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Reducing Climate Change Induced Flood at the Cost of Hydropower in the Lancang-Mekong River Basin

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Key Points:

- Reservoir can mitigate future flood risk from climate change at the cost of reducing hydropower generation in the Lancang-Mekong River Basin
- Reservoir regulation can delay the timing when flood risk exceeds the historical baseline by at least 20 years in Laos and Thailand
- Flood control measures would reduce hydropower at a magnitude of 5.4 times in China than downstream countries

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Hydropower dams are proliferating in the riparian countries of the Lancang-Mekong River Basin (LMRB) driven by the pursuit of renewable electricity and societal resilience to flooding. However, the tradeoffs between hydropower production and flood control are unclear in a changing environment. Here, we use a hydrological variable infiltration capacity model combined with a reservoir module to quantify the relative effects of climate change and reservoir operation on flood and hydropower generation in LMRB. Results show that while climate change would increase flood magnitude and frequency, adaptive reservoir operation can reduce flood magnitude by 5.6%–6.4% and frequency by 17.1%–18.9% at the cost of 9.8%–14.4% of basin-wide hydropower generation. Particularly, upstream reservoirs suffer more hydropower loss (5.4 times) than downstream ones when flood control is prioritized in reservoir regulation. Our findings have implications for integrated water and energy management at the transboundary river basin under climate change.

Plain Language Summary Dams and reservoirs provide two important services, i.e., flood control and hydropower generation. In this study, we seek to understand the future tradeoff between these two services provided by reservoir regulation in the transboundary Lancang-Mekong River Basin. Using a modeling based approach, we find that climate change will likely lead to more frequent and larger flood events, but reservoir operation, by regulating water discharges and levels in streams, can effectively reduce flood frequency and magnitude at the expense of hydropower generation. Our results highlight the importance of coordinating water and energy management across countries in this transboundary river basin.

1. Introduction

The Lancang-Mekong River, which traverses approximately 5,000 km in Asia, is an important international river flowing across six countries, that is, China and Myanmar at its upper reaches, Lao and Thailand at its midstream, and Vietnam and Cambodia downstream the river basin (Figure 1a). The river system provides water and food to more than 70 million inhabitants and sustains crop, livestock, and ecosystem of the basin (Varis et al., 2012). The human livelihoods (e.g., agriculture and fisheries) and ecosystem (e.g., wetlands) of the Lancang-Mekong River Basin (LMRB) rely heavily on the commonly shared water resources characterized by seasonal flood pulse (Arias et al., 2014; Byerlee et al., 2010; Hortle, 2007; Kummu, Lu, Wang, & Varis, 2010; Sabo et al., 2017). Even minor change in streamflow may profoundly impact social well-being and growth, affecting the millions of residents in LMRB (MRC, 2017).

Flow dynamics along the Lancang-Mekong River and its tributaries are likely subject to a substantial change due to climate change and new dam construction. Observation-based studies (Thirumalai et al., 2017; Wu et al., 2012) have shown that climate change leads to higher temperatures and more extreme weather conditions in LMRB, which will likely accelerate the hydrological cycle and affect rainfall, snowmelt, and river flows. Earlier snowmelt and increased precipitation driven by global warming have led to an increase in flood of LMRB (Wang, Lu, Zhao, et al., 2017). Flooding is a major disaster in LMRB, with 158 flood events recorded between 1994 and 2016 in Cambodia, Vietnam, Laos, and Thailand, causing 8,608 deaths and affecting more than 87 million people (EM-DAT, www.emdat.be). Although floods will help maintain

