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Key Points:
- The model coupled with reservoir regulation realistically simulated the effects of dams on floods in the Lancang-Mekong River Basin
- Climate change increases flood magnitude and frequency, but reservoir regulation reduces flood risk particularly in the upper basin
- Combining climate change and reservoir regulation, flood risk is reduced in the upper basin but still increases in the lower basin

Supporting Information:
- Supporting Information S1

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Dam Construction in Lancang-Mekong River Basin Could Mitigate Future Flood Risk From Warming-Induced Intensified Rainfall

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Abstract Water resources management, in particular flood control, in the Lancang-Mekong River Basin (LMRB) faces two key challenges in the 21st century: climate change and dam construction. A large-scale distributed Geomorphology-Based Hydrological Model coupled with a simple reservoir regulation model (GBHM-LMK-SOP) is used to investigate the relative effects of climate change and dam construction on the flood characteristics in the LMRB. Results suggest an increase in both flood magnitude and frequency under climate change, which is more severe in the upstream basin and increases over time. However, stream regulation by dam reduces flood risk consistently throughout this century, with more obvious effects in the upstream basin where larger reservoirs will be located. The flood mitigation effect of dam regulation dominates over the flood intensification effect of climate change before 2060, but the latter emerges more prominently after 2060 and dominates the flood risk especially in the lower basin.

Plain Language Summary In this study, we present a model-based projection of flood risk in Lancang-Mekong River. It is found that the basin will experience more frequent and bigger flood events in the future in response to climate change. Through reservoir regulation, flood risk can be mitigated particularly in the upper basin where large reservoirs are located. Combining climate change and reservoir regulation, flood risk is reduced in the upper basin but the increased flood magnitude and frequency from climate change still dominant in the lower basin.

1. Introduction

As the most important transboundary river in Asia, the Lancang-Mekong River originates from the Tibetan Plateau in China and flows through six countries (China, Myanmar, Lao PDR, Thailand, Cambodia, and Vietnam) before discharging to the South China Sea. The Lancang-Mekong River has a length of 4,350 km, a drainage area of over 795,000 km^2, and an annual discharge of 14,500 m^3/s (MRC, 2010a). Flood pulse is the key element that shapes the unique ecosystem and drives the high ecosystem productivity for the Lancang-Mekong River Basin (LMRB) (Kummu et al., 2006; Arias et al., 2012; Lamberts & Koponen, 2008; Västilä et al., 2010).

The LMRB is facing two major challenges to its water resources in the 21st century: potential climate change and ongoing and planned dam constructions (Lauri et al., 2012). A changing climate could modify rainfall patterns (Huntington, 2006; Schiermeier, 2011; Trenberth, 2011), leading to changes in the hydrological cycle (Nijssen & Lettenmaier, 2004). Combined with warming that has direct impacts on evapotranspiration, runoff generation can be significantly altered (Vörösmarty et al., 2000). On the other hand, anthropogenic activities such as reservoir operations and irrigation could disrupt the natural river flow and alter the characteristics of the hydrological regimes (Hall et al., 2014). Understanding the impacts of climate change and reservoir regulations on the LMRB is fundamental to planning and management of its resources.

During the second half of the twentieth century, the LMRB experienced an increase in extreme flood frequency and a slight decrease in flood magnitude, but the changes are more complex due to the differences of flood mechanism across the basin (Delgado et al., 2010). Previous studies found discernible climate change impacts, with a small increase in annual streamflow but significantly larger increases in interannual variation and an increase in flood peak and flood duration over the LMRB (Hoanh et al., 2010; Hoang et al., 2016; MRC, 2010b; Västilä et al., 2010; Hirabayashi et al., 2013). Despite uncertainty in the projection of precipitation (Thompson et al., 2013), future warming consistently shifts the flood peak date earlier due to earlier snowmelt in the basin (Kingston et al., 2011; Thompson et al., 2013).

Rapid population growth and economic development have increased the demand for water resources and energy in the past few decades (MRC, 2005, 2010b). More hydropower structures have been constructed in the LMRB (Grumbine & Xu, 2011; Johnston & Kummu, 2012; Keskinen et al., 2012). A 2007 study reported as many as 261 hydropower dams under construction or planned in the LMRB (King et al., 2007). The upper basin may experience heavier modification (Räsänen et al., 2012; Räsänen et al., 2017). Dams have inevitable impacts on the hydrological regime, including changes to high and low streamflow (Arias et al., 2012) and reduction of flood peak (Adamson, 2001; ADB, 2004; Blackmore et al., 2004; Hoanh et al., 2010; Liu et al., 2016).

