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# Research on water resources collaborative utilization based on complex networks: A case study of the Han River Basin

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**Abstract.** As China's social economy grows and the demand for water resources increases, the Han River Basin faces intensified supply-demand conflicts, reducing water resource utilization efficiency and threatening regional development. To address this, a network evolutionary game model based on complex network and evolutionary game theory was developed for collaborative water resource utilization. The study identified key dynamic factors influencing the game in the Han River Basin and analyzed its evolutionary rules. Simulations revealed that the profit-loss ratio and profit distribution rate significantly affect cooperative behavior. Furthermore, the network's topology exhibits small-world characteristics, and factors such as economic preferences, income distribution, and reward-punishment coefficients critically influence cooperation. Considering the current state of water resources and economic development, it is projected that comprehensive cooperation in the basin may take around 11 years to establish.

**Keywords:** Water resource utilization, Complex network; Evolutionary game theory; Evolutionary dynamics.

## 1. Introduction

As one of the most populous countries in the world, China is facing increasingly severe water resources management challenges, which are rooted in multiple factors such as geography, economy, and climate. Uneven distribution of water resources is one of the major challenges, especially the relative abundance in the east and shortage in the west, exacerbating the economic disparity between regions. With the rapid development of the economy, industrial water demand continues to rise, further exacerbating the contradiction between supply and demand, and climate change has also brought new challenges to water resources management, such as frequent droughts and floods. The government has actively promoted water resources management and protection as a top priority, and has adopted major project implementation plans and other measures to deal with water resource imbalances and supply-demand conflicts. For example, the South-to-North Water Diversion Project has provided important support to solve the water shortage problem in some areas. Faced with this background, it is urgent to explore game behavior in collaborative utilization of water resources to achieve sustainable development in the Han River Basin [1]. This article aims to analyze the network structure of China's collaborative utilization of water resources based on complex network and evolutionary game theory, and establish a corresponding game model to reveal the laws and characteristics of water resources management.

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In-depth study of the collaborative utilization mechanism of water resources can effectively solve problems such as uneven distribution of water resources and contradictions between supply and demand among regions, and promote the efficiency and fairness of water resources utilization. Especially for areas that span multiple provinces, have large drainage areas, and have numerous tributaries, it is very important to study the positive role of coordinated utilization of water resources in promoting economic and social development and ecological and environmental protection [2, 3]. In-depth research on the game behavior of collaborative utilization of water resources will help achieve the rational allocation of water resources among regions. In addition, combining the complex network perspective and evolutionary game theory to explore the game behavior of collaborative utilization of water resources will bring new ideas and methods to the field of water resources management [4, 5]. By drawing on research results and experiences in other fields, we can gain a deeper understanding of the game rules in water resources management networks and provide important support for water resources management.

## 2. Related Work

In water resources research, the system itself has the characteristics of a network. The locations in the water network can be regarded as nodes, and the edges represent actual rivers or connections between different locations. The introduction of complex network theory can effectively solve many water resource-related problems. When considering water resources systems as complex networks, properties such as clustering coefficient, centrality, average path length, and complex network evolution processes can well explain the characteristics of water resources systems.

These characteristics have been used in multiple studies, such as the study of extreme rainfall events by Boers et al [6], the analysis of precipitation characteristics in Canada by Sivakumar et al [7]. The exploration of the spatial distribution of rainfall in Australia by Jha et al [8].

The application of Halverson et al [9] in Canadian precipitation research, have verified the rationality of this theory in watershed description. In addition, complex network theory is also of great value to the optimization of water network monitoring systems.

## 3. Methodologies

### *3.1. Primary Notions and Assumptions*

In the process of collaborative utilization of water resources, the benefits of each subject are affected by the behavioral strategies of other subjects. Therefore, in order to better study the game behavior among the subjects, the following assumptions need to be made based on the characteristics of each subject. First, according to the topological structure analysis of the collaborative utilization network of water resources in the Han River Basin, the network has the characteristics of a small-world network, in which each node, that is, each water use subject, pursues the maximization of its own interests in the utilization of water resources. In this network, the game is continuous, and each node acts as an independent water subject.

