A Review of Application of Graph Model for Conflict Resolution in Water Resource Conflicts

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Abstract. Water resource conflicts denote the contradictions emerging among different stakeholders with respect to the acquisition, utilization, and protection of water resources. They are associated with regional security and sustainable development. Accordingly, it is imperative to collate the relevant research. The Graph Model for Conflict Resolution (GMCR) constitutes an essential tool for investigating multi-agent conflicts in recent years. Therefore, this paper scrutinizes the relevant literature on the application of GMCR in water conflict studies, delineates the deficiencies in the current development and potential research directions, with the aim of facilitating the resolution of related problems.

Keywords: Graph Model for Conflict Resolution (GMCR), Water Resource, Preference Optimization, Multi-agent Conflicts

1 Introduction

Water, being the source of life, has consistently played a significant role in guaranteeing people's livelihood and facilitating the development of the national economy. In recent years, due to the drastic alterations in climate and environment, water resources have become increasingly scarce, heightening the potential for conflicts in the acquisition, utilization, and protection of water resources, and directly influencing regional security and sustainable development. Hence, research on the multiple conflicts of interest among decision-makers in water resource conflicts, solving for the optimal equilibrium of the conflict situation, and offering methodological references for decision-makers in actual conflicts have emerged as research hotspots. GMCR, as an important model for resolving multi-agent conflicts of interest, has also been extensively utilized in the study of water resources conflicts. In this paper, through briefly summarize the emergence and development of GMCR, we can easy analyze its application achievements in water resources conflicts over the past 5 years, and indicate valuable research directions in the future, which can provide references for better addressing water resources conflicts.

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2 Literature Review

2.1 Forming and Development of GMCR

In order to summarize some valuable research directions of GMCR in water resources conflicts, corresponding relevant literature reviews are shown as follows:

Conflict refers to contradictions, oppositions, or struggles arising between two or more individuals, groups, organizations, or countries due to differences in goals, interests, values, or beliefs. In order to achieve their respective interests and goals, stakeholders must consider various action plans of other decision-makers and identify the most advantageous or reasonable strategic choices for themselves. Von Neumann and Morgenstern (1953)[1]introduced classical game theory and systematically applicated it to the economic field. However, due to its focus on the interaction between formalized incentive structures, emphasis on inherent game rules, and strong assumptions, it is difficult to be widely applied in practice. Fraser and Hipel (1979,1984)[2][3] developed F-H conflict analysis based on metagame analysis (Howard,1971)[4]. Later, Kilgour, Hipel, and Fang (1987,1993)[5][6] integrated it with the graph form to further advance it into the GMCR framework. This model provides a comprehensive and meticulous understanding of the past, present, and future dynamics of conflict situations. Since the introduction of GMCR, scholars have continuously refined the methodology to address uncertain preferences arising from incomplete information, calculate equilibrium states, and analyze evolving pathways.

Over the past 5 years, the development of GMCR mainly focus on the influence of behavioral factors on preference ranking in the modeling part.

A consensus model of conflict decision-making under fuzzy preferences was constructed by systematically expanding the consensus theory, (Zhang et al.,2022)[7], while Yu and Deng (2024)[8] expanded this work and used intuitionistic fuzzy sets to investigate the evolution of decision-makers' equilibrium states under different attitudes.

Sabino and Rego (2023)[9] introduced the optimism pessimism stability to allow for more types of attitudes under uncertainty. Yu and Deng (2024)[10] defined "win–win", "self-interested" and "neutral" these three different attitudes to calculate equilibrium solutions.

A fuzzy power asymmetry conflict analysis method for two decision-makers was proposed to further address the real-world conflicts with uncertainty (Chen et al.2024)[11]. Meanwhile, on the basis of the unequal status and tendency to form alliances among participants in environmental conflicts, Tian et al. (2024)[12] advanced a method for analyzing the stability of alliances under power asymmetry.