Considering both climate change and reservoir regulations is critically important for projecting future flood trends in the LMRB, but such studies have been rare. Hoanh et al. (2010) and MRC (2010b) suggested that reservoir regulations would increase low flow and decrease flood peak, while climate change would have the opposite effects. A study of two subcatchments of the LMRB suggested offsetting effects in dry seasons and reinforcing effects in flood seasons when climate change and reservoir operations are considered in combination (Ngo et al., 2016). When all the planned dam constructions are complete, the total active capacity of the LMRB is estimated to increase from 5 km^3 to more than 100 km^3 (Johnston & Kummu, 2012). This motivates the current study to consider both existing and future dam constructions and climate change for analysis of future flood trends in the LMRB.

2. Data and Methodology

The distributed hydrological model used in this study is Geomorphology-Based Hydrological Model (GBHM) (Yang et al., 2002). More information about GBHM can be found in the supporting information. Here in this study, the 5 × 5 km resolution GBHM-LMK model configured by Wang et al. (2016) is adopted.

The original GBHM-LMK model did not include a dam operation module, so the model is less skillful in the upstream basin where several large reservoirs are present on Lancang River (Wang et al., 2016). To simulate the effects of reservoir regulation on floods, the Standard Operation Policy (SOP) model (Morris & Fan, 1998) is coupled with the river routing module of GBHM-LMK (see details in supporting information).

Two flood series extraction methods are adopted in this study. The first uses the maximum daily discharge for each year to obtain the Mean Annual maximum Flood (MAF) to evaluate flood magnitude. The second applies the Peaks-Over-Threshold (POT) approach (Mallakpour & Villarini, 2015) to obtain flood frequency. Detailed description of these two methods can be found in supporting information.

We used the forcing data from five global climate models (GCMs) provided by the Intersectoral Impact Model Intercomparison Project (ISI-MIP) (Hempel et al., 2013). The five GCMs include GFDL-ESM2M, HadGEM2-ES, IPSL-CM5a-LR, MIROC-ESM-CHEM, and NorESM1-M, each bias corrected and statistically downscaled to daily and 0.5° resolution by ISI-MIP. All GCMs include two Representative Concentration Pathways (RCPs), a stabilization scenarios (RCP4.5) and a business-as-usual scenario (RCP8.5) (Moss et al., 2010).

As hydropower potential is mainly along the mainstream and official dam data are not available in the tributaries, only dams on the mainstream are considered in this study. Information on the active capacity, location, and regulation type of 22 commissioned, under construction or planned dams are collected from the Greater Mekong CGIAR (Consultative Group on International Agricultural Research) Research Program on Water, Land and Ecosystems (WLE) (CGIAR Research Program On Water, L. A. E. G, 2016). Detailed information of the dams is listed in Table S1 in the supporting information, and the dam locations are shown in Figure 1. The total active storage (i.e., storage that can be used for flood control, power production, and downstream water supply) of the 22 reservoirs is 33.67 km^3, accounting for more than 50% of total active storage in the LMRB. Among the dams listed, commissioned and under construction dams, including Nuozhadu and Xiaowan, are mainly located in upper LMRB and operated by China. Most dams on lower LMRB are at the planning stage except Xayabouri. This distribution pattern may have impacts on the flood regime in the future.

