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Strategic Analyses for a Cross-Basin Water Pollution Conflict Involving Heterogeneous Sanctions in Hongze Lake, China, within the GMCR Paradigm

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Abstract: The graph model for conflict resolution (GMCR) methodology was enhanced in this research for addressing cross-basin water pollution conflicts involving heterogeneous sanctions, as a more intuitive and straightforward definition for mixed unilateral improvements was proposed, followed by an integrated procedure for performing mixed stability analyses. Furthermore, the cross-border water pollution dispute that occurred in 2018 in Hongze Lake, China, is systematically modeled and strategically analyzed for the first time, using the improved GMCR method. In addition, an evolution analysis was carried out within the framework of GMCR for verifying the applicability of the eco-compensation mechanism in addressing cross-basin water pollution disputes. This case study demonstrates that the heterogeneity of sanctioning opponents could influence equilibrium outcomes and even change the evolution of conflict situations. Moreover, the developed novel approach is able to accurately predict the equilibrium outcomes of the conflict and provide more strategic insights and valuable findings in making effective conflict resolutions for solving cross-basin water pollution conflicts.

Keywords: cross-basin water pollution; conflict analysis; ecological compensation; graph model for conflict resolution; Hongze Lake; mixed stability analysis

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1. Introduction

Cross-basin water pollution refers to the environmental contamination across administrative regions within the same river basin caused by the fluidity of water pollution [1], meaning that the water pollution that originated in one area could be transported to another region in the same watershed. In China, cross-basin water pollution is increasingly pervasive in many river basins, such as the Yellow, Yangtze, and Songhua River Basins, causing severe water security issues and economic losses and even posing great threats to human and ecosystem health [2–4]. Meanwhile, mass environmental disputes across administrative regions have occurred frequently in China in recent years due to cross-basin water pollution [5,6]. For example, the cross-basin water pollution disputes took place in Huai River in 2013 (Anhui Province), Huangpu River in 2013 (Shanghai City), Tuo River in 2015 (Anhui Province), Hongze Lake in 2018 (Jiangsu Province), Shu River in 2020 (Jiangsu Province), etc. In inter-basin water pollution conflicts, the upstream and downstream belong to different political regions and do things in their own way, and they often argue back and forth regarding the source and responsibility of cross-regional pollution because of the lack of a unified joint pollution control mechanism. Inevitably, more and more cross-basin water pollution conflicts happen. Cross-border water pollution disputes have always been a tough and complex system problem that is difficult to deal with because a series of conflicts of interest and dynamic interactions in terms of moves and countermoves exist in multiple stakeholders or decision makers (DMs) involved, including the upstream and downstream governments, industrial enterprises and local residents situated in river basins, environmental non-governmental organizations, and so on.

Due to the behavioral diversity of DMs involved in cross-basin water pollution disputes, stakeholders are sometimes heterogeneous when sanctioning a focal DM's unilateral improvements, which may dramatically influence the equilibrium outcomes and resolutions for addressing the conflict. Specifically, when a focal DM moves to a more preferred state, some non-credible players may block the unilateral improvement (UI) of the focal DM by going to any reachable state regardless of preference, whereas credible players will utilize only their UIs as sanctions. For instance, there exist three main DMs in a water contamination dispute: the local government (LG), chemical plants (CP), and local residents (LR). To save on sewage treatment costs, CP may secretly discharge industrial wastewater into the surroundings, which may severely damage the local ecosystem and even endanger human health. From the perspective of CP, their opponents are LG and LR, in which the sanction by LG is credible if LG is economically oriented and pursues local economic growth instead of environmental protection, while the countermove from LR is non-credible and will take all possible actions at any cost to fight against CP when their health is threatened by the discharge of sewage by CP. Therefore, from the viewpoint of CP, the sanctioning behavior of LG and LR is heterogeneous instead of homogeneous. The sanctioning moves by heterogeneous and homogeneous opponents may be different and the heterogeneity of opponents could affect the outcomes and resolutions of cross-basin water pollution conflicts. Hence, an effective decision-making methodology is urgently needed for modeling and analyzing cross-border water pollution conflicts with heterogeneous sanction behaviors.

The graph model for conflict resolution (GMCR) is a very powerful and systematic methodology developed on the basis of the Metagame Theory [7] and F-H conflict analysis technique [8] for strategically modeling and analyzing real-world disputes arising from social, economic, and environmental areas, among others [9–11]. Compared with classical game theory, the GMCR methodology needs only relative preference information instead of cardinal utilities, and it has a richer set of solution concepts for portraying complex decision-making behaviors. GMCR has been applied to many water resource disputes, such as the Devils Lake outlet diversion conflict in United States [12], the cross-basin groundwater allocation dispute in Snake Valley, USA [13] and a water rights conflict in Iran [14]. The GMCR method is also employed for addressing cross-basin water pollution disputes [15,16]. However, the impact of heterogeneous sanctions on equilibrium outcomes and conflict resolutions were not taken into account in the aforesaid literature.

In this research, an intuitive definition for mixed unilateral improvements (MUIs), as well as a detailed procedure for performing mixed stability analyses, is put forward within the framework of GMCR to portray heterogeneous sanctioning behaviors in disputes, as it is more straightforward and easier to understand than that developed by Zhao et al. [17,18]. Subsequently, the cross-basin water pollution conflict regarding Hongze Lake that occurred on 25 August 2018 in China was systematically modeled any analyzed by using the general and mixed stability analysis approaches by which the equilibrium outcomes of the dispute can be predicted. One of the reasons for taking the Hongze Lake pollution incident as a case study is that the cross-basin water contamination issue took place in Hongze Lake for many years (1974, 2004, 2007, and 2018) but has not been well addressed until now. Another reason is that the decision-making behaviors of stakeholders involved in the dispute and their strategic interactions are diverse and complex, where both rational and irrational sanctions exist. Furthermore, we investigated the impact of cross-basin eco-compensation on the equilibrium outcomes and possible solutions for addressing this kind of cross-border water contamination dispute based on the evolution analysis approach of GMCR.

The rest of the paper is organized as follows. To begin with, the literature review is present in Section 2. Then, the basic concepts of GMCR methodology, logical definitions for MUIs and mixed stabilities, as well as a procedure for mixed stability analyses, are introduced in Section 3. In Section 4, the cross-basin water pollution conflict in Hongze Lake is systematically modeled by using the GMCR methodology, including the extraction of DMs, options, feasible conflict states, and preferences over states, as well as the drawing of a graph model for describing state transitions of DMs. Subsequently, the Hongze Lake conflict model is analyzed in Section 5 by using the general and mixed stability analysis techniques, respectively, followed by a brief discussion. Finally, conclusions, limitations, and future work are presented.

