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

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Submitted to *Hydrology and Earth System Sciences*

Special issue: Socio-hydrology and Transboundary Rivers

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 coupled human-water systems. Downstream countries rely on Mekong River for fisheries, agriculture, navigation and ecological services, 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

1. Introduction

Transboundary water management is an important and complex issue that has attracted much 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). Rivers serve multiple functions that benefit human societies 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 critical for water security, food security, energy security and ecosystem security in riparian countries or regions, which requires equitable and reciprocal benefit sharing for humans to realize the full potential of the services that rivers provide. Transboundary river cooperation could take different forms (Sadoff and Grey, 2005), and operating at different levels (Sadoff and Grey, 2002), such as information sharing for flood and drought mitigation, reservoir operations adapted to the needs of both upstream and downstream users, and joint ownership of water-related infrastructure.

Compared to water resources management in domestic river basins, management of transboundary rivers that cross national boundaries must deal with an additional complexity. The complexity arises from the structural challenge to cooperation that in such international river basins, two or more countries must organize cooperation despite potential differences in preferences for water uses and locational asymmetries in terms of access to water. 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. Even if a formal social contract (e.g., an international treaty) can be devised among stakeholders to institutionalize cooperation, enforcement of the contract remains another challenge (Petersen-Perlman et al., 2017). Because of the international nature of these contracts, there is usually no external body that can enforce the formal arrangements for cooperation in a binding way (Müller et al., 2017; Espey and Towfique, 2004). Despite the challenges in transboundary river cooperation, there are examples of successful cooperation in international rivers, including the Rhine River (Schultz, 2009), the Columbia River (Hamlet, 2003), and the Colorado River (Bernal and Solís, 2000). At the same time, there are also cases of cooperation failures, such as the Amu Darya and Syr Darya Rivers (Micklin, 2004; Tian et al., 2019). Much scholarly attention has been directed towards understanding what leads to success or failure in cooperation in transboundary river management.

Researchers have spent considerable efforts to analyze and understand the aforementioned question through empirical research and 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 in transboundary river basins globally, 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, including 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). Hydro-economic models that involve hydrological simulation and benefit calculation and allocation through benefit maximization or game theory (Li et al., 2019) are also common methods used to analyze the human-water interactions in transboundary rivers. In particular, multi-agent simulation models consider each riparian country as an independent decision-maker and focus on water allocation and benefit calculation (Teasley and McKinney, 2011; Giuliani and Castelletti, 2013). 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).

However, most of the model studies highlighted above have viewed cooperation in transboundary rivers in a static way and as an external variable, and whether to cooperate or not and the/or the extent of cooperation are set as boundary conditions. In other words, they only capture the one-way effect, i.e., how cooperation takes effect on water resources and the economy, instead of considering the two-way feedbacks including how cooperation evolves driven by different factors. In reality, transboundary river cooperation is evolutionary in nature. For example, in the Colorado River Basin shared by the USA and Mexico, industrialization and population growth have increased the stress on surface and groundwater resources and on water quality. Groundwater 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 the USA and Mexico have now become more cooperative in recent years (Frisvold and Caswell, 2000). The approaches used in studies to date do not accommodate the dynamic co-evolutionary nature of transboundary cooperation and conflicts, as seen for example in the Colorado River Basin, and are therefore not up to the task of seeking mechanistic explanations for the 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. This is a first step in this direction. Increased mechanistic understanding will help increase the scope of cooperation and avoidance of conflict in the future, and generate diverse benefits (Sadoff and Grey, 2002; Yu et al., 2019a). 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. 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, social, and geo-political processes (Di Baldassarre et al., 2019). Historical patterns of the 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 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, which to the best of our knowledge is the first model to include the evolutionary transboundary river cooperation as an internal variable, and couple the driven processes including hydrological variability, dam construction, political benefits, etc. It differs from extant models by considering transboundary river cooperation internally, dynamically and quantitatively. To attain the goal, we propose a novel quantification of cooperation level and political benefits, and conduct sentiment analysis of newspaper articles to validate the simulation of cooperation in Lancang-Mekong River Basin. The socio-hydrological model developed is used to mimic the mechanisms of cooperation 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.

2. 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 riverine 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 Lake (Kite, 2001) located in Cambodia. Correspondingly, due to the effects of upstream dam operations for hydropower generation, the downstream countries have faced concerns about benefit losses. Here the loss indicates deviation from their maximum expected benefit (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 was 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 these reservoirs 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 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 these water-related events and the cooperation dynamics, and provide mechanistic explanations based on socio-hydrologic interpretation of the emergent dynamics.

3. Socio-hydrological Model

We developed a transboundary river cooperation socio-hydrological model (TCSH model) to simulate the dynamics of cooperation and conflict observed in the 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 benefit 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. 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 weighted 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. Based on the estimation of economic benefits, the fourth module simulates the policy feedbacks 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 distributed around the whole basin provide meteorological inputs, including temperature, wind speed, humidity and radiation to calculate potential evapotranspiration based on the Penman-Monteith equation. Soils data is extracted from the 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).

As the hydrological model is used to provide simulations of natural runoff without the impacts of water withdrawal and reservoir operations, 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. 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 and tributaries Q_n before the impacts of human activities.

3.2 Reservoir operation

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 S_{dead}, and flood limited storage S_{flood} are listed in Table 1. Laos has aimed to be the “battery of Southeast Asia” (Stone, 2016) and 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. In order to couple the reservoir operation module with the other modules, we need to simplify the cascade of reservoirs in both China and Laos so that the optimization processes in reservoir operation module and benefit calculation module could be computed.

With the total storage of the Xiaowan and Nuozhadu reservoirs accounting 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 two reservoirs. For the reservoirs in Laos, since reservoirs on the mainstream have not been commissioned before 2019, only the completed tributary reservoirs are considered and aggregated by one virtual reservoir in the upper reaches, including some reservoir storages located in the relatively lower reaches in Laos (Li et al., 2019; WLE, 2018). The storage of the virtual Laos reservoir equals the sum of all Laos reservoir storages, and its hydropower generation is calibrated against the statistical data of the sum of hydropower generations in Laos. In the model, the virtual Laos reservoir is assumed to have live storage from 5,074 MCM in 2000 to 21,066 MCM in 2018, which was linearly interpolated over this time period and represents continuous dam construction in Laos. Overall, these simplifications through lumping the effects of many reservoirs are deemed reasonable for the purpose 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 and closely resemble the actual hydropower generation. As shown in Figure 4, the river system and its water diversion configuration are also simplified, where T_1, T_2 to T_6 indicate natural runoff of upstream and tributaries, W_1, W_2, W_3 are the water withdrawals for irrigation in Thailand, Cambodia and Vietnam. For each node, runoff flowing to the next node is calculated by the water balance equation, e.g., for Thailand,

$$Q_7 = Q_6 + T_5 - W_1 \tag{1}$$

where Q_7 is runoff flowing to Thailand from the upstream node, Laos, T_5 is inflow from tributaries in Thailand, W_1 is irrigation withdrawal in Thailand, and Q_7 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. 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 the flood season (June to October). If the actual storage of the $t-1$ 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 on the 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 (2) and (3). The actual storage of the next month $S_{r,t}$ is calculated based on the water balance equation. With the calculated water release under the self-interested scenario $Q_{r,NC}$, the total benefits of the three downstream countries will be optimized through water allocation among them.

