water

Review

Hydropower Dam Development and Fish Biodiversity in the Mekong River Basin: A Review

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Abstract: Over the last few decades, considerable concern has been expressed about the threat of Mekong River Basin hydropower dams to a range of important freshwater riverine fisheries, particularly for fish that seasonally migrate long distances. However, much less attention has been given to the threat of hydropower dams to fish biodiversity in the high-diversity Mekong River Basin, the focus of this paper. Through reviewing the existing state of knowledge regarding Mekong River Basin fish biodiversity, and threats to it, we argue that even though no species are definitively known to have been extirpated from the Mekong River Basin to date, hydropower dam development and various other developments nevertheless pose a serious threat to fish biodiversity. Indeed, dams typically significantly block fish migrations and fish larvae distribution, cause river fragmentation, fundamentally alter river hydrology, and change water quality, all factors that have the potential to intersect with each other and lead to significant species extirpation and extinction, or in some cases, functional extinction, when a small population remains but the important larger population is lost permanently. The circumstances are further exacerbated by the lag time between impact and when that impact becomes evident, cumulative impacts, a lack of consistent data collection, including the collection of base-line data, and insufficient post-project research related to biodiversity. We contend that much more could and should be done to ensure that the Mekong River basin's exceptional fish biodiversity is not variously diminished and destroyed during the coming years.

Keywords: Mekong; endangered species; extinction; extirpation; biodiversity; hydropower dams

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1. Introduction

Hydropower dam development in the Mekong River Basin has been and continues to be controversial, particularly due to the impacts of dam development on important fish migrations and associated fisheries [1–6]. Indeed, the negative impacts of dams on fish migrations [7], habitat quality and availability [8], spawning behavior [9], and larval fish diversity, survival, and dispersal [10], could heavily impact fisheries productivity in the Mekong region, resulting in significant declines in fish catches, less food security, and potentially nutritional problems for people dependent on small-scale fisheries for food [11–14].

While the impact of dams on wild-capture fisheries is certainly crucial, there is another important fish-related issue that receives far less attention: the negative impacts of hydropower dam development on aquatic biodiversity. Research, monitoring, and policy focusing on hydropower impacts on Mekong biodiversity is sparse [15–19] and more study is urgently needed, especially given the pace of hydropower development, the number of at-risk species, and scientific consensus that dams often lead to significant population declines and extinctions [20].

In this paper, we review the state of knowledge regarding fish biodiversity in the Mekong River Basin and the already existing and potential impacts of hydropower dam development on fish biodiversity. We argue that hydropower dam development represents an important and largely unmonitored threat to fish biodiversity in the Mekong River Basin, and that while the impact of dams on fisheries is critical for community food security, income and health, fish biodiversity issues warrant more study, particularly related to endangered, endemic, and data-deficient species as well as previously common (and economically important) fish undergoing major population declines [21]. One recent study found that the impact of river fragmentation on endangered fish has been greatly underestimated in the upper Mekong River, suggesting substantial impacts in the lower basin as well [22].

We begin by briefly reviewing the diversity of Mekong River Basin fish, including those categorized as near threatened, vulnerable, endangered and critically endangered on the IUCN Red List of Threatened Species. We then outline the state of hydropower dam development in the Mekong River Basin. We consider how fish biodiversity has already been negatively impacted by hydropower dams, and how it is likely to be negatively impacted moving forward. Finally, we offer some concluding remarks.

2. Fish Biodiversity in the Mekong River Basin

There has been much speculation regarding how many species of fish are found in the Mekong River Basin. Taki [23], in an early fish biodiversity study in Laos, reported that there were 201 fish species known from the Mekong River Basin in Laos. Fifteen years later, Kottelat [24] reported that there were 244 known fish species in the Mekong River Basin in Laos, Cambodia and Vietnam. Additional surveys in the 1990s led to the discovery of many new species. For example, Roberts [25] described two new large barbs, *Probarbus labeamajor* and *Probarbus labeaminor*, with the former reaching up to 70–80 kg in weight [26], and Roberts [27] described a large (up to 10 kg) gouramy, *Hemibagrus exodon*, from Laos. Moreover, the largest fish species in the Mekong River Basin, which reaches up to 500 kg [28–30], the giant freshwater stingray, *Urogymnus polylepis*, was also formally reported from the Mekong River Basin in Laos in the early 1990s [29]. The species was originally described as *Himantura chaophraya* from the Chaophraya River Basin in central Thailand [28] but was later reclassified based on updated taxonomic and genetic studies [31,32]. There is also the large cyprinid, *Luciocyprinus striolatus*, described from the upper reaches of the Mekong River in China in 1986 from juvenile specimens. In the 1990s, it was revealed that individual fish reaching between 70–100 kg were known from a number of large clearwater Mekong tributaries in Laos [30].

By 1996, there were 265 known species of fish in Laos, and by 1998 there were 357 fish species recognized as occurring in the country [33]. However, the Mekong River's fish biodiversity became particularly recognized when Rainboth [34] speculated that there could be as many as 1000 species of fish in the Mekong River Basin, and it has even been suggested that the number could be closer to 1200 [35,36].

Kottelat et al. [37] calculated, as part of an expert assessment sponsored by the International Union for the Conservation of Nature (IUCN), that there were about 500 formally described fish species from freshwater parts of the Mekong River Basin, although it was expected that many more remained undescribed by taxonomists. However, Rainboth et al. [38] reported that up to 3500 species of fish, including brackish water species and coastal marine species, are at least partially dependent on the Mekong River nutrients flowing from the river into a plume in the ocean. Another analysis, which combined established species lists, including Fishbase and Mekong River Commission data, resulted in 1345 Mekong River Basin fishes, including brackish water species [39]. However, Fishbase species identification is not always accurate, and many synonyms are included.