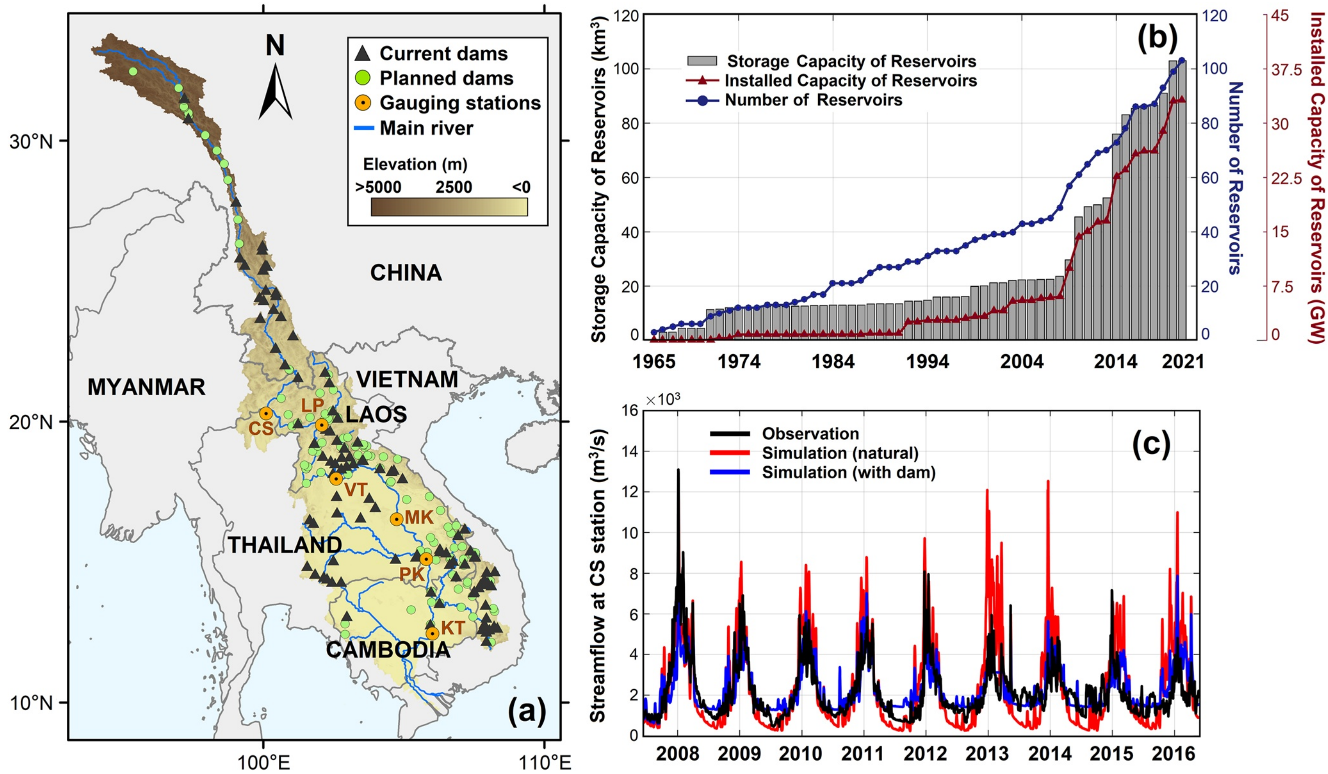

Figure 1. (a) The Lancang-Mekong River Basin (LMRB) with the dams and streamflow gauging stations (including Chiang Sean [CS], Luang Prabang [LP], Vientiane [VT], Mukdahan [MK], Pakse [PK], Kratie [KT]). (b) Changes in the number, installed capacity and storage capacity of reservoirs during 1965–2021 in LMRB. (c) Observed and simulated daily streamflow at CS stations in LMRB during 2008–2016 (Table S1 in Supporting Information S1).

ecosystems and fisheries in the Mekong delta (Sabo et al., 2017; Yang et al., 2019), increasing floods will put additional strain on water resources management and socioeconomic development.

Rapid urbanization, population growth, and economic development drive an increasing demand for energy in all countries within LMRB. Ensuring energy security while at the same time decarbonizing energy production has led to growing interests in the exploitation of renewable energy sources including hydroelectricity. Until 2008, the Lancang-Mekong River was one of the world's great rivers that remain largely undammed (Kareiva, 2012), with reservoir activity storage capacity only accounting for 2% of annual streamflow (Kummu et al., 2010). A substantial number of dams have been developed in this river and its tributaries to meet increasing needs for clean electricity (Grumbine, 2018; Hecht et al., 2019). According to the statistics, 103 hydropower reservoirs have been in operation by 2021 with an installed capacity of 33 GW. And the total storage capacity of these reservoirs is 100 km^3, representing approximately 23% of the mean annual streamflow at Kratie station (Figure 1b). The dams and reservoirs have been criticized because they changed natural flows and reduced floods (Han et al., 2019; Hoang et al., 2019; Li et al., 2017; Räsänen et al., 2017; Yun et al., 2020), which negatively affects ecosystem services and processes (e.g., reduce sediment and nutrient supply to downstream basins [Schmitt et al., 2018, 2019], and impede fish migration and reproduction [Anh et al., 2018]). However, dams and reservoirs can be an important source of clean energy that underpins socioeconomic development, they can also produce additional dry-season available water that benefits irrigation (Lacombe et al., 2014; Pokhrel et al., 2018).

The great challenge that LMRB faces is to develop sustainable energy supply while reducing flood threat under the changing climate. Because both hydropower production and flood control are highly dependent on river flow regulations, it is important to understand the tradeoff between these two important functions. A few studies have made attempts to analyze streamflow changes under reservoir impact in LMRB, however, often based on one single-fixed reservoir regulation strategy, without considering adaptive operation strategies (Hoang et al., 2019; Lauri et al., 2012; Wang, Lu, Leung, et al., 2017). Because climate change would increase the risk of floods, hydropower reservoir operation, as a potential adaptation option, could help reduce the risks at the cost of the hydropower production (Ngo et al., 2018; Padiyedath Gopalan et al., 2021; Shrestha et al., 2013; Thomas et al., 2021). Future hydropower generation in LMRB has been assessed under climate change, but considering only three upstream reservoirs (Zhong et al., 2019). The trade-off between flood reduction and hydropower production in LMRB's multiple dams under the changing climate, however, remains unclear.

