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A socio-hydrological framework for understanding conflict and cooperation with respect to transboundary rivers

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Abstract. Increasing hydrological variability, accelerating population growth and urbanisation, and the resurgence of water resources development projects have all indicated increasing tension among the riparian countries of transboundary rivers. While a wide range of disciplines develop their understandings of conflict and cooperation in transboundary river basins, few process-based interdisciplinary approaches are available for investigating the mechanism of conflict and cooperation. This article aims to develop a meta-theoretical socio-hydrological framework that brings the slow and less visible societal processes into existing hydrological–economic models and enables observations of the change in the cooperation process and the societal processes underlying this change, thereby contributing to revealing the mechanism that drives conflict and cooperation. This framework can act as a "middle ground", providing a system of constituent disciplinary theories and models for developing formal models according to a specific problem or system under investigation. Its potential applicability is demonstrated in the Nile, Lancang–Mekong, and Columbia rivers.

1 Introduction

There are 286 rivers around the world that cross the boundaries of two or more countries. When reaping the benefits of a transboundary river is perceived as a zero-sum game (Baranyai, 2020), riparian countries often experience more tension 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, and climate change consequences (Milman and Gerlak, 2020; Nordås and Gleditsch, 2007; Rai et al., 2017; Munia et al., 2016). Increasing hydrological variability under climate change, accelerating population growth and urbanisation, and the resurgence of water resources development projects may exacerbate tension 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 the mechanism behind conflict and cooperation in transboundary river basins is by no means a sim-

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ple challenge. Various disciplines have examined the factors that can contribute to conflict and cooperation with respect to transboundary rivers and, in doing so, have covered a wide range of parameters (Zeitoun et al., 2013; Petersen-Perlman et al., 2017; Fischhendler, 2008; Ho, 2017). Studies from a hydrological perspective cover 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 and Ray, 2011), climate change (Gleditsch, 2012), and negative impacts on ecological or other issues (Schmeier, 2014). Studies from an economic perspective include commercial trade (Espey and Towfique, 2004; Tir and Ackerman, 2009; Dinar et al., 2015) and the economic development level (Priscoli and Wolf, 2008). There are also studies from a cultural perspective, such as the saliency of the river (Hensel et al., 2008), the peacefulness of riparian relationships (Brochmann and Gleditsch, 2012), the identity or national values (Allouche, 2004), the perceived exposure to unilateral overexploitation of the resource (Elhance, 1999), and engagement with professional communities (Kibaroglu, 2008), and from a political perspective, such as the level of democracy (Brochmann and Hensel, 2009), the existence of transboundary treaties (Brochmann, 2012; Wolf et al., 2003; Tir and Stinnett, 2012; Dinar et al., 2015), the relative power of riparian states (Mirumachi and Allan, 2007; Zeitoun et al., 2013), the behaviour of the regional hegemon (Zeitoun and Warner, 2006), the domestic political rivalry, the political leadership (Dinar, 2009; Subramanian et al., 2014), and the institutional resilience (De Stefano et al., 2012). While this wide range of factors implies the importance of a multidisciplinary understanding, to our best knowledge, few process-based interdisciplinary approaches are available for investigating the mechanism of conflict and cooperation with respect to transboundary rivers, which compromises transboundary river management.

Socio-hydrology observes and explains unintended consequences as emergent phenomena of coupled human–water systems (Sivapalan et al., 2012; Di Baldassarre et al., 2019; Yu et al., 2020). As water connects to every aspect of the social, economic, and biophysical dimensions of the coevolutionary human–water systems at the river basin or regional scale, socio-hydrology adopts a meta-theoretical approach that incorporates theories and models used by different constituent disciplines. It offers a conceptual framework that acts as a "middle ground" between the meta-level concepts/theories and specific models driven by a particular context. This paper aims to develop a socio-hydrological framework for understanding conflict and cooperation with respect to transboundary rivers. First, an overview of the existing literature on conflict and cooperation in transboundary river basins is provided, which offers the constituent disciplinary and empirical basis for developing such a conceptual framework. Finally, the proposed framework is applied to three transboundary rivers, the Columbia River, the Lancang–Mekong River, and the Nile River, to illustrate its potential applicability.

