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*Evolutionary cooperation in transboundary river basins*

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# Water Resources Research

## RESEARCH ARTICLE

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### Key Points:

- The long-term evolution of cooperation in transboundary river basins is analyzed using an infinitely repeated game
- An all-cooperation strategy can lead to a Nash equilibrium of the transboundary game under effective cooperative mechanisms
- The evolutionary transition of transboundary river basins from conflict to cooperation can be classified into four stages

### Correspondence to:

J. Zhao,  
zhaojianshi@tsinghua.edu.cn

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## Evolutionary Cooperation in Transboundary River Basins

Yang Yu<sup>1,2</sup> , Pingzhong Tang<sup>3</sup>, Jianshi Zhao<sup>1</sup> , Bo Liu<sup>1,4</sup>, and Dennis McLaughlin<sup>2</sup> 

<sup>1</sup>State Key Laboratory of Hydrosience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing, China, <sup>2</sup>Parsons Laboratory, Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, Cambridge, MA, USA, <sup>3</sup>Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, China, <sup>4</sup>International Economic and Technical Cooperation and Exchange Center, Ministry of Water Resources of China, Beijing, China

**Abstract** Cooperation in transboundary river basins can make water resources systems more efficient and benefit riparian stakeholders. However, in a basin with upstream and downstream stakeholders that have different interests, noncooperative outcomes have often been observed. These can be described by a one-shot prisoners' dilemma game where noncooperation (defection) is a dominant equilibrium strategy. However, cooperative outcomes have also been observed in several transboundary settings, such as the Lancang-Mekong River Basin in Asia. Such cooperation motivates our research effort to refine relevant game theoretic descriptions to account for the evolution of players' behaviors, from conflict to cooperation. In this study, a repeated game model is proposed to analyze evolutionary transboundary cooperation. A generalized evolutionary cooperation pattern with four stages is summarized, starting with noncooperation and ending with in-depth cooperation. The Lancang-Mekong River Basin and three other typical transboundary river management case studies are chosen to validate our theoretical findings. Upstream and downstream stakeholder behaviors are analyzed for these case studies, in accordance with a game payoff matrix that accounts for incentives to cooperate. The results indicate that patience and incremental benefits can lead stakeholders to adopt a cooperative equilibrium strategy if appropriate institutional mechanisms are in place. Such mechanisms can be developed through negotiations that recognize the wide range of stakeholder interests that may influence the decision to cooperate. Our analysis suggests that game theory can provide useful insights into the conditions and institutional mechanisms that foster cooperative strategies for managing transboundary water resources.

### 1. Introduction

Transboundary river basins are crucial for the global economy and environment, covering over 45% of the Earth's land surface and accounting for 60% of global freshwater resources (Wolf et al., 1999). The most important feature of a transboundary river is that multiple riparian stakeholders share common water resources. These riparian stakeholders may place different demands on a transboundary river that can both create conflicts and provide opportunities for cooperation (Dinar et al., 2019). It is important to understand what factors motivate stakeholders to evolve from conflict to cooperation, especially in a way that increases the benefits for each stakeholder. Here we refer to this process as evolutionary cooperation. Institutional mechanisms play an important role in facilitating such cooperation. The design of cooperative mechanisms often needs a reasonable benefits-sharing scheme to ensure that every stakeholder can get better off in cooperation (De Bruyne & Fischhendler, 2013; Yu et al., 2019), which involves the game of various riparian stakeholders. Thus, understanding the strategies and behaviors of riparian stakeholders in the game is crucial to cooperative mechanism and institution design. This has been a critical challenge in transboundary water management and will become even more important in the future, as pressures on limited water resources continue to increase in transboundary river basins (Earle, 2013; Wolf, 2007).

The challenge of analyzing and achieving evolutionary cooperation is complicated by the diversity of riparian stakeholders, who may have different hydrological, historical, political, and cultural interests. The differing geographic locations and socioeconomic development levels of riparian stakeholders lead to different demands for water resources, which means their goals of river basin development may be inconsistent or even contradictory (Sadoff & Grey, 2002). Additionally, a loss of trust or the overuse of water resources can aggravate potential conflicts, leading to strategic counter-speculations over possible

transboundary river management outcomes. All of these complications make analyzing evolutionary cooperation difficult.

However, it is still possible to explore patterns of evolutionary cooperation by analyzing successful cooperative cases that have been observed in the real world. In some cases, such as the Lancang-Mekong River Basin (LMRB), there is evidence of a gradual evolution from noncooperation to cooperation. After the Second World War, there were constant conflicts in the development of the LMRB because of competing uses of water resources. However, a few cooperative institutions emerged to provide mechanisms for resolving conflicts, including the Mekong River Commission (MRC), Greater Mekong Regional Cooperation, and Lancang-Mekong Cooperation (Mekong River Commission (MRC), 1995; Greater Mekong Subregion, 2012; Lancang-Mekong Cooperation, 2017). These institutions pursued possible solution paths toward transboundary cooperation instead of conflict. A compelling event recently occurred in the LMRB in spring 2016, in which transboundary stakeholders chose to put aside their conflicts and cooperate after a severe drought occurred in the Mekong Basin (MRC, 2016a). China alleviated the crisis by releasing emergency water from its cascade reservoirs in the Lancang River to provide much needed supplemental irrigation water for the Mekong Delta. In return, the downstream countries agreed to support certain Chinese regional interests. Such cooperation among riparian stakeholders can bring about incremental benefits for multiple stakeholders (Sadoff & Grey, 2002). The long-term evolution toward cooperation that has occurred in the LMRB indicates a possible template for resolving conflicts in transboundary river basins.

Game theory, as a mathematical tool for strategic action analysis, can provide useful tools for studying stakeholder behaviors in transboundary river basins (Madani, 2010; Madani & Hooshyar, 2014; Read et al., 2014). Both noncooperative and cooperative game theory are relevant to particular water resources management problems. The basic concepts of noncooperative game theory describe individual optimal decision making and the Nash equilibrium (Nash, 1951). Relevant applications of noncooperative game theory to river basin management include the analysis of economic conflicts in the lower Mekong basin (Dufournaud, 1982), the Colorado River and Rio Grande River case along the US-Mexico border (Frisvold & Caswell, 2000), the Jordan River Basin case (Madani & Hipel, 2007), the case study of the Kura-Araks Basin (Khachatryan & Schoengold, 2019), and public goods management (Ristić & Madani, 2019). Cooperative game theory has been used to examine the allocation of benefits gained from cooperation (Madani & Hooshyar, 2014; Kilgour & Dinar, 2001; Kucukmehmetoglu & Guldmann, 2004; Wu & Whittington, 2006; Teasley & McKinney, 2011) as well as related issues such as the development of water negotiations and institutions (Frisvold & Caswell, 2000), wastewater emissions by riparian countries into a shared river (Fernandez, 2002; Fernandez, 2009), international fisheries agreements (Pintassilgo et al., 2015), and the allocation of ecosystem services (Fu et al., 2018). In particular, game theory has become an important tool for studying the LMRB, including the distribution of interests after the cooperation of Mekong countries (Liao & Hannam, 2013), the design of Mekong cooperation institutions (Douven et al., 2014), and the game of Mekong hydropower projects (Bhagabati et al., 2014). However, none of these studies specifically examined the factors that caused riparian stakeholders to transition from noncooperation to cooperation. There is a clear gap in water resources game theory literature between the analysis of purely noncooperative and purely cooperative behaviors. In between lies the important case of evolutionary cooperation, where players' behaviors gradually change from noncooperative to cooperative as they agree on mutually beneficial management strategies.

This paper aims to describe a new analytical framework for understanding evolutionary cooperation in transboundary river basins, based on an extension of classical game theory methods. The theoretical formulation relies on a general transboundary river game matrix describing stakeholder payoffs, which leads to an integrated model for transboundary river decisions that relies on concepts from a repeated game theory method. The LMRB is selected as a detailed case study of the model's capabilities. Additionally, policy implications are examined for three other transboundary river basins. The paper concludes with a summary of important insights provided by the game-theoretic approach.

## 2. Transboundary River Game Model

Analyzing decision making for transboundary river planning requires describing stakeholders' interests, infrastructure development, and decision options that are likely to change over time. Game theory

		Stakeholder 2	
		C	D
Stakeholder 1	C	$V_1^* + c, V_2^* - c$	$V_1^*, V_2^*$
	D	$V_1 + c, V_2 - c$	$V_1, V_2$

Figure 1. Payoff matrix for the generalized transboundary river game.

provides a quantitative theoretic foundation for incorporating these considerations. In this study, focus is given on decisions that evolve according to the rules of a repeated game. This perspective is critical for identifying cooperative strategies in dynamic environments, with multiple stakeholders who iteratively explore alternative strategies. Our game-theoretic analysis of transboundary river basin management has four components: (1) the identification of representative stakeholder groups, (2) the formulation of a stakeholder payoff matrix for a generalized one-shot static transboundary river game, (3) the formulation and evaluation of an associated repeated game that describes the evolution of stakeholder decisions over time, and (4) a description of the cooperative strategies derived from the repeated game. These components are described in more detail in the following sections.

