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

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Resolving transboundary water conflicts: Dynamic Evolutionary analysis using an improved GMCR model

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Abstracts

Accurately and objectively simulating the dynamic evolution of the behaviors of different decision-makers (DMs) is essential for identifying solutions to transboundary water conflicts. This research proposes an improved Graph Model for Conflict Resolution (GMCR) based on the benefits of DMs' behaviors to model the dynamic evolution of transboundary water conflicts. Additionally, the influence of third-party intervention on conflicts is investigated in depth. A demonstration area in the Yangtze River Delta on ecologically friendly development (DAYRD) in China is taken as the case study area. The results indicate that the improved GMCR model based on the benefit function can not only clearly identify the dynamic evolution path of transboundary water conflicts into cooperation, but also effectively avoid the

influence of the subjective factors of researchers or experts in traditional methods. In addition, a third party with higher powers is the key to resolving transboundary water conflicts in the DAYRD. The implementation of punishment measures by a third party can change the status quo of water conflicts and boost effective cooperation among governments. The punishment amount should be greater than the protection costs shared by local governments. These findings provide experience 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; Third party; Yangtze River Delta

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). Easily triggered transboundary water conflicts 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). On the one hand, the causes of transboundary water conflicts are the different interests of stakeholders in flood

control, water quantity, water quality or shipping, as well as economic development and protection costs (Yu et al., 2015; Yu et al., 2019b). The severity and complexity of transboundary water conflicts are determined by these interests (Yuan et al., 2020). If the interests and needs of stakeholders are not well coordinated, a water conflict will become deadlocked or grow even worse (Wei et al., 2010). On the other hand, conflicts, including transboundary water conflicts, are characterized by dynamic evolution (Ali et al., 2019; Yuan et al., 2020). In a conflict, when a decision-maker (DM) changes its strategic behavior, other DMs will make corresponding strategic 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 are essential for finding approaches to resolve transboundary water conflicts and promoting regional cooperation and sustainable development (UN Water, 2013; Veldkamp et al., 2017; Yu et al., 2019b).

As an effective method of resolving conflicts over complicated environmental issues between multiple DMs, game theory can achieve a more realistic simulation of the interest-based decision-making behavior of stakeholders (Dowlatabadi et al., 2020; Madani, 2010; Shi et al., 2016). Although cooperative and non-cooperative game models are generally used to analyze water conflicts, many of them are qualitative analyses that do not consider the dynamic evolutionary characteristics of conflict (Yuan et al., 2020; Zomorodian et al., 2017). The Graph Model for Conflict Resolution (GMCR) (Kilgour et al., 1987), which is a conflict resolution method developed based on classical game theory (Von Neumann and Morgenstern, 1944), can simulate the

dynamic evolution of the behavior of DMs (Kilgour and Hipel, 2005). The GMCR also has the advantages of simpler modeling and analysis processes and less user input information (Han et al., 2019). The GMCR analysis process commonly includes identifying the DMs and their decision sets, determining all feasible states, illustrating allowable state transitions (graph model), ranking the relative preferences, and finding the equilibrium points (stability analysis) (Fang et al., 2003a; Yu et al., 2015; Zanjanian et al., 2018). Currently, the GMCR has been widely used in water conflict research on, for example Devils Lake water conflict in America (Ma et al., 2011), Zhanghe River water allocation dispute in China (Chu et al., 2015), and Snake Valley groundwater allocation dispute in America (Philpot et al., 2016). Moreover, some studies have analyzed the efficacy of third-party intervention in transboundary water conflicts and shown that influential third parties can move conflicts towards the optimal state (Hipel et al., 2014; Yu et al., 2015; Zanjanian et al., 2018).

These previous studies show that the GMCR can conduct logical analysis and simulation of the evolution of decision-making behavior for many realistic water conflict issues (Dowlatabadi et al., 2020) as well as provide appropriate strategic guidance for resolving transboundary water conflicts (Fang et al., 2003a; Hipel et al., 2020; Yu et al., 2019a). However, at least two aspects can be substantially improved. First, determining the relative preferences of DMs is the most critical part of conflict analysis, as they determine the final equilibrium state of conflicts (Dowlatabadi et al., 2020; Ke et al., 2012; Zanjanian et al., 2018). The three commonly used preference ranking methods of the GMCR (option weighting, option prioritizing, and direct

ranking) 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). Although these approaches of the GMCR have the advantages of simplicity and usability, the evaluation results are easily affected by subjective factors such as the cognitions, attitudes, and values of researchers or experts (Zhao and Xu, 2019). Based on classical game theory, a change in the strategy options of DMs is determined by the benefits of strategic behavior (Madani, 2010; Nazari et al., 2020). Therefore, the preference ranking method based on the benefits of strategic behavior can more objectively simulate the relative preferences of DMs in real conflicts. Second, existing studies only confirm the importance of third-party intervention in achieving conflict resolution. The issues of how a conflict evolves after a third party intervenes, and under what circumstances the third party can move the conflict towards the optimal equilibrium state (cooperation) remain to be studied in depth.

The Yangtze River Delta is one of the largest economic center in China, and in 2018, the integrated regional development of the Yangtze River Delta was made a national strategy of China (The Central People's Government, 2018). Shanghai (SH), Jiangsu (JS), Zhejiang (ZJ), and Anhui are located in the Yangtze River Delta. Since the end of the last century, transboundary water conflicts have arisen between SH, JS, and ZJ. The three local governments have fallen into deadlock due to their different interests in flood control and drainage, water supply, and the water environment during the process of water resource sharing. However, in December 2019, to promote the high-quality integrated development of the Yangtze River Delta, the State Council of China

issued a policy to establish a demonstration area (DAYRD) in the junction area of SH, JS, and ZJ (The State Council, 2019). The implementation of the demonstration area policy places higher requirements for the effective resolution of transboundary water conflicts in the Yangtze River Delta. Therefore, coordinating the benefit demands with regard to water resource distribution between different DMs in the DAYRD and finding an effective and stable solution to transboundary water conflicts are crucial issues for the Yangtze River Delta to achieve high-quality integrated development.

The primary goal of this study is to construct a benefit-based preference ranking method to improve the GMCR model to simulate the dynamic evolution of transboundary water conflicts in the DAYRD. The specific objectives are to i) construct a preference ranking method based on the benefits of strategic behavior to improve the GMCR model; ii) apply the improved GMCR model to simulate the dynamic evolution of the strategic behaviors of DMs in transboundary water conflicts in the DAYRD; iii) identify the reasonable intensity of third-party intervention to resolve transboundary water conflicts in the DAYRD; and iv) propose practical solutions to effectively resolve transboundary water conflicts.

