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Can reservoir regulation mitigate future climate change induced hydrological extremes in the Lancang-Mekong River Basin?

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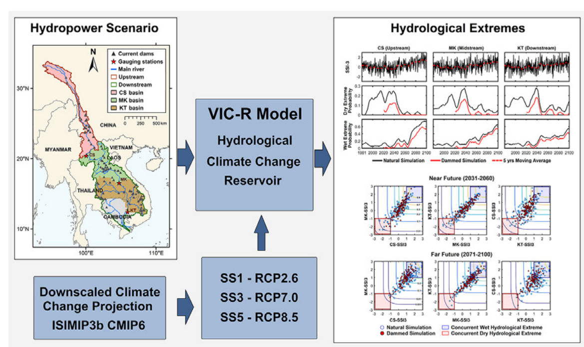
HIGHLIGHTS

- Concurrent hydrological extremes in Lancang-Mekong River basin are studied.
- Assessed the impact of climate change and reservoir on hydrological extremes
- Climate change will cause higher flood risk at the end of the 21st century.
- Reservoir regulation will reduce the hydrology extremes.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydrological extremes both dry extremes and wet extremes can be exacerbated by climate change and threat water security in Lancang-Mekong River Basin (LMRB). Reservoirs can be managed effectively mitigate the risks of these extreme events. However, current knowledge about changes in hydrological extreme events under climate change and the effectiveness of reservoir regulation in LMRB remains limited. This study fills the knowledge gap by evaluating the effectiveness of reservoir regulation for changing hydrological extremes in the 21st century. The VIC-Reservoir hydrological model forced by the bias-corrected CMIP6 climate forcing data were used to project the future streamflow changes in LMRB, and the copula-based joint Standardized Streamflow Index (SSI) was adopted to identify basin-wide dry and wet hydrological extremes. Our results indicate that the streamflow in LMRB will first decrease until 2038 and then increase under the SSP5-RCP8.5 scenario (Similarly, 2020 in the SSP1-RCP2.6 scenario and 2042 in the SSP3-RCP7.0 scenario), which will lead to a substantial increase in basin-wide dry hydrological extremes (up to 33% in the 2040s) and wet hydrological extremes (up to 363% by the end of the 21st century). Reservoir regulation can mitigate the basin-wide dry extreme events by 100% and the wet extreme by 32%. While the future dry hydrological extreme can be mitigated by reservoir regulation, the lack of the reservoir storage capacity to deal with wet hydrological extreme poses a challenge to transboundary water management in the basin.

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1. Introduction

Hydrological extremes including dry extreme and wet extreme have received widespread attention because they directly affect human activities (Liu et al., 2017; Long et al., 2013). As anthropogenic disturbance has reached unprecedented levels in recent decades, the terrestrial water cycle is undergoing rapid changes characterized as non-stationarity in hydrology, resulting in more extreme events, which would affect the agriculture, ecosystem, and socioeconomic development (Tang, 2020; Vandenberghe et al., 2011). As one of the most important transboundary rivers in the world, the Lancang Mekong River Basin (LMRB) is affected by the increasing hydrological extreme events (Räsänen and Kummu, 2013; MRC, 2019), which have threatened the safety of rain-fed agriculture, fishery, and hydropower infrastructure in this basin (Arias et al., 2014).

At the same time, climate change and rapid reservoir expansion have brought new challenges to LMRB (Lauri et al., 2012). Due to its monsoon climate, streamflow characteristics of LMRB are more susceptible to climate change. Hoang et al. (2016) and Kiem et al. (2008) pointed out that increased precipitation in the future will change streamflow patterns and increase flood risks in LMRB. Meanwhile, due to the demand for energy from population explosion and rapid urbanization, reservoir construction has expanded at an unprecedented rate since 2009. This large-scale reservoir expansion will regulate streamflow more significantly and have a profound impact. Yang et al. (2019) and Yun et al. (2020a) pointed out that the reservoir regulation will change the streamflow pattern greatly with increased flow in dry season and the reduced flow in wet season of LMRB. Under the combined impact of future climate change and hydropower development, the characteristics of hydrological extreme events in LMRB will change drastically.

In a large river basin such as LMRB, investigation of the hydrological extremes at a single location is not sufficient to represent the change characteristics of the entire basin. Many studies (AghaKouchak et al., 2014; Al-Faraj and Scholz, 2014; Liu et al., 2015; Zhang et al., 2017) indicated that, when suffering from basin-wide extremes (e.g., dry extremes or wet extremes), streamflow upstream propagated to downstream rivers, threatening water security and exacerbating floods/droughts in the whole basin, and affecting the water resource cooperation between riparian countries in transboundary river. Therefore, many studies (Liu et al., 2015; Zhang et al., 2017) used the concurrent extreme events between the headwater regions and downstream to represent the basin-wide extreme events.

LMRB is the critical region for geopolitics and economic cooperation in Asia, affecting the lives of nearly 100 million people. The upstream of the Lancang River is one of the most important water supply sources for downstream the Mekong River, especially in the dry season (contributing 35% of streamflow (Hecht et al., 2019)). The cooperation mechanism within LMRB can prompt riparian countries to tackle severe dry/wet hydrological extreme together through the deployment and cooperation of transboundary water resources (Kittikhoun and Staubli, 2018). However, suffering from basin-wide extreme events will threaten the existing water cooperation security in LMRB. Present research (Mohammed et al., 2018a) has pointed out that a 30% increase of streamflow in the Lancang River would result in a reduction in the Lower Mekong streamflow predictability by about 21%, and leading to more frequent flooding. Therefore, assessing the potential impact of climate change and reservoir expansion on basin-wide hydrological extreme events is crucial to sustainable development in the region.