(1) the identification of representative stakeholder groups, (2) the formulation of a stakeholder payoff matrix for a generalized one-shot static transboundary river game, (3) the formulation and evaluation of an associated repeated game that describes the evolution of stakeholder decisions over time, and (4) a description of the cooperative strategies derived from the repeated game. These components are described in more detail in the following sections.

### 2.1. Stakeholder Identification

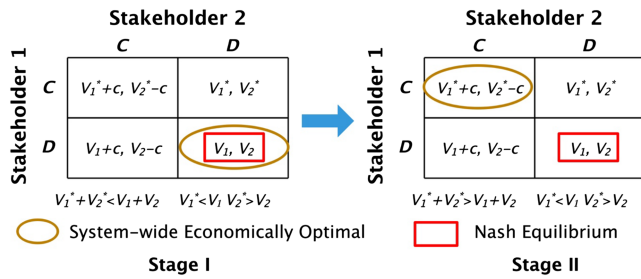
To simplify the complicated relationships among riparian countries in a transboundary river system using game theory models, stakeholders are divided into two generic groups. The first group ( $S_1$ ) is composed of stakeholders whose decisions would directly affect the overall benefits of the total river system. Group  $S_1$  could, for example, build and control upstream water resources facilities affecting the water available to other stakeholders. The second group ( $S_2$ ) is composed of stakeholders whose decisions are affected by the actions of group  $S_1$ . Group  $S_2$  could, for example, use water released by  $S_1$  to irrigate crops. It is assumed that (1) stakeholders are entirely rational; (2) the transboundary river game is based on current natural conditions, without considering changes to natural factors such as climate; (3) the impact of hydrological variation on stakeholders' benefits can be negligible when stakeholders evaluate their total payoffs in long-term games; (4) infrastructure development and cooperation can yield incremental benefits at the system level, which means the overall system-wide benefits of cooperative water use are greater than those of noncooperative water use (note that this assumption may not hold true for some river basins with severe water shortages); and (5) reservoirs are controlled and operated only by  $S_1$ .

It is important to note that the stakeholder groups (players) in our game formulation may have symmetric or asymmetric roles, depending on the decisions considered. However, the analysis considered here only distinguishes between decisions to cooperate and decisions to defect (i.e., not cooperate), which are equally available to all players. Differences in player access to infrastructure lead to differences in the way stakeholders cooperate, but not in their freedom to decide whether or not to cooperate. Thus, the player roles considered here are asymmetric, and Nash equilibrium concepts apply (Basar & Oldser, 1999).

### 2.2. Generalized One-Shot Transboundary River Game

Considering two representative stakeholder groups or players, a game that describes possible player decisions is proposed. Suppose that each player has two possible actions, defect ( $D$ ) or cooperate ( $C$ ). The payoff matrix for the associated game is shown in Figure 1. Here  $V_1^*$  and  $V_2^*$  are the direct benefits (utilities) from the river basin system that  $S_1$  and  $S_2$  could receive when  $S_1$  and  $S_2$  cooperate, respectively.  $V_1$  and  $V_2$  are the benefits that  $S_1$  and  $S_2$  could receive in the absence of cooperation (all-defect). It is possible that  $V_i^* < V_i$  or  $V_i^* > V_i$  (for  $i = 1, 2$ ), because cooperation may reduce one of the players' direct utilities while increasing the other's. For example, if  $S_1$  cooperates by releasing additional water needed by  $S_2$  at a time that reduces overall hydropower benefits to  $S_1$ , then  $V_1^* < V_1$ . However,  $V_2^* > V_2$ , because  $S_2$  will benefit from the additional water received.

To make cooperation feasible in such cases,  $S_1$  could seek a contract with  $S_2$  that provides compensation  $c$ . This compensation may consist of intangible benefits that go beyond the amount or economic value of extra water released or other actions of  $S_1$  that are deemed to be cooperative. An example might be compensation in terms of diplomatic support or indirect monetary compensation, such as increased trade. If  $S_2$  cooperates by agreeing to this contract, compensation  $c$  increases benefits to  $S_1$  while decreasing benefits to  $S_2$  under the strategy ( $C, C$ ) where both players cooperate. If  $S_2$  defects, then the utilities received by  $S_1$  and  $S_2$  are  $V_1^*$  and  $V_2^*$ . Similar reasoning applies to the entries in the second row of the payoff matrix, which describe the outcomes after  $S_1$  defects.



**Figure 2.** The payoff for players in a transboundary river game during two development stages, stage I and stage II. The blue arrow indicates that stage I could transition to stage II if infrastructure increases total utility.

It is assumed that for  $S_1$  to increase the utility of  $S_2$  (so  $V_2^* > V_2$ ), the utility of  $S_1$  must decrease (so  $V_1^* < V_1$ ) as in the above reservoir release example. Given this assumption, two game outcomes can be determined. If the overall result of cooperation does not increase total utility summed over both players, then  $V_1^* + V_2^* < V_1 + V_2$ , and cooperation will not produce the incremental system-wide benefits needed to support the compensation option. This time period, when available infrastructure does not allow  $S_1$  to increase total utility, is defined as stage I. Stage I could, for example, describe a situation in which there is no upstream reservoir storage. If or when either upstream or downstream development provides an increase in total utility, then  $V_1^* + V_2^* > V_1 + V_2$ . This time period is defined as stage II. Payoff matrices for these two development stages are

shown in Figure 2. In both stages I and II, the (D, D) strategy is a Nash equilibrium, because neither player can improve on action D, while the other decides D. In stage II, the joint decision (C, C) produces higher total utility than does (D, D), but it is not a Nash equilibrium (Hui et al., 2016). The stage II game is an example of a prisoner’s dilemma (Nowak & Sigmund, 1993).

The stage II game is a prisoner’s dilemma because both players can do better than (D, D) if they agree to cooperate by choosing (C, C), even though (C, C) is not an equilibrium solution (and is therefore vulnerable to instability, because either player can benefit by unilaterally defecting). On the other hand, the (D, D) solution in the stage I game is both a Nash equilibrium and a system-wide optimum, so it tends to persist even when new infrastructure makes (C, C) a new system-wide optimum (Hui et al., 2016). Generally, conflicting interests and inertia in a transboundary river basin management setting tend to perpetuate solutions that may be appropriate in the early stages of development, but become suboptimal when conditions change as a result of new development. A change in conditions that could prompt cooperation is expressed quantitatively by the utility inequalities, which change from  $V_1^* + V_2^* < V_1 + V_2$  in stage I to  $V_1^* + V_2^* > V_1 + V_2$  in stage II. Although this switch in inequalities may not happen immediately, it becomes more likely to occur as basin development expands and the possibilities increase for more efficient resource allocation between  $S_1$  and  $S_2$ .

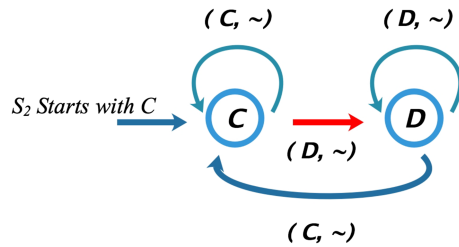
The prisoner’s dilemma game illustrated in stage II of Figure 2 reveals the potential benefits to be gained from cooperation. Not surprisingly, real-world cooperation has occurred between upstream and downstream river basin stakeholders, including in the cases mentioned in section 1 and discussed further in section 2.3. In the context of Figure 2, this outcome requires a strategic decision mechanism that promotes cooperation in the next stage of a repeated game, so that cooperation becomes a self-enforcing and reliable choice for both players.

### 2.3. Repeated game for long-term cooperation

The game represented by the payoff matrix in Figure 1 may be repeated many times by the same players during the long-term development of transboundary basins. During these repetitions (or iterations), the values of the variables are likely to change to reflect the consequences of infrastructure development, as well as changes in commodity prices, resource availability, and other economic and political factors. Repetitions of the game move through various development-related stages, such as stages I and II (described in the previous section), as direct benefits, compensation, and other factors involve.

In our formulation, stage I represents the point at which development is inadequate and incremental benefits are insufficient to provide cooperation opportunities. In this case, (D, D) represents a stable equilibrium solution. Stage II represents the point at which cooperation can increase benefits for all players. However, this stage starts with both players in the suboptimal (D, D) “all-defect” Nash equilibrium position. How can players move from this equilibrium to the optimal situation (C, C) achieved through cooperation, assuming that in each iteration, each player has perfect information about the decisions and payoffs in all previous iterations? That seems possible, because each player knows that (C, C) creates more benefits than does (D, D), because they know that the inequality conditions needed to achieve stage II (C, C) payoffs are satisfied.