To bridge above-mentioned research gaps, the variable infiltration capacity (VIC) (Liang, Lettenmaier, Wood, & Burges, 1994) model was coupled with a reservoir module (Yun et al., 2020) to investigate the tradeoffs between different reservoir operation strategies of hydropower production and flood control under the combined impacts of climate change and reservoir operation in LMRB. Our findings highlight the need for integrated management of hydropower production and flood control at the river-basin scale.

2. Data and Methodology

The distributed hydrological model VIC with a reservoir module incorporated (VIC-R) (Yun et al., 2020) was used to assess the impact of climate change and reservoir operation, the hydrological processes are simulated at a 0.25° spatial resolution. Previous studies pointed out that the hydrological model coupled with reservoir simulation (Dang, Chowdhury, & Galelli, 2020; Dang, Vu, et al., 2020) can simulate the seasonal streamflow changes in LMRB more accurately. When applying VIC-R model to LMRB, the simulated streamflow generally matches observed streamflow at the typical gauges with the Nash-Sutcliffe efficiency coefficient values over 0.61 (Figure 1c and Table S1 in Supporting Information S1) (Yun et al., 2020). More information on model description and performance of VIC-R can be found in Text S1 in Supporting Information S1.

From existing research (Shin et al., 2020; Yigzaw et al., 2018) and news, we compiled a comprehensive data set of 103 reservoirs in LMRB with detailed information (i.e., geolocation, height, function, storage capacity, and installed capacity, see Table S3 in Supporting Information S1). A number of representative reservoir operation strategies are considered in the reservoir model, that is, to prioritize hydropower generation (maintain a relatively high hydraulic water head to improve power generation), to prioritize flood control (maintain a relatively low hydraulic water head for incoming flood during wet season), and a variety of compromising strategies. More information about the reservoir operation rules can be found in the Supplementary Information Section 2.

Two flood series extraction methods, that is, mean annual flood (MAF) (Guo et al., 2014) and peak over threshold (POT) (Hirsch & Archfield, 2015) are used to evaluate flood magnitude and frequency, respectively. The MAF method calculates the average maximum daily streamflow per year to evaluate the flood magnitude in a selected period. The POT method applies the flood threshold selected from the baseline period to evaluate flood frequency in other comparative periods. For detailed instructions on these two methods, please refer to Text S3 in Supporting Information S1.

We used the future climate forcing data provided by Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b) (Lange, 2019a) in the VIC-R model to simulate future streamflow between 2021 and 2100. The ISIMIP3b climate input data provide bias-corrected CMIP6 climate forcing for three different scenarios including low-emission scenario SSP126 (SSP1-RCP2.6), mid-emission scenario SSP370 (SSP3-RCP7.0), and high-emission scenario SSP585 (SSP5-RCP8.5). Each SSP scenario contains five GCMs including GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL. The five GCMs are representative results selected by the ISIMIP project from the 19 GCMs data published in IPCC6, and they are bias-corrected and statistically downscaled based on the measured station data using ISIMIP3BASD v2.4.1 (Lange, 2019a) and W5E5 v1.0 (Lange, 2019b). Although the prediction result of a single GCM have large deviations in LMRB (Dong & Sun, 2018; Hasson et al., 2016), the use of ensemble of multiple GCMs can reduce this uncertainty (Thompson et al., 2014), and ISIMIP3b based on GCMs showed a good hydrological simulation performance in LMRB (Yun et al., 2021).

In the historical baseline period between 1980 and 2009, natural streamflow is simulated and corresponding MAF and POT are calculated as the baseline flood characteristics. The baseline hydropower generation was calculated by coupling historical climate with the reservoir module using the prioritizing hydropower production strategy, and the results confirm that this strategy conforms with the actual reservoir operation target in LMRB. In two future periods (i.e., the near future period [NF] 2031–2060 and the far future period [FF] 2071–2100), the natural streamflow and dammed streamflow under reservoir operation are simulated, based on which, the flood characteristics and hydropower generation are analyzed. We applied the ensemble mean method to present the projected results, that is, the ensemble means of simulation results from five GCMs is calculated. Please refer to Table S5 in Supporting Information S1 for detailed instructions.

3. Results and Discussion

3.1. Streamflow Projection Under Climate Change

Monsoon precipitation and temperature are the key factors determining the streamflow pattern in LMRB (Wang, Lu, Leung, et al., 2017). The temperature shows a significant increasing trend in all SSP scenarios. The acceleration of atmospheric circulation caused by the rising temperature leads to increasing precipitation in LMRB (Aadhar & Mishra, 2020). The precipitation in LMRB is projected to increase during 2031–2100 in SSP126 and SSP585 scenarios, and first decrease then increase in SSP 370 scenario (Table S6 in Supporting Information S1).

