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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 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 historically supported migratory fishes. We use 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 that ranged 290% to 412% more than the pre-impact period, while the Sesan River ranged 120% to 160% more than pre-impact. Dry season flows increased by 200±63% on average in the Sekong River, which is caused by releases from upstream dams. Meanwhile, Sesan River dry season flows increased by 100±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 functions.

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

1. Introduction

Hydropower dams are being developed extensively in developing regions, such as the Congo, Yangtze, Yellow, Amazon, and Mekong Rivers, which have complex tradeoffs among river ecosystems, local people, communities, and economies [1]. For instance, dams provide economic and social benefits, such as flood risk reduction [2,3], irrigation water [4], and electricity [5]. On the other hand, they may alter hydrology [6], destroy wetland destruction [7,8], degrade water quality [9], alter sediment transport [10,11], fragment rivers [12], reduce biological and ecological productivity [13], and contribute to biodiversity loss [14]. Flow alteration is a fundamental change to river systems, because it is a master variable that affects physical, chemical, and biological processes[15]. Typically, dams decrease flows in the wet season and increase them in the dry season [7,16], and magnitude, timing, frequency, duration, and rate of change can be affected [17,18]. Extended wet or dry periods may occur [19,20].

The Mekong River supports tremendous aquatic biodiversity, including ~1,200 fish species [21] and is home to aquatic invertebrates such as rotifers [22], aquatic insects [23,24], annelids, crustacean, and molluscs [25,26]. Fish from the Lower Mekong Basin (LMB) are a primary food source for local

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people [27,28], and fisheries provided an estimated ~US$11 billion per year to the economy in 2015 [29]. 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 Upper Mekong River mainstem in China [30]. In the LMB, at least 129 dams have been commissioned, including five mainstem dams in Laos. Hydropower dams in the LMB provide capacity for >30,000 megawatts (MW) of power generation, with estimated revenue of US$160 billion from all projects by 2040 [31]. One of the primary areas for hydropower dams in the LMB is the Sekong, Sesan and Srepok Rivers (3S Basin), which are a major tributary to the LMB (Figure 1). As of 2021, at least 51 dams were operating in the 3S Basin, with a combined generating capacity of 4,684 MW. The Sesan River has the most dams of the three basins, with 22 dams, and the Sekong has the fewest dams, with 14 dams [32].

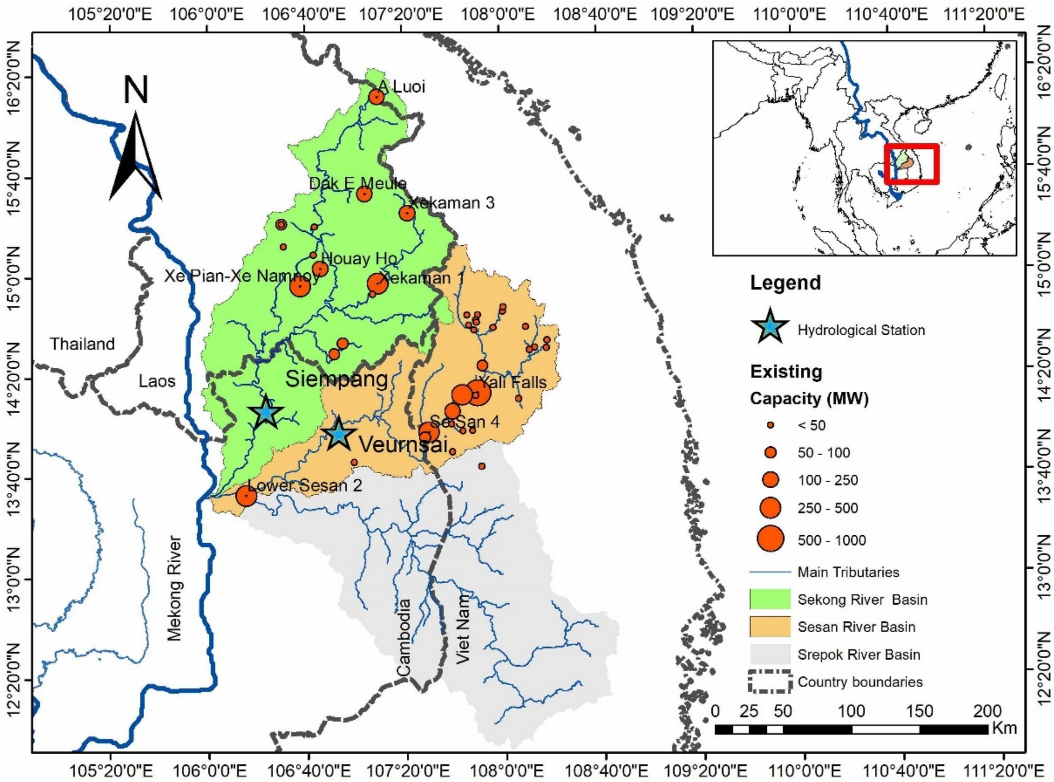

Figure 1. The Sekong and Sesan Rivers, with dams and monitoring stations.

