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Discussions

Socio-Hydrologic Modeling of the Dynamics of Cooperation in the Transboundary Lancang-Mekong River

You Lu [1], Fuqiang Tian [1], Liying Guo [1], Iolanda Borzi [2], Rupesh Patil [3], Jing Wei [1], Dengfeng Liu [4], Yongping Wei [3], David J. Yu [5,6], and Murugesu Sivapalan [7,8]

[1] Department of Hydraulic Engineering, State Key Laboratory of Hydro-science and Engineering, Tsinghua University, Beijing 100084, China

[2] Department of Engineering, University of Messina, Italy

[3] School of Earth and Environmental Sciences, University of Queensland, St. Lucia, QLD 4072, Australia.

[4] State Key Laboratory of Eco-hydraulics in Northwest Arid Region of China, Xi'an University of Technology, China

[5] Lyles School of Civil Engineering, Purdue University, West Lafayette, IN, USA,

[6] Department of Political Science, Purdue University, West Lafayette, IN, USA

[7] Department of Geography and Geographic Information Science, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

[8] Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

Correspondence to:

Fuqiang Tian, tianfq@mail.tsinghua.edu.cn

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Abstract

The transboundary Lancang-Mekong River Basin has experienced dynamics of cooperation over the past several decades, which is a common emergent response in transboundary human-water systems. Downstream countries rely on Mekong River for fisheries, agriculture, etc., while upstream countries have been constructing dams to generate hydropower. The dam construction and operation in upstream countries have changed the seasonality of streamflow in downstream countries, affecting their economic benefits. More recently, cooperation between upstream and downstream countries has been enhanced throughout the river basin. In this study, we introduce a quantitative socio-hydrological model to simulate hydrological processes, reservoir operations, economic benefits, policy feedbacks and therefore dynamics of cooperation within the Lancang-Mekong River basin. The model reproduces the observed dynamics of cooperation in the basin revealed by sentiment analysis of news articles. Hydrological variability such as droughts and human activities associated with reservoir operations affect dynamics of cooperation between the riparian countries, with importance attached to indirect political benefits of upstream playing an important role in the enhancement of cooperation. In this way, our study generated understanding of emergent cooperation dynamics in this transboundary river basin, and the socio-hydrological model used here provides a useful new framework to investigate and improve transboundary water management elsewhere.

Keywords: transboundary river basins, socio-hydrology, cooperation, emergent dynamics, mechanistic modeling

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Introduction

As an important and complex issue, transboundary water management has attracted increasing attention and efforts globally. Transboundary rivers refer to rivers shared by two or more countries (Wolf et al., 1999), or two or more states within individual countries. There are over 310 transboundary rivers spanning over 150 countries, covering more than 40% of the world's human population and land areas (UNEP, 2016;McCracken and Wolf, 2019). Transboundary water management in a reciprocal manner is critical to ensuring regional cooperation and sustainable development and to achieving water security, food security, energy security and ecosystem security for the human populations residing within these river basins. From a human perspective, rivers serve multiple functions such as water supply, irrigation, fishery, navigation, hydropower generation, and provision of numerous other ecosystem services. These functions can vary spatially within a river basin, and consequently, societal preferences for water use may also differ in different locations, leading to possible disputes and conflicts between upstream and downstream uses. Under these circumstances, cooperation among the various stakeholders is necessary, which requires equitable and reciprocal benefit sharing, for humans to realize the full potential of the services that rivers provide. Cooperation could take different forms (Sadoff and Grey, 2005), and operating at different levels (Sadoff and Grey, 2002). Forms and levels of cooperation can vary from unilateral actions and disputes, to collaboration, to joint action, and to integrated and coordinated approaches (Sadoff and Grey, 2005). For example, information sharing for flood and drought mitigation, reservoir operations adapted to the needs of both upstream and downstream users, joint ownership of water-related infrastructure and institutions for basin-wide cooperation are common forms of transboundary river cooperation.

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Compared to water resources management in domestic river basins, transboundary river management must deal with an additional complexity. The complexity arises from the fact that in transboundary river basins the different preferences for water uses may be separated by national or state boundaries. Under these circumstances, cooperation among stakeholders could be inter-twined with other issues, or are limited by riparian relations, compounded by institutional limitations (Wolf et al., 1999) and differing national economic and strategic interests. When combined with obstacles towards enforcement (Müller et al., 2017;Espey and Towfique, 2004), cooperation is much more difficult to achieve. The incompatible requirements or demands of different riparian countries or states and the absence of institutional arrangements to reconcile these differences may lead to sub-optimal outcomes for all stakeholders, leading to conflicts that may be harder to manage (Petersen-Perlman et al., 2017).

Despite the challenges in transboundary river cooperation, there are examples of successful cooperation and avoidance of conflict. Having experienced great losses due to environmental pollution and flooding, the countries sharing Rhine river in Europe have cooperated successfully to address shared goals of environmental protection and flood control over the last several decades (Schultz, 2009). However, there are also examples of failures to cooperate. Due to lack of unified and cooperative actions of the riparian countries, Amu Darya River and Syr Darya River in Central Asia suffered over-exploitation of their water resources which resulted in consequent disappearance of most water surface and ecological disaster in the once thriving Aral Sea (Tian et al., 2019). Therefore, it is worth investigating the fundamental question of what made the difference between examples of successful cooperation and those of conflict and failure.

Over the last several years, researchers have spent considerable efforts to analyze and understand the aforementioned question. Extant studies include empirical researches as well as modeling efforts (De Stefano et al., 2017;De Bruyne and Fischhendler, 2013;Bernauer et al., 2012;Beck et al., 2014). The International Water Events Database has collected cooperative and conflictive water interactions over global transboundary river basins, and provides useful data and frameworks for further statistical studies (De Stefano et al., 2010;Munia et al., 2016) and detailed investigations in specific basins (Feng et al., 2019). Statistical methods or case studies help to identify the broad factors affecting transboundary river cooperation. These have included: natural conditions (e.g., hydrological scarcity and variability) (Dinar et al., 2010;Dinar, 2009), political relations (Zeitoun and Mirumachi, 2008), power dynamics (Zeitoun et al., 2011;Petersen-Perlman et al., 2017), institutional arrangements (Dinar, 2009), and the relative levels of social and economic development (Song and Whittington, 2004). Hydrological-economic models that involve hydrological simulation and benefit calculation and allocation through benefit maximization or game theory (Li et al., 2019;Yu et al., 2019b) are also common methods used to analyze the human-water interactions in transboundary river. These modeling approaches have been applied to the Lancang-Mekong and the Nile river basins (Cai et al., 2003;Ringler and Cai, 2006;Arjoon et al., 2016;Basheer et al., 2018).

Most of the studies highlighted above have viewed the cooperation in transboundary rivers in a static way. However, a key aspect of cooperation by social actors (in this case riparian countries or states, representing the humans living in these states) is that cooperation itself is dynamic in nature, and transboundary river cooperation is also evolutionary. For example, in the Colorado River Basin shared by USA and Mexico, industrialization and population growth

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have increased the stress on surface and groundwater resources and on water quality. Ground water depletion and water pollution contributed to tension between the two countries from the 1940s. Following protracted negotiations, several treaties were signed and institutions built, with the result that the interactions between USA and Mexico have now become more cooperative in recent years (Frisvold and Caswell, 2000). Globally, the cooperative tendency reached its peak during 1971-1986, compared to the previous 1948-1970 and later 1987-1999 periods (Wolf et al., 2003). The relatively low cooperative tendency over the 1987-1999 period is thought to continue to the 2000-2008 period (De Stefano et al., 2010). The focus of transboundary water treaties, which symbolize cooperation, have been reported to shift from exploitation of water resources to sustainable water management and framework setting, with increased importance given to environmental health (Giordano et al., 2013). The approaches used in studies to date do not accommodate the dynamic co-evolutionary nature of transboundary cooperation and conflicts and are therefore not up to the task of seeking mechanistic explanations for observed dynamics of cooperation in transboundary river basins.

In this study, we aim to address this knowledge gap by adopting a process-based, socio-hydrologic framework to represent transboundary cooperation in the Lancang-Mekong river basin, which involves China, Myanmar, Laos, Thailand, Cambodia and Vietnam as riparian states. Using dynamic modeling to understand the mechanisms behind cooperative or conflictive actions of riparian countries, not only in a specific river basin, but also similarities and differences between basins, would help in elucidating key drivers that account for differences in the cooperation level and its dynamics over time. Increased mechanistic understanding will help increase the scope of cooperation and avoidance of conflict in the future, and generate economic, social, and geopolitical benefits (Yu et al., 2019a;Sadoff and Grey, 2002), which are expressed as "beyond the river" benefits by Sadoff and Grey (2002). Enhanced cooperation could lead to harmony in human-water relations generally and regionally, including equitable and sustainable use of water. Conversely, the continuation of conflicts could result in disordered water use, over-exploitation (Tian et al., 2019) and overall loss of amenities.

In approaching this aim, it is critical to capture the two-way feedbacks between the social system and the transboundary river system. Entering the Anthropocene era, human society and hydrological systems have become ever more tightly coupled, and in the long-term, co-evolution of the resulting coupled, socio-hydrological system has been shown to result in emergent dynamics and unintended consequences (Sivapalan and Bloschl, 2015). Examples include decadal asymmetric dynamics of human water consumption in several large semi-arid river basins in Asia (Tian et al., 2019), and the "pendulum swing" in agriculture water use and human development in both Eastern and Western Australia (Kandasamy et al., 2014). Socio-hydrology as a science explores the two-way feedbacks between human and water systems, necessary to understand and mimic observed emergent dynamics (Sivapalan and Bloschl, 2015). Driven by both natural and social forces, a transboundary river basin can also be viewed as a coupled socio-hydrological system, now with a distinct spatial (upstream-downstream) dynamics mediated by multiple riparian states. Observed patterns of cooperation and conflict in a transboundary basin can then be seen as a special case of emergent dynamics that results from interactions and feedbacks between the actions of water users or stakeholders in upstream and downstream riparian states and the interplay of associated hydrological, economic, and social, and geo-political processes (Di Baldassarre et al., 2019). Historical patterns of the

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intensity or levels of cooperation between riparian states are key indicators that can be used as targets of socio-hydrologic models developed with the aim of generating mechanistic understanding of the co-evolutionary paths followed by transboundary river basin management. In this study, we will present a coupled socio-hydrological model developed to simulate the dynamics of conflict and cooperation in transboundary river systems, and its application to the Lancang-Mekong river basin. The nature of shared use of the waters of the Lancang-Mekong River has significantly evolved over the last 60 years through cycles of cooperation and conflict. The socio-hydrological model developed here is used to mimic the mechanisms of cooperation and conflict in this basin in a way to gain basic understanding that may be transferred to transboundary river basins elsewhere.

