

Review

# A Meta-Analysis of Environmental Tradeoffs of Hydropower Dams in the Sekong, Sesan, and Srepok (3S) Rivers of the Lower Mekong Basin

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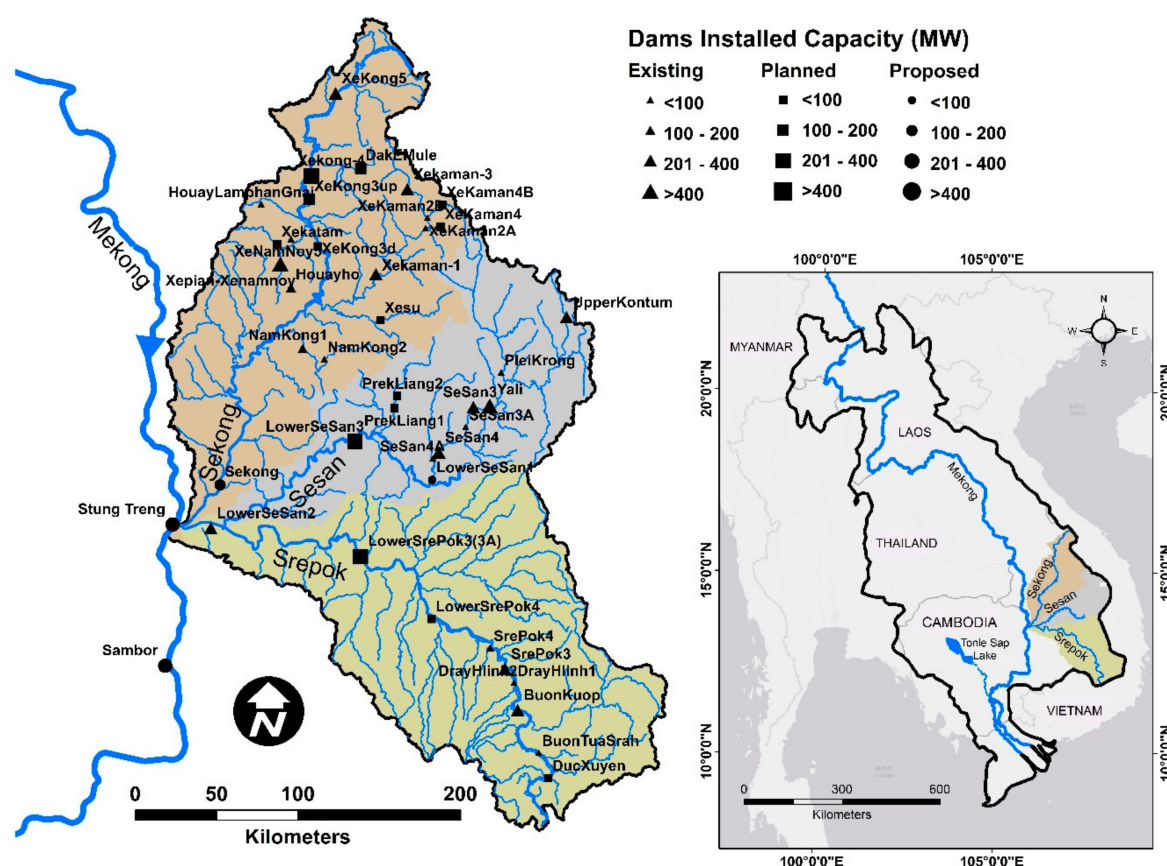
**Abstract:** In Mekong riparian countries, hydropower development provides energy, but also threatens biodiversity, ecosystems, food security, and an unparalleled freshwater fishery. The Sekong, Sesan, and Srepok Rivers (3S Basin) are major tributaries to the Lower Mekong River (LMB), making up 10% of the Mekong watershed but supporting nearly 40% of the fish species of the LMB. Forty-five dams have been built, are under construction, or are planned in the 3S Basin. We completed a meta-analysis of aquatic and riparian environmental losses from current, planned, and proposed hydropower dams in the 3S and LMB using 46 papers and reports from the past three decades. Proposed mainstem Stung Treng and Sambor dams were not included in our analysis because Cambodia recently announced a moratorium on mainstem Mekong River dams. More than 50% of studies evaluated hydrologic change from dam development, 33% quantified sediment alteration, and 30% estimated fish production changes. Freshwater fish diversity, non-fish species, primary production, trophic ecology, and nutrient loading objectives were less commonly studied. We visualized human and environmental tradeoffs of 3S dams from the reviewed papers. Overall, Lower Sesan 2, the proposed Sekong Dam, and planned Lower Srepok 3A and Lower Sesan 3 have considerable environmental impacts. Tradeoff analyses should include environmental objectives by representing organisms, habitats, and ecosystems to quantify environmental costs of dam development and maintain the biodiversity and extraordinary freshwater fishery of the LMB.

**Keywords:** hydropower planning; fish; hydrologic alteration; biodiversity; 3S Basin; connectivity

## 1. Introduction

Planning and constructing hydropower dams have historically taken precedence over analyzing their environmental effects. While hydropower dams provide renewable energy, they also alter streamflow, trap sediment, fragment rivers, disrupt fish migrations and spawning, degrade ecosystems, and reduce biodiversity [1–3]. Large-scale hydropower projects are being considered in some of Earth's most biodiverse systems, including the Mekong, Amazon, and Congo Basins [1]. These projects will have cascading repercussions for local communities and food security [4]. The effects of dams on natural streamflow have been well studied [5]; however, quantifying the benefits of dam development and their environmental losses is needed to plan and operate hydropower dams efficiently, maintain food security for local communities, contain conflict, and maintain species, habitat, and ecosystems [6].

Unprecedented hydropower development in the 802,000 square kilometer (km<sup>2</sup>) Mekong Basin embodies these challenges. Total hydropower potential in the Mekong Basin is estimated to be between 53,000 and 59,000 megawatts (MW) [7,8]. In the Lower Mekong Basin (LMB), which includes Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam, 59 hydropower dams have been commissioned as of 2015 and installed capacity exceeds 10,000 MW. This capacity accounts for 35% of the potential hydropower capacity of the LMB [4]. The Sekong, Sesan, and Srepok Rivers (the 3S Basin) combine to form a major tributary to the Lower Mekong River and are a hotspot for hydropower dam development (Figure 1). Since 1990, 27 dams have been built and another 16 are planned (Table S1). The 27 existing dams provide installed capacity of over 4800 MW and gross storage capacity of nearly 18,000 m<sup>3</sup> [2]. Thailand is a major hydropower importer from Lao PDR, while Vietnam imports power from Cambodia and China [9]. Hydropower development may be a promising path for power-importing countries to generate energy and economic growth [10], although cost-benefit analyses suggest that power-exporting countries like Cambodia and Vietnam will lose ecosystem services and gain little in hydropower benefits [11].