2 Study area

The demonstration area in the Yangtze River Delta on ecologically friendly development (DAYRD) (E120°21'7.20"-121°19'12", N30°45'28"-31°17'50") is located at the junction of three administrative regions (SH, JS Province, and ZJ Province) in the Yangtze River Delta, including the Qingpu District (SH), the Wujiang District (JS Province), and the Jiashan County (ZJ Province), with a total area of approximately

2,300 km^2 (Fig. 1). As a crucial transboundary river crossing through the junction area, the Taipu River is a crucial tie for the implementation of the DAYRD. The total length of the Taipu River is 57.6 km, of which 40.73 km is in JS Province, 1.63 km is in ZJ Province, and 15.24 km is in SH.

Fig. 1 Geographical location of the DAYRD.

Currently, there are four kinds of transboundary water conflicts related to different benefit demands in the DAYRD, i.e., river function, industrial development, water quality, and water quantity (Fig. 2). First, the Taipu River is a vital regional flood control channel of JS, while it is an indispensable source of drinking water source of SH and ZJ (Taihu Basin Authority, 2014). Second, SH and ZJ require JS to restrict and adjust the development of the textile industry to protect the water environment of the transboundary river, while JS is unwilling to take the loss of industrial development benefits. In addition, SH and ZJ's water quality target (higher than Grade II) for the Taipu River is higher than that of JS (higher than Grade III). Finally, SH and ZJ want JS to increase the amount of water supply from the Taipu River, while JS asserts that it

wishes to maintain the status quo.

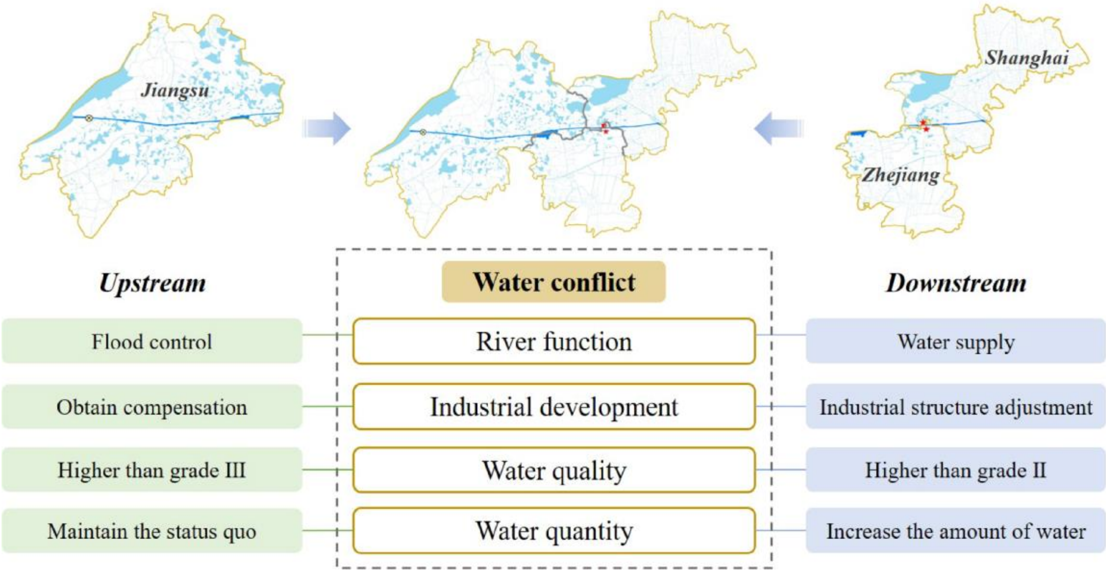

Fig. 2 Transboundary water conflicts in the DAYRD.

3 Methodology

To effectively balance the benefit demands of different DMs in transboundary water conflicts and to identify feasible conflict resolution solutions, this paper proposes an improved GMCR model to simulate and analyze water conflicts in the DAYRD**,** as shown in Fig. 3. First, based on the characteristics of transboundary water conflicts in the DAYRD, the DMs and their strategy options are described**.** Second, the feasible states and graph model of the improved GMCR model are clarified. Third, based on the benefits of the different strategies of DMs, a quantitative function is proposed to evaluate the costs and benefits of DMs' strategy options, and to determine the preference rankings. Fourth, we discuss the influence of third-party intervention on the equilibrium state, obtain the optimal state, and demonstrate the evolutionary path of transboundary water conflicts. Finally, policy implications for conflict resolution are proposed.

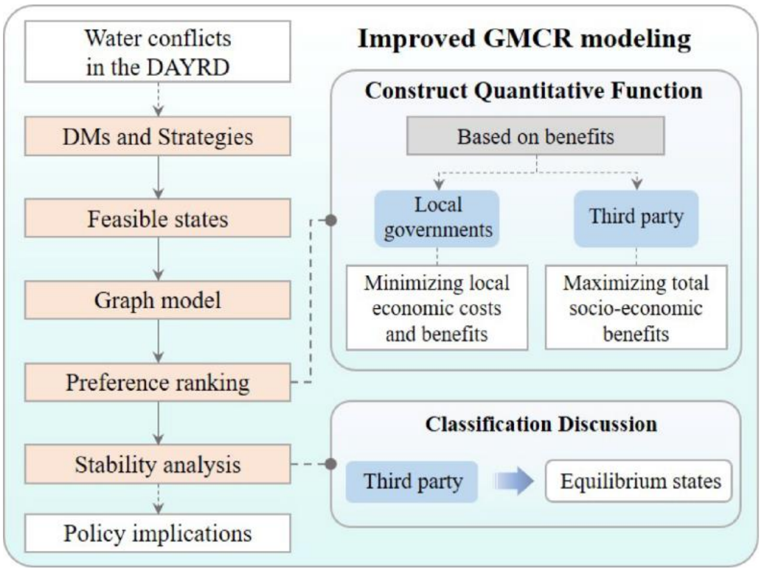

Fig. 3 Improved GMCR model for analyzing water conflicts in the DAYRD.

3.1 Decision-makers and strategies

The administrative units involved in transboundary water conflicts in the DAYRD included 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. Prior to the implementation of the DAYRD policy, the strategy of JS for transboundary water conflicts was to maintain, specifically, to maintain the status quo of the river function orientation, industrial development scale, pollution control efforts, and water supply amount, as shown in Table 1. The strategy of SH & ZJ was to compel JS to take effective actions to control water pollution and ensure the safety of the downstream water intake. As a river basin management authority that is subordinate to the central government, the TBA can intervene in transboundary water conflicts in the DAYRD as a third party. However, as it only has the power to plan, coordinate, and allocate water under normal conditions, the TBA can only persuade upstream and downstream DMs to cooperate (Shen, 2009). In this way, the upstream and downstream local governments will adhere

to their strategic choice, and transboundary water conflicts in the DAYRD will become deadlocked and difficult to resolve (Yu et al., 2015).

