

Article

The Impacts of Dams on Streamflow in Tributaries to the Lower Mekong Basin

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Abstract: The Lower Mekong Basin has had extensive hydropower dam development, which changes its hydrologic conditions and threatens the exceptional aquatic biodiversity. This study quantifies the degree of hydrologic change between pre-impact (1965–1968) and post-impact (2018–2021) peak hydropower development in two major tributaries of the Lower Mekong Basin—the Sekong River, with the fewest dams, and the Sesan River, with the most dams. Both rivers have historically supported migratory fishes. We used daily pre- and post-impact data and the Indicators of Hydrologic Alteration framework to evaluate streamflow changes from dam development. We found significant changes in low- and high-magnitude flows in the pre- and post-impact periods of dam development. For the Sekong River, minimum flow had large fluctuations, with increases of 290% to 412% compared to the pre-impact period, while the Sesan River’s minimum flow ranged from 120% to 160% more than pre-impact. Dry season flows increased by $200 \pm 63\%$ on average in the Sekong River, which was caused by releases from upstream dams. Meanwhile, the Sesan River’s dry season flows increased by $100 \pm 55\%$ on average. This study indicates that seasonal flow changes and extreme flow events occurred more frequently in the two basins following dam construction, which may threaten the ecosystem’s function.

Keywords: flow regime; hydrologic alteration; dam impact; extreme flow events; seasonal streamflow; 3S basin



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1. Introduction

Hydropower dams are being developed extensively in developing rivers, such as the Congo, Yangtze, Yellow, Amazon, and Mekong rivers, which introduces complex tradeoffs for river ecosystems and local people, communities, and economies [1]. For instance, dams provide economic and social benefits, such as flood and drought risk reduction [2,3], irrigation water [4], and electricity [5]. In addition to single-purpose dams, there are also multipurpose dams that serve as flood control, provide irrigation, and generate electricity [6]. On the other hand, they may alter hydrology [7], contribute to wetland destruction [8,9], degrade water quality [10], alter sediment transport [11,12], fragment rivers [13], reduce biological and ecological productivity [14], and contribute to prolonged and severe drought [15] and biodiversity loss [16]. Flow alteration is a fundamental change to river systems, because it is a master variable that affects physical, chemical, and biological processes [17]. Typically, dams decrease flows in the wet season

and increase them in the dry season [8,18]; therefore, flow magnitude, timing, frequency, duration, and rate of change can be also affected [19,20], which consequently leads to longer wet or dry seasons [21,22].

The Mekong River supports tremendous aquatic biodiversity, including ~1200 fish species [23], and is home to aquatic invertebrates such as rotifers [24], aquatic insects [25,26], annelids, crustaceans, and molluscs [27,28]. Fish from the Lower Mekong Basin (LMB) are a primary food source for local people [29,30], and fisheries provided an estimated ~US\$11 billion to the economy in 2015 [31]. Despite being ecologically, economically, and socially important, the Mekong River is a hydropower dam development hotspot. Since the mid-1990s, 11 mega dams have been constructed on the Upper Mekong River mainstem in China [32]. In the LMB, at least 129 dams have been commissioned, including 5 mainstem dams in Laos. Hydropower dams in the LMB have the capacity to provide >30,000 megawatts (MW) of power generation, with an estimated revenue of US\$160 billion from all projects by 2040 [33]. One of the primary areas for hydropower dams in the LMB is the area containing the Sekong, Sesan, and Srepok rivers (the 3S Basin), which are major tributaries to the LMB (Figure 1). As of 2021, at least 51 dams are operating in the 3S Basin, with a combined generating capacity of 4684 MW. The Sesan River has the most dams of the three rivers, with 22 dams, and the Sekong has the fewest, with 14 dams [34].