2 Overview of studies on conflict and cooperation with respect to transboundary rivers

2.1 Understandings from empirical and assessment studies

There are very rich empirical studies on conflict and cooperation in transboundary river management at global and local scales, and several global databases have been developed to aid in the assessment of these factors. The International Water Event Database (IWED; Wolf et al., 2003) documents global water events with respect to conflict and cooperation during the period from 1948 to 2008. The Transboundary Freshwater Dispute Database (TFDD) is a database specifically for global and regional assessment of water conflict and resolution processes (Munia et al., 2016). The Water-Related Intrastate Conflict and Cooperation (WARICC) dataset focuses on national water dispute events 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 categorises water conflict events based on the purpose of water control: 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 10 key aspects that facilitate collaborations between two or more countries (Baranyai, 2019; Strategic Foresight Group, 2015). Zeitoun and Mirumachi (2008) developed quantifiable, two-dimensional matrices (Zeitoun and Mirumachi, 2008) and then extend them in the form of the the Transboundary Water Interaction NexuS (TWINS), which focuses on the comparison of conflict and collaboration among different countries and how they evolve in time (Mirumachi and Allan, 2007). Wolf et al. (2003) developed a 15-point Basins at Risk (BAR) scale (Wolf et al., 2003) to classify and measure the extent of water conflict and cooperation. The Integrated Basin at Risk (iBAR) scale further includes inequalities and injustices in the consideration (Watson, 2015). Conca (2006) proposed the core normative elements for assessing transboundary governance: the equitable use principle, the 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 river basins at different temporal and spatial scales, and the assessment studies define and measure conflict and cooperation events with various sets of indicators. Although they provide rich descriptions of the phenomena of conflict and cooperation between riparian countries, these studies have limited abilities to reveal the cause–effect relationship or to predict future trends, mainly due to their limited link to process-based understanding of the phenomena.

2.2 Understandings from multiple disciplines

Hydrological studies have made major contributions to the understanding of conflict and cooperation in transboundary river basins. 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 river basins (De Stefano et al., 2017; Furlong et al., 2006; Nordås and Gleditsch, 2007). Hydrological models have been developed through integration with ecology, geomorphology, and other disciplines from natural sciences 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 agriculture, fisheries, energy production, navigation, and ecosystems in downstream countries. By analysing where, how, and when water can be possibly be harnessed and utilised, hydrological understanding forms the biophysical basis of transboundary river management (Newig and Rose, 2020).

Hydrological studies have been closely integrated with neoclassical economic models to simulate and explain human behaviours, focusing on tangible economic benefits and assuming that humans are rational actors with perfect information about all potential choices and their consequences (Schill et al., 2019). These hydro-economic models have been developed to assess the economic benefits of hydrological changes via dam storage and/or operation through a group of water production functions (Harou et al., 2009), with some functions specifically for simulating cooperation with respect to transboundary rivers (e.g. Espey and Towfique, 2004). Further relaxing the unbounded rationality of actors using behavioural economic models (Conlisk, 1996), Schill et al. (2019) recognised that whether people choose to cooperate or not, with respect to transboundary rivers, depends on one country's expectations regarding the absolute economic benefits, their benefits in previous periods as a reference level, relative gains compared with other countries, and intangible benefits (such as ecological, social, political, or diplomatic benefits). This led to integration with game theory, agent-based models, and system dynamic models to simulate conflict and cooperation with respect to transboundary rivers (Yu et al., 2019; Khan et al., 2017; Ding et al., 2016; Sehlke and Jacobson, 2005). However, criticisms of these models remain: there are constant difficulties in defining and differentiating social factors beyond their economic benefits. These models often minimise the social dimensions of cooperative behaviours by means of anonymous subjects, and they are unable to capture the diversity of human behaviours (Schlüter et al., 2017; Futehally, 2014; Ribes-Iñesta et al., 2006).

Institutional economics is another branch of economics study that focuses on the understanding of inter-organisational cooperation by assessing economic performance under different institutional contexts (Schmid, 2008). In transboundary river regions, institutional economics often collaborates with law to examine treaties and agreements to provide confidence and compliance for negotiation and to reduce the transaction costs of cooperation (Rees, 2010; Boin and Lodge, 2016; Saleth and Dinar, 2004). Some studies argue that institutional incapacity is the root cause of many water conflicts, where rapid changes in biophysical (e.g. unilateral development projects and unanticipated droughts or floods) and socio-economic (e.g. population growth and technological development) conditions have outpaced the institutional capacity to absorb these changes (Wolf et al., 2003). In broad natural resources management, Ostrom (2009) and studies stemming from the aforementioned work have developed a co-evolved social ecological system (SES) framework over the past 3 decades, which helps diagnose institutional misfits in regulating the interactions among resources, resource users, resource systems, and governance systems (Thiel et al., 2015). These studies provide a rich theoretical basis for understanding conflict and cooperation with respect to transboundary rivers from the institutional perspective; however, they have not been integrated into process-based hydrological models and, thus, have not been able to link the institutional incapacities or misfit influencing cooperation to the hydrological changes that they have resulted in.