Table 1 Decision-makEers 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 the river function orientation, industrial development scale, pollution control efforts, and water supply amount	Y
			2	Strengthen	Strengthening pollution control, increasing water supply, adjusting industrial construction, and eliminating pollution risks	
	Shanghai and Zhejiang	SH & ZJ	3	Compel	Compelling JS to adopt effective measures to control water pollution and ensure the safety of the downstream water intake	Y
			4	Share	Sharing the costs of JS in industrial structure adjustment, water pollution control and water supply	
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 non-cooperation, with the	

			aim of increasing the cost of non-cooperation

Note: "Y" represents the strategy option of DMs before the implementation of the DAYRD policy

However, after the implementation of the DAYRD policy, however, in December 2019, the central government implemented the DAYRD policy, which aims to speed up the resolution of conflicts between different stakeholders (SH, JS, and ZJ) and achieve regional cooperation. As a representative of the central government, the TBA has been given higher supervision and management powers and can implement reward or punishment measures. Therefore, the TBA expands the strategies to include reward and punishment (option 6 and option 7, respectively, in Table 1), which can influence the strategic options of local governments. In contrast, JS and SH & ZJ expand the strategies to include option 2 and option 4, respectively, in response to the intervention of the third party with higher authority.

3.2 Feasible states

Theoretically, each option of three DMs can be adopted or not. Given that seven strategies are explicated in Table 1 and there are two cases of each strategy, "yes" or "no", there are a total of 2^7 states, i.e., 128 states. Since one DM cannot simultaneously choose two or three strategies in each state, the infeasible states need to be eliminated. Finally, 12 states are retained as feasible states in transboundary water conflicts (Table 2).

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 Graph model

Fig. 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 state 1 to state 2 is equivalent to JS changing its strategy from "maintain" to " strengthen", and vice versa.

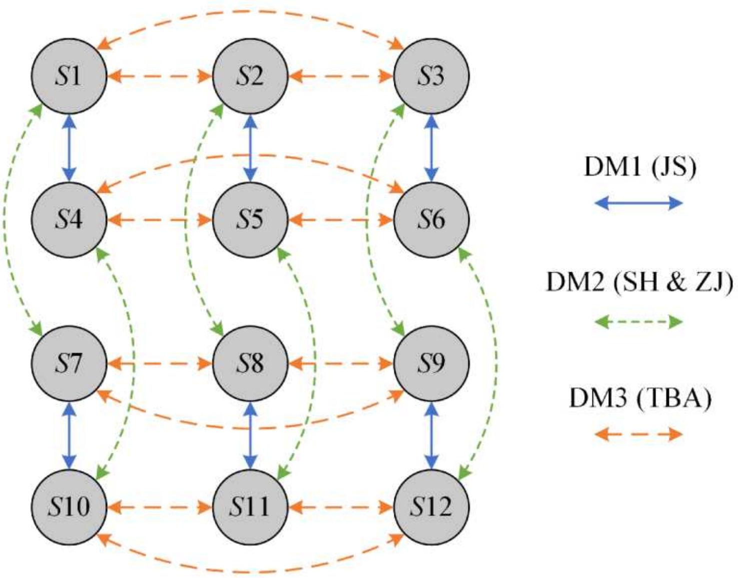

Fig. 4 Graph model of transboundary water conflicts.

3.4 Preference rankings based on benefits

Determining the preference rankings of each DM is one of the decisive steps in the GMCR 3ethod (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. Therefore, to accurately assess the preference rankings of DMs, the benefits and costs of each strategy should be considered.

As mentioned above, the main reason for transboundary water conflicts in the DAYRD is the imbalance in the distribution of water resource benefits. 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 maximization of local economic benefits (Chen et al., 2017). Table 3 presents the benefit demands and goals of different DMs in the DAYRD. The benefit demands of JS are reducing the losses in regional economic development, protection costs, and water rights. For SH & ZJ, ensuring the safety of the water intake is the primary target, and they are unwilling to actively share the costs of JS. As the management agency representing the central government, the TBA expects to fundamentally resolve the water conflicts between JS and SH & ZJ and to realize cooperation between local governments on the premise of ensuring the safety of the downstream water intake.

Table 3 Benefit demands and goals of different DMs.

DMs	Benefit demands	Goals
JS	Reducing the losses in regional economic development, protection costs, and water rights	Maximization of local economic benefits
SH & ZJ	Ensuring the safety of the water intake; they are unwilling to share the costs of JS	
TBA	Ensuring the safety of the downstream water intake, and providing compensation for the losses of JS	Maximization of total regional socioeconomic benefits

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

$$B = I - C \quad (1)$$

where B is the total benefits of the DM when adopting a given strategy; I is the income of the DM when adopting a given strategy; and C is the cost of the DM when adopting a given strategy.

Based on the benefit demands and goals of DMs, and equation (1), the benefits of the different strategies of JS, SH & ZJ and the TBA are evaluated.

(1) Local governments (JS and SH & ZJ)

Local governments are only concerned with local economic costs and benefits which are not only related to their strategy options but also affected by the strategy of the higher-power third party, the TBA. The process of calculating the benefits of local governments is as follows:

$$LocalB_{JS} = I_{JS} - C_{JS} \quad (2)$$

$$I_{JS} = \begin{cases} S, & i = 2, j = 4 \\ A, & i = 2, k = 6 \end{cases}$$

$$C_{JS} = \begin{cases} 0, & i = 1, k = 5 \ or \ 6 \\ P, & i = 1, k = 7 \\ C, & i = 2 \end{cases}$$

$$LocalB_{SH\ \&\ ZJ} = I_{SH\ \&\ ZJ} - C_{SH\ \&\ ZJ} \quad (3)$$

$$I_{SH\ \&\ ZJ} = \begin{cases} 0, & j = 3 \\ A, & j = 4, k = 6 \\ D, & i = 2 \end{cases}$$

$$C_{SH\ \&\ ZJ} = \begin{cases} P, & j = 3, k = 7 \\ S, & j = 4 \end{cases}$$

where i, j, and k represent the strategy options of JS, SH, and the TBA, respectively. For example, $i = 1$ means that JS will adopt strategy 1, maintain. $LocalB_{SH\ \&\ ZJ}$ is the local economic costs and benefits of JS; I_{JS} is the income of JS, and C_{JS} is the costs of JS. For example, $I_{JS} = S$ means that when JS chooses strategy 2 and SH & ZJ choose strategy 4, JS will obtain the income of S. $LocalB_{SH\ \&\ ZJ}$ is the local economic costs and benefits of SH & ZJ, $I_{SH\ \&\ ZJ}$ is the income of SH & ZJ, and $C_{SH\ \&\ ZJ}$ is the costs of JS. Table 4 presents and explains the benefit parameters of the different DMs' strategies.