2. Literature Review

2.1. Research on Cross-Basin Water Pollution Disputes

The existing studies regarding cross-basin water pollution disputes mainly focus on the cause–effect analysis, compensation mechanism design, and conflict evolution and resolutions. In regard to the cause–effect analysis of cross-basin water pollution, many scholars investigated the source and effects of pollution, as well as the impact of means and public policies on cross-border pollution control. The key factors that could reduce beggar-thy-neighbor behavior in transboundary pollution disputes were studied by Bernauer and Kuhn [19], and it was found that the observed effects of the variables vary considerably across forms of pollution. Using the empirical analysis method, Wang et al. [20] discussed the reasons that cause water pollution at political borders in China from the perspective of promotion incentives. Based on the evidence data of river-water-quality data in China, Lu [21] adopted the triple-difference method to evaluate the impact of central environmental protection inspection on cross-basin water pollution. To analyze the cost effectiveness of reducing water pollutant emissions in the Jialu River Basin in China, a game theoretic simulation model was established by Shi et al. [3] by taking into account the stability and fairness of cost allocation schemes. The environmental monitoring and impact assessment of Prut River cross-border pollution were discussed by Neamtu et al. [22]; they evaluated the water pollution level and impacts on the Prut River cross-border area from 2015 to 2019. Moreover, a cross-basin eco-compensation mechanism was designed for promoting cross-border joint prevention and control of water pollution. More specifically, two econometric models were developed by Li et al. [23] based on theoretical and empirical analyses for investigating a cross-basin eco-compensation mechanism of Songhua River Basin, and the polluter pays principle was verified in this research. Furthermore, Chen and Qi [24] studied the international dispute settlement mechanisms for the cross-basin water pollution dispute due to the Fukushima contaminated water discharge, using the qualitative analysis method. Considering the power and varying intensities of conflict, Zeitoun and Warner [25] constructed a conceptual framework of Hydro-Hegemony for an analysis of trans-boundary water conflicts. In addition to the aforementioned quantitative and empirical analyses, there are also some studies in relation to evolution analysis and conflict resolutions for cross-basin water pollution disputes, using game-theoretical techniques. The evolutionary game theory was utilized by Wang et al. [26] for exploring the interaction mechanism between upstream and downstream countries in transboundary river basins under the Belt and Road, and then the optimal ecological compensation mechanism was designed. Within the GMCR paradigm, Akbari et al. [15] strategically investigated a tripartite environmental conflict in the Tigris River Basin and claimed that the option for water diplomacy would generate new equilibria for addressing this dispute. Yang et al. [14] employed the improved GMCR method to analyze the dynamic evolution of cross-basin water conflicts in the Yangtze River Delta in China and then proposed some useful insights for resolving the cross-basin water conflict. Considering the fuzziness of stakeholders in ecological compensation conflicts, Wang et al. [27]

developed a graph model with intuitionistic preferences and then employed the proposed method for modeling and analyzing the ecological compensation conflicts in the Taihu Lake basin, China. Furthermore, a new grey inverse GMCR was constructed by Li et al. [28] to effectively mediate the water resources conflicts in the Poyang Lake Basin, China.

To summarize, the causes and effects of cross-basin water pollution disputes, the eco-compensation mechanism design, and the conflict evolution and solutions have been systematically discussed in current research. Most studies on cross-basin water pollution disputes are based on qualitative methods and empirical analyses. However, limited research has been conducted on strategic analyses established on game-theoretical approaches such as game theory and the GMCR methodology. Moreover, all of sanctioning behaviors of stakeholders involved in a cross-basin water pollution conflict are assumed to be rational of irrational (homogeneous) in the literature [15,16,27,28], and the impacts of heterogeneous sanctions on equilibrium outcomes and conflict mediation strategies are not discussed. Last but not the least, the effects of eco-compensation mechanisms are not investigated from the perspective of an evolution analysis within the framework of GMCR.

2.2. Research on the Solution Concepts in GMCR

To reflect different kinds of interactive behavior of DMs involved in a conflict, four basic solution concepts or stability definitions, namely Nash stability [29], general metarationality (GMR) [7], symmetric metarationality (SMR) [7], and sequential stability (SEQ) [8,30], have been developed to determine whether a state is stable for a DM under a specific solution concept within the GMCR paradigm. Subsequently, the four classical stabilities mentioned above were expanded to diverse solution concepts for handling conflicts with strength preference [31,32], unknown preference [33,34], hybrid preference [35–37], fuzzy preference [38–41], and DMs' attitudes [42–44]. In SMR, the sanctioning opponents are assumed to be irrational who move to any reachable states. In SEQ and in symmetric sequential stability (SSEQ) [45], however, the sanctions are rational, and the opponents can move only to more preferred states.

In the definitions of GMR and SMR, the focal DM who believes that all of the sanctions by its opponents are non-credible can be regarded as being conservative. Alternatively, the sanctioning opponents could be deemed to be irrational when their preferences are unknown to a conservative DM. The focal DM in SEQ and SSEQ, however, is adventurous since it believes that all of the sanctions are rational and that its opponents move only to more preferred states. In brief, all of the sanctioning opponents in the aforementioned stabilities are assumed to be homogeneous. In a real-world conflict, each decision maker (DM) has its own perception and behavior. When a focal DM unilaterally moves to a more preferred state, the sanctioning moves by opponents may be heterogeneous, in which non-credible rivals move to any reachable states to block the DM at any cost whereas credible opponents levy only unilateral improvements as sanctions. To handle a conflict with heterogeneous opponents, Zhao et al. [17,18] proposed a novel mixed stability analysis method based on the GMCR paradigm, in which an inductive method for obtaining MUIs and two types of mixed stabilities are formally defined. However, the definition of MUIs is not in an intuitive form and difficult to understand. Moreover, the detailed process for implementing the mixed stability analyses and applications on cross-basin water pollution disputes are not discussed by Zhao et al. [17,18].

2.3. Summary

The novelties of this research work in comparison with existing methods are summarized in Table 1.

As shown in Table 1, most of the research [20,22–25] in cross-border water pollution disputes is based on qualitative and empirical analysis methods, in which the preference of stakeholders and the complex strategic interactions among DMs are not taken into account. The dynamic interactions among stakeholders were investigated in some other studies [3,26], using game theory. However, the preference of DMs in the aforementioned research is represented by numerical utilities, which are difficult to obtain in real-world situations, and the sanctions by opponents are not considered. Within the framework of GMCR, cross-border water pollution disputes are modeled and analyzed in the literature [15,16,28], where only relative preferences are required, and the sanctioning moves by opponents are considered. Furthermore, the GMCR methodology provides various kinds of solution concepts for portraying the complex decision-making behaviors, such as GMR, SMR, SEQ, and so on, except for Nash. However, the sanctioning opponents are assumed to be homogenous (either irrational or rational) in the above studies. In many actual conflicts, the sanctions are heterogeneous. In other words, irrational and rational sanctioning moves could coexist. Therefore, the main novelty of this study is that the heterogeneous sanctioning behavior among stakeholders was taken into account when modeling and analyzing the cross-border pollution dispute in Hongze Lake, China, as compared to existing the literature.

Table 1. The novelties of this research work in comparison with existing methods.

Reference	Method	Preference	Stability	Sanctions by Opponents
Wang et al. [20]; Chen and Qi [24]; Zeitoun and Warner [25]	Qualitative analysis	Not consider	Not consider	Not consider
Neamtu et al. [22]; Li et al. [23]	Empirical analysis	Not consider	Not consider	Not consider
Shi et al. [3]; Wang et al. [26]	Game theory	Quantitative utility (difficult to obtain)	Nash	Not consider
Akbari et al. [15]; Yang et al. [16]; Li et al. [28]	GMCR	Relative preference (easy to obtain)	Nash, GMR, SMR, SEQ	Homogeneous (either rational or irrational DMs)
Wang et al. [27]	GMCR	Relative preference (easy to obtain)	IR, IGMR, ISMR, ISEQ	Homogeneous (either rational or irrational sanctions)
This research work	GMCR	Relative preference (easy to obtain)	MTS, MSMR (more general than traditional stabilities)	Heterogeneous (rational and irrational sanctions could coexist)

The main contributions of this research include the following: (1) a more intuitive and straightforward definition for MUIs and a specific procedure for mixed stability analyses are proposed in this paper within the GMCR paradigm for handing cross-basin water pollution disputes with heterogeneous sanctioning moves; (2) the cross-border pollution dispute in Hongze Lake is systematically modeled and strategically analyzed for the first time, using the improved GMCR methodology, in which the impact of heterogeneous sanctions of opponents on the equilibrium outcomes is discussed; (3) an evolution analysis based on GMCR is carried out in this research for verifying the applicability of the eco-compensation mechanism in addressing cross-basin water pollution disputes.

3. Methodology

3.1. Basic Concepts in GMCR

A real-world conflict can be modeled as $G = \langle N, S, \{A_i, \succsim_i: \ i \in N\}\rangle$ within the GMCR paradigm, containing four key elements [7–9]:

(1) $N = \{1, 2, \ldots, i, \ldots, n\}$, the set of DMs involved in the conflict, in which "n" is the total number of DMs;
(2) $S = \{s_1, s_2, \ldots, s_l, \ldots, s_m\}$, the set of feasible states, in which "m" is the total number of feasible states;
(3) A_i, the set of oriented arcs of DM $i \in N$, which records all the unilateral moves (UMs) in one step by DM i;

(4) $\succsim_i$, the preference relations of DM i, in which $q \succ_i s$ means that state q is more preferred to state s by DM i, and $q \sim_i s$ indicates that q is equally preferred to s by DM i. Furthermore, $q \succsim_i s$ means that $q \succ_i s$ or $q \sim_i s$.