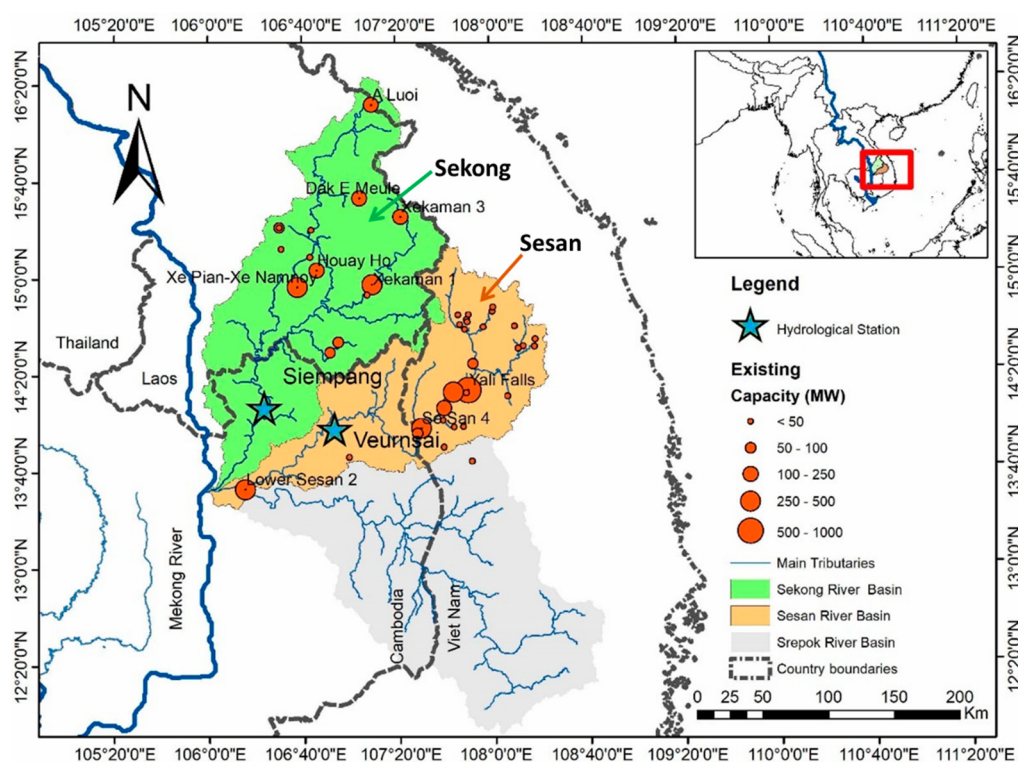


Figure 1. The Sekong and Sesan rivers, with dams and monitoring stations.

The impact of hydropower dam development is evidenced from one basin to another across the globe [35–38]. For instance, dam development in the Paraiba do Sul River Basin located in the southeast region of Brazil has disrupted sediment transport, causing significant coastal erosion and impacting socio-environmental resilience [37]. In southern Ethiopia, Africa, the Gibe III dam on the Omo River has had a significant negative impact on indigenous communities, including economic collapse, hunger, disease, environmental destruction, and interethnic conflict [38]. For the 3S Basin, past and ongoing hydropower dam development has led to deviated streamflow from natural regimes [35,36]. Piman, Cochrane, Arias, Green, and Dat [35] examined the effects of hydrologic change caused by hydropower dams in the whole 3S Basin, using the water assessment tool (SWAT) and the HEC-ResSim models, and found that the construction of new dams along the

main rivers of the 3S Basin can alter seasonal flows, leading to increased dry season flow and decreased wet season flow as part of a strategy to maximize electricity production. Oeurng and Sok [36] evaluated changes in flow and water quality in the Sesan River using the Indicators of Hydrological Alteration (IHA) framework, and discovered that significant hydrologic changes occurred during both the low flow and high flow periods following the construction of the Yali Falls dam in Vietnam. In this regard, understanding the impact of dam operation on flow changes is crucial for addressing sustainable river development concerns, including power generation and downstream ecosystem alteration, and can provide insights for better reservoir planning/building. Therefore, it is important to quantify and compare flow alteration before and after dam construction and between the least and most dammed rivers in the 3S.

In this study, we quantify the degree of hydrologic alteration prior to and following dam construction in the Sekong and Sesan rivers. For each river, we first assess the degree of daily hydrologic alteration during the pre-impact (1965–1968) and post-impact (2018–2021) periods of dam construction, using the 5th and 95th percentiles of flows to indicate the highest and lowest pulses, respectively. We then compare the hydrologic alteration between the two periods for each river and between the two rivers to compute the extent to which the hydrologic alteration differs. Low flows, represented by exceedance of the 95th percentile flows, are important for understanding the minimum flow requirement for ecological health and managing water resources during dry seasons. Exceedance of the 5th flow percentile indicates high flows, which are significant for describing flood events.

2. Materials and Methods

2.1. Study Area

The Sekong and Sesan rivers (2S) are major tributaries of the LMB and are important for irrigation, transportation, hydropower generation, fisheries, and ecosystem services. These rivers flow through portions of Laos, Cambodia, and Vietnam (Figure 1). The total watershed area of the two rivers is about 47,615 km², of which the Sekong Basin encompasses about 28,815 km², while the Sesan Basin is about 18,800 km² [39]. The wet monsoon season from May to October provides more than 80% of the annual rainfall. The dry season lasts from November to April, with cooler temperatures observed from November to January. The average annual rainfall can exceed 2500 mm and precipitation varies throughout the watersheds. The Sekong, Sesan, and Srepok rivers collectively contribute a mean annual discharge of ~2890 m³/s, which is ~25% of all streamflow to the Mekong River [40].

2.2. River Flow Data

Daily streamflow was measured by the Mekong River Commission (MRC) at the Siempang gauge station in the Sekong River and the Veurnsai gauge station in the Sesan River. Flow data for each river was divided into two periods: the pre-impact period (PreIm: 1965–1968) and the post-impact period (PostIm: 2018–2021). The pre-impact period was selected because no dams had been built in either river basin and daily data was available. The post-development period followed recent mega hydropower dam construction, including the Sesan 4 and Lower Sesan 2 dams in the Sesan River and the XeKaman 1 Dam in the Sekong River (Figure 2). The descriptive statistics of streamflow for the pre- and post-impact periods in both rivers is provided in Table A1.

