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Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin

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ABSTRACT

The Lancang-Mekong River Basin (LMRB) is one of the most important transboundary river basins in Asia. While climate change perturbs the streamflow and affects flood events, reservoir operation may mitigate or aggravate this impact. Therefore, quantitative assessment of the climate change impact and reservoir effect on the LMRB is a vital prerequisite for future hydropower development and environmental protection. This study aimed to estimate the variation of the streamflow and flood characteristics affected by climate change and reservoir operation within the LMRB. A reservoir module was incorporated into the Variable Infiltration Capacity (VIC) model to simulate the streamflow susceptible to the reservoirs. It was found that the reservoirs had a substantial influence on the streamflow during 2008–2016, when many reservoirs were constructed in the LMRB. The reservoirs across the Lancang River (the upper Mekong River located in China) reduced the annual average streamflow by 5% at Chiang Sean station (northern Thailand) in 2008–2016, whereas their influence became undetectable downstream of Vientiane station (northern Laos). The streamflow changes downstream of Mukdahan station at southern Laos (including the stations in Cambodia and southern Vietnam) were mainly attributed to the local reservoirs and climate change. Compared with the baseline period of 1985–2007, the upstream reservoir operation dramatically affected streamflow at the midstream stations with higher dry season streamflow (+15% to +37%), but lower wet season streamflow was less affected (−2% to −24%) in 2008–2016. Climate change increased the magnitude and frequency of the flood by up to 14% and 45%, respectively, whereas the reservoir operation reduced them by 16% and 36%, respectively. Our findings provide insights into the interaction between climate change and reservoir operation and their integrated effects on the streamflow, informing and supporting water management and hydropower development in the LMRB.

1. Introduction

As one of the largest transboundary river basins in Asia, the Lancang-Mekong River Basin (LMRB) plays an important role in economic development in Southeast Asia. The fishery, agriculture and hydropower sectors along the river are highly dependent on this commonly shared water resource (Arias et al., 2014). The fish in the Tonle Sap area contribute to about 80% of the total protein supply for the local inhabitants (Hortle, 2007), and the rice exports from the Mekong Delta account for 20% of the global total rice exports (Byerlee et al., 2010). Hydropower is the main source of energy in the basin (Hecht et al., 2019). However, the LMRB's annual streamflow varies greatly because of the tropical monsoon with over 75% of the runoff generated during the wet season (MRC, 2009), resulting in severe floods threatening human life, food production and the security of infrastructure. Some recent studies have also suggested that climate change can affect the streamflow in the LMRB, resulting in an increasing risk of flooding (Hoang et al., 2015; MRC, 2010; Trisurat et al., 2018).

In addition, on account of rapid urbanization and population expansion, the growing energy demand has led the countries within the

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LMRB to consider efficient hydroelectricity (Lacombe et al., 2014). As a consequence, numerous dams are under construction or in the planning phase (MRC, 2015; Grumbine, 2018). The number of dams in the LMRB is projected to reach 138 by 2025, and their storage capacity is estimated to be 21% of the total downstream flow (Hecht et al., 2019). There remains a controversy over the dam effects on the downstream flow, wetland reduction and sediment in the floodplain (Intralawan et al., 2018; MRC, 2017). Nevertheless, dam and reservoir construction is expected to reduce flood risk in the LMRB. The streamflow changes affected by the dams can alter the flood characteristics and further impact agriculture, natural environment fisheries and construction of infrastructure.

There have been considerable researches focusing on evaluating the hydropower impacts on historical flow regimes in the LMRB. Li et al. (2017) reported the critical implication of the upstream dam for the five gauging stations in 1960–2014. Räsänen et al. (2017) found that the mean streamflow at Chiang Sean station decreased by 32%–46% and increased by 121%–187% during July–August and March–May in 2014, respectively, compared with 1960–1990, as a result of the Nuozhadu reservoir. Moreover, Han et al. (2019) concluded a 95% contribution to the flow changes from human activities at Yunjinghong station in China for 2008–2014 and Mohammed et al. (2018) showed that a 30% upstream flow increase would affect the characteristics of downstream flood events and reduce the Lower Mekong streamflow predictability by about 21%.

The impact of the reservoir construction and operation on streamflow in the LMRB is poorly understood due to lack of reliable reservoir models. Lauri et al. (2012) predicted 25%–160% higher dry season flows and 5%–24% lower flood peaks at Kratie station in 2032–2042 compared with the period of 1982–1992 as a result of the hydropower generation. Wang et al. (2017a) estimated the effect of the reservoir on flood reduction for 2010–2099 in the LMRB with a daily-scale model. Many researches have focused on streamflow changes caused by the hydropower development and climate change separately (Hoang et al., 2015; Kummu et al., 2010; Liu et al., 2016; Trisurat et al., 2018). However, to our knowledge, few studies have focused on the combined impact in recent historical periods in the LMRB. It is crucial to assess the overall changes in streamflow and flood characteristics to climate change and reservoirs operations because these can represent a major challenge for water resources management and water security in the LMRB.

The main objective of this study was to quantify the simultaneous climate change and reservoir effects on streamflow and flood events in the LMRB. The Variable Infiltration Capacity (VIC) model was coupled with a reservoir model to simulate the natural streamflow and the effect of reservoir regulations from 1985 to 2016. The coupled hydrologic-reservoir model can help us better understand changes in the hydrological regime in the LMRB and provide insights into the interplay between climate change and reservoirs.

2. Study area and data

2.1. Study area

Located within the domain of 9°60′–33°80′N and 93°50′–108°60′E (Fig. 1), the Lancang-Mekong River is the 10th largest river in the world, with a length of 4800 km and annual streamflow of 14,500 m^3/s (Wang et al., 2017b). The south-west monsoonal climate gives rise to the distinctive dry season (from December to May) with little precipitation and wet season (from June to November) when about 80%–90% precipitation occurs. Doubling from 75 million in 2005 to a maximum of 145 million by 2050 (Varis et al., 2012), the growing population and urbanization have stimulated the demand for more hydropower and accelerated reservoir construction, leading to over 82 reservoirs in operation by the end of 2016 with a total storage capacity of 82.1 km^3 (MRC, 2017).

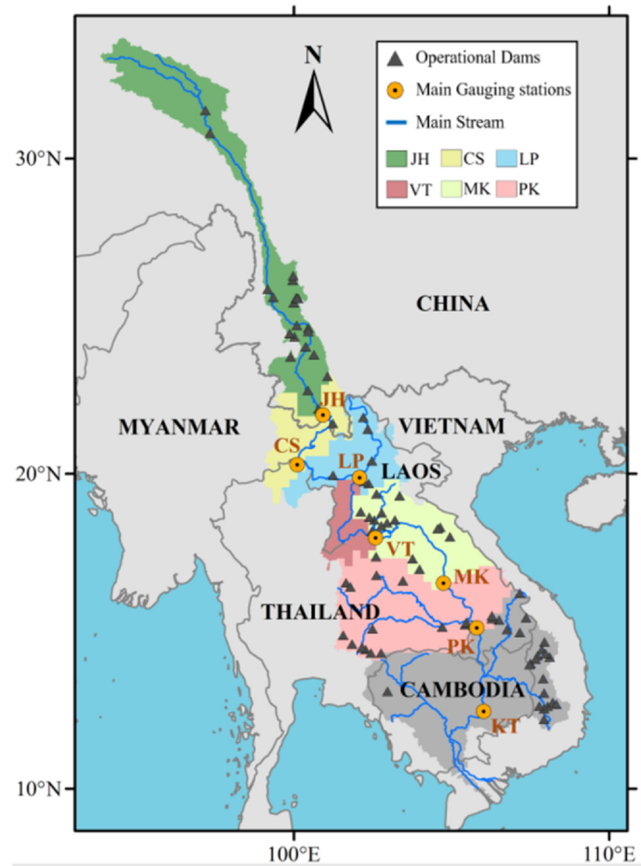

Fig. 1. The Lancang-Mekong River Basin (LMRB) with the hydropower dams and mainstream gauging stations analyzed in this study.