Based on the VIC simulation results, here we examine the relative change of streamflow in NF and FF, compared to the historical baseline period. In NF, the annual streamflow in SSP126 and SSP585 scenarios are projected to increase by 4.1%–6.2% and 0.2%–1.6%, respectively. The streamflow in SSP370 tends to decline by 2.2%–3.7%, due to negligible precipitation change and increasing evaporation driven by temperature rise (Table S7 in Supporting Information S1) (Konapala et al., 2020; Martens et al., 2018). In FF, the annual streamflow in all SSP scenarios will increase substantially. The streamflow change shows seasonal variation. Particularly, the streamflow in flood season (August–October, the period when 70% precipitation concentrated) shows a larger increasing trend than other seasons (Figure S4 in Supporting Information S1), which is consistent with the understanding that the extreme streamflow is more influenced by moisture supply that increases with temperature at a rate of approximately 7% per degree (Held & Soden, 2006; O'Gorman, 2015).

3.2. Impacts of Climate Change and Reservoir Regulation on Future Flooding

Reservoir regulation will interact with climate change to exert an impact on the river system. Here, we analyze future changes in the magnitude and frequency of floods (see Methods section) under different scenarios in LMRB compared to the baseline period. Three gauging stations, that is, Chiang Sean (CS), Mukdahan (MK) and Kratie (KT) located at upstream, midstream, and downstream the basin, are selected to investigate their spatially different responses to climate change and reservoir regulation.

The flood magnitude and frequency will continue to increase throughout this century in all SSP scenarios with different reservoir regulation strategies (see Figure 2). Under natural condition without reservoir regulation, the flood magnitude and frequency are projected to increase 9.0%–31.2% and 17.7%–44.1% by 2100, respectively (the intervals indicating results at upstream, midstream, and downstream the basin from different SSP scenarios, see Table S8 in Supporting Information S1). After considering the impact of the reservoirs, even using the reservoir operation strategy that prioritizes hydropower production, the flood magnitude, and frequency are reduced by 3.1%–3.3% and 6.3%–7.1%, respectively, in comparison to the natural condition in the future period. Changing reservoir operation strategy from prioritizing hydropower production to flood control leads to additional reductions of flood magnitude and frequency by 6.2%–6.4% and 17.3%–18.9%, respectively. It is worth mentioning that reservoir regulation leads to larger relative changes of flood magnitude and frequency at upstream station than midstream and downstream stations, because the ratio of reservoir storage capacity to annual streamflow at upstream LMRB is higher (i.e., 51.2%) than midstream and downstream the basin (i.e., 29.1% and 22.8%, respectively).

Flood magnitude and frequency can be reduced by changing reservoir operating strategies, which indicates the potential of reservoir regulation for future climate change adaptation in LMRB. It is estimated that after the 2050s, the flood frequency will exceed the historical baseline in SSP585 scenario when the reservoir

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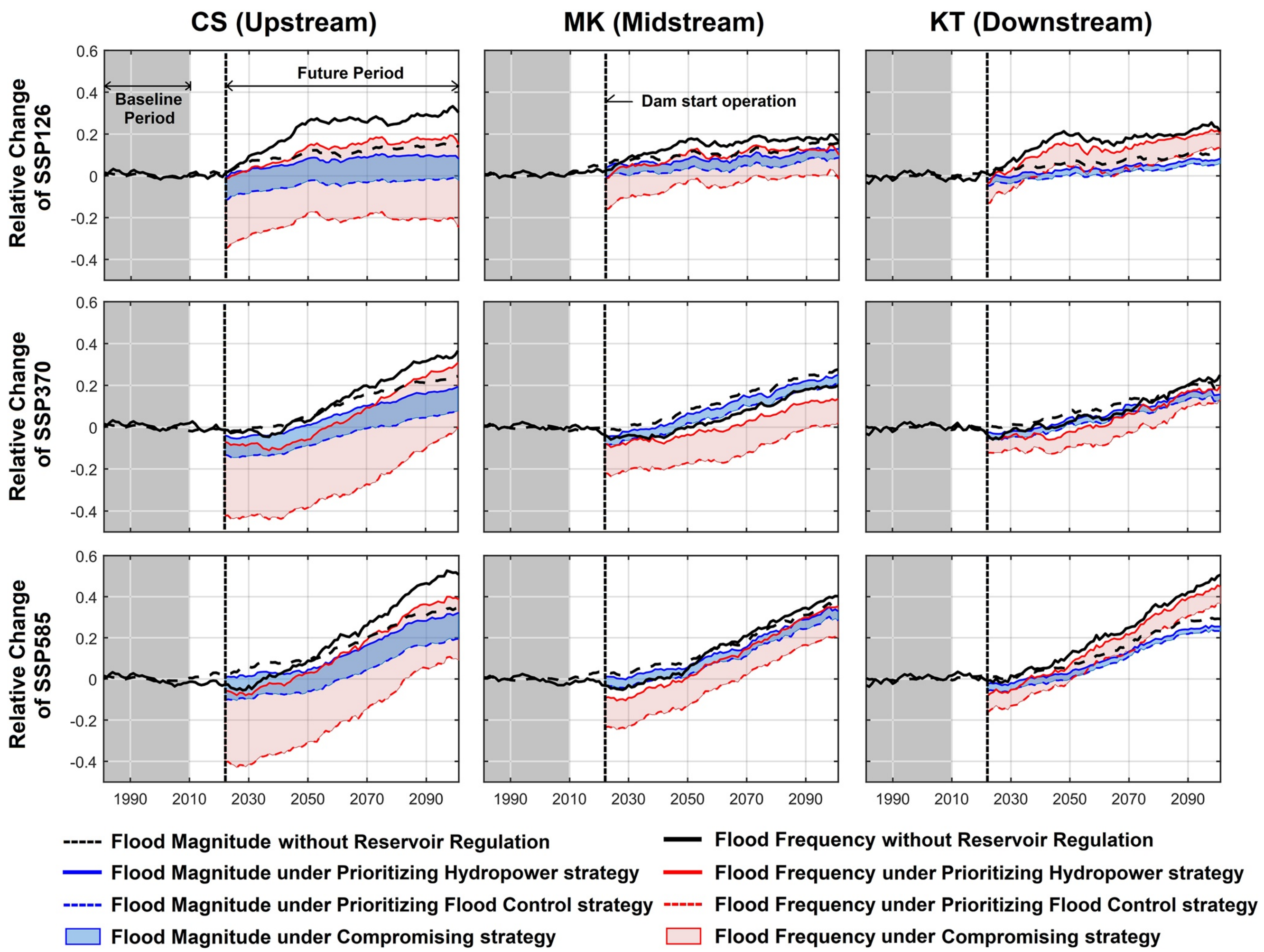