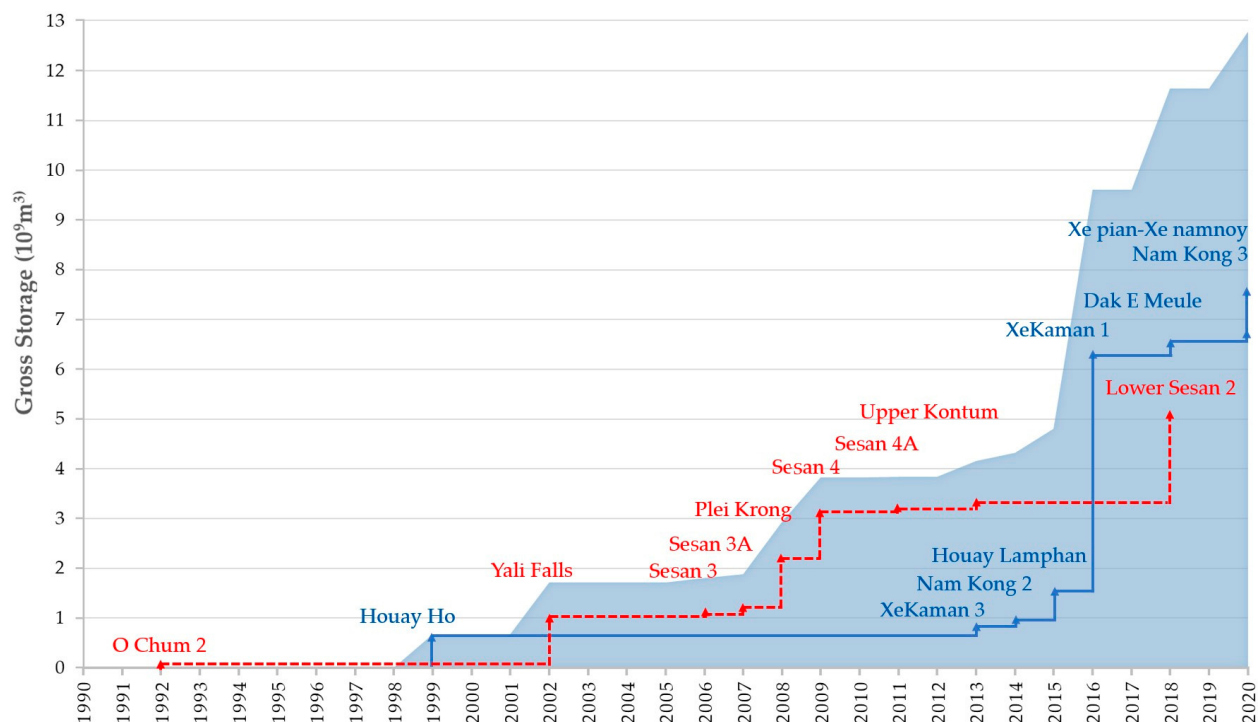


Figure 2. The cumulative reservoir storage for both river basins (gray shading), the Sekong River (blue line), and the Sesan River (red dashed line), with a timeline of dam construction.

2.3. Data Analysis

2.3.1. Indicators of Hydrologic Alteration and Extreme Flow Events

We used the IHA framework to quantify streamflow changes from hydropower dam development at study stream gauges. The IHA model is widely implemented and well-known for its effectiveness at quantifying flow changes [19,41–43]. For example, Van Binh et al. [41] utilized IHA to examine the long-term alteration of flow regime in the Mekong River. Piman [42] estimated how changes in land use, climate, and hydropower development affect the hydrologic alteration of the Srepok River using IHA. Zhou et al. [43] used IHA to analyze the cumulative effects of cascading reservoirs on the flow regime in the Jinsha River in China. Flow regime is central to sustaining ecosystem function, productivity, and the livelihoods of local people [12,44,45].

The IHA framework was created to assess streamflow alteration by detecting differences in the range of natural variability based on 33 parameters of hydrologic alteration [46,47]. The pre-impact period is our reference condition for natural flows. In this study, we used only 10 of the 33 parameters (Table 1) for the subsequent analysis identifying extreme flow events. We selected these 10 parameters as we focused on flow magnitude and duration in different periods, while the changes in extreme flow events were detected by flow duration curves and flow maxima and minima.

We used flow duration curves to assess changes in the low- and high-magnitude flows. The 5th (Q_5) and 95th (Q_{95}) exceedance probabilities of flow in each period were calculated, where Q_5 indicates high-magnitude flows and Q_{95} represents low-magnitude flows. Q_5 is a common metric for assessing how hydrologic alteration affects high flow conditions, such as evaluating the capacity of reservoirs to store large inflows [48]. To identify extreme flow events, we also used 1-, 3-, 7-, 30-, and 90-day minimum and maximum flows estimated by the IHA framework. These indicators are widely used [49].

Table 1. Summary of the hydrologic parameters of the IHA framework used in this study [46].