**Figure 1.** The Sekong, Sesan, and Srepok (3S) Basin with existing and planned hydropower dams.

The 3S Basin drains southern Lao PDR, Vietnam's Central Highlands, and northeastern Cambodia and has an outsized importance for Mekong River fisheries and ecology. The 3S Basin makes up 10% of the Mekong watershed's area, but provides up to 25% of streamflow and sediment load [10,12]. The 3S Rivers historically provided critical habitat for megafishes and migratory fishes [13]. Fish are the primary source of protein in the LMB, with 65 million people dependent on fish for food security [4]. More than 2.2 million tonnes of freshwater fish are caught each year, valued at USD 3.6 to 6.5 billion (2009 dollars) as a first sale value [14], with retail markets approximately doubling value [15]. Dam

construction in this basin therefore threatens freshwater biodiversity, a world-class fishery, and the health and livelihoods of many people dependent on fish for food.

Since early water resources systems models were developed more than 50 years ago, environmental objectives like natural streamflow, sediment transport, and aquatic habitat have become more emphasized worldwide and increasingly drive water management [16]. However, hydropower development in the LMB has been conducted on a project-by-project basis, rather than by creating optimal dam portfolios using systematic approaches that evaluate tradeoffs between hydropower benefits and environmental impacts [7]. Strategic assessments are now starting to be completed by researchers [3,7,17]. For example, recent research has shown that a different portfolio of dams could have equaled the current hydropower capacity in the Mekong Basin while more than doubling the current sediment supply to the delta [7]. Research that quantifies environmental losses with hydropower dam benefits is needed to identify dam sites, design details, and operating rules to minimize environmental impacts while generating hydropower.

We completed a meta-analysis to identify the aquatic and riparian environmental objectives considered in tradeoff analyses and to develop a comprehensive understanding of the benefits and environmental impacts of hydropower dams in the 3S Basin. We focused on the 3S Basin and the Tonle Sap-Mekong-3S Basin (Figure 1), to holistically consider aquatic habitat connectivity, habitat quality, and movement between fish spawning and rearing habitats. A review of environmental tradeoffs of hydropower generation has yet to be completed for the Mekong Basin or other regions undergoing extensive dam development. Our research questions were (1) did the timing of hydropower dam research correspond with dam development, (2) what environmental objectives were quantified in existing tradeoff analyses, (3) what decision variables were used in published research to evaluate human benefits and environmental losses of dam development, (4) what data are available for future studies and systems models, and (5) what research gaps exist? This analysis synthesized understanding of environmental tradeoffs, identified current knowledge gaps, provided recommendations to reduce the redundancy of future research, and determined promising pathways for sustainable hydropower planning and decision-making in the 3S Basin and LMB.

## 2. Study Area and Methods

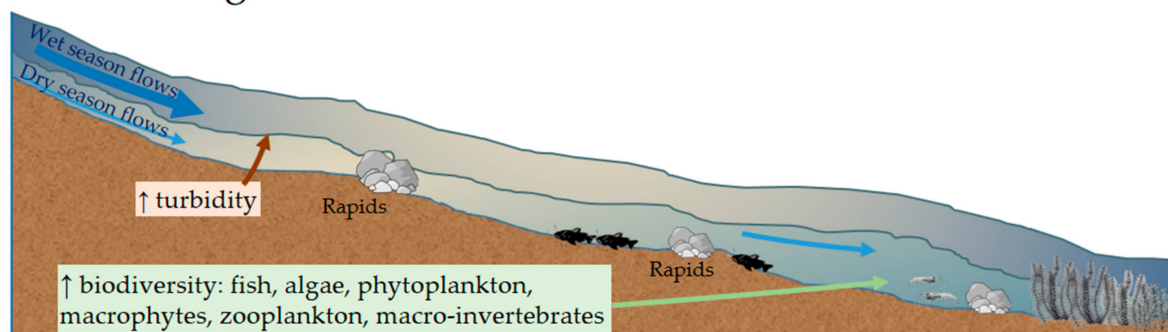
### 2.1. Study Area Background

The Mekong River is the world's second-most biodiverse river, after the Amazon River, with the largest freshwater fishery [3]. The Mekong River has 877 identified freshwater fish species. Migration status is known for only 24% of those species, and of those, 87% are migratory [18]. At least 329 fish species, nearly 40% of the species identified in the LMB, utilize the 3S Basin. This includes 89 migratory, 17 endemic, and 14 critically endangered fish species [19]. Many species depend on the extraordinary seasonal streamflow variability [20,21], with a well-defined wet season from May to October followed by a dry season from November through April (Figure S1).

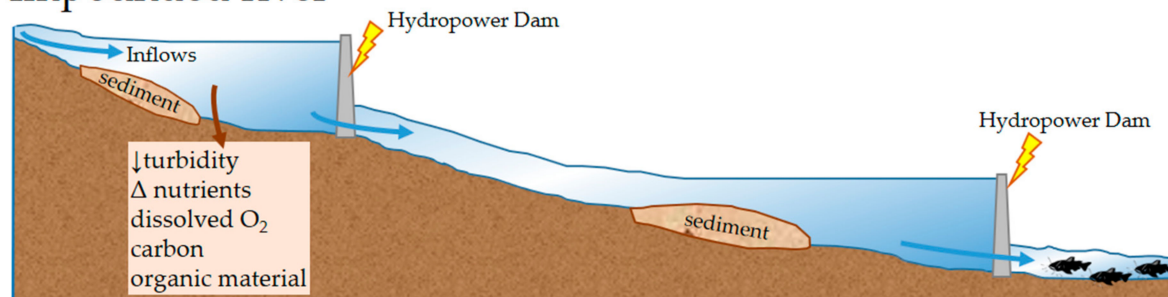
Dams have caused Lower Mekong streamflow to become more uniform throughout the year, as reservoirs are filled during the wet season and water is released through the dry season (Figure 2). A pronounced shift in Lower Mekong streamflow began by 2010, with more streamflow during the dry season and lower flows during the wet season than had been observed in the previous century [22]. Thus, the seasonal streamflow variability that a multitude of species rely on has been muted. The Mekong River historically transported approximately 160 million tons of suspended sediment per year. Dams trap sediment and sediment load is anticipated to decrease by 60–91% if hydropower is fully developed throughout the Mekong Basin [23,24]. As dams are built, habitat becomes fragmented longitudinally and latitudinally, blocking organism movement which is particularly problematic for megafishes and dozens of other species that migrate long distances to complete their life history [13,25] (Figure 2). Barbarossa et al. [26] estimated that longitudinal connectivity

will be reduced by approximately 20% if all large dams are built that are currently under construction or planned.