Researchers also investigated the stability theory of three psychological behavior characteristics (aggressive, conservative, and balanced) exhibited by decision-makers when facing risks (Zhao et al. ,2020)[15]. Han et al. (2022)[14] established a conflict decision-maker behavior analysis model for sequence stability, considering the overconfidence of decision-makers. The Minimax Regret Stability was proposed, given that DMs would feel regret for an unsatisfactory decision (Sabino and Rego,2024)[13].

Yin et al. (2023)[16] introduced a novel approach for modeling and analyzing the influence exerted by external stakeholders (ESs) within the GMCR framework. Four equilibrium solutions for GMCR were established based on grey preference influenced by externality (GPE-GMCR) (Li et al., 2024)[17]. Li et al. (2024)[18] proposed a graph model for conflict resolution that incorporates fuzzy preferences based on externality (FEGMCR), which utilizes fuzzy numbers to quantify both the uncertain preferences of DMs and the uncertain expectations of ESs.

2.2 Application of GMCR

GMCR is widely applied in finance, healthcare, government governance energy and environment and other domains since its proposal.

A dynamic interaction model for price conflict in a dual-channel supply chain based on GMCR is proposed, which was provided by the supply chain managers for a systematic and effective conflict analysis (Zhao & Xu,2017)[19]. Researchers also studied the conflict in financial business models between bank credit cards, and Ant Check Later (Xu & Wu,2023)[20]. Li et al. (2024) [21]constructed a GMCR-AHP model to analyze the governance process of labor-capital conflicts involving trade union organizations.

Jiang et al. (2019)[22] integrated the Rough Set theory and established a GMCR-RS conflict model to analyze the contradictions and conflicts among relevant stakeholders during the implementation of the separation of prescribing and dispensing system. GMCR-AHP method was proposed to analyze and optimize the conflicts among stakeholders involved in the utilization of bed resources (Cui et al., 2021)[23]. Liu et al. (2020)[24] utilized the Network Analytic Hierarchy Process (ANP) to construct the GMCR-ANP model, seeking the equilibrium solution under the payment method based on disease types.

In the realm of assisting government governance, GMCR was applied to improve the governance of urban community public spaces (Wang, 2019)[25], also could resolve conflicts of interest in highway projects (Huo et al.2021)[26], digital rural governance (Zhang et al.2023)[28], and conflicts in the allocation of elderly care resources for left-behind elderly in rural areas (Wang et al.2024)[27], as well as the old-age healthcare service system (Yang et al.,2024)[29].

Hipel et al. (1997)[30] proposed the Decision Support System GMCR in Environmental Conflict Management. Subsequently, GMCR has been extensively utilized in environmental conflicts. Wu et al. (2021)[33] applicated it to address the environmental crisis caused by N-nitroso dimethylamine (NDMA) contamination in the underground aquifer of Elmira, Canada, while Li et al. (2024)[31] applied to the plastic ban in Hainan conflicts among stakeholders. As stated by Addae et al. (2024)[32], a hybrid decision-making trial and evaluation laboratory (DEMATEL)- GMCR method was proposed to resolve energy production disputes in Ghana.

2.3 Application of GMCR in Water Resource Conflicts

Water resource conflicts encompass multiple aspects, including the acquisition, utilization, and governance of water resources, and are closely tied to regional security and sustainable development. Therefore, by focusing on the conflict of interests among multiple parties, applying conflict analysis methods, and formally modeling conflict game scenarios, through various types of stability analysis, we can identify the most favorable, most likely, and least favorable strategic choices, decision branches, and equilibrium situations, which can provide references for solving such problems.

To address the conflicts over water resources in the Zhanghe River Basin, Wu et al. (2021)[34] proposed an incomplete fuzzy preference framework for GMCR that accommodates both complete and incomplete fuzzy preferences. Their analysis of the positive social and economic benefits associated with water diversion across three provinces led to the conclusion that GMCR indicates that diverting water from Shanxi to Henan and Hebei is an effective strategy for resolving this conflict. Meanwhile, researchers have highlighted that, due to alterations in the water ecosystem, government and market involvement, as well as other contributing factors, most of these options represent short-term solutions rather than sustainable long-term strategies. In the long term, it is essential to ensure that water-saving initiatives in upstream provinces facilitate effective water transport; only then can a lasting resolution to conflicts over water resources in downstream areas be achieved.