The remainder of the paper is organized as follows. In Section 2, we will introduce the study area and the history of observed dynamics of cooperation and conflict. Section 3 will present the rationale and details of the socio-hydrological model, including the various modules and governing equations describing the various subsystems, and how they are coupled in a way to capture the dynamics of cooperation and conflict. Section 4 presents the simulation results and a discussion and interpretation of the results, followed by, in Section 5, a summary of the main conclusions and the understanding and insights gained from the study.

1. Study Area and Historical Timeline of Cooperation and Conflict Dynamics

Lancang-Mekong River is an important transboundary river located in Southeast Asia. As shown in Figure 1, it originates from the Tibetan Plateau in China, and over its entire length of 4900 km it passes through Myanmar, Laos, Thailand, Cambodia, and Vietnam (Wang et al., 2017). The Lancang-Mekong river basin drains an area of 812,400 km^2 and supports the water needs and livelihoods of over 65 million people (Ringler and Cai, 2006;MRC, 2018;You et al., 2014). The annual average discharge of Lancang-Mekong River flowing into the South China Sea is close to 475 billion m^3/year (Campbell, 2016). The drainage area of the upstream part, i.e., the Lancang River Basin in China, is 195,000 km^2, which accounts for 24% of the whole basin area. The Mekong River Basin in Myanmar, Laos, Thailand, Cambodia and Vietnam covers an area of around 600,000 km^2 (Li et al., 2017).

Starting from a relatively undeveloped basin in the 1950s, Lancang-Mekong River Basin has experienced rapid economic growth in recent decades (MRC, 2010). Although they all have many shared interests, different riparian countries within the Lancang-Mekong river basin benefit from different river functions. For example, while all riparian countries have the need to protect themselves from the negative impacts of floods and droughts and ensure the sustainability of ecosystem, the upper riparian states of China and Laos have constructed and plan to construct many dams, mainly for hydropower generation (Keskinen et al., 2012). For the downstream states of Thailand, Cambodia and Vietnam, agriculture and fishery are the main uses of the Mekong River. Irrigated agriculture is a major water consumer in the basin (MRC, 2018), and rice is the main staple crop (Campbell, 2016). In the lower Mekong region, especially in Cambodia and Vietnam, fishery not only employs a large number of people, but also sustains their protein demands (Campbell, 2016).

As an important and geopolitically sensitive region (Campbell, 2016), Lancang-Mekong River Basin has experienced both conflict and cooperation since the end of World War II under the impacts of changing geopolitical relationships, hydrological dynamics and socio-economic conditions. With the sponsorship of the United Nations Agency ECAFE, the Committee for

Coordination of Investigations of the Lower Mekong Basin was initiated in 1957, and early efforts included the setting up of comprehensive hydrological observations and the setting up of regional plans for hydropower, flood control and irrigation (Campbell, 2016). However, because of the withdrawal of Cambodia in 1977 due to political reasons, Thailand, Laos and Vietnam initiated the Interim Committee for Coordination of Investigations of the Lower Mekong, which took limited efforts towards regional cooperation. Until 1995, the four countries of the lower Mekong were part of the Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin, through which they established the Mekong River Commission (MRC). MRC was designed to enhance cooperation on water utilization and management, socio-economic development and ecosystem conservation (MRC, 1995). Although China signed an agreement on the provision of hydrological information on the Lancang-Mekong River in 2002, the efforts of MRC were limited due to the absence of the upstream states, namely China and Myanmar. Finally, the Lancang-Mekong Cooperation Mechanism (LMC) was initiated in 2016 to include all of the six riparian countries and thus enhance more comprehensive cooperation (Feng et al., 2019).

Specifically, cooperation in Lancang-Mekong River in the 21st century has been in the spotlight because of rapid changes in climatic and hydrological conditions, intensified human activity and geopolitical sensitivity of the region. Dam construction principally in the two upstream countries, China and Laos, has continued over three decades. Since 2010, large hydropower plants have been commissioned on the mainstream of Lancang-Mekong River (Han et al., 2019). Reservoir operations in the upstream increase dry season runoff and reduce runoff peaks during the flood season (Hoanh et al., 2010). The resulting changes in river flow were strongest in the upper Chiang Saen station in Thailand and less marked in the lower station Kratie in Cambodia (MRC, 2018). The resulting change of seasonality of river flows has a significant impact on the benefits of different water uses (Pokhrel et al., 2018), for example, wetland ecosystem services (Dudgeon, 2000) in Vietnam, and fish capture in the largest freshwater lake in Southeast Asian, Tonle Sap (Kite, 2001) located in Cambodia. Correspondingly, due to the effects of upstream dam operations for hydropower generation, the downstream countries faced concerns about benefit losses. Here the loss indicates deviation from their maximum expected benefit instead of absolute loss, because human values outcomes as gains and losses relative to a reference level (Kahneman and Tversky, 1979). To obtain indirect political benefits, which is described as “diplomatic returns” in Yu et al. (2019b), the upstream country China has worked to change flow regulations of their reservoirs to satisfy the demands of the downstream countries and achieve regional cooperation. One example of this is the emergency water release from China in 2016 to alleviate the effects of a severe drought in the lower Mekong basin (Yu et al., 2019b). This change of hydropower dam regulations in upstream countries can be regarded as an example of a cooperative response.

Figure 2 summarizes the hydrological and anthropogenic events in Lancang-Mekong River Basin. The upstream countries China and Laos have constructed or planned to construct dams on the mainstream of Lancang-Mekong River. Two major reservoirs on the mainstream, Xiaowan and Nuozhadu, went into production in 2010 and 2012 respectively. The filling and operation of reservoir caused the alteration of hydrological regimes in the downstream, i.e., increase of runoff in the dry season and reduction in the flood season. Economic losses compared to expected benefits caused by the change of hydrological seasonality and natural

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droughts, led to concerns raised by downstream countries, and tension and conflict. However, cooperation has been enhanced in recent years, exemplified by some cooperative actions of the upstream country China, such as emergency water release during a period of drought. We will use the socio-hydrological model to simulate the water-related events and the cooperation dynamics, and provide mechanistic explanations based on socio-hydrologic interpretation of the emergent dynamics.

2. Model

We will here introduce a transboundary river cooperation socio-hydrological model (TCSH model) that will be used to simulate the dynamics of cooperation and conflict observed in Lancang-Mekong River Basin. The causal loop presented in Figure 3 introduces the main components of the model. It simulates the change of river flow seasonality caused by reservoir operations, which causes loss compared to expected benefits to downstream countries in different sectors. The loss compared to expected benefits leads to demands by the downstream countries for more cooperation from upstream countries, to which the upstream countries respond with changes to their reservoir operations. The modeled levels of cooperation, and the resulting changes to reservoir operations, are determined by a balance between hydropower losses and indirect gain of geopolitical benefits by the upstream countries.

As seen in Figure 3, the socio-hydrological model couples four main parts, i.e., hydrological simulation, reservoir operation, economic benefit calculation, and policy feedback. A distributed catchment hydrological model is used to model natural streamflow inputs to the dams and is calibrated using observations at several stations along the Lancang-Mekong River and its tributaries. With available reservoir information, the reservoir operation module simulates two basic scenarios, i.e., maximizing upstream benefits versus maximizing downstream benefits. The results of these two operational scenarios are weight averaged to calculate actual water releases and reservoir storages. The economic benefit calculation module estimates the economic benefits for both upstream and downstream countries covering hydropower, irrigation and fishery sectors based on outcomes of the hydrological simulation and reservoir operation modules. The fourth module simulates the policy feedbacks through the estimation of economic benefits and operation weights through two key variables, i.e., cooperation demand of downstream countries and cooperation level of upstream countries. Outcomes of sentiment analysis of newspaper articles are used to evaluate the modeled cooperation demand. The calculation step length of the model is one month. Each of these components of the model is discussed in detail in the following sections.

3.1 Hydrological simulation

We use the distributed hydrological model THREW to simulate natural runoff of mainstream and tributaries without impacts of reservoir operations, i.e., Q_n in Figure 3. The THREW model has been applied to many river basins successfully, including rivers derived from mountainous areas and consisting of snow and glacier melt, and large-scale basins (Tian et al., 2006;Tian et al., 2008;Li et al., 2012;Mou et al., 2008). Based on the Representative Elementary Watershed (REW) approach (Reggiani et al., 1998), the THREW model uses the REW as the sub-catchment unit for hydrological simulations (He et al., 2015). The main runoff generation processes include surface runoff, groundwater flow, and snow and glacier melt.

In this study, we divide the Lancang-Mekong basin into 651 REWs on the basis of DEM data, as shown in Figure 1. The precipitation data is retrieved from TRMM data of 1998-2018. The accuracy of TRMM data for hydrological simulation in this region has been proven successfully (MRC, 2018). Thirty-two meteorological stations dispersed around the whole basin provide meteorological inputs, including temperature, wind speed, humidity and radiation to calculate potential evapotranspiration based on Penman-Monteith equation. Soil data is extracted from FAO world soil database, and LAI, NDVI and snow are obtained from MODIS data. Daily runoff observations of 6 stations on the mainstream of the Lancang-Mekong river include data of Jinghong (1998-2013), Chiang Saen (1998-2015), Luang Prabang (1998-2015), Nong Khai (1998-2007), Nakhon Phanom (1998-2015) and Pakse (1998-2006).