Since Kottelat et al.'s [37] assessment, many new fish species have been described from the Mekong River Basin (see [40–55]). The Nagao Natural Environment Foundation [56] reported that they found 540 fish species in the Mekong River Basin in Laos, Thailand, Vietnam and Cambodia, but did not include China or Myanmar. However, this book was not intended to be comprehensive. Although the exact number of species is far from certain, there are presently about 600 freshwater species known from the Mekong River Basin, not including brackish or salt-water species. Moreover, there are almost certainly many more species that still await discovery. Thus, it is estimated that apart from the Amazon Basin, and possibly the Congo River Basin, the Mekong is home to the highest diversity of fish species for any large river system in the world [35].

Crucially, Zakaria-Ismail [57] reported that endemism is especially common in the Mekong River Basin. Indeed, the Mekong region has a complex geological, hydrological and climatic history, and this has greatly influenced speciation and species distribution patterns in the basin [15,32,38]. Baran and co-authors [58] reported many Mekong endemics from subbasins such as the Sekong and Srepok, with 62 and 45 endemic fish, respectively, as well as 15 "superendemics" only found in the Sekong River Basin. The genus *Schistura* contains over 60 species, including many endemics, and appears to have undergone speciation at the subbasin level with dozens of unique species basinwide and novel species occurring in adjacent Mekong tributaries, especially in the rivers flowing into the Mekong from the Annamite Mountains [59]. Many of the Mekong Rivers' largest fish, including the Mekong giant catfish (*Pangasianodon gigas*), the giant salmon carp (*Aaptosyax grypus*), the wolf barb (*Luciocyprinus striolatus*), and two *Probarbus* species are endemic to the Mekong River. No fish are endemic to Tonle Sap Lake, perhaps because this vast floodplain habitat was formed relatively recently and is interconnected with the mainstream Mekong and many tributaries by the seasonal flood pulse [60].

The Mekong River supports many diadromous (both anadromous and catadromous) fish species [61]. Many diadromous species of fish exhibit diverse migration patterns and life history strategies [62,63]. For example, the catfish, *Pangasius krempfi* is known to be anadromous, as it migrates from the South China Sea and Mekong Delta in Vietnam up the Mekong River to as far as Laos and Thailand each year [64–66], while the Anguilla eel, *Anguilla marmorata*, is catadromous, spending most of its life in freshwater but spawning in the South China Sea (known as the Eastern Sea in Vietnam) [16,30].

The Mekong River Basin also supports one of the most diverse communities of shellfish (gastropods and bivalves) in the world [16], and Kottelat and Whitten [15] expected the Mekong to support a high diversity of crustaceans as well, although this paper only focuses on fish biodiversity. A number of species of Mekong fish rely on shellfish for a critical part of their diets, so shellfish diversity may well be linked with fish diversity, at least to some degree.

It is hard to say whether any fish have become extinct from the Mekong River Basin in recent decades. However, the large migratory anadromous sawfish (*Pristis microdon*) was previously known from the Mekong River up to at least the Khone Falls [29,30,67,68], but has not been found so far up the Mekong River for many decades now. In addition, the critically endangered large Mekong cyprinid species, *Aaptosyax grypus*, which reaches a weight of up to 30 kg [30], was only described in 1991 [69] and was feared extinct until its "rediscovery" in 2022. Nonetheless, the species remains extremely rare, and no studies exist on its ecology or population status. Other mega-fish species, including the two largest catfishes, *Pangasianodon gigas* and *Pangasius sanitwongsei* and the giant carp *Catlocarpio siamensis*, while not yet extinct, are all categorized as critically endangered in the wild [37]. Indeed, one reason for hope may be the continued presence of juveniles of many endangered species, indicating that spawning still occurs despite many threats [70]. For these and many other species with a commercial value, overfishing in inland waters often leads to an initial population decline and significant decreases in the number of larger fish, whereas hydropower development represents a more existential threat through disruption of life history patterns necessary for survival (e.g., spawning cues, spawning migrations to spawning grounds, juvenile dispersal, etc.) [71–73].

Although there have been no documented Mekong fish extinctions due to hydropower dam development, dams certainly pose an important looming threat to a number of fish species, both large and small, as is outlined below. Based on information about the impacts of hydropower development on fish from other river basins, extinctions may not occur immediately [74,75], and the period between environmental impact and species disappearance has been termed "extinction debt" [76]. If extinction debt is substantial, the number of threatened species is often underestimated. Lessons from the Chao Phraya River, for example, where species like *C. siamensis*, *P. sanitwongsei* and *U. polylepis* have been nearly extirpated, highlight the eventual population declines that result from decades of river regulation and fragmentation [77]. Long-term standardized population monitoring, studies on population status, and improved analytical tools can be used to understand the magnitude of extinction debt due to hydropower development [76]. First, however, some general background about Mekong River Basin dam construction is needed.

3. Hydropower Dam Development in the Mekong River Basin

Although plans were in the works for developing a number of large dams on the Mekong River as early as the 1950s and 1960s [78], the Second Indochina War and the Cold War more generally prevented hydropower dam development from occurring throughout much of the Mekong River Basin between the 1960s and early 1990s. Exceptions included the Nam Pung Dam located in Sakon Nakorn Province in 1965, the Nam Pong and Ubol Ratana dams in Khon Kaen Province in 1966, the Lam Pao Dam in Kalasin Province in 1968, the Chulabhorn Dam in Chaiyaphum Province in 1970, and the Sirindhorn Dam in Ubon Ratchathani Province in 1971 [79]. In Laos, the Nam Ngum dam was built on a Mekong tributary in Laos north of Vientiane in 1971 [80]. Elsewhere, conflict prevented the development of most of the dams envisioned by US planners during the 1950s.

However, when the Cold War ended in the early 1990s, hydropower dam building started again in the Mekong Region. Construction of the Pak Mun Dam in Ubon Ratchathani Province started with World Bank support in 1990 and was completed in 1994 [81,82]. Development of the Khong-Chi-Mun Scheme also started in the 1990s [83]. By the mid-1990s, the Houay Ho Dam in southern Laos, the Theun-Hinboun Dam in central Laos, and a few other dams were also constructed [84,85]. Meanwhile, in China, the first dam on the Lancang (Mekong) River, the Manwan Dam, was completed in 1993 [86], and in the Central Highlands of Vietnam, construction of the Yali Falls Dam began in 1993 and was completed in 2001 [87].