IHA Statistics Group	Regime Characteristics	Streamflow Parameter Used in This Study
Magnitude and duration of annual extreme water conditions	Magnitude, duration	Annual minima 1-day means Annual maxima 1-day means Annual minima 3-day means Annual maxima 3-day means Annual minima 7-day means Annual maxima 7-day means Annual minima 30-day means Annual maxima 30-day means Annual minima 90-day means Annual maxima 90-day means

2.3.2. Hydrologic Alteration between Periods and Rivers

To examine hydrologic changes between the two periods, the relative hydrologic change was computed as a percentage. The results from this analysis were then divided into three categories based on their relationship to the median: those less than or equal to the 33rd percentile, those between the 34th and 67th percentiles, and those exceeding the 67th percentile. These categories represent low, medium, and high degrees of hydrologic alteration, respectively [47]. The relative hydrologic change was as follows:

$$\text{Relative Hydrologic Change} = \frac{(\text{Post} - \text{Impact Flow}) - (\text{Pre} - \text{Impact Flow})}{\text{Pre} - \text{Impact Flow}} \times 100. \quad (1)$$

When the value of the relative hydrologic change is positive, it means that streamflow increased from the pre-impact to the post-impact period. Conversely, a negative value indicates a decrease in the streamflow of the studied rivers [50].

Moreover, flow data was also compared between the pre- and post-impact periods, between rivers, and between the wet and dry seasons (Figure A1) using the Kruskal–Wallis test. In total, six comparative analyses were completed (Table 2).

Table 2. Summary of comparative analyses made for this study.

Pre- vs. Post-Impact Comparison	Basin Comparison
(1) Dry season Sekong River Pre- vs. Post-Hydropower Impact	(5) Sekong vs. Sesan
(2) Dry season Sesan River Pre- vs. Post-Hydropower Impact	
(3) Wet season Sekong River Pre- vs. Post- Hydropower Impact	(6) Sekong vs. Sesan
(4) Wet season Sesan River Pre- vs. Post- Hydropower Impact	

3. Results

3.1. Changes in Flow Duration Curves and Flow Maxima and Minima

There was a larger increase in streamflow between the pre- and post-impact periods for Q_5 (the highest 5% of flows) than for Q_{95} (the lowest 5% of flows), and for the Sekong River than the Sesan River (Figure 3). The below table notes the magnitude of increased low and high flows between the pre- and post-impact periods for the Sekong and Sesan rivers.

Overall, the Sekong River—with the fewest dams—had larger flow increases before and after dam development than the Sesan River, which has fewer dams (Figure 4). The 1-, 3-, 7-, 30-, and 90-day minimum flows increased in the Sekong River by more than 250% following dam construction (Figure 4). Minimum flows in the post-impact period were 359–425 m³/s higher than in the pre-impact period. The 1-, 3-, 7-, and 30-day maximum flows were 50% higher than in the pre-dam impact period, while there was a negligible change in the 90-day maximum flow because it was only 1.3% higher in the post-impact

compared to the pre-impact period (Figure 4). For the Sesan River, minimum flows increased by 121–161% in the post-dam impact period. The 1-day maximum flow had a 56% increase, with smaller increases for the 3-, 7-, and 30-day maximum flows. The 90-day maximum flow in the Sesan River was the only minima/maxima metric that decreased following dam construction because a negative relative change of -10% was observed (Figure 4). Further details on both the pre- and post-impact flows and the minima/maxima metrics of the two rivers are provided in Figure A2.

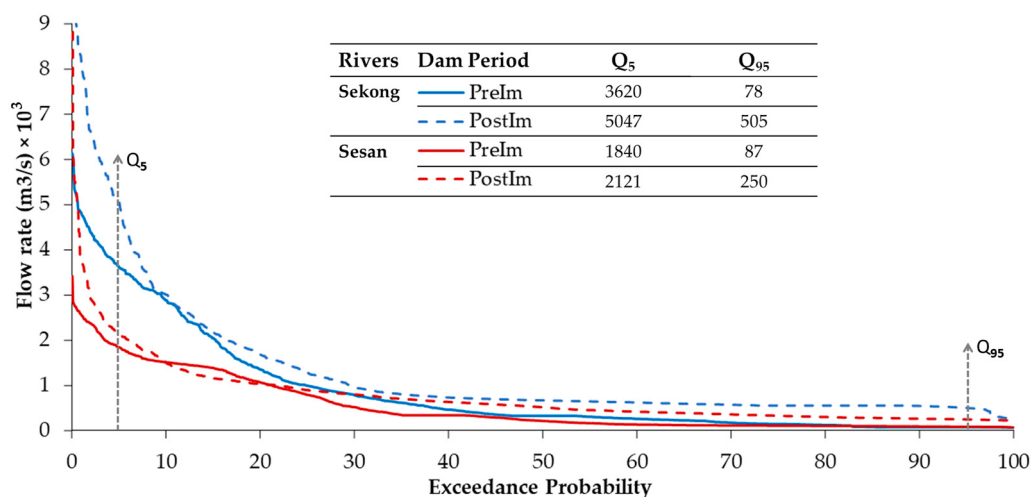


Figure 3. The flow duration curves for the pre- and post-impact periods at the Siempang station in the Sekong River and the Veurnsai station in the Sesan River.