(2) Third party (TBA)

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

$$\text{Primary object:} \quad TotalB_{TBA}^{P} = I_{TBA}^{P} - C_{TBA}^{P} \quad (4)$$

$$I_{TBA}^{P} = \begin{cases} 0, & i = 1 \ or \ j = 3 \\ B_1, & i = 2 \\ B_2, & j = 4 \end{cases}$$

$$C_{TBA}^{P} = 0$$

$$\text{Secondary object:} \quad TotalB_{TBA}^{S} = I_{TBA}^{S} - C_{TBA}^{S} \quad (5)$$

$$I_{TBA}^{S}=\begin{cases}2P, & k=7, i=1, j=3\\ P, & k=7, i\neq 1, j\neq 3\end{cases}$$

$$C_{TBA}^{S}=\begin{cases}2A, & k=6, i=2, j=4\\ A, & k=6, i\neq 2, j\neq 4\end{cases}$$

where $TotalB_{TBA}^{P}$ is the total regional socioeconomic benefits, which are the primary goal of the TBA; I_{TBA}^{P} is the total benefits brought by local governments by taking cooperative actions; C_{TBA}^{P} is the total costs brought by local governments by taking uncooperative actions; $TotalB_{TBA}^{S}$ is the income and costs of the TBA, which are the secondary considerations; I_{TBA}^{S} is the income that the TBA gains by punishing local governments; and C_{TBA}^{S} is the costs that the TBA losses by awarding local governments.

Table 4 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

Note: 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. B1, B2, P, A, C, S, D are all greater than 0.

3.5 Stability analysis

The equilibrium states can be identified and analyzed through stability analysis. The GMCR model has four fundamental stability concepts: Nash, GMR, SMR, SEQ

(Fang et al., 1993; Fang et al., 2003b; Kilgour and Hipel, 2005). Table S1 (Supplementary Material) provides the definitions and important features (including foresight, disimprovement, and knowledge of preferences) of the four stability concepts. In general, when all four kinds of stabilities are reached, the state is considered to be in equilibrium (Xu et al., 2019).

4 Results and discussion

4.1 Ranking of the relative preferences

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

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
JS	Maintain	0	0	-P	/	/	/	0	0	-P	/	/	/
	Enhance	/	/	/	-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 4. In state 7, state 8, and state 9, JS does not choose actions that are conducive to cooperation; thus, JS cannot obtain the money shared by SH & ZJ. "/" means no data.

The benefits of local governments under different strategies include C, D, S, A, and P. We need to compare the sizes of different parameters to determine the preference rankings. First, the safety of the water supply for millions of residents should be rank first; 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. 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 or 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 puts managers under enormous pressure because of economic costs. Due to the policy 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. Because of the influence of the relationship between 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 IV: $P \leq C\text{-}S$ and $S \geq P > 0$ (Table 5).

The implementation of strategy 2 can effectively ensure the safety of the downstream water supply, while strategy 4 is only conducive to the cooperation of local governments. The benefits of the safety of the downstream water supply are the greatest. Moreover, the TBA pays much more attention to total regional socioeconomic benefits than to its economic costs and benefits. Therefore, there is a relationship between the different values of the TBA's benefits: $B_1 + B_2 > B_1 > B_2 >> P$ (or A). Given the uncertainty of the size between different benefits, the various possible benefits rankings of DMs in the four cases are shown in Table 5.

Table 5 Benefits rankings of DMs with different sizes of P.

Case	Different sizes of P	DMs	Benefits rankings
I	P ≥ C > S	JS	0 > A+S-C > S-C > A-C > -C ≥ -P
			A+S-C ≥ 0 > S-C > A-C > -C ≥ -P
		SH & ZJ	D > A+D-S > D-S > D-P ≥ 0 > A-S > -S > -P
			D > A+D-S > D-S > 0 > D-P ≥ A-S > -S > -P
			D > A+D-S > D-S > 0 > A-S > D-P ≥ -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 ≥ A-C > -C
			A+S-C ≥ 0 > S-C > A-C > -P > -C
			A+S-C ≥ 0 > S-C > -P ≥ 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 ≤ C - S	JS	0 > A+S-C > -P ≥ S-C > A-C > -C
			A+S-C ≥ 0 > -P ≥ 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 ≥ P > 0	JS	0 > A+S-C > S-C > A-C > -P > -C
			0 > A+S-C > S-C > -P ≥ A-C > -C
			A+S-C ≥ 0 > S-C > A-C > -P > -C
			A+S-C ≥ 0 > S-C > -P ≥ A-C > -C
			0 > A+S-C > -P ≥ S-C > A-C > -C
			A+S-C ≥ 0 > -P ≥ S-C > A-C > -C
		SH & ZJ	D > A+D-S > D-P > D-S > 0 > A-S > -P ≥ -S
			D > A+D-S > D-P > D-S > 0 > -P ≥ 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

According to Table 5, there are 26 combinations of DM preference rankings, provided as 26 scenarios in Table S3 (Supplementary Material). Table 6 shows four preference rankings of DMs under the 4 cases, namely Scenarios 1, 9, 13, and 15.

Table 6 Preference rankings of DMs with different sizes of P.

Cases	Different sizes of P	DMs	Preference rankings	Scenario

I	P ≥ C > S	JS	S1 ~ S2 ~ S7 ~ S8 ≻ S11 ≻ S10 ~ S12 ≻ S5 ≻ S4 ~ S6 ≻ (~) S3 ~ S9	**s1**
		SH & ZJ	S4 ~ S5 ≻ S11 ≻ S10 ~ S12 ≻ S6 ≻ (~) S1 ~ S2 ≻ S8 ≻ S7 ~ S9 ≻ S3	
		TBA	S10 ~ S12 ≻ S11 ≻ S6 ≻ S4 ≻ S5 ≻ S9 ≻ S7 ≻ S8 ≻ S3 ≻ S1 ~ S2	
II	C > P > S; P > C - S	JS	S1 ~ S2 ~ S7 ~ S8 ≻ S11 ≻ S10 ~ S12 ≻ S5 ≻ S3 ~ S9 ≻ S4 ~ S6	**s9**
		SH & ZJ	S4 ~ S5 ≻ S11 ≻ S10 ~ S12 ≻ S6 ≻ S1 ~ S2 ≻ S8 ≻ S7 ~ S9 ≻ S3	
		TBA	S10 ~ S12 ≻ S11 ≻ S6 ≻ S4 ≻ S5 ≻ S9 ≻ S7 ≻ S8 ≻ S3 ≻ S1 ~ S2	
III	C > P > S; P ≤ C - S	JS	S1 ~ S2 ~ S7 ~ S8 ≻ S11 ≻ S3 ~ S9 ≻ (~) S10 ~ S12 ≻ S5 ≻ S4 ~ S6	**s13**
		SH & ZJ	S4 ~ S5 ≻ S11 ≻ S10 ~ S12 ≻ S6 ≻ S1 ~ S2 ≻ S8 ≻ S7 ~ S9 ≻ S3	
		TBA	S10 ~ S12 ≻ S11 ≻ S6 ≻ S4 ≻ S5 ≻ S9 ≻ S7 ≻ S8 ≻ S3 ≻ S1 ~ S2	
IV	S ≥ P > 0	JS	S1 ~ S2 ~ S7 ~ S8 ≻ S11 ≻ S10 ~ S12 ≻ S5 ≻ S3 ~ S9 ≻ S4 ~ S6	**s15**
		SH & ZJ	S4 ~ S5 ≻ S11 ≻ S6 ≻ S10 ~ S12 ≻ S1 ~ S2 ≻ S8 ≻ S3 ≻ (~) S7 ~ S9	
		TBA	S10 ~ S12 ≻ S11 ≻ S6 ≻ S4 ≻ S5 ≻ S9 ≻ S7 ≻ S8 ≻ S3 ≻ S1 ~ S2	

Note: "S1 ~ S2" means that the priority of state 1 is equal to that of state 2; "S8 ≻ S11" means that state 8 has priority over state 11; and S6 ≻ (~) S3 means that state 6 has priority over state 3, and that it is also possible that state 6 and state 3 have equal priority. Only one specific scenario among the 4 cases (I, II, III, IV) is shown, and the other 22 scenarios are presented in the supplementary data.