If DM i can unilaterally move to a state which is more preferred to the initial state, then this kind of move is called a unilateral improvement (UI). The set of UMs and unilateral improvements (UIs) for DM i can be defined as follows, respectively [10,11].

Definition 1. *Let $s,\ q \in S$ and DM $i \in N$. The set of UMs of DM i at state s can be denoted by*

$$R_i(s) = \{q \in S : (s,\ q) \in A_i\}. \tag{1}$$

Definition 2. *Let $s,\ q \in S$ and DM $i \in N$. The set of UIs of DM I at state s can be expressed by*

$$R_i^+(s) = \{q \in S :\ q \in R_i(s) \text{ and } q \succ_i s\}. \tag{2}$$

Let a coalition be $H \subseteq N$ and $H \neq \varnothing$. The reachable list of H at state $s \in S$ can be denoted by $R_H(s)$, including all the states that can be reached by any legal sequences of UMs by the DMs in H [8,9]. Note that no DM can move twice consecutively in $R_H(s)$.

Definition 3. *Let $s,\ q \in S$. State q can be reached by H from state s, as denoted by $q \in R_H(s)$, if and only if there exists a legal sequence $\{s_0,\ i_1,\ s_1,\ i_2,\ s_2, \ldots,\ s_{l-1},\ i_l,\ s_l, \ldots,\ s_{k-1},\ i_k,\ s_k\}$ in which $s_0,\ s_1, \ldots,\ s_k \in S$ and $i_1,\ i_2, \ldots,\ i_k \in H$, such that $s_0 = s$, $s_k = q$, and $s_l \in R_{i_l}(s_{l-1})$ for $l = 1,\ 2, \ldots,\ k$, with the constraint that $i_l \neq i_{l-1}$ for $l = 2,\ 3, \ldots,\ k$.*

Definition 4. *Let $s,\ q \in S$. State q is a UI from state s for H denoted by $q \in R_H^+(s)$ if and only if there exists a legal sequence $\{s_0,\ i_1,\ s_1,\ i_2,\ s_2, \ldots,\ s_{l-1},\ i_l,\ s_l, \ldots,\ s_{k-1},\ i_k,\ s_k\}$ in which $s_0,\ s_1,\ \ldots,\ s_k \in S$ and $i_1,\ i_2, \ldots,\ i_k \in H$, such that $s_0 = s$, $s_k = q$, and $s_l \in R_{i_l}^+(s_{l-1})$ for $l = 1,\ 2, \ldots,\ k$ with the constraint that $i_l \neq i_{l-1}$ for $l = 2,\ 3, \ldots,\ k$.*

Note that in Definition 4, each DM in H is credible and moves to only more preferred states, and this is different from that in Definition 3.

Let a focal DM $i \in N$, the set of other DMs except i, be $H = N\backslash\{i\}$, and the initial state $s \in S$. Then, the four classical solution concepts, i.e., Nash, GMR, SMR, and SEQ, can be formally defined as follows [10,11].

Definition 5. *State s is Nash stable for DM i, denoted by $s \in S_i^{Nash}$, if $R_i^+(s) = \varnothing$.*

In Nash stability, the focal DM i only takes into account its unilateral improvements from the initial state s but does not consider the counterattacks or sanctions from its opponents (one-step game).

Definition 6. *State s is GMR stable for DM i, denoted by $s \in S_i^{GMR}$, iff for any state $s_1 \in R_i^+(s)$, there exists at least one reachable state $s_2 \in R_H(s_1)$ by H such that $s \succsim_i s_2$.*

In GMR stability, DM i considers all possible sanctions by its opponents, H, after its unilateral improvements from state s (two-step game).

Definition 7. *State s is SMR stable for DM i, denoted by $s \in S_i^{SMR}$, if for any state $s_1 \in R_i^+(s)$, there exists at least one reachable state $s_2 \in R_H(s_1)$ by H, such that $s \succsim_i s_2$, and $s \succsim_i s_3$ holds for each state $s_3 \in R_i(s_2)$.*

In comparison to GMR, SMR stability further considers the re-movement by DM I (three-step game).

Definition 8. *State s is SEQ stable for DM i, denoted by* $s \in S_i^{SEQ}$*, if for any state* $s_1 \in R_i^+(s)$*, there exists at least one reachable state* $s_2 \in R_H^+(s_1)$ *by H such that* $s \succsim_i s_2$.

Compared to GMR, all of the counterattack actions by the opponents, H, are assumed to be rational in SEQ stability (two-step game).

The aforementioned four classical stabilities dynamically characterize the complex interactions and decision-making behaviors and can predict the equilibrium outcomes of conflict games with rational or irrational counterattacks and attitudes to risk (conservative or adventure) taken into account.

However, the counterattacks or sanctions of DM i's opponents are assumed to be homogeneous in GMR, SMR, and SEQ stabilities, either rational or irrational. In many conflicts, in fact, the sanctions could be hybrid or heterogeneous with both rational and irrational counterattacks, in which non-credible opponents take any countermoves regardless of preference when sanctioning, whereas credible players levy only unilateral improvements as sanctions. In order to describe this kind of heterogeneous sanctioning behaviors of stakeholders involved in a given conflict, the MUIs and two mixed stabilities are formally defined below, followed by a detailed procedure for carrying out the mixed stability analyses to systematically forecast the equilibrium outcomes or possible solutions for cross-basin water pollution disputes with heterogeneous sanctions.

3.2. Mixed Stabilities with Heterogeneous Opponents

Let a focal DM $i \in N$ and the set of its heterogeneous opponents be $O = N \backslash \{i\}$, and O consists of two subsets: the set of rational opponents, O_C; and the set of irrational opponents, O_{NC}. A mixed unilateral improvement (MUI) by heterogeneous opponents should satisfy the following three requirements:

(1) If DM $j \in O_C$, then the sanctioning DM j can shift only to more preferred states;
(2) If DM $j \in O_{NC}$, then sanctioning DM j can move to any reachable states regardless of preference;
(3) Each DM $j \in O$ cannot move twice consecutively.

Let $R_O^{\oplus}(s)$ be the set of MUIs for the heterogeneous opponents O from state s. The set of MUIs, $R_O^{\oplus}(s)$, can be defined similar to Definitions 3 and 4.

Definition 9. *Let* $s,\ q \in S$*. State q can be reached by the heterogeneous opponent O from state s, denoted by* $q \in R_O^{\oplus}(s)$*, if and only if there exists a legal sequence* $\{s_0, i_1, s_1, i_2, s_2, \ldots, s_{l-1},\ i_l, s_l, \ldots, s_{k-1}, i_k, s_k\}$ *in which* $s_0,\ s_1,\ \ldots,\ s_k \in S$ *and* $i_1,\ i_2, \ldots,\ i_k \in H$*, such that* $s_0 = s$, $s_k = q$, $s_l \in R_{i_l}(s_{l-1})$ *if* $i_l \in O_{NC}$ *and* $s_l \in R_{i_l}^+(s_{l-1})$ *if* $i_l \in O_C$ *with the constraint that* $i_l \neq i_{l-1}$ *for* $l = 2,\ 3, \ldots,\ k$.

In Definition 9, if DM i's opponent is credible, then it levies only UIs against DM i; if DM i's opponent is non-credible, then it can shift to any reachable states to block DM i.