Fig. 2a shows the changes in the number and storage capacity of the reservoirs from 1965 to 2016 in the LMRB. The reservoir active storage capacity accounted for only about 2% of the mean annual streamflow by 2008 and had little impact on streamflow (Kummu et al., 2010), while the total reservoir storage capacity increased rapidly in the following years and reached 22% of the mean annual streamflow at PK station (Fig. 2c). It was estimated that up to 2016, the reservoir storage capacity of each country was as follows: China (42.5 km^3), Laos (27.1 km^3), Thailand (9.5 km^3), Cambodia (0.5 km^3) and Vietnam (2.5 km^3) and 51% storage capacity was located upstream of JH (Fig. 2b).

2.2. Data

In this study, precipitation, temperature and wind speed data at a spatial resolution of 0.25° were obtained from the Global Meteorological Forcing Dataset (GMFD) (Sheffield et al., 2012, 2006) because of its good quality and accuracy in the LMRB (Tatsumi and Yamashiki, 2015). The streamflow observations in the LMRB (Table 1) were obtained from the China Hydrology Data Project Henck et al. (2011) and Mohammed et al. (2018). The streamflow observations at KT station contain major errors according to the Mekong River Commission annual report (MRC, 2018), therefore, KT station was not considered in the analyses (as explained in Section 5.3). Furthermore, the soil data and the land cover data were acquired from the Harmonized World Soil Database (HWSD) (FAO, 2012) and the Global Land Cover Characterization (GLCC) (Loveland et al., 2000) dataset, respectively. The digital elevation model (DEM) for the LMRB was selected from the Advanced Space borne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (https://doi.org/10.5067/ASTER/ASTGTM.003). The reservoir and dam data involved

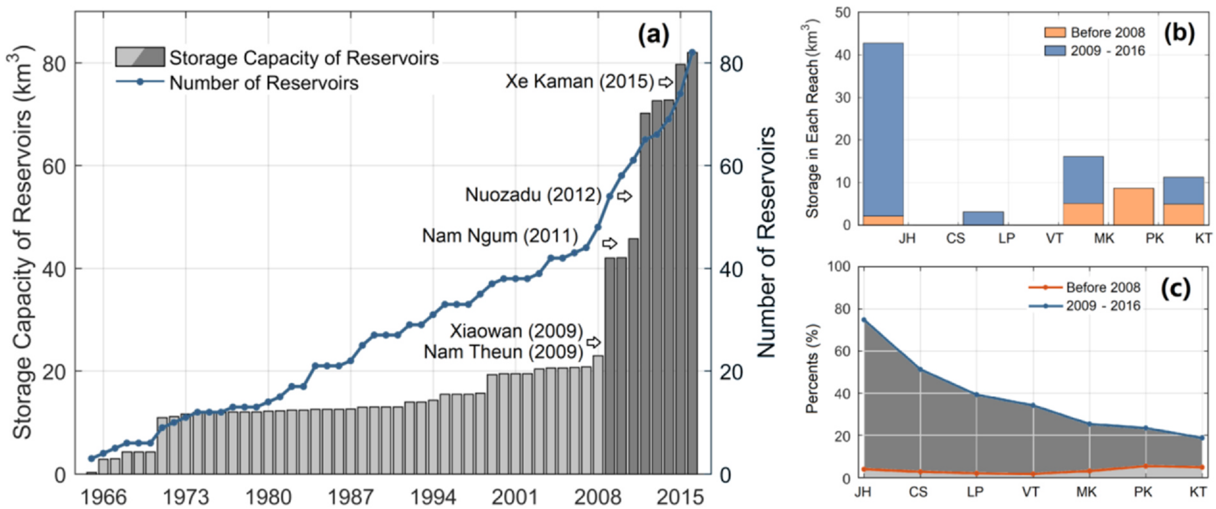

Fig. 2. Reservoirs in the LMRB: (a) Changes in the number and total storage capacity of reservoirs during 1965–2016. Different color bars are used to distinguish the periods of rapid increasing storage capacity. (b) Storage capacity of reservoirs in different reaches partitioned by seven gauging stations by 2008 and 2016. (c). Proportion of the total reservoir storage capacity in 2008 and 2016 to the mean annual streamflow.

in this study were obtained from the Greater Mekong Dam Database (GMDD, https://wle-mekong.cgiar.org/maps/).

3. Methods

3.1. The coupled VIC-Reservoir model in the LMRB

The VIC model (Hamman et al., 2018; Liang et al., 1994) is a macroscale hydrological model solving water and energy balances at the grid scale and considers the vegetation and topography at the sub-grid level. The VIC model takes snow and frozen ground into account, which makes it well suited to streamflow simulation in the LMRB. To evaluate the reservoir impact, an advanced Standard Operation Policy type 2 (SOP2) (Wang et al., 2017a) model was coupled with the VIC model (VIC − Reservoir) to imitate multiple reservoir operation in the routing module. The advanced SOP2 assumes reservoirs mainly to operate for flood control along with the environmental protection and power generation.

The VIC − Reservoir model operates as follows: First, the priority and the sub-basin of the reservoirs according to the river classification principle are determined (Tarboton et al., 1991). Second, the natural streamflow entering the reservoir is calculated, and then the natural streamflow is transformed into the dammed flow according to the reservoir operation rules. This operation is developed sequentially from the most upstream dams down to the most downstream ones, ensuring that any dam's operation accounts for the influence of all the upstream dams.

The VIC − Reservoir model developed in this study had a resolution of 0.25°, including 1303 sub-basins in the LMRB. This study mainly focused on the period from 2008 to 2016 with rapid reservoir development (39 new additions with 61 km^3 total storage capacity). The total and active reservoir storage capacity only accounted for 4% and 2% of the annual streamflow, respectively, before 2008 (Kummu et al., 2010). The VIC − Reservoir model needs input from climate forcing (precipitation and temperature), land use and soil maps, leaf area index and elevation in each grid cell. Following the previous works on the calibration of VIC (Park and Markus, 2014; Xue et al., 2016), we focused on the infiltration parameter b and three base flow parameters (D_s, D_{max} and W_s). Parameters used for the LMRB model calibration were obtained from the previous works of Hossain et al. (2017) and Dang et al. (2020), and parameters were slightly modified with manual model calibration. All other parameters in this model were left at their default values. The calibrated model parameters are listed in Table 2.

The VIC − Reservoir model was evaluated using the Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and model bias. The NSE is used to measure the overall performance of the model. The relative model bias is defined as the mean difference between the simulated and observed streamflow divided by the mean observed streamflow.

3.2. The advanced SOP2 reservoir operation rules

The advanced SOP2 reservoir operation module was developed by Wang et al. (2017a) and further improved in this study by including a dead storage capacity. In this operation module, one reservoir is represented by four parameters: the maximum storage S_m (m^3), the normal storage S_n (m^3), the dead storage S_d (m^3) and the flood-limited storage S_c (m^3). The flood-limited storage is the maximum reservoir storage allowed before the wet season to preserve sufficient storage capacity for the coming floods. The advanced SOP2 module assumes that the reservoir starts its operation immediately upon the construction completion date and divides reservoir operation into the preparation period and the operation period.

During the preparation period, the reservoir operates according to the following rules to fill the dead storage capacity, and the priority of

Table 1
Detailed information on six gauging stations along the Lancang-Mekong River mainstream.