Given on-going hydropower dam development, streamflow in 3S rivers have deviated from natural regimes [33,34]. Piman, Cochrane, Arias, Green and Dat [33], examined the effects of hydrologic change by hydropower dams in the whole 3S, 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 [34] evaluated changes in flow and water quality in the Sesan River using the Indicators of Hydrological Alteration (IHA) framework. They discovered significant hydrologic changes occurred during both the low flow and high flow periods following the construction of Yali Falls dam in Vietnam. The IHA model has been widely implemented and is well-known for its effectiveness at quantifying flow changes [17,35–37]. For example, Van Binh, Kantoush, Saber, Mai, Maskey, Phong and Sumi [35] utilized IHA to examine the long-term alteration of low regime of the Mekong River. Piman [36] estimated how changes in land use, climate, and hydropower development affect the hydrologic alteration of Srepok River using IHA. Zhou, Huang, Zhao, Ma and Sciences [37] used IHA to analyze the cumulative effects of cascading reservoirs on the flow regime in the Jinsha River in China. Since flow regime is central to sustaining ecosystem function, productivity, and the livelihoods of local people [11,38,39]. Understanding the impact of dam operation on flow changes is crucial for addressing transboundary 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 between the pre-impact (1965-1968) and post-impact (2018-2021) periods of dam construction using the 5^{th} and 95^{th} percentiles of flows to indicate the highest and lowest pulses, respectively. We then compare hydrologic alteration between the two periods for each river and between the two rivers. Low flows, represented by exceedance of 95^{th} percentile flows, are important for understanding minimum flow requirement for ecological health and managing water resources during dry seasons. Exceedance of the 5^{th} 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 km^2, of which the Sekong Basin encompasses about 28,815 km^2, while the Sesan Basin is about 18,800 km^2 [40]. 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. Average annual rainfall can exceed 2,500 mm and precipitation varies throughout the watersheds. The Sekong, Sesan, and Srepok Rivers collectively contribute a mean annual discharge of ~2,890 m^3/s, which is ~25% of streamflow to the Mekong River [41].

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 Se San 4 and Lower Sesan 2 Dams in Sesan River and 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.

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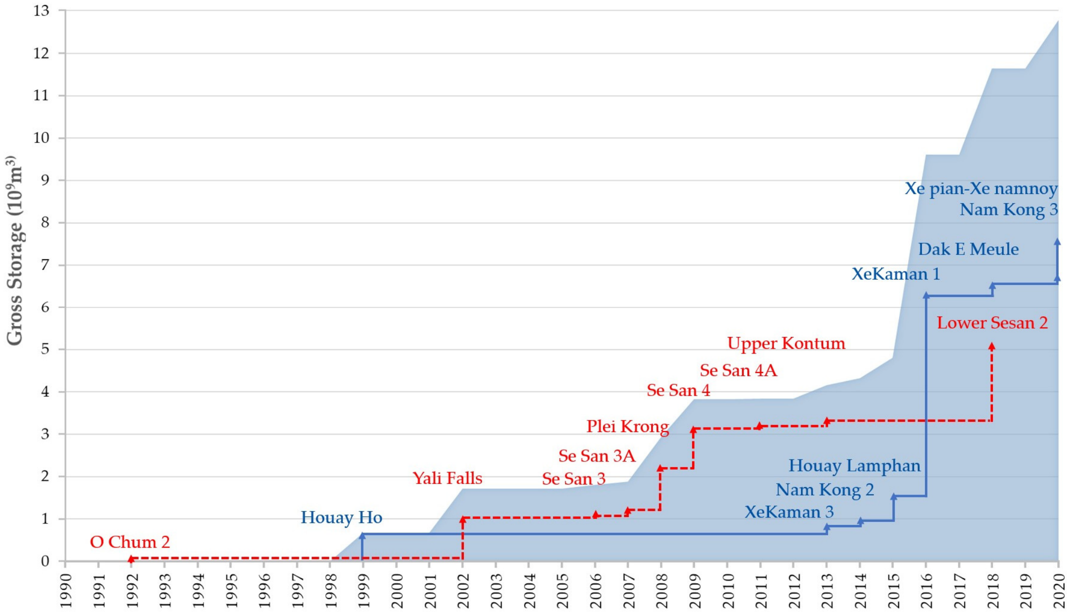

Figure 2. Cumulative reservoir storage for both river basins (gray shading), the Sekong River (blue line) and Sesan River (red dashed line), with a timeline of dam construction.