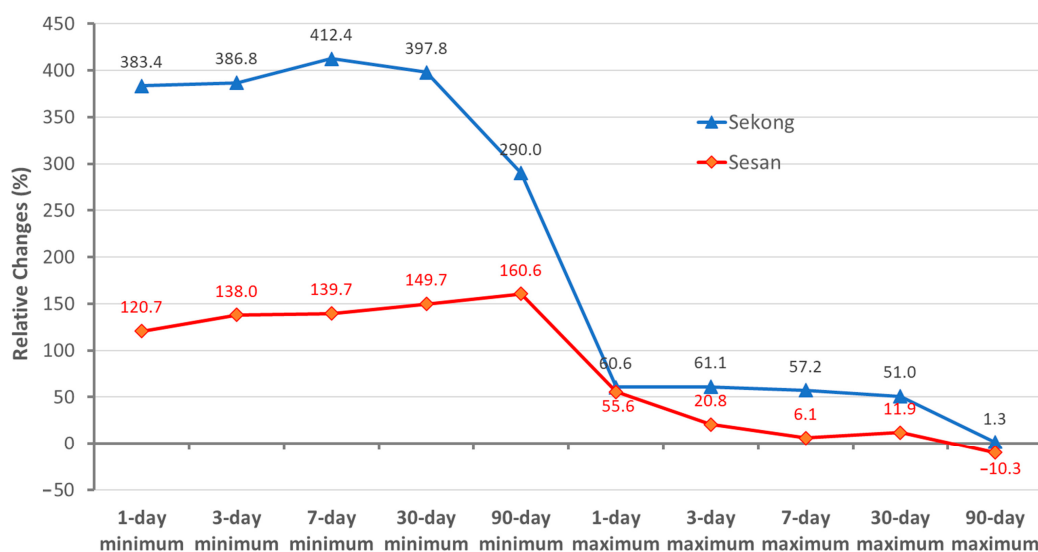


Figure 4. The percent changes in the post-dam development flow minima and maxima compared to the pre-dam development hydrology at the Siempang station in the Sekong River and the Veurnsai station in the Sesan River.

3.2. Hydrologic Alteration between Periods and River Basins

For the dry season, there was a high degree of hydrologic change ($200\% \pm 163$) in the Sekong River between the pre- and post-dam periods (Table 3). Following the post-dam period, streamflow in the Sekong River gradually increased from October to April (Nov–Apr). On average, April had the largest increase in streamflow between the pre- and post-dam periods. In the Sesan River, we also found a high degree of hydrologic change ($100\% \pm 55$), and increased streamflow occurred from September through May, during which April and May had the largest increased streamflow.

Table 3. The average monthly flows and relative changes for the pre- and post-impact periods at the Siempang station in the Sekong River and the Veurnsai station in the Sesan River. Orange and green highlights correspond to the dry and wet seasons, respectively.

Month	Sekong				Sesan			
	Pre- (m ³ /s)	Post- (m ³ /s)	Relative Change (%)	Degree of Change	Pre- (m ³ /s)	Post- (m ³ /s)	Relative Change (%)	Degree of Change
Nov	586	747	27	Low	408	723	77	High
Dec	396	632	60	Medium	330	496	50	Medium
Jan	278	667	140	High	234	364	55	Medium
Feb	209	627	200	High	157	284	81	High
Mar	136	567	315	High	119	305	156	High
Apr	100	557	457	High	116	326	181	High
Dry Season	284	633	200	High	227	416	100	High
Mean $\pm$ SD	± 182	± 70	± 163		± 120	± 168	± 55	High
May	234	565	142	High	133	387	191	High
Jun	692	675	−3	Low	640	501	−21	Low
Jul	1695	1075	−37	Medium	1275	855	−33	Low
Aug	2425	2406	−1	Low	1400	1151	−18	Low
Sep	2950	2891	−2	Low	1482	1766	19	Low
Oct	1032	1178	14	Low	633	986	56	Medium
Wet Season	1505	1465	18.8	Low	927	941	32	Low
Mean $\pm$ SD	± 1046	± 958	± 63		± 539	± 497	± 84	Low
Annual	894	1049	109	High	557	679	66	High
Mean $\pm$ SD	± 958	± 780	± 151		± 522	± 447	± 77	High

For the wet season, streamflow in the Sekong River decreased from pre-dam conditions from June to September, during which July had the greatest reduction (−37%). For the Sesan River, streamflow decreased from pre-dam conditions from June to August, and the largest decrease was found in July (Table 3).

The comparative results of the hydrologic changes between the two rivers indicate that streamflow increased significantly between the pre- and post-impact periods for both the Sekong and Sesan rivers in the dry season (Figure 5). Moreover, streamflow in the post-impact period was significantly higher in Sekong River than the Sesan River in the dry season. In the wet season, however, there was no significant change in streamflow between the pre- and post-impact periods for either river (Figure 5).