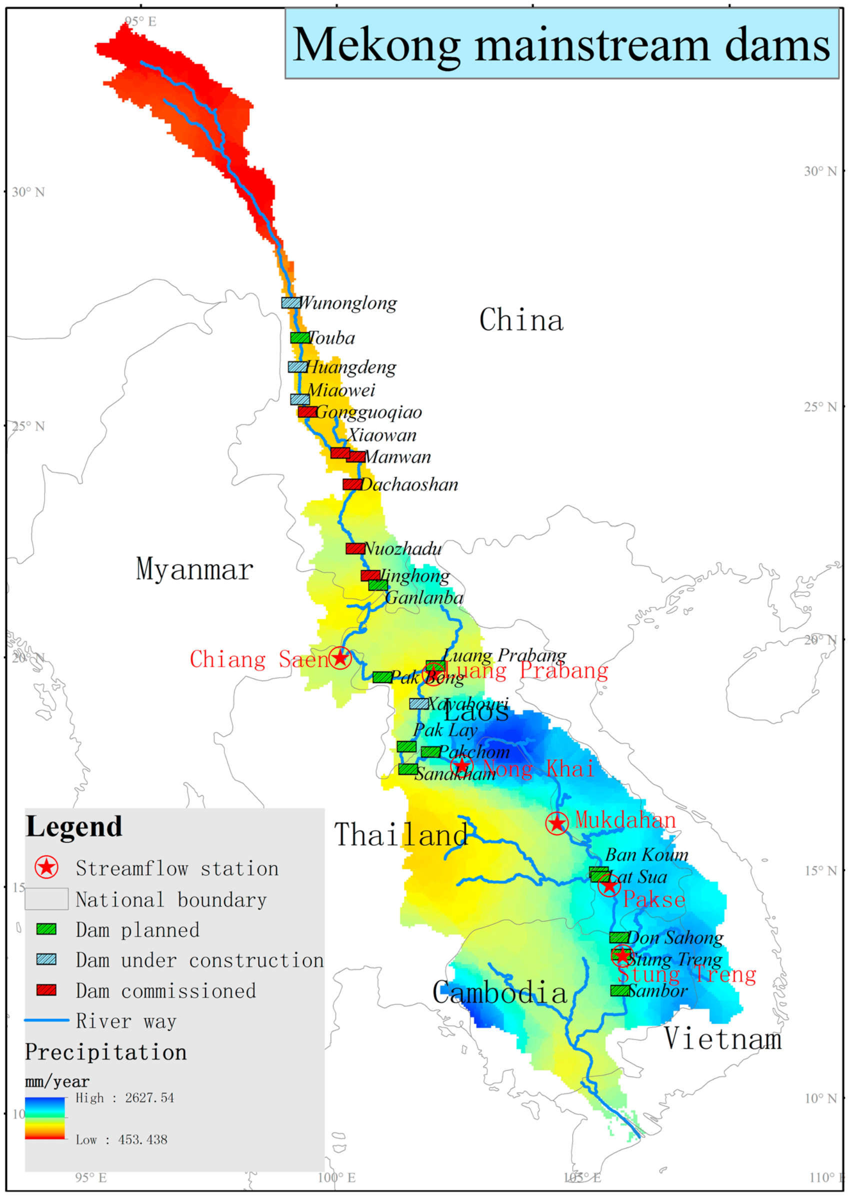

Figure 1. Map of the mainstream dams on the Lancang-Mekong River. Red stars refer to streamflow gauges. The background is the annual mean rainfall rate during baseline period provided by the five GCMs.

Daily discharge data for 1975–2004 at six gauges on the mainstream, namely Chiang Saen (CS), Luang Prabang (LP), Nong Khai (NK), Mukdahan (MK), Pakse (PS), and Stung Treng (ST) from upstream to downstream as shown in Figure 1, are obtained from the MRC historical observation data set (http://portal.mrcmekong.org/index).

Using the simulations from five Coupled Model Intercomparison Project Phase 5 GCMs as atmospheric forcings, GBHM-LMK produced a baseline simulation (BL) and a climate change simulation (CC) for the LMRB for the historical and future periods, respectively. GBHM-LMK-SOP was then used to repeat the two simulations for historical (RR, short for the reservoir regulation case) and future climate (CR, short for the climate change and reservoir regulation case) conditions with reservoir regulations. The four simulations are listed in Table S2. Each simulation covers 30 years for the baseline (1975–2004), near future (NF: 2010–2039), middle future (MF: 2040–2069), and far future (FF: 2070–2099). Comparison of the simulated and observed POT flood thresholds at six gauges on the mainstream shows that GBHM-LMK is quite skillful in capturing the flood