To facilitate analysis, the concept of automaton strategy is adopted to succinctly represent player behaviors in an iterated game. The automaton uses an internal state to keep track of the game history, with state



**Figure 3.** *TjT* automaton strategy for the repeated game illustrated for the decisions of Player  $S_2$ . The circles represent the possible  $S_2$  states, the arrows represent decisions, and the symbols in parentheses represent the previous states of  $S_1$  and  $S_2$ . The game is initialized with both players in the  $D$  state. On the first iteration Player 2 chooses  $C$ . A similar diagram applies to Player  $S_1$ .

transitions based on observed actions (Blume et al., 2015). The decisions made by the automaton depend on this internal state. Here only deterministic automata (without randomization) and pure strategies are considered in an infinitely repeated game within the stage. Although the payoff matrix varies throughout different stages, the payoff matrix in a certain stage can be assumed to be unchanging and to represent the total payoff values of the stage. For a given stage, gaming between the players is continuously repeated multiple times within a relevant, long time period. Players do not know at the outset how long the stage will last. Therefore, it is reasonable to assume that players will consider a game to be infinite rather than finite, because an infinitely repeated game can represent the unpredictability of gaming times and the discounted values of long future stakeholder benefits.

An automaton that describes player strategies in stage I must remain in the state  $(D, D)$ , because in that state it is both a Nash equilibrium and the solution that maximizes total system-wide utility. As conditions change, stage II begins at  $(D, D)$ . However, there is now a clear motivation for players to cooperate and move from  $(D, D)$  to  $(C, C)$ . One way for this to occur is for  $S_2$  to adopt a *tit-for-tat* (*TjT*) strategy by initially deciding to cooperate. After the initial decision to cooperate,  $S_2$  follows a standard *TjT* decision strategy, as diagrammed for the automaton in Figure 3. That is,  $S_2$  selects  $C$  in the next round if  $S_1$  selects  $C$ , and  $S_2$  selects  $D$  if  $S_1$  selects  $D$ .

In practice,  $S_2$ 's initial decision to cooperate might take the form of offering  $S_1$  compensation  $c$  in exchange for  $S_1$  agreeing to release water on a schedule that is beneficial for  $S_2$ . This decision is motivated by  $S_2$ 's knowledge of the potential benefits of cooperation, as well as empirical knowledge of the effectiveness of a *TjT* strategy in an iterated prisoner's dilemma (Nowak & Sigmund, 1993). If the compensation offered by  $S_2$  is sufficient to ensure that  $S_1$  benefits more from cooperation than from defection, then  $S_1$  is expected to accept the compensation and cooperate by making the desired release. We might term this a conditional *TjT* strategy for  $S_1$ , which specifies that  $S_1$  will continue to cooperate as long as the compensation is acceptable. Because  $S_1$  and  $S_2$  are both following *TjT* strategies and are both cooperating after their compensation agreement, they should continue to cooperate while the compensation condition is met. If external conditions change, then the compensation may need to be modified to maintain cooperation. Our perspective in this paper is that the *TjT* strategy is the desired solution to an infinitely repeated transboundary river basin game. This solution can be achieved when an effective cooperative mechanism is established (e.g., through a contract specifying appropriate compensation from  $S_2$  to  $S_1$ ).

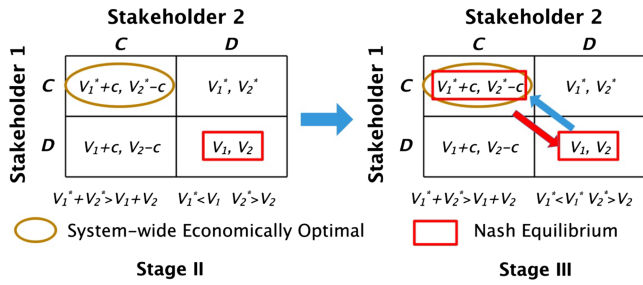
The compensation-based cooperative mechanism outlined above is effective if the compensation  $c$  ensures sufficient benefit to  $S_1$ . The key to characterizing this compensation is to calculate the utility for each player over the repeated game. However, the sum of the utilities over all periods in an infinitely repeated game is unbounded. To address this, it is assumed that the transboundary stakeholders discount the future with a discount factor  $\delta$ , where  $0 < \delta < 1$ . The larger the discount factor, the more patient a player becomes, weighing future payoffs by a larger amount relative to the current utility. For a *TjT* strategy, three conditions must be present to confirm that all-cooperation is another equilibrium: (1) If one player chooses to defect, it is better to regret (return to cooperate) earlier than later. (2) If one player chooses to regret after defecting, it is better than defecting forever. (3) It is better for one player to cooperate forever than to regret after defecting.

Because all past actions and utilities are assumed to be common knowledge for all players, the utility for each player under different actions can be quantified as follows:

If  $S_1$  or  $S_2$  initially decide to cooperate based on contract, and they both play *TjT*, the total discounted  $S_1$  and  $S_2$  utilities are  $U_{1C}$  and  $U_{2C}$ , respectively:

$$U_{1C} = (V_1^* + c) + (V_1^* + c)\delta + (V_1^* + c)\delta^2 + \dots = \frac{V_1^* + c}{1 - \delta} \quad (1)$$

$$U_{2C} = (V_2^* - c) + (V_2^* - c)\delta + \dots = \frac{(V_2^* - c)}{1 - \delta} \quad (2)$$



**Figure 4.** The payoff for players in a transboundary river game showing the transition from the prisoner's dilemma in stage II to the cooperative solution with  $\frac{V_1-V_1^*}{\delta} < c < (V_2^*-V_2)\delta$ . Particularly, Nash equilibrium is one-shot in stage II and is both one-shot and multishot in stage III.

If  $S_1$  or  $S_2$  do not agree to cooperate based on contract, and they both play *TfT* (i.e., each is not willing to wait for cooperation), then the total discounted  $S_1$  and  $S_2$  utilities are  $U_{1D}$  and  $U_{2D}$ , respectively:

$$U_{1D} = (V_1 + c) + V_1\delta + V_1\delta^2 \dots = c + \frac{V_1}{1-\delta} \quad (3)$$

$$U_{2D} = V_2^* + V_2\delta + V_2\delta^2 \dots = V_2^* + \frac{V_2\delta}{1-\delta} \quad (4)$$

If  $S_1$  chooses to cooperate immediately and in stage  $t$  after defecting, the total discounted  $S_1$  utilities are  $U_{10}$  and  $U_{1t}$ , respectively:

$$U_{10} = (V_1 + c) + V_1^*\delta + (V_1^* + c)\delta^2 + (V_1^* + c)\delta^3 + \dots \quad (5)$$

$$U_{1t} = (V_1 + c) + V_1\delta + V_1\delta^2 + \dots + V_1^*\delta^t + (V_1^* + c)\delta^{t+1} + \dots \quad (6)$$

If  $S_2$  chooses to cooperate immediately and in stage  $t$  after defecting, the total discounted  $S_2$  utilities are  $U_{20}$  and  $U_{2t}$ , respectively:

$$U_{20} = V_2^* + V_2\delta + (V_2^*-c)\delta^2 + (V_2^*-c)\delta^3 + \dots \quad (7)$$

$$U_{2t} = V_2^* + V_2\delta + V_2\delta^2 + \dots + V_1^*\delta^t + (V_1^* + c)\delta^{t+1} + \dots \quad (8)$$

The three conditions satisfying the optimal *TfT* strategy mentioned above are as follows: for condition (1),  $U_{10} > U_{1t}$  and  $U_{20} > U_{2t}$ ; for condition (2),  $U_{10} > U_{1D}$  and  $U_{20} > U_{2D}$ ; and for condition (3),  $U_{1C} > U_{10}$  and  $U_{2C} > U_{20}$ . Then, it can be concluded that when  $c > \frac{V_1-V_1^*}{\delta}$ , the *TfT* strategy in Figure 3 is the best response for  $S_1$ . Additionally, when  $c < (V_2^*-V_2)\delta$ , the *TfT* strategy in Figure 3 is the best response for  $S_2$ .

The above derivation implies that as long as  $\frac{V_1-V_1^*}{\delta} < c < (V_2^*-V_2)\delta$ , both players benefit by following *TfT* strategies, and cooperation will naturally evolve if they adopt these strategies. In that case, the (C, C) state is a Nash equilibrium, because neither player benefits by changing from C to D. Each subgame under different stages of the infinitely repeated game is equal to the original game, and the *TfT* strategy is a Nash equilibrium of the infinitely repeated game. Notably, a *TfT* strategy is not a perfect Nash equilibrium of the subgame, which means it would be not the best response for the stakeholders in any game path. Theoretically, for long-term repeated games, the revised grim trigger strategy is the perfect Nash equilibrium of the subgame, which also makes all-cooperation a strong constraint state, consistent with our stage development expectations (Nowak & Sigmund, 1993). However, the *TfT* strategy as a Nash equilibrium can effectively explain that all-cooperation is a stable equilibrium of the long-term game. Additionally, such result can be observed in the real world, which is more practical than a perfect subgame Nash equilibrium. This cooperative shift from (D, D) to (C, C) is defined as stage III, as shown in Figure 4.