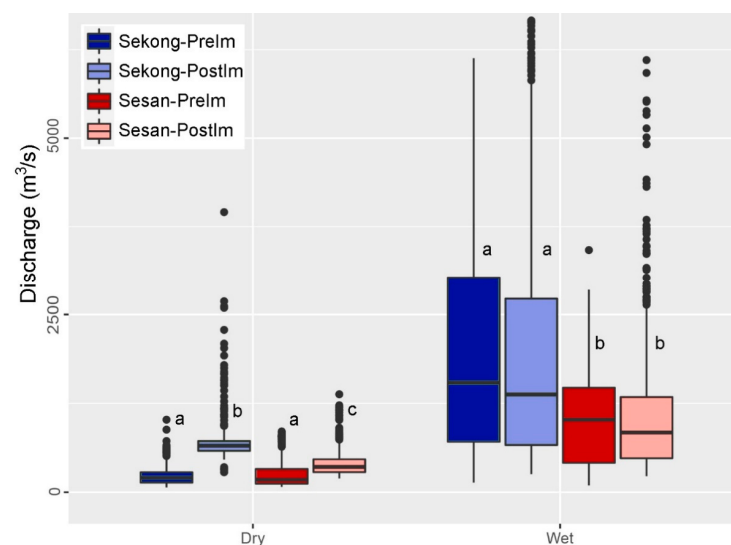


Figure 5. Box and whisker plots showing the differences in streamflow between the pre- and post-impact periods for each river, and between the rivers in dry and wet seasons. Different lower case letters in the boxplot indicate significant differences at the $p < 0.05$.

4. Discussion

Our study is the first to assess and compare the impacts of dams on streamflow in the least and most dammed rivers in the 3S Basin. Overall, we found that the post-impact flows are generally higher than the pre-impact flows for both rivers. Binh et al. [41], based on a long-term data analysis of the Mekong River, also revealed that flow regime alteration was more pronounced in the high-dam development period compared to the no-dam development period. This could be due to substantial change in the flood peak, flood frequency, flood duration, and high-flow discharges induced by dams [41]. Tian et al. [51] also indicate a similar finding from the Three Gorges Dam located in the Yangtze River of China.

The Sekong River had a higher volume of flows for both the Q_5 and Q_{95} compared to the Sesan River. This finding is relatively similar to that of a study by Oeurng et al. [40], who found that the annual flow of $1167 \text{ m}^3/\text{s}$ of the Sekong River was far higher than the $743 \text{ m}^3/\text{s}$ flow of the Sesan River. Higher precipitation in Sekong during dry and wet seasons also leads to higher Q_5 and Q_{95} [40], as in the case of other studies [52,53]. For the Sesan River, it is the most dammed river of the 3S Basin [34], with six mainstem dams that have a capacity of >100 Megawatts, which are the Plei Krong, Yali Falls, Sesan 3, Sesan 3A, Sesan 4, Sesan 4A (63 Megawatts), and Lower Sesan 2 Dams. Therefore, water can be trapped in the upstream dams located above the stream gauge station (except for Lower Sesan 2) (Figure A3) and, therefore, these dams contribute to a higher volume of flow overall.

For both rivers, streamflow significantly increased between pre-dam and post-dam periods in the dry season. Evidence of increased dry season flow and low flow has also been seen following hydropower dam development in other parts of the Mekong River Basin [41,54] and the Yangtze River of China [51]. This is because dam discharge retains water from the wet season to generate energy. For instance, between March and May 2016, 12.65 billion cubic meters of water was released from Jinghong hydropower dams in the Yunnan province of China, contributing to an increase of $602\text{--}1010 \text{ m}^3/\text{s}$ along the downstream Mekong mainstem river. For the wet season, however, we found no significant flow change, while previous studies have indicated decreasing wet seasonal flow due to dam operations [45,55,56]. This discrepancy can be attributed to the study periods, dam scenarios, and reservoir operation rules, as have been illustrated by Ziv et al. [30].

In the whole Mekong Basin, large-scale hydropower dam development has brought concerns regarding biodiversity loss [34,57], degradation of the ecosystem [58], and reduced ecosystem services [59]. However, small run-of-river hydropower dams have been found to be safe and environmentally friendly because they provide a reliable local and cross-border energy and water supply [60]. These solutions are eco-friendly, enhance energy security, reduce greenhouse gas emissions, and promote regional cooperation. They also offer economic benefits, improve water management, and support local communities by providing stable energy and better water resources [61].

This study, however, is lacking long time series data that could be included in the analysis. Although we have incorporated two periods representing the pre- and post-dam development, the results showed only the hydrologic change between two study points, rather than exploring the long-term trend of change and its intra- and inter-variations. Another interesting aspect to be taken into account is the inclusion of the other river (Srepok) in the 3S Basin, because this river is the second most dammed in the system [34], which allows the analysis of the environmental tradeoffs of hydropower dam development. Moreover, watersheds, annual precipitation, and extreme climate conditions are also key variables to include when analyzing the impacts of dams on river development. All of these would provide insight that could allow better management and sustainable development of the system.