4.2 Stability analysis

Based on the definitions of four kinds of stability concepts, we evaluated the equilibrium and stability of the states of DMs in each scenario under the four cases. As shown in Table 7, cases I, II, and III have strong equilibrium states, respectively states 9, 9, and 12, respectively, which satisfy all solution concepts. 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 most optimal in 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, adjusting industrial construction, and eliminating pollution risks. SH & ZJ choose the strategy of sharing the costs of JS, and the TBA select the strategy of punishing local governments for non-cooperation; hence, the conflicts will be resolved. However, in state 9, JS chooses the strategy of maintaining the status quo, which not only exacerbates the water conflicts but also fails to ensure the safety of the water supply. Therefore, state 12 is the optimal solution to transboundary water conflicts, which means that the TBA needs to increase its punishment intensity and control it, as $P > S$ and $P > C - S$ (i.e., the punishment amount should be greater than the protection costs shared by SH & ZJ and JS).

Table 7 Stability analysis results.

Case	**Different sizes of P**	**Scenario**	**State**	**Equilibrium**			
				Nash	**GMR**	**SMR**	**SEQ**
I	$P \geq C > S$	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	$C > P > S$; $P \leq C - S$	s13, s14	S9	Y	Y	Y	Y
IV	$S \geq P > 0$	s15, s16, s17, s18, s19, s20, s21, s22, s23, s24, s25, s26	None	/	/	/	/

Note: “Y” means satisfying the solution concept. “/” means no data.

4.3 Evolutionary path of conflicts

Fig. 6 demonstrates the evolutionary path of transboundary water conflicts in the DAYRD from state 1 to equilibrium state 12. Before the implementation of the DAYRD

policy, TBA, a third party without power, could not resolve the conflict between local governments through persuasion (the status quo of the conflicts). However, after the implementation of the DAYRD policy, the TBA had higher powers to reward or punish. 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, which makes the conflict evolve from state 3 into state 6. In such situations, considering the consequences of being punished, SH has to choose the strategy of sharing to avoid more losses. Therefore, the conflict finally reaches equilibrium state 12 from state 6. The evolution of the conflict states is shown in Table S2 (Supplementary Material).

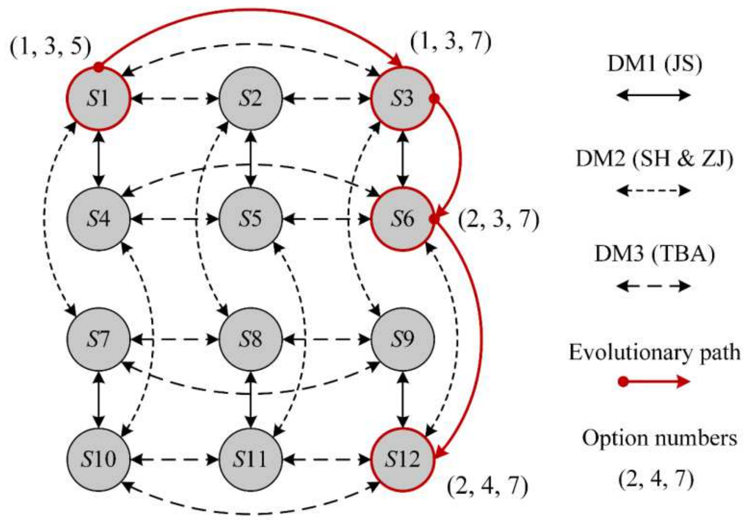

Fig. 6 Evolutionary path of transboundary water conflicts.

4.4 Advantages over traditional methods

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

First, the two traditional methods in the GMCR, i.e., 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 rankings results are very likely to be different (Zhao and Xu, 2019). In addition, most cooperative or non-cooperative 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). However, the improved GMCR model proposed in this paper based on strategy benefits can not only objectively evaluate the relative preferences of decision makers, but also simulate the dynamic evolutionary path of conflicts.

Second, most studies on third-party intervention in conflicts are theoretical discussions or mathematical statistical analyses, and studies on analyzing and modeling third-party intervention are rare (Kinsara et al., 2012). The existing modeling analysis studies are mainly based on the GMCR model to prove the importance of third-party intervention for conflict resolution (Han et al., 2019; Yu et al., 2015; Zanjanian et al., 2018), and they rarely identify the appropriate intensity of third-party intervention for resolving transboundary water conflicts. However, the improved GMCR model presented in this paper can identify the appropriate intensity of third-party intervention through classification discussion. The results show that when $P > S$ and $P > C - S$, the intervention of the TBA can effectively resolve transboundary water conflicts in the DAYRD. 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 way to resolve water conflicts in the process of integrated development as follows.

(1) Giving the third-party higher authority

To achieve the desired resolution, the participation of a third party with 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. TBA with higher power can formulate reasonable laws and regulations, like punishment mechanism and eco-compensation mechanism, which can positively guide upstream and downstream local governments to adopt cooperative strategy. In addition, TBA can establish a leading group which can provide a platform for upstream and downstream local governments to directly and effectively express their demands, i.e., river function, economic interest, water quality and quantity.

(2) Enacting reasonable laws and regulations

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.

5 Conclusions

To accurately and objectively simulate the dynamic evolution of the behaviors of different DMs and to find effective solutions to transboundary water conflicts, this study proposes an improved GMCR model. This model is applied to evaluate the strategic benefits of different DMs and to simulate the evolution of the conflicts between different DMs in the DAYRD. In addition, the influence of the intervention of a third party (TBA) on the evolution of conflicts is discussed in depth.

The results show that the improved GMCR model based on the benefit function can realize a reasonable evaluation of the preference rankings of DMs in conflicts. The advantages of the improved approach are that it can objectively simulate the dynamic evolution of transboundary water conflicts and identify the appropriate intensity of third-party intervention to move conflicts into cooperation. The results obtained from the stability analysis demonstrate that the river basin management authority (TBA), which is a third party representing the central government, is the key to resolving transboundary water conflicts in the DAYRD. Due to the implementation of the

DAYRD policy, the TBA has been given higher powers and can enact reasonable external coordination measures; specifically, the punishment amount should be greater than the protection costs shared by local governments. After the intervention of a third party with higher powers, conflicts can eventually move towards the optimal equilibrium state (State 12). In this state, JS chooses the strategy of strengthening protection, SH & ZJ adopt the strategy of sharing the protection costs, and the TBA implements punitive measures. Finally, a feasible solution path for transboundary conflicts in the DAYRD is provided based on three aspects, including giving the third-party higher authority, enacting reasonable laws and regulations and Establishing an eco-compensation mechanism.

