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Resolving Transboundary Water Conflicts: Dynamic Evolutionary Analysis Using an Improved GMCR Model

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Abstract
Accurately simulating the dynamic evolution of the behaviors of different decision-makers (DMs) is essential for identifying solutions to transboundary water conflicts. The purpose of this study is to present a dynamic evolutionary analysis model for simulating the behavior of different water users and solving the problem of transboundary water conflicts. To accomplish this goal, a revenue function, which can objectively evaluate the relative preferences of different DMs in water conflicts, was constructed to improve the graph model for conflict resolution (GMCR) model. A demonstration area in the Yangtze River Delta on ecologically friendly development (DAYRD) in China is applied to demonstrate the applicability of the improved method. The results show that the improved GMCR model based on the revenue function can accurately simulate the dynamic evolution of transboundary water conflicts and avoid the influence of subjective factors of researchers or experts in the traditional method. Additionally, the results indicated that water conflicts in the DAYRD can be transformed from the status quo (conflict) to the target state (cooperation) by effectively controlling the intensity of third-party intervention. These findings provide useful insights for the resolution of transboundary water conflicts and enhance our understanding of the role of third parties in transforming conflict into cooperation.

Keywords Transboundary water conflicts · Graph model for conflict resolution (GMCR) · Evolutionary analysis · Revenue function · Yangtze River Delta

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1 Introduction

The sustainable use of water resources is increasingly threatened by the combined impact of population growth, rapid urbanization, climate change, regional imbalances, water shortages, water pollution, and water safety, making the protection and management of water resources increasingly difficult (Garrick and De Stefano 2016; Lu et al. 2015; Zanjanian et al. 2018). Transboundary water conflicts, which are easily triggered among stakeholders in the process of water sharing, place additional pressure on coordination and cooperation across administrative regions (Degefu et al. 2016; Garrick and De Stefano 2016; Taravatrooy et al. 2019; Wei et al. 2010). Moreover, conflicts, including transboundary water conflicts, are characterized by dynamic evolution (Ali et al. 2019; Yuan et al. 2020; Zomorodian et al. 2017). In a conflict, when a decision-maker (DM) changes its strategic behavior, other DMs will make corresponding dynamic adjustments based on their interests (Nazari et al. 2020). Therefore, accurately identifying the interests of DMs and simulating the dynamic evolution of the behaviors of different decision-making processes are essential to finding approaches to resolving transboundary water conflicts and promoting regional cooperation and sustainable development (UN Water 2013; Veldkamp et al. 2017; Yu et al. 2019b).

To solve the complex water conflict issues among multiple DMs, various quantitative or qualitative approaches regarding conflict resolution have been proposed, including the multi criteria decision making (MCDM) method (Geressu and Harou 2015; Madani et al. 2014), cooperative and noncooperative game model (Dowlatabadi et al. 2020; Shi et al. 2016; Tarebari et al. 2018; Zanjanian et al. 2018), system dynamics model (Dong et al. 2019; Nandalal and Simonovic 2003; Tayia 2019), and graph model for conflict resolution (GMCR) (Han et al. 2019; Kilgour and Hipel 2005; Kilgour et al. 1987). Traditional MCDM methods and game theory are generally qualitative or quantitative analyses that do not consider the dynamic evolutionary characteristics of conflict (Di et al. 2020; Yuan et al. 2020; Zomorodian et al. 2017). System dynamics, as a computer simulation method, can analyze the dynamics of complex water sharing problems based on information feedback and mutual or recursive causality (Wang et al. 2018; Zomorodian et al. 2017). However, such types of models focus only on simulating the initial conditions and different scenarios and pay less attention to the influence of DMs' preferences and decision behavior on the evolution of conflicts (Tayia 2019). Moreover, these models have difficulty effectively identifying the evolutionary path of conflicts. The GMCR, as a conflict resolution method developed based on classical game theory, can simulate the dynamic evolution of the behavior of DMs (Kilgour and Hipel 2005). It also has the advantages of simpler modeling and analysis processes and less user input information (Han et al. 2019). The GMCR has been widely used in different fields of conflict analysis, e.g., national security (Langenegger and Hipel 2019; Li et al. 2009), climate change (He et al. 2020; Walker and Hipel, 2017), air pollution (Du et al. 2019), and water conflict (Chu et al. 2015; Philpot et al. 2016; Yu et al. 2015; Zanjanian et al. 2018).

These previous studies yield valuable information and insights for conflict resolution. Nevertheless, there are two aspects that can be substantially improved. First, although the GMCR can simulate the dynamic evolution of DM behavior, the preference ranking methods (including direct ranking, option prioritizing, and option weighting) in this model are based on the judgment of researchers or information provided by experts to evaluate the relative preferences of DMs (Fang et al. 2003a; Yin et al. 2017). Identifying the relative preferences of DMs is the most critical part of conflict analysis (Dowlatabadi et al. 2020;

Ke et al. 2012; Zanjanian et al. 2018). It is necessary to improve the GMCR to objectively evaluate the relative preferences of DMs in real conflicts. Second, it is important to study the impacts of a third party on the dynamic evolution of conflicts. However, most of the existing studies emphasize or prove the importance of third-party intervention in conflict resolution, while quantitative assessment of the concrete impact of the third party on the dynamic evolution of conflicts has rarely been carried out before (Hipel et al. 2014; Yu et al. 2015; Zanjanian et al. 2018).

To overcome these deficiencies, an improved GMCR model is proposed for simulating the dynamic evolution of transboundary water conflicts in the demonstration area in the Yangtze River Delta on ecologically friendly development (DAYRD). For this purpose, a revenue function that can objectively evaluate the preference rankings of different DMs was constructed to improve the GMCR model. Then, through the stability analysis of preference rankings, the dynamic evolution path of the transboundary water conflicts is identified. Moreover, the possibility of conflict resolution under different third-party intervention scenarios is analyzed. Finally, a summary of important insights concluded by the improved GMCR approach is provided for transboundary water resource managers.