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 framework was created to assess streamflow alteration by detecting differences in the range of natural variability, using 33 parameters of hydrologic alteration [42,43]. The pre-impact period is our reference condition for natural flows. In this study, we used only 10 of 33 parameters (Table 1) for the subsequent analysis identifying the extreme flow events.

Table 1. Summary of hydrologic parameters extracted from the analyzed IHA framework and their characteristics. From Richter et al. [42].

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

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 to assess how hydrologic alteration affects high flow conditions, such as evaluating the capacity of reservoirs to store large inflows [44]. 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 [45].

2.3.2. Hydrologic Alteration Between Periods and Rivers

To examine hydrologic changes between two periods, relative hydrologic change was computed as percentage. The results from this analysis were then were 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 degree of hydrologic alteration, respectively [43]. The relative hydrologic change was as following:

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

When the values 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 [46].

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 reduction 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 inset table notes the magnitude of low and high flows during the pre- and post-impact periods for the Sekong and Sesan Rivers.

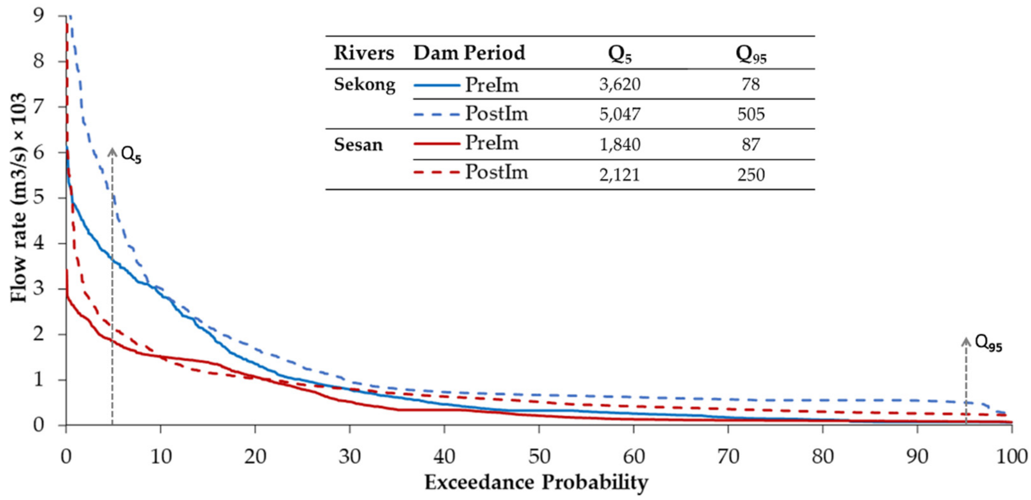

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Figure 3. Flow duration curves for the pre- and post-impact periods at the Siempang station in the Sekong River and the Veurnsai station in the Sesan River.

Overall, the Sekong River—with the fewest dams—had larger flow increases before and after dam development than the Sesan River, that had 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 m^3/s higher than the pre-impact period. The 1-, 3-, 7-, and 30-day maximum flows were 50% higher than the pre-dam impact period, while there was a negligible change for 90-day maximum flow (Figure 4). For the Sesan River, minimum flows increased by 120 – 160% 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 (Figure 4).