5. Conclusions and Implications

Overall, we found likely impacts of hydropower dam development on streamflow in the two river basins, most notably, significantly increased dry season flow and low

flow minima. We also found significant lower streamflow in the Sesan River than in the Sekong River. Our findings support previous research—which, in general, examines hydrologic change for the whole 3S Basin [35] or for one individual river [36]—with additional and detailed flow changes from the pre-dam period to the dammed period, and in particular analyzes the flow change difference between the most (Sesan) and least (Sekong) dammed rivers of the 3S Basin. Future work focusing on the sustainability management and development of the 3S Basin would benefit from conducting a time series analysis of streamflow and identifying the environmental tradeoffs of hydropower dam development. Moreover, assessing the attributes of watershed size, annual precipitation, and extreme climate conditions would also provide additional understanding of streamflow and water quality change patterns in the 3S Basin.

In the LMB, hydropower dam development has been found to have an immense impact on streamflow [62], fish biodiversity and biomass [30,34], and agriculture productivity [63]. The 3S Basin, an important watershed of the LMB, is vital for biodiversity as it provides pathways for migratory fish [34], and it also aids ecosystem services and local communities; limiting future dam development to maintain current riverine migration corridors and habitat connectivity should be a priority. Other alternatives are to optimize the existing dams' operation rules to improve environmental impacts [64].

Author Contributions: Conceptualization: R.K. and R.S.; methodology and formal analysis: R.K., K.C., R.S. and T.S.; investigation: T.S., C.O. and R.S.; data acquisition: R.S.; data curation: R.S. and R.K.; writing—original draft preparation: R.K. and R.S.; writing—review and editing: R.K., T.S., K.C., S.R.P., C.O. and R.S.; visualization: R.K., K.C. and R.S.; supervision: T.S., C.O. and R.S.; funding acquisition: R.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

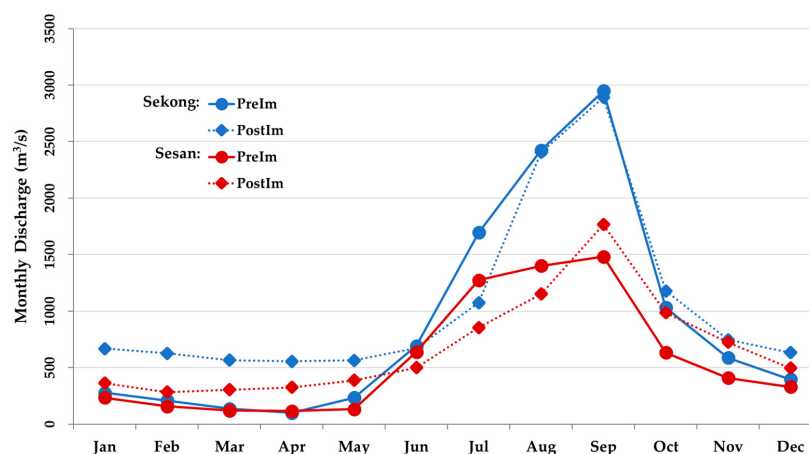


Figure A1. Monthly average discharge at gauge stations in the Sekong and Sesan rivers.

