operate–transfer” (BOT) agreement with a 10-year optional extension period, after which the dam would become fully owned by the Lao government (Shoemaker 1998; Whitington 2018). The original project included a large 48 m high dam across the Theun River, a 49 km^2 reservoir, and infrastructure to facilitate the diversion of water from the dam’s reservoir through a power generation plant and then into the Hai and Hinboun Rivers, tributaries to the Mekong River. The expansion was agreed to in 2007, and involves a 65 m high dam, and a 105 km^2 reservoir on the Gnouang River.

As various studies have indicated, the dam has led to a significant increase in water flow down the Hai and Hinboun Rivers to the Mekong, sometimes more than double the previous levels (Barney 2007; Blake et al. 2005; Shoemaker 1998). This diversion has resulted in well-documented downstream social and environmental impacts, including significant losses and long-term consequences for downstream communities, such as riverbank erosion, the destruction of aquatic habitat, and various impacts on human livelihoods, such as the loss of riverbank gardening and dramatic declines in fish catches (Barney 2007; Blake et al. 2005; International Rivers Network 1999; Shoemaker 1998; Warren 1999; Whitington 2018). In contrast, the reduction of flows in the Theun River has resulted in substantial social and environmental impacts downstream on the Theun (Shoemaker 1998; Warren 1999).

This example highlights a discrepancy in the application of the term ROR to describe the flow situation on the river where the facility was built. A crucial aspect is the diversion of water from one river (the Theun) to others (the Hai and Hinboun), is the categorizing of the diversion project as a “transbasin run-of-the-river project” (Shoemaker 1998; Warren 1999). The question arises as to whether a dam can be accurately classified as "run-of-the-river" when it redirects water from one river into another. The Theun Hinboun Power Company argues that it can, because the dam does not have significant active storage. This indicates how the term "run-of-the-river," at least to some actors, does not imply that the river is allowed to flow naturally. Instead, it is a technical term that relates to a dam’s active storage. In particular, this reveals how the "politics of classification" are employed to divert attention from a project’s serious negative impacts.

2.5 DISPLACEMENT: Belo Monte Dam Complex, Brazil

Brazil’s Belo Monte complex illustrates the falseness of ROR dams being either small, or “low impact.” Belo Monte is classified as ROR because the water level in the reservoir only fluctuates by one meter, making the complex depend on the flow of the river. The complex began blocking the Xingu River, a north-flowing tributary to the Amazon River, in 2015 (Figure 4). It was originally planned that up to five large storage dams upstream would have regulated flow, which would have flooded vast areas of Indigenous land (Fearnside 2006). Even though Brazil’s official statements since 2008 have claimed that the upstream dams will not be built, turbines with installed capacity totaling 11,233 MW have already been installed at Belo Monte (an amount around twice the maximum that could be justified by the river’s natural flow), suggesting that plans for the upstream dams continue unannounced (Fearnside 2017a). Since 2013, when the dam was under construction, Belo Monte has been used by Brazil’s authorities to argue for future projects that prioritize water storage (Fearnside 2017b).