There is also a more complicated situation wherein a player is willing to bear the loss caused by waiting for the other player to cooperate. However, the requirements are higher for the patience of both players, as well as the incremental benefits to both parties. For the sake of simplicity, we focus here on a simplified case where  $S_2$  proposes cooperation at the start of the game and  $S_1$  responds according to the basic *TfT* strategy in the next iteration.

The key to cooperation in a transboundary river basin is whether a reasonable compensation value  $c$  can be found in the specified range  $\frac{V_1-V_1^*}{\delta} < c < (V_2^*-V_2)\delta$ , called the negotiation space. A compensation  $c$  that lies in this range provides the basis for an effective cooperation mechanism, leading to a persistent all-cooperate strategy. Table 1 presents the variables that affect the negotiation space for transboundary river basin management policies.

The negotiation space provides flexibility in the allocation of the incremental benefits achieved from cooperation, because any compensation within the associated range of  $c$  values is acceptable to all players. The range of possible incremental benefit allocations that are compatible with this interval defines the core

**Table 1**  
Several Key Variables Relevant to Long-Term Cooperation

Variables	Description	Transboundary game implications
$V_1^* - V_1$	S <sub>1</sub> benefits	Upstream stakeholders gain or lose benefits from cooperation if $V_1^* - V_1 > 0$ or $V_1^* - V_1 < 0$ , respectively.
$V_2^* - V_2$	S <sub>2</sub> benefits	Downstream stakeholders gain or lose benefits from cooperation if $V_2^* - V_2 > 0$ or $V_2^* - V_2 < 0$ , respectively.
$c$	Compensation	Compensation from S <sub>2</sub> to S <sub>1</sub> makes cooperation possible. Compensation could be economic or noneconomic.
$\delta$	Patience	The discount rate quantifies the tendency of the stakeholder to defer benefits.

solution to the cooperative game. A result that lies within the core is sufficiently attractive to all players to ensure that no coalition of players is incentivized to defect to obtain better benefits (Myerson, 1993). The larger the compensation range, the more room for negotiation, and the easier it is to find a mutually agreeable cooperative solution.

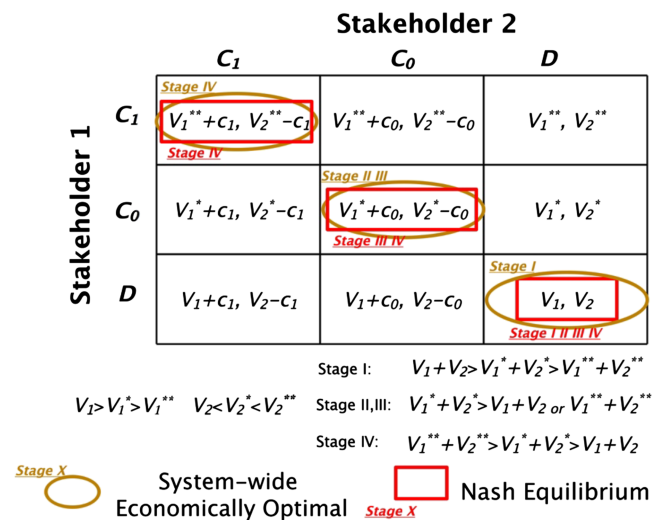
Transboundary river basin management arrangements are not fully cooperative at first and may only address limited aspects of the overall management problem (and therefore provide limited incremental benefits). If the players work in-depth to increase the incremental benefits, perhaps by jointly developing new infrastructure or agreeing to use limited resources more efficiently, the possibilities and benefits of cooperation may be greater. This perspective is described in the expanded payoff matrix in Figure 5. The expanded model treats stage III as a period of initial cooperation and adds a new stage IV, which is a period of in-depth cooperation. There are three possible actions for each player: initial cooperation ( $C_0$ ), in-depth cooperation ( $C_1$ ), and defection ( $D$ ). Additionally, there are three different direct utilities ( $V_1$ ,  $V_1^*$ , and  $V_1^{**}$ ) that define the associated payoff matrix shown in Figure 5. Figure 6 shows the *TfT* automaton that applies to this expanded game formulation.

The player actions ( $D, D$ ), ( $C_0, C_0$ ), and ( $C_1, C_1$ ) can all be Nash equilibria as well as system-wide optima for various stages of the game, depending on the relationships between the total utilities in the inequalities shown in the lower portion of Figure 5.

The four-stage repeated game summarized above retains the same general properties as the three-stage game. Players are motivated to cooperate as long as the direct utilities and compensation in each stage satisfy appropriate conditions and as long as both players follow a *TfT* strategy. In such cases, the cooperative Nash equilibria are system-wide optima that distribute the incremental benefits of cooperation in a way that is acceptable to both players. Similar principles may be used to define even more stages, accounting for the importance of changes in environmental and economic conditions, stakeholder interests, and infrastructure.

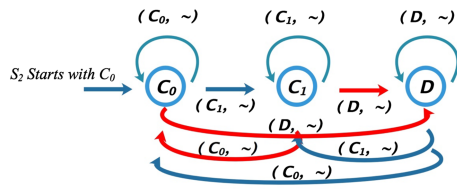
**2.4. Summary of Evolutionary Cooperation in a Transboundary Game**

Figure 7 summarizes the evolutionary cooperation described by the extended game matrix of Figure 5. This cooperation process passes successively through a series of stages indicated by blue arrows. In stage I, the transboundary river basin is undeveloped, with no incremental benefits to motivate cooperation. In stage II, incremental benefits appear gradually as a result of infrastructure development. However, transboundary stakeholders are trapped in a prisoner's dilemma without an effective cooperation mechanism. In stage III, the basic conditions for cooperation are met, and the players have moved from a ( $D, D$ ) equilibrium to a more beneficial ( $C_0, C_0$ ) equilibrium solution. In stage IV, additional basin development and infrastructure has provided the opportunity to increase incremental benefits, prompting both stakeholders to choose a more in-depth cooperation strategy. The last two stages are the result of the cooperative Nash equilibrium made possible by the *TfT* strategy. The most prominent features of these final stages are the construction of expanded water development facilities, measures to improve resource use efficiency, and



**Figure 5.** An expanded formulation of the transboundary river basin game. Stage I has no incremental benefits; stage II has incremental benefits, but there is no effective mechanism for cooperation; stage III meets the requirements for initial cooperation; and stage IV provides an opportunity for in-depth cooperation. Particularly, Nash equilibrium is one-shot in stages I and II and is both one-shot and multishot in stages III and IV.





**Figure 6.** An automaton for the transboundary game with constraints  $\frac{V_1 - V_1^*}{\delta} < c_0 < (V_2^* - V_2)\delta$  and  $\frac{V_1 - V_1^*}{\delta} < c_1 < (V_2^* - V_2)\delta$ .

improved international relations, which increase incremental benefits. However, the red arrows shown in Figure 7 indicate that the path of cooperative evolution can be reversed. When cooperative compensation does not fall in the specified interval, the all-defect solution reappears (Acemoglu & Wolitzky, 2014). To stabilize cooperation, it is necessary to maintain adequate incremental benefits, foster patience, and keep compensation values reasonable.

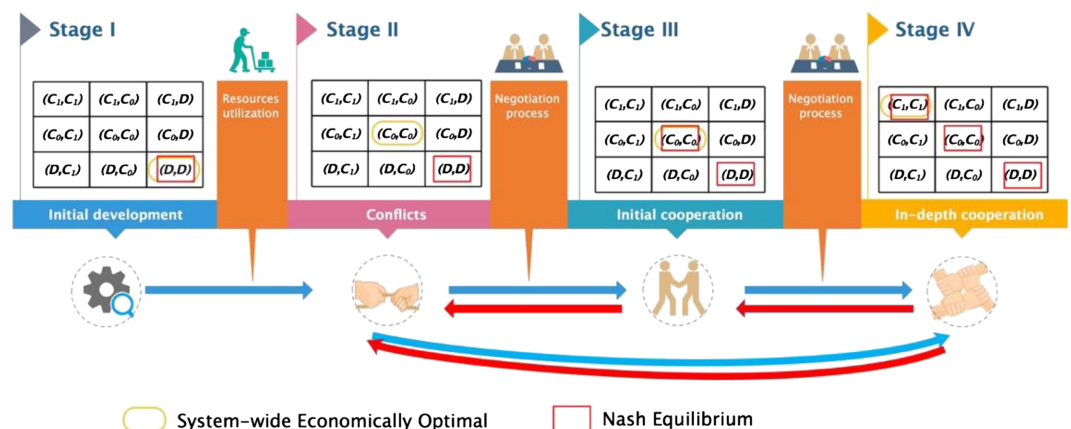
Our generalization of the transboundary river basin management process from a one-shot prisoner's dilemma game to an iterated game shows how cooperation can evolve with adequate infrastructure development, appropriate compensation mechanisms, and player adoption of a *TfT* strategy. The practical implications of this game-theoretic conceptual framework can be best appreciated by applying it to case studies that illustrate the diversity of real-world transboundary issues and possible solutions. Some examples are presented in the following sections.