### Free-flowing river



### Impounded river



**Figure 2.** Conceptual model showing top: a free-flowing 3S river with a seasonal flood-pulse, high turbidity, high biodiversity, high productivity, and habitat that is connected longitudinally and laterally to floodplains and wetlands. Bottom: an impounded river with a cascade of hydropower dams that remove the seasonal flood-pulse, trap sediment, fragment and reduce habitat, block organism movement, and diminish biodiversity and productivity.

Migratory fishes generally move upstream to spawn in 3S rivers with the wet season flood-pulse and migrate downstream to rear in Tonle Sap Lake or the Mekong Delta during the dry season [19,27] (Figure 1). Although dams have been proposed for the Sekong River, it currently remains undammed for much of its length (Figure S2). Cambodia announced a moratorium on building mainstem Mekong River Dams in 2020, putting construction of Stung Treng and Sambor Dams on indefinite hold [28]. Thus a fish passage corridor still exists between Tonle Sap Lake, the Mekong River, and the Sekong River. Lower Sesan 2, a 400 MW hydropower dam completed in 2018, blocks passage between the confluence of the Sesan and Srepok Rivers and the Mekong River.

#### 2.2. Literature Search

We searched Google Scholar, Proquest, and Scopus databases for English-language primary or secondary literature with the keyword search shown in Table 1.

**Table 1.** Literature search teams and criteria.

Mekong	AND	tradeoff OR trade-off	AND	dam OR hydropower	AND	Sesan OR Se San OR Sê San OR Srepok OR Sre Pok OR Serepôk OR Sekong OR Se Kong OR Sê Kông OR 3S
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We used different river names to find literature using the English, Lao, Vietnamese, and Cambodian spellings. All databases precede 1990, when the first dam was built in the 3S Basin, and continue to the present. Our search was completed in March 2020. We re-



viewed abstracts and included publications that focused on economic and aquatic/riparian environmental tradeoffs of current, existing, or proposed dams in the 3S basin or Tonle Sap-Mekong River-3S Basin habitat corridor. We used a snowball method to include publications that focused on human-environmental tradeoffs in the LMB, but were not returned in our search results, typically because they did not include derivations of Sesan, Srepok, Sekong, or 3S in their title or keywords (e.g., [7,11,22]).

To remain within the scope of our study, we excluded publications on governance, transboundary conflicts, negotiation strategies, international cooperation, and water law. We removed review papers so that results were not double counted. We also removed papers that described, but did not quantify tradeoffs. When multiple versions of the same research existed as conference papers or book chapters, we included only the most recent version. Finally, we excluded papers that focused on effects of Chinese dams on downstream habitats as this was outside the scope of our study.

We classified papers by study system (e.g., 3S, Sesan Basin, LMB, Mekong River), the specific dams or hydropower futures studied, human objectives of dams (e.g., regulated streamflow, hydropower generation, spatial configuration of dams, water storage capacity, water supply, and economic cost), and environmental objectives of dams (e.g., hydrologic change, sediment load, fish production, fish diversity, aquatic/riparian habitat area, wetland area, longitudinal connectivity, primary production, non-fish biota, greenhouse gas emissions, and nutrients). Some researchers quantified environmental impacts when more dams were built, using metrics like number of dams. We included those papers in our analysis because installed generating capacity or similar human objectives of dams are widely available for the 3S Basin and LMB [2,12,29].

### 2.3. Data Analysis

#### 2.3.1. Dam Building and Publication Patterns

We contextualized cumulative publication count with installed generating capacity ( $10^3$  MW) and gross storage ( $10^9$  m<sup>3</sup>) of dams constructed since 1990. We summarized mean discharge (m<sup>3</sup> s<sup>-1</sup>), full water level (m), gross storage ( $10^9$  m<sup>3</sup>), inundated area (km<sup>2</sup>), installed generating capacity ( $10^3$  MW), and energy production (GWh year<sup>-1</sup>) in Table S1 using data from [12,17,30,31].

#### 2.3.2. Human and Environmental Objectives in Tradeoff Analyses

We categorized human and environmental objectives in all studies, then mapped the frequency that specific human-environmental tradeoffs of hydropower dams were studied using the networkD3 package in R [32]. Some papers evaluated multiple human and environmental objectives, in which case each unique tradeoff was visualized as a separate link (Table S2). Human metrics could be easily interchanged because many studies provided dam information including hydropower generating capacity, reservoir capacity, and estimated or actual construction costs for dams [2,12,29,33]. We categorized papers and reports that used connectivity indices and freshwater health indices into the spatial configuration of dams category (e.g., [34–36]). Regulated streamflow was a human metric that researchers used to quantify environmental impacts like fish diversity (e.g., [10,37]), aquatic/riparian habitat area (e.g., [38,39]), or sediment load (e.g., [23,24]).

The hydrologic change environmental objective included all hydrologic and hydrodynamic impacts of dams (e.g., [38,40]). Sediment load research quantified changes in sediment transport and trapping from reservoirs (e.g., [2,24]). Fish production included surrogate variables like abundance, growth, biomass, and population (e.g., [3,41]). The fish diversity category included research where dam effects on specific fish species, guilds, assemblages, or families were quantified [10]. Aquatic/riparian habitat and wetland habitat studies measured areal change in aquatic and riparian habitats from dam development (e.g., [20,42]). Research on longitudinal connectivity examined fragmentation of river network connectivity (e.g., [26,34]). Primary production studies included analyzing sources of primary production during dry and wet seasons or quantifying gross primary production

with dam development (e.g., [37]). The non-fish biota category included research on aquatic species aside from fish and included earthworms, shellfish, and turtles [43]. Greenhouse gas emissions studies analyzed emission fluxes from reservoirs [44]. Lastly, the nutrients category included research on nutrient loadings or transformations from dams [11].

### 2.3.3. Tradeoff Meta-Analysis

We visualized multi-objective human-environmental tradeoffs of each existing, planned, and proposed dam in the 3S Basin using the *plotly* package in R [45]. This analysis used installed hydropower capacity, storage capacity, inundated reservoir area, and construction cost from Schmitt et al. [2], average change in migratory biomass from Ziv et al. [3], average trapped sediment load from Wild and Loucks [12], highest CO<sub>2</sub> emissions per energy unit from Rasanen [44], and active storage to mean annual flow volume ratio from Piman et al. 2016 [17]. Our approach compared and visualized multiple human and environmental tradeoffs for individual 3S dams, but did not consider marginal impacts as other dams were built. We did not include Stung Treng or Sambor Dams in our tradeoff analysis.

### 2.3.4. 3S Habitat Fragmentation

We summarized habitat connectivity in the 3S Basin using network components of rivers. Specifically, we used the Global River Classification (GloRiC) version 1.0 [46] in ArcGIS to calculate the number of disconnected stream components, average stream length per component, and maximum stream length of the largest component.