The hydrological model is used to provide simulations of natural runoff without the impacts of water withdrawal and reservoir operations. Therefore, we use the runoff data in the period before large reservoir construction for parameter calibration, i.e., runoff data of the period of 1998-2009. Runoff data of the hydrological stations on the mainstream are used for distributed calibration, i.e., the parameters are calibrated separately and in a spatially distributed manner. Specifically, the year of 1998 is used as a warm-up period, 1999-2004 as calibration period, and 2005-2009 is set as validation period. The simulated runoff of 2000-2018 is used as natural flow of mainstream tributaries Q_n before the impacts of human activities.

3.2 Reservoir operation

Reservoir construction in the upstream reaches of the Lancang-Mekong River has accelerated since 2000, and several large reservoirs on the mainstream have been constructed or are under construction. Among them, the largest two reservoirs in China with seasonal runoff regulation capacity (Yu et al., 2019b), namely Xiaowan and Nuozhadu, went into operation in 2010 and 2012 respectively. The basic information of Xiaowan and Nuozhadu including the total reservoir storage S_{total}, dead reservoir storage, and flood limited storage S_{flood} are listed in Table 1. The total storage of the two major reservoirs account for 90% of the total storage of the largest six reservoirs (Han et al., 2019). The cascade of reservoirs within China is simplified and approximated in this study by the Xiaowan and Nuozhadu reservoirs.

Laos has aimed to be the "battery of Southeast Asia" (Stone, 2016) and has started hydroelectric dam construction on the mainstream of the Mekong river in line with this ambition. Before that, Laos constructed many dams on its tributaries, which also impact the streamflow regimes of the Mekong River. According to MRC (2018), the expected live storage of reservoirs in Laos will ultimately reach 24,257 MCM, accounting for 73% of the flows left for the four downstream countries. For simplicity, we only consider the completed tributary reservoirs in Laos. They are aggregated by one proxy reservoir in the upper reaches, including some reservoir storages located in the relatively lower reaches in Laos (Li et al., 2019;WLE, 2018). In the model, the proxy reservoir used is assumed to have live storage from 5,074 MCM in 2000 to 21,066 MCM in 2018, which was linear interpolated and represents continuous dam construction in Laos.

Overall, these simplifications through lumping the effects of many reservoirs is deemed reasonable for the purposes of this study, because three reservoirs (Xiaowan and Nuozhadu in China and the aggregated Laos Reservoir) shown in Figure 4 capture most of the effects of reservoirs within the entire river basin. As shown in Figure 4, the river system and its water diversion configuration are also simplified, where T0, T1 to T6 indicate natural runoff of upstream and tributaries, W4, W5, W6 are the water withdrawal for irrigation in Laos, Thailand, Cambodia and Vietnam. For each node, runoff flowing to the next node is calculated by water balance equation, e.g., for Thailand,

$$\mathrm{QN4} = \mathrm{QN3} + \mathrm{T5} - \mathrm{W4} \tag{1}$$

where, QN3 is runoff flowing to Thailand from the upstream node, Laos, T5 is inflow from tributaries in Thailand, W4 is irrigation withdrawal in Thailand, and QN4 is runoff flowing to the downstream node, Cambodia.

For the operation of constructed dams, we consider two basic scenarios. The first scenario is the self-interested scenario (non-cooperation scenario, abbreviated by NC), in which the upstream countries, China and Laos, operate the dams considering only their own hydropower benefits B_h.

$$B_h = \mathrm{ph} \times 9.81 \times Q_r \times \Delta \mathrm{h} \times \eta \tag{2}$$

where, ph is the electricity price, Q_r is the monthly water release from the reservoir, Δh is the water head difference between the upstream and downstream, which is related to the actual storage S_r, and η is hydropower generation efficiency.

$$Q_{r,t} = max\{S_{r,t-1} + Q_{in,t} - S_{total}, 0, Q_{eco}\},\ \mathrm{t} = 1,2,3,4,5,11,12 \tag{3}$$

$$Q_{r,t} = max\{S_{r,t-1} + Q_{in,t} - S_{flood}, 0, Q_{eco}\},\ \mathrm{t} = 6,7,8,9,10 \tag{4}$$

Under this scenario, dams keep at their total storage S_{total} during the dry season (November to May) and their flood limited storage S_{flood} in flood season (June to October). If the actual storage of t-1 period $S_{r,t-1}$ is less than these two values the reservoir will store water to reach the amount; otherwise, the reservoir will release water. There are also constraints of minimum ecological release flow Q_{eco} to satisfy the requirements of ecosystem and navigation. Actual water release under the self-interested scenario $Q_{r,NC}$ is calculated using Equations (3) and (4). The actual storage of next month $S_{r,t}$ is calculated based on water balance equation.

The second scenario is the altruistic scenario (full-cooperation, abbreviated by FC), where the upstream countries operate dams to maximize the benefits of downstream countries. The calculation of the benefits to downstream countries will be introduced in Section 3.3. Under this scenario, the constraints contain maximum storage during dry season, maximum storage during flood season, minimum storage of dead storage and minimum ecological release flow. Then the processed results of actual water release $Q_{r,FC}$ will be used to calculate actual reservoir storage S_r based on the water balance equation.

As shown in Figure 3, with the calculated water release under the self-interested scenario $Q_{r,NC}$ and that under the altruistic scenario $Q_{r,FC}$, we obtain the weighted average scenario (WA scenario) and final actual water release Q_r by calculating their weighted average.

$$Q_r = Q_{r,NC} \times \delta_1 + Q_{r,FC} \times \delta_2 \tag{5}$$

where $\delta_1 + \delta_2 = 1$, and δ_2 is calculated using the cooperation equations while δ_1 is calculated as the residual $1 - \delta_2$, which will be introduced in section 3.4. It should be noted that the calculated Q_r by equation (5) should be revised if it violates the constraints of maximum storage during dry and flood seasons, minimum storage of dead storage and minimum ecological release flow. And the final actual reservoir storage S_r is calculated for hydropower benefit calculation.

3.3 Economic benefit calculation

In this study, we consider the hydropower benefits B_h of China and Laos, and agriculture benefits B_a and fishery benefits B_f of Thailand, Cambodia and Vietnam. The hydropower benefits calculation of China and Laos were introduced in section 3.2. Here agriculture benefits B_a only include irrigated rice without consideration of rain-fed crop production. Agricultural water withdrawals dominate water consumption in the downstream countries, and rice is the staple crop in this area. In this study, we use the FAO 33 crop water production function to calculate crop yields and irrigation benefits (Doorenbos and Kassam, 1979).

$$B_a = pa \times Y_a \times A \tag{6}$$

$$(1 - \frac{Y_a}{Y_m}) = K_y \times (1 - \frac{\mathrm{AET}}{\mathrm{PET}}) \tag{7}$$

where pa is price of rice, A is the rice irrigation area, Y_a and Y_m are actual and maximum crop yields, respectively. K_y is crop yield response factor, and AET and PET are actual and maximum evapotranspiration respectively. The information on the price of rice, irrigation area, rice yield and irrigation withdrawal of Thailand, Cambodia and Vietnam are listed in Table 2. Y_m is set as 8.5 ton/ha for all three countries (FAO, 2004). AET and PET are calculated based on potential evapotranspiration and irrigation amount, and the detailed methods could be found in Allen et al. (1998) and Kaboosi and Kaveh (2012).

Fishery is one of the dominant environmental water uses in the lower Lancang-Mekong River Basin, but it is difficult to quantify fishery benefits. In general, comprehensive fisheries models have many required inputs to calculate fishery benefits, such as mortality, recruitment, and fishing efforts (Baran and Cain, 2001). There are many studies focusing on the simulations of fishery benefits through their relationships with water level (Hortle et al., 2005) and flooded areas (Burbano et al., 2020). It is difficult to couple complex fishery models to our model, and there is not any standard function for fishery benefits up till now. Here, for simplicity, we only capture fishery benefits and do not include aquaculture benefits, since it is not significantly impacted by hydropower operation. Based on literature review, an increasing function of runoff with decreasing marginal increase was adopted to calculate capture fishery benefits, which is simple but effective in Mekong Basin (Ringler, 2001;Ringler and Cai, 2006).

$$iff = \arctan\left(\frac{Q-Q_{min}}{Q_{max}}\right) \times \left(1 - b \times \left(\frac{Q-Q_{min}}{Q_{max}} - c\right)^2\right) \tag{8}$$

$$B_f = pf \times iff - \text{Fcost} \tag{9}$$

where iff is the fishery production related to actual discharge Q, minimum discharge Q_{min}, maximum discharge Q_{max}, and two parameters b and c. In equation (9) to calculate fishery benefit B_f, pf is the fishery price and Fcost is fixed fishery cost. Overall, fishery benefits for downstream countries are related to actual runoff, maximum runoff, and minimum runoff. As shown in Figure 4, QN4, QN5, QN6 are used as actual runoff to calculate fishery benefits for Thailand, Cambodia and Vietnam respectively.

3.4 Policy feedback

Cooperation demands U of downstream countries arise from economic losses compared to expected benefits, and the upstream countries take cooperative action to obtain indirect political benefits, although this might reduce their hydropower generation benefits. Cooperative actions of upstream countries take effect in multiple forms, such as information sharing and joint investment (Sadoff and Grey, 2002). It is always difficult to quantify cooperation demand and cooperation level. As a first attempt, in this study we only consider change of operation rules of reservoirs as cooperative action and define the cooperation level C of upstream countries as the weight assigned to the operation rules to maximize downstream benefits when upstream countries operate their reservoirs, i.e., δ_2 in section 3.2. When cooperation level $\mathrm{C} = 1$, upstream countries operate dams to maximize the downstream benefits, i.e., altruistic scenario. If $\mathrm{C} = 0$, upstream countries will follow operation rules in Equations (3) and (4), which is consistent with the self-interested scenario.