Many researches have evaluated the impact of climate change on extreme events in LMRB. Thilakarathne and Sridhar (2017) and Yun et al. (2020b) indicated that LMRB will suffer from severe extreme meteorological droughts in the middle of the 21st century; Hoang et al. (2016) pointed out that climate change will increase future extreme high flow and flood risk in LMRB. However, these studies only dealt with the impact of climate change on extremes in LMRB without considering potential effect of reservoirs. The presence of large reservoir groups can mitigate the impact of meteorological extreme events and change the characteristics of hydrological extreme events (Wu et al., 2018). The latest studies have shown that the rapid reservoir development since 2009 has drastically changed the characteristics of flood events in the basin (Shin et al., 2020; Yun et al., 2020a). Yet these studies lack attention to future projection under climate change scenario. There are also studies (Lauri et al., 2012; Wang et al., 2017; Hoang et al., 2019) evaluated the impact of future climate change and reservoir operation on magnitude and frequency of flood, but ignored the changes in long-term hydrological extreme events in LMRB.

Therefore, to address the knowledge gap, the Variable Infiltration Capacity (VIC) hydrological model with reservoir module was used to project the combined impacts of climate change and reservoir regulation on streamflow, and the copula-based joint Standardized Streamflow Index (SSI) was adopted to identify basin-wide dry/wet hydrological extremes of LMRB in the 21st century. Our results can provide a scientific basis for the development of water resources cooperation and management strategies in LMRB. Such a study is particularly important due to the increasing risks of hydrological extremes from climate change in LMRB.

2. Lancang-Mekong River Basin

The Lancang-Mekong River Basin (Fig. 1) is one of the most important transboundary rivers in Asia, with a length of 4800 km and an area of 795,000 km^2. Located in the southwest monsoon climate zone, LMRB has a unique dry season (from December to May) and wet season (from June to November). Precipitation brought by monsoon is the

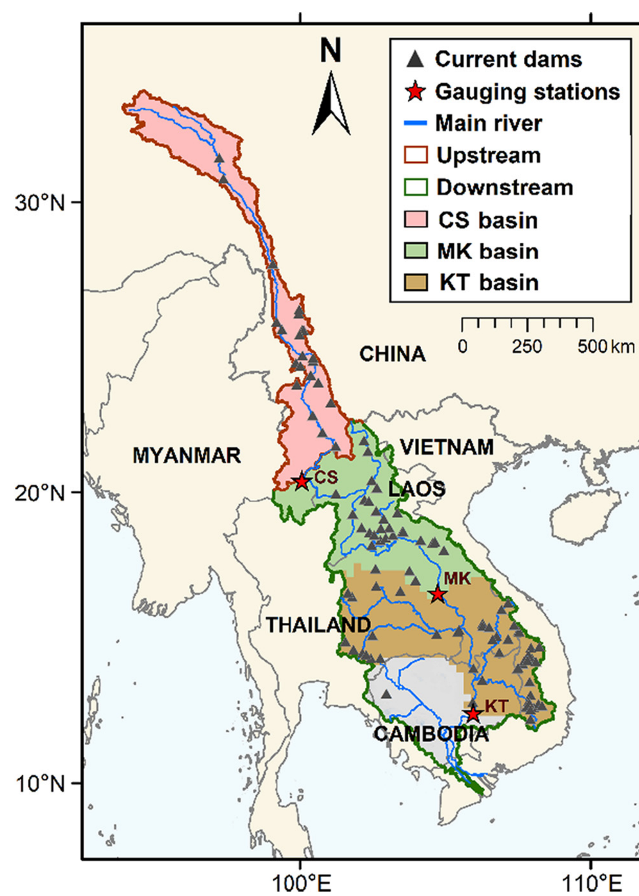

Fig. 1. The Lancang-Mekong River Basin (LMRB) with the dams and mainstream gauging stations (e.g., CS (Chiang Sean), MK (Mukdahan), and KT (Kratie)).

main source of the streamflow in LMRB, accounting for more than 50% of the annual flow. LMRB is generally divided into the upstream Lancang river basin and the downstream Mekong river basin (Munia et al., 2016). The Lancang river basin is dominated by plateau climate and subtropical monsoon climate, while the Mekong river basin is dominated by tropical rainforest climate and tropical monsoon climate. There are considerable differences in the distribution and characteristics of climate and water resources between the upstream and downstream. The streamflow from the upstream accounts for 17% of the annual streamflow in LMRB, and this proportion increases to 35% during the dry season (He and Hsiangte, 1996), which provides a critical water resource supply for the downstream basin.

More than 65% of the economic income to sustain 70 million people depends on irrigated agriculture in the downstream Mekong river basin (Pech and Sunada, 2008). With the rapid increase in energy and agricultural irrigation demand from these developing countries, reservoirs in LMRB have been built at an unprecedented rate since 2009 (MRC, 2017). Before 2008, LMRB was one of the least affected river basins by human activities in the world with the effective reservoir capacity accounted for only 2% of the annual streamflow (Kummu et al., 2010). By the end of 2021, the total storage capacity of 103 reservoirs under operation in this basin has reached a staggering number of 100.3 km^3, accounting for 23% of the annual streamflow (according to GMDD, the Greater Mekong Dam Database, https://wle-mekong.cgiar.org/maps/). These reservoirs are mainly distributed in three regions: Chiang Sean (CS) basin (upstream the CS station, with the total storage capacity of 42.7 km^3), Mukdahan (MK) basin (from CS station to MK station, with the total storage capacity of 28.6 km^3), and Kratie (KT) basin (from MK station to KT station, with a total storage capacity of 29.1 km^3). It is expected that the large number of reservoirs will have a massive impact on the river flows.