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

$$Q_{r,t} = max\{S_{r,t-1} + Q_{in,t} - S_{flood}, 0, Q_{eco}\},\ t = 6,7,8,9,10 \quad (3)$$

The second scenario is the altruistic scenario (full-cooperation, abbreviated by FC), where the upstream countries operate the dams to accommodate downstream water demands and 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. In this study, neither the self-interested scenario nor the altruistic scenario considers hedging rules in reservoir operation, although this is an extension that could be considered in further extensions of this study.

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.

$$Q_r = Q_{r,NC} \times \delta_1 + Q_{r,FC} \times \delta_2 \tag{4}$$

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. Here δ_2 reflects the extent to which the operating rules are adjusted to accommodate downstream water demands. It should be noted that the calculated Q_r by equation (4) is revised if it violates the constraints of maximum storage during dry and flood seasons, minimum storage of dead storage and minimum ecological release flow. The final actual reservoir storage S_r is used for hydropower benefit calculation and the calculated Q_r is used to optimize the total benefits of the three downstream countries.

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 are based on the water release Q_r and reservoir storage S_r, as shown in equation (5).

$$B_h = p_h \times 9.81 \times Q_r \times \Delta h \times \eta \tag{5}$$

where p_h is the electricity price extracted from MRC (2018), 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 which is calibrated against the annual power generation data.

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).

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

$$(1 - \frac{Y_a}{Y_m}) = K_y \times (1 - \frac{E_A}{E_P}) \tag{7}$$

where p_a is price of rice and retrieved from statistical data (MRC, 2018), 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 E_A and E_P are actual and potential 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). E_A and E_P 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 consider capture fishery benefits and do not include aquaculture benefits, since the latter 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).

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

$$B_f = p_f \times d - F_{cost} \tag{9}$$

where d 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, p_f is the fishery price extracted from statistical data (MRC, 2018) and F_{cost} 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, Q_7, Q_8, Q_9 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. 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 the cooperation level $C = 1$, upstream countries operate dams to maximize the downstream benefits, i.e., the altruistic scenario. If $C = 0$, upstream countries will follow operation rules given by Equations (2) and (3), which are consistent with the self-interested scenario.

Following the assumption that cooperation demand is increased due to economic losses compared to the 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, while the sensitivity of each economic sector is distinct.

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

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 benefit change of the sector, and the unit sector loss could lead to more severe negative impacts. In this model we assigned both ε_a and ε_f as 0.5 so that the agriculture and fishery losses are treated equally. The expected maximum benefits B_{amax} and B_{fmax} are 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 practice. This model is used to relate economic 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 the behaviors of other stakeholders and their own benefits (Iwasa et al., 2007; Suzuki and Iwasa, 2009a, b). In the logit dynamics model, the probability of cooperation P_r could be calculated as below:

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

where β is a shape parameter, 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 low indirect political benefit $B_{p,NC}$. If they choose to cooperate, besides the hydropower benefits under the altruistic scenario $B_{h,FC}$, the upstream country will gain higher indirect political benefits $B_{p,FC}$. Here we define the political benefit B_p as the benefit from avoidance of conflicts (Sadoff and Grey, 2002) and proportional to cooperation demand U and a political factor P as shown in equation (13). When the cooperation demand U is high, and the cost due to unsatisfactory of downstream and potential conflicts is high, the political benefit B_p will be low. 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, and the cooperation demand U will play a more important role in decision making. The equation to calculate the actual cooperation level C for upstream is as described in equation (14).

$$B_p = -U \times P \tag{13}$$

$$\frac{dC}{dt} = s \times \left[\frac{e^{\beta \times (\frac{B_{h,FC}}{B_{hmax}} - U_{FC} \times P)}}{e^{\beta \times (\frac{B_{h,FC}}{B_{hmax}} - U_{FC} \times P)} + e^{\beta \times (\frac{B_{h,NC}}{B_{hmax}} - U_{NC} \times P)}} - C \right] \tag{14}$$

where s is the responsive change rate reflecting the response speed of upstream countries, and $\frac{dC}{dt}$ indicates the change of cooperation level compared to the last period. $B_{h,FC}$ and $B_{h,NC}$ are calculated on the basis of water release and reservoir storage under altruistic scenario and self-interested scenario respectively by equation (5). Overall, cooperation levels C 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 $B_{h,FC}$ and $B_{h,NC}$, and the responsive change rate s. Compared to Laos, China regards the geopolitical values and diplomatic relations as more important (Urban et al., 2018). Therefore, the political factor P of China and Laos are set as 2 and 1, respectively, while the change rate s is assigned as 0.5. 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. Parameters in policy feedback module assigned here could be adjusted, so that the simulated downstream cooperation demand are consistent with the sentiment analysis results, which will be explained in Section 3.5.

The parameterization of the model could lead to uncertainty of simulations. In order to analyze the uncertainty of simulated cooperation demand caused by parameters, we choose six critical parameters shown in Table 3. Besides the values used in simulations, we choose two alternative values for each parameter, and simulate cooperation demand of downstream under each parameter combination. For each value of one parameter, there are 243 simulations with the other five parameters unfixed, which are used for uncertainty analysis.

3.5 Sentiment Analysis and Validation

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). 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). In this study, we use the sentiment analysis of newspaper articles in downstream countries in the Lancang-Mekong River Basin to reflect the changes in cooperation demands of downstream countries. The sentiment analysis is used to demonstrate the validity of the socio-hydrological model.

The detailed steps of sentiment analysis of newspaper articles and its application in Lancang-Mekong River have been introduced in Wei et al. (2020), and we will introduce the general steps briefly as follows. We used the Lexis-Nexis database to extract relevant information in English newspapers (Weaver and Bimber, 2008), sorted the data manually and conducted sentiment analysis. Although the English newspapers have the potential to miss some information when compared to local language newspapers, they are considered a reference to the government's foreign policy, and they can reflect national interests and political responses that riparian countries want to deliver to the international public (Wei et al., 2020). 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 is retrieved from the news database. 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 then corrected manually. Finally, sentiment category (positive or negative) and sentiment values of each piece of valid data ranging from -1 to 1 were obtained, with positive values indicating positive sentiment of the news towards the topic. We will then use the annual average sentiment values to evaluate simulated cooperation demand of downstream countries.

Because the analyzed newspaper needs to be in English due to the language difficulty, we could obtain continuous and relevant English newspapers only in Thailand among the downstream countries, while the other riparian countries did not have English language newspapers with broad coverage. 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, published in 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 automatic analysis and manual correcting, the sentiment values of each piece of news are chosen for statistical analysis, averaged for each year.

4. Results

4.1 Hydrological simulation and reservoir operation

As shown in Figure 5, the simulations at Jinghong, Chiang Saen, Luang Prabang and Pakse perform well with NSEs above 0.8 for the calibration period. The NSEs of validation period at the four stations are 0.84, 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 under-estimated the flow. The NSEs at Nong Khai and Nakhonphanom 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 (Q_3 in Figure 4) accounts for 66% of the discharge at Chiang Saen (Q_4 in Figure 4) and 20% of the discharge at Pakse (Q_7 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.