Figure 2. The 30-year moving average relative changes of flood magnitude and flood frequency with respect to the baseline period during 1980–2009 at three representative stations, namely, Chiang Sean (CS), Mukdahan (MK), and Kratie (KT) during 1980–2100 under three SSP scenarios.

operates for prioritizing hydropower generation. Switching the reservoir operation strategy to prioritize flood control can delay this timing to the 2070s at upstream (China) and midstream (Laos and Thailand) LMRB (Figure 3). The timing when the flood frequency exceeds the historical baseline in upstream and midstream LMRB can be delayed 70 years (from the 2030s–2100s) in SSP126 scenario and 30 years (from the 2060s–2090s) in SSP370 scenario. However, reservoir regulation is less effective in the downstream reaches of the basin. Even operating the reservoirs with the prioritizing flood control strategy, after the 2050s, downstream LMRB (Cambodia and southern Vietnam) will always encounter higher flood frequency than historical baseline in SSP 585 scenario (2070s in SSP126 scenario and 2080s in SSP370 scenario). Similarly, reservoir regulation is able to delay the timing when flood magnitude exceeds the historical baseline, although the length of delayed time is shorter than flood frequency.

3.3. Impacts of Climate Change and Reservoir Regulation on Future Hydropower Production

A total of 213,101 GW h yr^{-1} hydropower can be potentially generated from 103 dams in LMRB during the historical period according to VIC-R model, which is more than the total annual electricity demand in Laos, Cambodia, and Vietnam (MRC, 2019). Climate change will have an impact on hydropower production by affecting the streamflow through turbines. Although the annual streamflow will increase in NF, hydropower generation will decrease compared to the baseline period with the same prioritizing hydropower strategy (Figure 3). This can be explained by the seasonal variation in river flows: during NF, climate change will