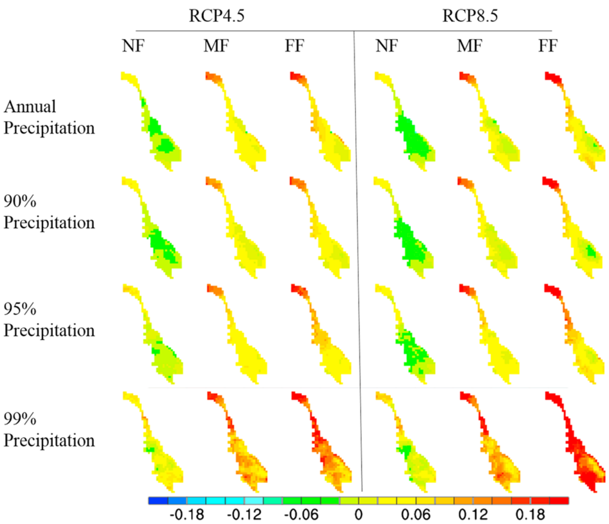

Figure 2. Mean relative change of annual, 90%, 95%, and 99% precipitation over the LMRB in the future projected by the five GCMs for the near future (NF), middle future (MF), and far future (FF) and two emission scenarios, (left) RCP4.5 and (right) RCP8.5.

thresholds in the LMRB (see details in supporting information). Reduction of biases in the RR simulation relative to the BL simulation shows additional skill of GBHM-LMK-SOP in capturing the effects of reservoir regulation on floods (Table S3).

3. Precipitation Trends Over the LMRB

The flood season of the LMRB is mainly controlled by the monsoon, with precipitation being the key factor of flood generation (Cook et al., 2012). Figure 2 shows the mean relative change of annual precipitation (CC/BL-1) over the LMRB projected by the five GCMs. Annual precipitation shows increase trends for both RCPs, but the spatial variation is quite significant, with larger increase in the headwater at high elevation and smaller increase or reduction in the lower basin.

Figure 2 also presents the relative change of the 90%, 95%, and 99% daily precipitation, as extreme rainfall events will have evident impacts on flooding (Schiermeier, 2011). The change patterns for the 90% precipitation are comparable to that of the annual precipitation, but the 95% and 99% precipitation show more prominent increases so that in the middle and far future, almost the entire LMRB is projected to experience increases in the 99% precipitation. The larger increase in extreme than mean precipitation is consistent with the understanding that mean precipitation is constrained by the energy supply (i.e., globally precipitation is balanced by evaporation, which is constrained by radiation), but extreme precipitation is more influenced by the moisture supply, which increases with warmer temperature at roughly 7% per degree of warming (Held & Soden, 2006; O'Gorman, 2015; Schiermeier, 2011). During NF, the warming is small and the emissions in RCP4.5 and RCP8.5 are comparable so the minor differences between the two scenarios may be related to differences in atmospheric circulation changes. During MF and FF, higher emissions in RCP8.5 than RCP4.5 result in larger warming and hence larger increase in atmospheric water holding capacity and extreme precipitation in the former. Overall precipitation regime is projected to change, and the upper basin is more vulnerable to warming. Such changes will certainly have impacts on flood regimes over the LMRB.

4. Flood Trends Over the LMRB

4.1. Flood Regimes Under Climate Change

Using the BL simulation as a reference, the impacts of climate change on MAF and flood frequency is analyzed. Figure 3 compares the MAF and flood frequency at six mainstream gauges between CC and BL simulation. MAF will increase under warming in the LMRB for both scenarios. Spatially, the relative change varies among the gauges, with CS and MK experiencing more significant increases. The differences among the gauges reflect the spatial patterns of changes in annual precipitation and extreme rainfall intensity. CS and MK show the largest changes in response to the larger precipitation regime shift in the upper basin. PS is influenced heavily by the streamflow at Mukdahan as the runoff generated between MK and PS only contributes about 20% of the streamflow at PS (MRC, 2005). As streamflow at MK only accounts for 59% of the total streamflow at ST (MRC, 2005), and annual precipitation and extreme rainfall intensity in the lower basin are not projected to increase by much (Figure 2), the increase of MAF at ST is much lower than MK and CS.

For flood frequency, the dependence of the changes on RCPs and time periods is comparable to that of MAF. But unlike MAF, the lower basin will experience more remarkable increase of flood events than the upstream basin. This may be caused by the different flood mechanisms between the upper and lower basins. In the upper basin, flood is mainly caused by snowmelt so flood magnitude may increase with warming but the frequency may be less affected. In the lower basin, flood is controlled by precipitation so more precipitation and heavier extreme rainfall events should increase the flood frequency.