3. Data and method

3.1. The VIC-Reservoir model

The VIC model (Liang et al., 1994) coupled with reservoir (VIC-Reservoir) was adopted in this study to simulate the hydrology in LMRB. This model was selected due to the demonstrated good performance in simulating the natural and dammed streamflow as well as capturing extreme flow changes in LMRB (Yun et al., 2020a). We used the model parameter values and data settings developed for LMRB by Yun et al. (2020a) with a daily scale model at the resolution of 0.25 degrees, based on the previous study, we have made minor adjustments to the model parameters. The soil data were acquired from the Harmonized World Soil Database (HWSD) (FAO, 2012), and the land cover data were obtained from the Global Land Cover Characterization (GLCC) (Loveland et al., 2000) dataset. The streamflow observation during 1981–2010 was obtained from Mohammed et al. (2018b). The reservoir and dam data were obtained from the GMDD and existing research (Shin et al., 2020), including 103 reservoirs expected to be under operation in 2021 with a total storage capacity of 100.3 km^3. Since actual hydropower dam operation data are unavailable, the VIC- Reservoir model assumes reservoirs to mainly operate for flood control, while taking into account environmental protection and hydropower generation. The operation rules are 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. Such a modeling strategy is highly relevant to the existing dam operations across LMRB. Detailed information on VIC- Reservoir model were given in Section 1 of the Supplementary Information.

3.2. Future climate projection by Global Climate Models

Global Climate Models (GCMs) have been commonly used to provide projections of future climate change. To reduce the uncertainty of future projections, projections from multiple GCMs under a range of emission scenarios are often used (e.g., Thompson et al., 2014). The Shared Socio-economic Pathways (SSP) represent different levels of urbanization and economic development, and Representative Concentration Pathways (RCP) represents different scenarios of potential future greenhouse emissions (Kriegler et al., 2014). The combination of SSP and RCP can comprehensively reflect the characteristics of future climate change.

From the Inter-Sectoral Impact Model Intercomparison Project 3b (ISIMIP3b) project (Lange, 2019a), this study obtained the bias-corrected CMIP6 climate forcing data of different combined SSP and RCP scenarios, including SSP126 (SSP1-RCP2.6), SSP370 (SSP3-RCP7.0), and SSP585 (SSP5-RCP8.5). SSP126 is the scenario with rational adoption and mitigation of sustainable development process; SSP585 is the scenario with high challenges for adaptation and mitigation to maintain the living standards for a fast-growing population; and SSP370 is the intermediate pathway between SSP126 and SSP585 (Kriegler et al., 2014).

Each SSP scenario contains five GCMs including GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The choice of the GCMs was based on the reliability evaluation results of a large number of GCMs according to ISIMIP3b (Lange, 2019a). The simulations of the selected GCMs had been statistically downscaled and bias-corrected using ISIMIP3BASD v2.4.120 (Lange, 2019a) and W5E5 v1.042 (Lange, 2019b), and the forcing data include precipitation, maximum and minimum temperature, wind speed during the historical period from 1981 to 2014 and the future period from 2015 to 2100. The performance of hydrological model forced by CMIP6 data is measured with the Nash-Sutcliffe efficiency coefficient (NSE) (Nash and Sutcliffe, 1970) and model bias for the period of 1981 to 2010.

$$\mathrm{NSE} = 1 - \frac{\sum_{t=1}^{T} \left(Q_o^t - Q_m^t\right)^2}{\sum_{t=1}^{T} \left(Q_o^t - \overline{Q_o}\right)^2} \tag{1}$$

$$\mathrm{bias} = \frac{\overline{Q_m} - \overline{Q_o}}{\overline{Q_o}} \tag{2}$$

where Q_m is the simulated streamflow, Q_o is the observed streamflow. Previous studies have suggested that hydrological modeling with NSE > 0.50 can be considered satisfactory (Moriasi et al., 2007).

3.3. Standardized Streamflow Index

The Standardized Streamflow Index (SSI) (Vicente-Serrano et al., 2012; Rivera et al., 2017; Chen et al., 2018) is an extension of the standardized precipitation index (Mckee et al., 1993) to streamflow. SSI is an index obtained by first calculating the distribution probability of river streamflow and then normalizing it. The magnitude of SSI can directly represent the dry and wet hydrological extremes in different periods. Following the previous works (Zhang et al., 2015, 2017), dry hydrological extreme occurs when the SSI values are smaller than −1, and a wet hydrological extreme occurs when the SSI values are larger than 1. The Standardized Streamflow Index is used to evaluate hydrological extremes, for this index reflects the streamflow changes and the impact from climate change and reservoir regulation directly. Considering that LMRB is located in the monsoon area, a 3-month scale SSI (SSI-3) was selected to capture the seasonal characteristics. One 30-year historical period (baseline period, 1981–2010) and two 30-year future periods (near future period, 2031–2060; far future period, 2071–2100) were selected in this study to evaluate future SSI-3 changes, the two future SSI-3 were calculated based on the historical distribution characteristics. The generalized extreme value distribution was selected as the fitting function of SSI-3 because its best-fitting effect according to Kolmogorov-Smirnov (Wilks, 1999) test ($p = 0.84$, the p values of Gamma, Pearson Type III, Lognormal are range from

0.69– 0.81). The SSI calculations are described in detail in previous studies (Vicente-Serrano et al., 2012; Rivera et al., 2017).

3.4. Copula function

Basin-wide hydrological extreme events are described as a situation that both upstream and downstream experience the same extreme events (e.g., concurrent dry extreme or concurrent wet extreme in upstream and downstream). Copula function is a connection function, which combines multiple random variables with correlation and different distribution characteristics, and has been widely used in hydrology research (Liu et al., 2015; Maeng et al., 2017; Zhang et al., 2017; Van de Vyver and Van den Bergh, 2018). In this research, copula functions were used to estimate the joint probability of concurrent dry/wet hydrological extremes in LMRB. Two dependent time series X and Y have distributions $F_X(x)$ and $F_Y(x)$, respectively. The joint distribution F(x, y) of X and Y is calculated as follows:

$$F(x,y) = P(X \le x, Y \le y) = C(F_X(x), F_Y(x)) \tag{3}$$

where P is the probability density function, C is the copula function, X is the SSI-3 at the upstream station, Y is the SSI-3 at the downstream station.