In 1998–1999, however, the Asian financial crisis crippled plans to build a large number of dams in the Mekong Region. For example, in 1998, South Korea's Dong Ah Construction Industries Company stopped constructing the Xe Pian Xe Namnoy Dam in southern Laos. Other projects envisioned for the Sekong River in southern Laos were also cancelled [84]. Moreover, the Energy Generating Authority of Thailand (EGAT) had previously agreed to invest in the construction of China's Jinghong Dam but decided to withdraw from the project in 2000 due to financial problems and a lack of energy demand in Thailand [88]. Due to a decline in market demand for hydropower energy and lingering financial difficulties associated with the Asian financial crisis, little hydropower development occurred in the lower Mekong River Basin during the early 2000s. The critical World Commission on Dams [89] study also discouraged donors from supporting new large dams. The only major hydropower project constructed during this period was the Nam Theun 2 Dam, which started construction in 2005 and was completed in 2010 [90].

In the 2010s, however, the circumstances changed, and hydropower dam development increased dramatically. In Laos, for example, as of February 2019, there were 61 hydropower dams, with an installed capacity of 7207 MW and the capacity to generate about 37,366 kilowatt-hours per year [91]. Moreover, dams were developed in a different way than before. No longer were they mainly funded by international donors, such as the World Bank and Asian Development Bank, but were instead developed as build-operate-transfer (BOT) projects, which involves private companies investing in dams, and after a set period of time, often 25–30 years, handing them over to the Lao government [89]. In addition, 36 hydropower dams were under construction in early 2019 and were expected to contribute 4184 MW of energy by the end of 2020. Furthermore, the government of Laos was planning to begin developing another 10,000 MW of electricity by 2020, and an additional 20,000 MW by 2030 [92], although the COVID-19 pandemic has since slowed down hydropower dam development in Laos [93].

In the meantime, in Cambodia, the highly controversial 400 MW-capacity Lower Sesan 2 Dam [65,94], the largest dam built in Cambodia to date, began construction in 2014 and was operational by 2018 [95].

China experienced considerable Mekong/Lancang large dam construction on the mainstream Lancang (Mekong) River during the 2010s, including the massive Xiaowan and Nuozhadu dams [96]. There are now 11 dams on the mainstream Lancang River in China [97], apart from a number of dams built on tributaries of the Lancang River in China.

Overall, dam construction has been occurring rapidly in the Mekong Region in recent years and shows little sign of slowing down in the near future. Table 1 includes hydropower dams in the Mekong River with an installed capacity of 100 MW or more.

Table 1. List of Mekong River Basin dams with 100 MW electricity generating capacity.

Project	Location	Developer	Power Capacity (MW)	Reservoir Area (km^2)
Wunonglong	Lancang/Mekong mainstream, China	PRC	990	
Lidi	Lancang/Mekong mainstream, China	PRC	420	3.7
Tuoba	Lancang/Mekong mainstream, China	PRC		
Huangdeng	Lancang/Mekong mainstream, China	PRC	1900	
Dahuaqiao	Lancang/Mekong mainstream, China	PRC	920	
Miaowei	Lancang/Mekong mainstream, China	PRC	1400	
Gonguoxiao	Lancang/Mekong mainstream, China	PRC	900	343
Xiaowan	Lancang/Mekong mainstream, China	PRC	4200	194
Manwan	Lancang/Mekong mainstream, China	PRC	1550	415
Dachaoshan	Lancang/Mekong mainstream, China	PRC	1500	26.25
Nuozhadu	Lancang/Mekong mainstream, China	PRC	5850	320
Jinghong	Lancang/Mekong mainstream, China	PRC	1750	510
Xayaburi	Mekong River, northern Laos. 150 km downstream from Luang Prabang	CK Power PLC, Thailand	1280	55.9
Don Sahong	Mekong River, southern Laos. Channel just above Cambodia border	Mega First Corporation Berhad, Malaysia and EdL	240	0.29
Nam Theun 2	Mekong tributary, Central Laos, Nakai Plateau	Electricite du France, EdL and others	1075	450
Nam Theun Hinboun and Expansion	Mekong tributary, Central Laos, Theun and Hinboun Rivers	EdL, GMS Power and Scatect	220 and 222	49 and 49
Nam Ngum 1	Mekong tributary, Central Laos, Nam Ngum River	EdL (Royal Lao Government)	155	370
Nam Theun 1	Mekong tributary, Central Laos, Theun River	Phonesack, EGCO and EdL	650	93.6
Houay Ho	Mekong tributary, Bolaven Plateau, southern Laos	Daewoo (original developer)	152	37
Nam Khan 2	Mekong tributary, northern Laos	China's Sinohydro Corporation	130	30.5
Nam Lik 1-2	Mekong tributary, northern Laos	China Water and Energy, Ltd. holding (90%) and EDL holding (10%)	100	24.4