According to Definitions 3, 4, and 9, one can determine that $R_O^+(s) \subseteq R_O^{\oplus}(s) \subseteq R_O(s)$. In particular, $R_O^{\oplus}(s) = R_O(s)$ holds if $O = O_{NC}$, and $R_O^{\oplus}(s) = R_O^+(s)$ holds when $O = O_C$. This indicates that Definition 9 is the same as Definitions 3 and 4 if all of the opponents are irrational and rational, respectively. The interrelationships among $R_O(s)$, $R_O^+(s)$, and $R_O^{\oplus}(s)$ are illustrated in Figure 1.

Mixed stabilities were developed by Zhao et al. [17,18] to systematically portray the different sanctioning behavior of heterogeneous opponents. Let DM $i \in N$ and the set of its heterogeneous opponents be $O = N \backslash \{i\}$. Then, two kinds of mixed stabilities can be defined as follows.

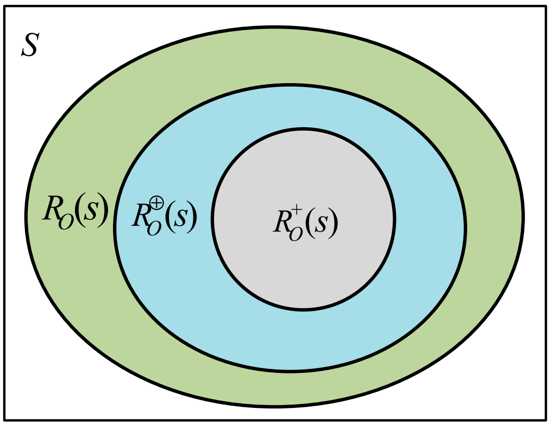

Figure 1. Logical interrelationships among $R_O(s)$, $R_O^{+}(s)$, and $R_O^{\oplus}(s)$.

Definition 10. *State $s \in S$ is mixed two-step stability (MTS) stable for DM i, as denoted by $s \in S_i^{MTS}$, if for every $s_1 \in R_i^{+}(s)$, there exists at least one state, $s_2 \in R_O^{\oplus}(s_1)$, such that $s \succsim_i s_2$.*

In MTS stability, DM *i* believes that its sanctioning opponents are heterogeneous, in which case some credible opponents levy only UIs to block DM *i*'s UIs, while some non-credible opponents go to any reachable states when sanctioning. Note that MTS in Definition 10 will be identical to GMR and SEQ if all of DM *i*'s opponents are non-credible and credible, respectively.

Definition 11. *State $s \in S$ is mixed SMR (MSMR) stable for DM i, as denoted by $s \in S_i^{MSMR}$, if for every $s_1 \in R_i^{+}(s)$, there exists at least one state, $s_2 \in R_O^{\oplus}(s_1)$, such that $s \succsim_i s_2$ and $s \succsim_i s_3$ for every $s_3 \in R_i(s_2)$.*

In comparison with Definition 10, DM *i* in Definition 11 considers not only the sanctions by its heterogeneous opponents but also its further reaction to escape from the deterrent by its opponents. Furthermore, MSMR stability will be the same as SMR and SSEQ if all of DM *i*'s opponents are non-credible and credible, respectively. The mixed stabilities and four classical stabilities are compared in Table 2.

Table 2. The comparisons of mixed stabilities and four classical stabilities.

Types	Stabilities	A Focal DM's Opponents	Steps
Classical Stabilities	Nash	The opponents are not taken into account.	One
	GMR	All of the opponents are homogeneous and non-credible.	Two
	SMR	All of the opponents are homogeneous and non-credible.	Three
	SEQ	All of the opponents are homogeneous and credible.	Two
Mixed Stabilities	MTS	The opponents are heterogeneous, including both non-credible and credible players.	Two
	MSMR	The opponents are heterogeneous, including both non-credible and credible players.	Three

A detailed procedure for implementing mixed stability analyses was purposefully designed, as shown in Figure 2, for addressing a conflict with heterogeneous sanctions.

As illustrated in Figure 2, the mixed stability analyses are divided into two stages: the modeling and analysis stages. In the modeling stage, the key DMs involved in the conflict, their options, feasible states, and each DM's preference should be identified. Furthermore, from the perspective of a particular DM, its credible and non-credible opponents should be determined. In the analysis stage, the outcomes of individual mixed stability analyses can be determined according to Definitions 10 and 11. Subsequently, the equilibria of the conflict can be obtained. A state is called an equilibrium if it is stable for all of the DMs under a particular solution concept in a conflict. Furthermore, one can conduct sensitivity analyses to determine how the changes of the elements in the modeling stage, such as DMs' preferences and opponents' different sanctioning behavior, can affect the results of the analysis. Consequently, valuable strategic insights can be attained to make more informed decisions for addressing the dispute.

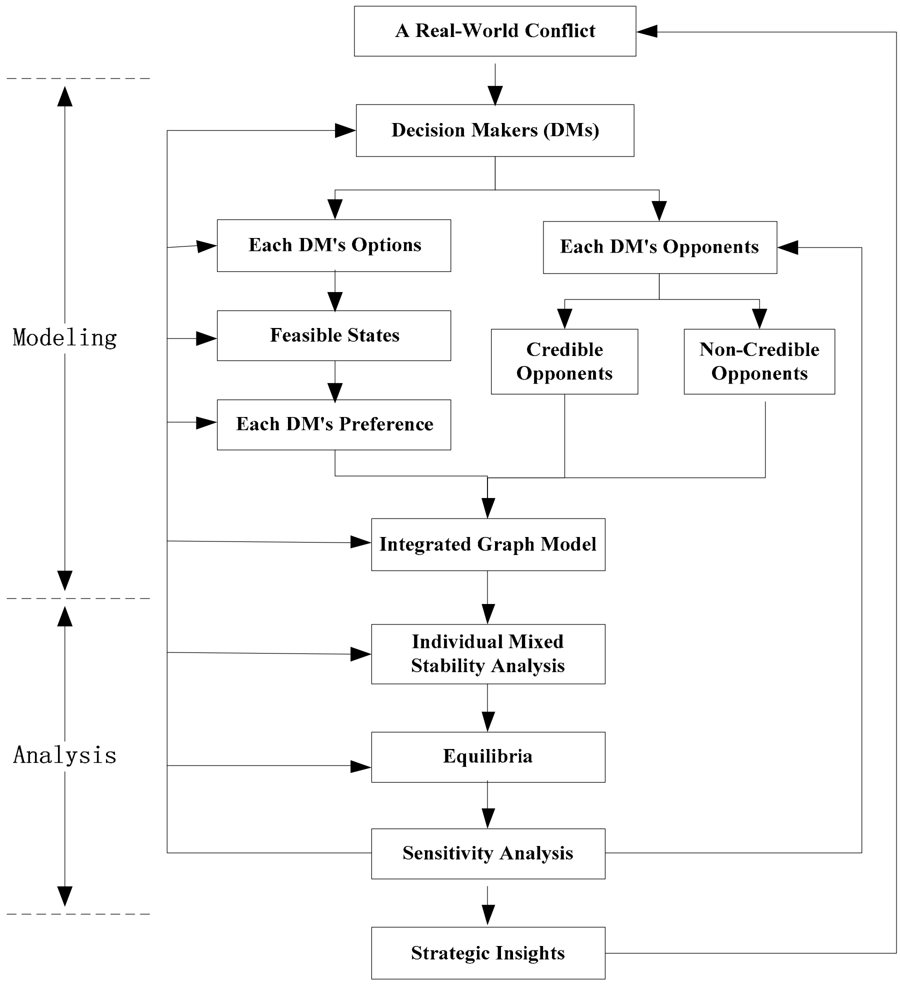

Figure 2. The procedure for mixed stability analyses.

Compared with existing research related to cross-border water pollution disputes, the improved GMCR methodology in this study incorporates the impact of heterogeneous sanctions that were not taken into account in the other literature on the optimal strategies of DMs and the equilibria of the transboundary pollution controversy and can provide useful strategic insights and meaningful information for addressing transboundary water pollution disputes with both rational and irrational sanctions.