### 3. Evolutionary Cooperation in the Lancang-Mekong Basin

#### 3.1. Lancang-Mekong River Basin

The Lancang-Mekong river is an important international transboundary river in Asia, with a total drainage area of approximately  $8.1 \times 10^5 \text{ km}^2$ . It flows through six countries, as shown in Figure 8: China, Myanmar, Laos, Thailand, Cambodia, and Vietnam. The climate of the LMRB ranges from temperate to tropical and is distinguished by highly seasonal rainfall controlled by the southwest monsoon, with clear wet and dry seasons (Johnston & Kummu, 2012).

The Lancang-Mekong River provides hydropower, irrigation, fisheries, wetlands, navigation, and other resources to the riparian countries it flows through. Agricultural water supply is crucial for rice-based traditional irrigation in downstream countries, which is a significant component of the total water use in the basin. Agricultural water withdrawals in Myanmar, Laos, Thailand, and Cambodia account for more than 90% of these countries' total water withdrawals, while the percentage in Vietnam is 68%. Therefore, the use of water for irrigation has led to significant conflicts between downstream stakeholders, particularly in dry seasons (MRC, 2011). Another major concern is hydropower development in the upstream region. China has built cascade reservoirs in the main stream of the Lancang River, which is the common name for the portion of the river that lies within China. These reservoirs can generate 15.6 GW of hydropower annually, which may impact the ecosystems and ultimately affect the fisheries of the downstream stakeholders. It is reported that 60% of the local population's protein intake comes from fish (MRC, 2010). Furthermore, the Mekong River supports a large number of diverse wetlands that have important social, economic, and cultural value. These wetlands play a vital role in the livelihoods of the local population and the socioeconomic development of the region (MRC, 2010). In summary, the significant interests of



**Figure 7.** The overall evolutionary cooperation process for a transboundary river game, including four stages that describe a gradual transition driven by development. This transition provides incremental benefits that foster cooperation.

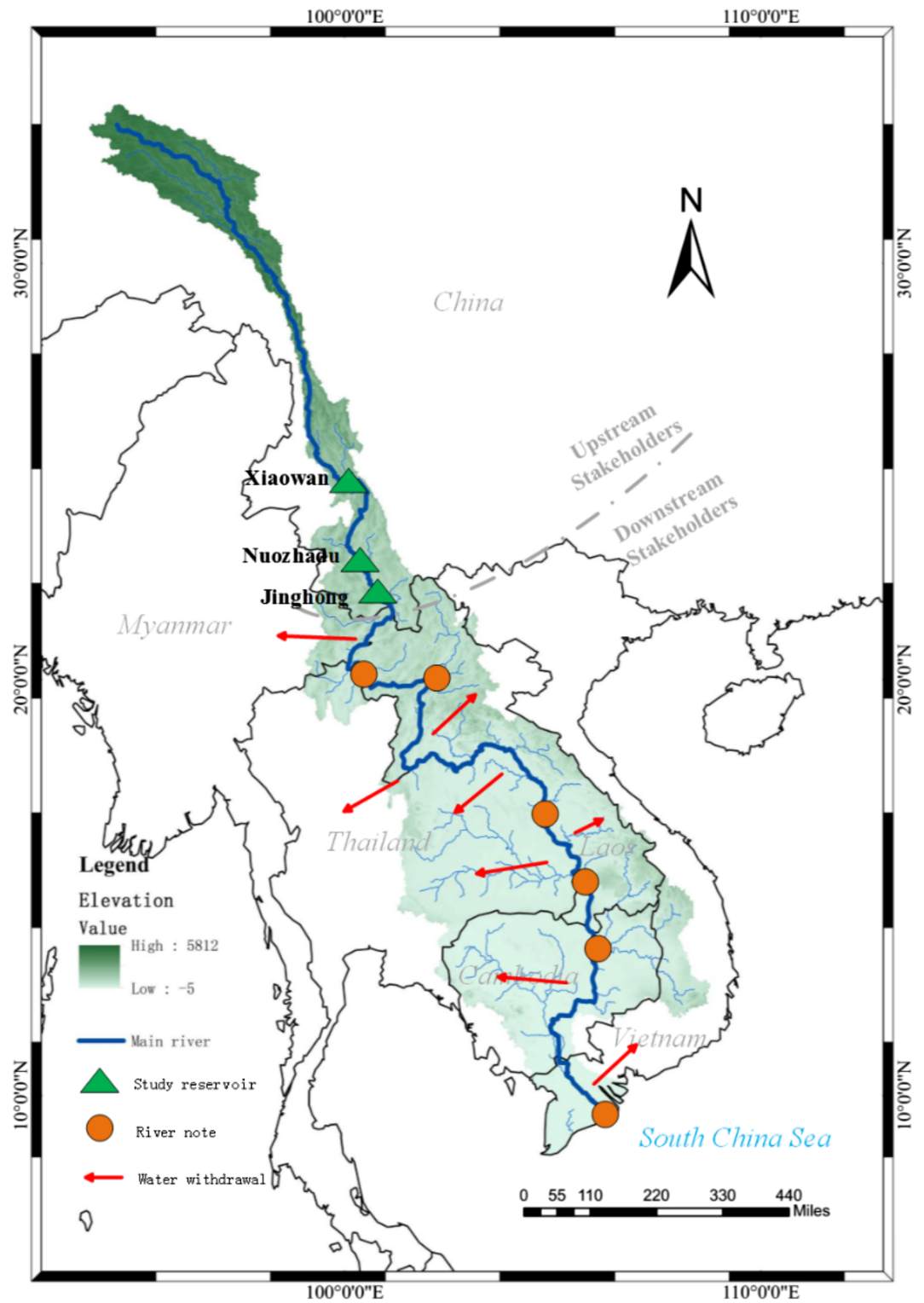


Figure 8. Overview of the Lancang-Mekong River Basin and the conceptual representation of the optimization model.

the downstream countries are agricultural water withdrawals, fisheries, and wetland ecosystems, while upstream hydropower dams produce substantial economic benefits for China. These lead to significant conflict between the upstream and downstream stakeholders.

Therefore, natural and economic conditions make it straightforward to divide the six riparian countries of the basin into upstream and downstream stakeholders. In addition to physical and economic conditions, political power has played an increasingly important role in the development of the LMRB and may produce cooperation between all stakeholders. An essential cooperative organization called the Mekong River Commission (MRC) was established in 1995, which includes the downstream countries of Laos, Thailand, Cambodia, and Vietnam. The MRC also has dialogue partners, China and Myanmar, who regularly attend MRC meetings, suggesting that there is considerable potential for cooperation at the basin level. Because Myanmar's claims on the basin's interests are relatively low, the four MRC countries can be integrated and considered to be one downstream stakeholder group, which simplifies the complicated relationships but allows for the application of game-theoretical analysis. Thus, the two representative stakeholders in the LMRB are China and the four MRC countries; these groups represent typical upstream and downstream stakeholders in the basin.

Water-related conflict in the LMRB has been an important issue since the 1980s. Before the 1980s, China, as an upstream stakeholder, had not yet developed the river. The incremental cooperative benefits of the whole basin were limited, and only the downstream countries had established cooperation mechanisms. In the middle to late 1980s, China began to develop hydropower (MRC, 2016b). According to the plan, eight cascade hydropower stations would ultimately be built on the middle and lower reaches of the Lancang River. These reservoirs, particularly some of the largest reservoirs such as the Xiaowan, Nuozhadu, and Jinghong reservoirs, changed the natural flow regime at several downstream gauging stations (Li et al., 2017). The changes in the flow regime affected downstream ecosystems and fisheries; meanwhile, the positive effects of flood prevention and flow supplementation provided by China's reservoirs were also significant. Thus, the operations of these reservoirs were expected to be optimized so that all stakeholders could benefit from reservoir development (Yu et al., 2019). However, the LMRB was in stage II during this period, because noncooperation was the normal state of the basin, as expected from the properties of the prisoner's dilemma.

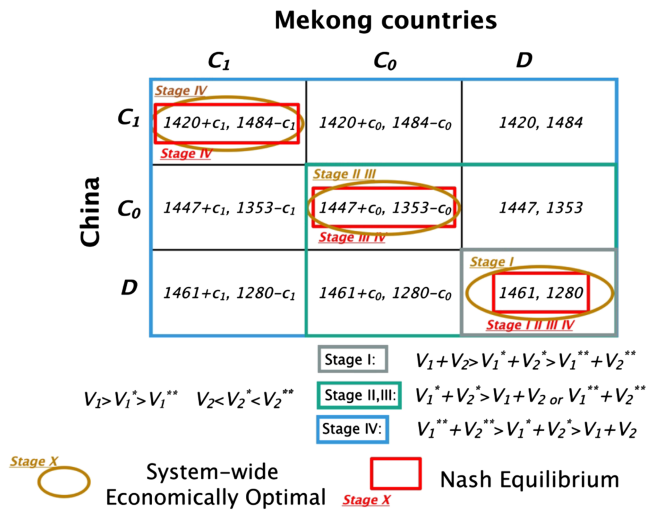
Since the 1990s, the Great Mekong Subregion Cooperation, the MRC, and the Association of Southeast Asian Nations-Mekong Basin Development Cooperation have worked together to promote upstream and downstream negotiations, suggesting that the LMRB was moving toward stage III. Although cooperation in the Lancang-Mekong River Basin was rare for a long time, some successful examples occurred in the 21st century. An interesting case took place, in which a severe drought occurred over the Mekong Basin in the spring of 2016. China implemented emergency water releases from its cascade reservoirs to mitigate downstream droughts (MRC, 2016a), which can be seen as a typical stage III event. The next section examines this event in detail.