Although the improved GMCR model and our research findings can provide insights for managing transboundary water conflicts in other regions, there are several limitations that need to be noted and that warrant further study. First, we mainly discussed the impact of third-party punishments on the evolution of conflicts based on the real-world conditions. However, the reward mechanism is also an effective measure for encouraging DMs to take cooperative actions. The influence of reward measures can be analyzed in future research. Second, it is difficult to obtain real-world data on the benefit parameters in the improved GMCR model. Therefore, if supported by real-world data on the benefit parameters in the future, our proposed model will be able to obtain more accurate preference rankings results.

Declarations

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Contributions: Mengjie Yang: Conceptualization, Formal analysis, Investigation, Methodology, Writing - original draft. **Kai Yang**: Conceptualization, Funding acquisition, Writing - reviewing and editing. **Yue Che**: Conceptualization, Writing - reviewing and editing. **Shiqiang Lu**: Validation, Resources. **Fengyun Sun**: Validation, Writing - reviewing and editing. **Ying Chen**: Formal analysis, Investigation. **Mengting Li**: Formal analysis, Investigation.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Consent for publication: Not applicable.

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Figures

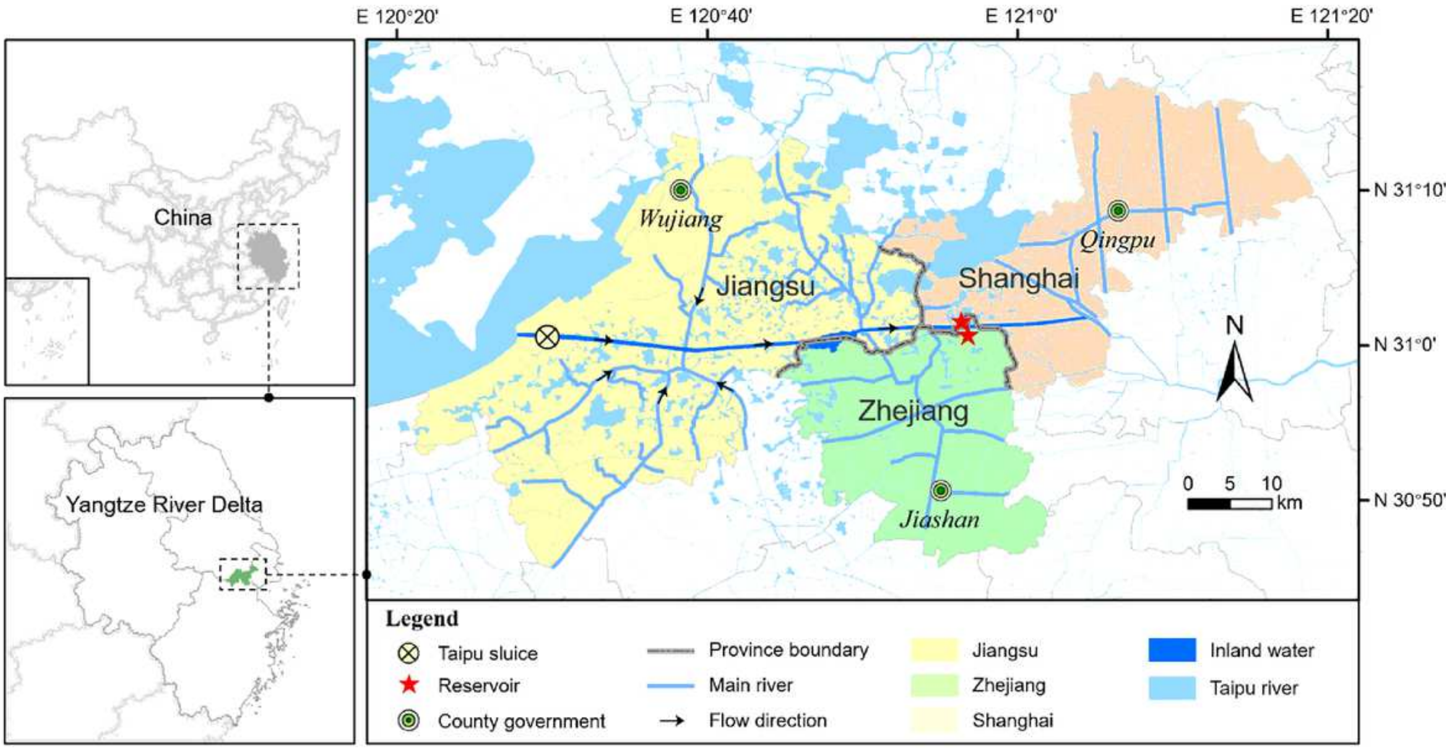

Figure 1

Geographical location of the DAYRD. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