Abbreviation	Station Name	Data Length	Time Step	Source
JH	Yun Jing Hong	1985/01–2016/12	Monthly	The China Hydrology Data Project
CS	Chiang Sean	1985/01/01–2016/12/31	Daily	Mohammed et al. (2018)
LP	Luang Prabang	1985/01/01–2016/12/31	Daily	Mohammed et al. (2018)
VT	Vientiane	1985/01/01–2016/12/31	Daily	Mohammed et al. (2018)
MK	Mukdahan	1985/01/01–2016/12/31	Daily	Mohammed et al. (2018)
PK	Pakse	1985/01/01–2016/12/31	Daily	Mohammed et al. (2018)

Table 2
Parameters and calibrated values used for the model simulations.

Sub-basin	b	D_s	D_{max}(mm/d)	W_s
Chiang Sean	0.2	0.2	7	0.5
Luang Prabang	0.3	0.2	6	0.7
Vien Tiane	0.4	0.2	5	0.9
Mukdahan	0.4	0.3	5	1
Pakse	0.5	0.6	4	1
Allowed range	0.001–1	0.001–1	0.1–50	0.1–1

the rules decreases from rule (a) to rule (c):

(a) Water balance rule:

$$S(t+1) = S(t) + Q_{in} \times \Delta t - Q_{out} \times \Delta t \quad (1)$$

(b) Water demand rule: if $Q_{in} \geq Q_d$, set $Q_{out} = Q_d$; in other situations set $Q_{out} = Q_{in}$.

(c) if $S(t+1) \geq S_d$, reservoir enters the operation period immediately.

where Q_{in} (m^3/s) is the incoming natural streamflow; Q_{out} (m^3/s) is the outgoing regulated streamflow; Δt is the time step (1 day in this study); $S(t)$ is the water storage in the reservoir at the time step t; and Q_d (m^3/s) is the water demand for the intended purposes.

After entering the operation period, the reservoir operates according to the following rules, and the priority of the rules decreases from rule (d) to rule (i):

(d) Water balance rule:

$$S(t+1) = S(t) + Q_{in} \times \Delta t - Q_{out} \times \Delta t \quad (2)$$

(e) Limitation of water storage capacity: $S_d \leq S(t) \leq S_m$

(f) Limitation of outflow: $Q_e \leq Q_{out} \leq Q_s$

(g) Limitation in the wet season: minimize the number of days that $S(t) \geq S_c$.

(h) Water demand rule: maximize the number of days that $Q_{out} \geq Q_d$.

(i) Limitation in the dry season: minimize the number of days that $S(t) \geq S_n$,

where Q_e (m^3/s) is the environmentally friendly streamflow and Q_s (m^3/s) is the maximum safe streamflow for the downstream area.

The parametersS_d, S_m, S_n and S_c can be obtained from the actual reservoir character data; Q_e is set as 30% of the annual average streamflow based on the recommended value from the Montana Method (Tennant, 1976) and Q_s is set as twice of the annual average streamflow. Q_d is set as the larger of the power generation flow of the reservoir (obtained from the actual values) and the water consumption (0.5 times the annual average streamflow according to Ringler et al. (2004)).

3.3. Identification of the streamflow break points

This study selected the period of 1985–2016 and six streamflow gauges (JH, CS, LP, VT, MK and PK in Fig. 1 and Table 1) to explore the reservoir impact on the streamflow on the seasonal and annual scales. Five out of the six (CS, LP, VT, MK and PK) with daily observations were used for model calibration, model validation and exploration of the flood characteristics at the daily scale.

The Mann–Kendall test (Hamed and Rao, 1998) was used to identify the break point of the annual streamflow time series at the six gauging stations from 1985 to 2016. A breakpoint in 2008 at JH station (0.05 significance level) indicated that the annual streamflow decreased significantly after 2008. Other stations reflected the same streamflow reduction trend, even though the changes were not statistically significant. This breakpoint corresponded to the construction of the largest reservoir in the LMRB, Nuozhadu (22,700 Mm^3, start construction in 2008), and the Jinhong reservoir (1400 Mm^3) also began power generation in June 2008. Existing research (Li et al., 2017; Han et al., 2019) has also identified 2008 as the breakpoint year in the LMRB.

This study divided research periods into two: baseline period (1985–2007) and impact period (2008–2016). The division was based on two reasons. First, the storage capacity of the reservoirs expanded rapidly after 2008 because of quick dam constructions (Fig. 2). Second, the streamflow exhibited a decreasing trend after 2008. The streamflow in the baseline period was considered as 'natural' flow. It should be noted that there are already limited reservoirs impacts before 2008, and this study focused on the contribution of the impact period only. The baseline period was further divided into two: 1985–1993 and 1994–2007 for model calibration and validation, respectively. For the impact period, two kinds of flows: natural flow and dammed flow were simulated using VIC and VIC-Reservoir models, respectively.

3.4. Flood characteristic indices

In order to describe the change of the flood characteristics, mean annual flood (MAF) (Guo et al., 2014) and peak over threshold (POT) (Hirsch and Archfield, 2015) were applied. MAF and POT are the commonly used indices to analyze changes within a long-term series of flood characteristics. In this case, MAF can represent the average flood magnitude, whereas POT can identify large floods and their frequency. Fig. 3 shows an example of the MAF and POT, in this case 1991–1993 is the baseline period, and 1994–1996 is the compared period.

The maximum daily streamflow is selected as the peak flood event for each year during the baseline period, the MAF is the average of these peak floods (mean value of three red bars in Fig. 3(a)) and represents the flood magnitude in this period. The same method is also employed to calculated the MAF during the compared period (mean

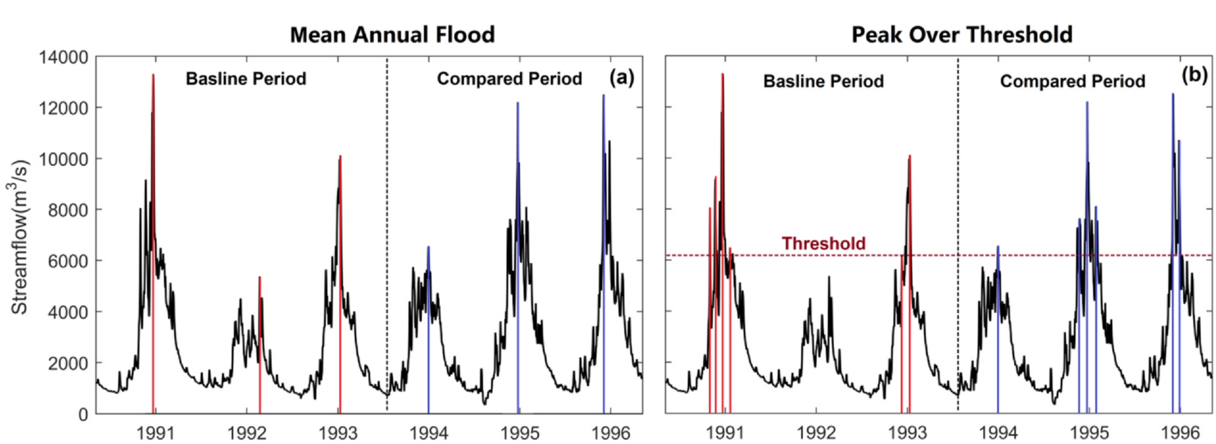

Fig. 3. Schematic of the mean annual flood (MAF) and peak over threshold (POT), the red and blue bars represent flood events in different periods. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