4. Conflict Modeling

4.1. Background

Hongze Lake (118°10′ E–18°52′, 33°06′–33°40′ N) is the fourth largest freshwater lake in China and the important water passage of the eastern part of the famous South-to-North Water Diversion Project. It is located in the lower reaches of the Huai River in the west of Jiangsu Province and within the boundaries of Huai'an and Suqian cities in Jiangsu Province. The lake is 65 km long and has an average width of 24.4 km. Its basin area is 160,000 square kilometers, with a total storage capacity of 13 billion cubic meters. The whole lake is composed of three major lake bays: Chengzi Lake Bay, Li Lake Bay, and Huai Lake Bay. The main upstream rivers entering Hongze Lake include Xinbian River and Xinsui River in Suzhou City, Anhui Province, as shown in Figure 3.

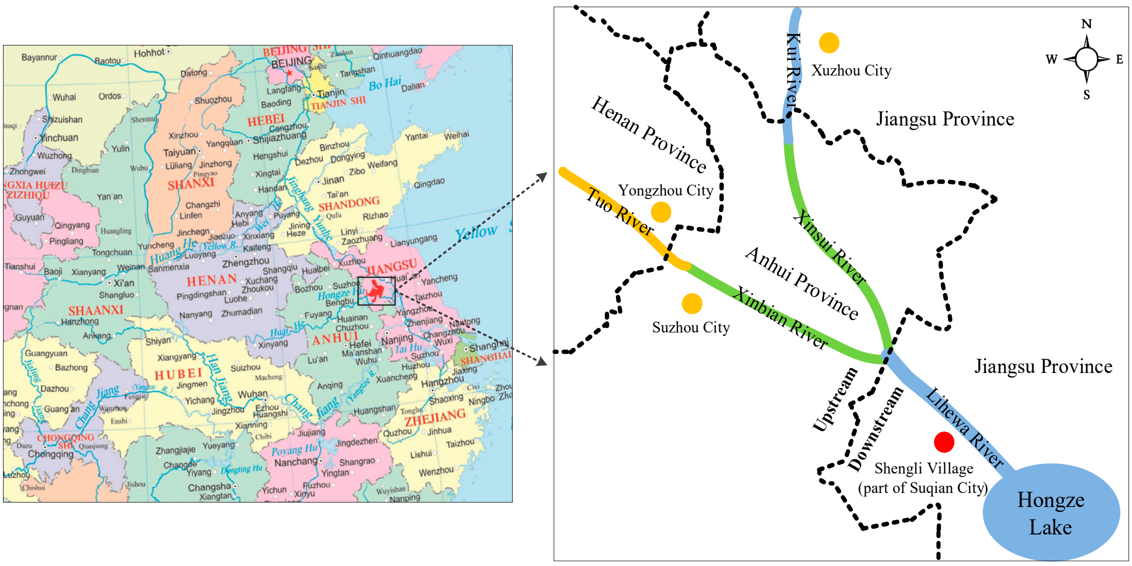

Figure 3. The watershed map of Hongze Lake, China.

On 25 August 2018, a large number of fish and crabs died in Shengli Village (the red area in Figure 3), Suqian City, Jiangsu Province, China, due to a sudden influx of upstream sewage from Suzhou City. The water pollution incident caused serious economic losses to local fishermen and severely damaged the ecosystem of Hongze Lake [46]. According to the preliminary investigation from the Environmental Protection Bureau (EPB) of Suqian City, the sewage came from the Xinbian River, which flows through Suzhou City, as shown in Figure 3. As shown in Figure 3, the upper reaches of Hongze Lake are the Lihe Wa, located in Sihong County, in Jiangsu Province, which is further divided into Xinsui River and Xinbian River, Suzhou City, Anhui Province. However, the upstream government of Suzhou City denied that this was the case and claimed that the dirty water originated in the Kui River, which flows through Xuzhou City, Jiangsu Province, as displayed at the top of Figure 3. Both of the environmental protection departments of Jiangsu Province and Anhui Province recognized that the sewage was discharged to Hongze Lake through Xinsui River and Xinbian River. However, the two sides disagreed on whether the source of sewage originated from Anhui Province or from Kui River, a tributary of Xinsui River in Jiangsu Province. Moreover, they differed in their presentations on the water-quality data of the Kui River. The Jiangsu side believed that the water quality of the Kuihe River was not bad when it entered Anhui from Jiangsu. However, the Anhui side claimed that when the Kui River reaches Anhui, the water quality is already very bad. Furthermore, the two sides did not reach an agreement on whether the upstream gates should be opened to release water in advance to inform the downstream in this pollution incident. There was also a dispute over the issue of compensation for fishermen.

In conclusion, there are three main controversies in the complex cross-basin water pollution conflict that occurred in Hongze Lake, China.

(1) Where does the sewage come from? It is still unknown whether the pollution is from the upstream rivers of Anhui Province or the Kui River in Xuzhou City located in Jiangsu Province.
(2) Does the sewage contain industrial wastewater? The downstream government of Suqian City in Jiangsu Province suspects that industrial wastewater from the upstream is the most likely cause of thousands of dead fish and crabs in Shengli Village. However, the upstream government of Suzhou City in Anhui Province claims that there were no polluting enterprises that discharged sewage into rivers.
(3) Who should take the responsibility for this cross-basin water pollution incident? The upstream and downstream governments have not yet reached an agreement about the

economic compensation for the local fishermen's losses and ecological pollution in Hongze Lake.

4.2. DMs, Options, and States

The stakeholders involved in the Hongze Lake cross-basin water pollution dispute include the upstream (Suzhou City, Anhui Province), the downstream (Suqian City, Jiangsu Province), environmental non-governmental organizations (ENGOs), the Ministry of Environmental Protection (MEP), and local fishermen. The MEP was not considered in this study since it is an indirect and external participant. Moreover, the local fishermen and the ENGOs are regarded as being one DM because they have common interest. Therefore, in this research, we mainly investigate the dynamic strategic interactions among three key decision makers (i.e., upstream, downstream, and ENGOs).

Since the upstream and downstream parties cannot reach an agreement on the aforementioned controversies, the cross-basin water pollution dispute in Hongze Lake is still ongoing and not well resolved up to now. This water pollution conflict concerning Hongze Lake can be formally investigated using the GMCR methodology. In the conflict model, the key DMs, their options, preferences, and transitions among states should be identified. According to the background, the main DMs involved in this dispute and their options are given as follows:

- The upstream government (upstream), Suzhou City, Anhui Province. The upstream failed to inform the downstream before it decided to open the floodgates, which caused cross-basin pollution and serious economic losses to the downstream. Since the source of sewage is still unknown, the Upstream has to decide whether or not to agree to negotiate regarding compensating the downstream's serious losses.
- The downstream government (downstream), Suqian City, Jiangsu Province. The downstream has two options: (1) whether or not to negotiate with the upstream regarding the compensation for the affected fishermen and the environmental ecological remediation in Hongze Lake; and (2) whether or not to appeal to the Ministry of Environmental Protection (MEP) of China for an intervention.
- Environmental non-governmental organizations (ENGOs) for environment protection, such as Friends of the Earth and the Environmental Investigation Agency. ENGOs have one option: whether or not to file a public interest litigation (PIL) in court against the environmental offenders involved in the severe cross-basin water pollution (lawsuit).

When each DM selects its options, a state comes into being. In this conflict, there are a total of four options, and, mathematically, the number of possible states is $2^4 = 16$. However, some states are infeasible, such as a state in which the upstream agrees to negotiate about the compensation for the downstream's losses, whereas the downstream does not intend to negotiate with the upstream. GMCR II is a very powerful and comprehensive decision support system for modeling and analyzing real-world conflicts [43,44]. The infeasible states in the cross-basin water pollution dispute can be removed in the GMCR II by using two logical option statements, "1&−2" and "−2&3", where the numbers represent the corresponding options. More specifically, the statement "1&−2" is used to eliminate states where the upstream agrees to negotiate with the downstream, but the latter one does not initiate to negotiate with the former one. Similarly, the statement "−2&3" is given for removing states where the downstream chooses not to negotiate with the upstream and meantime wants to call for the intervention of MEP.