Water releases from Xiaowan, Nuozhadu and the virtual Laos reservoir vary under the three scenarios, i.e., NC, FC and WA scenarios, and we compare them with natural water release without reservoir operation (NR scenario) during 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, 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 Reservoirs to downstream countries are higher than natural water releases (NR scenario) during non-flood season (November 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 the continuous WA scenario are lower than the simulated storages under the 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.

4.2 Economic benefit

Overall, the economic benefit simulations under WA scenario in each country and sector are reasonable compared to statistical data, as listed in Table 4. 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 2,000 million USD in 2018, while the annual generation of the two reservoirs is close to 40 billion kWh (Yu et al., 2019b). The Laos reservoir generated hydropower around 976 million USD while the statistical estimation of hydropower benefit to Laos in 2015 is 1,076 million USD (MRC, 2018), demonstrating 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 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., 685 million USD in 2018). Comparing the results in Figure 9 and Figure 10, under the WA scenario, the loss China and Laos need to bear is less than the gain of downstream countries in most years, which help to rationalize the cooperation actions and is consistent with the 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 downstream 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 3,600 million USD with irrigation withdrawals of 39 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 1,263, 593 and 1,728 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 (Cramb, 2020; MRC, 2018).

As for the capture fishery benefits, the losses during the years of reservoir filling and droughts are remarkable, approaching 215 and 162 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 20% with the impacts of the upstream dams. In 2018, the simulated fishery benefits of Thailand, Cambodia, Vietnam and the total fishery benefit are 118, 1,160, 179, and 1,457 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.

4.3 Cooperation demand and level

In Figure 11(a), the simulated cooperation demands reached high levels in 2004-2005, 2008, 2010, 2012-2013, 2015-2016. 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 2012-2013 are related to the constructions and operations of Xiaowan and Nuozhadu dam.

As shown in Figure 11(a), the cooperation level of Laos increased from the start at a slow speed and exceeded 0.33 in 2018. The recent fluctuation 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). The cooperation levels of China increased since the completion of the first major dam construction in 2010. The cooperation level of China exceeded that of Laos in 2016, and the rapid increase of cooperation level of China could be evidenced by China's cooperative actions in recent years, including initiation of Lancang-Mekong Cooperation (LMC) framework in 2015, which is a much broader framework that goes beyond water cooperation, and implementation of emergency water release to mitigate the negative impacts of droughts in downstream when the historically severe drought hit Mekong Basin in 2015 and 2016 (Middleton and Allouche, 2016).

As shown in Figure 11(b), 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. 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 shown in Figure 11(c). Simulated cooperation demand are high during 2005, 2008, 2010, 2012-2013, 2015-2016. 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. 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. Uncertainty analysis in Figure 12 shows that although the selection of these six critical parameters could lead to uncertainty of simulated cooperation demand of downstream, the trend and fluctuation pattern of the simulations are consistent, which proves the reliability of the simulations. It should be noted that while the given values of political factors lead to similarity in cooperation demands in Figure 12, the impacts of certain parameter on simulation should be investigated with larger range of values and more tests, which is left for future research.

5. 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. The 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 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 more 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 was able to capture 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 perform well against empirical observations of runoff, published statistics of economic benefits in the different sectors, and sentiment analysis results.

A novel feature of the model is the quantification of cooperation dynamics 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 cooperate 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. 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 quantified in the model to represent to what extent the upstream country would like to accommodate downstream water demands in reservoir operation. The increase of simulated cooperation level 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 concern and less criticism from downstream countries. Compared with the extant models, this socio-hydrological model is the first one, to the best of our knowledge, to include the co-evolutionary transboundary river cooperation as an internal variable instead of as a static and external variable in coupled hydrology-economic models. This particular feature enables the model to analyze the mid- and long-term cooperation dynamics in transboundary rivers.

The cooperation dynamics in the Lancang-Mekong river basin described in the socio-hydrologic model are common in many other transboundary river basins. In particular, losses compared to expected benefits of downstream countries from 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 compared to expected benefit, 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.

As an early version transboundary river socio-hydrological model, there is significant room for further improvement in the model formulation. With limited research and knowledge on the quantification of cooperation and political benefits, the parameterization of policy feedback module such as the political factor is relatively primitive. As the model is applied to more cases, these policy feedback parameters could be investigated to find some general patterns, which could be then used to determine the corresponding parameters a priori when applying to new cases. 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 the cascade of reservoirs. Additionally, in order to integrate the complex hydro-economic relationships into the model, agriculture and fishery benefits are calculated in the present model with rather simplified equations. There is room for significant improvement in these benefit calculations. Flood control is one of the most important functions of existing and planned future dams, but has been ignored in this study, which may have led to under-estimation of the benefits to both upstream and downstream countries. Simulations under different scenarios of climate change and human activities could provide projections of the dynamics of transboundary river cooperation and conflict, and thus provide useful insights for transboundary river management in the future.

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 Borzì and Rupesh Patil discussed the framework of the socio-hydrologic 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 and Fuqiang Tian prepared the manuscript, with significant inputs and edits by Yongping Wei, David J. Yu, and Murugesu Sivapalan, with contributions from all co-authors. Fuqiang Tian supervised the whole procedure of this study.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

We would like to acknowledge National Natural Science Foundation of China (51961125204), the Ministry of Science and Technology, China (2016YFA0601603), and National Natural Science Foundation of China (51779203) for financial support. We also acknowledge the support from the 2019 Summer Institute on Socio-hydrology and Transboundary Rivers held in Yunnan University, China.

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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. Critical parameters and values for uncertainty analysis

Denotation	Parameter	Value	Alternative Value
ε_a	sensitivity of agriculture loss	0.5	0.4, 0.6
ε_f	sensitivity of fishery loss	0.5	0.4, 0.6
P_c	China political factor	2	1.5, 2.5
P_l	Laos political factor	1	0.8, 1.2
s	responsive change rate	0.5	0.4, 0.6
β	shape parameter	1.5	1, 2

Table 4. Simulated economic benefits in 2018 and statistical benefits

Unit: Million USD	Simulated benefit	Benefit from statistical data
China hydropower	1,954	2,000
Laos hydropower	976	1,076
Thailand agriculture	1,263	1,314
Thailand fishery	118	120
Cambodia agriculture	593	592
Cambodia fishery	1,160	1,188
Vietnam agriculture	1,728	2,727
Vietnam fishery	179	195

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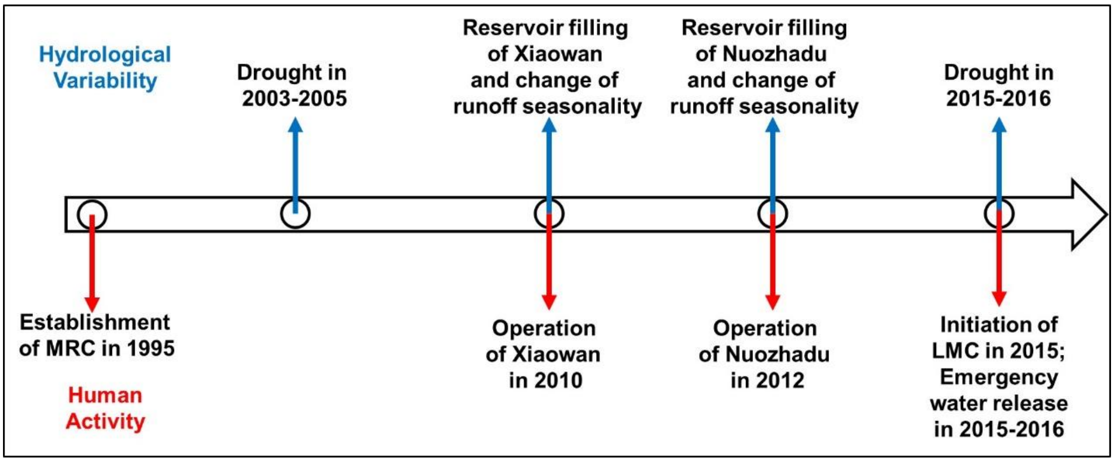