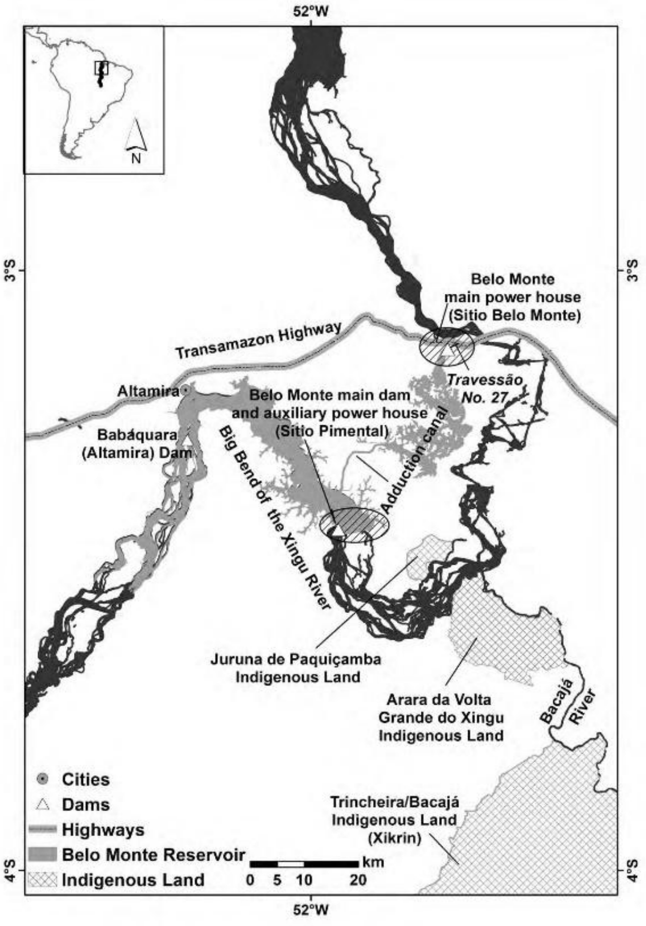

Figure 4. Map of the Belo Monte complex and surrounding area (Fearnside, 2017a).

The Belo Monte complex consists of two dams: the Pimental Dam functions as an intra-basin water diversion scheme. It diverts 80% of the river's flow through a canal and a series of dammed stream basins to a second dam (Belo Monte). The operational mode leaves a 130 km long section of the river with only 20-30% of its natural flow. Indigenous communities on the banks of this section of the Xingu River, known as the "*Volta Grande*" (or "Big Bend"), lost the fish and turtles that previously sustained them, as did a third group located on the Bacajá River, a tributary **(**Pezzuti et al. 2024).

The 516 km^2 reservoir created by the dam displaced 40,000 people, according to the Movement for Dam Affected People (Sullivan 2016), including both traditional riverside residents (*ribeirinhos*) and one-fourth of the city of Altamira. The displaced people were moved to "collective urban resettlements" on the outskirts of Altamira, where they had no income or means of producing food. *Ribeirinhos* and the Indigenous Peoples who remained along the *Volta Grande* lost almost all fish and other resources that sustained them (Magalhães and da Cunha 2017).

Besides displacing people, the Pimental Dam also blocked the migration of fish, despite having a fish passage, as most Amazonian fish fail to pass these barriers. Both the area flooded by the reservoir and the *Volta Grande* had rich endemic fauna that has now been severely damaged (Keppeler et al. 2022). The most famous victim is the zebra pleco (*Hypancistrus zebra*), a valuable aquarium fish adapted to rocky habitats in rapids. This species is expected to go extinct in the wild (Gonçalves 2011). The rapid variations in water level have taken a heavy toll on commercial fish species during the spawning season because they enter flooded forest areas that suddenly become either dry land or isolated pools of intolerably hot water (Ribas et al. 2023).

The Belo Monte complex also accelerated deforestation (Jiang et al. 2018) by attracting people to the area and increasing land values and yielding profits from land speculation (Barreto et al. 2011). Furthermore, a study measuring greenhouse gas (GHG) emissions at Belo Monte concluded that "...total GHG emissions are substantial even from this leading-edge ROR power plant. This argues in favor of avoiding hydropower expansion in Amazonia regardless of the reservoir type" (Bertassoli Jr. et al. 2021). The Science Panel for the Amazon concluded that no more dams of any type with installed capacity ≥10 MW should be built in Amazonia (Fearnside et al., 2021), as even dams smaller than 10 MW can cause significant impacts depending on various factors.

It may be a surprise to many that ROR dams are sometimes quite large and can result in large-scale human resettlement as well as many of same sorts of impacts associated with large storage dams.