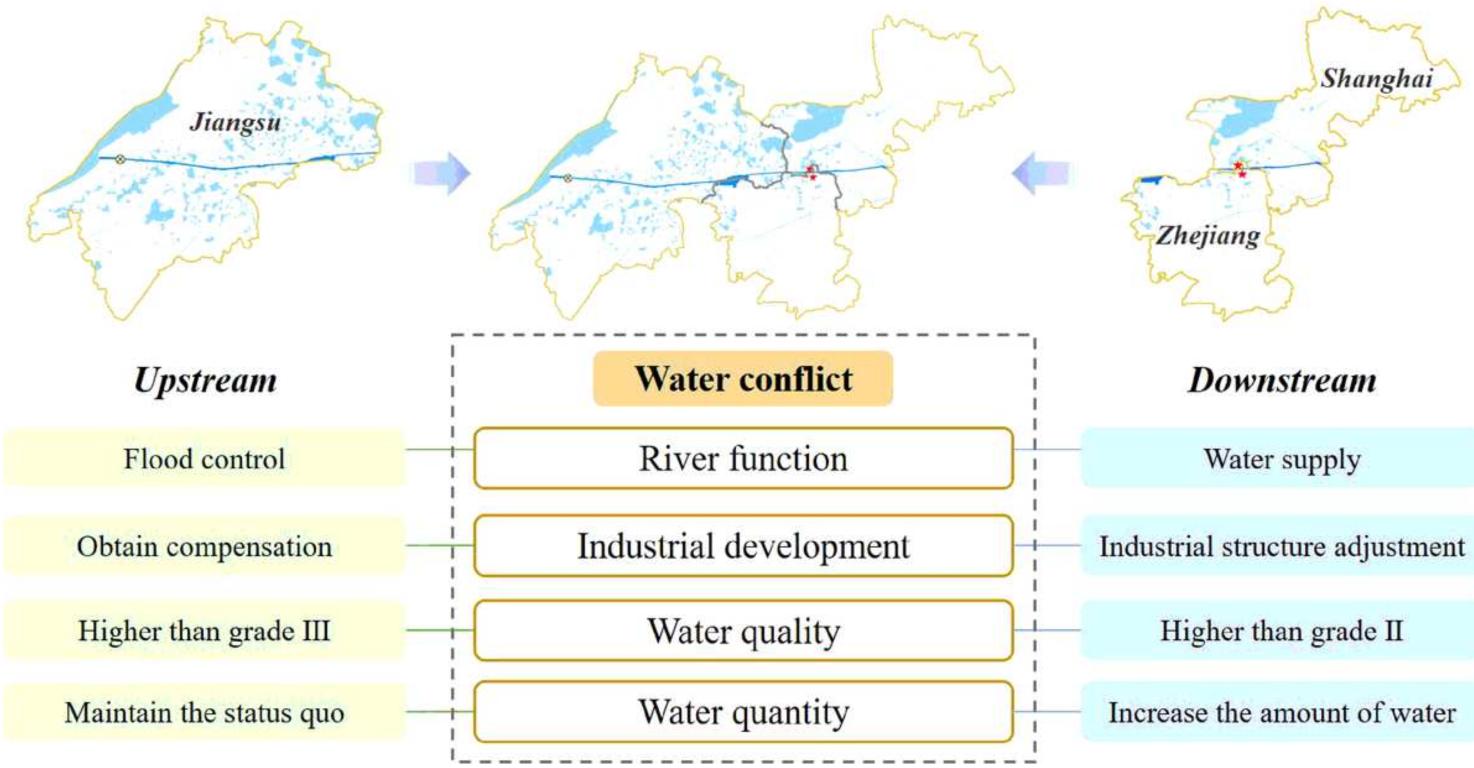

Figure 2

Transboundary water conflicts in the DAYRD. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

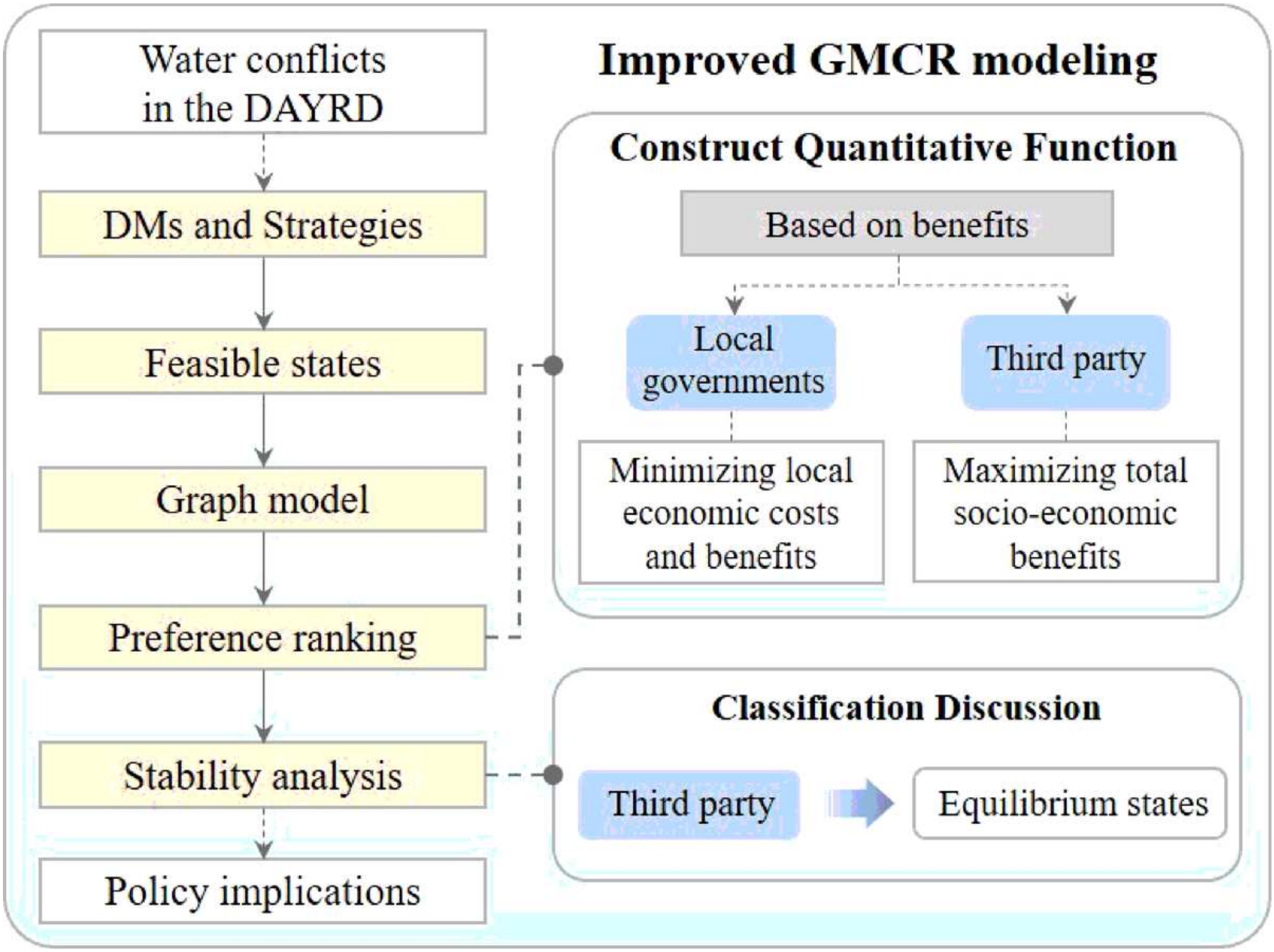

Figure 3

Improved GMCR model for analyzing water conflicts in the DAYRD.