After removing infeasible states, there are a total of 10 feasible states (s_1–s_{10}), as given in Table 3, where "Y" means that the corresponding option in the same row is selected, and "N" indicates that the option is not chosen. For instance, the fifth column in Table 3 is s_3 (Y Y N N), meaning that the upstream agrees to negotiate with the downstream about compensation for the cross-basin water pollution involving Hongze Lake (Y), the downstream wants to negotiate with the upstream and does not appeal for intervention by MEP (Y N), and the ENGOs does not file a PIL (N).

Table 3. Feasible states in the Hongze Lake dispute.

DMs	Options	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
Upstream	1. Agree	N	N	Y	N	Y	N	N	Y	N	Y
Downstream	2. Negotiate	N	Y	Y	Y	Y	N	Y	Y	Y	Y
	3. Appeal	N	N	N	Y	Y	N	N	N	Y	Y
ENGOs	4. Lawsuit	N	N	N	N	N	Y	Y	Y	Y	Y

4.3. Preferences and Graph Model

According to the background of the Hongze Lake cross-basin pollution conflict, each DM's preference over states can be determined by using the GMCR II software [47,48], as given in Table 4, in which the states are ranked from the most preferred on the left to the least preferred on the right.

Table 4. Preference ranking of DMs in the Hongze Lake dispute.

DMs	Preference Ranking from Most to Least Preferred
Upstream	$s_1 \succ s_2 \succ s_6 \succ s_7 \succ s_4 \succ s_9 \succ s_3 \succ s_8 \succ s_5 \succ s_{10}$
Downstream	$s_3 \succ s_8 \succ s_5 \succ s_{10} \succ s_9 \succ s_7 \succ s_1 \succ s_2 \succ s_4 \succ s_6$
ENGOs	$s_3 \succ s_{10} \succ s_5 \succ s_8 \succ s_9 \succ s_4 \succ s_7 \succ s_2 \succ s_6 \succ s_1$

The integrated graph for the cross-basin water pollution conflict involving Hongze Lake is displayed in Figure 4, in which the vertexes represent the feasible states, oriented arcs indicate the direction of state transitions, and labels on the arcs refer to the DM controlling the move. Note that an arc with double arrows means that the transition between two states is reversible.

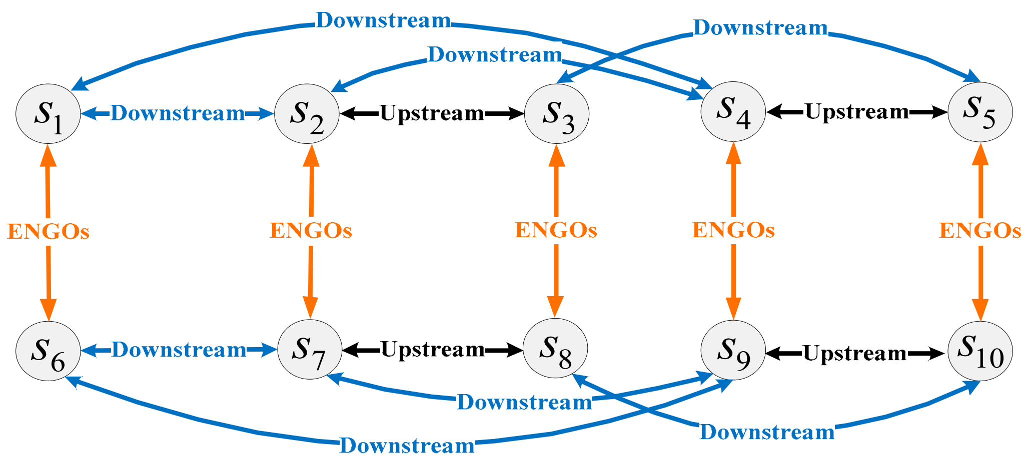

Figure 4. Integrated graph of the cross-basin water pollution conflict in Hongze Lake.

5. Results and Discussion

5.1. General Stability Analyses with Homogeneous Opponents

As mentioned earlier in Section 3, there are four classical stabilities within the GMCR paradigm, namely Nash, GMR, SMR, and SEQ, which can be utilized to conduct general stability analyses of the cross-basin water pollution conflict involving Hongze Lake. In the stabilities of GMR, SMR, and SEQ, all of the sanctioning opponents from each DM's viewpoint are assumed to be homogeneous, either non-credible or credible. Alternatively, the sanctioning behavior of each opponent in general stability analyses is the same or homogeneous from each DM's perspective as explained in Table 5.

Table 5. Homogeneous opponents from each DM's perspective in the Hongze Lake dispute.

Focal DM	**Homogeneous Opponents**	
	GMR/SMR	**SEQ**
Upstream	Both downstream and ENGOs are non-credible.	Both downstream and ENGOs are credible.
Downstream	Both upstream and ENGOs are non-credible.	Both upstream and ENGOs are credible.
ENGOs	Both downstream and upstream are non-credible.	Both downstream and upstream are credible.

Let $N = \{1, 2, 3\}$ be the set of DMs in the cross-basin water pollution dispute, in which the numbers 1, 2, and 3 represent upstream, downstream, and ENGOs, respectively. As explained earlier, $N\backslash\{i\}$ is the set of DM i's sanctioning opponents. If all of the opponents of a focal DM i are non-credible and credible, as shown in Table 5, then the set of their sanctioning movements at state s can be denoted by $R_{N\backslash\{i\}}(s)$ and $R^+_{N\backslash\{i\}}(s)$, respectively. Using Definition 3, the set of unilateral moves (UMs) by DM i's non-credible opponents at state s, $R_{N\backslash\{i\}}(s)$, is given in Table 6. Similarly, the set of unilateral improvements (UIs) by DM i's credible opponents at state s, $R^+_{N\backslash\{i\}}(s)$, is presented in Table 7, according to Definition 4.

Table 6. The set of UMs by non-credible opponents in the Hongze Lake dispute.

State	$R_{N\backslash\{1\}}(s)$	$R_{N\backslash\{2\}}(s)$	$R_{N\backslash\{3\}}(s)$
s_1	$\{s_2, s_4, s_6, s_7, s_9\}$	$\{s_6\}$	$\{s_2, s_3, s_4, s_5\}$
s_2	$\{s_1, s_4, s_6, s_7, s_9\}$	$\{s_3, s_7, s_8\}$	$\{s_1, s_3, s_4, s_5\}$
s_3	$\{s_5, s_8, s_{10}\}$	$\{s_2, s_7, s_8\}$	$\{s_1, s_2, s_4, s_5\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_5, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_5\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_1, s_2, s_4, s_7, s_9\}$	$\{s_1\}$	$\{s_7, s_8, s_9, s_{10}\}$
s_7	$\{s_1, s_2, s_4, s_6, s_9\}$	$\{s_2, s_3, s_8\}$	$\{s_6, s_8, s_9, s_{10}\}$
s_8	$\{s_3, s_5, s_{10}\}$	$\{s_2, s_3, s_7\}$	$\{s_6, s_7, s_9, s_{10}\}$
s_9	$\{s_1, s_2, s_4, s_6, s_7\}$	$\{s_4, s_5, s_{10}\}$	$\{s_6, s_7, s_8, s_{10}\}$
s_{10}	$\{s_3, s_5, s_8\}$	$\{s_4, s_5, s_9\}$	$\{s_6, s_7, s_8, s_9\}$

Table 7. The set of UIs by credible opponents in the Hongze Lake dispute.