In order to ensure its own water needs, it will adjust its decision-making at any time, regardless of the timeliness and execution delay of the decision-making. Secondly, in the collaborative utilization network of water resources in the Han River Basin, the behavioral strategy selection of each node is affected by factors such as the scale of the collaborative utilization network and policy rules. In terms of behavioral strategy selection, the behavioral selection strategy set of each water use subject is: water use subject = {participate in collaboration, not participate in collaboration}. Finally, according to the analysis of the characteristics of the water resources collaborative utilization network, there is heterogeneity among the water resource utilization entities in the network, that is, important node sets and general node sets.

The parameter settings of various types of nodes in the selection of water resource collaborative utilization strategies are shown in Table 1.

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**Table 1.** Parameter setting and corresponding explanations.

| Notions | Explanations |
|---|---|
| F | Only pursue the benefits of economic growth |
| α | economic preferences |
| E | Income status |
| k | Reward and punishment coefficients |
| R | Benefits brought by participating in utilization of water resources |
| S | Losses caused by not participating in collaborative utilization |

### 3.2. *Evolutionary Game Analysis of Collaborative Utilization*

In the water resource collaborative utilization network, we randomly select a pair of game subjects for evolutionary game analysis. These two subjects are water resource utilization subject 1 and water resource utilization subject 2. During the game, they face two strategic choices: participation and non-participation. We assume that the probability of water resource utilization subject 1 choosing to participate is x ($0 \leqslant x \leqslant 1$), and the probability of choosing not to participate is (1-x); the probability of water resource utilization subject 2 choosing to participate is y ($0 \leqslant y \leqslant 1$), the probability of choosing not to participate is (1-y). What needs to be noted here is that both x and y are functions of the evolutionary game time t. The expected return when water resource user 1 chooses to participate is Equation 1.

$$U_{11} = y\theta R + (1-y)^2[\theta(R-\alpha_2 S) + KE_2] \tag{1}$$

The expected return when water resource user 1 chooses not to participate is expressed as Equation 2.

$$U_{12} = y[\theta(R-\alpha_1 S) - KE_1 + \alpha_1 F] + (1-y)[\theta(R-\alpha_1 S-\alpha_2 S) + \alpha_1 F) \tag{2}$$

From the above two expected returns, it can be concluded that the replication dynamic equation of water resource utilization subject 1 is expressed as Equation 3.

$$\begin{aligned} f(x) = \frac{dx}{dt} = (y-1)[F\alpha_1 - \theta(\alpha_1 S - R + \alpha_1 S)] - y[\alpha_1 F + \theta(R-\alpha_1 S) - E_1 K] + \theta R y) \\ -x(x-1)[(y-1)^2(\theta R - \theta\alpha_2 S) + E_2 K] \end{aligned} \tag{3}$$

The expected return when water resource utilization subject 2 chooses to participate is Equation 4.

$$U_{21} = (1-\theta)xR + (1-x)[(1-\theta)(R-\alpha_1 S) + E_1 K] \tag{4}$$

The expected return when water resource user 2 chooses not to participate is Equation 5.

$$\begin{aligned} U_{22} = x[(1-\theta)(R-\alpha_2 S) - KE2 + \alpha_2 F] \\ +(1-x)[(1-\theta)(R-\alpha_1 S-\alpha_2 S) + \alpha_2 F] \end{aligned} \tag{5}$$

From the above two expected returns, it can be concluded that the replication dynamic equation of water resource utilization subject 2 is Equation 6.

$$f(y) = \frac{dy}{dt} = y(y-1)(\alpha_2 F - \alpha_2 S - E_1 K + E_1 K x - E_2 K x + \theta\alpha_2 S) \tag{6}$$

The above-mentioned replication dynamic equations of water resource utilization subject 1 and water resource utilization subject 2 are the updated probabilities during the evolution of the game behavior of the two subjects.