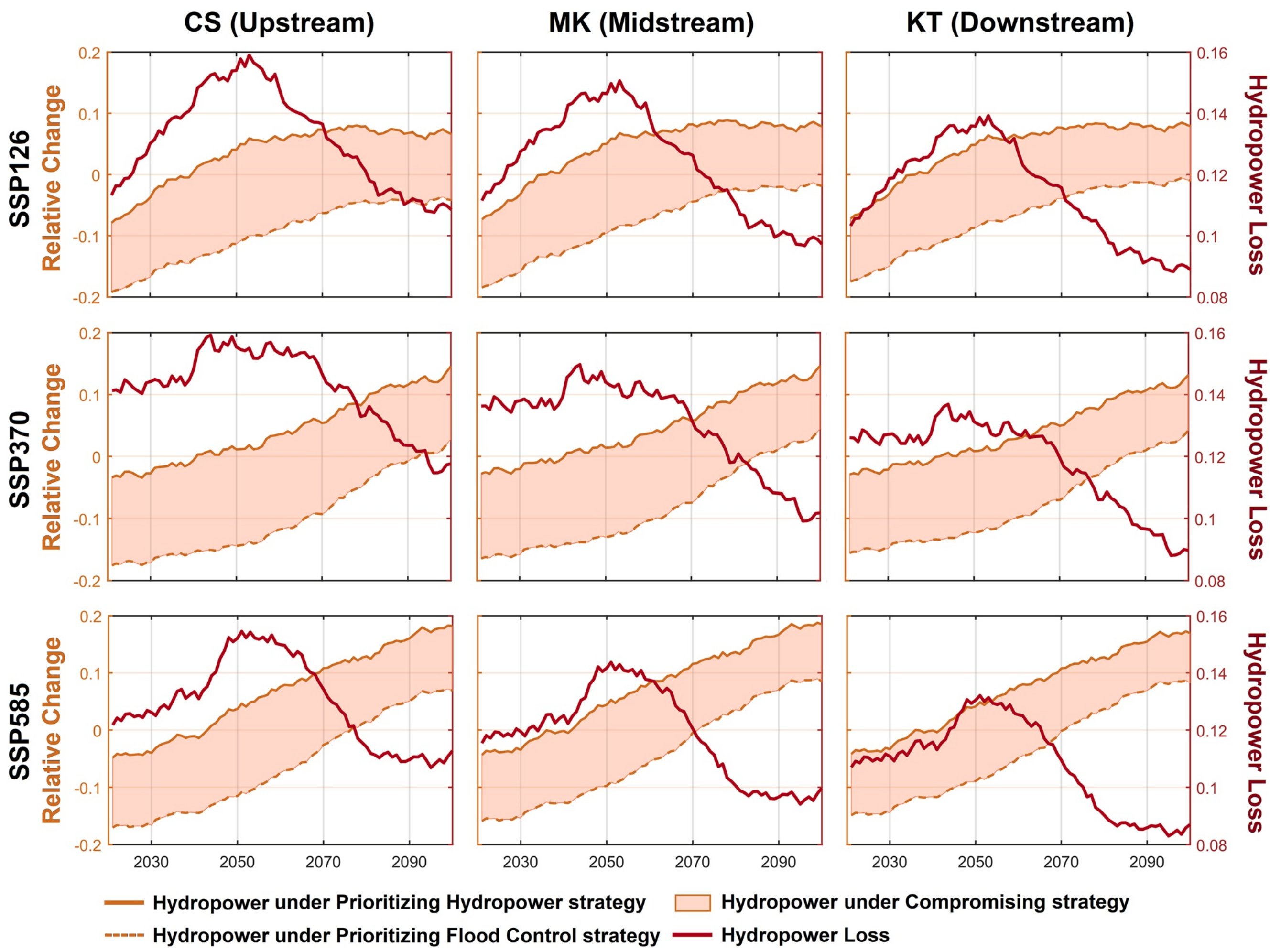

Figure 3. The 30-year moving average relative changes of hydropower generation with respect to the baseline period during 1980–2009 at three representative gauging stations, namely, Chiang Sean (CS), Mukdahan (MK), and Kratie (KT) during 2021–2100 under three SSP scenarios. Hydropower generation at each gauging station includes hydropower produced by all the upstream reservoirs. The hydropower loss is defined as the difference of hydropower generation using the two reservoir operation strategies compared to the baseline period during 1980–2009.

mainly increase wet season streamflow, whereas the dry season streamflow will decrease slightly (Figure S4 in Supporting Information S1). Restricted by the discharge capacity of the turbines in reservoirs, excessive streamflow in wet season will be abandoned without producing more hydropower; in contrast, decreased streamflow in dry season and a lower water level in reservoirs will together reduce the hydropower generation (Zhong et al., 2019). Nevertheless, the dry-season streamflow is projected to increase in FF, which will increase hydropower generation by 9.8%–11.5%.

Different reservoir operation strategies will also affect hydropower generation in LMRB. In dry season, the reservoirs continuously discharge water flows to meet downstream water demand and produce hydropower for both reservoir regulation strategies prioritizing hydropower production and flood control. In wet season, if hydropower production is a priority, the water level in reservoirs will be raised to maximize electricity production; if flood control is prioritized, water level in reservoirs is maintained low to preserve sufficient storage capacity for flooding in pre-flood season, which leads to a reduction of hydropower generation in comparison to the prioritizing hydropower production strategy. It is estimated that 9.8%–14.4% more electricity can be produced using the prioritizing hydropower production strategy than flood control strategy (Table S8 in Supporting Information S1).

The hydropower loss (i.e., defined as the difference of hydropower generation using the two reservoir operation strategies) was used to examine the effect of streamflow regulation on hydropower generation.

The result shows a first increasing then decreasing trend because of climate change driven seasonal and long-term streamflow changes. Before the 2050s, the decreased streamflow in the early wet season (from May to August) forces the reservoirs to maintain a low water level for a longer period for flood control, and the hydropower loss increases rapidly. After the 2050s, an increase in streamflow reduces the period when the reservoirs have low water levels using the strategy prioritizing flood control, and as a result the hydropower loss is reduced.

In the upper river reaches of LMRB where the large river drops 4,000 m in elevation from its headwaters in the Tibetan Plateau to the China-Laos border, the reservoirs have high dams and large water head differences. Upstream reservoirs can generate 71% of the hydropower with 55% of the installed capacity in LMRB. In comparison, reservoirs at midstream and downstream the basin only generates 10% and 19% of the electricity with 20% and 25% of the installed capacity, respectively (Table S4 in Supporting Information S1). As a result, the relative hydropower loss of upstream reservoirs is higher than those of midstream and downstream reservoirs. The curves of hydropower loss at midstream and downstream LMRB containing all upstream reservoirs show a similar pattern to that at upstream of the basin.