2 Study Area

The DAYRD (E120°21′7.20"-121°19′12", N30°45′28"-31°17′50") is located at the junction of three administrative regions in the Yangtze River Delta, including the Qingpu District of Shanghai (SH), the Wujiang District of Jiangsu Province (JS), and the Jiashan County of Zhejiang Province (ZJ), with a total area of approximately 2,300 km^2 (Fig. 1). This region is affected by the subtropical monsoon climate, and the average annual precipitation ranges from 1100 to 1400 mm. Most of this rainfall, however, is concentrated in the flood season from June to September, accounting for more than 50% of the annual total rainfall. The unique dish-shaped topography of this region

Fig. 1 Geographical location of the DAYRD. Jinze Reservoir was built in 2016, with a water intake of 3.51 million m^3/d, providing water for nearly 6.7 million people in Shanghai; Dingzha Reservoir was built in 2009, with a water intake of 0.3 million m^3/d, providing water for nearly 0.9 million people in Zhejiang

means that floodwaters easily accumulate but are difficult to drain (Zhang et al. 2017). Especially in the flood season, when this area is affected by typhoons and heavy rains, the demonstration area will face severe flood risk.

As an important transboundary river that flows through the provincial borders of JS, ZJ, and SH, the Taipu River is 57.6 km long and has a sluice gate (Taipu Sluice). Through control of the Taipu Sluice, the Taipu River can play a crucial role in flood control of the basin and supply water to downstream reservoirs. Approximately 3.0 billion m^3 of water annually is transported to SH and ZJ through the Taipu River, which accounts for approximately 20% of the outflow of Taihu Lake (Yao et al. 2015).

Due to the differences in socioeconomic development and the increasing demand for water resources, water distribution disputes between the upstream and downstream areas in the DAYRD have gradually intensified. In 2016, the Jinze Reservoir, located on the lower reaches of the Taipu River, was completed and began operations. It is responsible for supplying water to nearly 6.7 million residents in SH. To ensure the water safety of the two reservoirs (Jinze Reservoir and Dingzha Reservoir), SH and ZJ have put forward more stringent requirements regarding the quantity and quality of the Taipu River in the JS area. Specifically, SH and ZJ compelled JS to adopt effective measures to ensure that the water quantity and quality meet the requirements (Fig. 2). They have also asked JS to adjust the upstream industrial structure (i.e., reduce the scale of the textile printing and dyeing industry) to reduce the pollution load discharged into the Taipu River. However, considering that meeting the downstream requirements requires vast economic costs, JS hopes to maintain the status quo, unless the downstream provides economic compensation to compensate for the loss. Overall, the key issue of the water conflict in the DAYRD area is how to balance the upstream and downstream interests, i.e., to find a solution that not only achieves the downstream water safety goal but also makes up for the loss of upstream participation in protection.

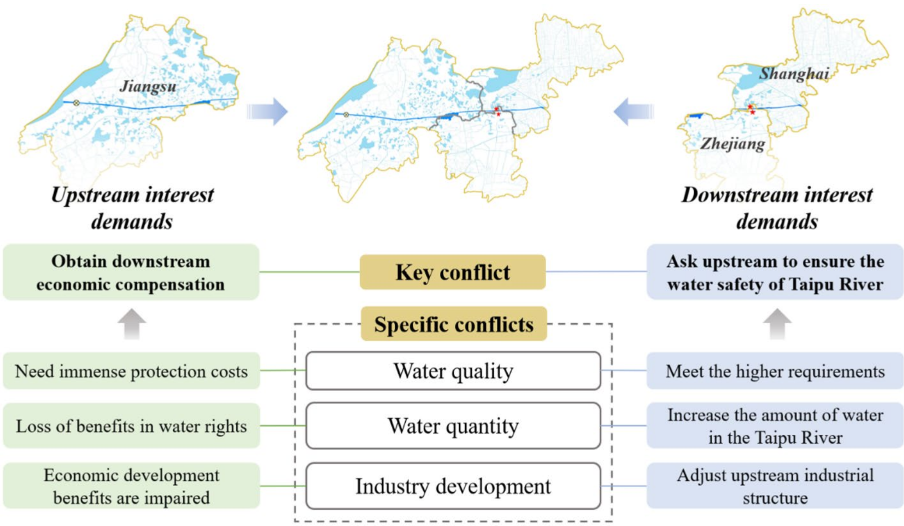

Fig. 2 Transboundary water conflicts in the DAYRD

3 Methodology

3.1 Model Framework

The overall framework of the proposed model is illustrated in Fig. 3 and includes four main components. The first part constructs the revenue function to evaluate objectively the benefits of different DMs. The second part is dedicated to modeling the water conflict in the DAYRD. In this part, based on the status quo of water conflicts in the DAYRD, DMs, strategies, and feasible states are identified, and the graph model of the improved GMCR model is illustrated. Moreover, based on the revenue function, the benefits of different strategies of local governments and the third party are evaluated to rank the preferences. In the third section, the conflict analysis results are analyzed from two aspects, stability analysis and evolutionary path of conflicts. Finally, valuable information is provided for water resource managers to resolve transboundary water conflicts.

3.2 Revenue Function

Determining the preference rankings of each DM is one of the decisive steps in conflict analysis (Dowlatabadi et al. 2020; Ke et al. 2012; Yu et al. 2019a). In general, the relative preferences of DMs are closely related to the benefits of each strategy they adopt (Garcia and Hipel 2017; Yu et al. 2015). If the benefits of strategy 1 are greater than those of strategy 2, then the DM will be more inclined to choose strategy 1 than to choose strategy 2.

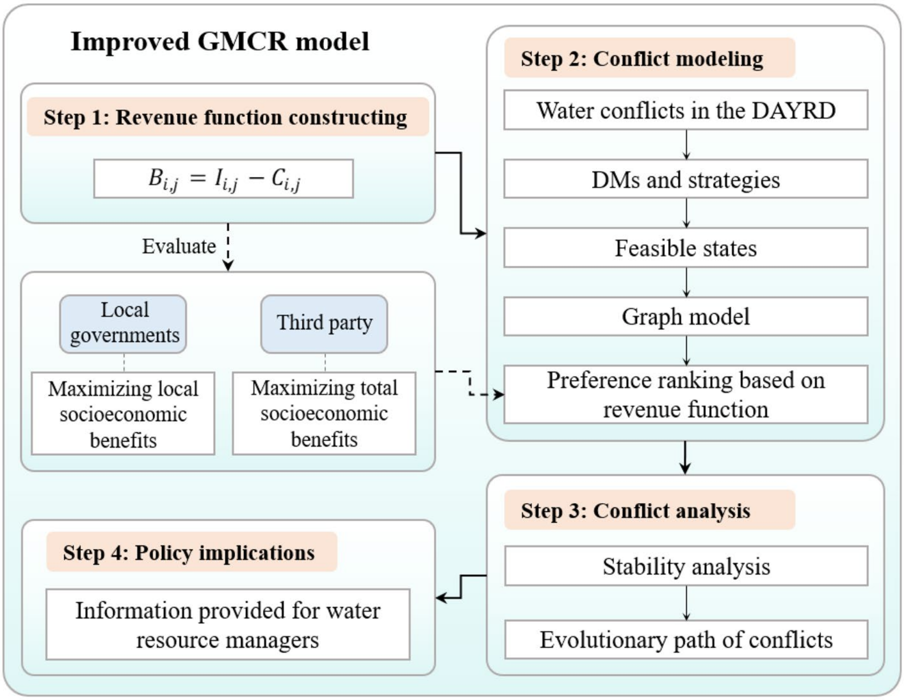

Fig. 3 Improved GMCR model for analyzing water conflicts in the DAYRD

Therefore, to accurately assess the preference rankings of DMs, the benefits and costs of each strategy should be considered.