Following the assumption that cooperation demand is increased due to economic losses compared to reference level, larger economic losses will cause greater community concerns and thus increased cooperation demands. According to the theory of reference dependence, humans evaluate gains and losses relative to a reference point (Schmidt, 2003), and the reference point could be the status quo (Tversky and Kahneman, 1991) or the level of aspiration (Siegel, 1957). Here we value the losses relative to the expected maximum benefits of sectors B_{amax} and B_{fmax}, i.e., as the differences between expected maximum benefits and actual benefits. As shown in equation (10), we assume that the cooperation demand is proportional to economic losses, but the sensitivity of each economic sector is distinct.

$$\mathrm{U} = \varepsilon_a \times \frac{B_{amax}-B_a}{B_{amax}} + \varepsilon_f \times \frac{B_{fmax}-B_f}{B_{fmax}} \tag{10}$$

where ε_a and ε_f are the sensitivity of agriculture loss and fishery loss. The sensitivities indicate the importance of each sector to the overall lower basin economy, and larger sensitivity means that downstream countries are more sensitive to the sector benefit change, and the unit sector loss could lead to severer negative impacts. The expected maximum benefits B_{amax} and B_{fmax} are also used for normalization.

For the cooperation level of upstream countries, we use a logit dynamics model (McFadden, 1981;Hofbauer and Sigmund, 2003) taken from environmental economics. This model is used to relate economic losses and benefits with the probability of cooperation. It has been widely used and proven effective to relate natural system dynamics with cooperation dynamics, e.g., the simulations of cooperation on pollution control among stakeholders, who behave responding to other stakeholders' behaviors and their own benefits (Iwasa et al., 2007;Suzuki and Iwasa, 2009a, b). In the logit dynamics model, the probability of cooperation Pr could be calculated as below:

$$\mathrm{Pr} = \frac{e^{\beta \times B_C}}{e^{\beta \times B_C} + e^{\beta \times B_N}} \tag{12}$$

where β is a shape parameter ranging from 0 to 1, B_C is the benefit of cooperation, and B_N is the benefit without cooperation.

Similarly, for upstream countries, if they choose not to cooperate, their benefit B_N will be hydropower generation benefits under self-interested scenario $B_{h,NC}$ and benefits from other sectors. If they choose to cooperate, besides the hydropower benefits under the altruistic scenario $B_{h,FC}$ and benefits of other sectors, the upstream country will also gain indirect political benefits, which is related to the cooperation demands of downstream countries. Here we assume that the political benefit is proportional to cooperation demand U and a political factor P. If the upstream country values the political relations with downstream countries and regards diplomatic benefits as important, as China has demonstrated in recent years, the value of political factor P will be higher. Therefore, the equation to calculate the actual cooperation level C for China is as described below, and the cooperation level for Laos should consider agriculture benefits additionally.

$$\frac{\mathrm{dC}}{dt} = \mathrm{s} \times \left[\frac{e^{\beta \times (\mathrm{U} \times P + \varepsilon_h \times \frac{B_{h,FC}}{B_{hmax}})}}{e^{\beta \times (\mathrm{U} \times P + \varepsilon_h \times \frac{B_{h,FC}}{B_{hmax}})} + e^{\beta \times \varepsilon_h \times \frac{B_{h,NC}}{B_{hmax}}}} - C \right] \tag{13}$$

where s is the responsive change rate reflecting the response speed of upstream countries, ε_h is the sensitivity of hydropower loss, and $\frac{\mathrm{dC}}{dt}$ indicates the change of cooperation level compared to the last period. As mentioned before, the cooperation level C equals the weight δ_2, so the cooperation demand and cooperation level will affect reservoir regulations, and in this way will drive the co-evolution of the coupled transboundary socio-hydrological system.

Empirical observational data is needed to evaluate the simulation of policy feedbacks. It is difficult to measure cooperation demand, particularly the cooperation among countries on a specific item, i.e., reservoir operation and water resources management. Sentiment analysis is an emerging tool to quantify social data, which exploits the denotation of words and assigns sentimental value to text strings by an algorithm (Bravo-Marquez et al., 2014;Abdul et al., 2018). It has already been used to provide information of the attitudes of Chinese citizens towards dam construction (Jiang et al., 2016). In this study we use the method of sentiment analysis of newspaper articles in Thailand, which are assumed to reflect the changes in cooperation demands of downstream countries. Newspaper articles could reflect public opinion on issues of interest to the community, which have been used in previous socio-hydrologic studies to monitor the evolution of environmental awareness vis a vis economic livelihood (Wei et al., 2017).

We used the Lexis-Nexis database to extract relevant information in English newspapers in Thailand (Weaver and Bimber, 2008), sorted the data manually and conducted sentiment analysis. Although the English newspapers could omit some information when compared to local language newspapers, they are important sources to analyze the dynamics of local public opinions. Firstly, key words for search (e.g., Mekong, water, dam, etc.) and search limitations (e.g., location of publisher) are set for this study, and data retrieval is conducted automatically. Secondly, manual data sorting was used to remove duplicates and irrelevant news. Thirdly, the sorted data was analyzed through coding to get the sentiment of each piece of news and corrected manually. This method has been used widely to explore the perspectives towards specific topics and the detailed steps have been introduced in Wei et al. (2020). Finally, each piece of valid data will provide information of news titles, publication year, sentiment category (positive or negative) and sentiment values. The sentiment values range from -1 to 1, with positive values indicating positive sentiment of the news towards the topic. We will use the sentiment values to evaluate simulated cooperation demand of downstream countries.

3. Results

3.1 Hydrological simulation and reservoir operation

As major mainstream dams commissioned after 2010, the runoff data before that time could roughly represent the natural runoff in Lancang-Mekong River. We use the observed runoff data of 1999-2005 at Jinghong, Chiang Saen, Luang Prabang and Pakse for parameter calibration of hydrological model, and use the rest of the data for validation. As shown in Figure 5, the simulations at the four stations perform well with NSEs above 0.8 for the calibration period. The NSEs of validation period at Jinghong, Chiang Saen, Luang Prabang and Pakse are 0.83, 0.80, 0.79 and 0.87 respectively. For most years, the simulations of troughs during dry seasons and peaks during flood seasons are reproduced rather well, except for some extreme flood events when simulations underestimated the flow. The accuracy over the dry and flood seasons is important for later simulation of water availability and economic benefits. Besides, we also use observations at two other stations, Nong Khai (1998-2007), and Nakhonphanom (1998-2009), for validation of the hydrological model. The NSEs at these three stations reach to 0.81 and 0.75 respectively, which indicates the applicability of the THREW model at different locations across the Lancang-Mekong river basin.

According to the observations and simulations, the annual discharge from China to downstream countries at Jinghong station (QL3 in Figure 4) accounts for 66% of the discharge at Chiang Saen (QN2 in Figure 4) and 20% of the discharge at Pakse (QN4 in Figure 4). As simplified in

Figure 4, runoff observed in Laos and Thailand account for 23% and 57% of the discharge at Pakse. The proportions of China and Laos in Pakse runoff are higher during non-flood seasons (November to May), and the change of seasonality of discharge in China and Laos caused by reservoir operations could affect the discharge and thus economic benefits in downstream countries.

Two basic scenarios of reservoir operations were set up. The first basic scenario is the self-interested scenario, when upstream China and Laos operate reservoirs following their own operation rules guided by self-interest only, as introduced in section 3.2. The other basic scenario is the altruistic scenario, when upstream countries China and Laos operate reservoirs to maximize the benefits of downstream three countries. Based the two basic scenarios, the weighted average scenario (WA scenario) is also analyzed. Water release from Xiaowan, Nuozhadu and the proxy Laos reservoir vary under the three scenarios, and we compare them with natural water release without reservoir operation (NR scenario) in non-flood seasons. We set the initial reservoir storage to maximum storage at the beginning of the year and simulate the water release under two natural hydrological conditions, i.e., dry year of 2015 and normal year of 2017. Initial value of cooperation level of China and Laos are both set to 0.5.

As shown in Figure 6(a-c and g-i), for both dry and normal years, the NC scenario keeps the largest storages and the FC scenario keeps the lowest storages. In a dry year like 2015, with the same cooperation level as in the normal year of 2017, reservoir storages under FC and WA scenarios are lower to satisfy the demands of downstream countries. Water releases from the three reservoirs under different scenarios in non-flood seasons in 2015 and 2017 are shown in Figure 7. The final weighted average water releases (WA scenario) from Nuozhadu and Laos

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Reservoirs to downstream countries are higher than natural water releases (NR scenario) during non-flood season (December to May), especially in the dry year of 2015. It is consistent with the phenomenon that reservoir operations increase discharge during non-flood seasons in downstream countries in recent years.

As shown in Figure 8, the simulated reservoir storages under continuous WA scenario are lower than the simulated storages under continuous NC scenario in all three reservoirs. As a cooperative action, reservoir regulations under the continuous WA scenario keep releasing more water, particularly during dry years when the demands of downstream countries are high. The simulated storage of Xiaowan and Nuozhadu under continuous WA scenario keep a relatively low level, because China values the indirect political benefits from downstream countries, which leads to high cooperation level of China, as it will be introduced in detail in section 4.3.

3.2 Economic benefit

China and Laos operate reservoirs to obtain hydropower benefits, and the agriculture benefits of Laos are also calculated. For each of the three downstream countries, benefits of agriculture, fishery and wetlands are simulated individually. Overall, the economic benefits simulations under WA scenario in each country and sector are reasonable compared to statistical data, as listed in Table 3.