2.6 LIVELIHOOD DISRUPTON: Rainy River International Dam, USA-Canada border

The 24.4 MW International Dam spans the Rainy River between Minnesota (USA) and Ontario (Canada). Because of the area's flat topography, this comparably small dam (9.1 m height) maintains the water level in the 932 km^2 Rainy Lake (*Gojiji-zaaga'igan*), a former wetland turned reservoir. European-descended residents and seasonal tourists typically only pay attention to the dam in high water years when lake water could have been released sooner to avoid flooding (Kraker 2022; IRLWWB 2023). However, the Indigenous Anishinaabeg in the area perceive the dam differently.

Prior to the construction of the dam between 1905 and 1909, the marshes above the dam sustained abundant Manoomin (wild rice, *Zizania palustris*) crops that sustained Indigenous Peoples for millennia (Birk and Richner 2004; Reid and Rajnovich 1991). Pushed by the newsprint industry and enabling settler-colonial governments, construction of the dam and others in the area virtually destroyed the Anishinaabe wild rice economy. *Manominikenshii*, the Anishinaabe wild rice culture, evolved under specific hydrological conditions regarding seasonally variable water levels, temperature, pH, turbidity, and nutrient loads affected by natural conditions, localized management (e.g., impoundment of bays and streams, seeding), and Ceremony (Strube 2021; Kinew 1995; Waisberg 1984). The dam, despite its characterization as a small ROR facility and temporary impoundment, has disrupted this delicate ecological system, upsetting the Anishinaabe's relationship with Manoomin with grave consequences for the Anishinaabeg's livelihood and sovereignty (Strube and Thomas 2021). Anishinaabe communities on the lake's southern shore migrated south due to the dam's effects on their economy (Child 2011). Without their main food staple, the Anishinaabeg on the Northern shore lost much of their autonomy and became increasingly dependent on the settler-colonial state, which in turn expanded its reach into this borderland through industrialization dependent on hydropower and water-level regulation (Strube 2021; Strube and Thomas 2021).

That a dam with such far-reaching impacts can be perceived by settlers as innocuous is the result of several discursive moves. Most critically, the hydrological studies and deliberations informing water regulation on the Rainy River have long erased Indigenous Peoples as political agents and rightsholders. Consequently, dam operations have long ignored wild rice and instead privilege the interests of waterfront residents, tourism, and local industry by providing constant lake levels.

Today, the facility is depicted by the operator as a "run-of-the-river plant" that is subject to restrictions on peaking operations, including adherence to Rainy Lake rule curves, minimum flow requirements, and control orders set by the International Joint Commission. However, while the dam does not retain and release water on demand like storage dams typically do, it does hold back water for "a few days," as one of the operating engineers admitted. Contradicting their public relations department's framing, an engineer called into question the characterization of the dam as ROR, instead offering "intermediate semi-run-of-river" as an alternative, yet similarly misleading classification (Strube 2021). This case study shows that reimagining older dams as ROR projects focuses public attention on environmental flows that align with contemporary management protocols, meanwhile detracting attention from significant negative impacts on local communities.

2.7 GREENWASHING: Đăk Psi 3 and 4 cascade, Central Vietnam

Despite its relatively short length of 81 km, the Đăk Psi River in Central Vietnam's Kon Tum province is the site of ten hydropower facilities on its main stem and tributaries. The Đăk Psi 3 (15 MW) and 4 (30 MW) cascade (hereafter DP3-4) was the first constructed, from 2007 to 2012. The project was subsidized through the Clean Development Mechanism (CDM) of the United Nations, which grants certified emission reduction credits to corporations that invest in renewable energy projects (Martins et al. 2013; Erlewein 2014). As part of CDM certification, the project was designated as ROR, which from the perspective of Vietnamese officials, implies minimal environmental impacts.

CDM-related and environmental impact assessment (EIA) reports consistently refer to the project as ROR; and diagrams depict the construction of "weirs'' without reservoirs, allowing for continuous flow. However, as built, the weirs create reservoirs and obstruct the flow of water, materials, and organisms (Figure 5). The claim that the project is ROR rested on the use of 2-3 km-long diversion tunnels leading from the weirs to powerhouses from where water was discharged back into the river channel.

