We greatly appreciate the positive comments from the Referee #1. Here we address those queries and concerns which are very constructive and highly valuable.

I believe the paper would benefit by bringing it all together a bit more. The synthesis table and how the case studies are similar or different in terms of various elements of the framework such as social motives, power, institutional capacity etc is useful but how such system components talk to each other is not clear from the narratives of the case studies.

Agreed.

We will revise the purpose of Section 4 as follows:

"We use the Columbia River, the Mekong River, and the Nile River, three well-known transboundary rivers, as case studies to demonstrate the applicability of this proposed framework (Figure 2). This framework adds values to the case studies by identifying the key variables and key links between variables that are crucial to understand the evolutionary dynamics of conflict and cooperation in these transboundary rivers, and influence stage transitions in these rivers. It will provide basis for developing formalized socio-hydrological models (Table 2)."

We will revise the section paragraph by paragraph to reflect similar or different in terms of various elements of the framework among case studies. We will add a summary paragraph to summarize these differences among the three case studies as follows:

"It is seen that the Columbia River provides a successful case so far for cooperation in transboundary rivers although there emerge changes in benefit distributions between the riparian countries that require further negotiations for cooperation. Sharing the same societal values, appreciating each country's power and rights, and strong institutional capacities (both hard and soft) are major drivers for success. The Mekong River provides a complex case for conflict and cooperation among six countries with their respective benefits, and diverse cultural and international political backgrounds. This case demonstrates that inclusion of economic, ecological, international political benefits is crucial to understand conflict and cooperation dynamics while recognizing the different institutional capacities in different countries. The Nile River provides an unsuccessful case of which unstable institutional capacities and unfavourable asymmetric power distributions were the root cause for strong conflict and weak cooperation. Therefore, the framework can identify key variables and links that explains conflict and cooperation in transboundary rivers."

Description of slow and fast dynamics is not so clear in the case studies. While the authors argue that hydro-economic treatment of transboundary river sociohydrology has gaps, they do not convincingly demonstrate that these gaps are filled by bringing in additional components through the case studies. I also think that the authors are unclear about how to 'quantify' various variables and concepts corresponding to these system components (also the sets of these variables and components appear to be 'open' sets) - they do allude to somethings in the paper (Table 1) but it is not clear to me how it is educating the slow and/or fast dynamics. Perhaps a more tangible effort to quantify some slow/fast dynamic equations (such equations can be conceptual in nature) will help. Also, some more tangible evidence of how some of its corresponding variables can be observed/measured, e.g. through behavioural experiments or surveys in ennvironmental psychology will help. Finally, what is it that neo-classical economics cannot explain that the proposed system components help explain in the narratives of the case studies? Almost all of the case studies can be explained by dynamic non-coperative game theory under uncertainty (evolving benefits, power, institutions, capacity and their feedbacks under exogenous shocks). So, what exactly the framework is accomplishing remains unclear and should be clearly brought forward. What is endogenous, what is exogenous to the system, how behavioral experiments/ environmental psychology data collection and analysis methods are being deployed, is it very slowly evolving culture/institutions and its effect on norms, perception of risk and capacity (given the time horizon of the case studies discussed) etc that are not covered by the current hydroeconomic models and needed to fully make sense of the presented narratives of the three basins?

Agreed.

As the reviewer's comments are high level and quite comprehensive, we will rewrite Section 3.1 - 3.2 as follows:

3.1 The framework concept

We develop a meta-theoretical framework to address the knowledge gaps in understanding conflict and cooperation in transboundary rivers which are identified in the section above. This framework will act as a 'middle ground' between the meta-level concepts and theories from related disciplines as introduced above and specific models driven by a particular context/a specific problem for building an interdisciplinary bridge to study the mechanism that drives conflict and cooperation in transboundary rivers.

