A socio-hydrological framework for understanding conflict and cooperation in transboundary rivers

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Abstract. Increasing hydrologic variability, accelerating population growth and urbanization, and resurgence of water resources development projects have all indicated increasing tensions among the riparian countries of transboundary rivers. This article aims to propose a socio-hydrological framework that incorporates the slow and less visible societal processes into existing hydrological-economic models, revealing the hidden feedbacks between societal and hydrological processes. This framework contributes to understanding the mechanism that drives conflict and cooperation in transboundary river management.

1 Introduction

There are 310 rivers around the world that cross the boundaries of two or more countries. When reaping the benefits of the river is perceived as a zero-sum game (Baranyai, 2020), riparian countries often experience more tensions than cooperation (Dinar, 2004). Divergent interests that drive such dynamics include water quantity, water quality, hydropower infrastructure development, flood management, navigation, economic development, environmental issues, climate change consequences (Milman & Gerlak, 2020; Nordås & Gleditsch, 2007; Rai et al., 2017; Munia et al., 2016). Increasing hydrologic variability under climate change, accelerating population growth and urbanization, and resurgence of water resources development projects exacerbate the tensions among the riparian countries of transboundary rivers (De Stefano et al., 2017). Thus, understanding the mechanism that drives conflict and cooperation is critically important for addressing this globally increasing issue.

Understanding what explains conflict and cooperation that arise in transboundary rivers is by no means a simple challenge. It is no wonder, therefore, that various disciplines have examined what can contribute to conflict and cooperation in transboundary rivers, and in doing so, covered a wide range of factors (Zeitoun et al. 2013; Petersen-Perlman et al., 2017; Fischhendler., 2008; Ho, 2017). They have been investigated from a hydrological perspective such as spatial location (Schmid, 2008), water availability (e.g., Toset et al., 2000; Furlong et al., 2006; Gleditsch et al., 2006), infrastructure development (De Stefano et al., 2017), external water dependency (e.g. Milman & Ray, 2011), climate change (Gleditsch, 2012), and presence of negative transboundary impacts or interlinkages between water and other issues (Schmeier 2014); from an economic perspective such as commercial trade (Espey and Towfique, 2004; Tir and Ackerman, 2009; Dinar et al., 2015), and economic development level (Priscoli and Wolf 2009); from a cultural perspective such as saliency of the river (Hensel et al., 2008), peacefulness of riparian relationships (Brochmann and Gleditsch, 2012), identity or national values (Allouche 2005), perceived exposure to unilateral overexploitation of the resource (Elhance 1999), and professionals communities (Kibaroglu, 2008); and from a political perspective such as level of democracy (Brochmann and Hensel, 2009), existence of transboundary treaties (Brochmann, 2012; Wolf et al., 2003a; Tir and Stinnett, 2012; Dinar et al., 2015), relative power of riparian states (Mirumachi and Allan 2007, Zeitoun et al. 2013), behaviour of the regional hegemon (Zeitoun and Warner 2006), domestic political rivalry, political leadership (Dinar 2009, Subramanian et al. 2014), and institutional resilience (De Stefano et al. 2012). While the wide range of factors implies the importance of using a multidisciplinary approach, there is yet to be a systemic understanding on how these disciplines, particularly social sciences, have been integrated with hydrology, which compromises theoretical development and practical management in transboundary rivers.

Transboundary rivers are complex adaptive systems of hydrological, environmental, economic, cultural, and political interdependencies among the riparian countries (Newig & Rose, 2020). Therefore, conflict and cooperation are emergent phenomena of the system arising from such interactions. Socio-hydrology, by observing and explaining unintended consequences as emergent phenomena in the co-evolution of coupled human and water systems, can provide an interdisciplinary system framework to understand conflict and cooperation in the complex transboundary river system (Sivapalan et al., 2012; Di Baldassarre et al., 2019; Yu et al., 2020). Socio-hydrology is meta-theoretical and thus should be compatible with theories and models used in different constituent disciplines. It requires a conceptual framework that acts as a 'middle ground' between the meta-level concepts and specific theories and models driven by a particular discipline or context. This framework would provide a general set of variables and relationships between them from which analysts can choose a subset and further specify according to a specific problem or a system being investigated (e.g., Ostrom 2009). In this way, the framework would provide a common language to compare different cases and phenomena. However, such a middle-ground framework in socio-hydrology for studying conflict and cooperation has been largely absent.