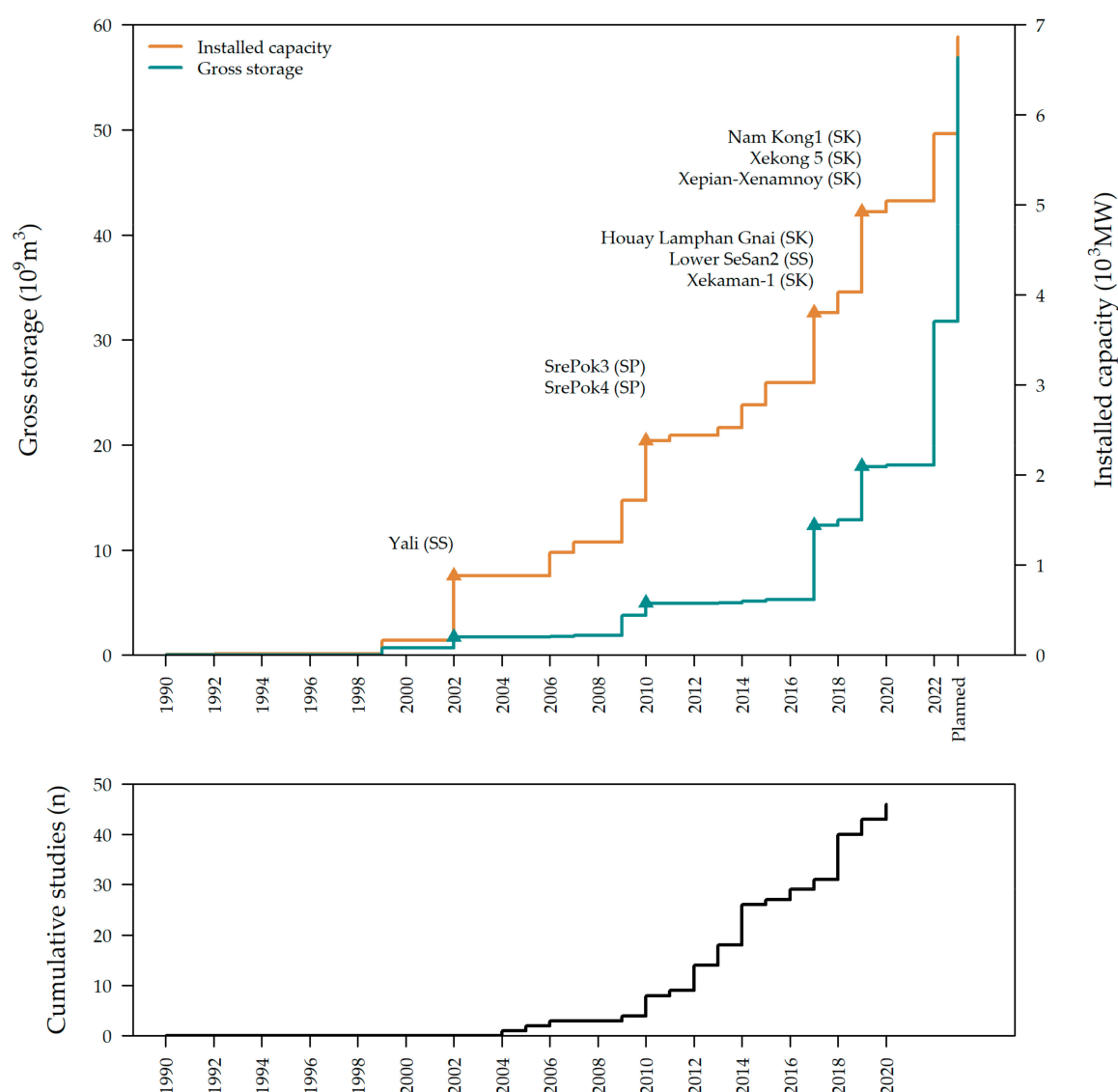
## 3. Results

### 3.1. Dam Building and Publication Patterns

Forty-six papers and reports met our literature search criteria. Thirteen papers focused on the Mekong Basin, 19 focused on LMB, and 14 focused on all or portions of the 3S Basin (Table S2). Dam planning and construction in the 3S Basin have clearly preceded published research (Figure 3). The first dam was completed in 1990 and the first scientific research on the environmental losses of hydropower dam construction was published in 2004. As a result, the apparent duration of dam construction in the 3S Basin (30 years) is currently almost twice that of the duration of environmental tradeoff research (16 years). However, when considering dam size, published environmental tradeoff research began only two years after the first large dam was completed. Environmental impact assessments were required for LMB dams, but were not returned in our literature review because they are often not publicly accessible. Thus, most research on the environmental effects of LMB dams have occurred after the fact and outside of the planning, permitting, and design process.

The first hydropower dam completed in the 3S Basin was Dray Hlinh 1, which is among the smallest dams built in the region, with an installed capacity of 12 MW and gross storage of 2.9 million cubic meters (Mm<sup>3</sup>) (Table S1). Yali, the first large dam, was completed more than a decade later in 2002, with installed capacity of 720 MW and gross storage of 1037 Mm<sup>3</sup> (Table S1). Cumulative hydropower capacity in the region increased markedly in years 2010, 2014, and 2018, as several large dams began operation (Figure 3). Published scientific research was slow to develop. From 2004 through 2011, only eight studies were published—with an average annual publication rate of one. The bulk of studies from our meta-analysis were published after 2011 (80.4%) with an average annual publication rate of 4.1 from 2012 through March 2020.

Not shown in Figure 3 are two proposed Mekong mainstem dams between Tonle Sap Lake and the 3S Basin (Figure 1). Projected installed capacity of Stung Treng and Sambor Dams is 980 MW and 2600 MW, respectively, and projected gross storage is 151 Mm<sup>3</sup> and 1450 Mm<sup>3</sup>, respectively. In March 2020, Cambodia announced a moratorium on mainstem Mekong River dams until 2030, during which time Cambodia will consider alternative energy sources [28].



**Figure 3.** Gross storage and installed capacity of current and planned hydropower projects in the 3S Basin (**top**) with cumulative number of studies through time (**bottom**). SS is Sesan River, SP is Srepok River, and SK is Sekong River.