Under the continuous WA scenario, China and Laos have obtained increasing benefits mainly due to ongoing dam construction. As Figure 9 shows, the simulated hydropower benefits of China approached 1,800 million USD in 2018, which is reasonable since the annual generation of the two reservoirs is close to 40 billion kWh (Yu et al., 2019b). The Laos reservoir generated hydropower around 1,100 million USD while the statistical estimation of hydropower benefit to Laos in 2015 is 1,076 million USD (MRC, 2018), proving the validity of economic benefit simulations in Laos. In Figure 9(a), the hydropower benefit of China under WA scenario is lower than NC scenario and higher than the FC scenario after 2012, indicating that cooperation actions (WA and FC) could harm the hydropower benefit of China. It is similar in Laos, as shown in Figure 9(b), but the benefits under WA resemble NC scenario are more due to the low cooperation level of Laos. The differences between the blue and red lines indicate the losses China and Laos need to bear if they cooperate altruistically to satisfy downstream demands and maximize downstream benefits.

When the two major reservoirs in China went into operation and cooperation levels increased after 2012, the total benefits of downstream three countries under WA scenario are higher than the NC scenario, although they cannot reach the high level of the FC scenario when China and Laos operate reservoirs merely for downstream benefits, as shown in Figure 10(a). The increase of downstream benefits under WA scenario is remarkable compared to NC scenario (e.g., 420 million USD in 2018), indicating the significance of cooperation of upstream countries for the benefits in downstream countries. The losses China and Laos need to bear is less than the gain of downstream countries, which help to rationalize cooperation actions to enhance regional benefits and is consistent with outcomes of simulations in other studies (Yu et al., 2019b;Li et al., 2019;Do et al., 2020). Notably, in the dry years of 2015-2016, cooperative action of upstream countries could mitigate the losses of downstream countries, but their benefits would still be lower compared to those in normal years.

The downstream benefits of agriculture and fishery under the WA scenario are shown in Figure 10(b). Simulated agriculture benefit in 2018 is around 4,000 million USD with irrigation withdrawals of 35 billion m^3, while the statistical irrigation withdrawal of the three countries is 47 billion m^3 (FAO, 2019). The simulated agriculture benefits of Thailand, Cambodia and Vietnam are 1,355, 595 and 2,011 million USD respectively, which are consistent with the statistical values for irrigated rice in Table 4, i.e., 1,314, 592 and 2,727 million USD. Statistical values for irrigated rice are calculated by the irrigation areas (Cramb, 2020), irrigated rice production per unit area and rice price (MRC, 2018).

As for the capture fishery benefits, the losses during the years of reservoir filling and droughts are remarkable, approaching 224 and 181 million USD in 2010 and 2015, respectively. The reduction of fishery capture is consistent with the outcomes of study by Orr et al. (2012), which estimated that losses of fishery capture could reach to 20% with the impacts of upstream dams. In 2018, the simulated fishery benefits of Thailand, Cambodia, Vietnam and the total fishery benefit are 116, 1,146, 178, and 1,440 million USD, while the corresponding statistical values are 120, 1,188, 195 and 1,503 million USD. The statistical fishery values are estimated on the basis of fishery production (Burbano et al., 2020) and fishery prices (MRC, 2018). Overall, the simulated benefits of downstream countries in the three economic sectors are basically consistent with statistical values.

3.3 Cooperation demand and level

As introduced in section 3.4, two key variables in the policy feedbacks contain cooperation demand of downstream countries and the actual cooperation level of upstream countries. In the model, cooperation demand of downstream countries was assumed to be related to the losses in the different sectors compared to maximum possible benefits, and the sensitivity to agriculture loss and fishery loss, expressed in terms the parameters ε_a and ε_f. We calculated the cooperation demands of the three downstream countries based on benefit calculations, and the simulated cooperation demands reached to high levels in 2004-2005, 2010, 2012-2016 (Figure 11). These peaks are caused by benefit losses compared to other years. The losses in 2004-2005 and 2015-2016 arose from recorded droughts (MRC, 2018), while the losses in 2010 and 2012-2014 are related to the constructions and operations of Xiaowan and Nuozhadu dam. Cooperation levels of China and Laos are simulated separately so that they could decide their own weights used in reservoir operations. Cooperation levels are related to downstream cooperation demand U, political factor P reflecting how much upstream countries value the indirect political benefits that can be gained from downstream countries, upstream benefits when cooperating or not, and the change rate s that reflecting the response speed of upstream countries. Compared to Laos, China regards the geopolitical values and diplomatic relations as more important (Urban et al., 2018). Therefore, the political factor P and change rate s of China are set as 2 and 0.1, respectively, while those of Laos are 1 and 0.02, respectively. As shown in Figure 11, the cooperation level of Laos increased from the start at a slow speed and exceeded 0.17 in 2018. The slowly increasing trend of cooperation level of Laos could be reflected by the on-going disputes and negotiations between Laos and other MRC members in respect of reservoir construction by Laos on the mainstream of Mekong River since 2009 (Hensengerth, 2015). China finished the first major dam construction in 2010 and the increase of cooperation levels started then. Compared to Laos, the increase rate is much higher, especially when the major reservoirs were constructed and China adjusted their operational rules before 2015. The rapid increase of cooperation level of China could be proven by the cooperative actions from China in recent years. China initiated Lancang-Mekong Cooperation (LMC) framework in 2015, which is a much broader framework that goes beyond water cooperation. When the historically severe drought hit Mekong Basin in 2015 and 2016, China implemented emergency water release to mitigate the negative impacts of droughts in downstream (Middleton and Allouche, 2016).

To evaluate the simulation outcomes of cooperation demands of downstream, we conducted sentiment analysis towards the reservoir constructions and operations in upstream China and Laos. Because the analyzed newspaper needs to be in English due to the language difficulty, and we can only obtain continuous and relevant English newspapers in Thailand among the downstream countries, we selected Thailand newspaper articles for the sentiment analyses used for evaluation. The data processing is similar with that used in Wei et al. (2020), but we adjusted the key words and filtering rules to fit our goals. From the database of Lexis-Nexis, we extracted in total 4,622 pieces of data with keywords related to the dam constructions and regulations in China and Laos, which are published by Thai newspapers. Then we selected 592 pieces of relevant articles by removing duplicates and irrelevant news manually. The 592 valid pieces of news cover the period of 2000-2018. Through coding and manually correcting, the sentiment values of each piece of news are provided for statistical analysis. As shown in Figure 12, the number of news articles concerning the impacts of upstream reservoirs increased significantly after 2010, from less than 20 pieces each year to over 70 pieces in recent years. The means of sentiment values fluctuate greatly in early years, which is caused by relatively small numbers of pieces of news. In 2004, 2010-2012 and 2015, sentiment results reached low values through the years, reflecting that the concerns and criticisms from Thailand towards China and Laos on dam operation were high compared to normal years. The dynamics of sentiment values are basically consistent with the simulations of cooperation demand of Thailand shown in Figure 12. Simulated cooperation demands of Thailand are high during 2005, 2009-2010, 2012-2015. Similar to the cooperation demand of the three downstream countries introduced before, the peaks of cooperation demand and concerns from downstream in 2005 and 2015 are ascribed to droughts and losses, while the concerns in 2010 and 2012 are due to the effects of dam constructions at Xiaowan and Nuozhadu during these two years. According to Wei et al. (2020), topic analysis shows that most of the negative publications in Mekong countries are related to the constructions and operations of dams, which is consistent with our results. Besides the factors mentioned above, based on the text information of news, another reason why concerns increased in 2010-2012 is that Laos started to construct Xayaburi dam, which is the first dam Laos constructed on the mainstream of Mekong River and is regarded as a violation of the 1995 Mekong Agreement (Herbertson, 2013). Overall, our simulations of cooperation demands reflect the empirical dynamics of downstream countries obtained through sentiment analyses.

4. Discussion and Conclusions

This paper presented the development and application of a coupled socio-hydrological model to simulate the dynamics of cooperation and conflict in the transboundary Lancang-Mekong river basin in Southeast Asia. Lancang-Mekong is a typical transboundary river where the upstream mountainous area is rich in hydropower and lower plain areas are suitable for irrigation and are rich in fisheries. Dam construction and operations in upstream countries (China, Laos) have changed the seasonality of downstream river flows, which have impacted the benefits gained by downstream countries, notably in terms of agriculture and fishery, both of which rely on the discharge of rivers. When downstream countries faced benefit losses

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compared to maximum benefits as a result, they led to community concerns, which they tend to blame on upstream countries. Once the dams were constructed and were in place, the most available and effective cooperative action to avoid regional conflicts was to operate the reservoirs in a way to achieve basin-wide synergy between upstream and downstream countries (Do et al., 2020). While upstream countries may have lost some economic benefits by sacrificing some of their hydropower generation to benefit downstream countries, by doing so they also stood to gain indirect political and economic benefits, e.g., better diplomatic relations and more investment opportunities in downstream countries (Sadoff and Grey, 2002).

The socio-hydrological model presented in this paper captured the dynamics of such cooperation and conflict through the coupling of modules representing hydrology, reservoir operation, economic benefits and policy, which is simple but comprehensive. The interplay among hydrological, economic and political factors is important, because hydrological variability and human activities could impact the dynamics of cooperation jointly. The model simulations were evaluated by using empirical observations of runoff and published statistics of economic benefits in the different sectors. The model simulated cooperation demands by downstream countries reached to high levels during dry years of 2004-2005 and 2015-2016, and the dam filling years of 2010 and 2012. These patterns were consistent with outcomes of sentiment analysis carried out based on articles published in English language newspapers in one downstream country, Thailand, proving the validity of policy feedbacks embedded in the socio-hydrological model.