Contributing to the filling of knowledge gaps between multidisciplinary (in particular social sciences) linkages with hydrology is the objective of this study. This will be done through three steps. First, an overview of the existing literature on conflict and cooperation in transboundary rivers from multiple disciplines and the integration of social sciences with hydrology will be provided. This will provide an understanding of the preliminary concepts in a wide range of disciplines on conflict and cooperation and identify the gaps in their linkages with hydrology. This is a precursor to the next step: proposition of a conceptual socio-hydrological framework. This framework will act as a ‘middle-ground’ (an interdisciplinary bridge) with a general set of variables and possible relationships between them to consider for studying the mechanism that drives conflict and cooperation in transboundary rivers. In the final step, the proposed framework is applied to three cases of transboundary rivers (the Columbia River, the Lancang-Mekong River, and the Nile River) to illustrate its potential utility.

2 Overview on conflict and cooperation studies in transboundary rivers

2.1 Understandings from empirical/assessment studies

There are very rich empirical studies on conflict and cooperation in transboundary river management in global and local scales. Several global databases have been developed. The International Water Event Database (IWED) (Wolf et al., 2003) documents global water events on conflict and cooperation during 1948–2008. The Transboundary Fresh Water Dispute Database (TFDD) is a database specifically for global and regional assessment on water conflict and resolution processes (Munia et al., 2016). The Water-Related Intrastate Conflict and Cooperation (WARICC) dataset focuses on events of national water dispute among 35 countries in the Mediterranean, the Middle East, and the Sahel from 1997 to 2009 (Bernauer et al., 2012). Various sets of indictors have also been developed to evaluate the level of conflict and cooperation from different perspectives. The Pacific Institute categorizes water conflict events based on the purpose of water control, where water is considered as a “military tool” or a “political tool” (Pacific Institute, 2009). The Water Cooperation Quotient identifies formal agreements, river basin commissions, ministerial meetings, technical projects, joint monitoring of water flows, floods, dams and reservoirs, high political commitment, integration into economic cooperation, and actual functioning as ten key aspects that facilitate collaborations between two or more countries (Baranyai, 2020; Strategic Foresight Group, 2015). Zeitoun and Mirumachi have developed quantifiable, two-dimensional matrices (Zeitoun & Mirumachi, 2008), then extend them as the Transboundary Water Interaction NexuS (TWINS) that focuses on comparison of conflict and collaboration among different countries and how they evolve in time (Mirumachi & Allan, 2007). Wolf et al. developed a 15-point “Basins at Risk (BAR) scales” (Wolf et al., 2003) to classify and measure the extent of water conflict and cooperation. The Integrated Basin at Risk (iBAR) further includes inequalities and injustices into consideration (Watson, 2015). Conca (2006) proposed the core normative elements for assessing transboundary governance: equitable use principle, no-harm principle, sovereign equality and territorial integrity, information exchange, consultation with other riparian states, prior notification, environmental protection, and peaceful resolution of disputes.

These databases provide a global picture of conflict and cooperation events in transboundary rivers from different temporal and spatial scales and the assessment studies define and measure conflict and cooperation events with various sets of indicators. These studies provide rich description on the phenomena of conflict and cooperation, however, due to no link with process-based, cause-effect analysis, they have limited ability to reveal the adaptive evolution and predict future trends of conflict and cooperation between riparian countries.

2.2 Understandings from multiple disciplines

Hydrological studies have made major contributions to the understanding of conflict and cooperation in transboundary rivers. They include site-specific and topic-specific studies on the impacts of spatial location, water availability, external water dependency, climate change, and infrastructure development in transboundary rivers (De Stefano et al., 2017; Furlong et al., 2006; Nordås & Gleditsch, 2007). Hydrological models have been developed to assess the biophysical consequences of conflict (unilateral action without agreement among riparian countries) and the biophysical possibility of cooperation by simulating the impact of upstream alternations of water quantity, flow duration, water quality and river morphology on the agriculture, fisheries, energy production, navigation and ecosystems in downstream countries. By analysing the possibilities of where, how and when water can be harnessed and utilised, hydrological understanding forms the biophysical basis for transboundary river management (Newig & Rose, 2020).

Neoclassical economics has dominated the simulation and explanation of human cooperation behaviour. It explains cooperation in riparian countries from a purely economic perspective, focusing on the tangible outcomes received by these countries and assuming them as rational actors with perfect information about all potential choices and their consequences (Schill et al., 2019). Hydrological models have been widely integrated with economic models, often referred to as hydrological-economic models to simulate cooperation in transboundary rivers by optimizing the incremental economic benefits through a group of water production functions under a set of specific societal constraints (Harou et al, 2009). Thus, influences from the social dimension are only considered as residuals from explanations of rational economic behaviour. These models have been criticized for being overly simplistic and unable to capture the diversity of human behaviour (Schlüter et al., 2017), thus failing to reflect the reality of conflict and cooperation in transboundary rivers (Wei et al., 2021).