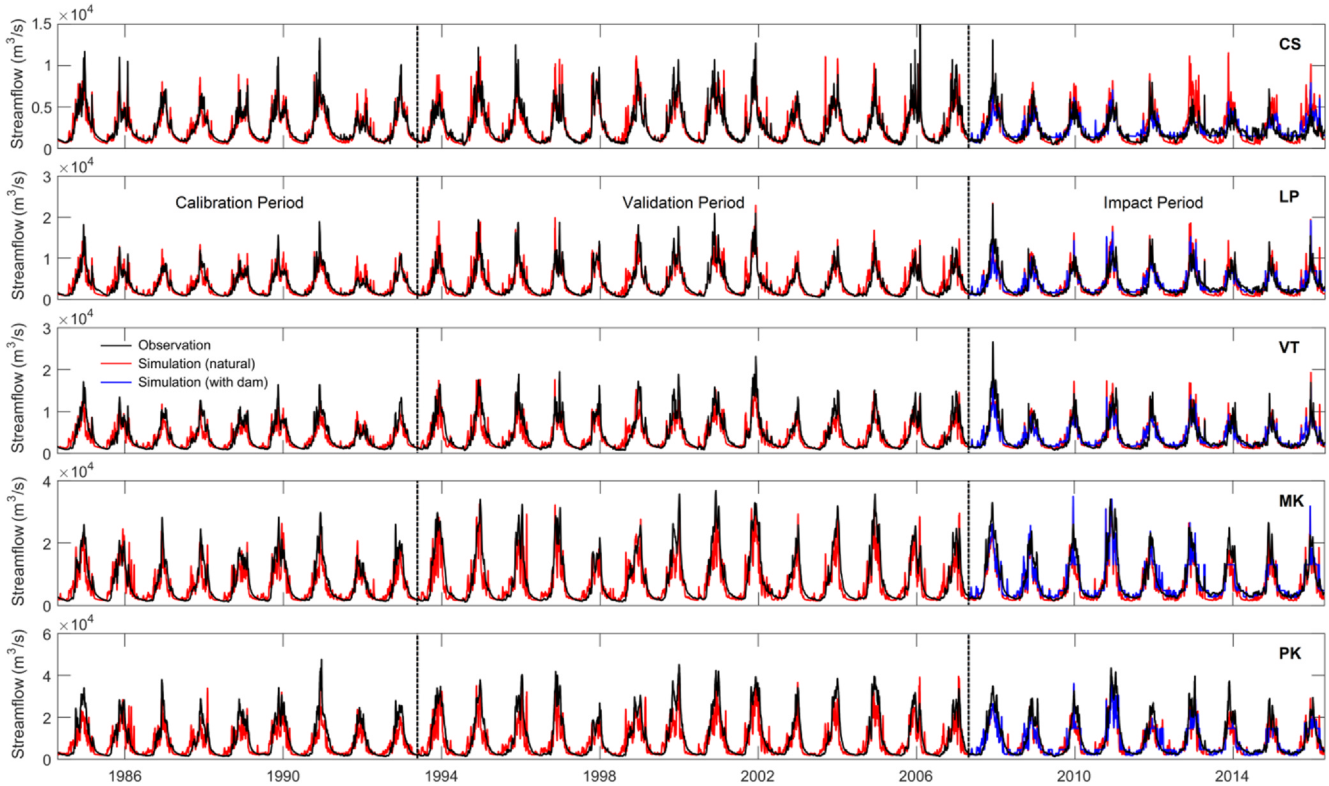

Fig. 4. Observed and simulated daily streamflow at five selected stations in the LMRB for the calibration (1985–1993), validation (1994–2007) and impact (2008–2016) periods.

value of three blue bars in Fig. 3(a)).

The POT selects streamflow values exceeding a threshold that corresponds to two events per year on average during the baseline period (e.g. red bars representing six flood events in three years in Fig. 3(b), and red dotted line represents the selected threshold). This threshold is used in the comparison period to detect flood events (e.g. blue bars in Fig. 3(b)). It is important to note that only one peak is considered during a 15-day window, which avoids counting the same flood event twice or more. POT can be used to reflect changes in flood frequency among different periods.

4. Results

4.1. Performance of the VIC − Reservoir model

Fig. 4 shows the simulated daily streamflow using the VIC model at the five selected stations, and Table 3 shows the model performance metrics. The NSE ranges from 0.69 to 0.76 and model bias ranges from −4% to 5% during the calibration (1985–1993) and validation period (1994–2007). The NSE of the simulated daily natural streamflow decreased to −0.13 at CS and to 0.39 at VT in the impact period. With regard to simulated daily streamflow considering the reservoir influence, the NSE increased to 0.61–0.75 and that of CS showed the greatest improvement. Model bias also decreased at CS, LP, VT and PK after considering the reservoir influence. Reservoir operation reduced the wet season streamflow and increased the dry season streamflow, making the dammed streamflow simulation closer to the observations. Previous studies have suggested that the hydrological modeling with NSE > 0.50 can be considered satisfactory (Moriasi et al., 2007).

The flood indicators MAF and POT calculated from the natural flow and dammed flow were used for comparison with the observed values (Table 4). The POT shows the selected thresholds when the annual average flood frequency is twice in the baseline period, and shows the annual average flood frequency in the impact period based on the selected thresholds. The observed flood characteristics were close to the simulated natural flow in the baseline period, whereas both MAF and POT calculated from the simulated natural streamflow were overestimated in the impact period. The streamflow simulation with the reservoir impact agreed well with the observations, indicating that the VIC − Reservoir model was able to effectively capture the flood events in the LMRB during 1985–2016.

Table 3
Performance metrics of simulated daily streamflow at five selected stations in the LMRB for the calibration (1985–1993), validation (1994–2007) and impact periods (2008–2016).

Station	Calibration		Validation		Impact period (natural)		Impact period (with dam)	
	NSE	Model bias	NSE	Model bias	NSE	Model bias	NSE	Model bias
CS	0.76	−3%	0.71	1%	−0.13	10%	0.61	4%
LP	0.75	3%	0.74	5%	0.53	3%	0.68	0.3%
VT	0.71	2%	0.69	3%	0.39	4%	0.66	2%
MK	0.75	−2%	0.73	−3%	0.66	−3%	0.70	−3%
PK	0.74	−3%	0.74	−4%	0.69	−2%	0.75	−3%

Table 4
Performance of MAF and POT at five selected stations in the LMRB during 1985–2016 under different scenarios.

Name	Baseline period				Impact period					
	MAF (m^3/s)		Thresholds of POT (m^3/s)		MAF (m^3/s)			Flood frequency of POT (per year)		
	Obv.*	Sim.	Obv.	Sim.	Obv.	Sim.	Sim. (with dam)	Obv.	Sim.	Sim. (with dam)
CS	10,505	10,360	7350	7198	7010	9308	6436	0.44	1.56	0.67
LP	14,593	15,324	10,040	10,918	14,062	17,456	15,021	2.56	2.89	2.17
VT	15,461	15,043	11,714	12,038	15,458	17,141	16,012	1.78	2.39	2.11
MK	27,918	26,544	21,200	22,758	26,565	26,357	25,805	2.33	2.44	2.06
PK	35,142	33,418	28,365	29,184	33,581	32,915	31,672	1.67	1.89	1.44

*Obv., Observation; Sim., Simulation.