Cognitive psychology and cultural sociology provide a rich understanding of cooperative behaviours from the perspective of social comparison, self-reflection, and a mental model of the future (Schlüter et al., 2017). Social psychologists recognise that people are fundamentally different regarding their social values and personality traits. These values and traits are the 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 and Stiglitz, 2016). Two opposing social value orientations are typically recognised: 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 if they do not (Bogaert et al., 2008). Schwartz (1992) and Howat (2021) identify 10 basic values of social motivation, including openness to change, conservation, self-transcendence, self-enhancement, conformity, and others, and they also discuss their relationships to each other. These theories imply that encouraging cooperative behaviour may require different approaches. Most studies on conflict and cooperation with respect to transboundary rivers from these disciplines are conceptual, focusing on the prominence of water, identity or national values, and perceived exposure to resource overexploitation (Baranyai, 2020; Brochmann and Gleditsch, 2012; Elhance, 1999), and they have also not been integrated into hydrological models; thus, we are yet to understand how values influence hydrological changes.

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 to understanding cooperative behaviours with respect to transboundary rivers (e.g. Giordano and Wolf, 2003; Munia et al., 2016). Politics is the study of power (Lasswell, 2003). Hydro-politics is one research field in which politics is applied in transboundary water management; this research field is characterised by hegemonic configurations in the form of geographical locations, and it argues that the most powerful riparian countries have an advantage over their weaker neighbours regarding water allocation for enforcing a cooperative agreement favourable to the more powerful countries (Mirumachi and 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 the cooperation and stability of water use (Milman and Gerlak, 2020). Cooperation in hydro-diplomacy is considered to be 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 (1992) and Howat (2021) 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 and 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.

In Table 1, we summarise the broad knowledge spectrum of understanding regarding conflict and cooperation in transboundary river basins. It is found that the current understanding sets limitations on the analytical capacity to reveal the mechanism that drives conflict and cooperation, but the information available provides a rich theoretical and empirical basis for developing a meta-theoretical socio-hydrological framework.

3 A socio-hydrological framework for understanding conflict and cooperation with respect to transboundary rivers

3.1 The framework concept

We develop a meta-theoretical framework that 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/specific problem to study the mechanism that drives conflict and cooperation with respect to transboundary rivers. We develop this framework based on the complex adaptive system theory, recent advances in 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 socio-hydrological framework (Elshafei et al., 2014), which argues that the human–water relationship should be considered as a co-evolved, complex adaptive system. Its collective behaviours emerge through its non-linearity, heterogeneity, multiple equilibrium states, and cross-scale dynamics (Norgaard et al., 2009).

Specifically, we consider transboundary rivers as complex adaptive systems comprising water management (hydrological), ecological, economic, cultural, institutional, and political subsystems in each riparian country (Fig. 1 demonstrates a case involving two riparian countries). These subsystems co-evolve, with each affecting the others in each riparian country over a long time frame. During the co-evolutionary processes, it is widely recognised that hydrological and economic variables are "fast" characteristics, which work at the scale of seconds to years, and that ecological and societal variables are relatively "slow" characteristics, which often work at the scale of decades to centuries (Sivapalan et al., 2012). The slow variables (subsystems) often show a pattern of "punctuated equilibrium", characterised by a long period of stasis that is interrupted by a more rapid change which disrupts the equilibrium (Gould and Eldredge, 1972). For example, the "cultural (societal value) lag" is well noted in the literature (Rosenschöld et al., 2014). It is often observed that the power status could sometimes not change for decades or even several thousands of years in ancient periods, but it can change suddenly via an elected political leader in modern times. It is the interaction of fast processes and slow processes that determine the system thresholds that, if crossed, cause the system to move into a new state (Sivapalan et al., 2012).

In this framework, cooperation (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 (Fig. 1). In typical hydro-economic models, cooperation is defined as a binary variable (0 or 1) to examine the evolutionary dynamics of cooperation (Espey and Towfique, 2004). This only involves the fast processes: change in water management con-

Table 1. Current disciplinary and empirical understandings of conflict and cooperation with respect to transboundary rivers.

	Contributions	Strengths and gaps
Empirical and assessment studies	Describe the phenomena of conflict and cooperation in real systems	Rich description and assessment in the context of hydrological change but have not been integrated with hydrological models
Hydrology and its integration with ecology and geomorphology	Simulate the biophysical consequences of conflict and the biophysical conditions of cooperation with respect to transboundary rivers	Well developed in this context
Neoclassical and behavioural economics	Assess the economic feasibility of cooperation	Economic models have been well integrated with hydrological models but they do not explain the rationality of cooperative behaviours
Institutional economics	Explains institutional factors of cooperative behaviours	Rich theoretical and empirical development but often integrated with hydrological models with a comprehensive index, resulting in the lack of an explicit link between hydrological changes and institutional incapacity or misfit
Cultural sociology and psychology	Explain social motives (values) of cooperative behaviours	Rich theoretical development but often integrated with hydrological models using an anonymous variable, resulting in the lack of an explicit link between hydrological changes and different social motives for cooperation
Political science	Explains international political factors of cooperative behaviours	Rich theoretical development in the context of hydrological change but has not been integrated with hydrological models