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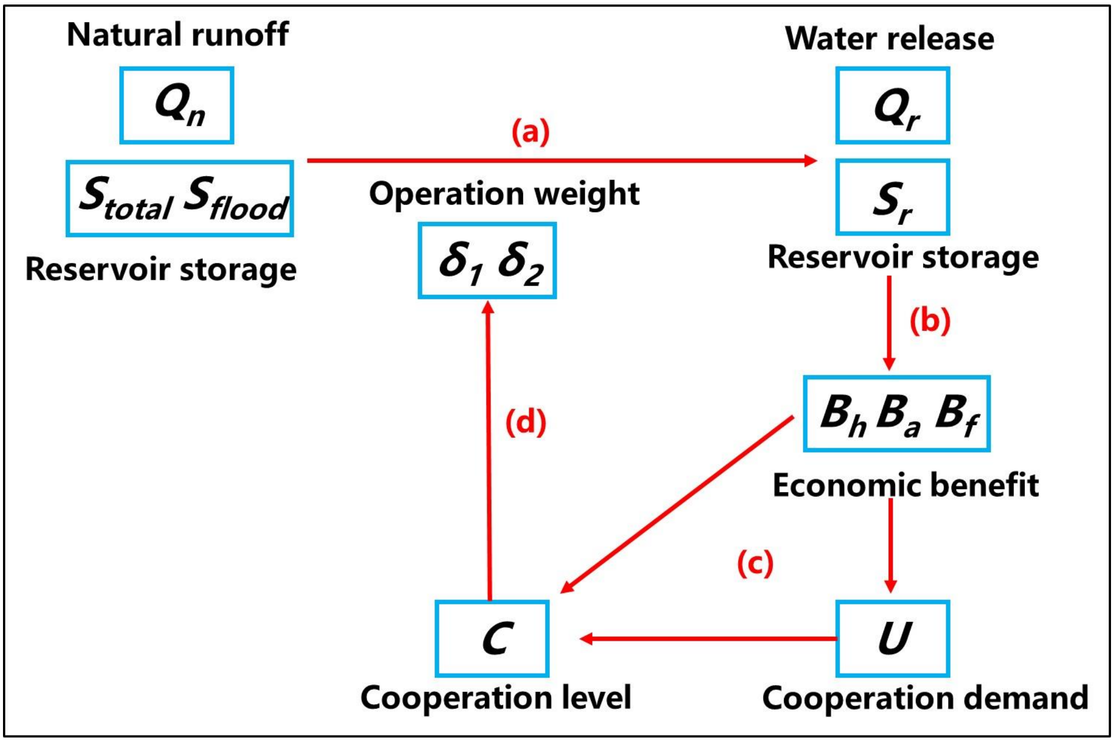

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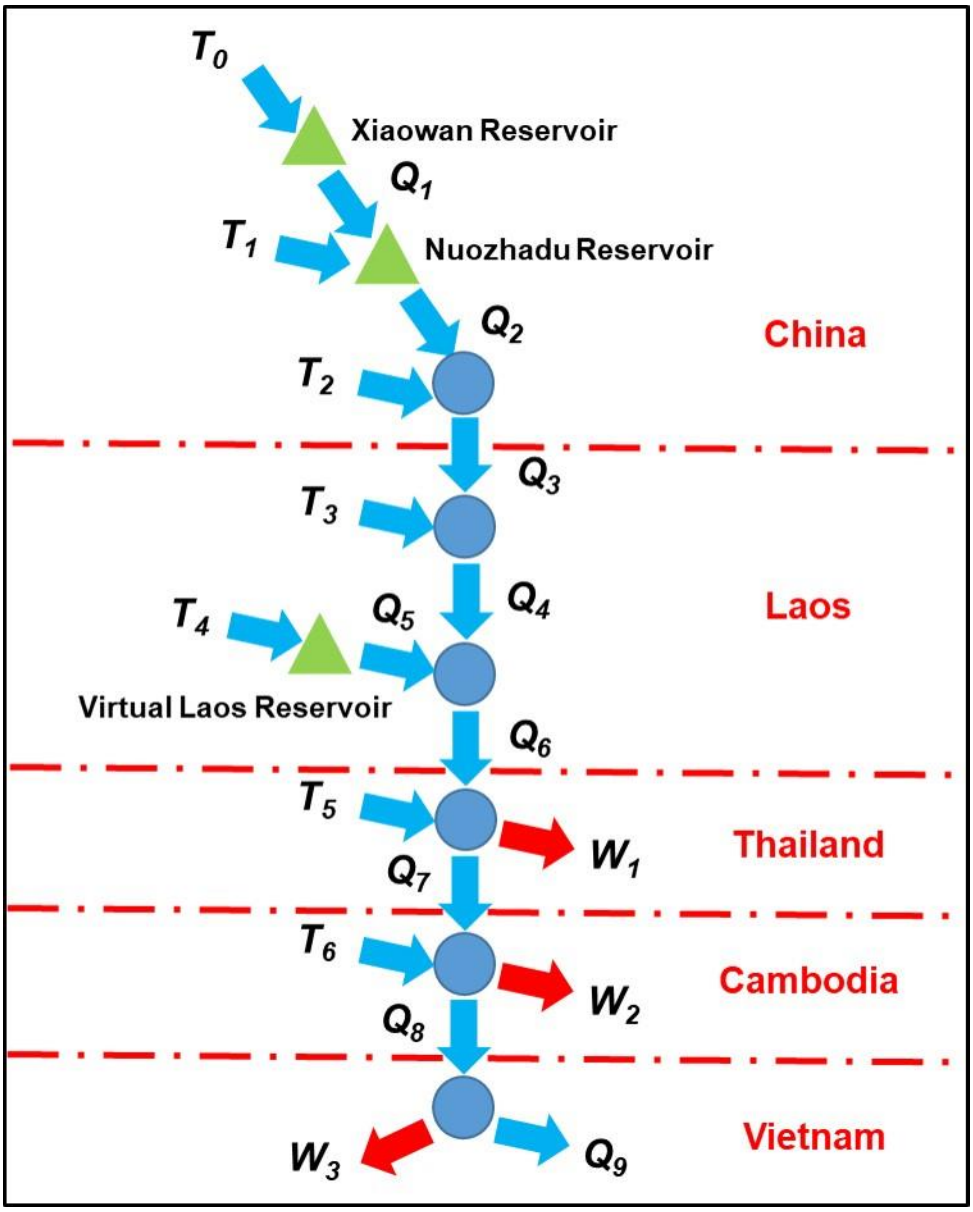