### 3.2. Typical Cooperative Event for Automaton Strategies in a Particular Year

An optimization model developed by Yu et al. (2019) provides a convenient way to quantify the payoffs for stakeholders in the LMRB. This model determines the annual water use patterns that will maximize the sum of the economic benefits from hydropower generation in the Lancang River, as well as irrigated agriculture, fish production, and wetlands in the Mekong River. In the Lancang River, the model includes three major cascade reservoirs: the Xiaowan, Nuozhadu, and Jinghong reservoirs. The Xiaowan and Nuozhadu reservoirs can regulate seasonal streamflow with large storage capacities and have a significant impact on downstream flow regimes. The Jinghong reservoir is located near China's borders, and its release directly determines downstream stream flows. In the optimization model, irrigation, fisheries, and wetland water demands represent the main economic interests of the riparian stakeholders. The objective function of the model is expressed as

$$\text{Max} \left( Vg + \sum_{n=1}^{tn} Va_{(n)} + \sum_{n=1}^{tn} Vf_{(n)} + \sum_{n=1}^{tn} Vw_{(n)} \right) \quad (9)$$

where  $Vg$  is the annual profit from hydropower, aggregated by daily values (\$US million, only in CHN);  $Va_{(n)}$  is the annual profit from agriculture, aggregated by monthly values (\$US million);  $Vf_{(n)}$  is the annual profit from fisheries, aggregated by yearly values (\$US million);  $Vw_{(n)}$  is the annual profit from wetlands, aggregated by monthly values (\$US million);  $n$  is the stakeholder index in the basin; and  $tn$  is the total number



**Figure 9.** Payoff (\$ million) for stakeholders in the Lancang-Mekong River Basin during a dry year. Particularly, Nash equilibrium is one-shot in stages I and II and is both one-shot and multishot in stages III and IV.

LMRB, incremental benefits appear during the cooperation in stage II (indicated by the green box), but cooperation has not been observed during this stage; (3) the benefits and mutual cooperative (*TjT*) decisions of the players cause the game to reach a cooperative Nash equilibrium in stage III; and (4) an analysis of the potential incremental benefits from more in-depth cooperation describes the gains that will be achieved if the players are able to progress to stage IV, as shown by the blue box. Those quantitative model principles are consistent with the discussion in section 2.

The values shown in the payoff matrix include both calculable economic benefits (given numerically) and incalculable compensation (shown as  $c_0$  and  $c_1$ ). If adequate compensation is provided, the cooperative ( $C_1, C_1$ ) strategy produces the highest benefits for the whole basin. Table 2 summarizes the arrangement achieved in spring 2016.

Although some of the factors mentioned above and listed in Table 2 are difficult to describe quantitatively, they had profound effects on the cooperation process. During the 2016 emergency water supply event, compensation  $c$  was mainly political compensation. During that period, the first Lancang-Mekong cooperation

of stakeholders cooperating with China (i.e.,  $tn = 1$  when China runs independently, and  $tn = 2$  when China cooperates with the MRC). This equation is applied in different forms by using different values of  $tn$  in the game theory formulation to analyze instances of both noncooperation and cooperation. For cases where China does not join the cooperation, the time index is  $tn = 1$  (i.e., China runs independently), and the benefits to other stakeholders can be calculated following the released streamflow from the upstream reservoirs. More details of the model can be found in Yu et al. (2019).

A typical dry year is selected as the hydrological input to the model to highlight the highest potential for transboundary cooperation. As shown in Figure 9, the results based on the model solution are divided into stages I–IV, with different Nash equilibria and system-wide optimum configurations.

Different cooperation levels depend on different reservoir release settings of the model in China, leading to different payoff matrix scales indicated by the gray, green, and blue boxes under different stages: (1) in the early stages of development without water infrastructure, conflict only occurs in stage I (indicated by the gray box); (2) with the development of the

**Table 2**  
Main Factors Affecting Lancang-Mekong River Basin Cooperation in Spring 2016 (Stage III)

Factor	Description	Upstream	Downstream	$C$	Reference
Water demands	MRC countries need irrigation from the river in the dry season, while China needs water for hydropower generation.	★	☆	↑	(MRC, 2010)
Outside options	If negotiation fails, Mekong countries will face significant losses and China will face diplomatic pressure.	☆	☆	/	(Larson, 2016; Reuters, 2016)
Location	China can determine the availability of water downstream.	★	☆	↑	(MRC, 2010)
Economic power	China's economy is significantly larger than the economies of the MRC countries.	★	☆	↑	(Ming-hui, 2012)
Natural conditions	MRC countries rely heavily on the Mekong river, and there are few other sources of water during droughts.	★	☆	↑	(Larson, 2016)
Politics	China needs the support of downstream countries on regional political issues.	☆	★	↓	(Xinhua, 2016)

*Note.* ★ indicates that this factor may provide the stakeholder an advantage in the negotiation, ☆ indicates a disadvantage, ↓ indicates that this factor may decrease compensation decrease, and ↑ indicates a possible increase in compensation.

**Table 3**  
Main Factors Affecting Longer-Term (Stage III and Stage IV) Lancang-Mekong River

Factor	Description	Mechanism
$V_1 - V_1^*$	Upstream cooperative losses	(1) Loans and investments for supporting production capacity and equipment manufacturing cooperation among the Mekong countries (2) Upstream hydrological information and technology sharing (3) Hydropower losses due to cooperative reservoir operations ...
$V_2^* - V_2$	Downstream cooperative benefits	(1) Hydraulic engineering investments and technology inputs (2) Irrigation benefits during dry seasons (3) Upstream hydrological information disclosure ...
$c$	Compensation	(1) Diplomatic and political support (i.e., South China Sea issue) (2) High-quality food trade ...
$\delta$	Patience	(1) The long-term expectations of the stakeholders regarding the game (2) Negotiation capabilities of China and MRC ...

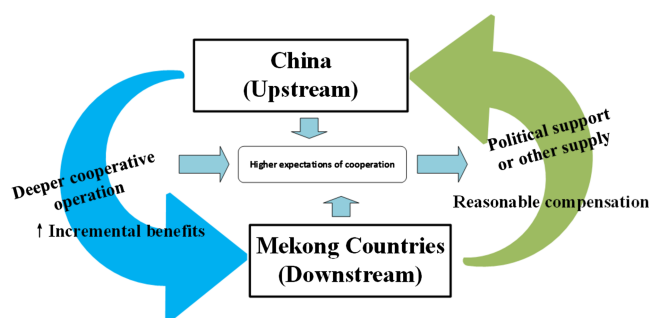
leaders' meeting was held in China (China Daily, 2016), and tensions eased between Vietnam and China regarding the South China Sea issue (Xinhua, 2016).

The transboundary cooperation achieved during the 2016 drought is part of a larger context of cooperation among LMRB countries. In 2014, Prime Minister Li Keqiang of China proposed the Lancang-Mekong Cooperation mechanism on behalf of the Chinese government, which received a positive response from all of the basin countries. The Lancang-Mekong Cooperation aimed to promote the social and economic development of the six Lancang-Mekong countries, advance the Belt and Road Initiative through consultation and collaboration, realize the United Nations 2030 Sustainable Development Agenda and Goals, facilitate the development of the ASEAN community, and promote South-South cooperation (Xinhua, 2018a). In 2018, representatives from six Lancang-Mekong Cooperation countries passed an initiative to enhance water resources cooperation during a forum held in Kunming, the capital of southwest China's Yunnan Province. These initiatives indicate that LMRB cooperation will gradually enter stage IV and in-depth cooperation will start in the future. Under the influence of a long-term cooperation mechanism, the variables in the Lancang-Mekong River game matrix have been given additional new connotations. Table 3 explains several variables in the game matrix; these variables are more complicated than those in a traditional one-shot transboundary river game.

Currently, the Mekong countries are more supportive and understanding of China with respect to political and diplomatic problems, and they are actively responding to the call for support of China's Belt and Road Initiative. On the other hand, China has taken the initiative to abandon considerable water benefits, in order to reduce the negative downstream impacts of hydropower development, including canceling the last cascade hydropower station, Mengsong, in the middle and lower reaches of the Lancang River. China is also increasing investments to ameliorate the negative environmental impacts of hydropower stations. These

facts indicate that the LMRB is moving toward stage IV (Lancang-Mekong Cooperation, 2018; Xinhua, 2018b). Figure 10 describes the process of cooperative evolution needed to sustain longer-term cooperation.