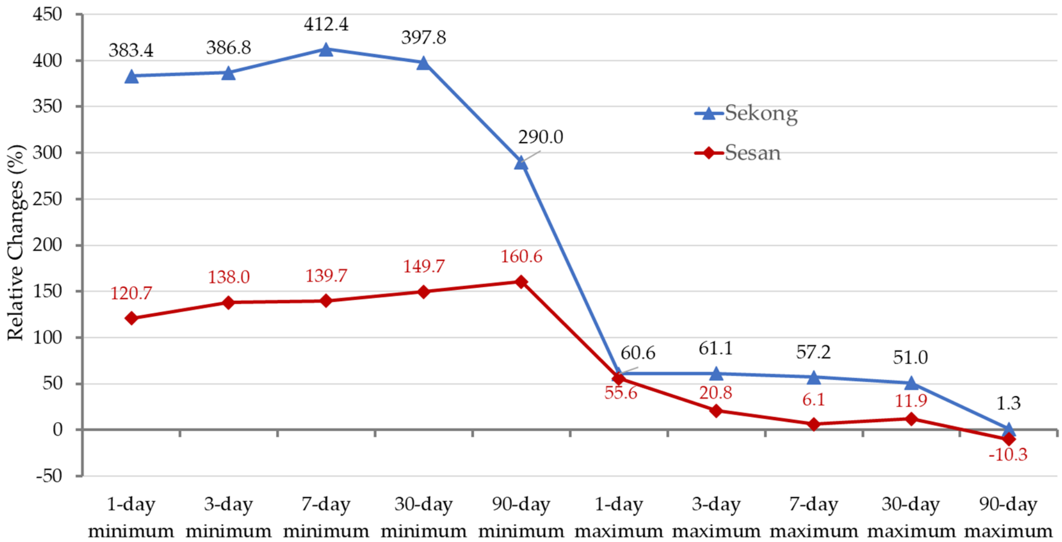

Figure 4. Percent change of post-dam development flow minima and maxima compared to pre-dame development hydrology at the Siempang station in the Sekong River and the Veurnsai station in the Sesan River.

3.2. Hydrologic Alteration between Periods and River Basins

Streamflow in the Sekong River increased in October through May following dam construction, with an average dry season (Nov-Apr) increase of 200% (Table 3). On average, April had the largest increase in streamflow between the pre-and post-dam construction periods. Streamflow decreased from pre-dam conditions from June to September in the wet season, during which July had the greatest reduction (-37%). For the Sesan River, streamflow increased from pre-dam conditions from September through May, with a mean dry season increase of 100%. Flow decreased from pre-dam conditions from June to August, during the wet season. Streamflow decreased most in July in the Sesan River.

Streamflow increased significantly between the pre- and post-impact periods for both the Sekong and Sesan Rivers in the dry season (Figure 5, Table 3). There was no significant change in streamflow between the pre- and post-impact periods for either river in the wet season. Streamflow in the post-impact period was significantly higher in Sekong River than the Sesan River in the dry season.

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Table 3. Average monthly flow and relative change 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 highlighted 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 Mean ±SD	***284 ±182***	***633 ±70***	***200 ±163***	***High***	***227 ±120***	***416 ±168***	***100 ±55***	***High***
May	234	565	142	High	133	387	191	High
Jun	692	675	-3	Low	640	501	-21	Low
Jul	1,695	1,075	-37	Medium	1,275	855	-33	Low
Aug	2,425	2,406	-1	Low	1,400	1,151	-18	Low
Sep	2,950	2,891	-2	Low	1,482	1,766	19	Low
Oct	1,032	1,178	14	Low	633	986	56	Medium
Wet Season Mean ±SD	***1,505 ±1,046***	***1,465 ±958***	***18.8 ±63***	***Low***	***927 ±539***	***941 ±497***	***32 ±84***	***Low***
Annual Mean ±SD	**894 ±958**	**1,049 ±780**	**109 ±151**	**High**	**557 ±522**	**679 ±447**	**66 ±77**	**High**