A novel feature of the model is the quantification of policy feedbacks between upstream and downstream countries in the form of a logit dynamics model. The logit dynamics model operates in a way that willingness to cooperate increases when there are greater benefits to be gained if the parties cooperated and fewer benefits if they do not. A particular strength of the logit model is that it could explicitly include geopolitical factors that add to the indirect benefits that upstream countries may gain through increased cooperation. The potential benefit increase for upstream countries through cooperation, which may include direct economic benefits such as eco-compensation and indirect political benefits, is assumed to boost their willingness to cooperate. When upstream countries value the indirect political benefits more and are thus more responsive to the downstream concerns, the cooperation level would increase, which is consistent with the cooperative actions taken by China in recent years. Over the last two decades, cooperation demands of the downstream countries increased over drought years and over the years of reservoir filling. The surge of downstream concerns towards upstream countries needs to be treated appropriately, otherwise the concerns could turn into more severe conflicts. The losses of the downstream relative to maximum expected benefits could be mitigated by cooperative actions of upstream countries, i.e., change of reservoir regulation, which will lead to less concerns and less criticism from downstream countries.

As an early version transboundary river socio-hydrological model, there is significant room for further improvement in the model formulation. The current model simulated the effect of hydroelectric power generation in multiple dams in China and Laos in a lumped manner, which has a negative impact on the accuracy of reservoir releases, and hence on benefit calculation for downstream countries. The situation can be improved in the future through more distributed simulation of a cascade of reservoirs. Additionally, in order to integrate the complex hydro-economic relationships into the model, agriculture and fishery benefits are calculated in the

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present model with rather simplified equations. There is room for significant improvement in these benefit calculations. Flood control is one of the important functions of existing and planned future dams, but has been ignored in this study, which may have under-estimated benefits to both upstream and downstream countries. In future studies, with inclusion of more accurate reservoir operation rules, hydro-economic relationships and consideration of flood losses and impacts on ecosystem, a more advanced model could be used for sensitivity and scenario analyses under future scenarios of possible climatic, socio-economic and political changes. Sensitivity analysis will help to identify dominant influential factors and explore the consequences of changes to the coupled human-nature system and upstream-downstream feedbacks. Climate change and the expansion of human activities, including reservoir construction and irrigation area expansion, will affect the water supply, water demand, economic benefits and cooperation dynamics in transboundary rivers. Simulations under different scenarios of climate change and human activities could provide projections of the dynamics of transboundary river cooperation and conflict. The results of both sensitivity analysis and scenario analysis will provide useful insights for transboundary river management in the future and can help the riparian countries to enter into regional cooperative behavior to maximize collective benefits synergistically and advance water resource sustainability.

Finally, the kinds of transboundary dynamics that transpired in the Lancang-Mekong river basin and described in the socio-hydrologic model are commonly found in many transboundary river basins. In particular, benefit losses to downstream countries by the actions of upstream countries such as dam construction, water extraction and pollution, can be counterbalanced by the willingness to cooperate by upstream countries, by sharing some economic benefits with downstream countries as compensation for their loss of economic benefits, in return from indirect geopolitical benefits and investment opportunities. By capturing these mechanisms and by accounting for the effects of hydrologic variability and reservoir releases on the economic benefits of the various water uses in the quantification of willingness to cooperate, the socio-hydrological model presented in this paper provides an objective scientific framework to underpin transboundary water management and negotiations elsewhere.

Code/Data availability

The data is available on request from the corresponding author (tianfq@mail.tsinghua.edu.cn).

Author contribution

You Lu, Fuqiang Tian, Liying Guo, Iolanda Borzi and Rupesh Patil discussed the framework of model. You Lu developed the model code and performed the simulations. Jing Wei, Dengfeng Liu, Yongping Wei and David J. Yu discussed and revised the model. You Lu, Fuqiang Tian and Murugesu Sivapalan prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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List of Figure Captions

Table 1. Reservoir information of Xiaowan and Nuozhadu

Reservoir	Commissioned Year	Total Reservoir Storage (MCM)	Flood Limited Storage (MCM)	Dead Reservoir Storage (MCM)
Xiaowan	2010	15,300	13,104	5,946
Nuozhadu	2012	21,749	19,344	10,414

Table 2.Irrigated agriculture information of Thailand, Cambodia and Vietnam

	Thailand	Cambodia	Vietnam	Data Source
Rice price (USD/ton)	243.8	267.6	248.0	MRC (2018)
Irrigated Area (million ha)	1.425	0.505	1.921	Cramb (2020)
Rice yield (ton/ha)	3.78	4.38	5.72	MRC (2018)
Irrigation withdrawal (MCM)	16240	1680	29120	AQUASTAT

Table 3. Simulated economic benefits in 2018 and statistical benefits

Unit: Million USD	Simulated benefit	Benefit from statistical data
China hydropower	1,767	2,000
Laos hydropower	1,083	1,076
Thailand agriculture	1,355	1,314
Thailand fishery	116	120
Cambodia agriculture	595	592
Cambodia fishery	1,146	1,188
Vietnam agriculture	2,011	2,727

Vietnam fishery	178	195

Figure 1. Map of Lancang-Mekong River Basin, Subbasin Division and Hydrological Stations

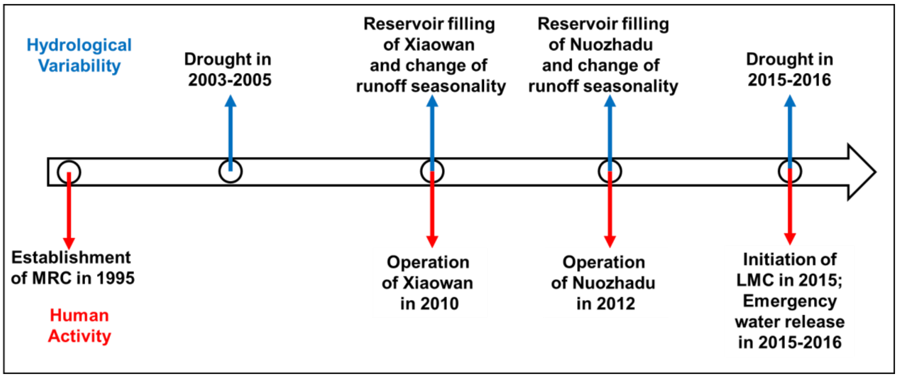


Figure 2. Timeline of hydrological and anthropogenic events in Lancang-Mekong River Basin