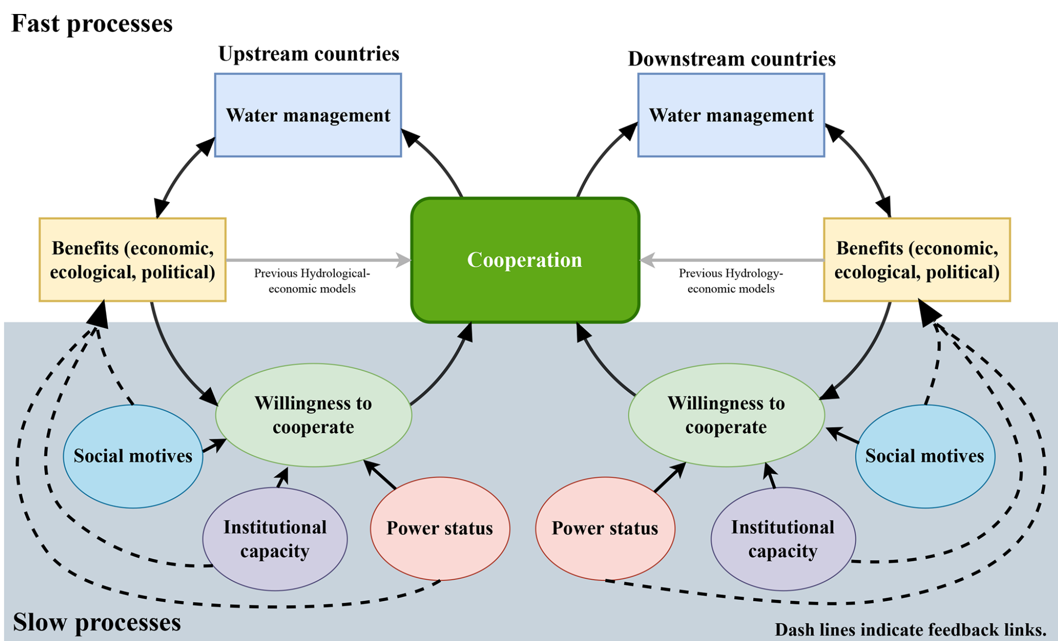

Figure 1. A socio-hydrological framework for understanding conflict and cooperation with respect to transboundary rivers.

ditions, change in the resultant benefits, and cooperation as a result of their interactive feedbacks (as indicated in the upper part of Fig. 1).

This framework extends the existing understanding of cooperation from integrated hydro-economic models to include the willingness to cooperate, which is a hidden variable representing the slow societal processes (as shown in the lower part of Fig. 1). We consider the willingness to cooperate as a continuous variable from two opposing ends (0–1), conceived as dynamic, iterative, and adaptive, thus it undergoes spirals and cycles (Patrick, 2014). It is a slow variable influenced by both fast processes and slow processes. On the one hand, it is directly influenced by the benefits that one country will potentially receive, including short-term and direct economic benefits, long-term ecological benefits, and indirect political benefits in international affairs. These benefits will be achieved through changes 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 a primary driver of the willingness to cooperate, and they also determine how a country perceives their benefits (i.e. the weighting that they exert on different kinds of benefits, such as economic, ecological, or political advantages). Institutional capacity, a path-dependent societal variable, indicates the adaptive capacity of a riparian country that can promote and maintain the cooperation. It includes the hard capacity (engineering/technology for water resources development) and the soft capacity (formal and informal regulatory processes and the organisations involved). In addition, both the geographical location (the spatially dependent level) and economic/political power impact the extent to which riparian countries are willing to cooperate. These societal variables are often slow factors that express the change in status with time and reflect the relational aspects with respect to specific countries. Furthermore, in this framework, it is recognised that a feedback exists between change in social motives, power status, and institutional capacity and change in economic, ecological, and political benefits, which are functions of changes in hydrology. This feedback reflects the co-evolutionary characteristics of transboundary rivers as a complex adaptive system.

It should be noted that changes in the willingness to cooperate occur in both domestic and international contexts. Beside the endogenous variables discussed above, the exogenous factors influencing conflict and cooperation in transboundary river basins include climate change, natural and human disasters, population growth, urbanisation, changes in sovereignty and national security, changes in the national boundary, and changes in bilateral or multilateral relations on a case-by-case basis. In addition, there are other types of cooperation between countries, such as cooperation in economic sectors, trading, science, and technology, which are considered as the exogenous factors in this framework.

3.2 Framework specification

To further bridge the framework concepts described above as a middle ground between the meta-level concepts and specific models with specific contexts, this section provides a general description and measures of each subsystem as well as the relationships between these subsystems, from which analysts can develop a set of variables and specify the relationships between these variables according to the specific problems or systems under investigation (Table 2).