Each dam has been included in tradeoff analyses an average of 9 times, although Lower Sesan 2 has been evaluated nearly twice as often and Srepok 4A was studied just once (Figure 4). The proposed Sekong Dam, which could block remaining migratory passage to 3S tributaries has rarely been studied. Ten studies evaluated no specific dams, rather they assessed environmental losses using regulated flows. Alternative dam futures based on scenarios developed by Mekong River Commission's second Basin Development Plan (BDP2) [33] and the International Center for Environmental Management (ICEM) [8] were used by many researchers. BDP2 included alternatives for the Definite Future (Lancang River and 26 tributary dams through 2015), Foreseeable Future (30 planned tributary dams and 11 mainstem dams through 2040), and Long-term Future (water resources development through 2050) [33]. ICEM alternatives include no mainstem dams, 11 mainstem dams, and 77 tributary dams within the Mekong Basin [8]. Twelve studies used iterations of those dam futures, although names or alternatives were slightly different so that it was not immediately transparent which specific dams were included in their tradeoff analyses. We classified those studies as having unavailable data about dams that were studied.

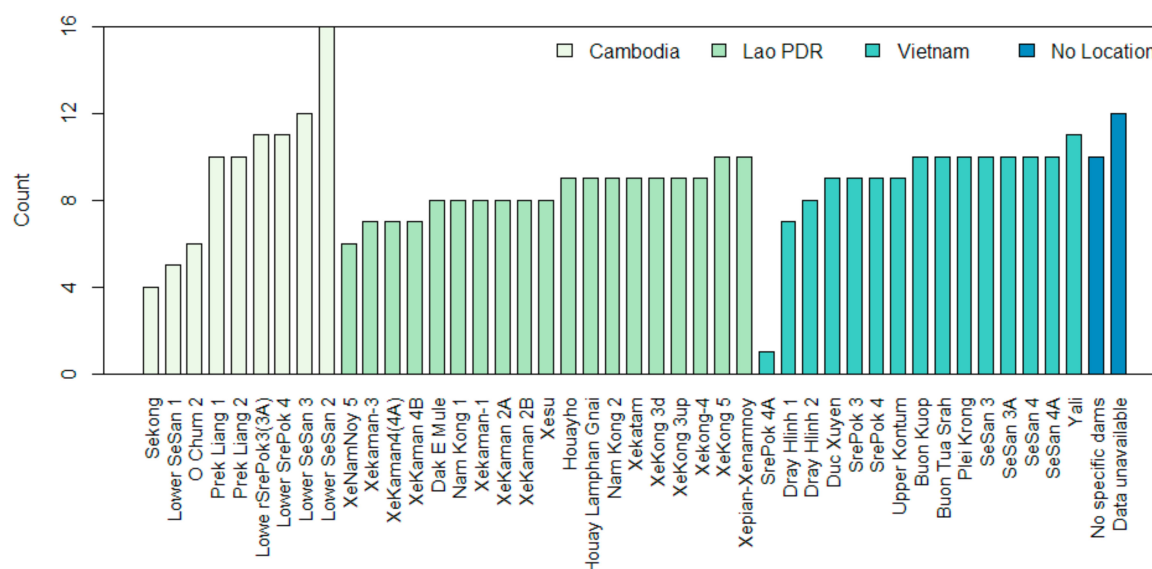


Figure 4. Number of times that 3S dams have been studied.

### 3.2. Human and Environmental Objectives in Tradeoff Analyses

Researchers disproportionately studied hydrologic and sediment environmental objectives (Figure 5, Table S2). Across all 46 studies, 24 (52%) quantified hydrologic change, 15 (33%) quantified impacts of dams on sediment load, 14 (30%) quantified fish production, and 12 (26%) studied aquatic or riparian habitat area. Of the 14 papers that focused exclusively on the 3S Basin, 9 studies (64%) quantified hydrologic change from dam development, while 5 studies (36%) quantified dam impacts on sediment load. Fish production was commonly quantified in the Mekong Basin (14 studies, 30%), but was uncommon in the 3S Basin (1 study, 7%). Non-fish aquatic species were also quantified in only one study (7%) of the 3S Basin. Dam impacts on wetland area (6 studies, 13%), nutrient loading (4 studies, 9%), primary production (3 studies, 7%), and greenhouse gas emissions (1 study, 2%) were rarely studied in the LMB and were not evaluated for the 3S Basin.

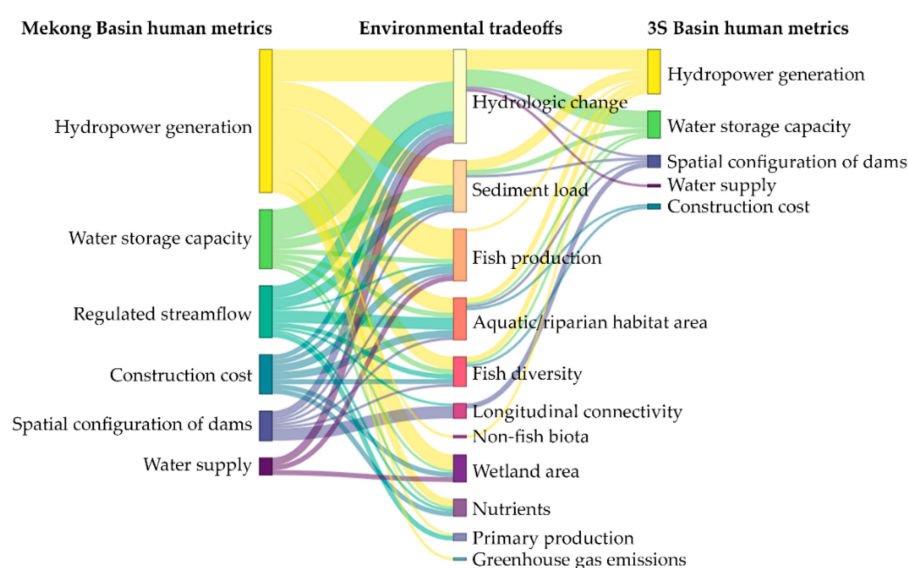


Figure 5. Human objectives of dams mapped to environmental losses that have been studied in the Mekong and 3S Basins. The width of the links is proportional to the frequency that tradeoffs have been studied.



Physical processes are more straightforward to represent mathematically in models and were more commonly evaluated for the LMB and 3S Basin. Studies that included at least one physical process objective, including hydrologic change, sediment load, habitat and wetland area, and longitudinal connectivity accounted for 89% of all studies and 100% of 3S Basin studies. Ecological objectives are more difficult to incorporate into tradeoff analyses because relationships are often non-linear, poorly understood, or lack data to validate model fit [47]. Yet, 46% of all studies and 14% in the 3S Basin included at least one ecological objective of fish production, fish diversity, non-fish biota, nutrient loading, primary production, or greenhouse gas emissions. This suggests that incorporating ecological relationships in hydropower dam decision-making is possible.