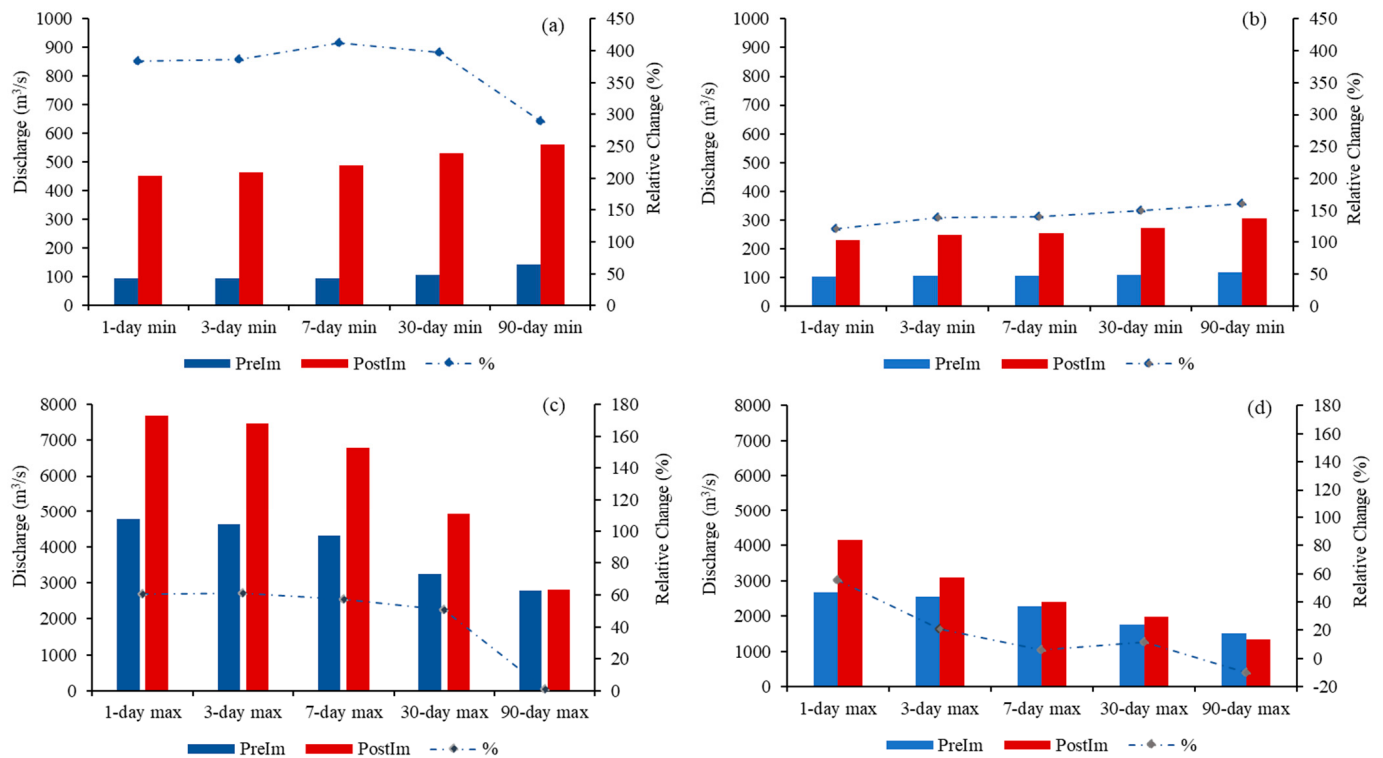


Figure A2. The observed minimum/maximum discharges (flows) and the corresponding relative changes in the Sekong (a,b) and Sesan (c,d) rivers.

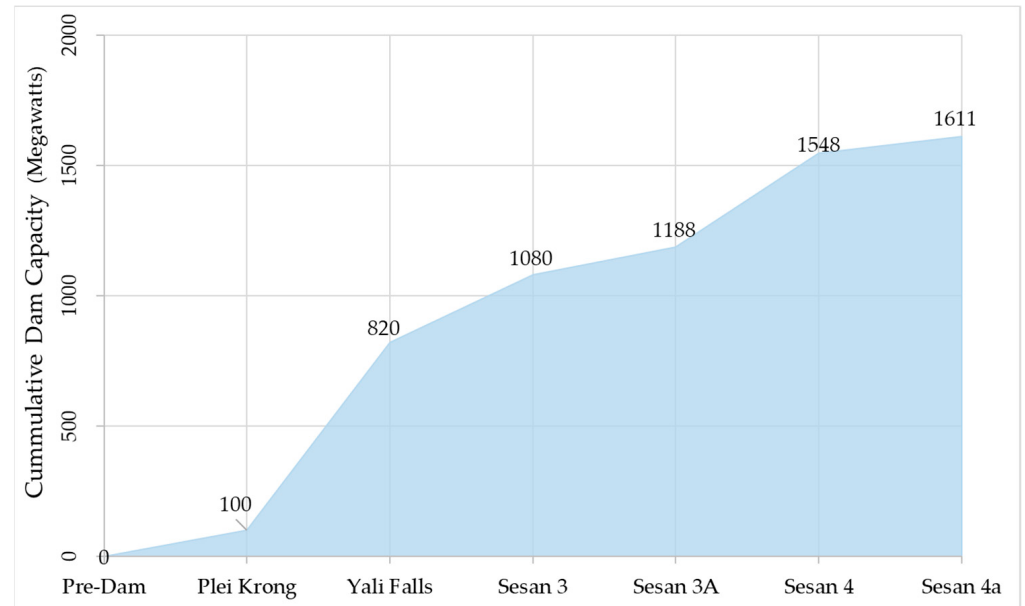


Figure A3. The cumulative storage of upstream dams above the studied gauge station in the Sesan River.

Table A1. The descriptive statistics of streamflow for the pre- and post-impact periods in the Sekong and Sesan rivers (m³/s).

	Dry Season				Wet Season			
	Sekong		Sesan		Sekong		Sesan	
	Pre-	Post-	Pre-	Post-	Pre-	Post-	Pre-	Post-
Mean	226.5	708.3	248.1	415.0	1903.0	2085.3	1023.2	1093.6
Median	202.0	654.0	177.0	357.4	1540.0	1374.0	1020.0	840.7
SD	132.0	304.3	172.1	194.0	1387.3	1965.2	669.3	898.7
Min	68.0	281.0	75.0	193.3	135.0	255.0	95.0	225.2
Max	1020.0	3956.0	855.0	1377.3	6130.0	10,301.0	3420.0	6101.5
Range	952.0	3675.0	780.0	1184.0	5995.0	10,046.0	3325.0	5876.4

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