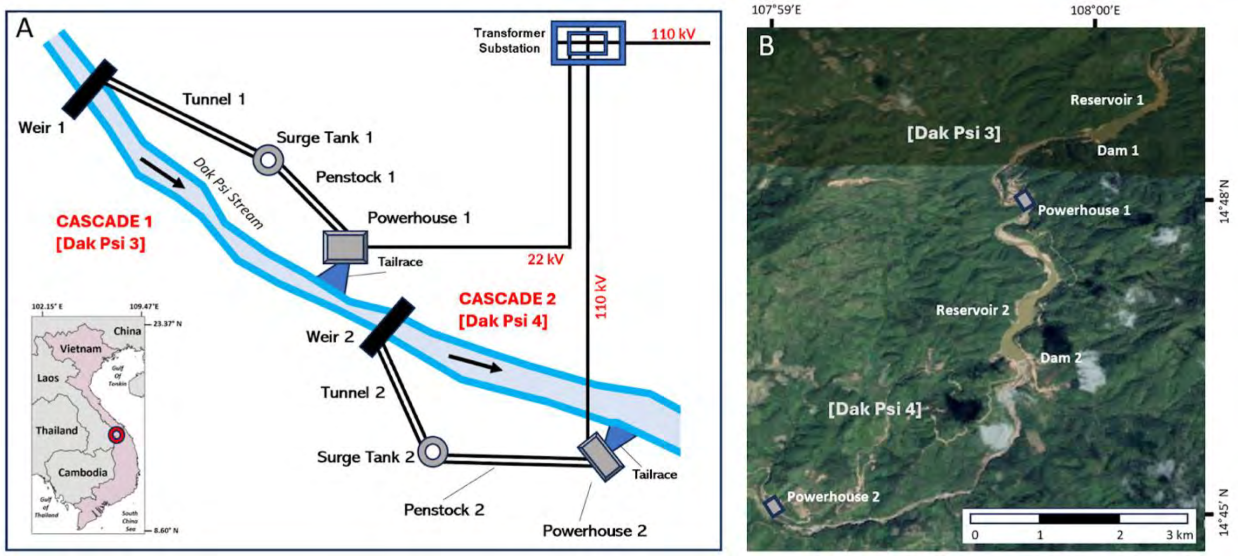

Figure 5. (A) Redrawing of the schematic of the Đăk Psi 3-4 project submitted for EIA and CDM approval, circa 2011 (Dak Psi, 2023; the original orientation and features/elements are maintained, except those highlighted in red). (B) Đăk Psi 3-4 cascade circa 2021. Structures labelled "weirs" function as dams, creating 15-25 ha reservoirs and limiting downstream flows along a length of 2-3 km.

ROR labeling was crucial both to securing CDM financing and a positive EIA. The CDM Project Design Document states the following (UNFCCC 2006): "Đăk Psi 3, 4 Hydropower Project is a run-of-river type. … Therefore, the negative impacts are fairly limited in scope."· In turn, the EIA and consultative process carried out prior to the dam's construction proceeded from the assumption that a small ROR facility would have limited environmental impact. It did not highlight some of the most important foreseeable impacts of the facility, including the blocking of environmental flows, ecological fragmentation, and the dewatering of downriver reservoirs. Impact assessments focused on short-term effects during construction rather than the long-term impacts on local ecologies.

Contrary to the scenario sketched out by project backers, the years since the construction of the dams along the Đak Psi have seen the transformation of the river's ecologies. After completion, the stream section below the dam became dewatered. Villagers describe how, before the dam, the riverbanks were rocky and supported lush green trees. Today, due to increased sedimentation downstream, sand has filled up the riverbed, raising the water and exposing farmland along the riverbank to floods during the wet season. In addition, during the dry season, water levels in the river are insufficient for their daily human needs (Du Toan 2022).