It can be seen from Table 2 that the measurement of social motives (values) is a big challenge in this framework, as is also the case when developing socio-hydrological models (Di Baldassarre et al., 2019). The commonly adopted methods for measuring values (in the social motive context) are surveys, experiments, and in-depth interviews and participant observation. Surveys, which contain survey items that participants are asked to rate along a nine-point (or less) scale, are an important part of the methodological repertoire for research on values. However, these measures may be subject to measurement error due to the discrepancy between how people respond to surveys and how they actually behave (Schwartz, 1992). The experimental approach, such as examining cooperation in games, is powerful, as it measures actual behaviours, but it has less external validity and is more difficult to generalise (how well the results can be generalised to situations outside of the experiment and how well the subjects in the experiment represent the general population) (McClintock, 1978). In-depth interviews and participant observation have the advantage of uncovering how people articulate their values, rather than asking them to react to survey items, but this approach is labour-intensive and also difficult to generalise across studies (Dietz et al., 2005). In addition, all of these methods are often cross-sectional in time or only reflect the change in values over a short time frame; thus, they cannot meet the longitudinal (decades or longer) requirement for simulating complex adaptive systems. Recently, the importance of discourse in changing values has been emphasised, as communication with other individuals shapes and reshapes the emphasis that we place on values (Habermas, 1991). 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 and 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 that is rooted in a context–mechanism–outcome configuration and allows for triangulation by multiple data sources (Pawson and Tilley, 1997; Wei et al., 2018; Newig and Rose, 2020; Olsen, 2004). With this approach, we have tracked the evolution of the societal value placed on water using media data under different research contexts (Wei et al., 2017; Xiong et al., 2016; Wu et al., 2018). In transboundary river regions, we quantitatively tracked the societal values regarding the conflict and cooperation of the riparian countries in the Lancing-Mekong River during the period from 1991 to 2018, which is published in the same issue (J. Wei et al., 2021). There are multiple relationships between these subsystems, which are outlined in Table 2. As described in Sect. 2, there are well-developed integrated hydrology–ecology–geomorphology models and hydro-economic models. The general guidelines for developing the socio-hydrological models and mathematically specifying the fast and slow processes have been well developed in the literature (e.g. Elshafei et al., 2014, 2015; Sivapalan and Blöschl, 2015).

Table 2. The description and measures of each subsystem in the framework concept.

Subsystem	General description	Measure
Water management	– Water supply (dam storage) and water management (dam operation) – Water demands	– Water supply is directly obtained from hydrological gauge stations or simulation. – Water demand varies from sector to sector and is directly obtained from the water bureaus.
Benefits	– Economic benefits include hydropower generation, flood control, irrigation, fishing, and others. – Ecological benefits include those for the catchment, stream, and floodplains. – International political benefit could be the reputation of a country in the world.	– These benefits are functions of their water uses. – These functions should be derived based on the respective disciplines: neoclassical economics, eco-hydrology, and international politics (as described in Sect. 2).
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 continuous variable reflecting the dynamic process of cooperation	- A continuous variable between 0 and 1 that is a function of benefits, social motives, power status, and institutional capacity – The "Cooperation" variable switches from 0 to 1 when the "Willingness to cooperate" variable reaches 1.
Social motives	– Value reflection of different countries with respect to cooperation; there are different types of motives for cooperation.	– Measured as an index from 0–1 to reflect the social motives on cooperation from weak to strong. This measure should be designed based on cognitive psychology and cultural sociology (as described in Sect. 2).
Institutional capacity	– Variables reflecting the adaptive capacity of each riparian country to absorb systems changes; they can be classified into hard capacity and soft capacity.	– Various indicator-based approaches and datasets have been developed to assess the institutional capacity (as described in Sect. 2). Selection of these approaches and datasets should be based on institutional economics (as also described in Sect. 2).
Power status	– Variables expressing the socio-economic ranking of a country in the world and the geographical location (the spatially dependent level) of this country in a transboundary river.	– Measured as an index from 0 to 1 to reflect the socio-economic development level of a riparian 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 the global socio-economic development index and power are available. Both the direct assessment and selection of available datasets should be based on politics (as described in Sect. 2).

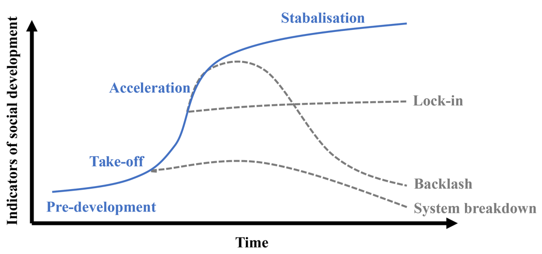

Figure 2. Stages and possible pathways of the development of a societal system (adopted from Rotmans et al., 2001, and Rotmans, 2005).