3.4. Tradeoff Between Flood Control and Hydropower Production Through Reservoir Regulation

While climate change leads to an increasing trend in flood magnitude (frequency) and hydropower production, reservoir regulation creates a tradeoff between the provision of energy and flood management in LMRB. Before the 2070s, reservoir regulation can reduce the increasing flood magnitude and frequency driven by climate change to the baseline level at the cost of reducing hydropower generation using a reservoir regulation strategy compromising flood control and hydropower production. After the 2070s, even if flood control is prioritized in reservoir regulation, the flood magnitude and frequency will always exceed the historical baseline level.

Figure 4a shows the average hydropower loss of individual reservoirs in 2071–2100. When the reservoir strategy is shifted from prioritizing hydropower generation to flood control at the end of 21st century, on average 7.9% electricity will be lost in each reservoir under the high emission SSP585 scenario in LMRB. Particularly, upstream reservoirs suffer a reduction of 10.2% hydropower on average, which is much higher than those at midstream and downstream reservoirs. Figures 4b and 4c display the tradeoffs between hydropower production and flood control at upstream, midstream, and downstream LMRB. In order to maintain a relatively low flood magnitude and frequency, the upstream, midstream, and downstream reservoirs suffer 21,568, 2,799, and 3,491 GW h yr^{-1} hydropower losses, respectively between 2031 and 2060. Benefited from climate change, the hydropower loss of the downstream reservoirs during 2071–2100 decrease by half compared to that during 2031–2060, while the upstream reservoirs always suffer high flood reduction cost. To reduce flood, it is estimated the hydropower generation in the upstream reservoirs decreases by 11.1% (16,677 GW h yr^{-1}) in 2071–2100, whereas the hydropower loss in midstream and downstream LMRB are 6.2% (1,304 GW h yr^{-1}) and 4.3% (1,799 GW h yr^{-1}), respectively.

Our results indicate that large hydropower loss in upstream reservoirs can benefit downstream flood control in LMRB. If regulated properly, many large reservoirs located close to the China-Myanmar border in the upper reaches of the river basin can play an important role in reducing the flooding in the middle reaches of Myanmar and Laos; Similarly, reservoirs located in upstream and midstream LMRB are able to change downstream flood characteristics of Cambodia, which will in turn affect the freshwater fishery in Tonle Sap Lake and agriculture in the Mekong Delta. It should be pointed out that countries located in different streams have different demands, for example, midstream countries (e.g., Thailand and Laos) may need to reduce floods to ensure agricultural and hydropower production, while downstream countries (e.g., Cambodia and Vietnam) may require high floods to increase fishery production and reduce seawater erosion. The dependence of flood control at midstream and downstream countries in LMRB on upstream reservoir regulation requires transboundary coordination on integrated water management. This would be achieved by urging existing organizations (such as the Mekong River Commission) and emerging basin-wide organizations (such as the Lancang-Mekong Cooperation) to embrace basin-wide water resources and hydropower planning and cooperation. For example, China has shared the water level and streamflow data of Jinghong