Table 1. *Cont.*

Project	**Location**	**Developer**	**Power Capacity (MW)**	**Reservoir Area (km^2)**
Nam Ngiep 2	Mekong tributary, northern Laos	China Water and Energy, Ltd. holding (90%) and EDL holding (10%)	180	
Nam Ngum 2	Mekong tributary, central Laos	Ch Karnchang and Ratchaburi Holdings	615	122.2
Nam Ngum 5	Mekong tributary, central Laos	Sinhydro Corporation	120	15
Nam Ou 2	Mekong tributary, northern Laos	Sinohydro Corporation	120	15.7
Nam Ou 5	Mekong tributary, northern Laos	Sinohydro Corporation	240	17.22
Nam Ou 6	Mekong tributary, northern Laos	Sinohydro Corporation	180	17.01
Xe Pian-Xe Namnoy	Mekong tributary, Bolaven Plateau, southern Laos	SK Engineering and Construction, Korea Western Power, Ratchaburi Electricity Generating Holdings	410	533
Xekaman 1 and Xekaman Sanxay	Mekong tributary, southern Laos	Songda Corporation	322	
Xekaman 3	Mekong tributary, Sekong River Basin, southern Laos	EVN, EdL	250	5.2
A Luoi	Mekong tributary, Sekong River Basin, Vietnam	EVN	170	
Buon Kuop	Mekong tributary, Sesan River Basin, Vietnam	EVN	280	47
Plei Krong	Mekong tributary, Sesan River Basin, Vietnam	EVN	100	53
Sesan 3	Mekong tributary, Sesan River Basin, Vietnam	EVN	260	6.4
Sesan 4	Mekong tributary, Sesan River Basin, Vietnam	EVN	360	
Sre Pok 3	Mekong tributary, Srepok River Basin, Vietnam	EVN	220	
Yali Falls	Mekong tributary, Sesan River Basin, Vietnam	EVN	720	64.5
Lower Sesan 2	Mekong tributary, Sesan River, Stung Treng, Cambodia, 25 km upstream from Mekong	China's Hydrolancang International Energy, Royal Group, Electricite du Vietnam	400	75
Pak Mun	Mekong tributary, Mun River, Ubon Ratchathani, Thailand, 6 m upstream from Mekong	EGAT	136 (part of year)	60
Lam Ta Khong	Mekong tributary, Nakorn Ratchasima, Thailand	EGAT	500	37

Figure 1 is a map of the hydropower dams in the Mekong River Basin that have an installed capacity of 100 MW or more (Figure 1).

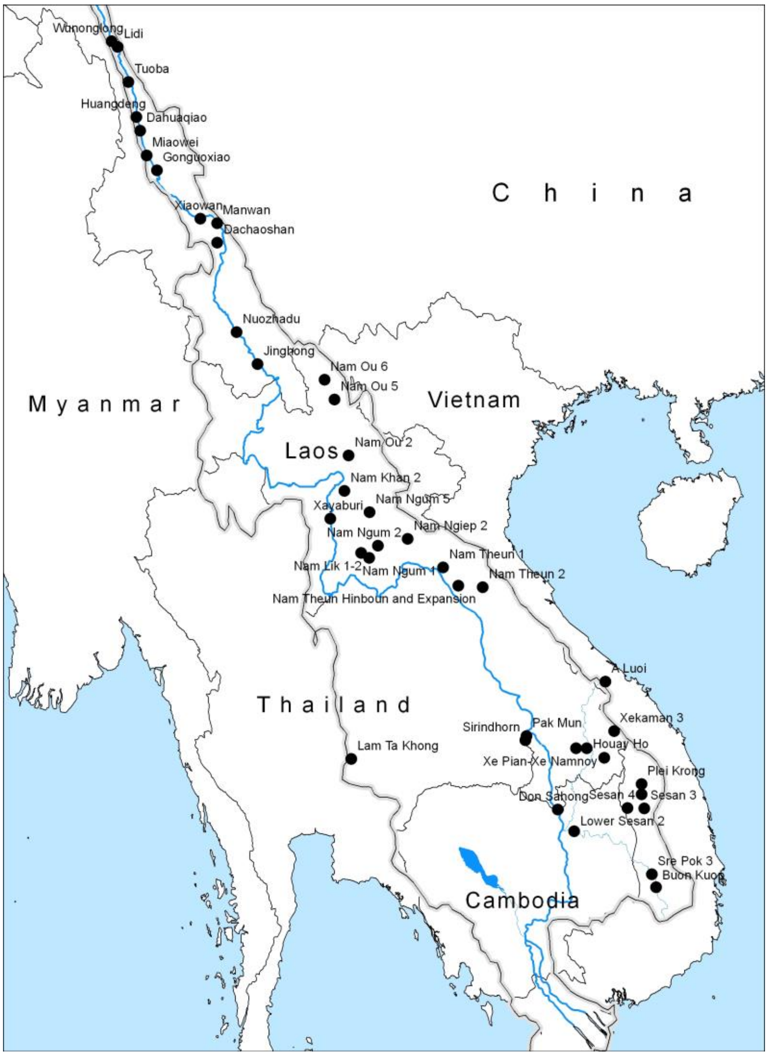

Figure 1. Map of the Mekong River Basin and hydropower dams with installed capacity of 100 MW or more.

4. The Impacts of Hydropower Dam Development on Mekong Fish Biodiversity: Past, Present and Future

Quantifying the impacts of hydropower development on Mekong fish biodiversity is a challenging exercise due to the accelerating pace of hydropower development, the lack of consistent and comprehensive environmental impact assessments, cumulative risks posed by multiple dams, lagged response time of fish populations to multiple stressors caused by dams, complex and poorly understood life histories of many Mekong fish species, and lack of regular monitoring of fish conservation status. Nonetheless, in areas within the Mekong River Basin that have been dammed and where long-term monitoring has occurred, data indicate lower fish abundance and diversity in dammed rivers. Phomikhong and colleagues found lower diversity and abundance of fish in the dammed Mun and Gam Rivers, compared to the undammed Songkhram River [98]. SEARIN and AoP [99] reported that many species of fish disappeared from fishermen's catches after the Pak Mun River was built on the lower Mun River in northeastern Thailand, but that many of those species returned to the Mun River after the gates of the Pak Mun dam were opened for a full year following anti-dam protests. In addition, an analysis of catch data from the Sekong, Srepok, and Sesan Rivers found reduced diversity following dam construction and fragmentation, and increased diversity in less regulated rivers (research in review). Moreover, fish assemblages show a lagged response to anthropogenic threats (and impacts from hydropower manifest in many different ways), so immediate, more measurable impacts will likely be restricted to direct effects (e.g., blocking spawning migrations, flooding spawning habitat, disrupting spawning cues, delaying larval dispersal), whereas measuring long-term, indirect, and cumulative impacts (e.g., reduced flood pulse, increased fishing adjacent to dam sites, reduced river productivity, and lower sediment loads) will require longer-term study and more robust monitoring.