An important relationship that needs to be developed is that between the willingness to cooperate and three societal variables: social motives (values), institutional capacity, and power status. It is widely recognised that many societal changes are gradual processes in time following a sigmoid function (S-shaped curve) (e.g. Choi et al., 2015; Ghanbarnejad et al., 2014). We adopted the transition theory on societal evolution by Rotmans et al. (2001) and Rotmans (2005) (Fig. 2), which identifies a predevelopment phase, during which the current status quo remains for the system; a take-off phase, during which the process of change becomes visible as the state of the system begins to shift; an acceleration phase, during which visible structural changes occur relatively rapidly; and a stabilisation phase, during which the societal system change stabilises. Societal transitions can fail in any of these phases, as indicated by a backlash or a lock-in situation, and the whole system may even collapse when uncertainties and risks of chaos are too high.

Thus, we can consider the temporal development of each of social motive, institutional capacity, and power status in the form of a sigmoidal function (Hofbauer and Sigmund, 2003) as follows:

$$S_i(t) = a + \frac{k}{1+e^{-t}}, \tag{1}$$

where $S_i(t)$ is the societal dynamics at time t, i represents the social motive, institutional capacity, and power status, a and k are the constant values representing the respective scale and rates of development in time, and e is the Euler number.

It is obvious that the stronger the social motive and institutional capacity for cooperation, the higher the willingness to cooperate. However, a stronger power status can have positive or negative influences on the willingness to cooperate, depending on the direction of social motive. For example, China 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 conceptual function between the willingness to cooperate and the three societal variables can be written as follows:

$$\text{Willingness to cooperate}(t) = f\, S_{\text{social motives}}(t)^{g\left[S_{\text{institutional capacity}}(t),\, S_{\text{power status}}(t)\right]}, \tag{2}$$

where f is a power function chosen to consider social motive as the primary driver (i.e. base of the power function) for cooperation in comparison with institutional capacity and power status, and g is the index function reflecting the parallel importance of institutional capacity and power status to the willingness to cooperate. However, we suggest that the relations between these variables in different case studies should be investigated based on the types variable dynamics and the existing qualitative and descriptive understandings of the interactions among these variables in the context of the social sciences, as described in Sect. 2 (Sterman, 2001; Pentland, 2015). With enough understanding from the inductive perspective, more theoretical formulations can be established.

Following this, these societal variables need to be calibrated using societal data. The fact 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) is recognised as a weakness in existing socio-hydrological models. There are many existing societal data available for model calibration, including global databases and indicator-based assessments of conflict and cooperation (as discussed in Sect. 2), with the datasets also reflecting the global socio-economic development index, power, and reputation (Treverton and Jones, 2005). Finally, model uncertainty should be noted, as the transboundary river is a complex adaptive system characterised 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 socio-hydrological model, but projections of possible future trends may be useful to inform future transboundary river management (Srinivasan et al., 2017).

4 Applicability of the proposed framework in three case studies of 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 (Fig. 3). We will firstly narrate the evolutionary dynamics of conflict and cooperation in these transboundary rivers according to their development stages; we will then use Fig. 2 and Table 2 to identify the key subsystems from the narratives of each case river in order to see if the framework can grasp the core dynamics of conflict and cooperation in these transboundary rivers.

4.1 Narratives

4.1.1 The Columbia River

The Columbia River starts in British Columbia (BC) and has a basin that extends 670 807 km^2. The basin covers seven US 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 a 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.

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

In Stage II (early 1960s–early 1990s), joint studies began after the 1948 flood event to explore possible storage sites in Canada and analyse the benefits of sharing the river between the countries. It was concluded that the benefits of