In a separate dispute regarding water resource allocation between upstream and downstream areas of DAYRD-located at the intersection of three administrative regions within the Yangtze River Delta-Yang et al. (2019) [35]first integrated a benefit function into GMCR, determining both optimal third-party intervention intensity and optimal conflict evolution paths. The consequences reveal that the enhanced GMCR model based on the revenue function has the ability to accurately simulate the dynamic development of cross-border water conflicts and evade the influence of subjective factors from researchers or experts in the traditional way. Furthermore, the findings imply that water conflicts in the DAYRD can be changed from the current situation (conflict) to the desired state (cooperation) by effectively controlling the intensity of third-party interference. These disclosures present valuable viewpoints for the resolution of transboundary water conflicts and improve our understanding of the role of third parties in converting conflict to cooperation.

Chu et al. (2022)[36] employed lexicographical preference ranking to dynamically characterize ecological and environmental conflicts in the middle route water source area, emphasizing that management agencies should implement various incentive mechanisms for local governments to guide these conflicts toward a balanced resolution. Similarly, Li et al. (2023)[37] conducted research on conflicts within the upper, middle, and lower reaches of Poyang Lake basin by developing a novel grey-inverse graph model. The findings suggest that the Jiangxi Provincial Government should also create an ecological compensation mechanism based on targeted policy subsidies and penalties to ensure rational allocation of water resources throughout the basin.

Xu et al. (2021) constructed a 0-1 multi-objective programming third-party mediation model based on the inverse problem theory of GMCR, designed the model solution, and applied it to the conflict event caused by the serious deterioration of water quality in Hongze Lake in 2018. The proposed method can find the strong equilibrium solution that enables the upstream and downstream regions to make the minimum preference concession, effectively assist the third party in formulating mediation strategies, accelerate the speed of conflict resolution, and promote the coordinated development of the upstream and downstream regions.[43]

Based on uncertainty theory and the cognitive preference model, an inverse graph model for conflict resolution has been developed and applied to investigate transboundary water resource conflicts in the Lancang-Mekong River Basin. The results indicate that third-party management plays a crucial role in problem-solving. Firstly, it can directly foster a win-win situation among all decision-makers by capturing the preferences of various stakeholders. Secondly, effective monitoring by third parties can expedite the stabilization process for all involved parties, while also facilitating sustainable transboundary water allocation. The proposed methodology and analytical outcomes offer decision support for third-party management agencies dealing with conflicts over transboundary water resources and provide a scientific basis for mediating similar water resource disputes both within and beyond China. (Gu et al., 2023)[38].

Zhang et al. (2022)[7]conducted a research on the consensus model for conflict decision-making based on fuzzy preferences and applied it to a series of conflicts caused by China's construction of cascading hydropower dams on the lower reaches of the Mekong River. It was concluded that if the consensus preference was adopted, that is, if both parties paid more attention to each other's consensus preferences, the equilibrium solutions to the conflict would be s_2, s_4, and s_5. Specifically, s_2 means that China chooses to continue dam construction for power generation and the Mekong River Commission (MRC) selects to negotiate with China. s_4 indicates that China not only maintains the status quo but also shares hydrological information and technology with the MRC and supports member countries in developing water conservancy projects. s_5 indicates that China decides not to continue the development project and the conflict resolves automatically. However, when the non-consensus preference was adopted, the only strong equilibrium solution was s_5, meaning that only when China chose not to continue the water conservancy project could the conflict end. It can be seen that the conflict stability under fuzzy consensus and non-consensus preferences is more in line with diversity and the actual situation, and can assist decision-makers more accurately in making decisions.