We develop this framework based on the complex adaptive system theory and recent advances on understanding the coupled human-environment relationships from social-ecological systems (Folke et al, 2005), the Coupled Human and Nature Systems (CHANS) (Liu et al, 2007) and the social-hydrological framework (Elshafei et al, 2014). A complex adaptive system is of non-linearity, heterogeneity, multiple equilibrium states and cross-scale dynamics to present emergent behaviours. Specifically, we consider transboundary rivers as complex adaptive systems comprising water management (hydrological), ecological, economic, cultural, institutional, and political subsystems in each riparian country (Figure 1, demonstrating a case involving two riparian countries). These subsystems co-evolve, each affecting the others in each riparian country in a long timeframe. It is widely recognised in the co-evolutionary processes, hydrological and economic variables are of "fast" characteristics which work at the scale of seconds to years, and ecological and societal variables are relatively "slow" which often work at the scale of decades to centuries. Those slow variables (subsystems) often show a pattern of "punctuated equilibrium" (Gould & Eldredge, 1972) characterized by a long period of stasis being punctuated by a more rapid change that disrupts the equilibrium. For example, the 'cultural (societal value) lag' is well noted in the literature (Rosenschöld et al., 2014). Power status sometimes could not change for decades, even several thousands of years in ancient periods, but it could change suddenly through an elected political leader in modern times. It is the interaction of 'fast' processes and 'slow' processes that determine the system thresholds which, if crossed, cause the system to move into a new state (Sivapalan et al., 2012).

In this framework, **cooperation (whether to cooperate or not) occurs as the emergent behaviour between subsystems among riparian countries, which is a result of non-linear responses and multiple feedbacks between these subsystems (Figure 1). In conventional hydrology-economic models, whether to cooperate or not is defined as a binary variable (0, 1) to examine the evolutionary dynamics of cooperation. It only involves the fast processes indicated in upper part of Figure 1. As the cooperation continues, the value of cooperation will always be 1. It only involves the fast processes: water management conditions, the resultant benefits, and their direct feedbacks as indicated in the upper part of Figure 1. The slow processes that influence the cooperation decision in each riparian country's system are largely neglected. This framework extends the existing understanding of cooperation from integrated hydrology-economic models to include the willingness to cooperate, a hidden variable representing the slow societal processes (as the processes in lower part of Figure 1).**

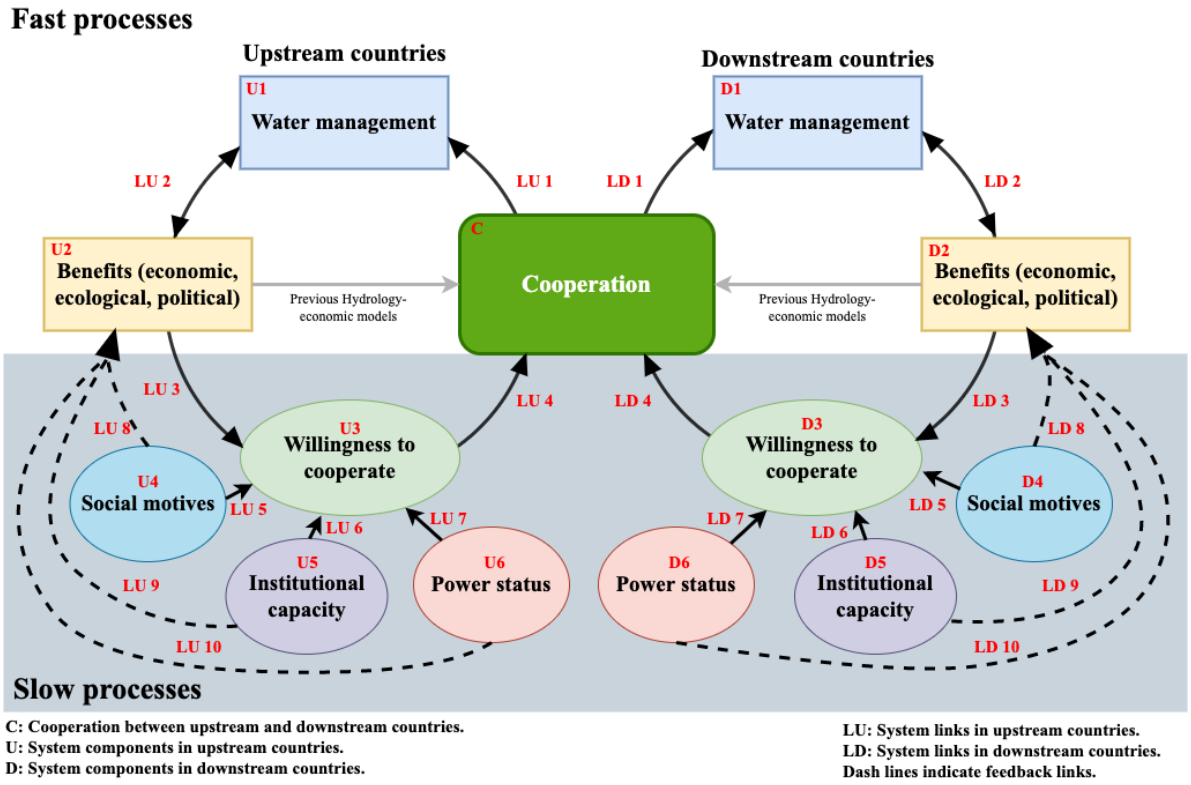

Figure 1. A social-hydrological framework for understanding conflict and cooperation in transboundary rivers.