In the whole basin, CS and KT stations (Fig. 1) were selected to represent the upstream and downstream in LMRB respectively. In addition, considering the distribution of downstream reservoir and the cooperation between Thailand and Laos (Li et al., 2019), we have added MK stations to evaluate changes in the sub-basins. That is, select CS and MK as the upstream and downstream stations of sub-basin CS-MK, respectively; and select MK and KT as the upstream and downstream stations of sub-basin MK-KT, respectively.

Copula types are the types of distribution functions used to connect multiple variables, and different copula types will affect the connection effect. This study evaluated the adaptability of eight common copula types, including AMH, Gumbel, Frank, Clayton, A12, A14, FGM, Gauss, in the SSI-3 joint distribution of concurrent dry/wet hydrological extreme in LMRB according to the copula weight theory (Huard et al., 2006). Among them, A14 had the highest weight value in CS-KT (0.316), A12 had the highest weight value in MK-KT (0.462) and CS-MK (0.566). Thus, A12 and A14 copula were selected as the connection function in this study.

4. Result

4.1. Model calibration and validation

The hydrological module in VIC- Reservoir was calibrated and validated for three mainstream stations (i.e., CS, MK, and KT in Fig. 1) by Yun et al. (2020a), and this calibration was performed sequentially from upstream stations to downstream stations. With the same model settings, we evaluated the performance of the VIC- Reservoir model driven by the CMIP6 forcing data in the historical period (1981–1994). Fig. 2 shows the monthly simulated streamflow using the VIC model driven by the ISIMIP3b Bias Correction forcing data at the three selected stations. The NSE ranges from 0.80 to 0.93 and model bias ranges from −0.09 to 0.05 during the calibration (1981–1994) and the validation period (1995–2010) (Table 1).

4.2. Streamflow variation under the impact of climate change and reservoir regulation

The climate change scenarios considered in this study show a consistently increasing trend of the precipitation and temperature (95% confidence with Mann-Kendall test) in the future periods in LMRB compared with the baseline period. Among the future changes of three SSP scenarios, SSP126 has a higher precipitation increase (+4.6% ~ +6.1%) and

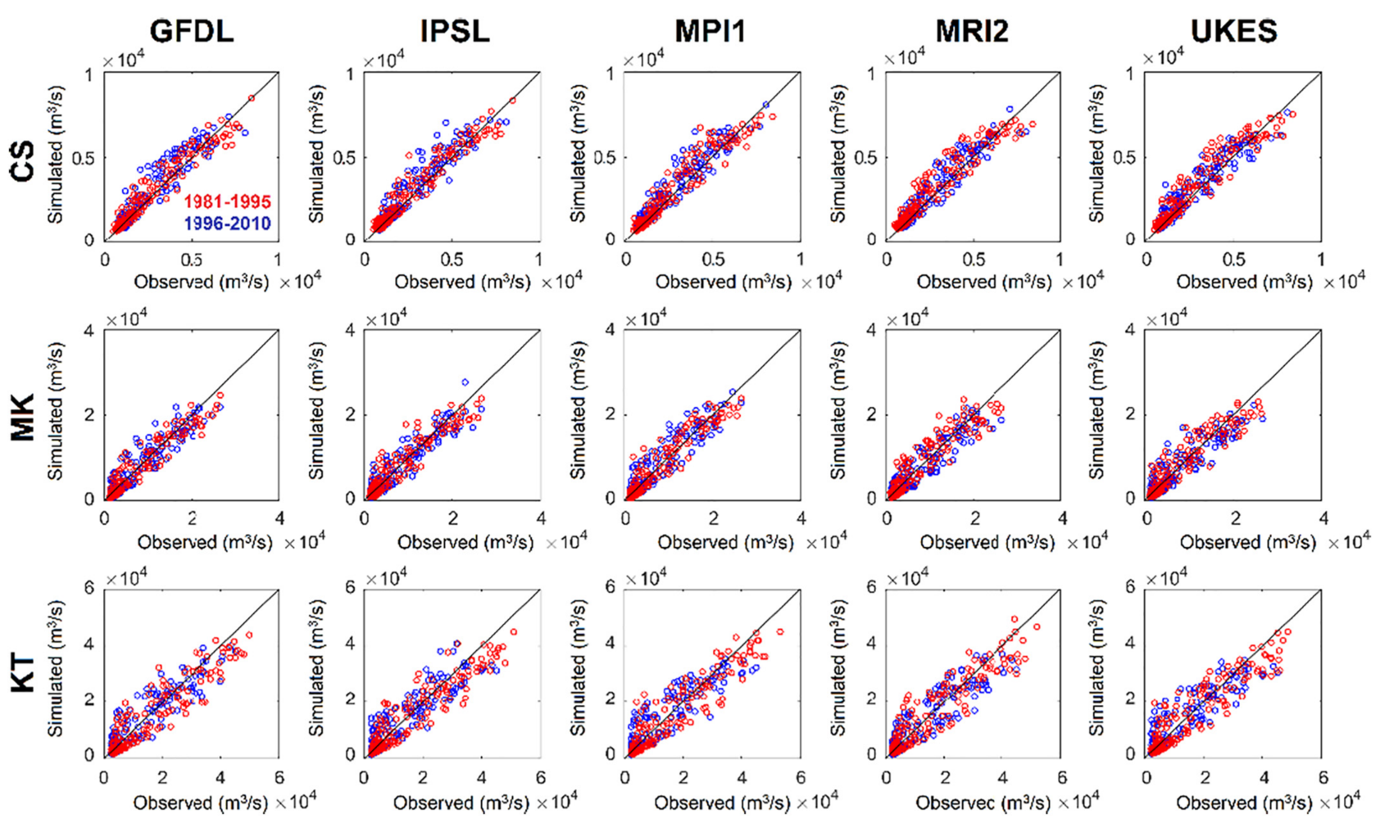

Fig. 2. Observed and simulated monthly streamflow at the three selected stations in LMRB for the calibration (1981–1994) and validation (1995–2010) periods.