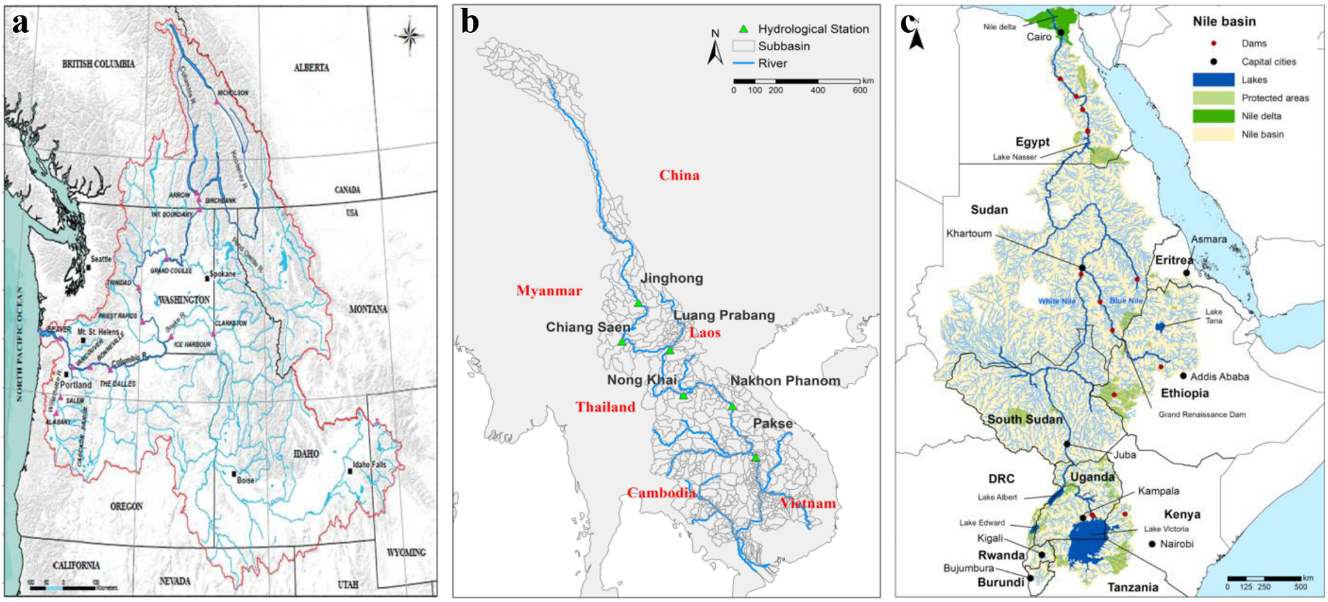

Figure 3. The case study examples, **(a)** Columbia River (Jay and Naik, 2011), **(b)** Lancang–Mekong River (Lu et al., 2021), **(c)** Nile River (Allan et al., 2019), used in this paper.

cooperation were 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 US paid Canada USD 64.4 million to rent 8.45 million acre-feet (1.04×10^{12} L) 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 US side. Canadian dams must be operated to lower reservoir levels and provide storage space during spring and summer in order to capture water upstream and prevent flooding. In addition, the US pays Canada 50 % of the projected US power benefit generated by Canadian storage, also known as the "Canadian Entitlement", for the expected avoidance of flood damage through 2024. In exchange, the controlled release of these dams provided an opportunity for more efficient hydropower production in the downstream region due to more predictable and flexible flows. The cooperation through the treaty has been used as a pinnacle for international cooperation on non-navigational water uses.

In 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 has increased the value at risk. Moreover, 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 in order 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 the water temperature, and increase the 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 utilise water that could otherwise be used to produce hydropower. At the same time, the US continues to pay the same Canadian Entitlement agreed upon in the treaty, which has created the perception of decreased hydropower benefit on the US side. The US entity estimated that the value of Canadian storage and downstream power value should be around USD 26 million in electricity (about 1/10 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 Canadian Entitlement (e.g. additional benefits of navigation, recreation, irrigation, and fisheries) and that additional costs should be borne by the US. These different arguments from Canada and the US will be the basis for renegotiations on cooperation beyond 2024.

4.1.2 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 Southeast Asia and is home to a population of over 60 million people. 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 population lives in rural areas, and the population's livelihoods and food supply are highly dependent on the river system (FAO, 2011). Conflict and cooperation in the Lancang–Mekong Basin has mainly evolved around the construction of large dams and water distributions (De Stefano et al., 2017; J. Wei et al., 2021), which is demonstrated using five stages from 1999 to 2018 (Lu et al., 2021 and J. Wei et al., 2021).

Stage I (1999–2003) was characterised by limited conflict in the basin due to the 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 was signed by all (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 decreased significantly for downstream countries. Cooperative demand peaked for both upstream and downstream countries in 2005 (J. Wei et al., 2021).

In Stage III (2006–2009), China agreed to provide hydrological information on the Lancang–Mekong River to improve the understanding of changes in the upstream hydrological systems (Yorth, 2014). The volume of cargo trade from China to the downstream region also increased in order to provide additional economic benefits to the riparian countries.

Stage IV (2010–2016) was featured by the 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 that resulted from these upstream dam constructions included an increase in dry-season runoff and a reduction in the runoff peak during the flood season (Hoanh et al., 2010). Vietnam censured China for increasing salinisation and degrading the downstream ecological system (Yorth, 2014). Severe droughts in 2015 and 2016 further reduced the economic benefits from fishery and agriculture for the downstream countries. The losses suffered with respect to fishery totalled about USD 162 million in 2015. This aggravated the concerns and criticisms of downstream countries against upstream countries.

During Stage V (2017–present), the impacts of ecological degradations from the last stage were recognised by all riparian countries, and the willingness to cooperate increased for most countries (J. 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, it was 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 (J. Wei et al., 2021).

4.1.3 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 are classified as low. The conflict and cooperation dynamics with respect to the Nile River management is demonstrated using four stages.

In Stage I (1956–1989), Egypt and Sudan reached a bilateral agreement in 1959 to divide the Nile water between the two countries with hydraulic infrastructure in place. The exclusive rights to utilise the Nile waters provided huge economic benefits and the bonus of hydropower for Egypt (Allan, 1999), which largely impacted other countries' socio-economic development due to their limited access and rights to use the water (Kameri-Mbote, 2007). In addition, in 1973 and 1984–1985, major droughts struck Ethiopia killing millions of people; this 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 the willingness to cooperate remained elusive up until the end of 1990s. This was because Egypt remained the most powerful riparian country capable of influencing the hydro-political interactions across the basin, whereas other countries exhibited a weak capacity to change their status due to their limited ability to exert power at both the regional and international levels (Cascão, 2009; Cascão and Nicol, 2016).