In this case, the transformation of local lives, livelihoods, and ecologies was justified in the name of the decarbonization of energy production. CDM financing is intended to support green, carbon-offsetting projects that would not otherwise be built due to a lack of capital. However, the construction of Đak Psi 4 began in 2007, one year before the project's operators applied for CDM financing. Thus, the carbon credits associated with the CDM financing effectively subsidized further fossil fuel use, resulting in a net gain in carbon emissions and implicating DP3-4 in a global system of "greenwashing" of hydropower, which has been termed the "theater of decarbonization" (Sasges and Ziegler 2023; 2024). The DP3-4 cascade case study demonstrates how manipulation of terms supports greenwashing, silencing critiques of hydropower project impacts. This is part of a global rhetoric exploiting the idea that all hydropower, regardless of its specifics, helps reduce climate change.

2.8 CUMULATIVE IMPACTS: Jirau and San Antonio Dams, Brazil

Brazil's Santo Antônio and Jirau hydroelectric plants on the Madeira River, a key Amazon tributary, were completed in November 2011 and September 2012, respectively. These are the first dams in the Madeira River complex. Both projects contribute to the regional power grid, with installed capacities of 3,580 MW (Santo Antônio) and 3,750 MW (Jirau). Being very large dams at 49.5 m (Santo Antônio) and 62 m (Jirau), it is not surprising that grave concerns were raised in their Environmental Impact Report (RIMA) and EIA. The environmental agency also faced intense political pressure to approve licensing (Fearnside 2014a). These dams are classified as ROR because there is very little fluctuation of the water level behind them, and because power is being generated by the river's natural flow rather than by drawing down stored water (Fearnside, 2014a). During the licensing process, documents such as the strategic environmental evaluation and the economic viability study prominently featured a photograph of a ROR dam with no reservoir, located on Europe's Danube River, falsely implying that the Madeira River dams would be similarly reservoir free (Fearnside 2014b).

The dams in the Madeira River have disrupted the distribution of fish throughout the basin, which, in turn, has impacted the livelihoods and food security of over 50,000 people across Peru, Bolivia, and Brazil (Doria et al. 2018). The Santo Antônio and Jirau Dams have negatively affected the migration of the large catfish, *Brachyplatystoma rousseauxii*, known as "*dourado*," which, prior to the dams, was responsible for generating over 14,000 tons of fish biomass just in the Brazilian portion of the river. *Dourado* migrated from the mouth of the Amazon River and ascended the Madeira River to reproduce in the Bolivian and Peruvian Andes, and larvae and juveniles descended to the Amazon River's mouth. The Santo Antônio and Jirau Dams now obstruct the migration of both adult and juvenile fish (Hauser et al. 2019).

Dam construction raised the Madeira River's average water level by 10 m, reshaping the landscape. The flooding associated with the complex created backwater zones at tributary junctions, causing chemical changes and thermal stratification. The flooded area following the installation of the Madeira complex exceeded the planned area by 341 km^2 (64.5%), submerging an additional 160 km^2 of natural forest (Cochrane et al. 2017). These losses have had profound social consequences, displacing thousands of people from their homes, destroying their livelihoods, and significantly reducing their access to food (Fearnside 2014a).

The decomposition of inundated plant biomass, coupled with the formation of backwater regions, introduces an additional concern related to the Jirau and Santo Antônio Dams: the release of greenhouse gases. Dams in the Amazon region emit methane (CH_4) and carbon dioxide (CO_2) from both the vegetation and the soils that are flooded, and the emissions from the flooded vegetation elevate CH_4 emissions by 33% and CO_2 emissions by 28%, compared to the soil alone (de Faria et al. 2015). Collectively, the Jirau and Santo Antônio Dams will emit an estimated average of 76 Tg of carbon over 100 years, equivalent to nearly 800,000 tons of carbon annually.