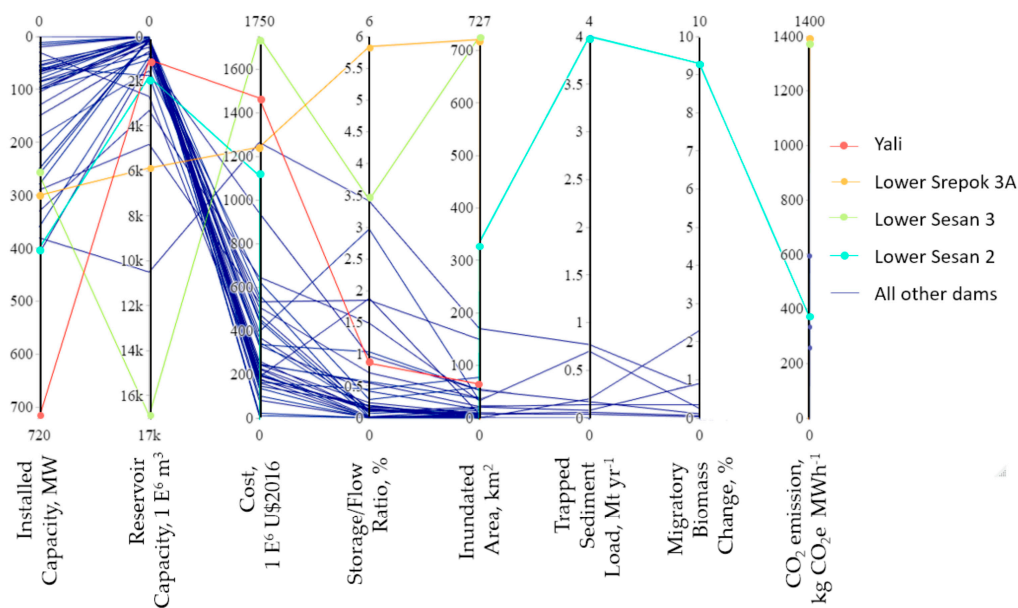
Most studies quantified human metrics of dams using hydropower generation and water storage capacity (Figure 5). Outside of the 3S Basin, regulated streamflow was another common metric as a proxy for hydropower dam operation and was used in 12 studies (26%). Across all studies, 25 (54%) used hydropower generation as a human objective, while 14 studies (30%) used reservoir storage capacity. In the 3S Basin, 12 studies (86%) used hydropower generation as an objective and 8 (57%) used reservoir storage capacity. Spatial configuration of dams, construction cost, and water supply were more rarely used to quantify human objectives of dams.

### 3.3. Decision Variables in Tradeoff Analyses

Decision variables are flexible and controllable parameters in models. Finding their value is the goal of modeling. In optimization modeling, decision variables determine the value of the objective function and in simulation modeling, decision variables are changed among model runs. Six papers analyzed all possible combinations of dams using multi-objective evolutionary algorithms or similar multi-objective approaches [2,3,7,17,34,44]. Of the papers that we reviewed, the most common decision variable was alternative future dam scenarios (Table S2). Future dam alternatives provided by BDP2 and ICEM proved invaluable for researchers to represent environmental impacts from streamflow changes due to hydropower dam construction. These alternatives were used in 18 studies that we reviewed (e.g., [11,12,35,42,48,49]). However, specific futures varied among studies, producing results that were not directly comparable. Furthermore, alternatives were often named similarly to BDP2 and ICEM alternatives, but names of specific dams were not listed, reducing the transparency of research (Figure 4). Alternative dam operations, design, and siting were decision variables that are increasingly used to quantify the environmental tradeoffs of hydropower dams in the 3S Basin and LMB [22,48,50–55]. These papers often had a small spatial extent, for example focusing on single dams or reaches, and complemented studies that evaluated alternative dam construction futures.

### 3.4. Tradeoff Meta-Analysis

Multi-objective tradeoffs were compared among 3S dams (Figure 6) using eight human and environmental performance criteria. Each axis represents a unique objective with performance increasing toward the bottom of the figure and each line shows a 3S dam. Performance was unavailable for some objectives, in which case performance was shown as points on axes for those objectives where data were available. Lines and points indicate where performance in one objective cannot be improved without degrading performance in other objectives. Lines with steep slopes between axes indicate conflict between objectives. The named red, orange, yellow, and green lines and points indicate dams with pronounced tradeoffs between human and environmental objectives.



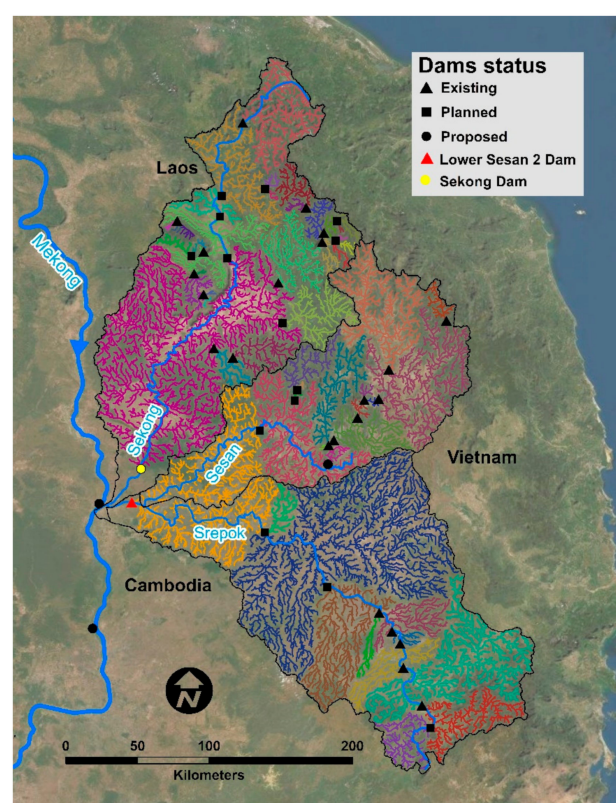
**Figure 6.** Parallel axis plot of tradeoffs among competing human and environmental objectives. Each axis represents a different objective with better performance at the bottom. Each line shows tradeoffs for different existing or planned dams. Environmental objectives are unavailable for some dams. Data for human objectives of installed capacity, storage capacity, and cost were from [2]. Environmental objectives and data sources include inundated area [2], Storage-flow ratio [17], average trapped sediment load [12], CO<sub>2</sub>e emissions per energy unit [44], and average change in migratory biomass [3].

In general, conflicts exist between installed hydropower capacity and environmental objectives of storage/flow ratio, inundated area, trapped sediment load, migratory fish biomass change, and CO<sub>2</sub>e emissions (Figure 6). Smaller dams with less capacity to generate hydropower had less severe tradeoffs with environmental objectives, although this analysis did not represent marginal impacts as dams are built sequentially (Figure 6).