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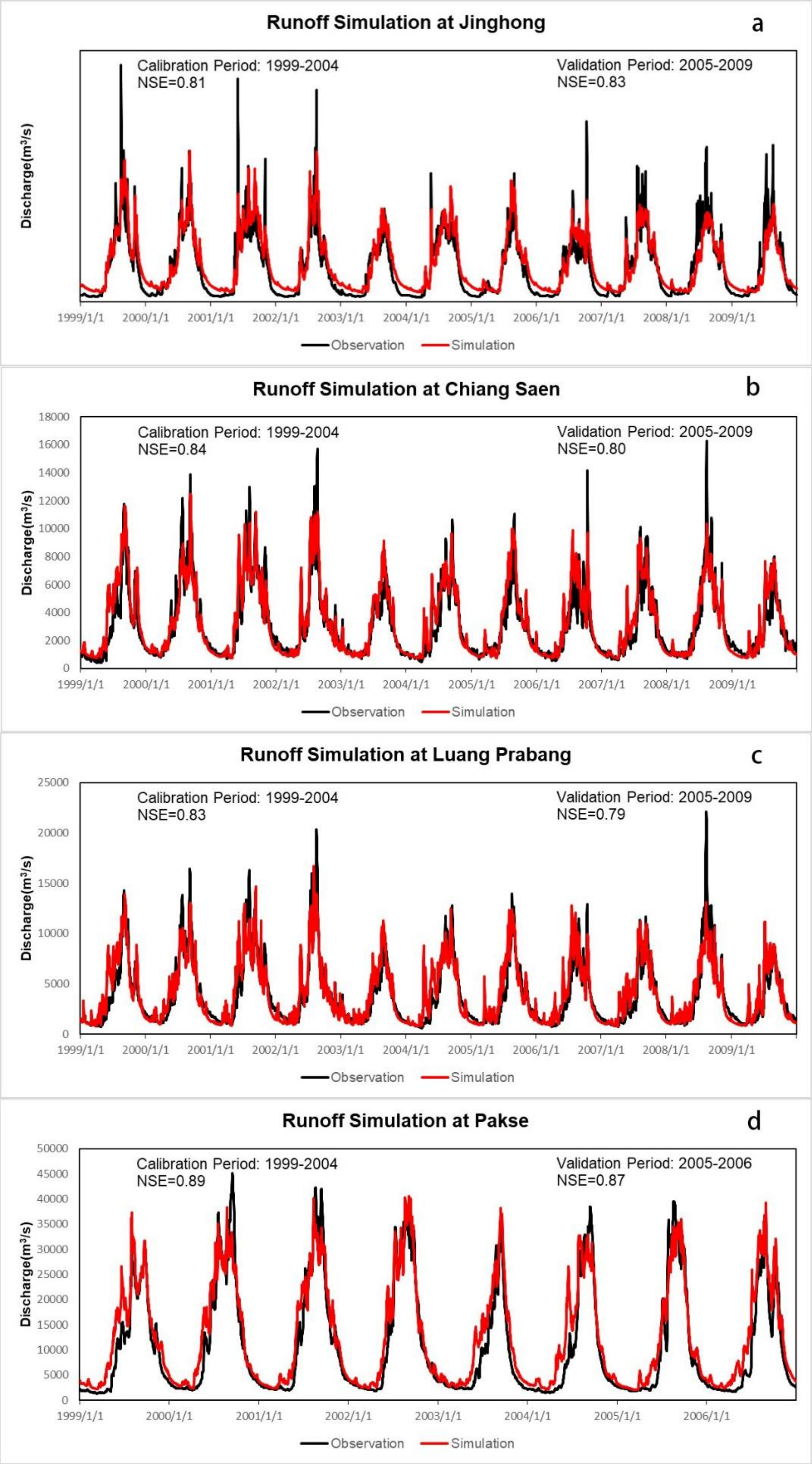

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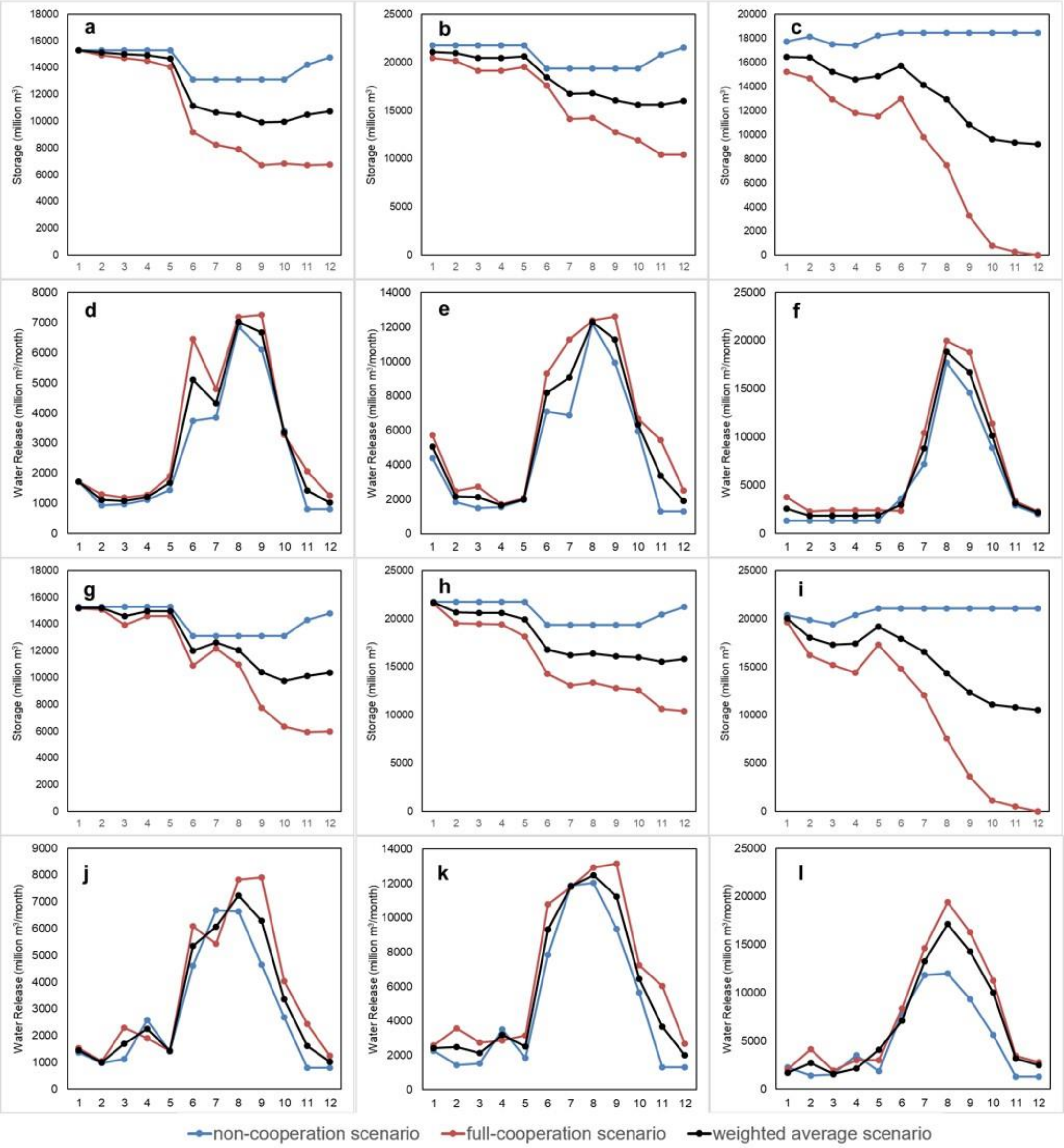