These dams received carbon credits through the CDM (see Vietnam case study above) despite having been built for reasons unrelated to carbon reduction, thereby allowing the countries that purchased these credits to emit without really offsetting carbon emission, thus contributing even more to global warming (Fearnside 2015). Carbon projects often assume hydropower dams have no emissions; however, methane generated in stratified tributaries entering the Santo Antônio reservoir has been found to be released in substantial quantities downstream of the dam (Fearnside, 2015). These findings underscore the fact that ROR projects can have significant environmental and social impacts, including cumulative impacts, both locally and regionally, as well as significantly contributing to greenhouse gas emissions.

4. Discussion

4.1 Synthesis of case study impacts

The case studies in Section 3 reveal how the term "run-of-the-river" (ROR) has been inconsistently applied to hydropower facilities of varying designs and scales. In addition, the labeling of these dams as ROR by developers often fails to reflect their significant environmental and social impacts. For instance, the construction of Brazil's Belo Monte Complex resulted in the displacement of approximately 40,000 people, highlighting severe social consequences akin to those criticized in mega dam projects. Similarly, the Santo Antônio and Jirau Dams on the Madeira River, with heights of 50-60 m, created reservoirs nearly two-thirds larger than anticipated, flooding 16,000 hectares of natural forest beyond the predicted area.

Damming the Rainy River has led to the loss of wetland habitats long crucial to the Indigenous Anishinaabe peoples, echoing a broader trend of livelihood disruptions caused by large ROR dams. Such impacts extend to other groups affected by dams such as Pak Mun in Thailand and Theun-Hinboun in Laos, where hydrological changes and other ecological impacts have been significant.

Ecologically, ROR dams can severely disrupt fish migrations, fragment fish populations, and damage critical habitats, as seen with the Pak Mun Dam in Thailand and the series of ROR dams along Austria's Mur River. A particularly concerning issue is turbine mortality for downstream-migrating fish, even with mitigation measures like bar racks and migration corridors. This mortality, especially for juvenile and small-bodied fish, varies by species and turbine type, but the cumulative effects from multiple passages can drastically reduce fish populations (Knott et al. 2023a, b; Pracheil et al. 2016; Radinger et al. 2022).

Although ROR dams have often been associated with maintaining environmental flows or replicating natural downstream patterns (Dyson et al. 2003; Hayes et al. 2018), the case studies presented here demonstrate that water diversions and hydropeaking can significantly affect downstream flow regimes. For example, the Theun-Hinboun Dam in Laos diverts substantial water flow between river catchments, and Brazil's Belo Monte Dam dramatically reduces flows over a

130 km stretch through diversion. Similarly, the Dak Psi 3-4 cascade in Vietnam diverts water from the dam to the power plant 2-3 km downstream, leaving the intermediate river reach dry for much of the year. In Austria, ROR dams have also caused significant downstream impacts through daily hydropeaking, despite lacking the active storage typically associated with such effects.

Some projects have used the ROR label for greenwashing purposes, including securing environmental approvals and funding, despite causing considerable harm. For instance, the Jirau and Santo Antônio dams in Brazil and the Đăk Psi 3/4 dams in Vietnam were branded as ROR to gain credibility under the CDM, even as they resulted in significant environmental and social impacts that were often downplayed or ignored in assessments (Baird and Green, 2020). Ironically, these dams also emit substantial greenhouse gases, contradicting the CDM's intentions (Barros et al. 2011).

4.2. Other Evidence of Adverse ROR Impacts

Complementing the impacts reviewed for the eight case studies in Section 3 are numerous investigations conducted worldwide. We found 59 empirical studies on ROR impacts using a systematic search on related keywords. These studies are from 20 countries, including Austria, Brazil, Canada, China, France, India, Japan, Norway, and the USA. The ROR facilities range from small weirs to large dams on international rivers such as the Danube, Rhône, and Columbia. This diversity reflects the lack of a common definition or design for ROR dams globally (Csiki and Rhoads 2010; McManamay et al. 2016; Kuriqi et al. 2021).