Behavioural economics emerges through relaxing the unbounded rationality of actors in the neoclassical economic models (Conlisk, 1996). It argues that decision-makers' preferences are not only deeply influenced by their living environments, social norms, traditional cultures, but also by the inability of policymakers to consistently compare outcomes and their 'mental inertia' over a long timeframe (Schill et al., 2019). In transboundary rivers, whether people choose to cooperate or not relies on one country's expectations on absolute economic benefits, their benefits in previous periods as a reference level, relative gains compared to other countries, and intangible benefits such as ecological, social, political, or diplomatic benefits. Hydrological models have been integrated with the game theory, agent-based models, and system dynamic models to simulate conflict and cooperation in transboundary rivers (Yu et al., 2019; Khan et al., 2017; Ding et al., 2016; Sehlke and Jacobson, 2005). Among the obvious weaknesses in these models, the one highlighted here is that there are constant difficulties in defining and accounting for every set of influential factors, often minimising the social dimensions on cooperative behaviours by means of anonymous subjects (Futehally, 2014; Ribes-Iñesta et al., 2006).

Institutional economics is another branch of economics, which focuses on the understanding of inter-organizational cooperation by assessing economic performance under different institutional contexts (Schmid, 2008). In transboundary rivers, institutional economics often collaborates with law to examine treaties and agreements to provide confidence and compliance for negotiation and to reduce transaction costs of cooperation (Rees, 2010; Boin and Lodge, 2016; Saleth and Dinar 2004). Some studies argued that institutional incapacity lies at the root of many water conflicts, where rapid biophysical (e.g. unilateral development projects, unanticipated droughts or floods) and socio-economic changes (e.g. population growth, technological development) have outpaced the institutional capacity to absorb these changes (Wolf et al., 2003). Yet, these studies lack support from process-based hydrological understanding. Hydrological models often simulate institutional conditions and transaction costs of cooperation using the game theory, which suffer from the same shortcomings as mentioned in behavioural economic studies.

Cognitive psychology and cultural sociology provide a rich understanding of cooperative behaviours from the perspective of social comparison, self-reflection, and mental model of the future (Schlüter et al., 2017). Social psychologists recognise that people are fundamentally different in respect of their social values and personality traits. These values and traits are primary drivers of cooperative motives and choice behaviour, which can have a mixed influence on cooperation in the situation of social dilemma (Bogaert et al., 2012; Hoff & Stiglitz, 2016). Two opposing social value orientations are typically recognized: a pro-self and a pro-social orientation. Pro-socials believe that it is efficient and fair to cooperate, whereas pro-selves cooperate because they believe that they will be worse off when they do not (Bogaert et al., 2008). Schwartz (1992) and Howat (2019) identify 10 basic values of social motivation including openness to change, conservation, self-transcendence, self-enhancement, conformity, and others, and discuss their relationships to each other. These theories imply that to encourage cooperative behaviours may require different approaches. The commonly adopted method for value measure in these disciplines is to observe the actual choice behaviour in a typical small-scale and short-term experiment. A shortcoming of this method is that it is impossible to unambiguously separate an individual's natural inclination from the situational determinants that also impact behaviour. Most studies on conflict and cooperation in transboundary rivers from these disciplines are conceptual, focusing on the prominence of water, identity or national values, and perceived exposure to resource overexploitation (Baranyai, 2019; Brochmann & Gleditsch, 2012; Elhance, 1999) and they have not been integrated into hydrological models.

In part due to the salience of equity, sovereignty, diplomacy and national security in transboundary river management, scholars in political science and international relations have also made important contributions in understanding cooperative behaviours in transboundary rivers (e.g., Giordano & Wolf, 2003; Munia et al., 2016). Politics is the study of power (Lasswell, 2003). Hydro-politics is characterized by hegemonic configurations in the form of geographical locations, wherein the most powerful riparian countries have an advantage over their weaker neighbours on water allocation and enforce a cooperative agreement (Mirumachi & Allan, 2007; Zeitoun et al., 2011). Another research field is hydro-diplomacy (water diplomacy), which refers to an approach that seeks to establish or improve cooperation and stability over water use (Milman & Gerlak, 2020). Cooperation in hydro-diplomacy is considered as a two-way interaction between domestic politics and international politics, bounded with concerns of sovereignty around core values (the importance of water in national security) and cultural constructions that date back generations (e.g. the religious dimensions of water) (Warner, 2016). Schwartz et al. (2014) and Howat (2019) used eight political values to understand intergroup conflict: equality, civil liberty, self-reliance, free enterprise, military strength, blind patriotism, law and order, and traditional morality. Both hydro-politics and hydro-diplomacy argue that transboundary river management is all about "a political process subject to the whims of power" (Zeitoun & Mirumachi, 2008), leaving little room for economic cooperation. It is fully agreed in both fields that hydrological knowledge (hydrology) is the basis. However, hydrological models have not been integrated with political or diplomatic understandings.