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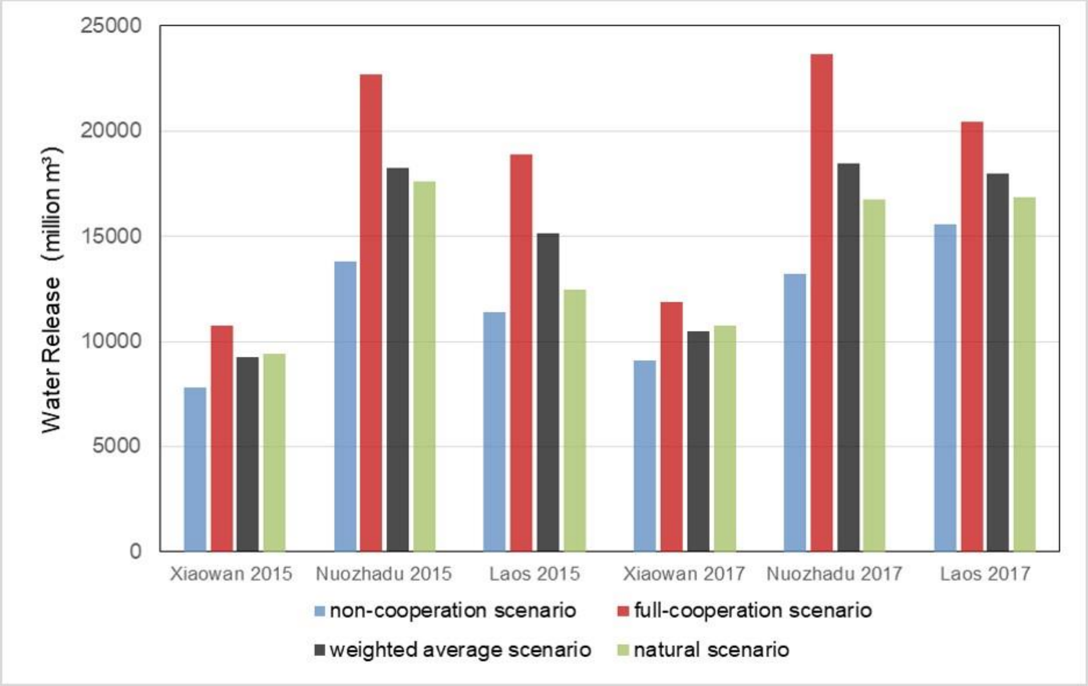

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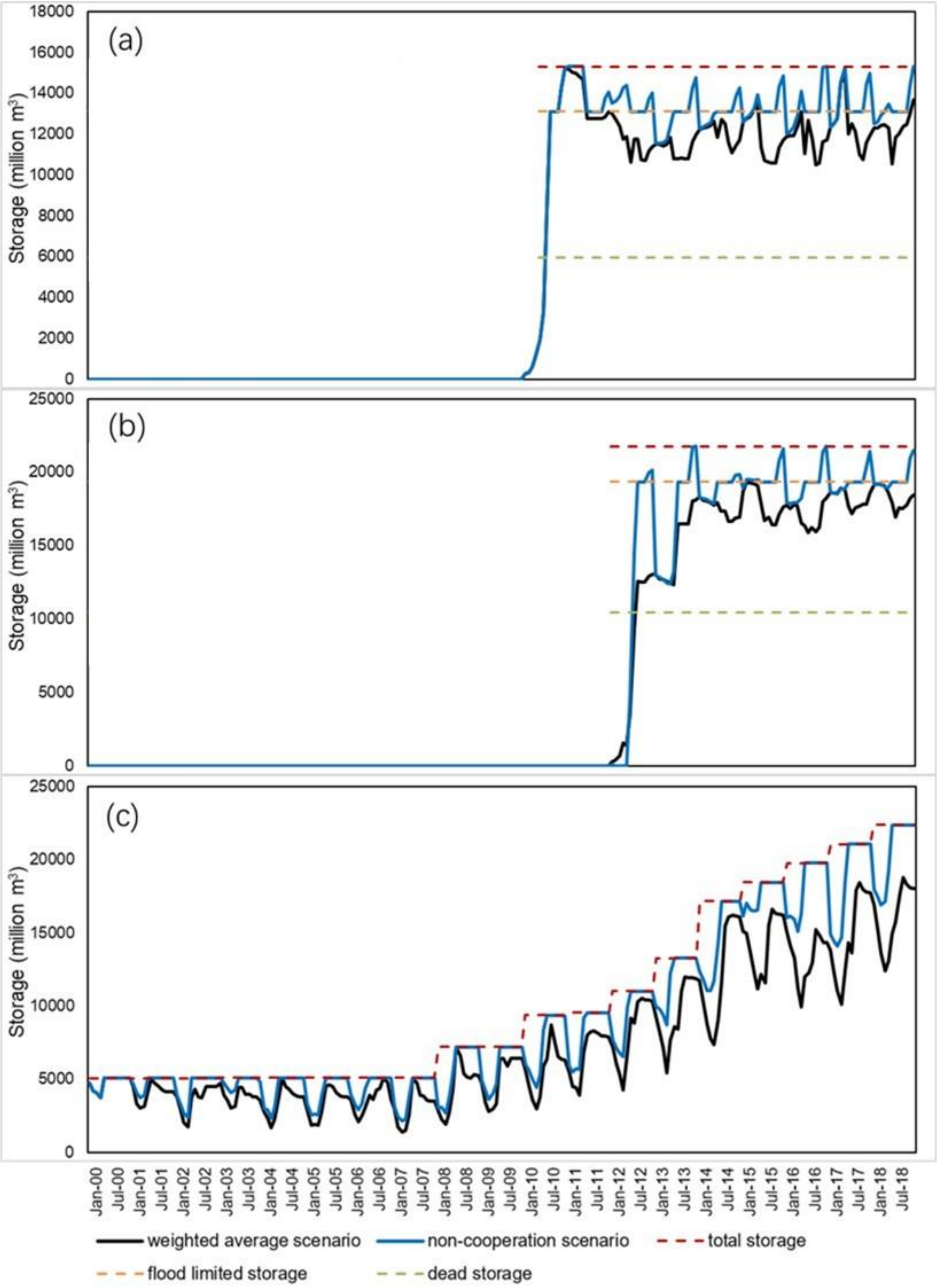