Willingness to cooperate is a slow process influenced by both fast processes and slow processes. On one hand, it is directly influenced by the benefits one country will potentially receive, including short-term and direct economic benefits, long-term ecological benefits, and indirect political benefits that reflect the relative power of water management in transboundary rivers. These benefits will be achieved through change in water management, e.g., changing dam storage and then streamflow. On the other hand, the willingness to cooperate is also influenced by social motives, power status, and institutional capacity. Social motives are the primary driver of the willingness to cooperate and they also determine how one country perceive their benefits, i.e., the weighting they exert on different kinds of benefits (economic, ecological, political). Institutional capacity, a path-dependent societal variable, indicates the adaptive capacity that can promote and maintain the cooperation. It includes the hard capacity (engineering/technology on water development and harness) and the soft capacity (formal and informal regulatory processes and organizations involved in). Both geographical location (the spatial dependent level) and economic/political power impact the extent to which riparian countries are willing to cooperate. These societal variables are slow ones which express the change in status with time and reflect the relational aspects vis-a-vis specific countries. Furthermore, feedbacks between the change in social motives, power status and institutional capacity and change in economic, ecological, and political benefits, which are functions of change in hydrology, are recognised in this framework. With these feedbacks the unintended and undesired outcomes can be observed and explained as emergent phenomena from cooperation.

It should be noted that changes in willingness to cooperate occur in domestic and international contexts. Beside the endogenous variables discussed above, the exogenous factors with indirect impacts on the conflict and cooperation processes in water including climate change, natural and human disasters, population growth, urbanisation, change in sovereignty and national security, change in national boundary, and change in bilateral or multilateral relations should be considered. In addition, there are other types of cooperation between countries, such as cooperation on economic sectors, trading, science, and technology, they are considered as the exogenous factors in this framework.

3.2 Framework specification

To contextualise the framework concepts described above as a 'middle ground' between the meta-level concepts and a specific model, this section provides a general set of variables and possible relationships between them from which analysts can choose a subset or all and further specify them according to a specific problem or a system being investigated. We list the definitions and measures of these variables to our best knowledge (Table 1).

Table 1. The definition and measure of the variables in framework concept.

Sub-System	Variables and definition	Measure
Water management	Water supply (dam storage) and water management: dam operation (water release). Water demands.	Directly obtained from hydrological gauge stations or simulation. Water demand varies from sector to sector.
Benefits	Economic benefits include hydropower supply, flood control, irrigation, fishing, and others. Ecological benefits include those at catchment, in stream and floodplains. International political benefit is the reputation of a country in the world.	These benefits are functions of their water demands. They should be derived based on their respective disciplines (neoclassical economics, eco-hydrology and international politics).
Cooperation	Change in existing water sharing agreement or treaty among riparian countries, a status variable.	A Boolean variable: 0 (no change) or 1 (change).
Willingness to cooperate	A latent process variable reflecting the dynamic process of cooperation.	A continuous variable between 0 and 1. It is a function of benefits, social motives and power status and institutional capacity. The Cooperation variable switches from 0 to 1 when Willingness to cooperate reaches 1.
Social motives	Value reflection of different countries on cooperation. There are different types of motives for cooperation.	Measured as an index of 0-1 to reflect the social motives on cooperation from weak to strong. It can be measured by sentiment coding in the media, survey on the stakeholders in riparian countries or expert assessment on the events of conflict and cooperation. All these measures should be designed based on cognitive psychology and cultural sociology.
Power status	Variables expressing the social-economic ranking of a country in the world and the geographical location (the spatial dependent level) of this country in a transboundary river.	Measured as an index of 0-1 to reflect the socio-economic development level of a country from weak to strong. It can be assessed based on the relative socio-economic and power status of the riparian countries. Many datasets reflecting global social-economic development index and power are available. The spatial dependent level is a measurement of relative power among the riparian countries. Both direct assessment and

		selection of available datasets should be based on international politics.
Institutional capacity	Variables reflecting the adaptive capacity to absorb systems changes. They can be classified into hard capacity and soft capacity.	There are abundant approaches to assess the institutional capacity. Various indicator-based datasets have also been developed in literature to reflect the differences of institutional capacity. Both direct assessment and selection of available datasets should be based on institutional economics.