Table 1
The NSE and model bias of 5 GCMs at three gauging stations during 1981–2010.

Years	Calibration period (1981–1995)						Validation period (1996–2010)					
Station	CS		MK		KT		CS		MK		KT	
Type	NSE	Bias	NSE	Bias	NSE	Bias	NSE	Bias	NSE	Bias	NSE	Bias
GFDL	0.93	−0.02	0.87	−0.04	0.85	−0.03	0.89	0.03	0.81	−0.09	0.83	−0.04
IPSL	0.93	−0.01	0.86	−0.05	0.88	−0.01	0.90	0.04	0.82	−0.07	0.82	−0.04
MPI1	0.91	−0.01	0.88	−0.01	0.87	0.01	0.90	0.04	0.84	−0.07	0.82	−0.02
MRI2	0.90	0.04	0.85	−0.06	0.85	0.05	0.88	0.01	0.83	−0.04	0.83	−0.07
UKES	0.91	0.03	0.84	−0.04	0.85	0.01	0.89	0.02	0.81	−0.05	0.80	−0.04

limited temperature rise (+1.3 °C ~ +1.6 °C), SSP370 has a limited precipitation change (−1.6% ~ +2.0%) but higher temperature rise (+1.7 °C ~ +3.7 °C), and SSP585 combines the highest precipitation increase (+2.3% ~ +9.6%) and the highest temperature rise (+1.9° C ~ +4.6 °C). In the near future (2031–2060), with limited temperature rise and increase in precipitation, the annual streamflow under the SSP126 scenario will increase by 4.1% ~ 6.2%, while the annual streamflow in the SSP370 and SSP585 scenarios will change −3.7% ~ −2.2% and 0.2% ~ 1.6%, respectively, because of the little precipitation change and the additional evaporation caused by the rapid temperature rise. In the far future period (2071–2100), the annual streamflow under three SSP scenarios will increase substantially (up to +15.8%).

Fig. 3 shows the monthly streamflow changes at three representative stations under the impacts of climate change and reservoir regulation during the different future periods and SSP scenarios compared to the baseline period. Compared to baseline period, climate change will change the future monthly streamflow, resulting in great changes in wet season streamflow (−8% ~ +37%) and dry season streamflow (−21% ~ +18%). Different from the large impact of climate change, the impact of the reservoir regulation on future annual streamflow is small. However, reservoir regulation can dramatically affect the seasonal pattern of the streamflow, leading to higher dry season streamflow (up to 59%) and lower wet season streamflow (down to −25%) compared to the baseline period (Fig. 3). Modified streamflow patterns under the reservoir regulation scenarios are consistent for all SSP scenarios and stations considered, only with a difference in the magnitude. In general, climate change has large impacts on both the annual and seasonal streamflow, while reservoir regulation has large impacts on seasonal streamflow.

4.3. Changes in hydrological extreme events

With the streamflow changes, hydrological extreme events also vary. Fig. 4 displays the time-series of changes in SSI-3, dry hydrological extreme probability, and wet hydrological extreme probability in LMRB. The SSI-3 values at the three representative stations display a trend of the first decline and then continue to increase in the 21st century (with 95% confidence). According to the Mann–Kendall test, the breakpoint of SSI-3 at CS, MK, and KT stations is 2038 in the SSP585 scenario. Similarly, the breakpoint of SSI-3 is 2020 in SSP126 and 2042 in SSP370, respectively. This result indicates that although the streamflow has been decreasing in recent years, it is expected to increase during the future period. At the same time, the increase rate of SSI-3 at CS station (0.28/10 yrs) is higher than that at MK station (0.19/10 yrs) and KT station (0.14/10 yrs), which indicates that the upstream of the basin is more sensitive to the climate change.

In addition, we calculated the changes in the probability of hydrological extreme events in LMRB. Under the SSP585 scenario, the probability of dry extreme increases before the 2040s and will reach a peak of 28% in 2038; after the 2040s, the dry extreme probability will rapidly decrease. After considering the impact of the reservoir, the dry extreme probability is controlled within 17%, which suggests that reservoir regulation can mitigate dry hydrological

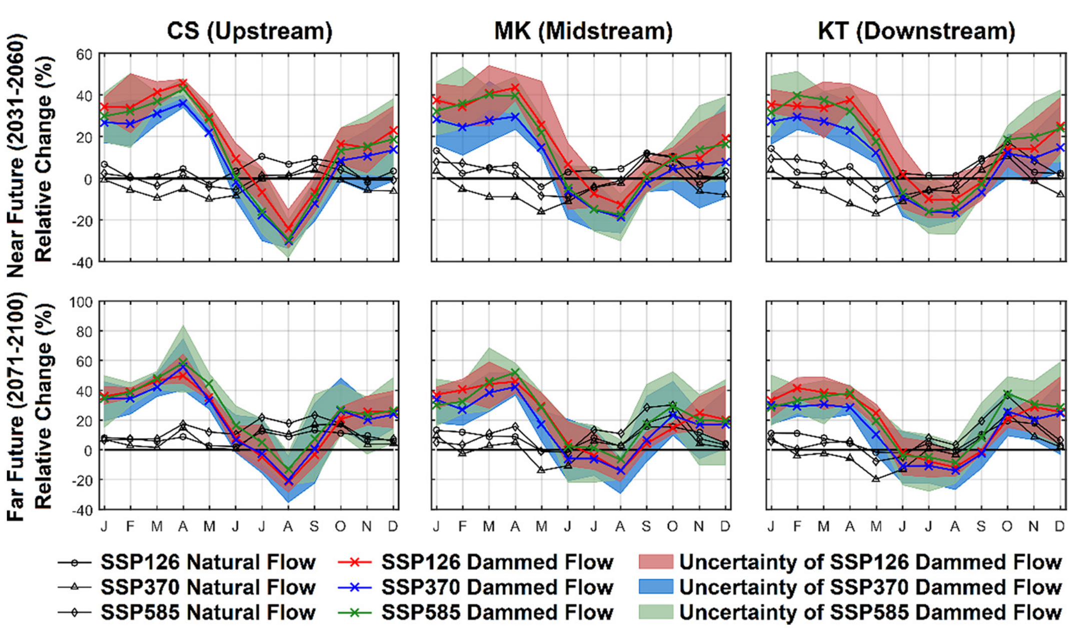

Fig. 3. Projected monthly streamflow changes at the three representative stations under the impacts of climate change and reservoir regulation during the two future period and under the three SSP scenarios compared to the baseline period (1981–2010). Lines are ensemble means of the five GCMs, and area represents the uncertainty of five GCMs.