The physical interdependence and connectivity of transboundary rivers give rise to regional studies that focus on management integration. Establishing linkages is considered as the basis for benefit-sharing and crucial for cooperation in transboundary river management (Warner, 2016). These studies hold that issue trading and package deals enable greater economic efficiency (Wolf, 2010). The rationality underlying this is that conflict and cooperation cannot be understood by neglecting the broader social and political contexts of transboundary riparian countries (Kibaroglu, 2019). While these linkage concepts can broaden the solutions of cooperation in transboundary rivers, no empirical study with hydrology models has demonstrated its practicability and it is also recognized that linkage with broader unbounded contexts could make conflict and cooperation even more complex and difficult to manage.

We sum up current understandings on conflict and cooperation in transboundary rivers as follows: hydrological models have been developed to simulate the biophysical consequences of conflict and the biophysical conditions of cooperation in transboundary rivers. They have been well integrated with neoclassical economic models to simulate the feasibility of cooperation. Recent developments on hydrology by integrating the game theory, agent-based models and system dynamic models into hydrological models intend to overcome the over-simplicity in neoclassical economic models by capturing the diversity of human behaviours, however, these models are criticized on their weak and inexplicit representation of social dimensions. Psychology and sociology provide rich descriptions on social motives (values) as primary drivers of cooperative behaviours but encounter difficulties in integrating with hydrological models as most of their findings are qualitative in nature. Similar lack of integration is also found in hydro-politics and hydro-diplomacy, which emphasize the power differences between riparian countries. More importantly, conflict and cooperation have never been understood as an emergent outcome from the co-evolved processes in a complex system (except Lu et al., 2021 on this issue). Therefore, current understandings have limited analytical capacity to reveal the mechanism that drives conflict and cooperation.

3 A social-hydrological framework for understanding conflict and cooperation in transboundary rivers

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 hydrological-economic models, whether to cooperate is defined as a binary variable (0, 1) to examine the evolutionary dynamics of cooperation. 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 interactive feedbacks as indicated in the upper part of Figure 1 (see also Sadoff and Grey, 2002). 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 hydrological-economic models to include the willingness to cooperate, a hidden variable representing the slow societal processes as shown in the lower part of Figure 1.