Obviously, to observe and measure the variables in the societal system is a big challenge. In the existing socio-hydrological models, it remains ad hoc and is often expressed as an anonymous variable or a representative indicator due to the absence of long-term observations of human behaviour (Di Baldassarre et al., 2019). The availability of 'big data' e.g. news media has provided an unprecedented opportunity to analyse and model the complex structures and dynamics in the societal systems (Bhattacharya & Kaski, 2019). We have developed an approach to integrate "thick descriptive" societal data into hydrological models by transforming narratives into quantitative data through a content coding scheme which is rooted in a context-mechanism-outcome configurations and allows for triangulation by multiple data sources (Pawson & Tilley, 1997; Wei et al., 2018; Newig & Rose, 2020; Olsen, 2004). With this approach, we have tracked the evolution of societal value on water with media data for different research contexts (Wei et al., 2017; Xiong et al., 2016, Wu et al., 2018;). For example, we quantitively tracked the societal values on conflict and cooperation of the riparian countries in the Mekong river during 1991-2018 by using cumputer-based sentiment mining in the newpapers collected in the LexisNexis, which is published in the same issue (Wei et al., 2021).

Functions between societal variables and hydrological variables and between societal variables then need to be developed. It is obvious that the stronger the social motives for cooperation, the higher the willingness to cooperate. The stronger the institutional capacity, the higher the willingness to cooperate. However, the power status may behave differently. Stronger power status can have positive or negative influences on the willingness to cooperate, depending on the direction of social motives. For example, China, which is located upstream of the Mekong River (geographical strength) and has stronger economic/political power than other riparian countries, but it does not always positively support cooperation. The functions between these variables are often expressed in a logit form (Hofbauer and Sigmund, 2003). However, we suggest that the relations between these variables in different case studies should be investigated based on the types of dynamics of these variables and existing qualitative and descriptive understandings of the interactions among these variables in social sciences (Sterman, 2001; Pentland, 2015). With enough understandings from the inductive perspective, some more theoretical formulations can be established.

Following that, these societal variables need to be calibrated with the societal data. It is recognised as a weakness in existing social-hydrological models that the societal components (e.g., represented by environmental awareness or community sensitivity) were not directly calibrated with societal data (Di Baldassarre et al., 2019). There are many existing societal data available for model calibration, including global databases and indicator-based assessment on conflict and cooperation discussed in the previous section, also those datasets reflecting global social-economic development index, power, and reputation (Treverton & Jones, 2015). We see that to calibrate the conflict and cooperation in the transboundary rivers provide an opportunity to improve the development of socio-hydrological models in general. Finally, model uncertainty should be noted as the transboundary river is a complex adaptive system which is characterized by non-linearity, heterogeneity, multiple equilibrium states and cross-scale dynamics. We may not be able to make predictions of cooperation in the traditional sense and the conventional sensitivity analysis may not perfectly fit for this kind of social-hydrological model. Rather, projections on possible future trends may be useful to inform future transboundary river management (Srinivasan et al., 2017).

In a word, this framework, by bringing the slow and hidden societal processes into existing hydrology-economic models on transboundary rivers, understand the cooperation from a binary variable (0, 1) underlying the fast processes to a continuous process between (0-1) with combination of cooperation and willingness to cooperate underlying the interaction between fast processes and slow processes. It enables observations of the change of cooperation status and societal processes underlying it for development of formal models to simulate feedbacks between change in social processes and change in hydrology through the benefit functions. Thus, this socio-hydrological framework can explain the unintended and undesired outcomes and contributes to understanding of the mechanism that drives cooperation between riparian countries. Compared to the existing hydrology-economic models with the game theory, it mechanistically and quantitatively explains residuals from explanations of rational economic behaviour (uncertainly), thus provide more precise and comprehensive knowledge on conflict and cooperation management in transboundary rivers.

I also think the figures and language at places can be improved.

Agreed.

Our apologies for the grammar errors and improper use of language. We will carefully revise the whole manuscript.

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