Therefore, to accurately assess the preference rankings of DMs' strategy selection, this article constructs the following revenue function to calculate the benefits of the different strategies of DMs:

$$B_{i,j} = I_{i,j} - C_{i,j} \tag{1}$$

where $B_{i,j}$ denotes the total benefits of DM i under strategy group j; $I_{i,j}$ denotes the income of DM i under strategy group j; and $C_{i,j}$ denotes the cost of DM i under strategy group j.

3.3 Conflict Modeling Based on the Improved GMCR Approach

3.3.1 Decision-Makers and Strategies

The first step of GMCR analysis is to identify the relevant DMs and their strategies. As previously mentioned, the administrative units involved in transboundary water conflicts in the DAYRD include SH, JS Province, and ZJ Province. Since SH and ZJ have the same benefit demands, to simplify the model, they can be regarded as one DM. JS has two available strategies to choose from, "Maintain" or "Strengthen". There are also two available strategies for SH & ZJ, "Compel" or "Share". The Taihu Basin Authority (TBA), which is subordinate to the central government, can intervene in transboundary water conflicts in the DAYRD as a third party through "Persuade", "Award", and "Punish". Details about the DMs and their strategies are shown in Table 1, where Y signifies the status quo.

3.3.2 Feasible States

Theoretically, each option of three DMs can either be adopted or not. Given that seven strategies are explicated in Table 1 and that there are two cases for each strategy, "yes" or "no", there are a total of 2^7 states, i.e., 128 states. Considering that some conflicting states are unlikely to occur, infeasible states can be eliminated to reduce the complexity of the analysis process (Zanjanian et al. 2018). For example, since one DM cannot simultaneously choose two or three strategies in each state, the infeasible states need to be eliminated. Ultimately, 12 states are retained as feasible states in transboundary water conflicts (Table 2).

3.3.3 Graph Model

According to the feasible states, the graph model, i.e., the state transition diagram, can be illustrated. The graph model refers to whether the DM can move a feasible state from one state to another when the strategies of other DMs remain unchanged (Xu et al. 2019). Figure 4 illustrates the graph model of transboundary water conflicts in the DAYRD. The circle represents the feasible state, and the arrow indicates that one state can be transformed into another state. The double-headed arrow means that the two states are reversible and can be transformed into each other. For example, the transition from S1 (State 1) to S2 (State 2) means that JS changes its strategy from "Maintain" to "Strengthen" when the strategies of other DMs remain unchanged.

Table 1 Decision-makers and their strategies in transboundary water conflicts in the DAYRD

Decision-Makers		Abbreviation	Options	Strategy	Explanation	State
Local governments	Jiangsu	JS	1	Maintain	Maintaining the status quo of pollution control efforts, water supply amount, and industry scale	Y
			2	Strengthen	Strengthening pollution control, increasing water supply, and adjusting industrial structure	
	Shanghai and Zhejiang	SH & ZJ	3	Compel	Compelling JS to adopt effective measures to control water pollution and ensure the safety of the Taipu River	Y
			4	Share	Sharing the costs of JS in protecting the water safety of the Taipu River	
Third party	Taihu Basin Authority	TBA	5	Persuade	Persuading local governments to cooperate	Y
			6	Award	Rewarding local governments for cooperation, including providing pecuniary compensation or technical support	
			7	Punish	Punishing local governments for noncooperation, with the aim of increasing the cost of noncooperation	

Table 2 Feasible states in transboundary water conflicts

Decision-Makers	Strategy	States											
		1	2	3	4	5	6	7	8	9	10	11	12
JS	1. Maintain	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes	No	No	No
	2. Strengthen	No	No	No	Yes	Yes	Yes	No	No	No	Yes	Yes	Yes
SH & ZJ	3. Compel	Yes	Yes	Yes	Yes	Yes	Yes	No	No	No	No	No	No
	4. Share	No	No	No	No	No	No	Yes	Yes	Yes	Yes	Yes	Yes
TBA	5. Persuade	Yes	No	No	Yes	No	No	Yes	No	No	Yes	No	No
	6. Award	No	Yes	No	No	Yes	No	No	Yes	No	No	Yes	No
	7. Punish	No	No	Yes	No	No	Yes	No	No	Yes	No	No	Yes

3.3.4 Preference Rankings Based on Revenue Function

To rank the DMs' preferences, it is necessary to calculate the different strategy benefits of the DMs according to the revenue function. In general, in the process of transboundary water resource allocation, the river basin management authority pays attention to total regional socioeconomic benefits, while local governments pursue the maximization of local economic benefits (Chen et al. 2017). Based on the benefit demands and