For example, the Don Sahong Dam, which was recently completed on a channel of the Mekong River on the Lao side of the Laos-Cambodia border, may be obstructing the movement of *Pangasianodon gigas*, a critically endangered species [15], up the Mekong, since the species was previously known to migrate up the Hou Sahong channel [68]. The channel has now been totally blocked by the dam. While it is true that other channels in the Khone Falls area have been opened up to allow fish to migrate more easily upstream, and that these efforts along with the banning of the use of large fish traps have made it easier for fish to migrate upriver [100], it is unclear whether the giant catfish will be able to negotiate these channels when moving upstream, since they reach up to 300 kg [30,72,73], and the channels that have been opened up are much smaller and shallower than the Hou Sahong channel. Furthermore, large catfishes are unlikely to be able to migrate successfully downstream past the turbines of the dam, although they could make it down other unobstructed channels in the Khone Falls area. The point is that while the Don Sahong Dam was not the reason that Mekong giant catfish was assessed as being at high risk of extinction, the dam is likely blocking the spawning migrations of a critically endangered fish, and thus negatively contributing to an already dire situation. River fragmentation from dams increases fish extinction risk [101,102].

Similarly, the Xayaburi dam, as well as the planned Luang Prabang and Sanakham dams in Lao PDR, will bisect, and potentially present a formidable obstacle, to the migration of the Mekong River giant catfish and other threatened species. One group of highly migratory and endangered fishes, the Pangasiid catfish, are an important food fish in the Xayaburi region and along the Lao/Thai border. These catfish move extensively between Vietnam, Cambodia, Lao PDR, and Thailand [64]. Pangasiid catfish are particularly vulnerable to threats from dams because of their migratory behavior, requirements for specific water quality and flow, and a complex life history that is dependent on the seasonal floods [29,103,104]. Pangasiid catfish may be capable of migrations between the Mekong delta and Lao dam sites, meaning the impacts of the dams in Lao PDR could be felt over a very large area from northern Thailand to northeastern Thailand, southern Laos, Cambodia, and Vietnam. Four species of Pangasiid catfish, Mekong giant catfish (*Pangasianodon gigas*), giant pangasius (*Pangasius sanitwongsei*), river catfish (*Pangasianodon hypophthalmus*), and silver-toned catfish (*Pangasius krempfi*) are listed by IUCN as critically endangered, endangered, or vulnerable. Moreover, Baran et al. [58] identified a further 19 species of endangered species that could be impacted by dams. Table 2 includes a list of 25 threatened fish species in Cambodia. Many of these species are especially vulnerable to the impacts of the dam since they have been previously identified as being at elevated risk of extinction and any additional negative impacts will exacerbate their already perilous situation.

Table 2. Twenty-five threatened fishes of the Cambodian Mekong. CR = Critically Endangered; EN = Endangered; VU = Vulnerable. While Cambodia supports both high fish diversity and high fisheries productivity, overfishing and illegal harvest, habitat degradation and fragmentation, and changes to hydrology and climate pose significant risk to species survival.

Scientific Name	Common Name	IUCN Red List Category
Aaptosyax grypus	Giant salmon carp	CR
Balantiocheilos ambusticauda	Burnt-tail fish	CR
Catlocarpio siamensis	Giant barb	CR
Datniodes pulcher	Siamese tiger perch	CR

Table 2. *Cont.*

Scientific Name	Common Name	IUCN Red List Category
Pangasianodon gigas	Mekong giant catfish	CR
Pangasius sanitwongsei	Giant pangasius	CR
Probarbus jullieni	Jullien's golden carp	CR
Schistura bairdi	Baird's Schistura	CR
Hemitrygon laosensis	Mekong stingray	EN
Luciocyprinus striolatus	Giant wolf barb	EN
Pangasianodon hypophthalmus	Striped river catfish	EN
Probarbus labeamajor	Thick-lipped barb	EN
Scleropages formosus	Asian bony-tongue	EN
Urogymnus polylepis	Giant freshwater whipray	EN
Bangana behri	Two-headed carp	VU
Cirrhinus microlepis	Small-scaled mud carp	VU
Datnioides undecimradiatus	Mekong tiger perch	VU
Hypsibarbus lagleri	Trey chhpin thom (Khmer)	VU
Mystus bocourti	Trey kanchos kdaung (Khmer)	VU
Osphronemus exodon	Elephant ear goramy	VU
Oygaster pointoni	Bamboo leaf fish	VU
Pangasius krempfi	Kremp's catfish	VU
Scaphognathops bandanensis	Bandan sharp-mouth	VU
Tenualosa thibaudeaui	Laotian shad	VU
Wallago attu	Wallago	VU

In addition, some fish species in the Mekong River Basin have been listed by IUCN as critically endangered because of their restricted range (i.e., they appear to inhabit one particular section of the Mekong River), and the habitat through the known range of the species is threatened by planned hydropower dams. For example, the endemic loach, *Schitura bairdii*, has so far been collected at only two locations, in the mainstream Mekong River in Stung Treng Province and in southern Laos just below the Khone Falls. Thus, because this species is believed to inhabit rapids, and because these rapids are threatened by the construction of the planned Stung Treng Dam, the species was categorized as critically endangered [15]. There have also been reports of expanded ranges of endangered species such as *Dasyatis laosensis* and *Chitala ornata* in the Lancang/Mekong in China and *Tenualosa thibaudeaui* in the Sekong, Sesan and Srepok River Basins in Cambodia. It has been hypothesized that artificial conditions including barrier effects by hydropower dams and shifts in food availability may be driving these changes in species distribution [105]. In summary, hydropower can affect species distribution and habitat in hard to understand ways, with the potential of serious impacts both to restricted-range species and other at-risk fish.

Fish species may become extinct by being blocked from accessing critical habitat for spawning or feeding by one or more large dams. For example, *Pangasius krempfi*, which is listed as vulnerable by IUCN, constitutes a single population of fish that migrate each year from the South China Sea to their unknown spawning grounds [64,106,107], probably somewhere in northern Laos. If a large dam was built on the mainstream Mekong, and the spawning *P. krempfi* could not reach a suitable location to spawn, this could certainly lead to the extinction of this Mekong endemic. That is why the species is listed as vulnerable by the IUCN [15].