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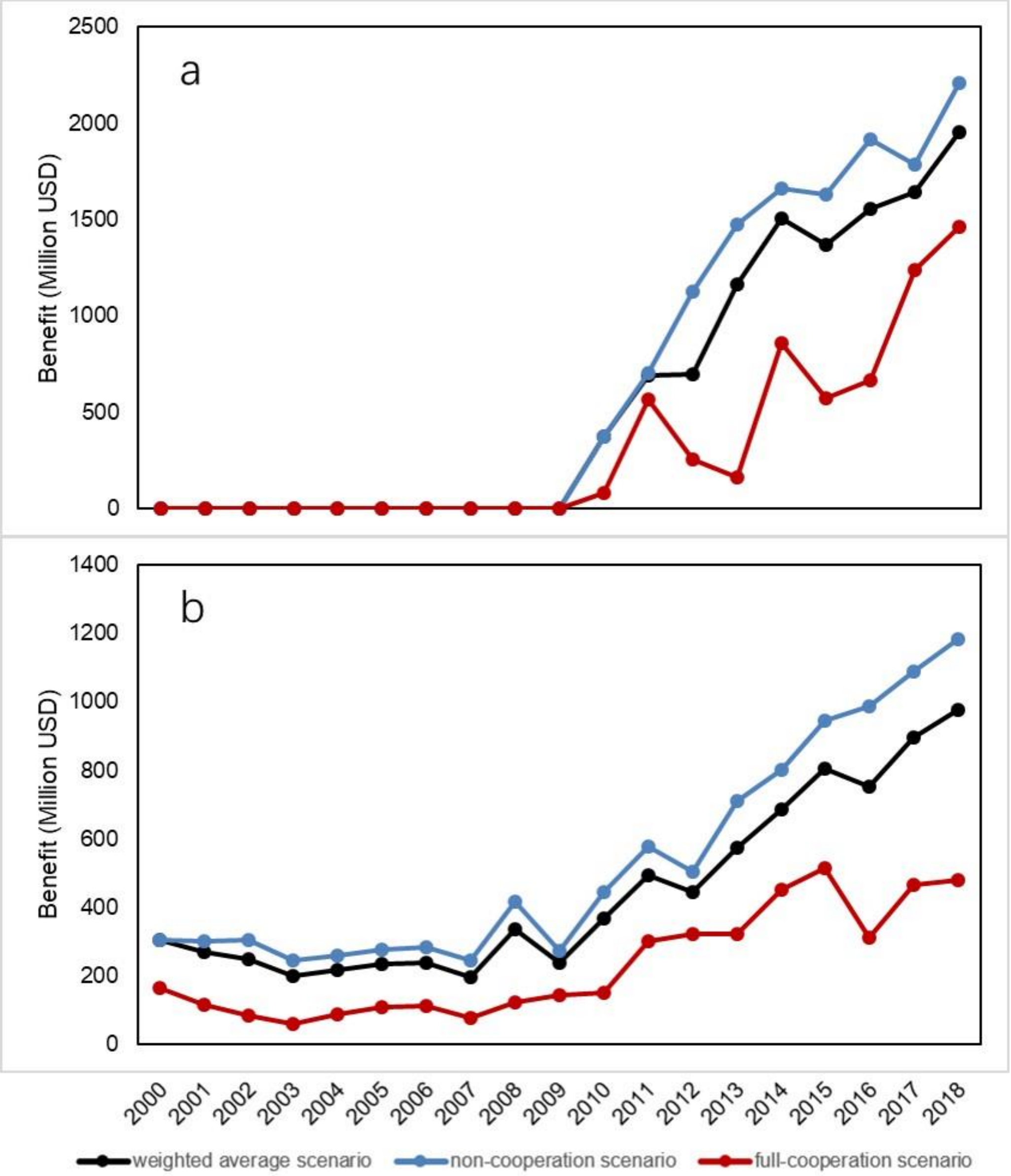

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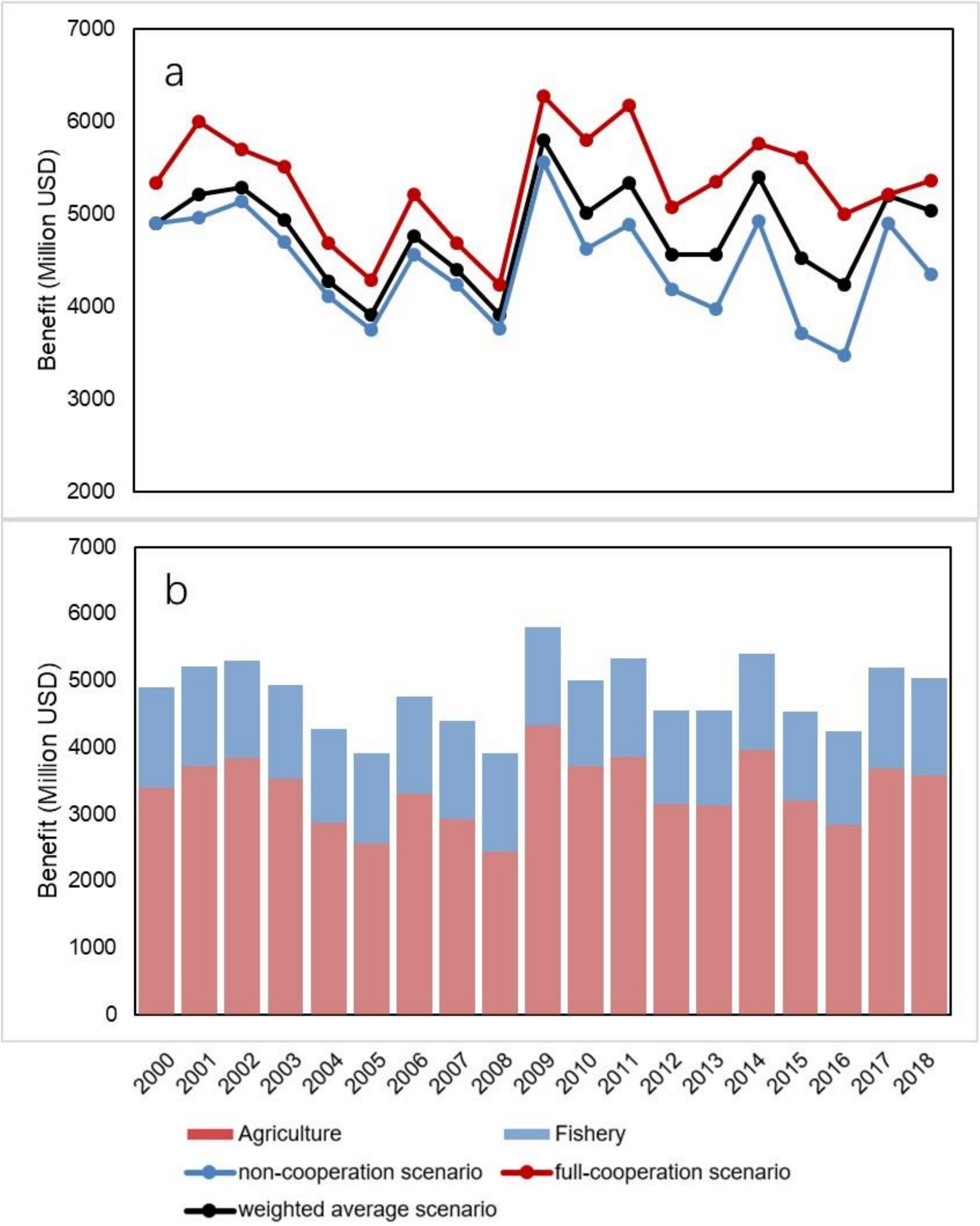