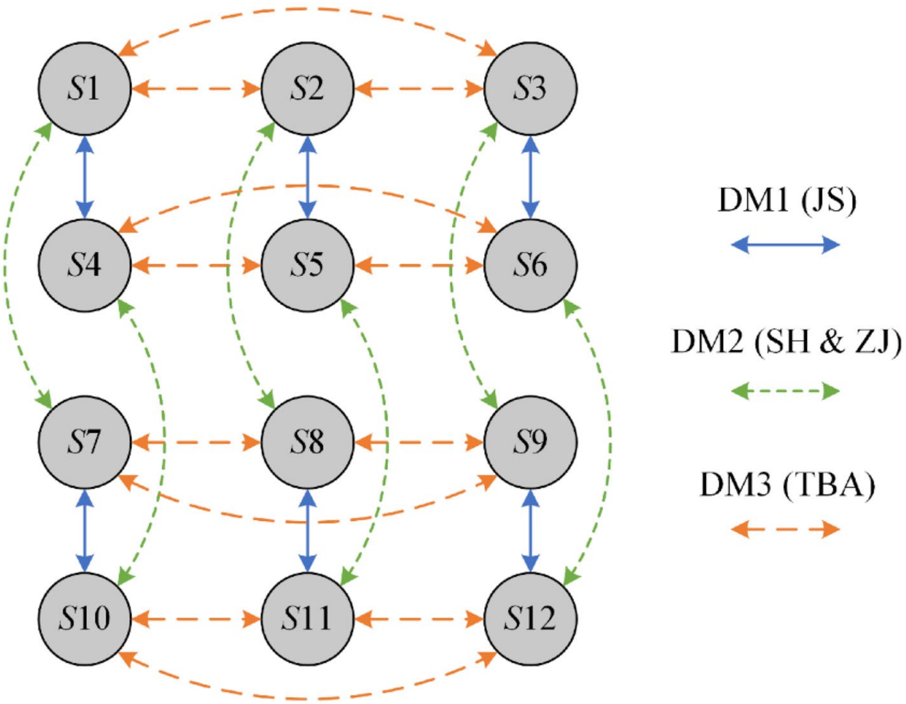

Fig. 4 Graph model of transboundary water conflicts

goals of DMs and Eq. (1), the benefits of the different strategies of JS, SH & ZJ, and the TBA are evaluated.

For local governments (JS and SH & ZJ), the process of calculating the benefits is as follows:

$$LocalB_{JS,j} = I_{JS,j} - C_{JS,j} \tag{2}$$

$$LocalB_{SH\&ZJ,j} = I_{SH\&ZJ,j} - C_{SH\&ZJ,j} \tag{3}$$

where $LocalB_{JS,j}$ and $LocalB_{SH\&ZJ,j}$ represent the local economic costs and benefits of JS and SH & ZJ under strategy group j, respectively; $I_{JS,j}$ and $I_{SH\&ZJ,j}$ represent the income of JS and SH & ZJ under strategy group j, respectively; $C_{JS,j}$ and $C_{SH\&ZJ,j}$ represent the cost of JS and SH & ZJ under strategy group j, respectively; and j represents the different strategy groups, i.e., feasible states.

For the third party (TBA), the total regional socioeconomic benefits are the priority goal, while economic costs and incomes are secondary considerations. The process of calculating the benefits of the TBA is as follows:

$$Primary\ object : TotalB^P_{TBA,j} = I^P_{TBA,j} - C^P_{TBA,j} \tag{4}$$

$$Secondary\ object : TotalB^S_{TBA,j} = I^S_{TBA,j} - C^S_{TBA,j} \tag{5}$$

where $TotalB^P_{TBA,j}$ and $TotalB^S_{TBA,j}$ represent the total regional socioeconomic benefits and the income and costs of the TBA under strategy group j, respectively; $I^P_{TBA,j}$ and $I^S_{TBA,j}$ represent the total benefits brought by local governments through taking cooperative actions and the income of the TBA, respectively; and $C^P_{TBA,j}$ and $C^S_{TBA,j}$ represent the total costs brought by local governments through taking uncooperative actions and the costs of the TBA, respectively.

Table 3 presents and explains the benefit parameters of the different DMs' strategies according to traditional game models (Yu et al. 2019b; Yuan et al. 2020).

Table 3 Benefit parameters of DMs' different strategies

Parameter	Explanation
B_1	When JS chooses strategy 2 (Strengthen), the socioeconomic benefits that the TBA can obtain
B_2	When SH & ZJ choose strategy 4 (Share), the socioeconomic benefits that the TBA can obtain
P	The punishment amount imposed on JS and SH & ZJ when the TBA chooses strategy 7 (Punish)
A	The reward amount for JS and SH & ZJ when the TBA chooses strategy 6 (Award)
C	The total protection costs that JS needs to pay when choosing strategy 2 (Strengthen)
S	Part of the total protection costs that JS needs SH & ZJ to share when SH & ZJ choose strategy 4 (Share)
D	When JS chooses strategy 2 (Strengthen), the benefits that SH & ZJ can obtain due to the safety of the water supply

Each benefit parameter is assumed based on the assumptions of Yu et al. (2019b) and Yuan et al. (2020) regarding the payoff of DMs in game models. B_1, B_2, P, A, C, S, D are all greater than 0

4 Results and Discussion

4.1 Ranking of the Relative Preferences

Figure 5 shows the benefits of DMs in different feasible states of transboundary water conflicts in the DAYRD.

The benefits of local governments under different strategies include C, D, S, A, and P, as shown in Table 3. To determine the preference rankings, the sizes of different parameters should be compared. First, the safety of the water supply for millions of residents should be a priority. Thus, D is greater than C, the protection cost of JS. Next, the S that SH & ZJ share with JS should be part of C. Because when $S \geq C$, the cost of protection is completely borne by SH & ZJ, which is hard to achieve, as doing so does not meet the goal of regional co-construction and sharing nor serve the interests of SH & ZJ. Moreover, although providing rewards is a vital means for prompting DMs to take cooperative actions, the reward amount usually needs to be large enough to be effective, which places enormous pressure on managers due to the economic costs. Considering the regional development goal of the DAYRD and the economic pressure of the TBA, the reward amount should be less than S, i.e., $S > A$.

P, the punishment amount of the TBA, which represents the intensity of TBA intervention, is discussed under different situations. Considering the influence of the size of P, C, and S on the stable states of conflicts, the relationships between the size of P, C, and S are divided into four cases for in-depth discussion: I: $P \geq C > S$; II: $C > P > S$ and $P > C\text{-}S$; III: $C > P > S$ and $P \leq C\text{-}S$; IV: $S \geq P > 0$ (Table 4).

In addition, for the TBA, there is a relationship between the benefit values of its different strategies: $B_1 + B_2 > B_1 > B_2 >> P$ (or A). Because the implementation of strategy 2 (Strengthen) can effectively ensure the safety of the downstream water supply, while strategy 4 (Share) is only conducive to the cooperation of local governments, the safety benefits of the downstream water supply are the greatest for the DAYRD. Moreover, the TBA pays considerably more attention to total regional socioeconomic benefits than to its economic costs and benefits. Given the uncertainty of the size among different benefit parameters, the various possible benefits rankings of DMs in the four cases are shown in Table 4. According to Table 4, there are 26 combinations of DM preference rankings, provided as 26 scenarios in Table S1 (See Supplementary Material).