### 3.3. Network Evolution Dynamics Method

To study the evolutionary game behavior of collaborative water resource utilization within complex networks, this article utilizes MATLAB to construct a model comprising several components:

- Network initialization. Complete the construction of complex networks and initialization of collaborative utilization network parameters. From Chapter 3, it can be seen that the complex network of water resources collaborative utilization has small-world characteristics. In the initialization stage, a water resources collaborative utilization network with N nodes was established based on the generation rules of the small-world network. At the beginning of the game, assume that y individuals choose to participate in the strategy, and 1-y individuals choose not to participate in the strategy. The initial strategy selection ratio is {participate (strategy C): do not participate (strategy D) = y: 1-y}. We call the proportion of collaborative utilization participants in the entire group at a specific game moment as the collaborative utilization cooperation rate f.
- Determine the rules of the game. As the evolutionary game begins, each water user adopts an initial strategy. The game proceeds, and outcomes are calculated based on a predefined benefit matrix.
- Strategy update. Within this framework, each water user must adjust its own strategy after a round of gaming. Each individual's strategy adjustment must follow the FEMI rules. Its strategy in the next round of game is the new strategy selected after the previous round of game. The corresponding collaborative utilization participation rate will change in each round of game.
- Network structure adjustment. The topology of the network is dynamic; connections between nodes may change or break, reflecting changes in strategy and collaboration failures.
- Calculation of cooperation rate. The cooperation rate among participants is computed after each round. The simulation continues until this rate stabilizes, concluding with the final behavior derived from the evolutionary game.

## 4. Experiments

### 4.1. Stability Analysis

The judgment of the four equilibrium points requires further analysis of their stability, so as to obtain a stable strategy point that meets the requirements. Under this strategy point, D(J)>0, T(J)<0, both are established simultaneously, and the subjects participating in the cooperation are basically The income after adding the reward income and excluding the accumulated game income is greater than 0. The basic income of the subjects who do not participate in cooperation is less than 0 after excluding the penalty losses and adding the accumulated game income. After analyzing and solving the evolutionary game model, the equilibrium point of the evolutionary game under certain conditions was obtained. The stability of the system was further analyzed and solved. The results are shown in Table 2.

**Table 2.** Equilibrium point stability analysis.

| Equilibrium point | D(J) | T(J) | Stability |
|---|---|---|---|
| (0,0) | + | + | Unstable |
| (0,1) | − | Indefinite | Saddle point |
| (1,0) | − | Indefinite | Saddle point |
| (1,1) | + | − | ESS |

It can be seen from Table 2 that when the equilibrium point (1,1) is satisfied, it is a stable strategy point that meets the requirements, that is, when both parties choose to participate in the collaborative utilization strategy, the evolution of the two water users is shown in Figure 1, where (a) is the evolution of the first subject, and (b) is the evolution of the second subject.

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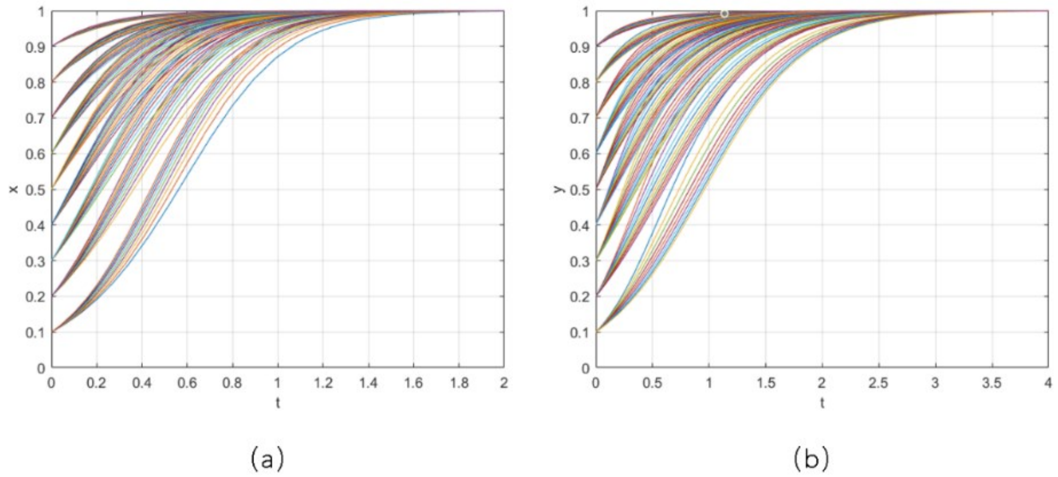


**Figure 1.** The evolution of subject 1 and subject 2.

*4.2. Profit and Loss Analysis*

Small-world network models with a scale of 30 and 100 nodes were selected for simulation experiments, and the parameters of gains and losses were gradient set. The results are shown in Figures 2.