In Figure 3, the differences in the change of MAF and flood frequency between the RCP4.5 and RCP8.5 scenarios are comparable to the differences in change in extreme precipitation between the two scenarios

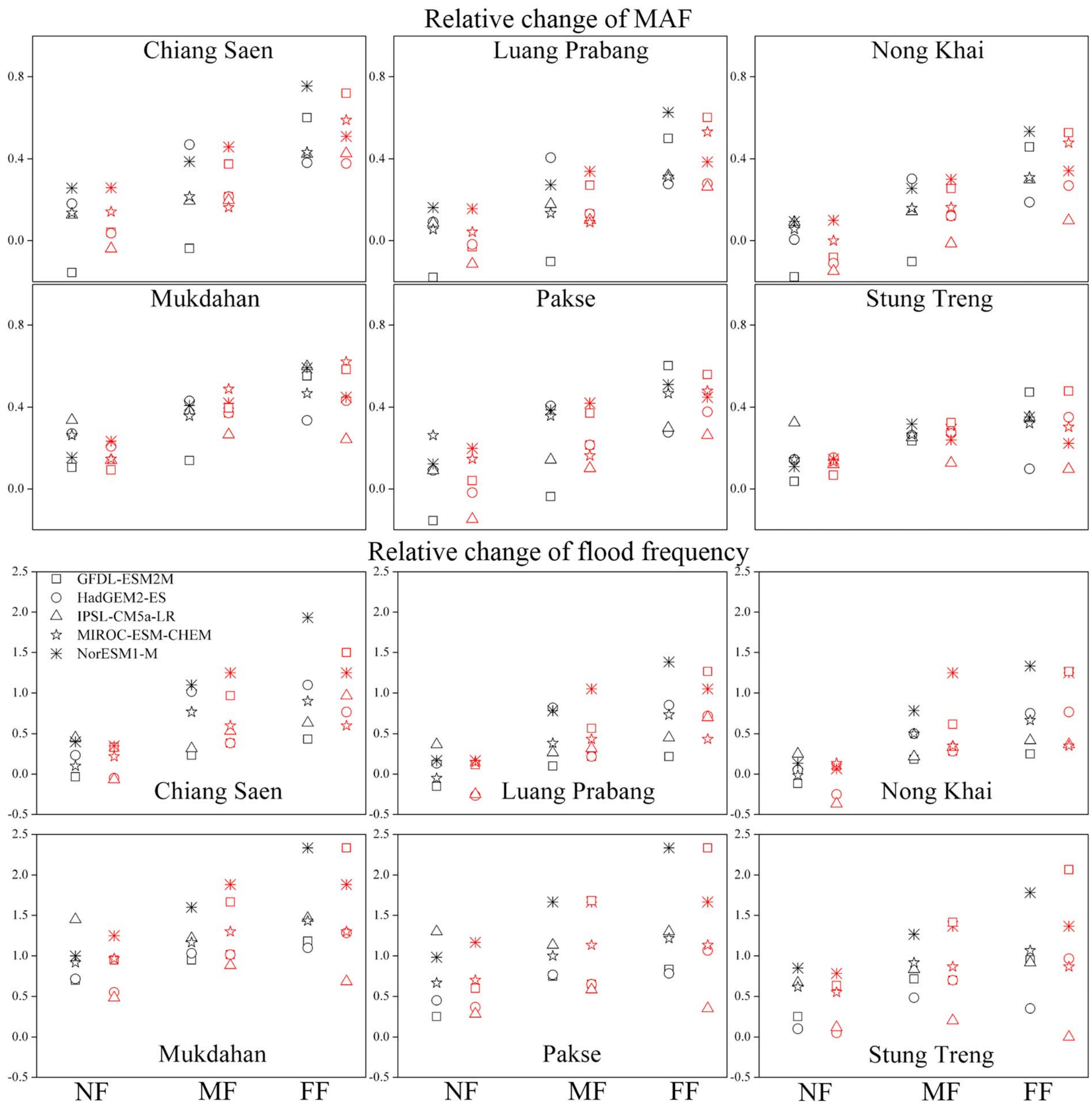

Figure 3. Relative change of MAF and flood frequency under climate change (i.e., CC/BL-1) at six gauges over the LMRB in the near future (NF), middle future (MF), and far future (FF) for the RCP4.5 (black) and RCP8.5 (red) scenarios. Different symbols represent different GCMs.

shown in Figure 2, that is, larger increases in RCP8.5 than RCP4.5 during MF and FF but vice versa during NF. The more striking result from Figure 3 is the much higher rate of increase in flood frequency than MAF, which may have an obvious physical explanation. In the monsoon-dominated LMRB basin, an increase in annual precipitation (Figure 2) will generally increase soil moisture. A wetter soil is more conducive to flood because even a medium rainfall event may trigger flooding. Hence, combined with the increase in extreme rainfall intensity, flood frequency will increase more due to the compounding effect. Flood magnitude, on the other hand, depends mainly on the magnitude of extreme rainfall (Cook et al., 2012; Sivapalan et al., 2005), so the rate of increase in MAF may be smaller compared to that of flood frequency.