Wang et al. (2024)[39] incorporated the concept of information asymmetry into GMCR to analyze conflicts concerning the sustainable utilization of water resources in the Niangziguan Springs Basin. The findings of the asymmetric stability analysis disclose that the government ought not to sanction factories' excessive utilization of water resources without authorization, as this imposes significant pressure on the total water resources reserves of the area. Concurrently, the results imply that an information disparity exists between the government and factories. The government can capitalize on its information superiority to formulate efficacious environmental protection measures, while factories need to undertake appropriate adjustments and compromises in line with the government's preferences. The article further contends that the government should enforce stringent environmental laws and policies to ensure the sustainable utilization of water resources and suggests that the government should intensify cooperation among different departments during the policy formulation process.

Researchers have successfully addressed the shortcomings of traditional methods in managing decision-maker heterogeneity, limited rationality, and the absence of theoretical support for preference ranking organization during the GMCR modeling phase by incorporating a GMCR framework that integrates mixed information processing and prospect theory. Additionally, they have refined the Preference Ranking Organization Method (PROMETHEE) utilized for enhancing evaluations, thereby providing a viable preference ranking approach for the GMCR modeling stage. The study was applied to a real-world case involving ecological conflicts in the Huangshui River and conducted through multi-dimensional comparative analysis. The findings indicate that state s_4 represents a conflict equilibrium solution; specifically, it suggests that the government can implement measures to amend the existing work plan while ensuring that the factory accepts these modifications and actively collaborates to address industrial wastewater discharge issues. Through cooperation between governmental authorities and factories to revise the work plan, this approach aims to ensure a policy solution conducive to protecting local water resource environments. (Liu et al., 2025)[40].

3 Discussion

Over the past five years, researchers have explored the impact of behavioral factors in GMCR, such as consensus, attitude, and psychological behavior characteristics, on preference ranking. By introducing concepts such as fuzzy theory, power asymmetry theory, and gray preference, they have further optimized the solutions for stability analysis and evolutionary path analysis. At the same time, they have made applications in finance, healthcare, government governance, and other fields, providing references for decision-makers to make decisions that maximize benefits in complex conflict situations. Meanwhile, scholars have analyzed water resource conflicts in different basins using GMCR by updating preference ranking methods, introducing benefit functions, and integrating information asymmetry concepts. They have discovered the important role of upper management institutions in achieving conflict equilibrium through ecological compensation and incentive mechanisms, as well as the role of third-party mediation institutions. The equilibrium solutions for conflict analysis in various basins also provide methods and solutions for similar problems.

Scholars currently face some limitations in application of GMCR in water resource conflicts, namely: The first one is complex power relationships among various gaming parties have not been fully considered. The second one is the lack of systematic preference ranking theory, and preference ranking still exhibits strong subjectivity and uncertainty. The final one is the equilibrium solutions are mostly short-term solutions, failing to take into account attribute changes and cognitive differences in the actual decision-making process.

Although researchers have conducted in-depth studies on the systematic utilization of GMCR, there are still gaps in analysis of alliances and alliance stability among decision-makers in complex environments, conflict analysis under power asymmetry, and impact of external decision-makers on decision-making situations.

4 Conclusion

In this paper, we firstly reviews and summarizes the formation of GMCR and its impact on preference ranking by external decision-makers over the past five years. Then elaborates on the applications of GMCR in finance, healthcare, government governance, energy, and the environment. And describes the achievements of GMCR in addressing water resource conflicts over the past five years and summarizes the beneficial reference schemes and measures for resolving water resource conflicts.

As Yu et al. (2020)[41] pointed out, in the context of climate change and environmental changes, water resources are related to regional security and sustainable development. The scarcity can cause deterioration of the political situation within the region, further increasing the likelihood of water resource conflicts. Therefore, research on water resource conflicts is not only to provide reference for solving existing conflict issues, but also to prevent the occurrence of future water conflicts and maintain long-term national stability.

Based on corresponding limitations, future research directions are shown: Firstly, researchers can introduce various preference definitions to further improve the ranking of decision-makers' options in water resource conflicts. Secondly, efficient heuristic algorithms can be introduced to optimize preference ranking, reducing subjectivity and uncertainty. Finally, existing models for studying water resource conflicts, such as the Rubinstein Bargaining Model (Fu et al.2024)[42], which can be combined to further optimize the results of GMCR.

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