Other species, such as *Gyrinocheilus pennocki*, a medium-size bottom species, are not even listed as near threatened, but may actually be vulnerable, endangered or critically endangered due to the construction of the Lower Sesan 2 Dam in northeastern Cambodia.

When the first author visited the dam site in 2019, soon after the dam had been completed and fully closed, villagers informed him that at the beginning of the rainy season, when the species is known to migrate from the mainstream Mekong River up the Sesan River [108], they were able to catch large numbers of this species right in front of the dam. Large schools of fish were clearly being impeded from migrating upstream, and while a small fish ladder has been added to the dam, these bottom fish were apparently not using it because they would need to swim up at the top of the water column to do so, and this species does not exhibit such behavior. This raises a number of questions. First, will this species be able to adapt and successfully spawn elsewhere even if the fish cannot reach their normal spawning ground? In addition, do all the *Gyrinocheilus pennocki* make this critical migration, or do others migrate to other rivers, such as the Sekong River, resulting in them being able to reproduce and survive despite the population blocked by the Lower Sesan 2 Dam being negatively impacted?

Answers are required for these critical questions before it can be said with any certainty to what extent *Gyrinocheilus pennocki* is being threatened by the Lower Sesan 2 dam. There are still many questions about this species and dam impacts on it that cannot be answered with any certainty by scientists or others. Indeed, it at least seems highly likely that the population of *G. pennocki* being blocked by the dam will be negatively impacted, but the degree to which they will be impacted is uncertain, even if prevailing knowledge suggests that the impact is likely to be significant. Indeed, uncertainty is a key characteristic of dam building in the Mekong region, as has been made clear by Whitington [85], in his important work about the Theun-Hinboun Hydropower Project in central Laos. Whitington is particularly interested in the temporal latency of changes caused by the Theun-Hinboun Dam, asserting that the active production of uncertainty leads to degraded environments, but also to the production of novel ecologies.

Another species that has experienced localized impacts, but not the extinction of the species, relates to the Mekong small catfish *Pangasius macronema.* Baird et al. [109] documented the communal fishery, but due to the construction of the Don Sahong Dam in southern Laos, the fishery no longer exists, as the fish cannot migrate past the dam, although they can go up other channels at the Khone Falls, and the habitat suitable for the communal traps was flooded when the dam was constructed and no longer exists.

Another threat that dams have on fish, which could lead to extinctions over a somewhat longer period of time, is population fragmentation, which occurs when populations of fish become isolated from other populations of the same species. Consequently, both populations are reduced and become more vulnerable to threats, such as inbreeding, thus reducing the potential for resiliency and increasing the risk that certain populations might be extirpated, or that endemic species could eventually become extinct, following island biogeography theory [110–112].

Another way that certain fish species could become extinct is due to changes in water quality and hydrology downstream through dam water releases. Although water quality can change for a variety of reasons [113], dams often seriously alter water quality, including through changes in sediment loads, changes in chemical and nutrient contamination, changes in water temperatures [86,112,114], and reductions of oxygen content in stagnant or partially stagnant reservoirs [112,115]. Toxic blue-green algae can flourish in some reservoirs and cause problems for humans and animals downstream when released [65,87]. Dams can also cause other significant hydrological changes downstream that can cause important impacts on fish species downstream [112,115,116], including affecting spawning, migrations, feeding and other behavior, and ultimately biodiversity. The Mekong River is believed to transport 160 million tonnes of sediment a year, which includes a lot of important nutrients, including phosphorous, nitrogen and potassium [117].

Different types of dams can reduce and change sediment transport and water quality differently. For example, large dam reservoirs can result in oxygen-deficient “dead zones”, which negatively affect the cells, tissues and organs of fish and other aquatic organisms, thus making it difficult for much to survive there. Projects with smaller reservoirs tend to have less impact on water quality, but they can still hold back sediment loads at critical times of the year, and sometimes they release unusually large amounts of sediment, which can also result in adverse downstream impacts. Sediment deposition changes downstream can negatively impact aquatic life. Sediment load changes can also affect water temperature significantly, which can in turn affect spawning and other changes in aquatic life behavior, although there has been little research on this topic in the Mekong River Basin. There are many aspects that need to be considered in the Mekong River Basin (see [117]).

There is also the question of cumulative impacts, an increasingly important issue, but one that is also quite complex and difficult to make definite conclusions about. Thus, while one dam may not lead to a serious population decline or the extinction of a fish species, the construction of two or more dams within the species range could be particularly devastating [112], and the impacts of dams also typically combine with other impacts [118]. Crucially, we often do not know where the tipping point is for certain species, particular places, and different kinds of impacts, and we may not be able to know about such impacts before they have actually resulted in a species becoming extinct or extirpated, even if the species was not particularly threatened by a single dam. For example, hundreds of distinct populations of Pacific salmon were extirpated by the cumulative impacts of dams in the Columbia River basin. As cumulative impacts grew, populations in headwaters streams were particularly affected, resulting in the complete disappearance of all species of Pacific salmon from headwater regions in British Columbia, Canada [119].

Another issue worth mentioning is that extinction is the most likely to threaten endemic species, because they are not found in other rivers, and the Mekong is well known for its endemism [37]. Broadly speaking, endemic species are more likely to be threatened with extinction than species found in multiple river basins. Moreover, there are some species that were previously believed to be found in multiple rivers, including the Mekong, that have now been shown to be Mekong endemics (i.e., see *Bagarius* revision, [43]. There are also cases, such as with giant pangasius (*P. sanitwonsgei*), river catfish (*P. hypopthalmus*), seven-striped barb (*P. jullieni*), and giant freshwater stingray (*U. polylepis*), that do occur elsewhere but have disappeared from many areas; thus, the Mekong River is a last refuge. In 2022, many rare species were found in the Cambodian Mekong: For example, the Mekong giant catfish was found upstream of Phnom Penh, *Aaptosyax grypus* was reported from the Stung Treng area, a world-record sized giant freshwater stingray was tagged and released near Kratie, widespread reports of runs of *Tenualosa thibeaudeai* were received, especially from the Srepok River, as well as records of juvenile *Catlocarpio saimensis* and *Probarbus* spp., *Dasyatis laosensis*, and the endemic *Hemibagrus exodon*. While it is unclear why so many rare fish were reported from Cambodia in 2022, it is worth noting that no mainstream dams have been built on the Cambodian Mekong and the main rivers and floodplain are relatively connected and intact.