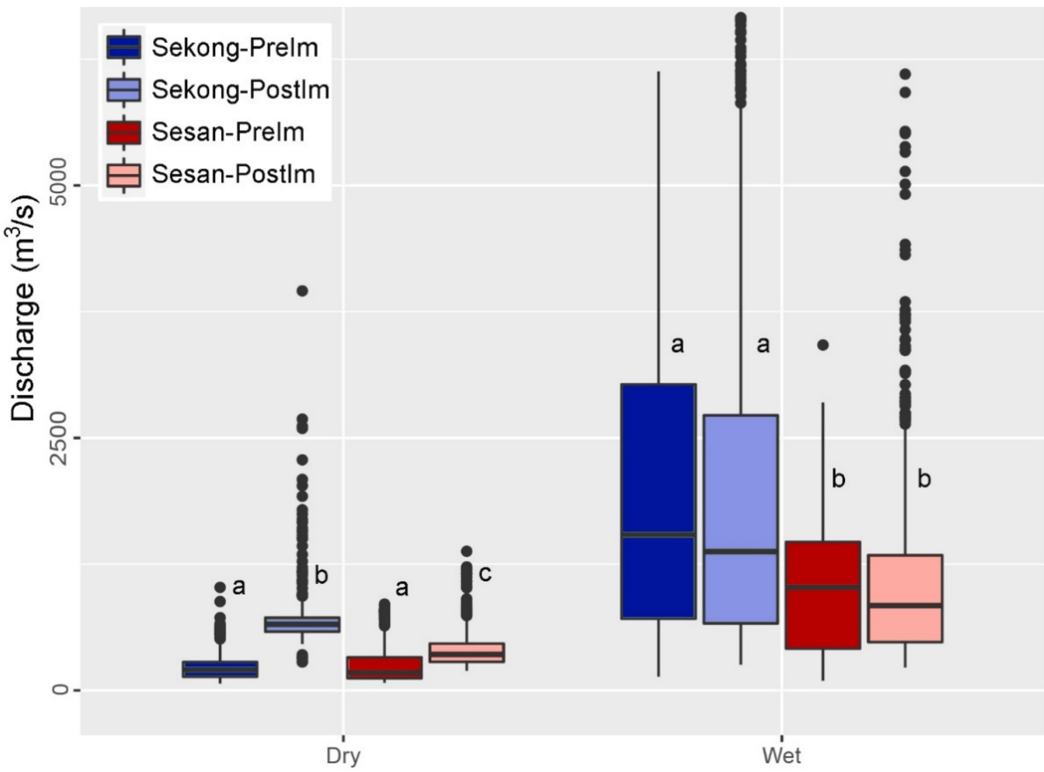

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Figure 5. Box and whisker plots showing the differences in streamflow between the pre- and post-impact period for each river, and between rivers in dry and wet seasons.

4. Discussion

Overall, we found that the post-impact flows are generally higher than pre-impact flows for both rivers. Binh et al. [35], 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 of the flood peak, flood frequency, flood duration, and high-flow discharges induced by dams [35]. Tian et al. [47] also indicate a similar finding from the Three Gorges Dam located in the Yangtze River of China.

Sekong River had a higher volume of flows for both the Q_5 and Q_{95}, compared to Sesan River. This finding is relatively similar to the study of Oeurng et al. [41] who found that the annual flow of 1,167 m^3/s of the Sekong River was far higher than that of 743 m^3/s for the Sesan River. Higher precipitation in Sekong during dry and wet seasons also leads higher Q_5 and Q_{95} [41], as in the case of other studies [48,49]. For the Sesan River, it is the most dammed river of the 3S Basin [32], with six mainstem dams that have capacity >100 Megawatts, including 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 A2), and therefore contributed to higher volume of flow in overall.

For both rivers, streamflow significantly increased between pre-dam and post-dam periods in dry season. The evidence of increased dry season flow and low-flow also occur following hydropower dam development in the other parts of the Mekong River Basin [35,50] and the Yangtze River of China [47]. This is because dam discharge retained water from the wet season to generate energy production. For instance, between March and May 2016, an amount of 12.65 billion cubic meters of water was released from Jinghong hydropower in Yunnan province of China, contributing to an increased 602-1,010m^3/s along the downstream Mekong mainstem river. For the wet season, however, we found no significant flow change whilst previous studies have indicated decreasing wet seasonal flow due to dam operations [39,51,52]. This discrepancy can be subjected to the studies period, dam scenarios, and reservoir operation rules.

5. Conclusion

Overall, we found likely impacts of hydropower dam development on streamflow in the two river basins, most notably as significantly increased dry season flows and low flow minima metrics. We also found significant lower streamflow in Sesan River than in Sekong River. Size of watershed, annual precipitation and extreme climate condition explain differences in streamflow between the two basins.

As the 3S basin is vital for biodiversity, ecosystem services and local communities, limiting future dam development to maintain current riverine migration corridors and habitat connectivity should be a priority.