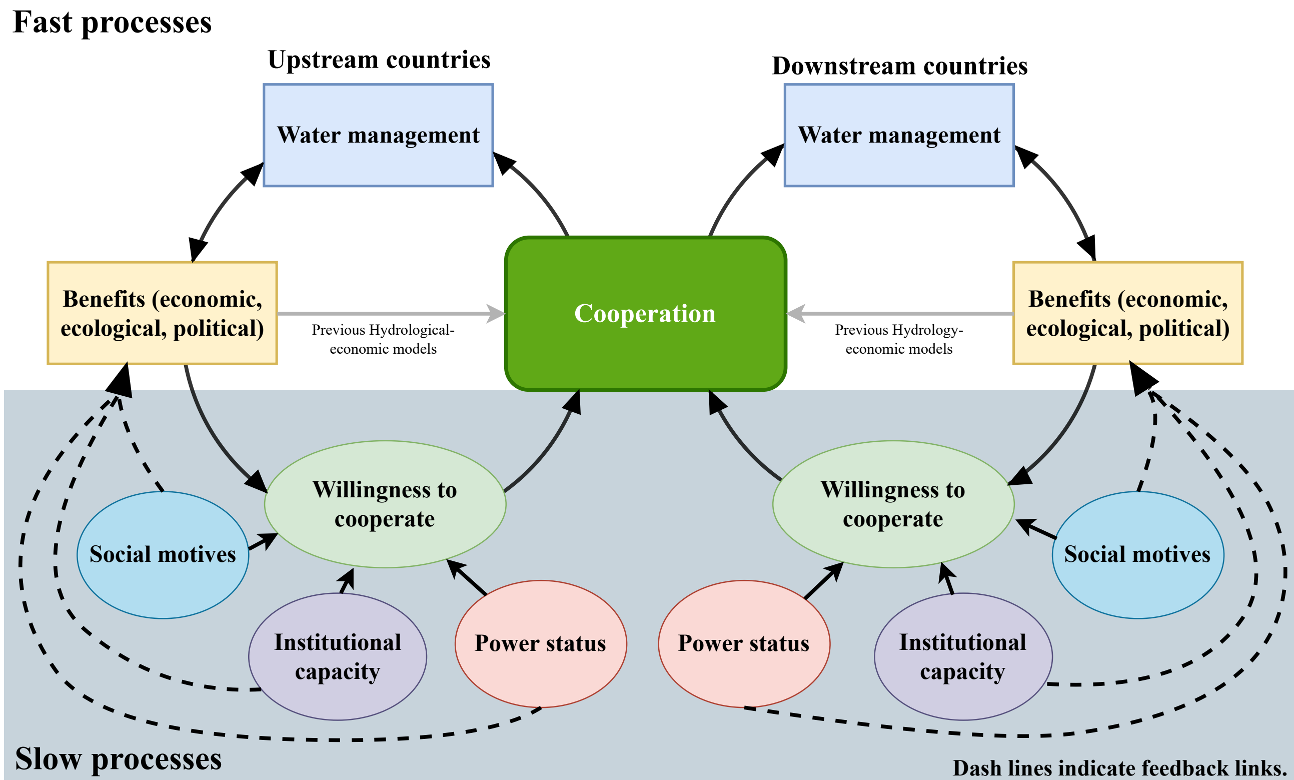

Figure 1. A social-hydrological framework for understanding conflict and cooperation in transboundary rivers.

Willingness to cooperate is a slow variable 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 on a case-by-case basis. 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 generation, 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 use. 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 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. 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 Lancang-Mekong River during 1991-2018 by using computer-based sentiment mining in the newspapers 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 and 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 Lancang-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 hydrological-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 interacting between both fast 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 hydrological-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.

4 Applicability of the proposed framework in three case transboundary rivers

We use the Columbia River, the Lancang-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).

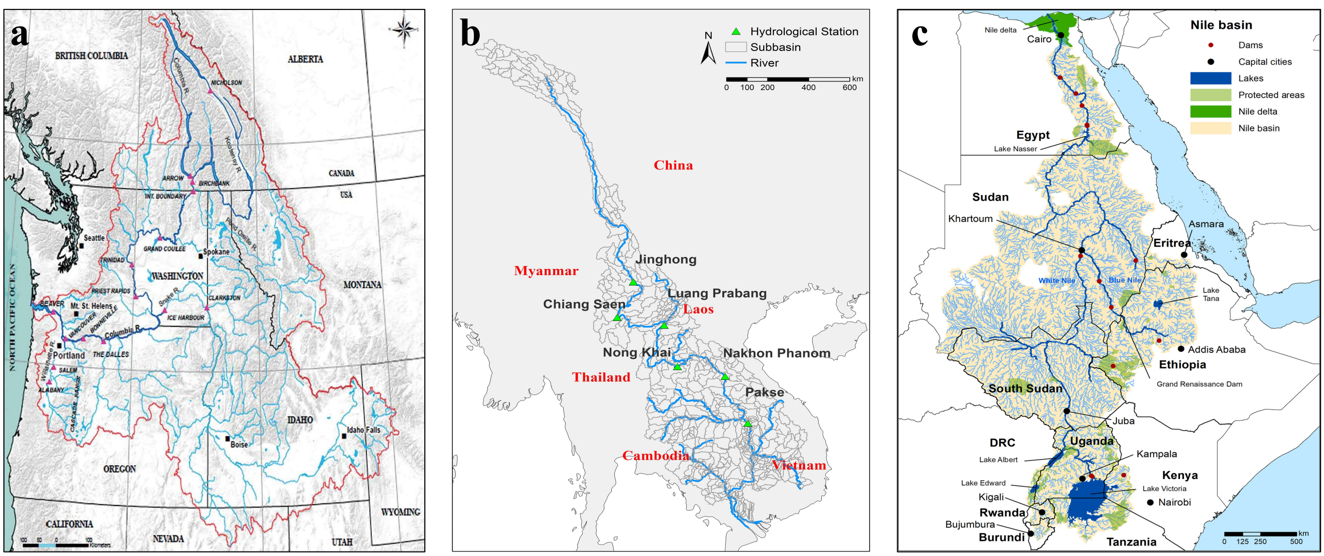

Figure 2. Case examples: (a) Columbia River (Jay & Naik, 2011), (b) Lancang-Mekong River (Lu et al., 2020), (c) Nile River (Allan et al., 2019).