Many studies focus on specific impacts, such as the adverse effects on benthic organism communities, including macroinvertebrates (Dessaix et al. 1995; Fanny et al. 2013; Wang et al. 2016; Anderson et al. 2017; Bilotta et al. 2016; Silverthorn et al. 2018; Mihara et al. 2024). Other organisms affected include diatoms (Wu et al. 2010; Wang et al. 2022a, b), algae (Shuka et al. 2013; Wu et al. 2009), plankton (Li et al. 2018; Rose et al. 2019; Zanon et al. 2024), amphibians (Dare et al. 2020), and insects (Malmqvist and Englund 1996). Negative impacts on fish community dynamics are also well-documented (Simonović et al. 2021; Baumgartner et al. 2020; Ticiani et al. 2023).

For instance, on the Tay River in Scotland, Robson (2013) observe that ROR dams reduced water flow in depleted reaches, restricted upstream access, and caused combined barrier and abstraction effects. Linares et al. (2018) report that ROR impacts primarily affected dam reservoirs and adjacent downstream stretches, facilitating invasive species dominance. Bejarano et al. (2019) note that ROR-diversion power plants impact river reaches downstream, particularly in nival and stable river types. Magilligan et al. (2021) observe that while ROR dams do not significantly disrupt sediment connectivity, they affect ecological connectivity.

Research on the St. Maurice River in Canada shows that ROR dams can disrupt ecosystem processes such as carbon cycling and mercury dynamics, potentially leading to elevated mercury levels in aquatic organisms (Ponton et al. 2021; Leclerc et al. 2023). Tashiro et al. (2015) report that ROR dams can reduce daily gross production and community respiration below dams under low flow conditions. Almeida et al. (2019) documents increased biochemical oxygen demand and CO2 partial pressure due to the influx and mineralization of organic matter. Sow et al. (2016) highlight the role of shallow depths and submerged macrophytes in nutrient and sediment retention.

Several studies highlight hydro-geomorphological impacts. Reduced stream flow can lead to sediment accumulation and erosion downstream due to sediment shortages and increased flood velocities (Summer et al., 1994). For a large ROR facility on the Rhône River, significant geomorphic changes due to a century-long reduction in sediment supply have been observed (Dépret et al. 2019). Other research indicates that low-head ROR dams create conditions of limited sediment supply downstream, affecting local and downstream ecological habitats (Casserly et al. 2020).

In Italy, the River Po experienced significant degradation following ROR dam construction due to altered flow regimes and sediment transport disconnection (Bizzi et al. 2015). In Spain, the Upper Garonne River saw channel narrowing after ROR dam construction, leading to new management practices involving downstream flushing actions (Bulteau et al. 2022). Wildman and MacBroom (2005) report that low-head ROR dams cause sediment accumulation and stream widening, leading to dam removal. Pearson et al. (2016) note that ROR dams may induce brief periods of sediment methane flux to the atmosphere, with potential impacts from dam removal.

From a social perspective, Rousseau (2020) report on greenwashing tactics in Yunnan, China, where a dam recognized as ROR caused significant impacts to local villagers. Ullah et al. (2023) note that a large ROR plant on the Indus River in Pakistan affected river flow regimes, groundwater levels, and land use, exacerbated by inadequate compensatory measures.

In contrast, some studies report minor impacts. Csiki and Rhoads (2014) found that small ROR dams in Illinois do not substantially alter channel morphology or act as major sediment traps. Hocking et al. (2021) report an increase in rainbow trout biomass due to controlled flow diversions, maintaining natural flow regimes. Copeman (1997) observe no adverse effects on sediment and benthic invertebrates but cautioned about rivers with more variable flows. Neupane et al. (2023) report a favorable increase in ecosystem service values associated with ROR development in Nepal, despite significant land use changes.

Finally, in support of the studies from the literature, several syntheses conclude that ROR hydropower plants have moderate to significant impacts on river ecosystems. Anderson et al. (2015) conclude that ROR schemes can reduce habitat complexity, alter riparian vegetation, and disrupt longitudinal connectivity. Csiki and Rhoads (2010) discuss how ROR dams impact river geomorphology, potentially causing downstream scour. Gibeau et al. (2017) identify three pathways through which ROR hydropower affects salmonids. Kuriqi et al. (2021) emphasize that small ROR plants significantly alter natural flow regimes and harm fluvial ecosystems.