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
JS	Maintain	0	0	-P	/	/	/	0	0	-P	/	/	/
	Strengthen	/	/	/	-C	A-C	-C	/	/	/	S-C	A+S-C	S-C
SH & ZJ	Compel	0	0	-P	D	D	D-P	/	/	/	/	/	/
	Share	/	/	/	/	/	/	-S	A-S	-S	D-S	A+D-S	D-S
TBA	Persuade	0	/	/	B_1	/	/	B_2	/	/	B_1+B_2	/	/
	Award	/	0	/	/	B_1-A	/	/	B_2-A	/	/	B_1+B_2 -2A	/
	Punish	/	/	2P	/	/	B_1+P	/	/	B_2+P	/	/	B_1+B_2

Fig. 5 The benefits of DMs in different states. Each benefit parameter is presented and explained in Table 3. In states 7, 8, and 9, because JS does not choose actions that are conducive to cooperation, JS cannot obtain the money shared by SH & ZJ. "/" means no data

Table 4 Benefits rankings of DMs with different sizes of P

Case	Different sizes of P	DMs	Benefits rankings
I	$P \geq C > S$	JS	$0 > A+S-C > S-C > A-C > -C \geq -P$
			$A+S-C \geq 0 > S-C > A-C > -C \geq -P$
		SH & ZJ	$D > A+D-S > D-S > D-P \geq 0 > A-S > -S > -P$
			$D > A+D-S > D-S > 0 > D-P \geq A-S > -S > -P$
			$D > A+D-S > D-S > 0 > A-S > D-P \geq -S > -P$
			$D > A+D-S > D-S > 0 > A-S > -S > D-P > -P$
		TBA	$B_1+B_2 > B_1+B_2-2A > B_1+P > B_1 > B_1-A > B_2+P > B_2 > B_2-A > 2P > 0$
II	$C > P > S$; $P > C-S$	JS	$0 > A+S-C > S-C > A-C > -P > -C$
			$0 > A+S-C > S-C > -P \geq A-C > -C$
			$A+S-C \geq 0 > S-C > A-C > -P > -C$
			$A+S-C \geq 0 > S-C > -P \geq A-C > -C$
		SH & ZJ	$D > A+D-S > D-S > D-P > 0 > A-S > -S > -P$
		TBA	$B_1+B_2 > B_1+B_2-2A > B_1+P > B_1 > B_1-A > B_2+P > B_2 > B_2-A > 2P > 0$
III	$C > P > S$; $P \leq C-S$	JS	$0 > A+S-C > -P \geq S-C > A-C > -C$
			$A+S-C \geq 0 > -P \geq S-C > A-C > -C$
		SH & ZJ	$D > A+D-S > D-S > D-P > 0 > A-S > -S > -P$
		TBA	$B_1+B_2 > B_1+B_2-2A > B_1+P > B_1 > B_1-A > B_2+P > B_2 > B_2-A > 2P > 0$
IV	$S \geq P > 0$	JS	$0 > A+S-C > S-C > A-C > -P > -C$
			$0 > A+S-C > S-C > -P \geq A-C > -C$
			$A+S-C \geq 0 > S-C > A-C > -P > -C$
			$A+S-C \geq 0 > S-C > -P \geq A-C > -C$
			$0 > A+S-C > -P \geq S-C > A-C > -C$
			$A+S-C \geq 0 > -P \geq S-C > A-C > -C$
		SH & ZJ	$D > A+D-S > D-P > D-S > 0 > A-S > -P \geq -S$
			$D > A+D-S > D-P > D-S > 0 > -P \geq A-S > -S$
		TBA	$B_1+B_2 > B_1+B_2-2A > B_1+P > B_1 > B_1-A > B_2+P > B_2 > B_2-A > 2P > 0$

4.2 Stability Analysis

Based on the definitions of four kinds of stability concepts (See Supplementary Material for Table S2) (Fang et al. 2003b; Kilgour and Hipel 2005), we evaluate the equilibrium and stability of the states of DMs in each scenario under the four cases. As shown in Table 5, there are strong equilibrium states which satisfy all solution concepts in cases I, II, and III, i.e., state 9, 9, and 12. However, no equilibrium state simultaneously satisfies the four solution conceptions in case IV. Since there is a significant difference between states 9 and 12, we need to evaluate the strategy of each DM in both states to judge which equilibrium state is the best for solving transboundary water conflicts. The difference between state 9 and state 12 mainly lies in the different strategic choices of JS. In state 12, JS adopts the strategy of strengthening pollution control, increasing the water supply, and adjusting the industrial structure. SH & ZJ choose the strategy of sharing the costs with JS, and the TBA selects the strategy of punishing local governments for noncooperation;

Table 5 Stability analysis results

Case	Different sizes of P	Scenario	State	Equilibrium			
				Nash	**GMR**	**SMR**	**SEQ**
I	P ≥ C > S	s1, s2, s3, s4, s5, s6, s7, s8	S12	Y	Y	Y	Y
II	C > P > S; P > C-S	s9, s10, s11, s12	S12	Y	Y	Y	Y
III	C > P > S; P ≤ C-S	s13, s14	S9	Y	Y	Y	Y
IV	S ≥ P > 0	s15, s16, s17, s18, s19, s20, s21, s22, s23, s24, s25, s26	None	/	/	/	/

"Y" means satisfying the solution concept. "/" means no data

hence, conflicts will be resolved. However, in state 9, JS chooses the strategy of maintaining the status quo, which not only fails to ensure the safety of the water supply but also exacerbates the water conflicts. Therefore, state 12 is the optimal solution to transboundary water conflicts, which means that the TBA needs to increase and control its punishment intensity, i. e., P > S and P > C-S (the punishment amount should be greater than the protection costs shared by SH & ZJ or JS).

4.3 Evolutionary Path of Conflicts

Figure 6 demonstrates the evolutionary path of transboundary water conflicts in the DAYRD from state 1 to equilibrium state 12. To solve the water conflicts in the DAYRD,