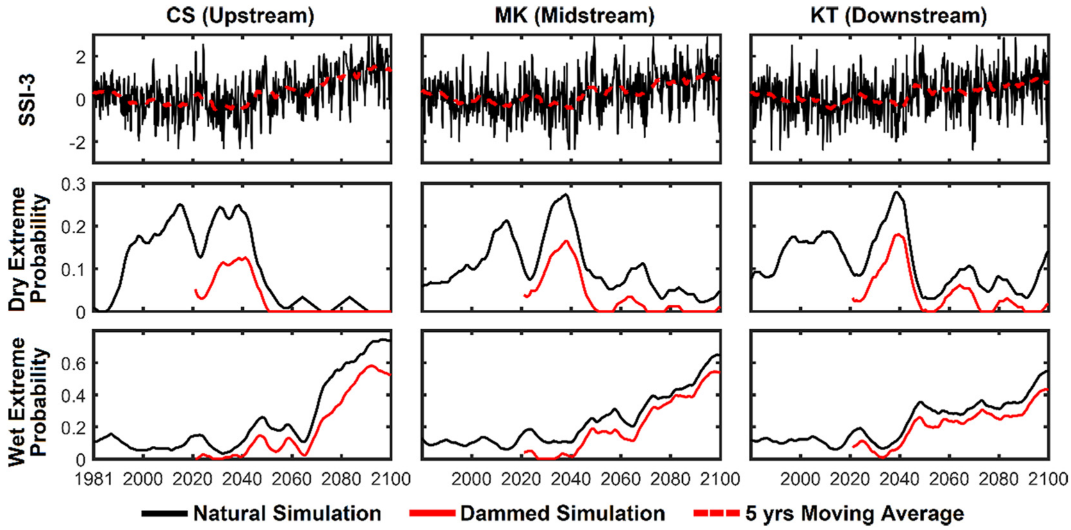

Fig. 4. Time series of SSI-3, dry extreme probability, and wet extreme probability at the three representative stations during 1981–2100 in LMRB under SSP585 scenario. The SSI-3 is calculated based on the average of the five GCM simulations. The probability of hydrological extreme is calculated from the 30-year moving value. Please refer to Supplementary Figs. S1 and S2 for the results of SSP126 and SSP370, respectively.

extreme. At the same time, the probability of wet extremes will increase rapidly under the impact of climate change. It is estimated that by the end of the 21st century, the wet extreme probability in LMRB will increase up to 72%, and the reservoir regulation could decrease this probability to 60%. Similar changes also appear in SSP126 and SSP370 scenarios, though there are differences in the magnitude. On the whole, LMRB will suffer from more dry hydrological extremes in the near future period and more wet hydrological extremes in the far future period, and the reservoir regulation can reduce the occurrence of extreme events.

4.4. Changes in concurrent extreme events

We also analyzed the changes in basin-wide and sub-basin extreme events by evaluating the changes of concurrent dry and wet hydrological extremes among different stations in LMRB. Fig. 5 shows the joint probability distribution of the SSI-3 at different stations, periods, and scenarios, and Table 2 provides detailed information about frequency and probability change. During the historical period (1981–2010), the occurring probability of basin-wide concurrent dry extreme is 5% and the probability of concurrent wet extreme is 6.7% in LMRB.

For the near future under SSP126 scenario with rapid streamflow increase, the probability of basin-wide (CS-KT) concurrent wet extreme has increased by 150% and concurrent dry extreme has decreased by 50%. On the contrary, the near future SSP370 scenario with limited precipitation change and rapid temperature rise has decreased the probability of concurrent wet extreme by 50% and increased the probability of concurrent dry extreme by 183%. Besides, for the near future period, SSP585 has a moderate increase in the probability of concurrent wet and dry extremes by 50% and 33%, respectively. Reservoir regulation would effectively reduce the probability of concurrent dry extreme by 50% ~ 80% under SSP126 scenario (decrease by 44% ~ 83% under SSP370, and by 50% ~ 88% under SSP585) and wet extreme by 12% ~ 65% under SSP126 scenario (decrease by 0% ~ 50% under SSP370 and by 6% ~ 46% under SSP585) during the near future period.

In the far future, the results for the three SSP scenarios are relatively consistent. Across all the SSP scenarios, with the increase in streamflow caused by climate change, the probability of basin-wide concurrent dry extremes is continuously decreased (−17% ~ −83%), and the probability of basin-wide concurrent wet extreme is substantially increased (125% ~ 363%). After considering the reservoir regulation, the probabilities of concurrent dry extreme and wet extreme have been reduced by 33% ~ 100% and 6% ~ 32%, respectively.