4.1 The Columbia River

The Columbia River starts in British Columbia and has a basin that extends 670,807 km^2. The basin covers seven U.S. states (Washington, Oregon, Idaho, Wyoming, Montana, Nevada, and Utah) and drains to the Pacific Ocean via Oregon. Only 15% of the river's length flows through Canada, but the Canadian portion accounts for 38% of the average annual flow. The river has multiple domains of use: hydropower, fishing, irrigation, recreation, navigation, and ecosystem. Millions of people in the Pacific Northwest rely on these services. The river has high volume and large seasonal variability of flow. Downstream areas face significant flood risks because of strong seasonality of flow and spring snowmelt peaks. The evolution of conflict and cooperation in the Columbia River can be divided into three stages.

At Stage I (~early 1960s), development increased along the river in Washington and Oregon. Strong seasonality of flow and spring snowmelt peaks posed significant threats and caused damages. In 1948, flooding driven by snowmelt and heavy rainfall breached the levee and destroyed Vanport, Oregon's second largest city, as well as Trail, B.C. It caused dozens of deaths and extensive property damage in both the U.S. and Canada. These floods were the impetus for the U.S. to seek cooperation with Canada. The U.S. found it difficult to capture enough water to control flood levels within its portion of the river. At the same time, more than 90 percent of the potential damages in the basin are in the downstream portion of the river.

At Stage II (early 1960s ~ early 1990s), joint studies began after the 1948 flooding to explore possible storage sites in Canada and analyse the benefits of sharing river between the countries. It was concluded that cooperation benefits are more advantageous to both sides than options available through individual operation. Following negotiations, the Columbia River Treaty was completed in 1964 to manage the river for the joint benefit of both countries, focusing on flood control and hydropower. Under this agreement, the U.S. paid Canada $64.4 million to rent 8.45 million acre-feet of storage space in Canada. These funds were used to build and operate three large storage dams (Keenleyside, Mica, and Duncan) on the Canadian side and the Libby Dam on the U.S. side. Canadian dams must be operated to lower reservoir levels and provide storage space during spring and summer to capture water upstream to prevent flooding. In addition, the U.S. pays Canada 50% of the projected U.S. power benefit generated by Canadian storage, also known as the "Canadian Entitlement", for the expected avoidance of flood damages through 2024. In exchange, the controlled release of these dams provided an opportunity for more efficient hydropower production in the downstream because of more predictable and flexible flows. The cooperation through the Treaty has been used as a pinnacle for international cooperation on non-navigational water uses.

At Stage III (early 1990s ~ present), changing socio-environmental conditions have altered the context of the 1964 treaty. Urban development, such as the City of Portland, along the downstream portion of the river that has increased the value at risk. Also, tribal groups and First Nations whose existence depend on the river have suffered loss of fish (salmons and steelhead) from dam construction. They requested their sovereignty right (cultural and natural resources) to be respected. Thirteen species of anadromous salmon, steelhead, and sturgeon are listed under the Endangered Species Act (ESA). By the 1990s, salmon and steelhead populations reached alarmingly low levels, prompting aggressive action at the Federal level to impose stronger regulations on dam operators to adjust their operating strategies to support the recovery of fish. The primary operational change is that hydropower operators must augment seasonal river flows and increase spill at dams to assist downstream migration of juvenile fish, decrease water temperature, and increase flow velocity. Spills occur when hydropower operators divert some portion of the river flow, particularly in spring and summer, away from the hydropower turbines, which allows for fish to pass the dam without risking injury. However, hydropower producers experience financial losses because these spills utilize water that could otherwise be used to produce hydropower. At the same time, the U.S. continues to pay the same Canadian Entitlement agreed upon in the Treaty, which has created the perception of decreased hydropower benefit on the U.S. side. The U.S. entity estimated that the value of Canadian storage and downstream power value should be around $26 million USD in electricity (about 1/10th of the estimated worth of the Canadian Entitlement) because it does not consider fishery needs, agriculture, non-Treaty dams, and annual variability in precipitation. Canada, on the other hand, argues that the value provided by Canadian storage is much higher than the current Entitlement (e.g., additional benefits of navigation, recreation, irrigation, and fisheries), and that additional costs should be borne by the U.S. These different arguments from Canada and the U.S. will be base for renegotiations on cooperation beyond 2024.