Yali Dam was the first large dam built in the 3S Basin with installed capacity of 720 MW (Table S1). It was completed in 2002 and has more generating capacity than all other existing, planned, and proposed dams with less environmental harmful changes to storage/flow ratio and inundated area. Lower Sesan 2, which was completed in 2018, trapped more sediment than other 3S dams and was most harmful to migratory fish biomass. Planned Lower Sesan 3 dam would inundate the most area, which is a proxy for longitudinal and latitudinal habitat loss and fragmentation. Planned Lower Srepok 3A Dam would have the largest storage/flow ratio, a metric of flow alteration. Lower Sesan 3 and Lower Srepok 3A are also anticipated to produce the highest CO<sub>2</sub>e emissions per energy unit. Notably, proposed Lower Srepok 3A and Lower Sesan 3 Dams have less generating capacity, but considerably larger reservoirs, than existing Yali and Lower Sesan 2 Dams. Large reservoirs correspond with inundated area, storage/flow ratio, and CO<sub>2</sub>e emissions environmental tradeoffs.

### 3.5. 3S Habitat Fragmentation

Prior to dam construction, 10,331 km of streams were accessible to migratory fishes in the Sekong Basin (Figure 7). If Sekong Dam is built, it would disconnect the 3S Basin from the mainstem Mekong River and Tonle Sap Lake, blocking 4784 km of habitat to the next existing and planned dams upstream (pink stream segments in Figure 7). This segment is the largest section of connected habitat and represents 46% of pre-dam stream length. Nineteen dams have been built or are planned upstream of the proposed Sekong Dam, resulting in 32 disconnected stream segments, with an average stream length of 323 km (3% of the pre-dam length).



**Figure 7.** Fragmented stream segments, shown with different colors, in the 3S Basin from existing, planned, and proposed dams.

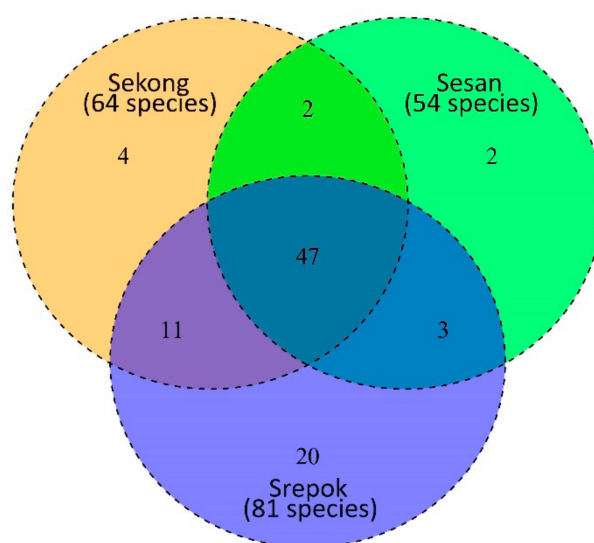
A total length of 18,701 km of streams exist upstream of Lower Sesan 2 Dam (Figure 7). Construction of Lower Sesan 2 disconnected the Sesan and Srepok Rivers with the Mekong River and blocked 2535 km of stream segments to the next upstream dams (orange segments in Figure 7). There are 20 existing and planned dams upstream of Lower Sesan 2, which separate these basins into 25 disconnected segments, with an average of stream length of 748 km, and a maximum length of 5035 km. Thus, the average connected stream length is 4% of the original pre-dam length, and the longest intact stream length that is 27% of the original pre-dam length.

#### 4. Discussion

We analyzed English-language published and gray literature that quantified human and environmental tradeoffs of hydropower dam development in the 3S Basin and Tonle Sap-Mekong-Sekong corridor. Dam planning and construction has been ongoing since 1990, and preceded research in this region. Environmental impact assessments were required for all dams in the LMB, but these reports were not returned in our search and are typically not publicly available. In general, the environmental impact assessments required for LMB dam planning were often incomplete, did not account for cumulative impacts of dams, nor did they consider alternative locations, operations, or technologies [56]. Generally, there was more emphasis on energy development than on environmental impacts. However, studies that evaluate environmental losses from hydropower dams have recently increased, with an average of 4.1 papers per year since 2012. Hydrologic change, sediment load, fish production, and aquatic/riparian habitat area were the most common environmental objectives studied. Fewer researchers analyzed dam development effects on fish diversity, longitudinal connectivity, non-fish aquatic species, wetland habitat area, nutrient loading, primary production, or greenhouse gas emissions, although those environmental losses were quantified in at least one paper or report. Better representing ecological impacts of

hydropower dams is needed to fully understand their environmental tradeoffs and this is an area that merits research and innovation.

Our meta-analysis highlighted dams with conflicts between human and environmental objectives. Lower Sesan 2 had considerable tradeoffs with migratory fish biomass [3] and trapped sediment [12]. Planned Lower Sesan 3 would have substantial CO<sub>2</sub>e emissions [44] and inundate the most area [2]. Planned Lower Srepok 3A would have the highest CO<sub>2</sub>e emissions [44] and a large storage/flow ratio [17]. Since Lower Sesan 2 has blocked fish passage for at least 85 migratory fish species to the Sesan and Srepok Rivers [57], maintaining connectivity and passage between Tonle Sap, the Mekong River, and the lower Sekong River takes on greater importance. The proposed Sekong Dam should be avoided because it would block longitudinal connectivity [36] and migratory fish passage for at least 64 species between spawning and rearing habitats [13,57] (Figure 8). Cambodia's ten-year moratorium (2020–2030) on building mainstem Mekong River dams highlights the value of fish passage and the uncertainty of dam building when other energy sources may be economically competitive or less environmentally damaging. Foregoing the proposed Sekong, Sambor, and Stung Treng dams would maintain one free-flowing tributary for much of its length, while providing hydropower from dam cascades in other tributaries. Giving up Sekong Dam supports research showing that building dams in the downstream reaches of tributaries should be avoided [47], and that managing rivers for either human or environmental benefits can provide greater economic and environmental benefits than managing for both human and environmental benefits simultaneously on multiple rivers [6,58].



**Figure 8.** Overlap among the 89 migratory fish species that use 3S rivers. The number of species in brackets indicates the total number of migratory fish species that utilize each watershed. Data from [57].