The changes of hydrological extremes in sub-basins are consistent with that for the whole basin. In most scenarios, the probability of concurrent extremes during CS-KT (basin-wide) is higher than that in CS-MK and MK-KT (two sub-basins). Besides, benefited from the basin-wide reservoir regulation, the probability of concurrent extreme events during CS-KT has the highest reduction compared to other sub-basins. The results of CS-KT stations are more scattered. This is because the streamflow will be more affected by other factors, as the spatial distance between the stations increases. All in all, compared with historical periods, LMRB will have more concurrent dry extreme in the middle 21st century under SSP370 (+183%) and SSP585 scenarios (+33%). And the three SSP scenarios have shown a consistent change in the late 21st century, that is, LMRB will encounter more concurrent wet extremes (up to 363%) and fewer concurrent dry extremes (decreased by 83%). And reservoir regulation can effectively reduce the future concurrent extreme events in LMRB.

5. Discussion

This study evaluated the impacts of climate change and reservoir regulation on hydrological extreme events of LMRB in the 21st century with help of the VIC-Reservoir hydrological model and bias-corrected CMIP6 climate forcing data. Climate change and reservoir expansion are important issues involving political, economic, and ecological interests of countries in LMRB. This comprehensive assessment helps to improve our understanding of future changes in LMRB's hydrological extreme events.

Our results show that climate change will continually increase the seasonal fluctuation of streamflow in LMRB. Regulation of 103 reservoirs under operation by 2021 in LMRB can adjust the seasonal flow to decrease wet season flow (down to −25%) and increase dry season flow (up to 59%), although it shows a limited impact on the annual streamflow. Previous studies (Hoang et al., 2019; Lauri et al., 2012) showed similar streamflow variations, although there are magnitude differences due to the different reservoirs considered.

Climate change will pose new challenges to water resource management. LMRB will encounter more frequent dry hydrological extremes in the near future period and more frequent wet hydrological extremes in the far future period. It is worth mentioning that, the three SSP scenarios

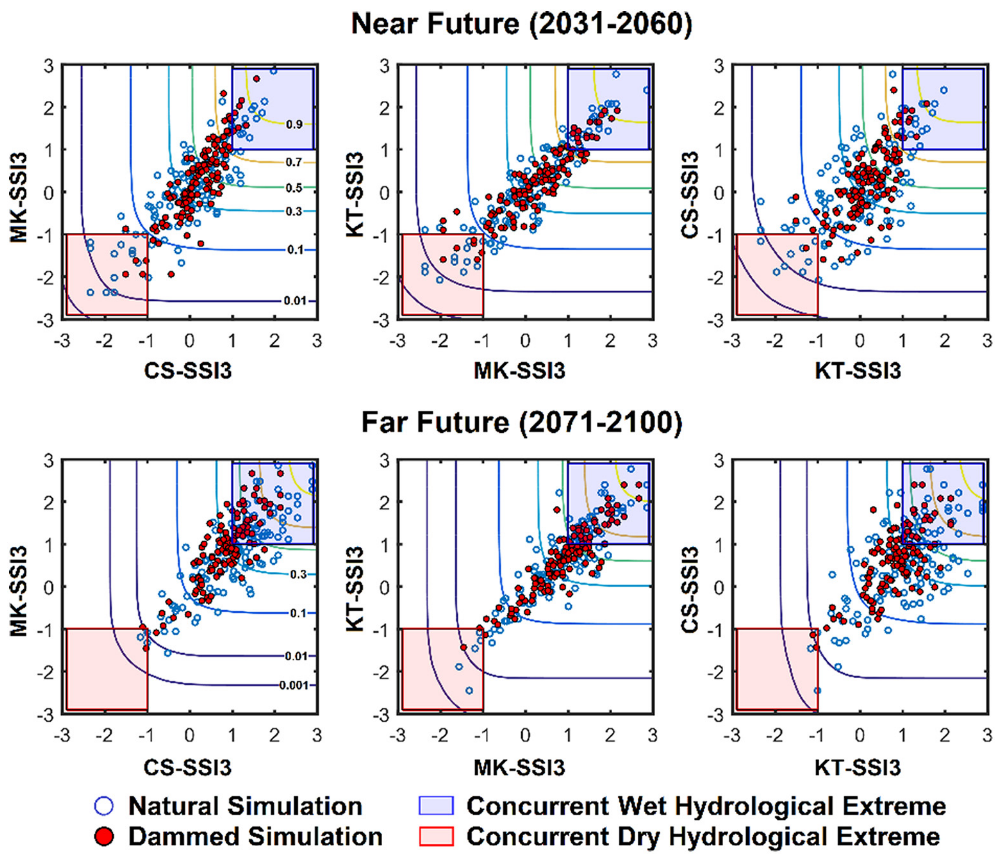

Fig. 5. Level curve of the joint probability distribution of the SSI-3 at different stations and for different periods under SSP585 scenario. The red frame area indicates the concurrent dry hydrological extreme (SSI-3 ≤ −1), the blue frame area indicates the concurrent wet hydrological extreme (SSI-3 ≥ 1). Please refer to Supplementary Figs. S3 and S4 for the results of SSP126 and SSP370, respectively.

indicate consistent result of substantially increasing basin-wide wet extremes (up to 363%) and less basin-wide dry extremes (decreased by 83%) at the end of the 21st century. The change of extreme event impacted by global warming is consistent with the previous studies, including an increase in near future meteorological/hydrological drought (Sam et al., 2019) and an increase in far future flood risks (Hoang et al., 2016; Wang et al., 2017).

At the same time, reservoir regulation can mitigate hydrological extreme events under future climate change. The peak value of basin-wide dry extreme probability and wet extreme probability will decrease by 88% and by 32%, respectively, and the regional dry/wet hydrological extremes will also be reduced. Previous studies carried out in other basins (Wu et al., 2018; Guo et al., 2020) indicated that properly operated reservoirs can delay the propagation of extreme events from meteorological processes to hydrological processes, and reduce hydrological extreme events by releasing water during dry period and storing water during wet period. Although focused on different basins, these results are consistent with our findings. In addition, Wang et al. (2019) pointed out that reservoirs are more effective in mitigating short-term extreme events (return period less than 2 years), but limited in

Table 2
The number and relative changes of concurrent dry/wet hydrological extremes in different periods and different scenarios. The total number of events in each period is 120 (30 years). Relative change in natural simulation is compared to the baseline period, and relative change in dammed simulation is compared to the natural simulation at the same period.