State	$R^+_{N\backslash\{1\}}(s)$	$R^+_{N\backslash\{2\}}(s)$	$R^+_{N\backslash\{3\}}(s)$
s_1	$\{s_6, s_7, s_9\}$	$\{s_6\}$	$\varnothing$
s_2	$\{s_1, s_6, s_7, s_9\}$	$\{s_7\}$	$\{s_1\}$
s_3	$\varnothing$	$\{s_2, s_7\}$	$\{s_1, s_2\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_9\}$	$\{s_1, s_2\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_7, s_9\}$	$\varnothing$	$\{s_7, s_9\}$
s_7	$\{s_6, s_9\}$	$\varnothing$	$\{s_9\}$
s_8	$\{s_3\}$	$\{s_2, s_3, s_7\}$	$\{s_7, s_9\}$
s_9	$\varnothing$	$\varnothing$	$\varnothing$
s_{10}	$\{s_3, s_8\}$	$\{s_9\}$	$\{s_7, s_8, s_9\}$

Using the GMCR II; [47,48] software, the results of the general stability analyses for the cross-basin water pollution conflict can be determined, as summarized in Table 8, in which "E" is the abbreviated form of equilibrium. Moreover, under a particular stability, the check "√" means that the state in the same row is stable for the DM in the column, and an asterisk "*" indicates that the state in the same row is an equilibrium which is stable for each DM. As illustrated in Table 8, s_2 is an equilibrium state under GMR stability; s_7 is an equilibrium state under both GMR and SMR stabilities; and s_9 is a strong equilibrium state under all of the Nash, GMR, SMR, and SEQ stabilities.

Table 8. The equilibrium outcomes of general stability analyses for the Hongze Lake dispute.

State	Nash				GMR				SMR				SEQ			
	1	**2**	**3**	**E**	**1**	**2**	**3**	**E**	**1**	**2**	**3**	**E**	**1**	**2**	**3**	**E**
s_1	√	√			√	√			√	√			√	√		
s_2	√				√	√	√	*	√		√		√	√		
s_3		√	√			√	√			√	√			√	√	
s_4	√				√		√		√		√		√			
s_5						√	√			√	√			√	√	
s_6	√		√		√		√		√		√		√		√	
s_7	√		√		√	√	√	*	√	√	√	*	√		√	
s_8		√				√	√			√	√			√	√	
s_9	√	√	√	*	√	√	√	*	√	√	√	*	√	√	√	*
s_{10}			√			√	√			√	√			√	√	

5.2. Mixed Stability Analyses with Heterogeneous Opponents

As mentioned above, the opponents of each DM in general stability analyses are assumed to be homogeneous, meaning that every opponent's sanctioning behavior is the same. When determining the stability results under GMR and SMR, for example, both upstream and ENGOs are regarded as being non-credible from the perspective of the downstream. In this cross-basin water pollution dispute involving Hongze Lake, however, ENGOs should be considered credible when sanctioning since ENGOs and downstream share a common interest that upstream agrees to negotiate regarding compensating the economic losses of downstream. Therefore, from the downstream's viewpoint, upstream is non-credible, and ENGOs are credible when sanctioning, meaning that the downstream's opponents are heterogeneous instead of homogeneous. The heterogeneous opponents of each DM in the cross-basin water pollution dispute are presented in Table 9, which is different from that shown in Table 5.

Table 9. Heterogeneous opponents from each DM's perspective in the Hongze Lake dispute.

Focal DM	**Heterogeneous Opponents (MTS/MSMR)**	
Upstream	Downstream is non-credible.	ENGOs is credible.
Downstream	Upstream is non-credible.	ENGOs is credible.
ENGOs	Upstream is non-credible.	Downstream is credible.

When the opponents are hybrid or heterogeneous, their sanctioning movements could be different from those in Tables 6 and 7, which may further influence the results of the analysis. By employing Definition 9, the set of mixed unilateral improvements (MUIs) by heterogeneous opponents can be obtained as shown in Table 10. By comparing Table 10 with Tables 6 and 7, one can find that the sanctioning movements by heterogeneous opponents at some states differ from those made by homogeneous (either non-credible or credible) opponents in Table 5. For example, ENGOs can move to a more preferred state, s_7, from s_2. Then, it may consider the countermoves by its two opponents, upstream and downstream, at s_7. There are three possible cases with respect to the sanctioning opponents when they together sanction the UI by ENGOs:

(1) Both upstream and downstream are non-credible (the fourth row and second column in Table 5). The set of their UMs from s_7 is $R_{N\setminus\{3\}}(s_7) = \{s_6, s_8, s_9, s_{10}\}$, as shown in Table 6. The homogeneous movements by upstream and downstream are displayed step by step in Figure 5a.

(2) Both upstream and downstream are credible (the fourth row and third column in Table 5). The set of their UIs from s_7 is $R^{+}_{N\setminus\{3\}}(s_7) = \{s_9\}$, as shown in Table 7. The homogeneous movements by upstream and downstream are illustrated in detail in Figure 5b, in which "Downstream$^+$" means that the DM is credible.

(3) Upstream is non-credible, whereas downstream is credible (the fourth row in Table 9). The set of their MUIs from s_7 is $R^{\oplus}_{N\setminus\{3\}}(s_7) = \{s_8, s_9, s_{10}\}$, as shown in Table 10. The mixed sanctioning movements by the upstream and downstream are illustrated in Figure 5c.

Table 10. The set of MUIs by heterogeneous opponents in the Hongze Lake dispute.

State	$R^{\oplus}_{N\setminus\{1\}}(s)$	$R^{\oplus}_{N\setminus\{2\}}(s)$	$R^{\oplus}_{N\setminus\{3\}}(s)$
s_1	$\{s_2, s_4, s_6, s_7, s_9\}$	$\{s_6\}$	$\varnothing$
s_2	$\{s_1, s_4, s_6, s_7, s_9\}$	$\{s_3, s_7, s_8\}$	$\{s_1, s_3\}$
s_3	$\{s_5, s_8, s_{10}\}$	$\{s_2, s_7, s_8\}$	$\{s_1, s_2\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_5, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_5\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_7, s_9\}$	$\varnothing$	$\{s_7, s_8, s_9, s_{10}\}$
s_7	$\{s_6, s_9\}$	$\{s_2, s_3, s_8\}$	$\{s_8, s_9, s_{10}\}$
s_8	$\{s_3, s_5, s_{10}\}$	$\{s_2, s_3, s_7\}$	$\{s_7, s_9, s_{10}\}$
s_9	$\{s_6, s_7\}$	$\{s_{10}\}$	$\{s_7, s_8, s_{10}\}$
s_{10}	$\{s_3, s_5, s_8\}$	$\{s_9\}$	$\{s_7, s_8, s_9\}$

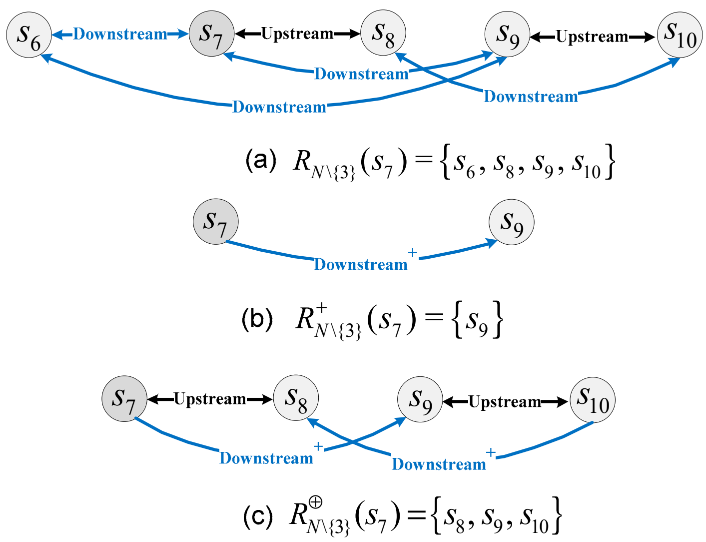

Figure 5. Graphs illustrating state transitions by (**a**) non-credible opponents, (**b**) credible opponents, and (**c**) heterogeneous opponents.