4.2 The Lancang-Mekong River

The Lancang-Mekong River Basin spans 795,000 km^2 across six countries (China, Myanmar, Thailand, Laos, Vietnam, and Cambodia) in South-East Asia with over 60 million populations. It is one of the largest and longest transboundary rivers and has one of the most productive inland fisheries in the world (MRC, 2018; Yorth, 2014). About 85% of the basin's populations live in rural areas, whose livelihoods and food are highly dependent on the river system (FAO, 2011). Conflict and cooperation in the Lancang-Mekong Basin mainly evolved around constructions of large dams and water distributions (De Stefano et al., 2017; Wei et al., 2021), which demonstrated five stages from 1999 to 2018 (Lu et al., 2021 and Wei et al., 2021).

Stage I (1999 ~ 2003) was characterised by limited conflict in the basin due to absence of dam construction (Yorth, 2014). The Agreement on "the cooperation of the Lancang-Mekong River Basin for sustainable development" was signed by all members in the Lancang-Mekong River Commission (Hirsch and Cheong, 1996). Riparian countries shared the economic benefits from the Lancang-Mekong River, for example, agricultural and fishery development provided high economic returns to the downstream countries (Lu et al., 2021). Stage II (2004 ~ 2005) was characterised by unexpected hydrological changes due to the severe droughts. The changes in the hydrological systems of all riparian countries were beyond the agreement in Stage I, which led to increased conflict among riparian countries as the economic benefits from agriculture and fishery reduced significantly for downstream countries. Cooperative demand peaked for both upstream and downstream countries in 2005 (Wei et al., 2021). At Stage III (2006 ~ 2009), China agreed to provide hydrological information of the Lancang-Mekong River to improve understanding of changes in the upstream hydrological systems (Yorth, 2014). The volume of cargo trade from China to downstream also increased to provide additional economic benefits to the riparian countries.

Stage IV (2010 ~ 2016) was featured by rapid construction of dams, leading to changes in the hydrological and ecological systems. Upstream countries (i.e. China and Laos) had strong interests in hydropower development to increase their domestic economic benefits. China started to construct the Xiaowan dam in 2010 and the Nuozhadu dam in 2012. The downstream hydrological changes resulted from these upstream dam constructions included increase in dry season runoff and reduction of runoff peak in the flood season (Hoanh et al., 2010). Vietnam censured China for increasing salinization and degradation of the downstream ecological system (Youth et al., 2014). Severe droughts in 2015 and 2016 further reduced the economic benefits from fishery and agriculture of the downstream countries. The losses of fishery benefit were about USD 162 million in 2015. This aggravated concerns and criticisms of downstream countries against upstream countries. During Stage V (2017 ~ present), the impacts of ecological degradations from last stage were recognised by all riparian countries and the willingness to cooperate for most countries increased (Wei et al., 2021). China regarded the geopolitical values and diplomatic relations as an important international political benefit (Urban et al., 2018) in addition to economic benefits, therefore more willing to cooperate with other riparian countries (Lu et al., 2021). Major hydropower projects had been completed and several treaties and plans were signed towards cooperation (Wei et al., 2021).

4.3 The Nile River

The Nile River with an estimated length of 6800 km is one of the longest rivers in the world. It covers about 10.3% of the African continent and has a total population of about 250 million people. The river is shared by 11 countries. The stakes and interests of Egypt, Sudan and Ethiopia are classified as very high and those of Uganda, Tanzania, Kenya, Burundi and Rwanda, Eritrea, South Sudan and the Democratic Republic of Congo as low. The conflict and cooperation dynamics in the Nile River management demonstrated four stages.

At Stage I (1956 ~ 1989), Egypt and Sudan reached bilateral agreement in 1959 to divide the Nile water between the two countries with hydraulic infrastructure in place (refer to Agreement between the Republic of the Sudan and the United Arab Republic for the full utilization of the Nile waters). The exclusive rights to utilize the Nile waters enabled huge economic benefits and bonus of hydropower for Egypt (Allan, 1999), which largely impacted other countries' socio-economic developments due to their limited access and rights to use the water (Kameri-Mbote 2007). In addition, in 1973 and 1984-1985, major droughts stroke Ethiopia killing millions of people, which raised Ethiopia's awareness of its needs to develop the Nile waters (Gebrehiwot et al, 2011). In stage II (1989 ~ 1998), Ethiopia started to ask for transboundary cooperation and wanted to share the water of the Nile. Negotiation and lobbying were intensive but up until the end of 1990s, the willingness to cooperate remained elusive. This was because Egypt remained the most powerful riparian country capable of influencing the hydro-political interactions across the basin, while other countries exhibited weak capacity to change their status due to their limited capacity to exert power at both regional and international levels (Cascão, 2009; Cascão & Nicol, 2016).