4.3. Prospects for Monitoring and Adaptive Management

The above sections describe socio-ecological impacts of ROR facilities, impacts that are often much more seriously than typically recognized. However, a certain degree of mitigation is possible. Best-practice mitigation measures often related to the operation of these projects. For example, water can be released to more closely mimic natural flows (an environmental flows regime). This can include periodic channel-forming discharges (Hayes et al. 2018), water releases for the purposes of fish protection (Haug et al, 2022). In addition, fish passes to support migration (Silva et al., 2018) and restrictions on flow ramping (hydropeaking) (Moreira et al., 2019) can also help partially mitigate the impacts.

However, a strict monitoring scheme is needed at existing facilities to ensure that projects are managed to reduce environmental impacts. This needs to include regular assessments of water quality (including water temperature) and aquatic biota, but also continuous monitoring of river discharge. Involving local people and making data publicly available is also important to help ensure that impacts are minimized. The iterative framework of adaptive management can help to formulate new management actions by integrating new information and paying close attention to both ecological and social factors (Gunderson et al., 2016; Sendzimir & Schmutz, 2018). Ultimately, however, we contend that many of the serious negative impacts of ROR dams cannot be easily or fully mitigated.

5. Conclusion

The review of eight case studies, along with numerous studies from the literature consulted, reveal that while ROR dams may appear less harmful than large storage dams, they frequently result in significant negative impacts, including community displacement, ecological degradation, and disruption of local livelihoods. This reality challenges the prevailing perception that ROR dams are benign sources of renewable energy.

We identify substantial inconsistencies in how the term "run-of-the-river" is applied across different geographical, ecological, and socio-political contexts. ROR is broadly used to describe various hydraulic structures built across river channels for hydropower generation, but its definition lacks clarity. For some, ROR refers to dams that form reservoirs without active storage or have insufficient capacity for seasonal water management. Others use the term to denote dams that maintain minimal discharge to preserve environmental flows, or they associate ROR with small hydropower facilities, regardless of their specific design. The absence of a standardized definition renders the term ROR susceptible to rhetorical manipulation rather than being a precise engineering concept. This ambiguity allows hydropower proponents to downplay the potential negative impacts of ROR dams. As Csiki and Rhoads (2010) argue, ROR is not a scientific term but a commonly accepted phrase in river management, likely derived from older "reservoirless" hydroelectric facilities.

Historically, hydropower advocates have used ROR to describe dams with minimal dead storage needed for consistent water release to generate electricity. Despite claims that ROR dams allow rivers to flow freely, their designs frequently prioritize optimizing water release for power generation over maintaining natural river dynamics (Anderson et al. 2015). Further, definitions that describe ROR as systems where discharges approximate the sum of inflows—relying on natural flows and minimal reservoir fluctuations—often neglect the impact of structures that obstruct two-way flows, significantly disrupting migrating fish and other aquatic organisms. While ROR dams often feature smaller reservoirs than traditional storage dams, which may result in less severe hydrological alterations and fewer resettlement issues, they can still cause substantial disruption to social and ecological systems. This aligns with early warnings from Roberts (1995) regarding the detrimental impacts of ROR dams proposed to be built on the Mekong River.

In conclusion, the numerous reports of negative impacts of ROR dams challenge the narrative that they are inherently clean and sustainable, underscoring the need for a more nuanced understanding of ROR facilities. To address this issue, it may be necessary to reserve the term ROR for designs that genuinely preserve environmental flows and develop new classifications that more accurately reflect the disruptive features of other hydropower facilities. Such measures are essential not only to prevent the misleading use of the term ROR but also to foster hydropower development as a genuinely renewable energy source that benefits society as a whole.

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