Author Contributions: Conceptualization: R.K. and R.S.; methodology and formal analysis: R.K., K.C., R.S. and T.S.; investigation: S.T., 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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Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Appendix A

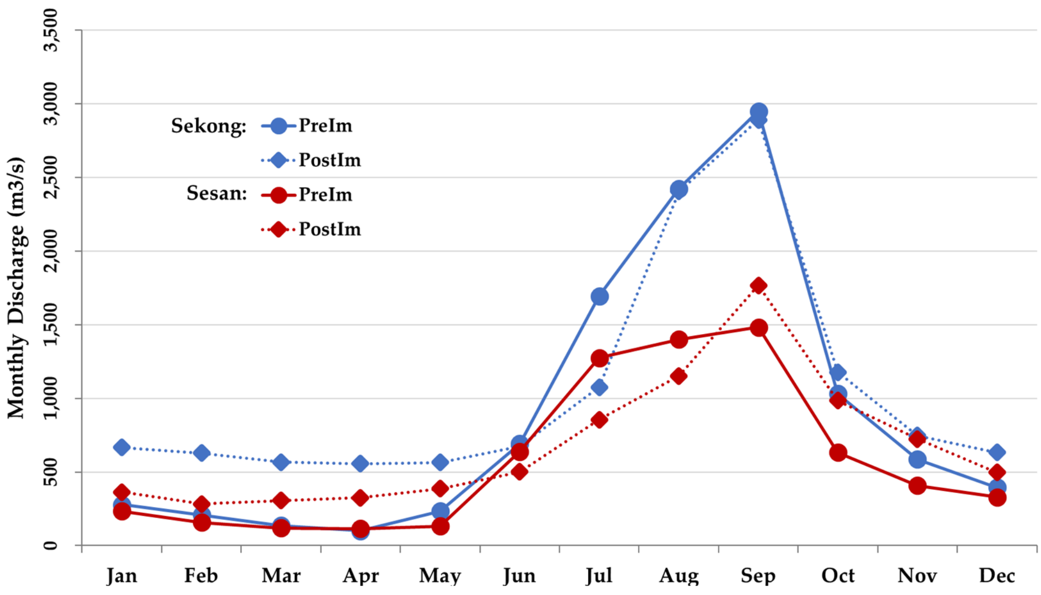

Figure A1. Monthly average discharge at gauge stations in the Sekong and Sesan Rivers.

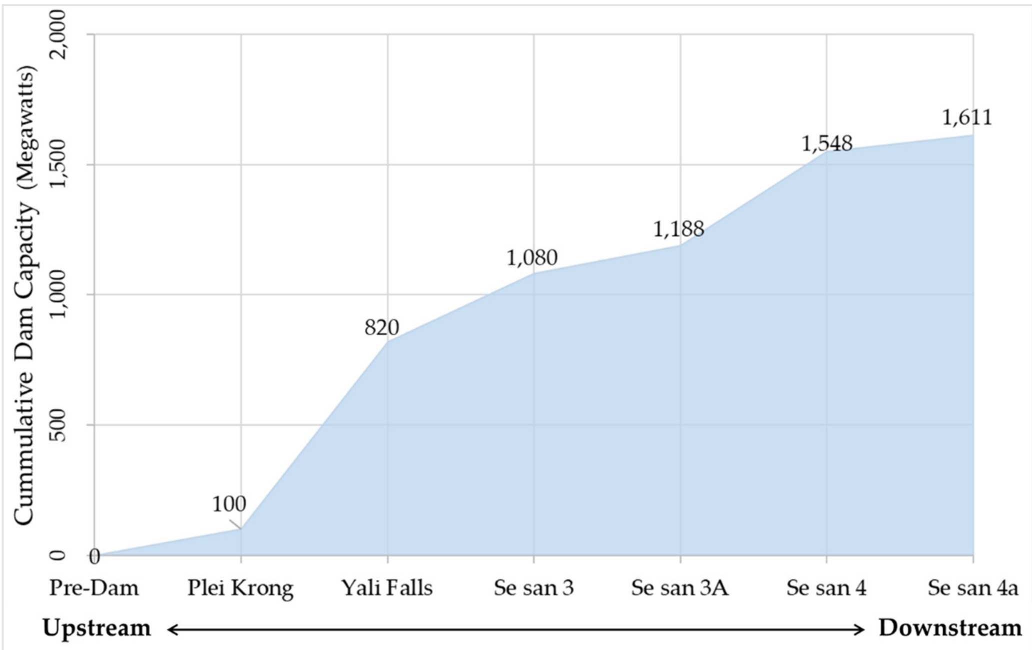

Figure A2. Cumulative storage of upstream dams above the studied gauge station in Sesan River.

Table A1. Descriptive statistics of streamflow for the pre- and post-impact periods in the Sekong and Sesan Rivers (m^3/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	10301.0	3420.0	6101.5
Range	952.0	3675.0	780.0	1184.0	5995.0	10046.0	3325.0	5876.4

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