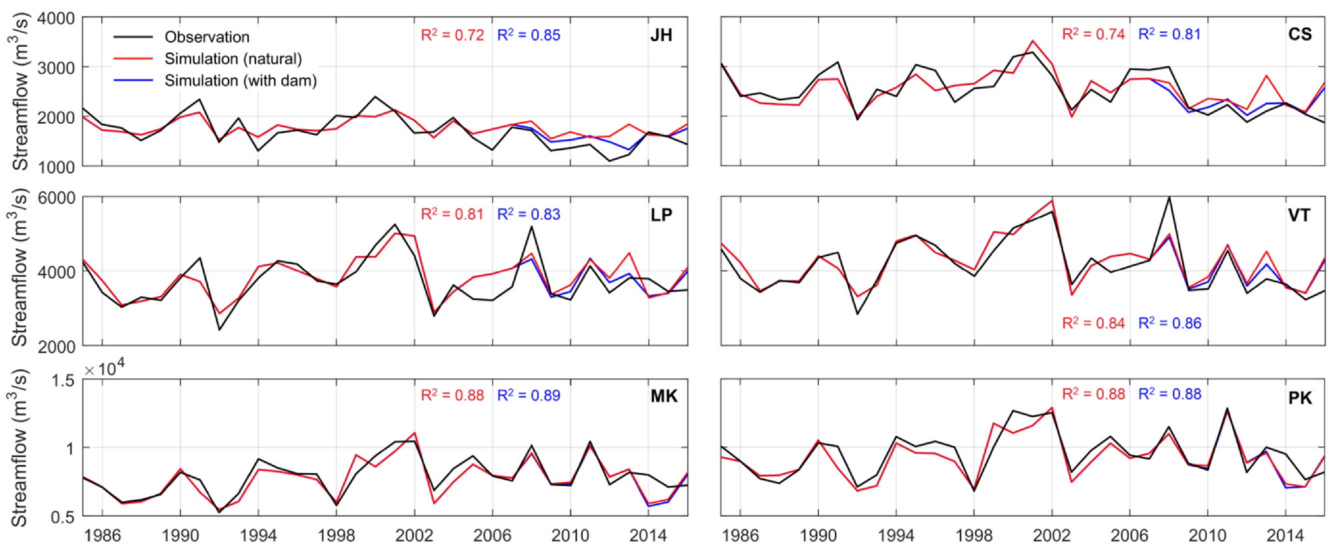

Fig. 5. Annual time series of the observed streamflow and simulated streamflow (natural and dammed) at six selected stations in the LMRB. Red R^2 represent the correlation coefficient between natural simulation and observation, and blue R^2 represent the correlation coefficient between dammed simulation and observation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.2. Streamflow changes in the LMRB

Fig. 5 shows the annual time series of the observed streamflow and simulated streamflow at the six stations. The model without the reservoir module was less effective (R^2 were between 0.72 and 0.88) to simulate the interannual streamflow variability. After considering the impact of reservoir, the interannual variability of the simulated flow using the VIC-Reservoir model agreed well the observed variability (R^2 were between 0.81 and 0.89). The simulated streamflow with the reservoir module included revealed a clear decrease in flow over the periods of 2009–2010 and 2012–2013 at JH and CS, these flow reductions were mainly caused by the reservoir water storage at Xiaowan (construction completion date 2009/09) and Nuozhadu (construction completion date 2012/09).

Fig. 6 displays the changes in seasonal and annual average streamflow and their relative changes at the six stations over the period of 2008–2016 compared with baseline period (1985–2007). The observed flows showed a considerable decrease after 2008 at most stations in the LMRB, especially at JH, CS and VT., whereas the simulated natural flow showed little change. The observed streamflow decreased in the wet season (−211.37 to −1149.39 m^3/s, −2% to −32%) and increased in the dry season (+107.71 to +816.87 m^3/s, +11% to +34%). Different from the huge seasonal streamflow change, the change in annual streamflow is relative small. However, the change in annual streamflow is large (> 10%) at JH (−407.63 m^3/s, −23%) and CS (−474.99 m^3/s, −18%) stations. The simulated natural flows showed reductions in the dry season from JH to VT stations decreased by up to 22% relative to the observed increase. The streamflow in the wet season and at the annual scale had increased at most stations (LP, VT MK and PK). With respect to the reservoir impact, the streamflow variability reduced by increasing dry season streamflow (+15% to +37%) and decreasing wet season streamflow (−2% to −24%) in the LMRB. The simulated dammed streamflow showed better agreement with the observed streamflow, despite the dammed streamflow in the dry season was overestimated at JH and CS station.

4.3. Quantification of the impacts of reservoirs on streamflow

The effects of reservoirs on the seasonal and annual streamflow in the LMRB are shown in Fig. 7. In contrast to the baseline period, the annual average streamflow has decreased at all of the stations as a result of the reservoir water storage. The impact decreased from the upper reaches to the lower reaches. The annual average streamflow at the JH and CS stations decreased by 7% (−135.8 m^3/s) and 5% (−119.4 m^3/s), respectively, and there was a decreasing trend from the LP (−3%) to PK stations (−1%). The reservoir operation acutely increased the dry season streamflow (+21% to +55%) and reduced the wet season streamflow (−7% to −21%) for the impact period at the JH, CS, LP and VT stations.

In comparison with the VT station, the annual average streamflow at the MK and the PK stations decreased because of the huge reservoir storage capacity in the VT–MK sub-basin (16,100 Mm^3) and the MK–PK (8700 Mm^3). The streamflow changes at the MK and PK stations were very limited (−2%–4%) if only the reservoir impact upstream of the VT station was considered. The streamflow changes were slightly larger (−5%–12%) if the impact of all of the reservoirs was considered. These

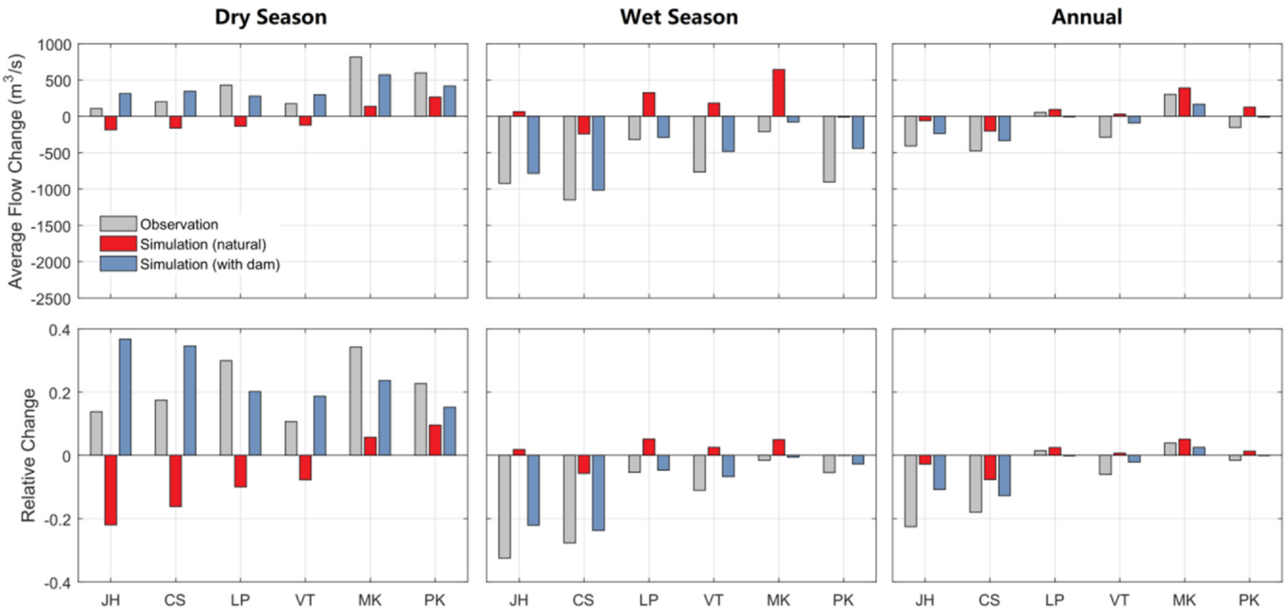

Fig. 6. Average and relative change of the observed streamflow and simulated streamflow at the seasonal and annual scale in the impact period (2008–2016) compared with the baseline period (1985–2007).

results indicate that the streamflow changes downstream of the MK station would be affected more by the reservoirs downstream of the VT station (−3%–8%).