Type			CS-MK				MK-KT				CS-KT			
			Dry	RE	Wet	RE	Dry	RE	Wet	RE	Dry	RE	Wet	RE
Baseline Period 1981–2010			11		13		13		12		6		8	
Near future 2031–2060	SSP126	Nature	5	−55%	25	92%	6	−54%	25	108%	3	−50%	20	150%
		Dam	1	−80%	11	−56%	2	−67%	22	−12%	1	−67%	7	−65%
	SSP370	Nature	26	136%	4	−69%	25	92%	8	−33%	17	183%	4	−50%
		Dam	6	−77%	2	−50%	11	−56%	7	−13%	3	−82%	2	−50%
	SSP585	Nature	14	27%	13	0%	11	−15%	19	58%	8	33%	12	50%
		Dam	4	−71%	7	−46%	6	−45%	17	−11%	1	−88%	7	−42%
Far future 2071–2100	SSP126	Nature	2	−82%	42	223%	4	−69%	32	167%	1	−83%	27	238%
		Dam	1	−50%	31	−26%	2	−50%	27	−16%	0	−100%	21	−22%
	SSP370	Nature	4	−64%	29	123%	11	−15%	20	67%	5	−17%	18	125%
		Dam	1	−75%	28	−3%	5	−55%	19	−5%	0	−100%	17	−6%
	SSP585	Nature	3	−73%	50	285%	5	−62%	40	233%	3	−50%	37	363%
		Dam	1	−67%	41	−18%	2	−60%	32	−20%	2	−33%	25	−32%

responding to long-term extreme events (return period more than 6 years). Thus the future studies need to consider the changing characteristics of extreme events on a longer time scale.

It is worth mentioning that, these results are based on the ideal operation scenario of hundreds of reservoirs built in the five countries in LMRB. Similar results had been concluded in other studies (Wheeler et al., 2018; Yu et al., 2019), which showed that reservoir operation established on the in-depth international water resource cooperation can alleviate hydrological extreme events in transboundary rivers. However, cases in other transboundary rivers (López-Moreno et al., 2009; Al-Faraj and Scholz, 2014) showed that reservoir operation that lacks international cooperation would give priority to ensuring the water resources utility in upstream countries (e.g., unrestrained water consumption during drought, and excessive discharge during flood), which would have a negative impact to the downstream countries, especially when the upstream and downstream encounter concurrent basin-wide hydrological extreme events. Therefore, water resources cooperation and management among riparian countries are needed to tackle the constantly changing climatic conditions. For example, emergency releases from upstream reservoirs can mitigate severe drought in the downstream countries in March 2016 (Tiezzi, 2016; Hecht et al., 2019). And the healthy development of emerging basin-wide organizations (e.g., the Lancang-Mekong Cooperation) will provide an important foundation for cooperation in LMRB.

There are some limitations in this study. We have adopted a fixed flood prevention strategy as the main purpose to operate all reservoirs, without considering the tradeoff between flood control, hydropower production, and irrigation. In the actual process, some reservoirs are mainly used for hydropower generation and irrigation when flood risk is limited and controllable. However, on considering the future population explosion and urbanization in LMRB, this strategy is particularly important in the near future periods (with limited flood risk) because it prompts the reservoir operators to balance between different operational targets to satisfy the needs, which leads to further streamflow changes. In the far future, the threat from high flood risk due to climate change will force the reservoir to focus on flood control. Therefore, while this study explores the potential of the reservoirs for flood control in an idealized setting, future researches are needed to explore the impact of different reservoir strategies on the streamflow changes in LMRB.

6. Conclusions

This study evaluated the changes in hydrological extreme events caused by climate change and reservoir regulation in the Lancang-Mekong River Basin with help of the VIC-Reservoir hydrological model and bias-corrected CMIP6 climate forcing data. Our results show that:

(1) The streamflow in LMRB is projected to firstly decrease until 2038 and then increase under the SSP585 scenario (Similarly, 2020 in SSP126 scenario, and 2042 in SSP370 scenario), which will lead to an increase in regional dry hydrological extreme probability (up to 28%) during the mid-21st century and regional wet hydrological extreme probability (up to 72%) at the end of the 21st century. At the same time, the basin-wide dry hydrological extreme (up to 33% in the 2040s) and wet hydrological extreme (up to 363% by the end of 21st century) will increase substantially. Similar trends also appear under SSP126 and SSP370 scenarios, though there are differences in the magnitude.

(2) The existing reservoirs can mitigate the impact of climate change on streamflow to decrease wet season flow (down to −25%) and increase dry season flow (up to 59%), reducing the probability of the basin-wide dry hydrological extreme (decreased by 100%) as well as the wet hydrological extreme (decreased by 32%). Despite the capacity of reservoir regulation to mitigate the increased risk, LMRB will still encounter more frequent basin-wide wet hydrological extremes that triple the historical number during the late 21st century.

Our research provides a reference for assessing the impact of climate change and reservoir regulation on streamflow changes and basin-wide hydrological extremes in LMRB, which will provide important support for water resources management and cooperation in LMRB. This research assumes that all reservoirs are operated for flood control purposes. In real situations, some reservoirs may be mainly used for hydropower generation or irrigation. Thus, the estimated flood control effect represents an upper limit and a higher flood risk can be expected.

CRediT authorship contribution statement

Xiaobo Yun: Conceptualization, Methodology, Software, Writing – original draft. **Qiuhong Tang:** Conceptualization, Writing – review & editing. **Jiabo Li:** Writing – review & editing. **Hui Lu:** Writing – review & editing. **Lu Zhang:** Writing – review & editing. **Deliang Chen:** Writing – review & editing.

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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Appendix A. Supplementary data

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