As indicated previously, the mixed sanctioning movements by heterogeneous opponents could affect the equilibria of the cross-basin water pollution dispute involving Hongze Lake. To reflect different sanctioning behavior of heterogeneous opponents in Table 11, the mixed stability analyses developed in the second part are utilized to obtain the stability results of the conflict, as given in Table 11. Note that, in Table 11, the notation

"×" indicates the different results in comparison with the results in Table 8. For instance, s_2 is not MTS and MSMR stable for ENGOs in Table 11, whereas it is GMR and SMR stable in Table 8. The reason is that downstream, who is regarded as being credible instead of non-credible, cannot move to a less preferred state, s_6, from s_7 when sanctioning if ENGOs moves to a more preferred state, s_7, from the initial state, s_2. Similarly, s_7 is not MTS and MSMR stable for downstream, since ENGOs is credible and cannot prevent downstream from moving to a more preferred state, s_9, starting at s_7. Moreover, s_4, which is unstable for ENGOs under SEQ stability in Table 8, becomes MTS stable in Table 11 because credible upstream and non-credible downstream can move together to s_7, which is less preferred to s_4 by ENGOs.

Table 11. The equilibrium outcomes of mixed stability analyses for the Hongze Lake dispute.

State	**Nash**				**MTS**				**MSMR**			
	1	**2**	**3**	**E**	**1**	**2**	**3**	**E**	**1**	**2**	**3**	**E**
s_1	√	√			√	√			√	√		
s_2	√				√	√	×	×	√		×	
s_3		√	√			√	√			√	√	
s_4	√				√		√		√		√	
s_5						√	√			√	√	
s_6	√		√		√		√		√		√	
s_7	√		√		√	×	√	×	√	×	√	×
s_8		√				√	√			√	√	
s_9	√	√	√	*	√	√	√	*	√	√	√	*
s_{10}			√			√	√			√	√	

5.3. Discussion

By comparing the equilibria of Tables 8 and 11, one can find that only s_9 is an equilibrium, while both s_2 and s_7 are no longer equilibria in the cross-basin water pollution conflict, as is consistent with the real situation. To calm down the strong protests from the local fishermen, the downstream government planned to negotiate with the upstream government to provide economic compensation. However, the upstream did not agree to negotiate with the downstream and delayed its decision since the source of the sewage flowing to the downstream was still unknown. On 30 October 2018, an environmental protection organization in China called SIP Lvse Jiangnan Public Environment Concerned Center filed public interest litigation against the environmental offenders involved in the severe cross-basin water pollution. Therefore, the mixed stability analysis approach provides more insightful and reasonable findings than general stability analyses for handling a conflict with heterogeneous sanctioning opponents.

To solve such cross-border water pollution issues, effective market-oriented means or public policies should be adopted as soon as possible for adjusting the complex interest relationship among stakeholders and exploring a new cooperative win-win solution in which the upstream actively strengthens ecological protection and the downstream supports the upstream. In the Hongze Lake pollution conflict, the key controversy is that the two sides disagreed on whether the source of sewage originated from Anhui Province or Jiangsu Province. To clearly figure out who should be in charge of the cross-basin water pollution issue, therefore, a cross-provincial horizontal ecological compensation mechanism could be systematically established based on regular water quality monitoring at inter-provincial borders. More specifically, if the water-quality-monitoring data become worse in the cross-border section of the two provinces, this means that the water pollution comes from the upstream, and Anhui Province should afford Jiangsu Province an ecological compensation fee. Otherwise, the water contamination is from the downstream, and Jiangsu Province should take the responsibility of the water pollution control of Hongze Lake. In addition, financial rewards could be assigned to the upstream for encouraging it to strengthen ecological governance and cooperation with downstream if the water quality at inter-provincial boundaries meets the standards. Furthermore, the cross-regional compensation funds can be used to compensate for water environmental protection, water pollution remediation, losses of local residents, etc.

The cross-basin eco-compensation mechanism makes the upstream more willing to negotiate with the downstream for possible solutions to resolve the Hongze Lake dispute. As a result, the conflict situation evolves from s_9 to s_{10} by the upstream, which prefers to agree to a negotiation with the downstream; it then moves from s_{10} to s_8 due to the withdrawal of the appeal by the downstream and eventually shifts to s_3 from s_8 by ENGOs, as illustrated in Table 12. Moreover, s_3 is the state in which both the upstream and downstream prefer to negotiate with each other regarding the compensation for the affected fishermen and the environmental ecological remediation in Hongze Lake without any appeal or lawsuit, making it a good solution for mediating cross-basin water pollution disputes. Last but not the least, effective measures could be taken for exploiting the role of participation supervision of ENGOs who increasingly become an important force in promoting ecological protection in the cross-basin water pollution control.

Table 12. Evolutionary path analysis from s_9 to s_3 in the Hongze Lake dispute.

DMs	Options	s_9		s_{10}		s_8		s_3
Upstream	Agree	N	→	Y		Y		Y
Downstream	Negotiate	Y		Y		Y		Y
	Appeal	Y		Y	→	N		N
ENGOs	Lawsuit	Y		Y		Y	→	N

6. Conclusions

Cross-basin water pollution conflicts pose great threats to water quality, human health, and ecosystems. The strategic interactions among stakeholders involved in those disputes are dynamic and complicated. Moreover, the sanctioning opponents are usually heterogeneous or hybrid, instead of homogeneous, in which case, some opponents move to any reachable states, whereas others levy only unilateral improvements when sanctioning. To illustrate the mixed unilateral improvements (MUIs) more intuitively and directly by heterogeneous sanctioning opponents, a direct and intuitive definition for MUIs is presented in this paper. Subsequently, a comprehensive procedure was purposefully designed in this research to conveniently execute mixed stability analyses and forecasting the possible resolutions of a conflict with heterogeneous opponents.

To demonstrate how the mixed stability approach can be applied to a real-world conflict, a cross-basin water pollution conflict that occurred in Hongze Lake, China, was systematically modeled and analyzed by using general and mixed stability analyses, respectively. The case study demonstrates that the heterogeneous sanctions could affect the outcomes of a conflict, and it is more reasonable and realistic to regard the sanctioning opponents as being heterogeneous in the cross-basin water pollution dispute. Furthermore, the mixed unilateral improvements by heterogeneous opponents from some states are different from unilateral movements and unilateral improvements by homogeneous opponents, thus greatly influencing the equilibria of the conflict. By comparing the results of the general and mixed stability analyses, one can find that mixed stabilities provide more meaningful and reasonable insights than classical stabilities can. The predicted results of stability analyses provide an important decision-making basis for mediating or resolving the Hongze Lake trans-border pollution disputes. Furthermore, the case study shows that an effective solution for addressing the cross-basin water pollution issue in Hongze Lake is the co-funded eco-compensation mechanism based on the results of regular water quality monitoring in cross-border areas. The ecological compensation strategy could boost the motivation of the upstream to participate in cross-basin water pollution control and enhance the cooperation of the upstream with downstream in ecological governance. This makes the conflict state evolve from the equilibrium state s_9 to a better state, s_3, where both the upstream and downstream choose to cooperate with each other for addressing the cross-border water contamination dispute.

The improved GMCR approach could be used to forecast the outcomes and evolutionary trend of environmental disputes with dynamically strategic interactions and heterogeneous sanctions. Moreover, this research provides a very general theoretical analysis framework with wide applicability, which could be employed for modeling and analyzing any strategic environmental disputes that occur in any countries or international regions. One can refer to the procedure in Figure 2 for more specific details about the application process. However, we considered only three main decision makers and their key options in the Hongze Lake conflict model. In the future, other stakeholders, such as the local fishermen and social media, as well as their possible choices, could be taken into account when modeling and analyzing the Hongze Lake cross-basin water pollution dispute. In fact, the journalists and lawyers also played an important role in the Hongze Lake water pollution dispute. In the future study, they could be regarded as being an independent decision maker if their standpoint is different from the ENGOs. Furthermore, an opponent in mixed stabilities could be non-credible at some states and credible at other states, thus indicating that the sanctioning behavior of an opponent may dynamically change in terms of the initial state. Hence, the mixed stability analysis approach could be extended by considering the dynamic sanctioning behavior of heterogeneous opponents in the future.

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