Fig. 8 presents the temporal variation of the reservoir impact to the seasonal and annual streamflow change in the impact period (2008–2016) against the mean values during the baseline period (1985–2007) in the LMRB, where CS, VT and PK represent the upstream, midstream and downstream areas, respectively. The reservoir impact showed the remarkable streamflow increase in the dry season and streamflow reduction in the wet season. In both wet season and annual scales, the reservoirs showed a huge impact in 2009–2010 and 2012–2013, corresponding to the times at which Xiaowan (2009/09) and Nuozhadu (2012/09) started the power generation and impounded the dead storage capacity. The annual impact of the reservoirs has steadily eased over time, indicating that the main effect of the reservoirs is seen in the seasonal streamflow. The annual streamflow decrease in 2009–2013 was ascribed to the dead storage capacity of the reservoir, but this effect disappeared after 2015.

4.4. Flood event changes during the historical period

The flood events vary in response to the streamflow changes in the

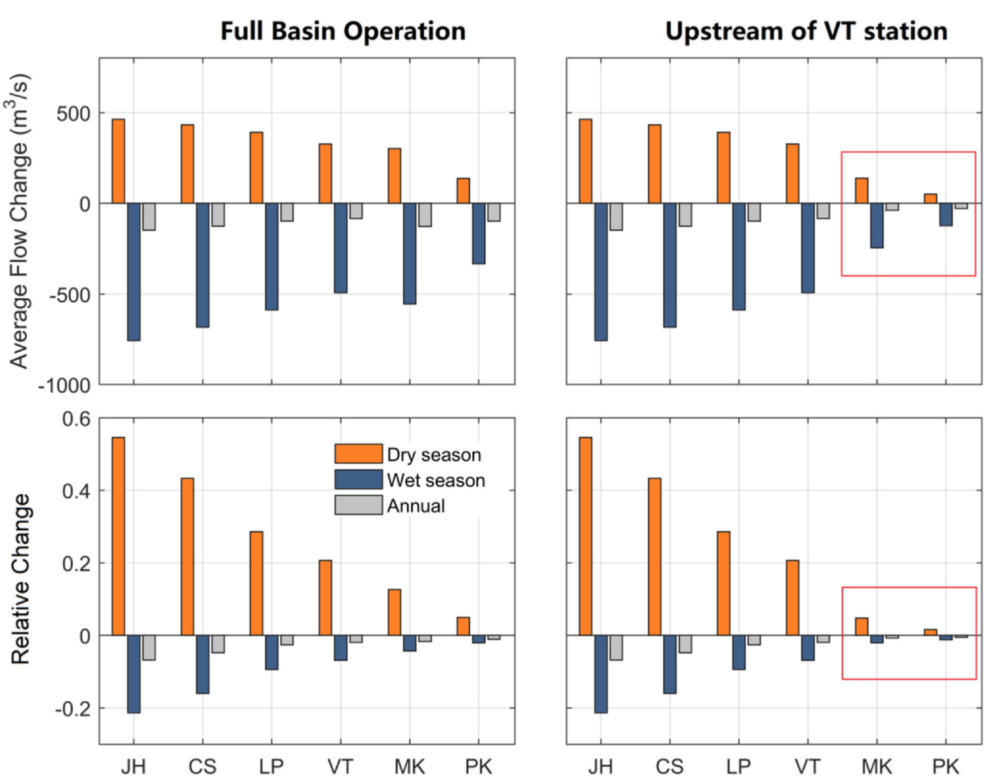

Fig. 7. Reservoir impact on seasonal and annual streamflow changes under different scenarios during the impact period (2008–2016). Reservoir impact was calculated from the difference between the dammed simulation and natural simulation in Fig. 6. "Full Basin Operation" represents the impact of all of the reservoirs in the LMRB, whereas "Upstream of VT Station" only considers the reservoir impact upstream of the VT station. The red box indicates the affected stations.

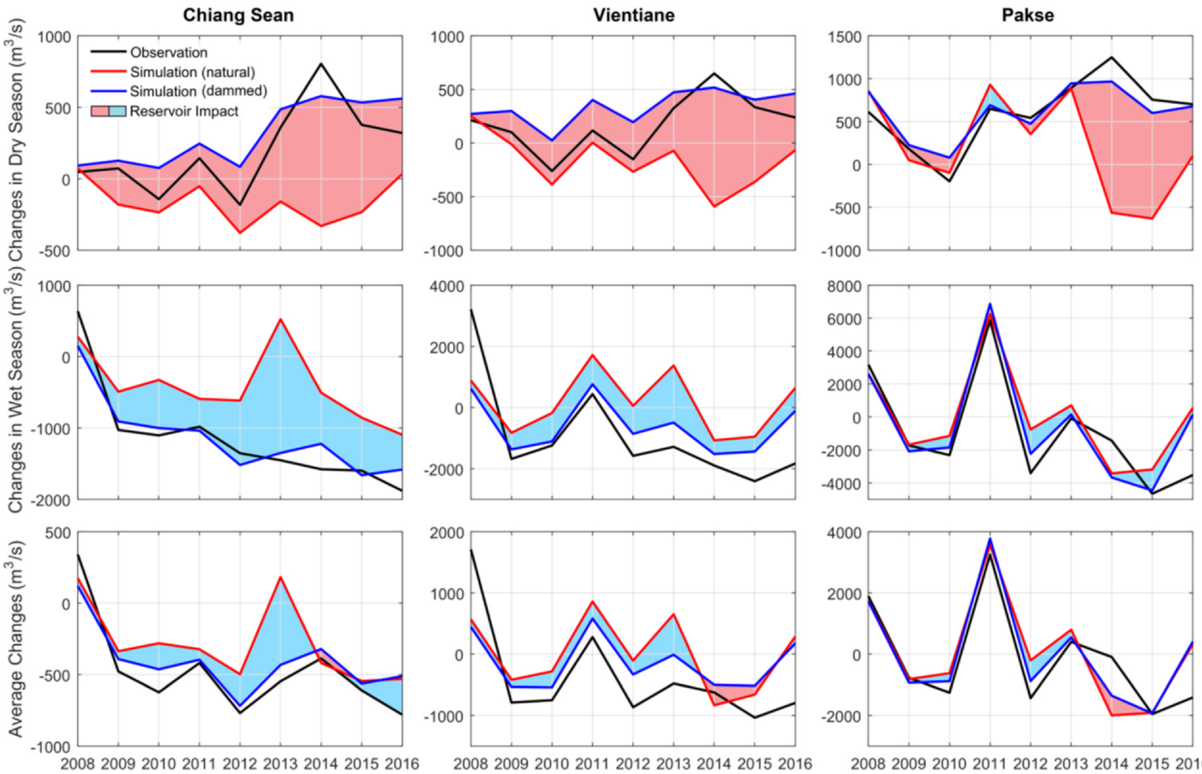

Fig. 8. Temporal variation by the reservoirs to seasonal and annual average streamflow changes in Chiang Sean, Vientiane and Pakse stations in the impact period (2008–2016) compared with the value over the baseline period (1985–2007). The changes were calculated from the streamflow per year during the impact period minus the mean value over the baseline period. The reservoir impact represents the difference between the dammed simulation and natural simulation. The red and blue areas indicate that the reservoir operation has increased or decreased the streamflow, respectively.