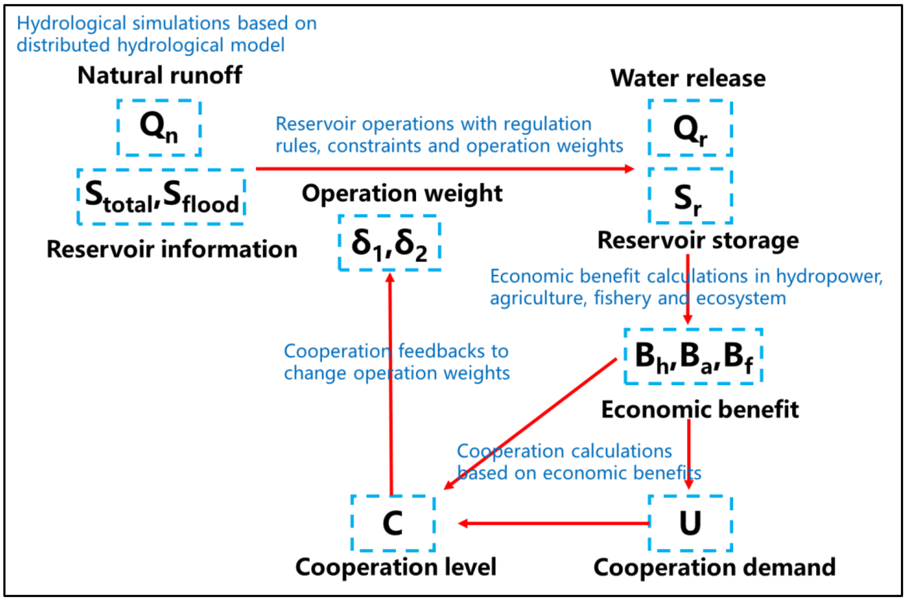


Figure 3. Framework of Transboundary River Socio-Hydrological Model

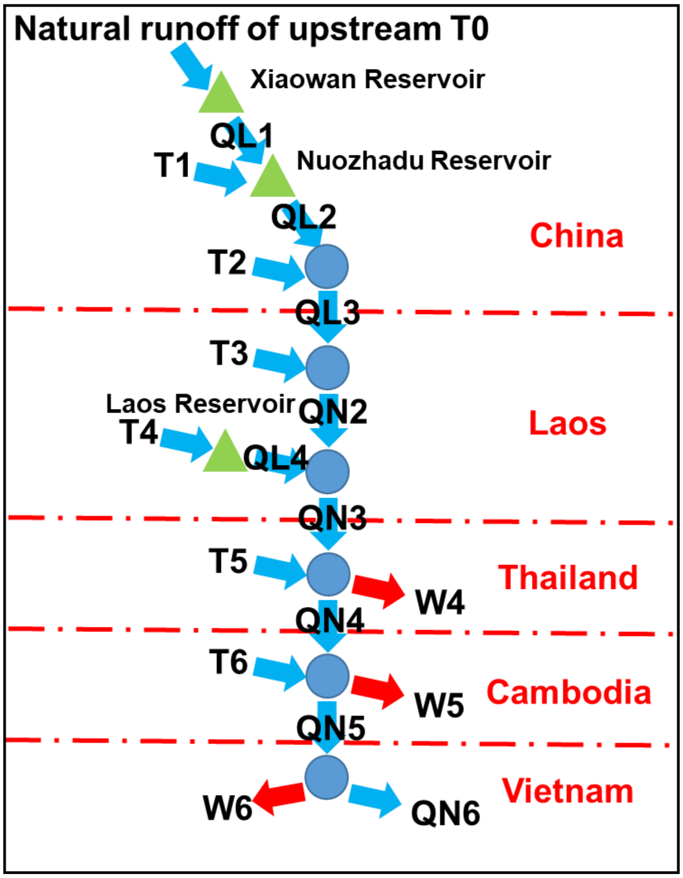


Figure 4. Framework of simplified water system in Lancang-Mekong River Basin

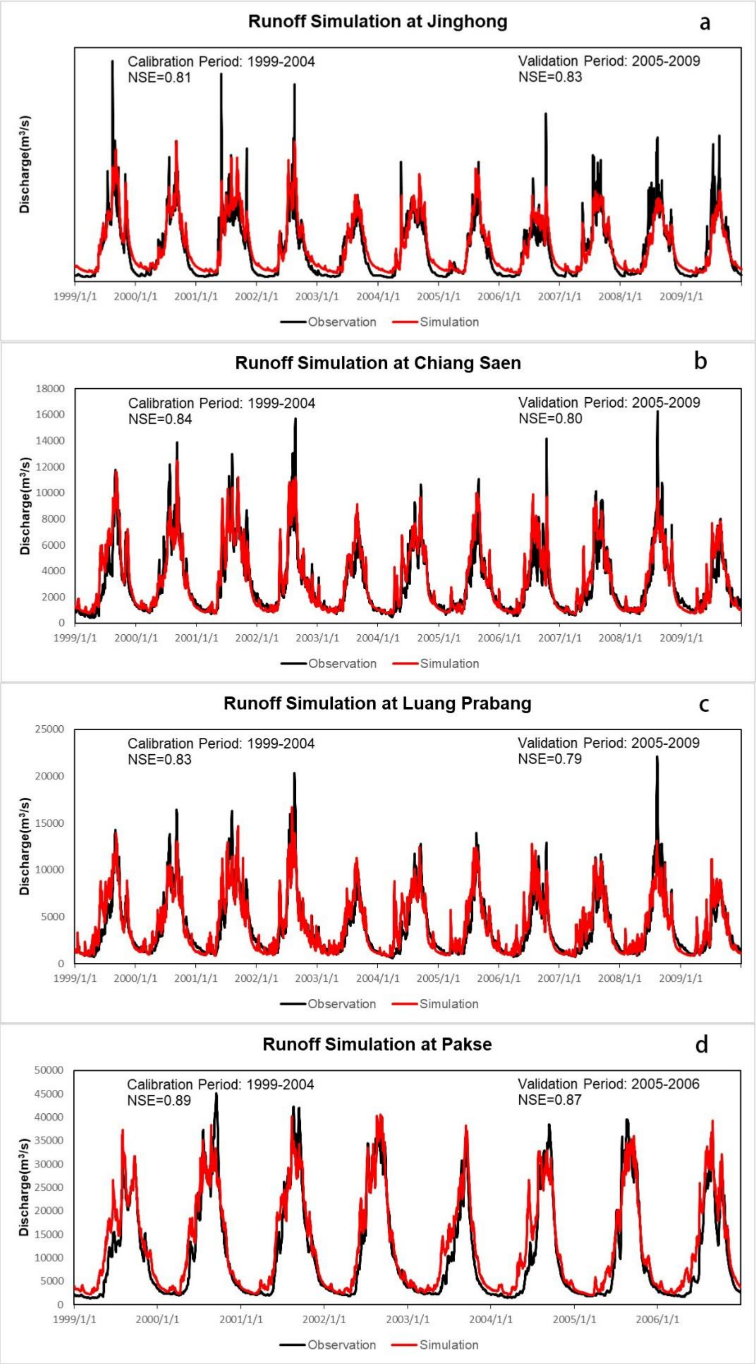


Figure 5. Daily Runoff simulations at Jinghong (a), Chiang Saen (b), Luang Prabang (c) and Pakse (d)

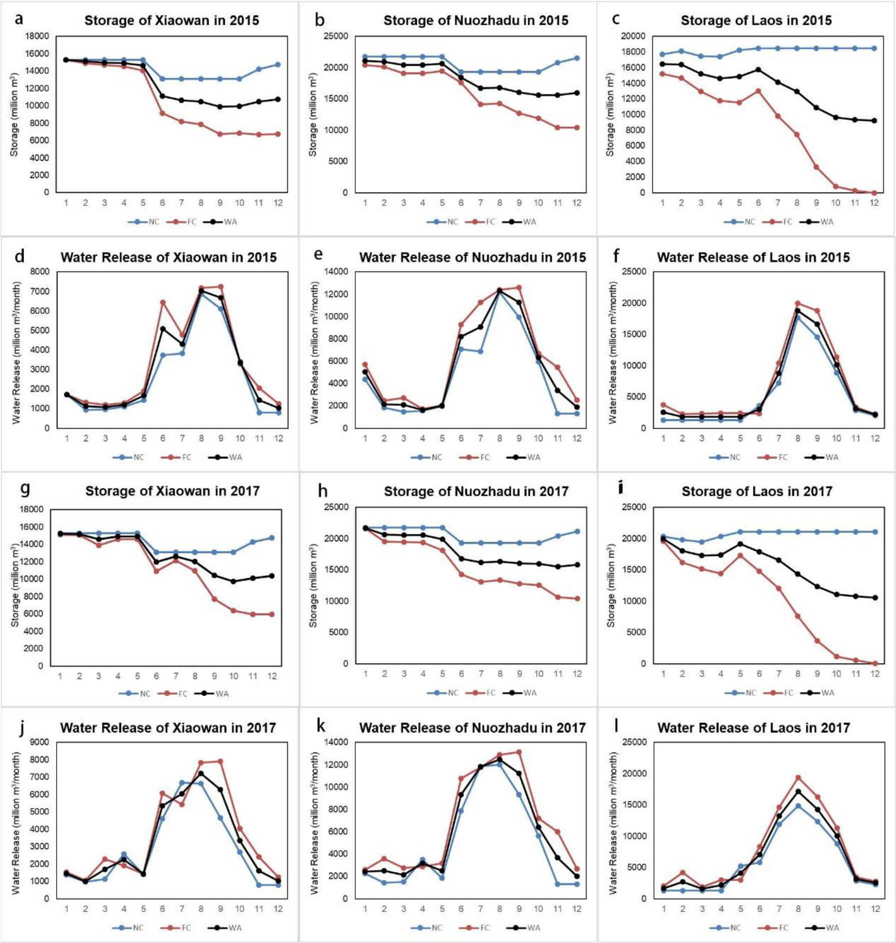


Figure 6. Reservoir storage and water release simulations of Xiaowan, Nuozhadu and Laos Reservoirs in 2015 (a-f) and 2017 (g-i).

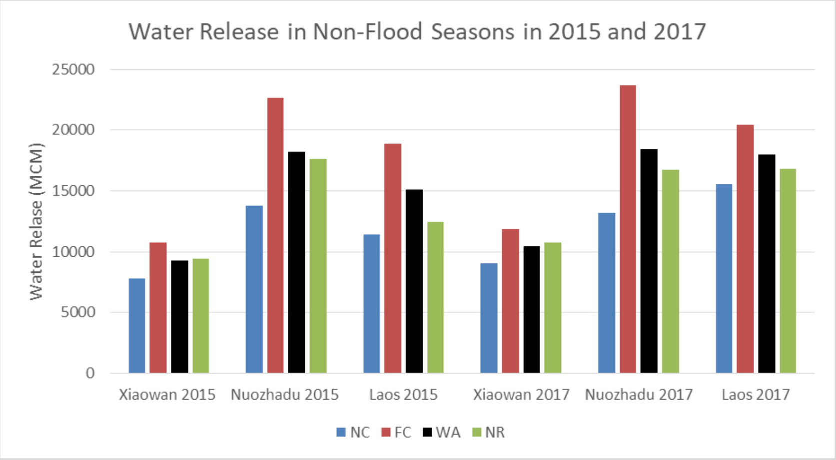


Figure 7. Water release of Xiaowan, Nuozhadu and Laos Reservoirs in non-flood seasons in 2015 (dry year) and 2017 (norm year) under different scenarios

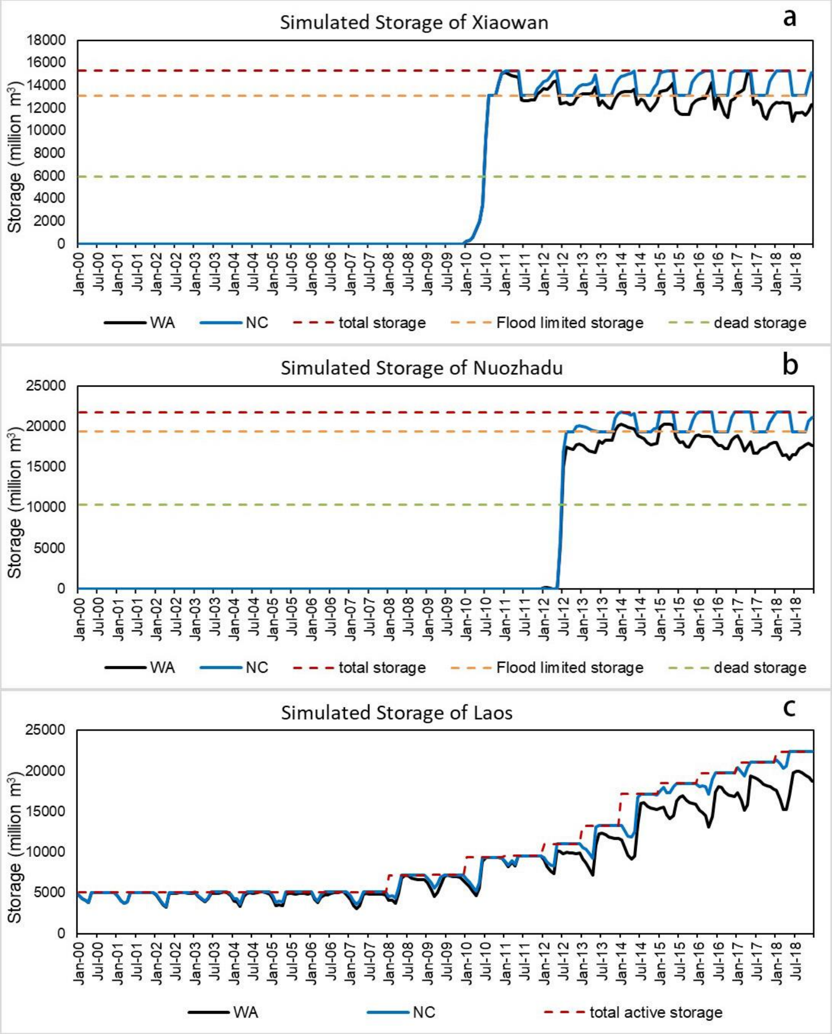


Figure 8. Simulated storage dynamics of Xiaowan (a), Nuozhadu (b) and Laos reservoirs (c)