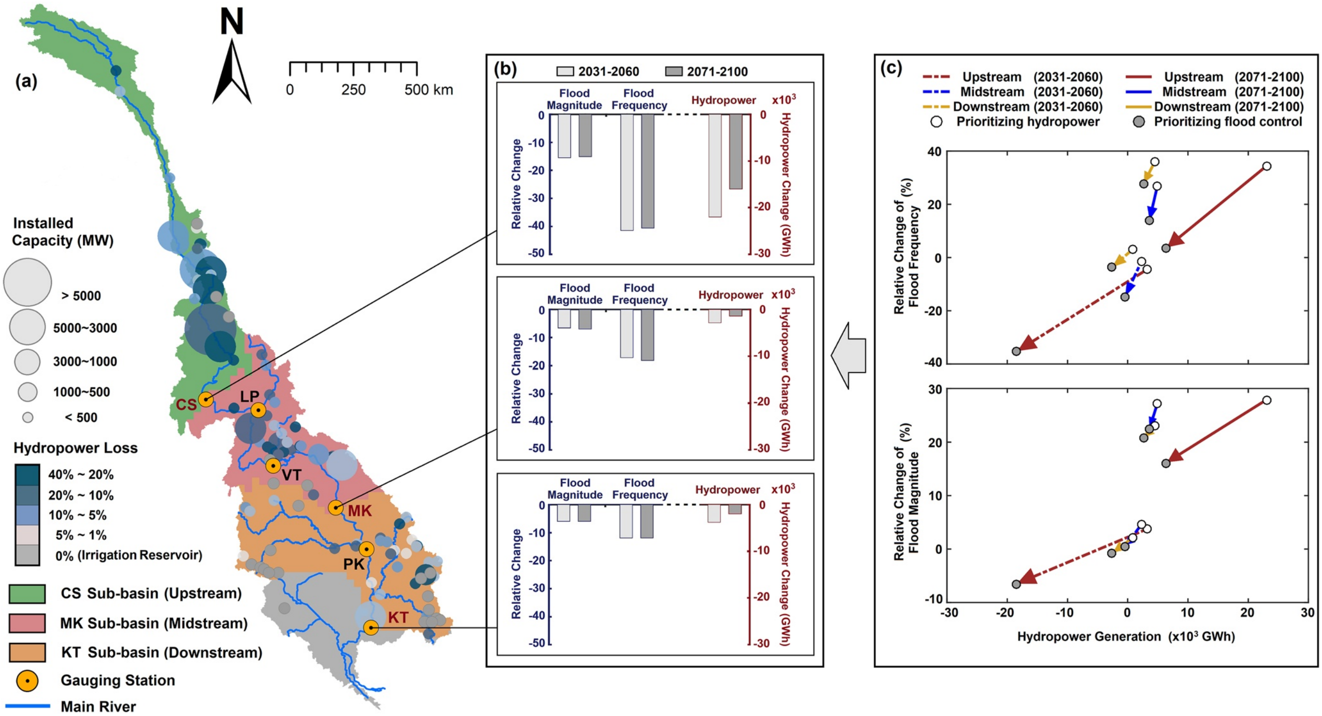

Figure 4. (a) Average hydropower loss of different reservoirs in 2071–2100 under SSP585 scenario in LMRB. Please refer to Figure S5 in Supporting Information S1 for the results of SSP126 and SSP370. (b) The changes in flood magnitude, flood frequency and hydropower when switching between prioritizing hydropower generation and flood control strategies at three sub-basins during the near future period (NF, 2031–2060) and the far future period (FF, 2071–2100). (c) The tradeoffs between hydropower production and flood control at upstream, midstream, and downstream LMRB in 21st century. The relative changes in flood characteristics with respect to the baseline period of 1980–2009 are provided in *y*-axis, and difference of hydropower generation compared to the baseline period of 1980–2009 is provided in *x*-axis.

station (near the China-Myanmar border) since November 2020, which will provide an important basis for supporting cooperation in LMRB.

4. Discussion and Conclusion

A lack of comprehensive analysis assessing the impacts of climate change and multiple reservoir operation strategies on LMRB's flood characteristics and hydropower generation hinders the development of effective climate change adaptation plans. Assessment of the tradeoffs between flood control and energy supply in this study, especially the conclusion that reducing future flooding at downstream countries is at high cost of hydropower generation at the upper reaches, will provide a vital reference for the water and energy management and cooperation between countries along this transboundary river.

It should be pointed out that although CMIP6 has a better effect of capturing the monsoon in Southeast Asia compared with CMIP5 (Xin et al., 2020), climate models still struggle to represent some phenomena, such as the impact of ENSO on the monsoon (Aadhar & Mishra, 2020). Poor-performing GCMs might be associated with poor representation of land-atmospheric feedback and convection in the CMIP6-GCMs (Aadhar & Mishra, 2020; Ashfaq et al., 2017). We used the ensemble of multiple GCMs which is effective in reducing the uncertainty of climate projections (Thompson et al., 2014).

In addition, limited by the data accuracy, we assumed that all the hydropower dams have in-dam turbines. It should be noted that some reservoirs on tributaries in Lower Mekong region divert water to other catchments and their turbines are far from the main dams (Hecht et al., 2019), this will increase the reservoir hydraulic head and lead to an underestimation of the hydropower generation, and the inter-basin flow transfer will increase/decrease the flow of tributaries (about 200 m^3/s) and affect hydropower generation at these tributary reservoirs.

Moreover, due to the assumed storage capacity curve and the overestimated precipitation of CMIP6 in 2019, the simulated hydropower generation of upstream reservoir is 20% higher than the observed value. Although a 30-year evaluation period and a relative change method were used in the hydropower analysis to reduce the impact of errors, more work is needed to improve hydropower modeling. Furthermore, construction of new LMRB's reservoirs in future may lead to high-flood reduction capacity and increasing hydropower generation. And potential agreements between countries in the Mekong region, and renewable energy plans (e.g., photovoltaic, wind, and biomass) in the emerging countries of LMRB may also have an impact on hydropower generation and flood control (Chowdhury et al., 2021; Siala et al., 2021).

In summary, we present a method to assess the combined impacts of climate change and reservoir regulation on flood and hydropower production, with an application to LMRB reservoirs. Our results indicate that there are tradeoffs between flood control and hydropower generation by reservoir operation at upstream, midstream and downstream countries in LMRB under climate change. LMRB is likely to experience climate change driven increasing flood magnitude and frequency in the coming decades under natural conditions, which can possibly be offset by reservoir regulation at the expense of hydropower generation. The method used in this study can be adapted to apply in other river basins where hydropower is rapidly expanding, such as the Amazon, Congo, and Nile.

Data Availability Statement

All data used in this study are publicly available. The bias-adjusted future atmospheric climate input data is available at the ISIMIP3b project via https://doi.org/10.48364/ISIMIP.842396.1 (Lange & Büchner, 2021). The reservoir data used in this study are provided in supporting information (Table S3 in Supporting Information S1). This reservoir data can also be accessed from Shin et al. (2020)'s research (https://doi.org/10.1029/2019WR026449). The data of reservoir depth and storage are available at the Global Reservoir Geometry Database via https://doi.org/10.5281/zenodo.1322884.

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