A handful of papers made a compelling case for decision-making that better recognized environmental impacts in LMB because they creatively incorporated ecological objectives of rivers [3,11,22] or because they provided strategic sequencing of dam development [7]. Ziv et al. [3] coupled a simple model of fish population and biodiversity to evaluate change in migratory fish biomass with added hydropower generation across multiple dams. Their approach provided an elegant example of incorporating ecological objectives into decision-making. Intralawan et al. [11] completed an economic tradeoff analysis between hydropower generation and ecosystem services in LMB and determined the total net economic impact of mainstem and tributary dams is negative USD 7.3 billion when costs to reservoir fisheries, aquaculture, capture fisheries, wetlands, cultural services, sediment, and nutrients are included. This contrasted MRC's BDP2 Basin Development



Plan which estimated a positive economic impact of USD 33.4 billion by omitting most environmental objectives [33]. Wild et al. [22] evaluated alternative siting, design, and operations for Cambodia's proposed Sambor Dam to maximize energy and larval fish passage. The authors recommended addressing ecological concerns prior to and on equal footing as energy benefits. A short while later, Cambodia announced a moratorium on building Sambor and Stung Treng mainstem dams [28]. Finally, Schmitt et al. [7] optimized the sequence of dam construction to minimize sediment trapping from hydropower dams in the LMB. The authors showed that the same hydropower benefits could have been generated while trapping approximately half the sediment than is currently trapped behind dams and prioritized future dam construction to maximize hydropower generation and minimize sediment trapping.

#### 4.1. Redundancy of Hydrologic Modeling and Future Recommendations

The redundancy of hydrologic and hydraulic modeling in the LMB was notable. Three modeling review papers have been written [59–61], with Jensen [60] describing the Mekong Basin as “flooded with models”. Yet, modeled streamflow data were rarely publicly available or provided with supplemental information of publications. Streamflow models and data developed in 2012 are available from Mekong Flows (<http://www.mekongflows.com>) for 1986–2006 baseline conditions, and multiple dam futures, operations, and climate change alternatives [17,20,38–40,48,62,63]. Although more than half of the studies that we evaluated quantified hydrologic changes from dam development, we were unable to locate other shared models or simulated streamflow for alternative hydropower dam futures. Hydroshare's Mekong data and model sharing platform (<https://www.mekongwater.org/>) and the Mekong River Commission's data portal (<https://portal.mrcmekong.org/home>) returned no publicly discoverable modeled hydrology data for alternative dam futures. Sharing models and data improves the reproducibility of research [64] and reduces research redundancy, which is imperative in the Mekong Basin, where non-streamflow relationships with dam development are beginning to be quantified. Evaluating ecosystem response to dam development is recommended for ecological sustainability of multi-objective hydropower operation [65].

The Mekong River Commission has developed basin-wide dam development scenarios for baseline, definite future dam development, year 2030 foreseeable future dam development, and year 2060 long-term future dam development [33]. These scenarios are routinely incorporated into current research (e.g., [11,12,35,42,48,49]), highlighting the importance of defined dam future alternatives for research and decision-making. An opportunity exists for the Mekong River Commission to provide modeled hydrologic and hydraulic data to support decision-making, reduce model and research redundancy, and harmonize model assumptions. A blueprint for success exists from the Intergovernmental Panel on Climate Change, which has developed compatible datasets to understand anticipated climate impacts and promising adaptations [66]. The Mekong River Commission and other research funders could also require that data and models are shared publicly, as is required by a growing number of publishers [67] to ensure that data and results are available and transparent for decision-makers.

#### 4.2. History and Future of Tradeoff Analyses in Dam Planning and Operations

Environmental impacts were not quantified in dam-building eras in the United States or Europe [68,69], although environmental movements followed dam-building when costs of degraded systems were better quantified. Environmental regulations have since often steered water management [70–72]. Given current understanding of aquatic systems and the value they provide, water projects in the United States and Europe would be sited, designed, and operated differently if they were built today [73]. In fact, more dams are now removed in North America and Europe than are built [69].

Overestimating hydropower benefits while ignoring environmental degradation from dam development is costly. This is already clear in the 3S Basin and LMB. Evidence has emerged that hydropower benefits have been overestimated [74,75]. In Lao PDR,

hydropower production costs 20% more than anticipated during dry periods when thermal power is required to meet energy demand. During wet years, limited transmission line capacity results in unused hydropower [76]. As mentioned above, including costs of lost capture fisheries, sediment transport, and nutrients in the cost-benefit analysis for LMB dams resulted in a projected total economic impact that was negative USD 7.3 billion [11], whereas BDP2 estimated a positive economic impact of USD 33.4 billion without fully quantifying the environmental costs [33].

Environmental degradation in the LMB is already occurring from hydropower dam operations which increase dry season streamflow and reduce the flood-pulse [22]. Further repercussions are anticipated. For example, hydrologic alteration threatens flooded forest habitats surrounding Tonle Sap Lake, including RAMSAR wetlands and a UNESCO biosphere reserve [10,77]. The productivity of the world's largest inland fishery at Tonle Sap Lake is in decline [78,79], jeopardizing food security for 65 million people [4]. Water quality has been impaired in the Mekong River downstream of the 3S Basin, including Tonle Sap Lake and the Mekong Delta [80,81], and sediment trapping in reservoirs has endangered agricultural production and increased the frequency of seawater intrusion in Vietnam's Mekong Delta (MRC 2005). The extinction of rare and endangered species like the Mekong giant catfish and the Irrawaddy dolphin are probable if environmental and ecological tradeoffs of hydropower development are ignored [82,83].

At a broader scale, dam building also affects terrestrial systems and society. For example, dam building contributes to deforestation as forests are cleared around reservoirs, roads and other infrastructure are built, settlements form, and forest is converted to agriculture [84]. These changes are coupled with climate warming, which is anticipated to increase drought frequency of intensity in the 3S Basin and LMB [85]. Dam building and extreme streamflow variability pose natural hazard risk to society by reducing agriculture, employment opportunities, gross domestic product, and food security in the LMB [86,87].

Quantifying environmental impacts is an opportunity for dam planning that has the potential to preserve aquatic species, habitats, ecosystems, ecosystem services, human livelihoods, and food security while providing hydropower. Hydropower dams are one of many substantial changes anticipated in the 3S Basin and LMB. Other threats include ongoing deforestation, urbanization, and climate change [84,88]. Ignoring the environmental costs of hydropower development in the 3S Basin and LMB is likely to be costly. This paper and the existing body of research provides broad support to more fully consider the environmental losses and costs of hydropower dams in the 3S Basin to guide sustainable hydropower decision-making. Quantifying environmental losses from hydropower development, especially ecological losses, is of utmost importance to maintain valuable ecosystems and migratory corridors, and avoid overestimating the net benefit of hydropower development.

**Supplementary Materials:** The following are available online at <https://www.mdpi.com/2073-441/13/1/63/s1>, Figure S1: Maximum, average, and minimum streamflow at Chatangoy (Sekong River) and Ban Kamphun (Sesan and Srepok Rivers) gaging stations from 1960 to 2002, Figure S2: Longitudinal profile of existing, planned, and proposed dams on mainstem Sekong, Sesan, and Srepok Rivers, Table S1: Dams in the 3S Basin and their attributes, Table S2: Papers included in review, study system, human and environmental objectives, and decision variables.

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