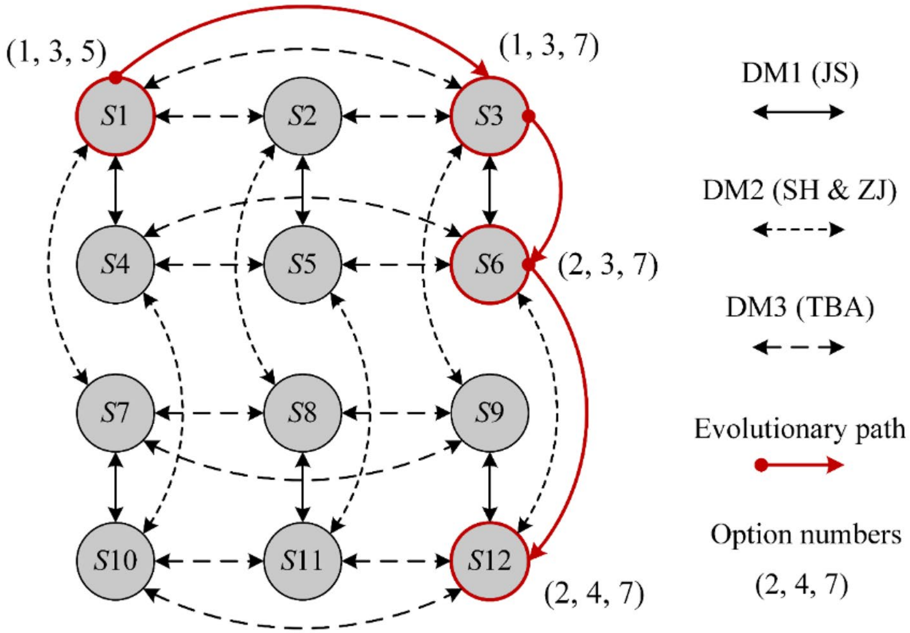

Fig. 6 Evolutionary path of transboundary water conflicts

the central government can empower the TBA with a higher power, i.e., the TBA can issue policies of rewards and punishments to prompt local governments to take cooperative measures. When the TBA chooses the punishment strategy based on overall benefits, the conflict will move from state 1 to state 3. After learning about the TBA's actions, JS will be more inclined to choose the strategy of strengthening rather than the strategy of maintaining the status quo, thereby evolving the conflict from state 3 into state 6. In such situations, considering the consequences of being punished, SH & ZJ have to choose the strategy of sharing to avoid further losses. Therefore, the conflict ultimately reaches equilibrium state 12 from state 6. The evolution of the conflict states is shown in Table S3 (See Supplementary Material).

4.4 Advantages Over Traditional Methods

Our research results indicate that compared with traditional approaches, the improved GMCR model has the following two advantages.

First, the traditional preference assessment methods in the GMCR, i.e., direct ranking, option prioritizing, and option weighting, are easily affected by subjective factors such as the cognitions, attitudes, and values of researchers or experts. If a researcher does not provide reasonable and sufficient preference statements, or if the assessment is conducted by different researchers or experts, the preference ranking results are very likely to be different (Zhao and Xu 2019). In addition, most cooperative or noncooperative game models focus only on performing qualitative analysis of water conflicts without considering the dynamic evolution of such conflicts (Yuan et al. 2020; Zomorodian et al. 2017). Although some studies use a system dynamics model to realize the dynamic simulation of water conflict, these models focus only on future scenarios of water conflict under different initial conditions and fail to consider the influence of DMs' preferences and decision behavior on the evolution of conflict (Tayia 2019; Wang et al. 2018; Zomorodian et al. 2017). However, the improved GMCR model proposed in this paper based on strategy benefits can not only objectively evaluate the relative preferences of DMs but also simulate the dynamic evolutionary path of conflicts.

Second, the existing analytical studies on third-party intervention in conflicts have sought mainly to prove the importance of third parties but have rarely quantitatively identified the appropriate intensity of third-party intervention for resolving transboundary water conflicts (Han et al. 2019; Kinsara et al. 2012; Yu et al. 2015; Zanjanian et al. 2018). However, the improved GMCR model presented in this study can identify the appropriate intensity of third-party intervention. The results show that when the punishment intensity of the third party is greater than the cost of protection shared by local governments ($P>S$ and $P>C-S$), the transboundary water conflicts in the DAYRD can be resolved. These findings can provide feasible approaches for water conflict resolution in other regions, such as third-party mediation.

4.5 Policy Implications

Based on the analysis results, this paper attempts to propose a feasible solution to the transboundary water conflict in the DAYRD as follows.

(1) Giving the third party higher authority.

To achieve the desired resolution, the participation of a third party with a higher power in the conflict is effective (Hipel et al. 2014; Zanjanian et al. 2018). It is necessary to give the third party (TBA) higher authority, relying on the DAYRD policy enacted by the central government. River basin management authorities such as the TBA with higher power can formulate reasonable laws and regulations (Yu et al. 2015), such as punishment mechanisms and eco-compensation mechanisms, which can positively guide upstream and downstream local governments to adopt cooperative strategies. In addition, the TBA can establish a leading group that can provide a platform for upstream and downstream local governments to express their demands directly and effectively, i.e., those regarding water quality, water quantity, and economic benefits.

(2) Enacting reasonable laws and regulations.

The establishment of river basin organizations and the signing of agreements (treaties) are considered to be ways to effectively reduce the possibility of water conflicts (Petersen-Perlman et al. 2017). Once stakeholders understand how relevant laws and regulations affect their benefits, they are more motivated to consider actions that are conducive to cooperation (Acemoglu and Wolitzky 2014; Yu et al. 2019b). As a third party with higher powers, the river basin management authority will be able to formulate a reasonable punishment system, and the punishment amount should be greater than the protection costs shared by local governments to prompt local governments to take cooperative actions. In addition, to ensure that the water quality of the transboundary river meets standards, a system of unified goals, unified monitoring, and unified supervision should be enacted.

(3) Establishing an eco-compensation mechanism.

In the process of water sharing, it is necessary not only to consider the benefits of different DMs but also to clarify their respective obligations (Yuan et al. 2020). The principle of fair and reasonable distribution is the basis for resolving most water sharing conflicts (Lankford 2013). As a market mechanism, ecological compensation is conducive to coordinating the benefits of different DMs and promoting cooperative development (Liu and Mao 2020; Sun et al. 2017). Therefore, a fair and reasonable eco-compensation mechanism, led and supervised by the river basin management authority, should be established in the DAYRD. Specifically, on the basis of considering regional rainfall characteristics and initial water rights allocation, the TBA should objectively evaluate the benefit loss of the upstream and the share that the downstream should bear to formulate a reasonable ecological compensation standard.

5 Conclusions

This paper presents an improved GMCR model for objectively simulating the dynamic evolution of transboundary water conflicts. The applied methodology is the first to integrate the revenue function into the graph model for conflict resolution method. Moreover, the optimal third-party intervention intensity and the optimal conflict evolution path are identified. The introduced model is examined in the DAYRD in China.

The results show that the improved GMCR model based on the revenue function can not only simulate the dynamic evolution of transboundary water conflicts but also improve the limitations of the subjective judgment of researchers or experts in traditional methods. The results also demonstrate that reasonable punitive measures imposed by the third party help to reduce the possibility of water conflicts, consequently enhancing the stability of regional cooperation and regional sustainable development. These results confirm the applicability and effectiveness of the improved method in the simulation and resolution of transboundary water conflicts. Therefore, the proposed model can provide valuable information for the design of feasible water management strategies for other transboundary rivers by simulating the dynamic evolution of different stakeholder behaviors and regulating the intervention intensity of third parties.