Overall, evolutionary cooperation in the LMRB can be summarized as shown in Figure 11.



**Figure 10.** The process needed to sustain long-term cooperation in the LMRB.

## 4. Case Analysis of Other Transboundary River Basins and Policy Implications

### 4.1. Cases of Other Transboundary River Basins

Based on the cooperation process shown in Figure 7, some other cases, that is, the Nile River, Columbia River, and Rhine River, are analyzed to demonstrate evolutionary patterns of cooperation in transboundary river basins.

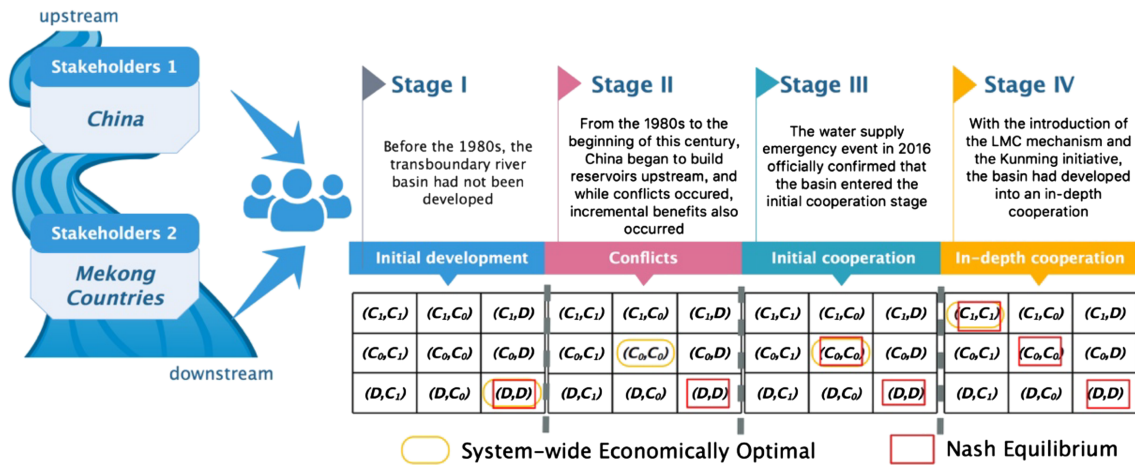


Figure 11. The evolutionary cooperation in the LMRB and the quantitative payoff matrix under each stage.

The Nile River is generally considered the longest river in the world, with 6,700 km of length that is shared by 11 riparian countries. Water conflicts in the Nile River also have specific general characteristics, including water allocation and water resources development projects (Kameri-Mbote, 2007). In the early stage of Nile River development, only Egypt carried out significant projects on the river, such as the Aswan High Dam, without consultation with upstream stakeholders. Thus, there was little potential for cooperation in the basin, because Egypt always had a large share of the Nile water, which can be defined as stage I (Kalpakian, 2017). However, as the claims of upstream countries developed, deeper conflicts gave birth to the potential for cooperation in stage II. Although the Nile Basin Initiative (NBI) was established in 1999, because of the lack of trust between the participating countries, the NBI did not play any role in negotiations and was dissolved (Tafesse, 2001). Until 2010, most riparian countries joined the Nile initiative, marking the start of cooperation and the potential evolution from stage II to stage III (Kalpakian, 2017). However, good cooperation did not last long. Ethiopia's unilateral Grand Ethiopian Renaissance Dam project, currently under construction on the Blue Nile, once again triggered conflicts among Nile stakeholders (Tawfik, 2016). Research has shown that the dam would bring incremental benefits to stakeholders in the Nile River if the cooperative operation of upstream reservoirs was implemented (Basheer et al., 2018). However, cooperation in the Nile River basin has since returned to stage II (i.e., conflict) from stage III (i.e., initial cooperation), because of a lack of trust and a lack of benefit sharing mechanisms (Basheer et al., 2018). Although the NBI tried to encourage cooperation in the basin, an effective cooperation mechanism that includes effective benefit-sharing schemes and betrayal punishment measures needs to be further negotiated (Wheeler et al., 2018). This will provide evolutionary direction, allowing the Nile River basin to

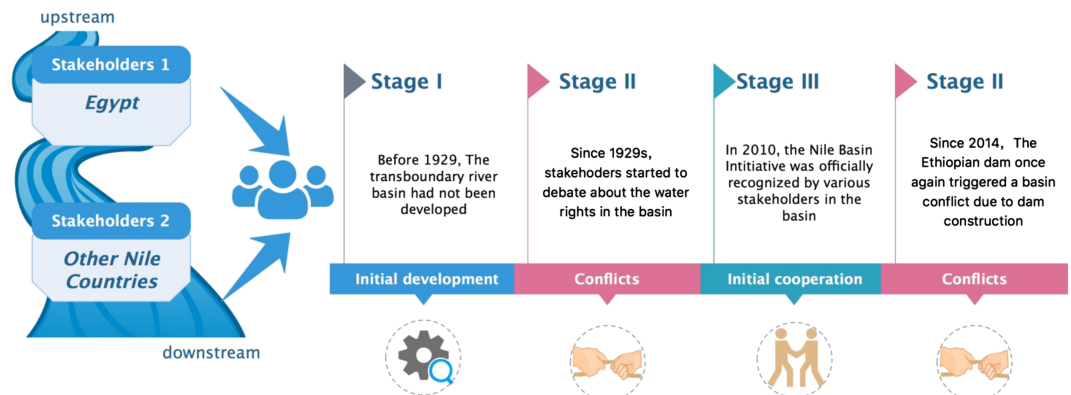
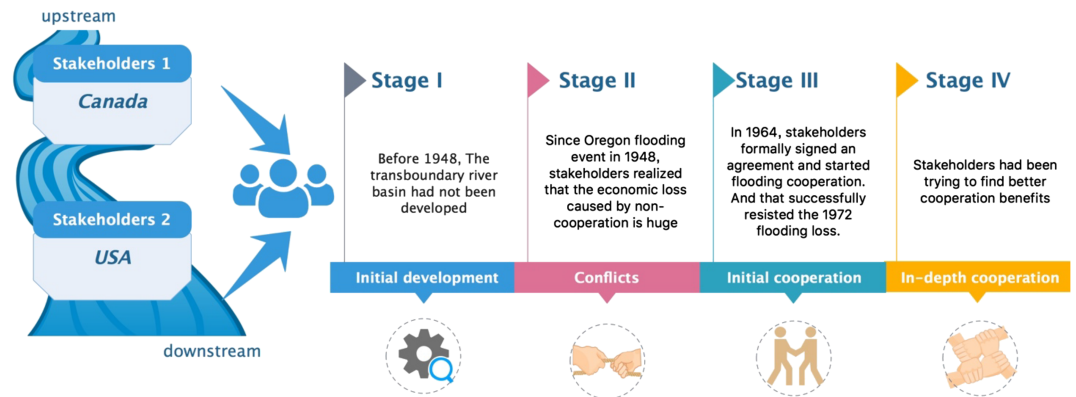


Figure 12. Evolutionary cooperation in the Nile River.



**Figure 13.** Evolutionary cooperation in the Columbia River.

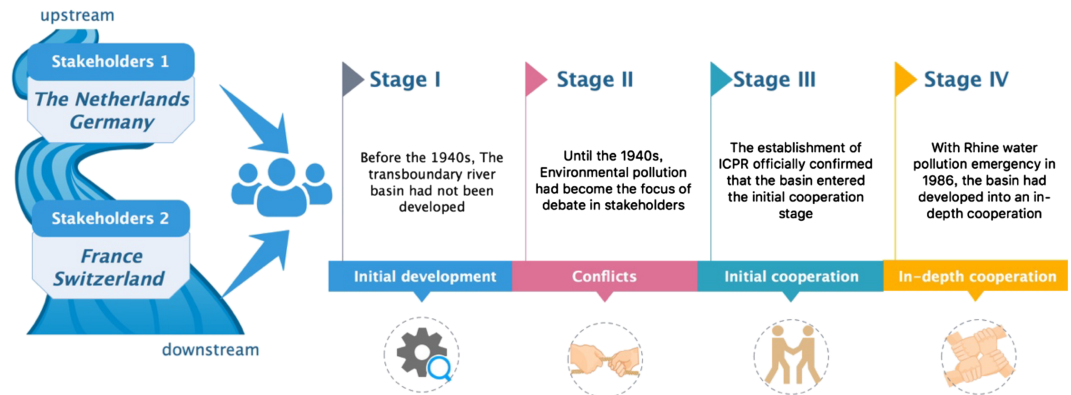
achieve long-term cooperation. A schematic of evolutionary cooperation patterns in the Nile River is shown in Figure 12.