In Stage III (1999–2010), a new cooperation process was initiated that unfolded into two parallel tracks: (1) the technical track, the Nile Basin Initiative (NBI), started as a temporary initiative to manage transboundary issues; and (2) the policy track aimed to drive negotiation toward the Cooperative Framework Agreement (CFA) (Cascão and Nicol,

Table 3. Key subsystems of the three river case studies identified based on the framework.

Subsystem	Case-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 and flood control – Ecological benefits: protection of salmon	– Economic benefits: hydropower, flood control, irrigation, and fishing – Ecological benefits: preventing downstream salinisation – International political benefit	– Economic benefits: irrigation and hydropower
Cooperation	– Existence of treaty, but it is due for renewal in 2024	– No formal treaty or agreement 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 cooperate	– Higher end of the range between 0 and 1	– Largely varied across the range between 0 and 1	– Lower end of the range between 0 and 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

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 (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 and Nicol, 2016). The Joint Multipurpose Project (JMP), which started in 2005, reached a stalemate in 2009, while the upstream countries decided to sign the CFA in 2010. External financial support for the JMP decreased, and Ethiopia realised that the direct economic benefits that it gained from the projects were limited, despite the growing economic need in Ethiopia between 2000 and 2010. At the same time, the Arab Spring started in Egypt and signalled the decline of its political stability (which caused foreign investments in Egypt to further decline to zero). As a result of both indirect and unintended consequences, the multilateral cooperation failed.

In Stage IV (2011–present), Ethiopia stated its intention to construct the Grand Ethiopia Renaissance Dam (GERD). Sudan also recognised the benefits of the GERD and the necessity to expand irrigation due to the 2008 food crisis, making it more willing to cooperation on joint water management in the Nile. Sudan has now shifted from siding with Egypt to being more open to cooperation with Ethiopia. An agreement has been reached for Sudan to buy electricity from Ethiopia once the dam is finished and to potentially gain water for irrigation.

4.2 Key subsystems in the evolutionary dynamics of conflict and cooperation of each case river

The key subsystems identified from the narratives in Sect. 4.1 are summarised in Table 3. It is shown that, to date, the Columbia River provides a successful case study of cooperation with respect to a transboundary river, although changes in the benefit distributions between the riparian countries have emerged, which requires further negotiation to ensure continued cooperation. Sharing the same societal values, appreciating each country's power and rights, and strong institutional capacities (both hard and soft) are major drivers of success. The Lancang–Mekong River provides a complex case of conflict and cooperation among six countries with their respective benefits as well as their diverse cultural and international political backgrounds. This case demonstrates that the inclusion of economic, ecological, and international political benefits is crucial to understand conflict and cooperation dynamics while recognising the different institutional capacities in different countries. The Nile River provides an unsuccessful case study in which unstable institutional capacities and unfavourable asymmetric power distributions were the root cause of strong conflict and weak cooperation. Therefore, the framework presented in this study can identify key changes in the subsystems that drive conflict and cooperation with respect to transboundary rivers.

This preliminary application will provide a narrative basis for developing formalised socio-hydrological models in each specific case. A formalised modelling of conflict and cooperation on the Lancang–Mekong River based on this socio-hydrological framework has been developed by most authors of this paper and is published in this special issue (Lu et al., 2021).

5 Conclusion

This paper developed a meta-theoretical socio-hydrological framework for understanding conflict and cooperation in transboundary river regions. It incorporates the slow and hidden societal processes into existing hydro-economic models, establishes the feedbacks between societal and hydrological processes via benefit functions, and enables observations of changes in the cooperation process and the societal processes underlying them, thereby contributing to revealing the mechanism that drives conflict and cooperation. This meta-theoretical framework can act as a middle ground, providing a system of constituent disciplinary theories and models from which analysts can develop a set of variables and specify the relationships between these variables to formulate models according to a specific problem or system under investigation. It can also act as a platform to incorporate advanced understanding from multiple disciplines including ecology, economics, sociology, and political sciences for better understanding and evaluation of conflict and cooperation in transboundary river basins.

As demonstrated in the narrative 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 almost 300 transboundary rivers globally. This analysis will assist in explaining why conflict and cooperation are different in different transboundary river basins and in identifying effective modes of cooperation for more sustainable transboundary rivers.

Data availability. No data sets were used in this article.

Author contributions. YW, DY, JW, MS, and FT contributed to the development of the conceptual framework. YW and GL were responsible for the literature review. DY, JW, and GL developed the case study. SW significantly contributed to writing and rewriting the manuscript, and MG, YL, and FS reviewed it.

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