Although there is so far no evidence from the Mekong River Basin that the introductions of non-native fish or other species could result in Mekong fish being extirpated or made extinct, based on what we know about non-native introductions in other parts of the world [120], non-native invasives must be mentioned as a potential threat which could cause future extinctions. Predators may pose the most important threat [121], but other scenarios related to competition for food or other resources also sometimes occur [120]. Welcomme and Vidthayanon [118] looked at the potential threat of non-native fish introductions in the Mekong Region. They found that there could be problems with non-native introductions, but they did not consider it to be a particularly serious challenge in the Basin at the time. Indeed, of the 201 fish species that Baird [16] identified from the Khone Falls area in Khong District, Champasak Province, southern Laos, during the period, only five were non-native, and all of those were only encountered occasionally. However, as aquaculture becomes more prevalent in the region, and habitats become more stressed due to dam and other developments, we can expect the number and quantity of invasive fish species to increase in the future, and for those species to have more of an impact on native species. Other non-fish invasive species have, however, have already negatively impacted aquatic habitats and water quality in the lower Mekong River Basin, including water hyacinth (*Eichhornia crassipes*) [122] (p. 115), and *Mimosa pigra* L. (Leguminosae, Mimosoideae), a deciduous shrub native to tropical America which forms dense, thorny growth. Both are difficult to eradicate [123].

Another important issue is that species cannot be listed as near threatened, vulnerable, endangered or critically endangered unless there is sufficient data to make a determination. Thus, Kottelat et al. [37] categorized many species as "data deficient", and even for those with more data, where a determination was deemed possible, there were always significant remaining gaps in knowledge. This makes prediction extremely challenging. Many IUCN listings for Mekong species need to be updated and are based on dated and incomplete information.

It is also possible that certain species, such as the *Tenualosa thibaudeaui*, may be severely impacted by a dam or by other changes, as appears to have been the case for the mainstream Mekong population in the Khone Falls area [29], where the species became not actually fully extinct, but functionally extinct in terms of its influence on ecosystem processes and other species. A small population may remain, but the bulk the population may be lost, thus leading to significant losses without actually becoming extinct. This sort of impact should be considered important for biodiversity, even if the species has not become extinct. For example, a heavy decline in a population can negatively affect other species that may feed on the species, or other impacts on ecosystem services only produced by a species when they are found in significant numbers (see [124]).

5. Uncertainty

While we know enough to predict many of the impacts that hydropower dams in the Mekong will have on fish biodiversity, one serious problem for Mekong Basin fish species is, as already mentioned, a lack of baseline data, especially for species that are likely to be heavily impacted by hydropower dams. There is often insufficient data collected before dams are built, but also during post-construction periods, when it is important to determine if certain species have been negatively impacted or not, and if they have been impacted, to what extent. For example, new loach species (genus *Schistura*) are being found in many large Mekong tributaries being surveyed by ichthyologists, but not all rivers have been surveyed for fish, either before or after a dam has been built on the river. Thus, we do not know the state of the river before a dam was built on it, which makes pre- and post-dam comparisons extremely problematic.

One particular problem is that there has not been much dedicated research to studying species of fish most likely to be threatened by particular dams, even though the threat can be assumed. Thus, there is almost never complete life cycle information for particular fish species that are likely to the threatened by hydropower dam development. This increases the uncertainty of how particular dams are likely to affect particular species. One common problem in the Mekong is that much of the data about fisheries and fish losses are produced by private companies in order to meet regulatory requirements of governments, particularly through producing environmental impact assessments (EIAs). Often the data created during these studies are not available to the public, or for inclusion in broader scale analyses or meta-analysis. The quality of these data are often poor or questionable, and in some cases, none or very little new empirical data are collected to produce these studies. Thus, these studies sometimes contribute very little to understanding the actual threats to vulnerable fish species.

While high dams with large reservoirs often pose the greatest risk to fish, dams with less or no active reservoir storage, often referred to as run-of-the-river dams, also often pose serious threats to fish biodiversity. The particular circumstances and impacts of projects differ. For example, the Pak Mun Dam in Ubon Ratchathani Province, Thailand, has already caused serious negative impacts to fish populations that historically migrated from the Mekong River up the Mun River [82,89,122,125,126], and run-of-the-river dam development on the mainstream Mekong River also pose a significant threat to migrating fish, important fisheries and fish biodiversity [104,127], including plans for the Stung Treng and Sambor dams along the Mekong River in northeastern Cambodia. The Sekong A dam on the Sekong River in southern Laos is another serious threat to fish migrations. Based on current knowledge of Mekong fish biodiversity, patterns of endemism, and areas identified as critical habitat for endangered species, hydropower in the lower Sekong River (such as the Sekong A dam) and the lower Mekong River in Cambodia (such as the Stung Treng and Sambor dams) would be particularly devastating. Indeed, Sor and colleagues (in review) found that species diversity in free-flowing rivers like the Sekong might be increasing as diversity in dammed rivers decreases. We understand many of the expected impacts, but there often remains a degree of uncertainty when it comes to hydropower development (see [85]).

6. Preventing and Mitigating Hydropower Dam Impacts on Fish Biodiversity

Hydropower dams in the Mekong River Basin clearly pose serious threats to fish biodiversity. Given the threats hydropower pose to freshwater biodiversity, mitigating negative impacts on vulnerable species reduces the risk of species extinction. Xu and Pittock [18] assessed the effectiveness of mitigation measures in the upper Mekong basin, determining that different measures had varying degrees of success and no dam avoided adverse effects entirely. Obviously, the best way to avoid the impacts of dams on fish is simply not to build them, or not to develop the projects with the greatest impacts, such as those that block the most important fish migrations [11], divert large amounts of water from basin to basin [128], or most alter the hydrology and water quality [115]. Indeed, sufficient energy can now be produced through solar and wind power, which can be done at a relatively low cost and with relatively fewer impacts [1]. Thus, more solar and wind generated energy could lead to less fish extinctions, at least in theory.