4.2. Flood Regimes Under Reservoir Regulation

The effects of reservoir regulation on floods are investigated by comparing the simulations from GBHM-LMK and GBHM-LMK-SOP during 1975–2004 driven by historical simulations from the GCMs (i.e., the BL versus RR

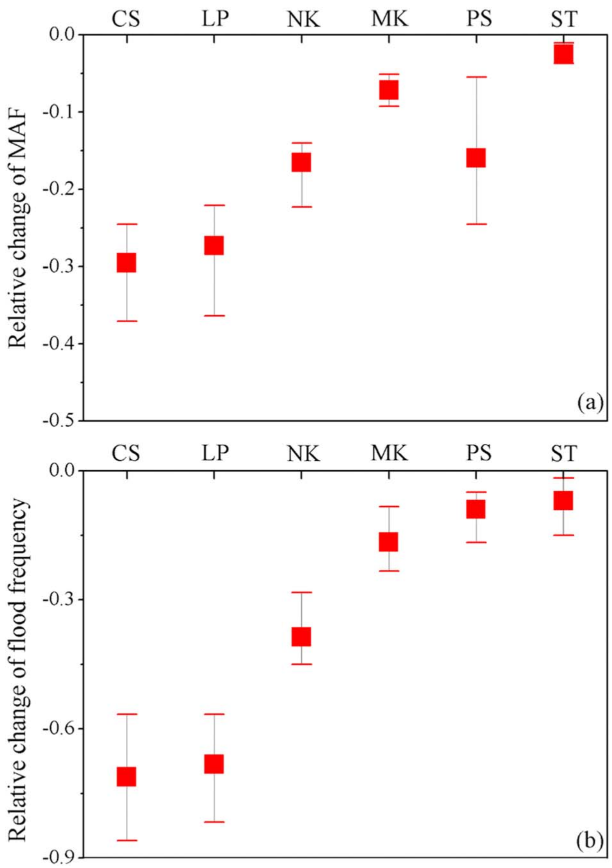

Figure 4. Relative change of (a) MAF and (b) flood frequency with reservoir regulation (i.e., RR/BL-1) at six gauges over the LMRB during the baseline period 1975–2004. (CS, Chiang Saen; LP, Luang Prabang; NK, Nong Khai; MK, Mukdahan; PS, Pakse; and ST, Stung Treng). Different symbols represent different GCMs.

simulations). Figure 4 compares the relative change in MAF between the BL and RR simulations at the six gauges. Clearly, reservoir regulation suppresses MAF but the reduction generally decreases from upstream gauges (−29.5% at CS) to downstream gauges (−2.6% at ST), except for PS. This can be explained by the distribution of dams on the mainstream. If we define a Reservoir Impact Index (RII) as the total upstream reservoir storage capacity normalized by the annual streamflow volume to quantify the reservoir regulation effects at the gauge (Wang et al., 2017), we can see that upstream gauges have higher RII values mainly because the annual discharge is much smaller (see Table S4) so they will be impacted more heavily than downstream gauges. Note that here the definition of RII does not account for the impacts of dam locations. Although PS has a very low RII value (0.106), reservoir regulation reduces MAF remarkably (−15.9%) because PS is immediately downstream of two dams, including Lat Sua, the largest reservoir in the lower basin. As a result, discharge at PS will be more directly modified by the released water from the two dams (as comparing to the dams that are farther upstream), which magnifies the effect of reservoir regulations.

Similarly, flood frequency change due to reservoir regulation shows striking reductions at upstream gauges (−72.0% at CS) and much smaller reductions at downstream gauges (−6.0% at ST). This can also be explained by the RII values. Interestingly at Pakse, the decrease of flood frequency is not that remarkable (−9.0%), unlike the reduction in MAF (−15.9%). This is because the flood peak at Pakse can be suppressed by reservoir, which reduces MAF, but due to the relatively small capacity of reservoir (lower RII value), the regulated flood peak may be still higher than the flood threshold value so the flood frequency change is small. Importantly, the decrease of MAF at CS, LP, and NK is less than 30% (Figure 4), but the decrease of flood frequency is much more remarkable (up to 70%). This means reservoir regulation is more effective in mitigating flood frequency than flood peak value.