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Declarations

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References

Acemoglu D, Wolitzky A (2014) Cycles of Conflict: An Economic Model. Am Eco Rev 104:1350–1367. https://doi.org/10.1257/aer.104.4.1350

Ali S, Xu H, Al-amin AQ, Ahmad N (2019) Energy sources choice and environmental sustainability disputes: an evolutional graph model approach. Quality Quantity 53:561–581. https://doi.org/10.1007/s11135-018-0775-9

Chen YZ, Lu HW, Li J, Ren LX, He L (2017) A leader-follower-interactive method for regional water resources management with considering multiple water demands and eco-environmental constraints. J Hydrol 548:121–134. https://doi.org/10.1016/j.jhydrol.2017.02.015

Chu Y, Hipel KW, Fang LP, Wang HM (2015) Systems methodology for resolving water conflicts: the Zhanghe River water allocation dispute in China. Intern J Water Resour Develop 31:106–119. https://doi.org/10.1080/07900627.2014.933096

Degefu DM, He WJ, Yuan L, Zhao JH (2016) Water Allocation in Transboundary River Basins under Water Scarcity: a Cooperative Bargaining Approach. Water Resour Manag 30:4451–4466. https://doi.org/10.1007/s11269-016-1431-6

Di D, Wu Z, Wang H, Lv C (2020) A Double-Layer Dynamic Differential Game Model for the Optimal Trading Quantity of Water and Price Setting in Water Rights Transactions. Water Resour Manag 34:245–262. https://doi.org/10.1007/s11269-019-02437-y

Dong Q, Zhang X, Chen Y, Fang D (2019) Dynamic Management of a Water Resources-Socioeconomic-Environmental System Based on Feedbacks Using System Dynamics. Water Resour Manag 33:2093–2108. https://doi.org/10.1007/s11269-019-02233-8

Dowlatabadi N, Banihabib ME, Roozbahani A, Randhir TO (2020) Enhanced GMCR model for resolving conflicts in a transboundary wetland. Sci Total Environ 744:140816. https://doi.org/10.1016/j.scitotenv.2020.140816
Du JL, Liu Y, Forrest JYL (2019) An interactive group decision model for selecting treatment schemes for mitigating air pollution. Environ Sci Pollut Res 26:18687–18707. https://doi.org/10.1007/s11356-019-05072-7
Fang LP, Hipel KW, Kilgour DM, Peng XY (2003a) A decision support system for interactive decision making - part I: Model formulation. IEEE Transactions on Systems, Man, and Cybernetics. Part C (applications and Reviews) 33:42–55. https://doi.org/10.1109/Tsmcc.2003.809361
Fang LP, Hipel KW, Kilgour DM, Peng XY (2003b) A decision support system for interactive decision making - Part II: analysis and output interpretation. IEEE Transactions on Systems, Man, and Cybernetics. Part C (applications and Reviews) 33:56–66. https://doi.org/10.1109/TSMCC.2003.809360
Garcia A, Hipel KW (2017) Inverse engineering preferences in simple games. Appl Math Comput 311:184–194. https://doi.org/10.1016/j.amc.2017.05.016
Garrick DE, De Stefano L (2016) Adaptive capacity in federal rivers: coordination challenges and institutional responses. Current Opinion Environ Sustain 21:78–85. https://doi.org/10.1016/j.cosust.2016.11.003
Geressu RT, Harou JJ (2015) Screening reservoir systems by considering the efficient trade-offs—informing infrastructure investment decisions on the Blue Nile. Environ Res Let 10:125008. https://doi.org/10.1088/1748-9326/10/12/125008
Han QY, Zhu YM, Ke GY, Lin HL (2019) A Two-Stage Decision Framework for Resolving Brownfield Conflicts. Intern J Environ Res Pub Health 16:1039. https://doi.org/10.3390/ijerph16061039
He SW, Hipel KW, Xu HY, Chen Y (2020) A Two-Level Hierarchical Graph Model for Conflict Resolution with Application to International Climate Change Negotiations. J Syst Sci Syst Eng 29:251–272. https://doi.org/10.1007/s11518-019-5448-2
Hipel K, Kilgour DM, Kinsara RA (2014) Strategic Investigations of Water Conflicts in the Middle East. Group Decision and Negotiation 23:355–376. https://doi.org/10.1007/s10726-012-9325-3
Ke GY, Li KW, Hipel KW (2012) An integrated multiple criteria preference ranking approach to the Canadian west coast port congestion conflict. Expert Syst App 39:9181–9190. https://doi.org/10.1016/j.eswa.2012.02.086
Kilgour DM, Hipel KW (2005) The graph model for conflict resolution: Past, present, and future. Group Decision and Negotiation 14:441–460. https://doi.org/10.1007/s10726-005-9002-x
Kilgour DM, Hipel KW, Fang L (1987) The graph model for conflicts. Automatica, 23: 41–55. https://doi.org/10.1016/0005-1098(87)90117-8
Kinsara RA, Kilgour DM, Hipel KW (2012) Conflict resolution and mediation. IEEE International Conference on Systems, Man, and Cybernetics (SMC), 2780–2784. https://doi.org/10.1109/ICSMC.2012.6378169
Langenegger TW, Hipel KW (2019) The Strategy of Escalation and Negotiation: The Iran Nuclear Dispute. J Syst Sci Syst Eng 28:434–448. https://doi.org/10.1007/s11518-019-5421-0
Lankford B (2013) Does Article 6 (Factors Relevant to Equitable and Reasonable Utilization) in the UN Watercourses Convention misdirect riparian countries? Water Intern 38:130–145. https://doi.org/10.1080/02508060.2013.780687
Li KW, Levy JK, Buckley P (2009) Enhancing National Security and Energy Security in the Post-911 Era: Group Decision Support for Strategic Policy Analysis under Conditions of Conflict. Group Decis Negot 18:369–386. https://doi.org/10.1007/s10726-008-9147-5
Liu Y, Mao D (2020) Integrated assessment of water quality characteristics and ecological compensation in the Xiangjiang River, south-central China. Ecol Indic 110: 105922. https://doi.org/10.1016/j.ecolind.2019.105922
Lu YL, Jenkins A, Ferrier RC, Bailey M, Gordon IJ, Song S et al (2015) Addressing China's grand challenge of achieving food security while ensuring environmental sustainability. Sci Adv 1:e1400039. https://doi.org/10.1126/sciadv.1400039
Madani K, Sheikhmohammady M, Mokhtari S, Moradi M, Xanthopoulos P (2014) Social Planner's Solution for the Caspian Sea Conflict. Group Decis Negot 23:579–596. https://doi.org/10.1007/s10726-013-9345-7
Nandalal KDW, Simonovic SP (2003) Resolving conflicts in water sharing: A systemic approach. Water Resour Res 39. https://doi.org/10.1029/2003WR002172
Nazari S, Ahmadi A, Kamrani Rad S, Ebrahimi B (2020) Application of non-cooperative dynamic game theory for groundwater conflict resolution. J Environ Manag 270: 110889. https://doi.org/10.1016/j.jenvman.2020.110889