When the option of stopping a dam from being developed cannot be achieved, for whatever reason, there are other things that can be done to reduce potential impacts: first, require rigorous, publicly available environmental impact assessments of hydropower projects within the Mekong River Basin, including projects like the Sekong A dam which will generate a modest amount of electricity but is likely to have oversized environmental impacts. Several studies have shown that main river dams seriously affect fisheries [5,129,130]. Even with well-designed fish passage, appropriate environmental flows, and better information on fish ecology, it is still very challenging to prevent negative impacts [124]. The risk of permanent damage to Mekong biodiversity and fisheries production is too great, and the cost too high, to move forward based on inadequate information.

Managing dams to improve environmental flows is one approach that can help mitigate negative hydropower dams on aquatic biodiversity. Environmental flows relates to how water releases from dams are managed in order to coincide with natural riverine cycles [131], to partially or fully mimic natural daily and seasonal flows, and to reduce downstream impacts [132,133]. The World Commission on Dams (WCD) [89] originally introduced the concept of environmental flows, but maintaining environmental flows can cost a considerable amount of money, which is one of the reasons why it has not been implemented much in the Mekong River Basin [134].

Diadromous species are particularly vulnerable to the impacts of hydropower development because of their life histories that often involve long migrations, natal homing, and the existence of genetically distinct stocks [135]. Populations of diadromous species have declined significantly in many regions, including North America, Europe, Asia, and New Zealand [74,135,136]. This pattern of decline suggests the Mekong's diadromous species likely face similar threats from hydropower and other forms of river fragmentation.

Maintenance of river connectivity is a key issue for maintenance of both biodiversity and fisheries production. Many species of Mekong fish have complex life cycles that involve long-distance migrations. Migratory fish represent 40 to 70% of the Mekong's freshwater fish production [137] and most Mekong fish are migratory to some extent [138].

Maintenance of migratory pathways is crucial to protect biodiversity. Fish rely on the natural, seasonal hydrological cycles of the Mekong River Basin. Flows often cue fish to migrate or spawn, and the high flows of the rainy season open up vast habitats for feeding fish. Likewise, people use hundreds of different fishing methods, and most of these methods are adapted to a specific site, flow and time of year [139]. Changes to the natural flow of the river, especially artificial fluctuations in flow, low floods, shorter floods, or late floods, will decrease both biodiversity and fish catch [4,5].

Research on the ecology and conservation status of Mekong River Basin fish is urgently needed. Lessons from other river basins highlight the need for regular basinwide fish surveys. Without regular monitoring, it is impossible to determine if, when, or why a species has disappeared. For example, on the Yangtze River in China, there was a 40-year gap between fish surveys, and the most recent survey failed to detect 140 fish species that were historically present in the basin [74]. It is very difficult to mitigate threats like those posed by dams without detailed information on the ecology and species interactions of Mekong fish.

Action plans can be developed to help prioritize and focus efforts on protecting particular species, habitats, etc. Currently, there are no comprehensive conservation action plans for any species of Mekong fish. Plans should address key factors that typically hinder effective conservation action, such as distribution and critical habitat, migratory behavior, fish/flow relationships, as well as knowledge gaps, future research priorities, and descriptions of governance structures that may be used to protect focal species [140]. For example, this would be useful for at least all IUCN Red-listed species. In addition, genetic analysis could be done to help show where new species exist, and how populations of particular species are divided up, allowing for developing better strategies to protect certain species and populations [141–144]. Since many large Mekong River Basin fish species stay in deep-water pools, especially during the dry season, protecting these pools is another option for protecting certain fish species, particularly large threatened species, as can be seen from work done so far in southern Laos [145–148], northern Thailand [149,150], Cambodia [17], and elsewhere.

The best opportunities for restoration or rescue efforts occur well before a species is determined to be near extinction. Therefore, research and conservation should occur in parallel to robust, realistic risk assessments of existing and planned hydropower development.

7. Conclusions

This paper represents an effort to encourage more of a focus on the near threatened, vulnerable, endangered and critically endangered Mekong fish species, because the fast pace of hydropower dam development occurring the Mekong River Basin in recent years is likely to lead to an increase in fish extirpation and extinction, even though few people or projects are focusing on this critically important issue.

We do not have sufficient data or knowledge to develop well-informed strategies for avoiding the extirpation and extinction of various Mekong River species. Thus, more efforts need to be made to fill in important gaps in knowledge, while at the same time making use of what we already known to take action. For example, action plans need to be developed for various fish species, including IUCN-listed fish species, but also other species not yet listed by IUCN due to there not being sufficient data to justify such classification.

More importantly, sincere efforts need to be made to implement well-informed and well-designed species conservation action plans. That is, we need to conduct more research that targets IUCN-listed species. This should include studies involving various scientific techniques [21,107,141,151–153]. Crucially, however, we especially need to rely more on the tremendous local and Indigenous knowledge about Mekong fish that is held by community members in various parts of the basin but has so far not been sufficiently drawn upon for making important management decisions (see, for example, [115,154–158]). Ultimately, it is imperative that we adopt a multi-pronged approach that takes advantage of all the tools available to us. Otherwise, we can expect many tragic fish extinctions to occur in the near future.

Fish biodiversity has clearly not received sufficient attention by either researchers or governments in the Mekong region. In order to "bend the curve" of freshwater biodiversity loss, priority actions include coordinated and open-access research, protection of migration corridors, river connectivity and environmental flows, identification and conservation of critical habitat, and species conservation action plans for the most vulnerable aquatic animals [159–161]. A growing body of evidence shows that fisheries productivity and biodiversity are closely linked, and that protecting aquatic biodiversity yields fisheries benefits [162]. Thus, this paper serves as a call for much more targeted attention to this crucial issue, both in relation to research and action-oriented efforts to ensure that pending fish extinctions do not occur, or at least occur to a lesser degree that is likely to occur if more and sustained efforts do not occur.

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