Overall, dams on the mainstream can effectively suppress flood peak and reduce flood frequency on the LMRB. Due to the distribution of dams in the mainstream (large reservoirs mainly located in the upper basin), the upper basin will benefit more from reservoir regulation.

4.3. Flood Regimes Under Climate Change and Reservoir Regulation

Figure 5 presents the relative change of MAF and flood frequency in the future with climate change and reservoir regulation. Compared with Figure 3, including reservoir regulation has a dramatic effect on MAF at upstream gauges. In NF and MF, MAF is reduced at CS, LP, and NK instead of increase with climate change alone implying reservoir regulation has larger control on upstream gauges. However, as climate change effects increase with time, the relative change of MAF becomes positive in FF for both RCP4.5 and RCP8.5, but the rate of increase (around 15%) is much lower than without reservoirs (around 40%). On the contrary, MAF increases in the downstream gauges, MK and ST, regardless of the periods or scenarios, which means climate change has larger control on flood at the lower basin. This can be explained by the dam distribution listed in Table S4 showing the limited reservoir capacity for flood control at the downstream gauges, so climate change effects dominate. At PS, the increase of MAF is generally small because PS is located just downstream of two reservoirs that effectively reduce MAF and counter the increase due to climate change.

Flood frequency changes show very similar patterns as MAF with negative changes at upstream gauges and positive changes at downstream gauges, and the changes of flood frequency are generally amplified relative to those of MAF. We can conclude that reservoir regulation will have larger impacts on upstream gauges while climate change will have larger impacts on downstream gauges with the planned and commissioned dams.