Petersen-Perlman JD, Veilleux JC, Wolf AT (2017) International water conflict and cooperation: challenges and opportunities. Water Intern 42:105–120. https://doi.org/10.1080/02508060.2017.1276041

Philpot S, Hipel K, Johnson P (2016) Strategic analysis of a water rights conflict in the south western United States. J Environ Manag 180:247–256. https://doi.org/10.1016/j.jenvman.2016.05.027

Shi GM, Wang JN, Zhang B, Zhang Z, Zhang YL (2016) Pollution control costs of a transboundary river basin: Empirical tests of the fairness and stability of cost allocation mechanisms using game theory. J Environ Manag 177:145–152. https://doi.org/10.1016/j.jenvman.2016.04.015

Sun J, Dang Z, Zheng S (2017) Development of payment standards for ecosystem services in the largest interbasin water transfer projects in the world. Agric Water Manag 182: 158–164. https://doi.org/10.1016/j.agwat.2016.06.025

Taravatrooy N, Nikoo MR, Adamowski JF, Khoramshokooh N (2019) Fuzzy-based conflict resolution management of groundwater in-situ bioremediation under hydrogeological uncertainty. J Hydrol 571:376–389. https://doi.org/10.1016/j.jhydrol.2019.01.063

Tarebari H, Javid AH, Mirbagheri SA, Fahmi H (2018) Multi-Objective Surface Water Resource Management Considering Conflict Resolution and Utility Function Optimization. Water Resour Manag 32:4487–4509. https://doi.org/10.1007/s11269-018-2051-0

Tayia A (2019) Transboundary Water Conflict Resolution Mechanisms: Substitutes or Complements. Water 11:1337 https://doi.org/10.3390/w11071337

UN Water (2013) Transboundary waters. https://www.unwater.org/water-facts/transboundary-waters. Accessed 1 Jun 2021

Veldkamp TIE, Wada Y, Aerts JCJH, Doll P, Gosling SN, Liu J et al (2017) Water scarcity hotspots travel downstream due to human interventions in the 20th and 21st century. Nat Commun 8:15697. https://doi.org/10.1038/ncomms15697

Walker SB, Hipel KW (2017) Strategy, Complexity and Cooperation: The Sino-American Climate Regime. Group Decis Negot 26:997–1027. https://doi.org/10.1007/s10726-017-9528-8

Wang H, Zhang J, Zeng W (2018) Intelligent simulation of aquatic environment economic policy coupled ABM and SD models. Sci Total Environ 618: 1160–1172. https://doi.org/10.1016/j.scitotenv.2017.09.184

Wei S, Yang H, Abbaspour K, Mousavi J, Gnauck A (2010) Game theory based models to analyze water conflicts in the Middle Route of the South-to-North Water Transfer Project in China. Water Res 44:2499–2516. https://doi.org/10.1016/j.watres.2010.01.021

Xu L, Zhang Q, Shi XP (2019) Stakeholders strategies in poverty alleviation and clean energy access: A case study of China's PV poverty alleviation program. Energy Policy 135:111011. https://doi.org/10.1016/j.enpol.2019.111011

Yao H, Qian X, Yin H, Gao H, Wang Y (2015) Regional Risk Assessment for Point Source Pollution Based on a Water Quality Model of the Taipu River, China. Risk Analysis 35: 265–277. https://doi.org/10.1111/risa.12259

Yin KD, Yu L, Li XM (2017) An Improved Graph Model for Conflict Resolution Based on Option Prioritization and Its Application. Intern J Environ Res Pub Health 14:1311. https://doi.org/10.3390/ijerph14111311

Yu J, Hipel KW, Kilgour DM, Fang LP (2019a) Fuzzy levels of preference strength in a graph model with multiple decision makers. Fuzzy Sets Syst 377:71–84. https://doi.org/10.1016/j.fss.2018.12.016

Yu J, Kilgour DM, Hipel KW, Zhao M (2015) Power asymmetry in conflict resolution with application to a water pollution dispute in China. Water Resour Res 51:8627–8645. https://doi.org/10.1002/2014wr016257

Yu Y, Tang PZ, Zhao JS, Liu B, Mclaughlin D (2019) Evolutionary Cooperation in Transboundary River Basins. Water Resour Res 55:9977–9994. https://doi.org/10.1029/2019wr025608

Yuan L, He WJ, Degefu DM, Liao ZY, Wu X, An M et al (2020) Transboundary water sharing problem; a theoretical analysis using evolutionary game and system dynamics. J Hydrol 582:124521. https://doi.org/10.1016/j.jhydrol.2019.124521

Zanjanian H, Abdolabadi H, Niksokhan MH, Sarang A (2018) Influential third party on water right conflict: A Game Theory approach to achieve the desired equilibrium (case study: Ilam dam, Iran). J Envirn Manag 214:283–294. https://doi.org/10.1016/j.jenvman.2018.03.023

Zhang H, Liu S, Ye J, Yeh PJF (2017) Model simulations of potential contribution of the proposed Huangpu Gate to flood control in the Lake Taihu basin of China. Hydrol Earth Syst Sci 21:5339–5355. https://doi.org/10.5194/hess-21-5339-2017

Zhao SN, Xu HY (2019) A Novel Preference Elicitation Technique Based on a Graph Model and Its Application to a Brownfield Redevelopment Conflict in China. Intern J Environ Res Pub Health 16:4088. https://doi.org/10.3390/ijerph16214088

Zomorodian M, Lai SH, Homayounfar M, Ibrahim S, Pender G (2017) Development and application of coupled system dynamics and game theory: A dynamic water conflict resolution method. PLoS One 12:e0188489. https://doi.org/10.1371/journal.pone.0188489