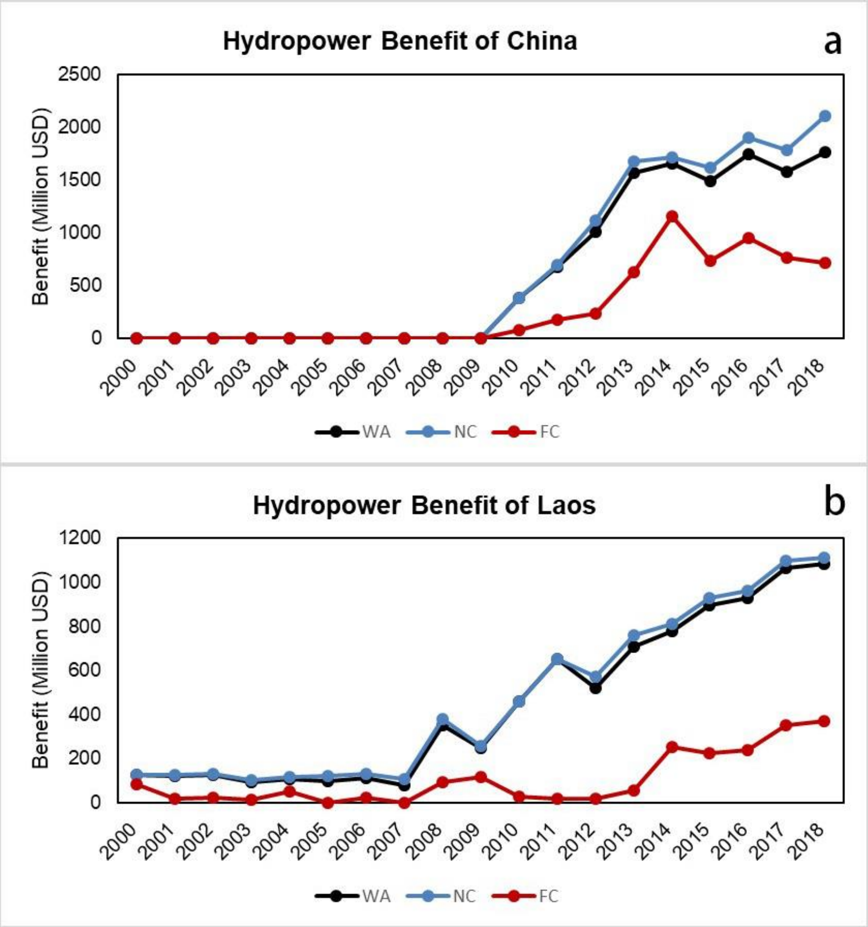


Figure 9. Benefit of upstream China (a) and Laos (b) under the three different scenarios

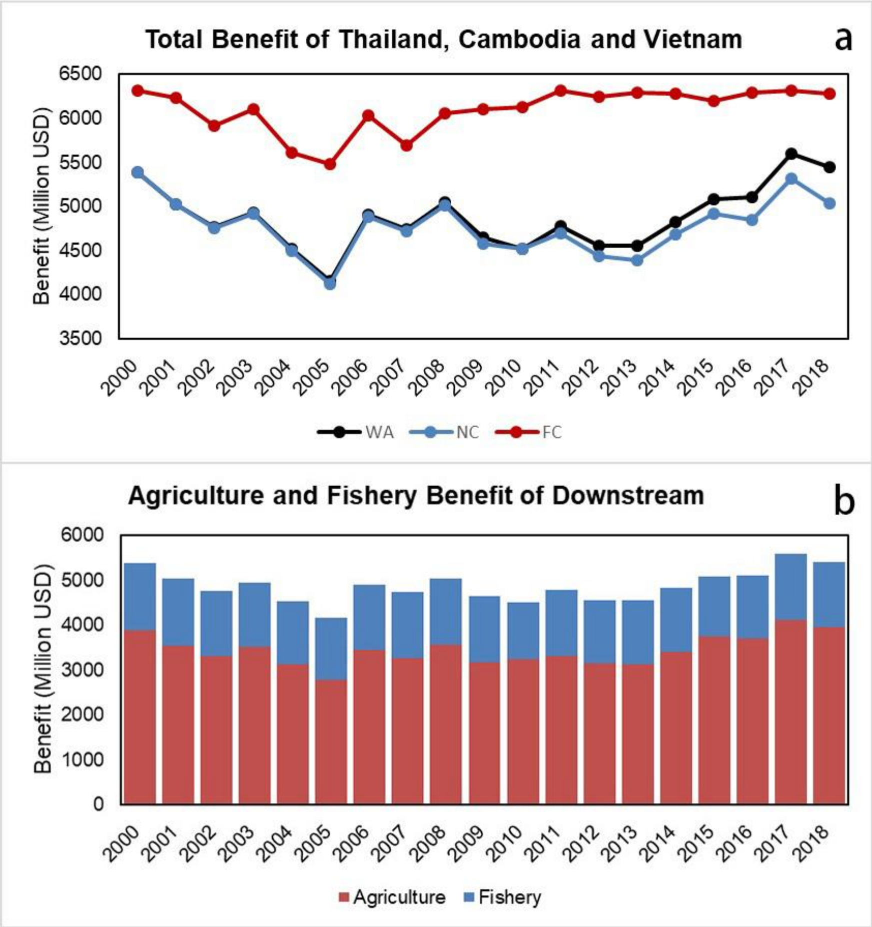
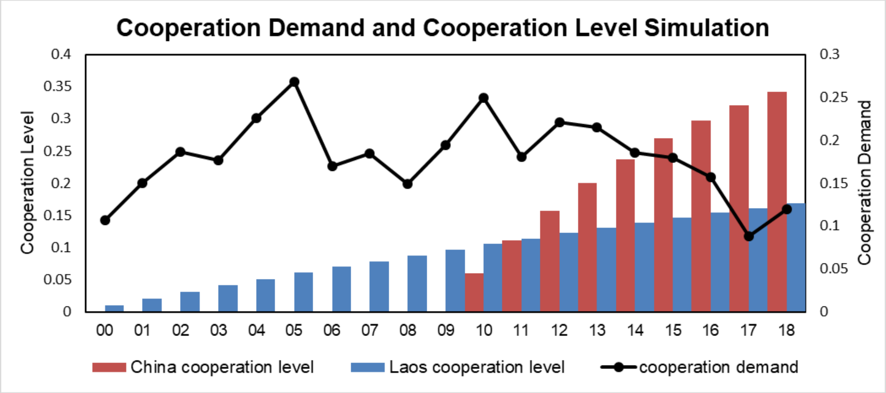


Figure 10. Agriculture and fishery benefit of downstream Thailand, Cambodia and Vietnam under the three different scenarios



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1032 Figure 11. Simulation of cooperation demand of downstream and cooperation level of China

1033 and Laos

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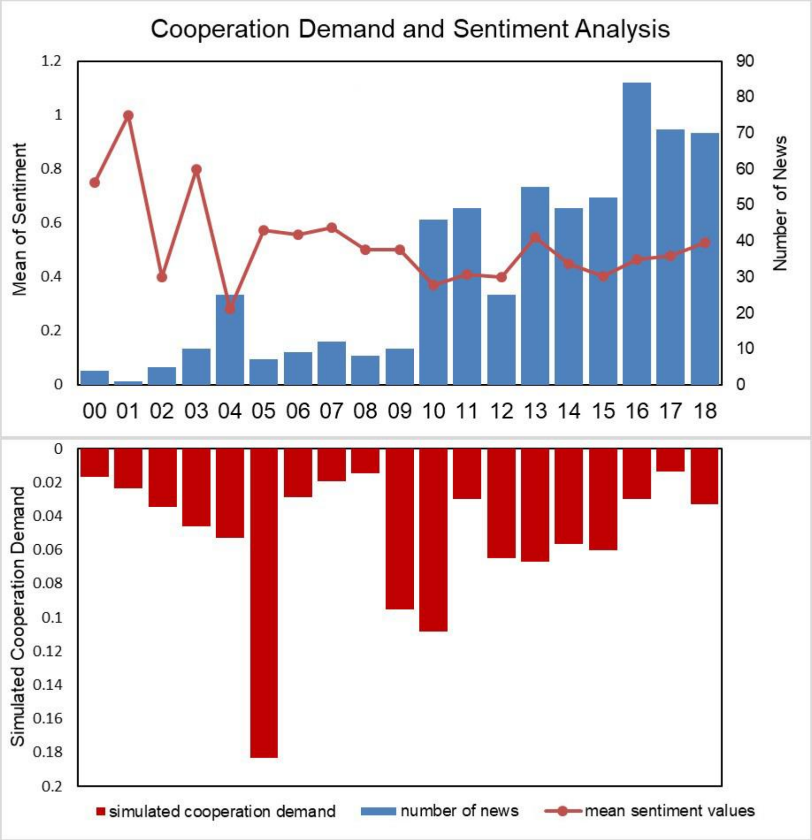

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1036 Figure 12. Simulation of cooperation demand and newspaper sentiment analysis of Thailand

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