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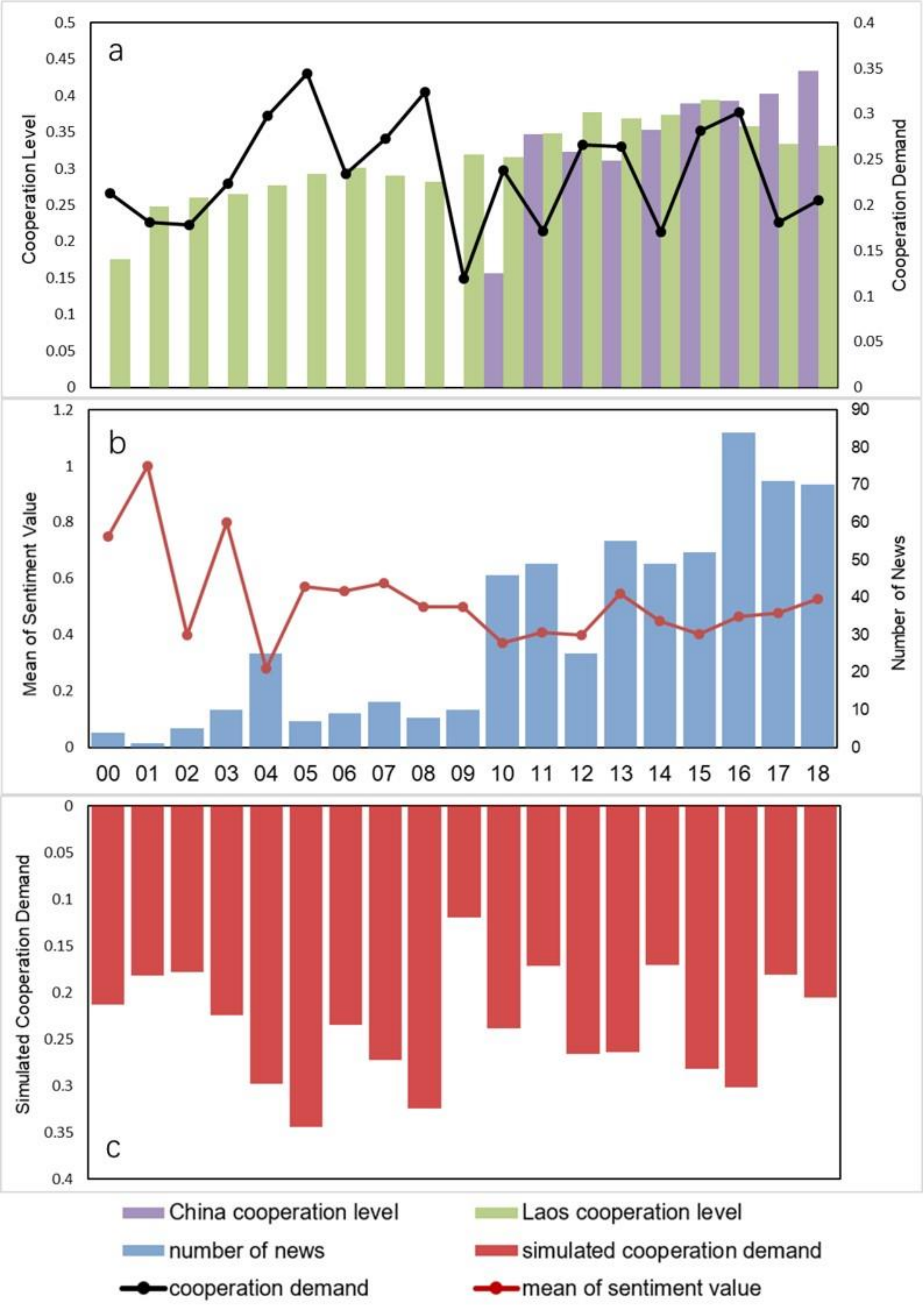

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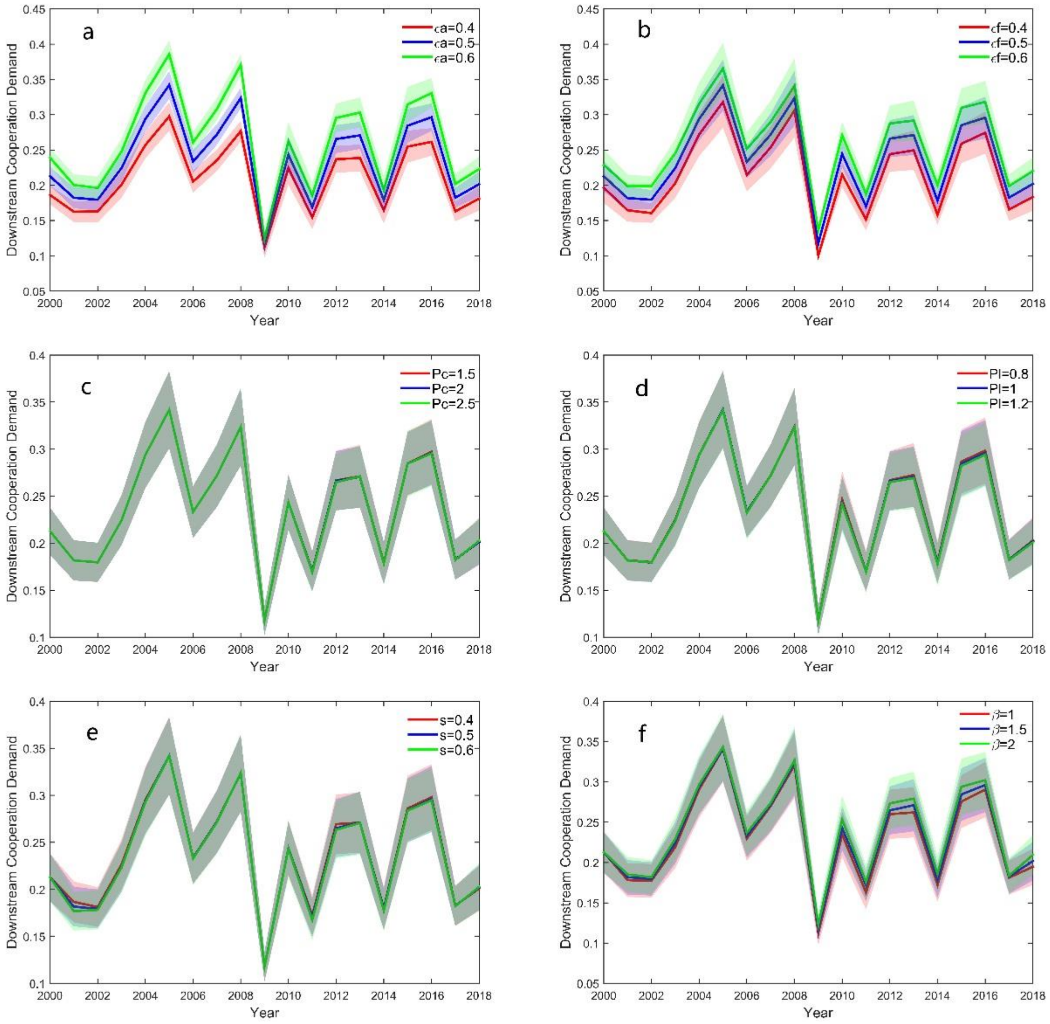

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