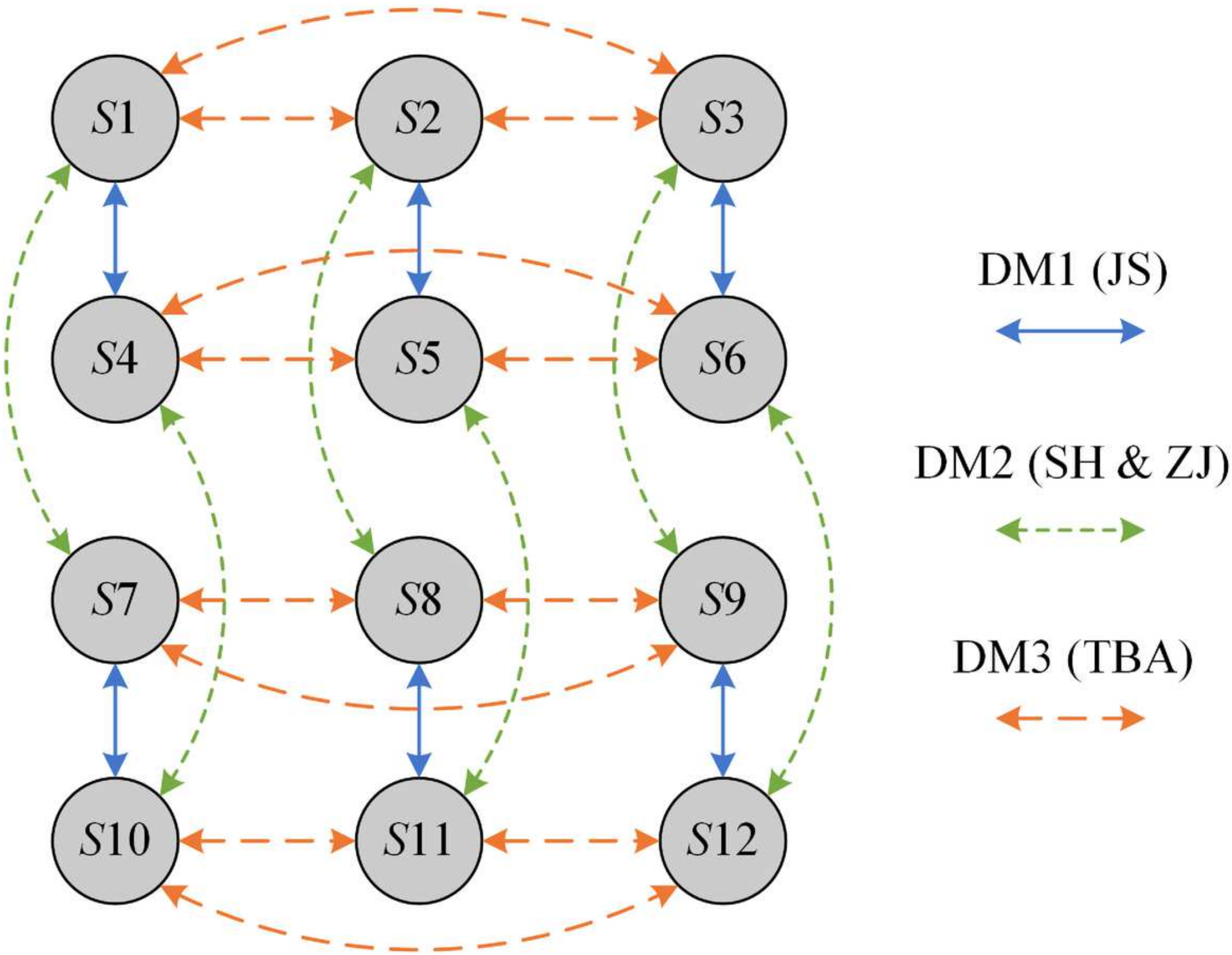

Figure 4

Graph model of transboundary water conflicts.

		S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12
JS	Maintain	0	0	-P	/	/	/	0	0	-P	/	/	/
	Enhance	/	/	/	-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

Figure 5

The benefits of DMs in different states. Each benefit parameter is presented and explained in Table 4. In state 7, state 8, and state 9, JS does not choose actions that are conducive to cooperation; thus, JS cannot obtain the money shared by SH & ZJ. “/” means no

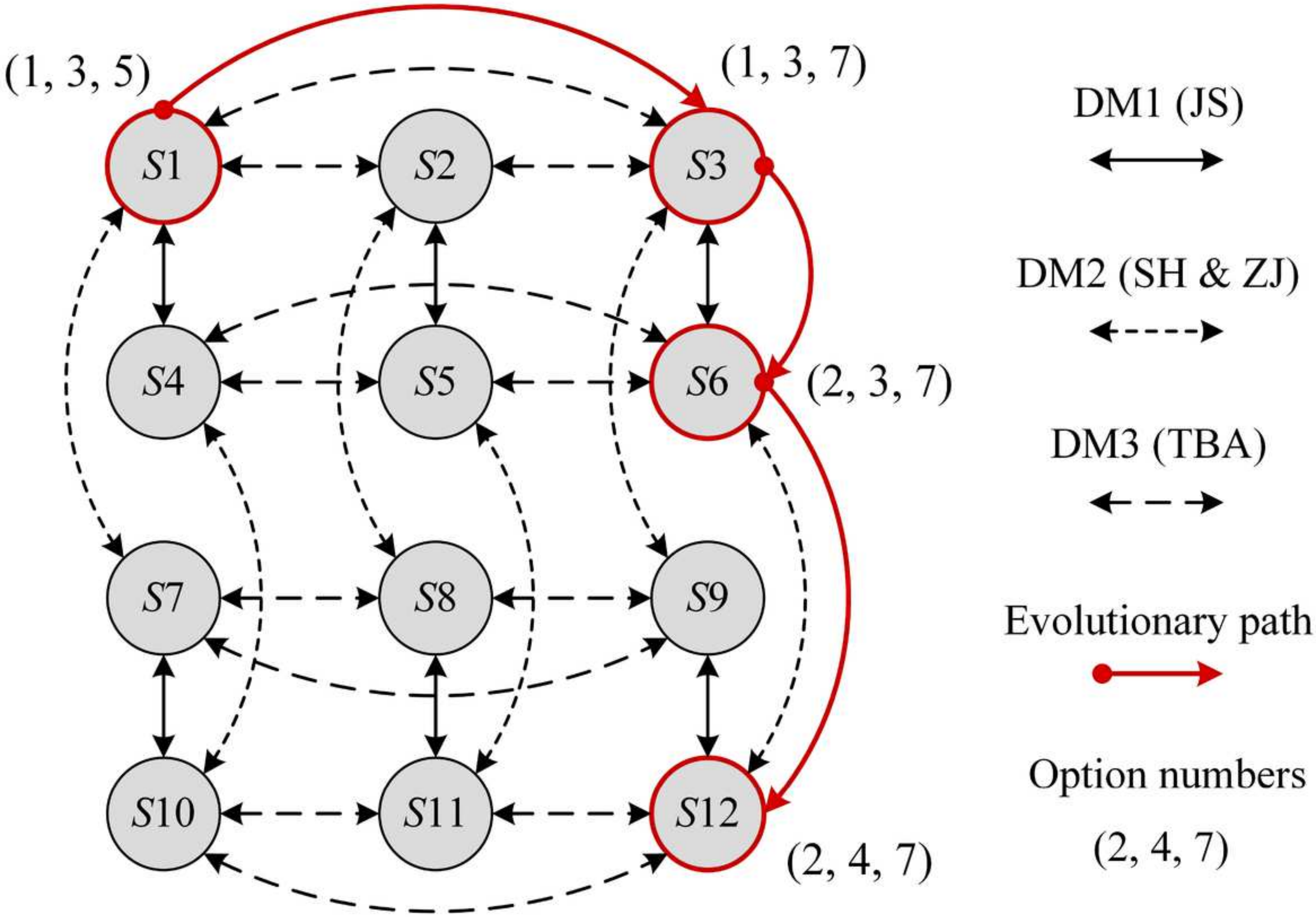

Figure 6

Evolutionary path of transboundary water conflicts.

Supplementary Files

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