The Columbia River flows from Canada (upstream) to the United States (downstream) and is a transboundary river with regular flooding. Natural disasters drive changes in the payoff benefits structure between upstream stakeholders and downstream stakeholders, leading to the possibility of cooperation being gradually valued (Hirt & Sowards, 2012). In particular, after the flood that had severely damaged the city of Vanport in Oregon in 1948, the 1964 USA-Canada Columbia River Treaty was signed, implying a transition from stage II to stage III (Cosens, 2010). In this case, dams were constructed in upstream Canada to control floods and provide hydropower to the United States. Additionally, the United States compensated Canada for the construction of dams by sharing their hydropower supply benefits (Krutilla, 2019). Both countries were better off. As cooperative efforts developed, upstream Canada sought more compensation, while downstream USA wanted Canada to play a more critical role in flood control and environmental protection (Shurts, 2012). Therefore, challenges to cooperation still exist. However, this would not prevent the evolution of cooperation between Canada and the United States from stage III to stage IV. The evolutionary cooperation pattern for the Columbia River is shown in Figure 13.

The Rhine River is the longest river in Western Europe and is widely used by the bordering riparian countries for drinking water, irrigation, and sewage disposal. The main industrial areas in Europe are also concentrated in the Rhine Valley, causing the river to be polluted by riparian stakeholders (Bernauer & Moser, 1996). Before the emergence of environmental problems, the incremental benefits from cooperation were not significant in the Rhine River, because the water demands of riparian countries could be met without cooperation, implying a stage I status (Verweij, 1999). Starting in the late 1940s, conflicts related to environmental pollution appeared between upstream and downstream stakeholders, indicating stage II (Dieperink, 2000). Because of the lack of reasonable cooperation mechanisms, the prisoner's dilemma game lasted for more than 10 years in stage II. With the establishment and development of the International Commission for the Protection of the Rhine in the 1950s, cooperation in the Rhine River was initiated, producing incremental benefits to the riparian stakeholders and leading the basin into stage III (Dieperink, 2000). The landmark event that moved the Rhine River from stage III to stage IV was the 1986 Rhine water pollution incident (Dieperink, 2000). A chemical plant in Switzerland seriously polluted the river, severely damaging the aquatic ecosystem and drinking water supplies. Taking the pollution incident in 1986 as a starting point, the Rhine River Basin entered a long-term cooperation period of integrated river basin management (Dinar, 2009). Reasonable cooperation mechanisms and mutual trust among riparian stakeholders have made long-term cooperation more stable after years of repetition. The evolutionary cooperation pattern for the Rhine River is shown in Figure 14.

#### 4.2. Policy Implications of Evolutionary Cooperation in Transboundary River Basin Management

The game-theoretic analysis of the case of the Lancang-Mekong River, as well as the other three typical transboundary basins, suggests three basic principles for evolutionary cooperation (Figure 15):

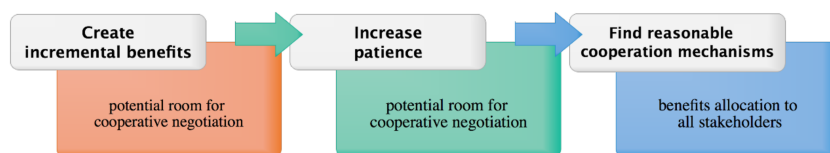


**Figure 14.** Evolutionary cooperation in the Rhine River.

*Incremental benefits are the foundation for cooperation along transboundary rivers.* If and only if cooperation produces incremental benefits, then both upstream and downstream stakeholders may cooperate. The maximization of total benefits provides more potential space for cooperation negotiations. The two in-depth cooperation cases (the Columbia River and the Rhine River, currently in stage IV) occurred in basins with developed economies. The LMRB is transitioning from initial cooperation (stage III) to in-depth cooperation (stage IV), a transition accompanying the development of the riparian countries' economies. Cooperative reservoir operations in the region are expected to yield huge incremental benefits shared by all of the stakeholders in stage IV. However, in-depth cooperation was not achieved in the Nile River case, and conflicts resumed. In that case, the economies of the riparian countries were not well developed in recent years because of the unstable political environment. These facts suggest that well-developed economies in a transboundary river basin can make the incremental benefits from cooperation more significant and therefore increase the probability of cooperation. In contrast, a bad economic situation may decrease the value of cooperation, thereby lowering the probability of cooperation.

*Increasing patience among stakeholders is crucial to achieving long-term cooperation.* Once incremental benefits are produced, increasing patience among stakeholders can enhance the range of options available for long-term cooperation. As can be seen from the cases, in-depth cooperation requires a long evolution time, usually decades or more. During this long evolution period, stakeholders will experience more pain from noncooperation (e.g., flood damage in the Columbia River basin or pollution in the Rhine River basin). They can better understand the importance of future benefits and value of cooperation, thereby increasing foresight and patience. Patience may be influenced by the political decisions and ideologies of countries in the basin and the credibility of agreements. In the Nile River basin, riparian countries lost their patience because agreements lacked credibility and because of political conflicts among countries. The LMRB is an interesting case in which riparian countries' patience continuously increased with improving regional economic and political conditions, resulting in a continuous evolution toward cooperation.

*An effective cooperation mechanism is the guarantee of an excellent cooperation strategy.* The negotiation process often means the determination of cooperation mechanisms, and cooperative compensation and betrayal losses should be controlled within a reasonable negotiated range. Compensation can include direct economic compensation (engineering investment, financial compensation, and trade convenience) and less direct non-economic compensation (political support and information sharing). Here an effective cooperation mechanism, which includes formal agreements and implementing organizations, plays a crucial role.



**Figure 15.** Key steps to promoting cooperation for the transboundary game (in gray boxes) and their outcomes (in boxes below).



As can be seen from the four cases, the two in-depth cooperation cases (the Columbia River and Rhine River, currently in stage IV) have formal agreements and effective implementations, which ensure basin-level cooperation. Some agreements and organizations are in place for the Nile River (e.g., NBI). However, these mechanisms are too weak to maintain basin-level cooperation. In contrast, in the LMRB, agreements and organizations for cooperation are becoming stronger and more effective with the evolution of basin-level cooperation.

Although realistic evolutionary cooperation in transboundary rivers is more complicated than it is in our game-theoretic model, the model clearly illustrates the quantitative aspects of the principles and provides a conceptual framework that is general enough to include nonquantitative aspects. Reasonable compensation provides the essential incentive for cooperation between stakeholders, and a lack of cooperation is likely to produce economically inefficient results, as suggested by the prisoner's dilemma game. Once riparian stakeholders understand how conflicts affect their benefits, they are more motivated to consider mechanisms that enhance the stability and optimality of the basin management strategy (Read et al., 2014). In the case of the LMRB, we only consider the optimization of existing reservoir operations and ignore the impact of new reservoirs. These changes of reservoir operations will complicate evolutionary cooperation and deserve further study. Further game-theoretical studies of planning processes and institutions could help achieve more economically efficient transboundary use of valuable water resources. They could also have positive effects that go beyond water management to facilitate broader political and economic cooperation.

## 5. Conclusion

In this paper, game theory methods were applied to establish an integrated framework to analyze evolutionary cooperation in transboundary river basins, based on tangible and intangible payoff benefits. New insights into the general problem of managing a transboundary river system are provided. First, incremental benefits after cooperation are crucial to cooperation among riparian stakeholders, although there is a dilemma in the beginning. The repeated game analysis showed that a system-wide optimal solution is possible to achieve. Upstream and downstream stakeholders may have the best strategy and choose to cooperate and accept higher optimal individual benefits. Second, an automaton using a *TFT* strategy was used to systematically illustrate how to reach a cooperation agreement. It was found that the negotiation space can be formulated by the reasonable compensation value  $c$  in the range  $\frac{V_1 - V_1^*}{\delta} < c < (V_2^* - V_2)\delta$ , implying that the incremental benefits from cooperation and patience are two important factors for cooperation. Finally, a generalized cooperation pattern for the transboundary river basin was summarized, including four stages: stage I, with no incentive to cooperate because of development; stage II, with a prisoner's dilemma for the no-cooperation mechanism; stage III, with initial cooperation supported by benefit sharing; and stage IV, with formal in-depth cooperation facilitated by effective mechanisms.

Based on an optimization model that quantified stakeholder payoffs, evolutionary cooperation in the LMRB was explored in detail. This case further examines the applicability of the game-theoretic framework and its conclusions. Additionally, three other transboundary river basins were analyzed to demonstrate evolutionary patterns of cooperation. Three basic principles for evolutionary cooperation were summarized based on the theoretical and case analysis. First, incremental benefits are the foundation of cooperation along transboundary rivers. Second, increasing patience among stakeholders is crucial to achieving long-term cooperation. Third, an effective cooperation mechanism guarantees an excellent cooperation strategy. These principles and implications are helpful for understanding the diversity of real-world transboundary issues.

The applicability of this game theoretical framework is limited by the assumptions and simplifications mentioned in the paper. However, conclusions from the game-theoretical analysis seem unlikely to change. Although many uncertainties exist, a better understanding of the evolutionary patterns toward cooperation can help riparian stakeholders avoid the worst outcomes in noncooperative situations, encouraging transboundary river basins to move from conflict to cooperation. Future work is expected to explore the impact factors and uncertainties of transboundary river basin cooperation.

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