At Stage III (1999 ~ 2010), new cooperation process initiated, which unfolded into two parallel tracks. The technical track, Nile Basin Initiative (NBI), started as a temporary initiative to manage transboundary issues; and the policy track to drive negotiation toward Cooperative Framework Agreement (CFA) (Cascão & Nicol, 2016). The riparian countries established new cooperative norms through joint activities under a Shared Vision Program (SVP) and two Subsidiary Action Programmes (SAPs), one for the Eastern Nile (ENSAP) and one for the Nile Equatorial Lakes respectively (NELSAP). ENSAP and NELSAP, through multiple projects promoted the joint identification and planning of hydraulic projects that would bring tangible benefits to these countries (Cascão & Nicol, 2016). Joint Multipurpose Project (JMP), started in 2005, reached the stalemate in 2009, while the upstream countries decided to sign the CFA in 2010. External financial support for the JMP decreased and Ethiopia realized that the direct economic benefits it gained from the projects were limited, regardless the growing economic needs between 2000 and 2010 in Ethiopia. At the same time the Arab Spring started in Egypt and signalled the decline of its political stability (which causes foreign investments in Egypt to further decline to zero). As a result of both indirect and unintended consequences, the multilateral cooperation failed. At Stage IV (2011 ~ present), Ethiopia stated its intention to construct the Grand Ethiopia Renaissance Dam (GERD). Sudan also recognized the benefits of the GERD and necessity of expanding irrigation due to the 2008 food crisis, making it more willing to cooperation for joint water management in the Nile. Sudan has now shifted from siding with Egypt to being more open to cooperation with Ethiopia. Agreement has been made for Sudan to buy electricity from Ethiopia once the dam is finished and to potentially gain water for irrigation.

It can be seen from the analysis above that the proposed social-hydrological framework can cover the evolutionary dynamics of conflict and cooperation in these transboundary rivers. The variables of the framework important to each case are summarized in Table 2.

Table 2. Site-specific characteristics of the three case rivers in application of the framework.

System component	Site-specific characteristics		
	The Columbia River	**The Lancang-Mekong River**	**The Nile River**
Water management	Water management: dam operation.	Development of dam storage and water management (dam operation).	Development of dam storage.
Benefits	Economic benefits: hydropower, flood control. Ecological benefits: protection of salmon.	Economic benefits: hydropower, flood control, irrigation, fishing. Ecological benefits: preventing from downstream salinization. International political benefit.	Economic benefits: irrigation and hydropower.
Cooperation	Existence of Treaty but it is due to renew in 2024.	No formal treaty or agreement exist for all riparian countries. Only with regional agreement and basin–wide cooperation initiative.	Existence of formal bilateral agreements, but all have stopped functioning.

Willingness to cooperation	Higher end of the range between [0, 1].	Largely varied across the range between [0, 1].	Lower end of the range between [0,1].
Social motives	Homogeneous with minor difference.	Highly varied due to different cultural background.	Homogeneous with little difference.
Power status	Almost equivalent.	Upstream countries with stronger socio-economic power.	Downstream countries with stronger socio-economic power.
Institutional capacity	Very high in both hard and soft institution in both countries.	Moderate level.	Very weak in all riparian countries.

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 Lancang-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. It should be noted that a formalized modelling of conflict and cooperation on the Lancang-Mekong River based on this social-hydrological framework has been developed which is also published in this special issue (Lu et al, 2021).

5 Conclusion

The social-hydrological framework proposed in this paper brings the slow and hidden societal processes into existing hydrological-economic models and establishes the feedbacks between societal and hydrological processes via benefit functions. It contributes to revealing the mechanism that drive conflict and cooperation and the development of socio-hydrology by improving representation and measurement of societal variables. Furthermore, this meta-theoretical framework can act as a platform for understanding potential knowledge gaps in integrating hydrology with multiple disciplines including ecology, economics, sociology, and political sciences regarding conflict and cooperation in transboundary rivers.

As demonstrated in the application of this framework in the Nile, Lancang-Mekong, and Columbia Rivers, this framework will provide a common language and consistent template for comparative analysis of conflict and cooperation dynamics in over 300 transboundary rivers globally. This analysis will assist in explanation of why conflict and cooperation are different in different transboundary rivers and identification of effective modes of cooperation for more sustainable transboundary rivers.

Data and code availability

Not applicable.

Author contribution

Y.Wei, D. Yu, J.Wei, M. Sivapalan, and F. Tian contributed to development of the conceptual framework. Y. Wei and G. Li contributed to literature review. D. Yu, J. Wei, and G. Li contributed to case study development, S. Wu significantly contributed to writing and rewriting of the manuscript, M.Ghoreishi, Y. Lu, and F. Souza contributed to reviewing of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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