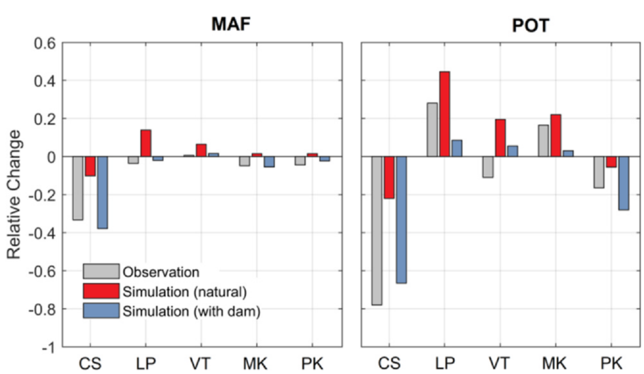

Fig. 9. Relative changes of flood magnitude (MAF) and frequency (POT) at the five selected stations in the impact period (2008–2016) compared with the baseline period (1985–2007).

LMRB. Fig. 9 shows the relative changes of flood magnitude and frequency at the five stations (CS, LP, VT MK and PK) in the impact period (2008–2016) compared with the baseline period (1985–2007). The observed magnitude and frequency of the floods at the five stations in the impact period reduced relative to the baseline period, with the magnitude reduction of 33% at CS and the frequency decreases of 78%, 11% and 17% at CS, VT and PK, respectively. The simulated natural streamflow shows that climate change increased the flood magnitude by 14%, 6%, 2% and increased the frequency by 45%, 20%, 22% at LP, VT and MK, respectively. In consideration of the reservoir operation impact on LP, VT and MK stations, the flood magnitude reduced by 16%, 5% and 7%, respectively, and the frequency reduced by 36%, 14% and 19%, respectively. Climate change and reservoir together affect the flood magnitude (total change of −38%) and frequency (total change of −67%) at the CS station. Overall, the reservoir operation effectively reduces the flood risk raised by climate change in the LMRB.

In contrast to the effective reduction of the flood frequency, the reservoir construction and operation in the LMRB seemed to have only a small effect on the flood magnitude reduction. Despite the large number, most LMRB reservoirs have relatively small storage capacity compared to the streamflow besides Nuozhadu and Xiaowan, so their flood control capacities are limited during large flood events. MAF calculated from the dammed simulation was close to the observed value, while the POT decrease was greater than the observed value (Fig. 9). The VIC − Reservoir model regards the flood prevention as the prime regulation target and maximizes water release before the wet season. However, the actual reservoir operation may not maximize water release for the sake of irrigation and hydropower, leading to a lower flood protection capacity than the modelled value.

Fig. 10 shows the flood frequency variation at the five stations in the LMRB during 1985–2016. In the baseline period, the average flood frequencies of the natural simulation and observation increased analogously, while the observed value decreased greatly during the impact period. This indicates that the reservoir construction and operation have reduced flood frequency in the LMRB.

5. Discussion

This study evaluated the impacts of climate change and reservoir operation on the streamflow and flood events in the LMRB over the impact period of 2008 – 2016 against the baseline period of 1985–2007 with the VIC − Reservoir hydrological model. The VIC model can accurately simulate the seasonal streamflow characteristics of the LMRB (Tatsumi and Yamashiki, 2015), while the VIC − Reservoir model can effectively illustrate the impact of the reservoir on the streamflow. Reservoir construction in the LMRB is an important topic involving the development of politics, ecology and the economy in Southeast Asia. A

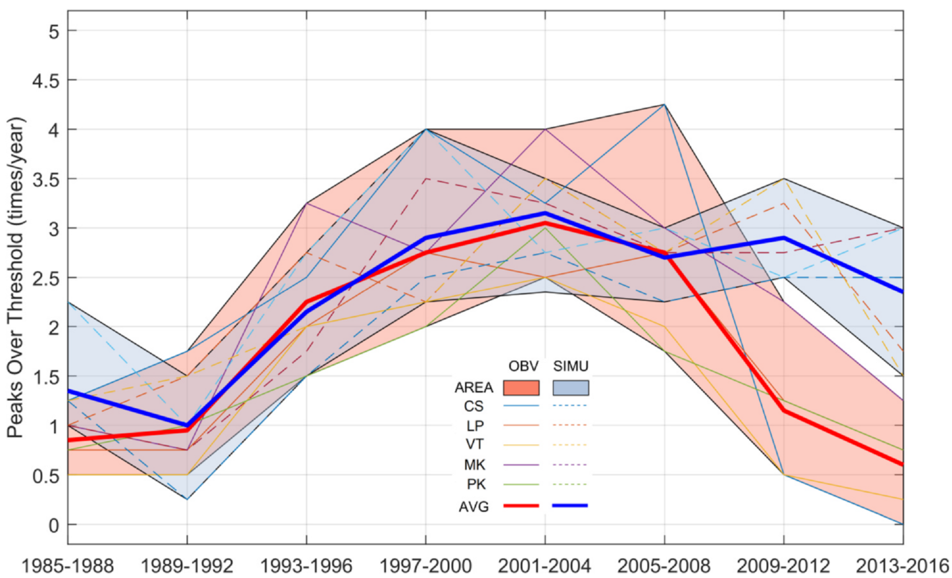

Fig. 10. Variation in the observed flood frequency (red line and shading) and simulated natural floods frequency (blue line and shading) at the five selected stations during 1985–2016. Here, OBV represents observations and SIMU represents simulation. The time interval of flood frequency calculation was 4 years. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

comprehensive assessment of climate change and reservoir impacts will help us better understand streamflow variation in this basin.

5.1. Main findings

The one of the finding shows that the reservoirs reduced the streamflow variability by increasing dry season streamflow (+15% to +37%) and decreasing wet season streamflow (−2% to −24%) in the LMRB. The reservoir operation had a greater impact on increasing the streamflow at the JH, CS, LP and VT stations in the dry season and diminishing the streamflow at the JH and CS stations in the wet season. This impact of the reservoir was tremendous in the upstream station VT but continues to decrease along with the streamflow increases at the stations further downstream. This streamflow alteration pattern by the reservoirs operation is in line with earlier studies including Lauri et al. (2012), Piman et al. (2013), and Hoang et al. (2019). This similarity is partly due to the similar hydropower development information and gauging stations data from the Mekong River Commission. However, our results show considerably higher streamflow increases during the dry season at CS station (+37%) compared to a projected increase of 17% by Hoang et al. (2019). The overestimated dry season streamflow may be because we have considered more Chinese reservoirs and assumed these reservoirs mainly operated for flooding control.

Another finding is that the streamflow changes downstream of the MK station would be affected more by the reservoirs downstream of the VT station (−3%–8%) instead the reservoirs in China (−2%–4%). The upstream reservoir in China decreased the streamflow at the CS station (−5% in northern Thailand), but this reduction from the upstream reservoirs became undetectable after the VT station (southern Laos). This result is consistent with the recent estimates of human activities in the LMRB by Li et al. (2017) and Han et al. (2019) that concluded the impact of the human activities upstream in China was not detected downstream of the LP station. Note that these studies calculated the effects of the human activities as the difference between natural simulation and observation, and our study quantitatively assessed the impact of the reservoir.

This study also shows that the reservoir operation in 2008–2016 eliminated the flood risk increased by climate change in the LMRB. Although climate change increased the flood magnitude by up to 14% and the frequency by up to 45%, the reservoir operation reduced the flood risks by 16% and 36% in the corresponding parts of the LMRB. Based on limited reservoir data (8 constructed in 2008–2016 and 14 will be constructed during 2017–2025), Wang et al. (2017a) concluded the similar conclusion with our results that the reservoir can effectively reduce the flood risk in the LMRB, On considering that the number of dams in the LMRB is projected to reach 138 by 2025 (Hecht et al., 2019), the reservoir will have a greater impact on the flood in the future period.