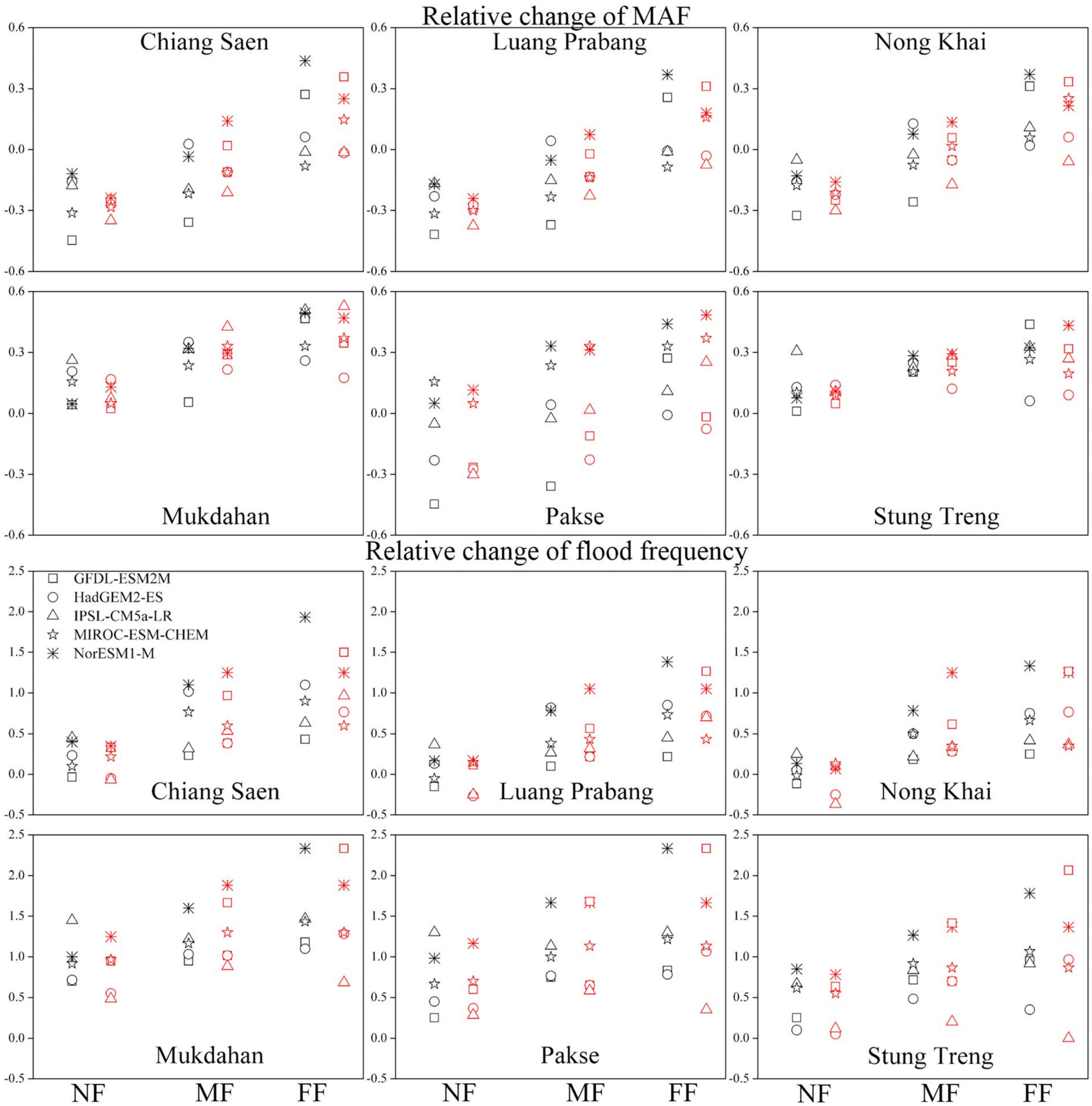

Figure 5. Same as Figure 3 but for relative change of MAF and flood frequency under climate change with reservoir regulation (i.e., CR/BL-1) at six gauges over the LMRB in the near future (NF), middle future (MF), and far future (FF) for RCP4.5 (black) and RCP8.5 (red).

Furthermore, Figure S2 shows the relative change of MAF and flood frequency between the CR and CC simulations to isolate the reservoir effects in the future. It is clear that reservoir regulations can reduce flood magnitude and flood frequency at all six gauges and two scenarios at different levels. However, the difference between upper and lower basins is striking. At the most upstream gauge CS, reservoir regulation suppresses MAF by more than 25% and flood frequency by more than 60%. On the contrary, at the farthest downstream gauge ST, reservoir regulation only reduces flood peak and flood frequency, by 3% or less. Lastly, the figure indicates that the relative effects of reservoir regulation decrease over time as climate change effects emerge more prominently with larger warming.

5. Summary and Discussion

This study presents the latest assessment of the impacts of climate change and reservoir regulation on flood risk over the LMRB using a distributed hydrological model coupled to a simple operation model, GBHM-LMK-SOP. Comparing four simulations (BL, CC, RR, and CR), the individual and combined impacts of climate change and reservoir regulation on flood magnitude and frequency are evaluated at six gauges on the mainstream.

Annual precipitation and extreme rainfall intensity are both projected to increase over the LMRB, with the rainfall regime in the upper basin more vulnerable to climate change. Climate change will intensify flood risk, with flood frequency increasing at a higher rate (10%–140%) than flood magnitude (5%–55%). On the contrary, reservoir regulation can effectively suppress flood magnitude and reduce flood frequency, and the impact is larger for flood frequency than flood magnitude. Reservoirs have larger impacts on upstream gauges (−29.5% on magnitude and −72.0% on frequency at CS) and weaker impacts on downstream gauges (−2.6% on magnitude and −6.0% on frequency at ST), as large reservoirs are mainly located in the upper basin. Combining climate change and reservoir regulation, striking differences are projected for gauges at the upper versus lower basin, with decreases in flood risk at the upper gauges and increases at the lower gauges. In other words, reservoir regulation will dominate the flood regime at the upper basin and climate change will dominate the flood regime at the lower basin. Hence, for the lower basin, more mitigation measures or optimization of hedging rules are needed to reduce flood risk due to climate change.

Using five GCMs and two emission scenarios, our results (Figures 3–5) show that uncertainty in projecting flood changes is mainly related to uncertainty in the GCM projections. The largest uncertainty is found in projecting flood frequency at downstream gauges where flood generation is mainly driven by precipitation, which is more variable than snowmelt. Uncertainty propagation from upstream may also add to the uncertainty in flood frequency downstream. Large uncertainty is also found in projecting MAF changes at PS where uncertainty in flood is amplified by reservoir regulations. Future works should further address uncertainties and explore dam operation rules for adaptive water management in the region. Lastly, while dam constructions have significant potential for managing flood risk, their impacts on ecosystems should also be considered for developing holistic strategies for planning and managing the LMRB.

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