5.2. Major implications of reservoirs

Substantial changes in the LMRB's streamflow affected by reservoirs will likely have important implications for agricultural production, water management and ecosystem dynamics. On the one hand, the increased dry season flow and decreased wet season flow as a result of the LMRB reservoir operation could lead to greater benefits. The increased dry season flow could mitigate the saltwater intrusion in the Vietnamese Mekong Delta and benefit the crop irrigation in favor of the agricultural production in the LMRB (Kondolf et al., 2014). In addition, reservoirs can increase the resilience of the basin to natural fluctuations such as drought and flood. For instance, the upstream reservoirs in the LMRB released the emergency water to overcome the downstream drought during the super El Nino event in 2016. Moreover, the general flow decrease in the wet season can reduce flood risk. In comparison with the simulated natural flow, the dammed simulation and observation data indicate that the reservoir effectively offsets the flood magnitude and frequency from 2008 to 2016. According to the EM-DAT (https://www.emdat.be/), the number of flood events in the four downstream countries increased in 1985–2008 but decreased dramatically after 2008 (Fig. 11). The reservoirs could have reduced extreme high-flow risks from climate change in most parts of the LMRB.

On the other hand, the reservoirs also likely result in the potential adverse influence. The large alterations to the natural streamflow regime stimulated by the reservoir operation will generate disturbances to aquatic ecosystems and the vegetation distribution (Yang et al., 2019). Dams may impede fish migration and reproduction, resulting in reduced food security (Anh et al., 2018), particularly when the fisheries are the primary supply of protein for the local inhabitants and a major source of economic income in the Tonle Sap Lake area. Many new reservoirs are under construction or in the planning stage in southern Laos and this would further reduce both streamflow and sediment transport in the wet season. This would deplete soil nutrient provision and exacerbate riparian erosion in the Mekong Delta (Schmitt et al., 2017).

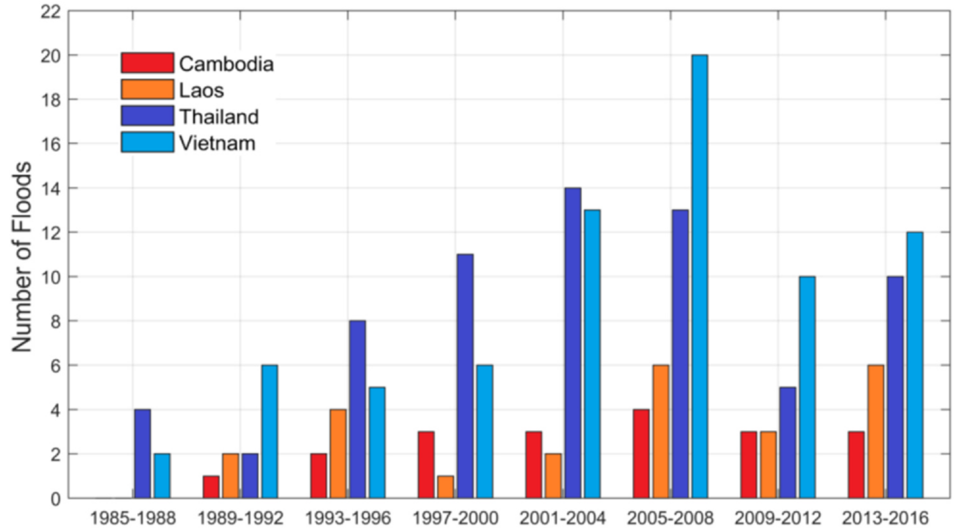

Fig. 11. Changes of flood events number in the four major countries in the LMRB (according to EM-DAT).

5.3. Limitations and perspectives for future research

There are some limitations in our research that require further investigations. Because of the lack of reservoir operation data, our model was set to fill the reservoir immediately after the reservoir began generating power, whereas the reservoir may actually begin to fill a few years after its construction. Moreover, under actual circumstances, reservoirs usually function for multiple purposes, such as power generation, water supply, flood control and irrigation. As a result, the simulation outcome may not be accurate if the reservoir operation rules change. The water storage in the reservoir will increase the area of the river channel, as suggested by the 600% river evaporation increase by 2014 compared with the 1990s (Räsänen et al., 2017). Limited by the model resolution, we did not consider the influence of reservoir impoundment which might increase the superficial area of the river channel and the related evaporation. Agriculture and inland aquaculture are the pillar industries of the LMRB, and an increasing need for food supply driven by the population explosion has forced downstream countries to expand their planting area. Hoang et al. (2019) pointed out that the rapid expansion of the planting area would reduce the annual streamflow by 4% in the LMRB. Liu et al. (2020) showed that the forest areas have shrunk by 77,735 ha and the inland aquaculture area has increased rapidly by 720,913 ha since 2009 (Liu et al., 2020). The shrinking forest land but expanding inland aquaculture areas would lead to the regional evaporation changes and exert a far-reaching influence on the LMRB streamflow. These factors not considered in models may lead to uncertainties in the simulation. The global change factors that drive change of the terrestrial water cycle in the LMRB need further discussion in future research (Tang, 2020).

At the same time, due to the unused of KT station, the impact of a large number of reservoirs in southern Laos and southern Vietnam has not been assessed in this study. Although the KT station is a very representative station in the LMRB and has widely been used in recent studies (Hoang et al., 2019; Kummu et al., 2010; Lauri et al., 2012; Mohammed et al., 2018), the Mekong River Commission annual report (MRC, 2018) indicated that the streamflow data at KT station contain major uncertainties and errors. The local hydrologist measures the water level at the KT station, and then transforms it into the streamflow data based on the rating curve established in the 1980s (Institute of Hydrology, 1988). Park et al. (2020) reported that KT station and its surrounding area were subjected to severe riverbed mining activities after 2000, leading to the changes in the rating curve. Therefore, the reliability of the streamflow data at the KT station requires future research.

This study provides critical reference for future relevant research. The dead storage capacity of reservoir and powerful streamflow modification effects of hydropower dam's operation requires careful considerations. The costs and benefits of the future largescale hydropower developments should be detailed evaluated across multiple sectors and regions in the LMRB. Another possible research direction is to assess the impacts of the variation in the streamflow and flood characteristics on the water resources and food supply (including fishery, agricultural production) under the future urbanization and population growth scenario.

6. Conclusions

This study aimed to estimate the flood events impacted by climate change and reservoir operation in the Lancang-Mekong River Basin with the advanced VIC − Reservoir model. On the basis of the Mann–Kendall test results and the reservoirs construction history, we divided the time into the baseline period (1985–2007) and the impact period (2008–2016). The major findings are summarized as follows:

(1) During 2008–2016, China's reservoir construction decreased the annual streamflow by 5% ($-119.4\ m^3/s$) in northern Thailand and substantially increased the dry season flow (+15% to +37%) and reduced the wet season flow (−2% to −24%). Nonetheless, this impact became undetectable in the downstream of VT station (northern Laos).

(2) The streamflow changes downstream of the MK station would be affected more by the reservoirs downstream of the VT station (−3%–8%) instead the reservoirs in China (−2%–4%). The upstream reservoir in China decreased the streamflow at the CS station (−5% in northern Thailand). The streamflow changes in the downstream region at southern Laos, Cambodia and southern Vietnam are mainly associated with the local reservoirs and climate change.

(3) The reservoir operation in 2008–2016 reduced both magnitude and frequency of the flood events in the LMRB. Even though climate change exacerbated the flood magnitude by up to 14% and the frequency by up to 45%, the reservoir operation reduced the flood risks by 16% and 36% in the LMRB.

Our research presents a reference for assessing the overall impact of climate change and reservoir operation on the flood events with the VIC − Reservoir model to enhance water resource management and strategic decision making in the LMRB. Further investigations are needed to comprehensively evaluate the influence of future streamflow changes on local ecosystems and socioeconomics.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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