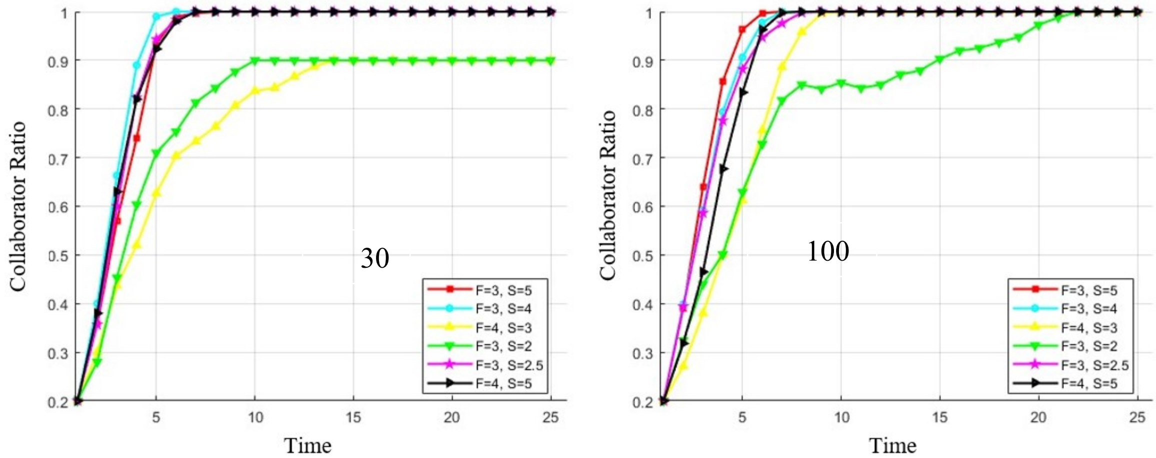


**Figure 2**. Evolution results of cooperation rate under different profit and loss ratios when the scale is 30 and 100.

It can be seen that in a water resource collaborative utilization network with a scale of 100, the influence of important nodes will play a certain role. Under a long-term game, the proportion of water users in larger-scale networks choosing to cooperate is larger. Eventually, more water users will choose to participate in cooperation.

Small-world network models with network sizes of 30 and 100 nodes were selected to conduct economic preference simulation experiments. The simulation results are shown in Figure 3.

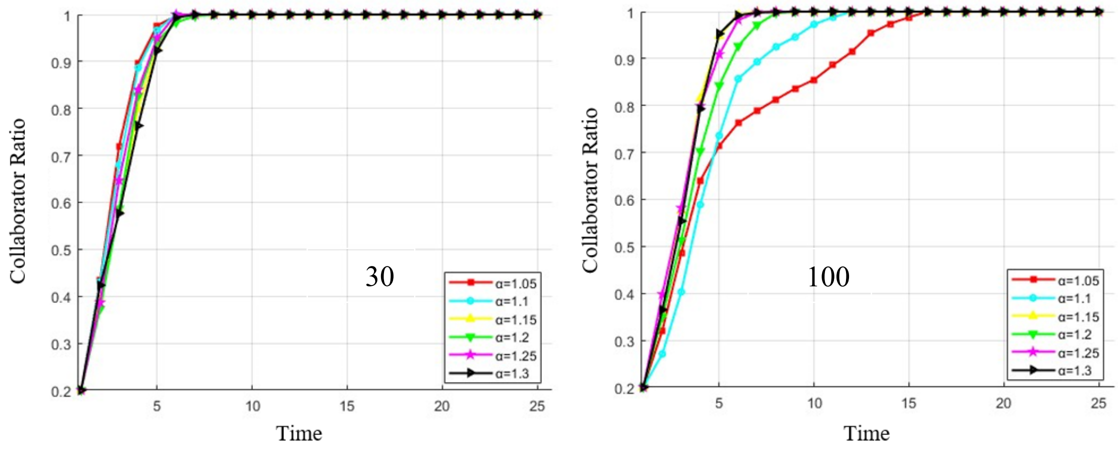


**Figure 3.** Evolution results of cooperation rate under different economic preferences when the scale is 30 and 100.

## 5. Conclusion

Water resources management in the Han River Basin faces multiple challenges, including geographical, economic and climatic factors. Uneven distribution of water resources is one of the main challenges, leading to differences in water use and economic development among regions. In order to solve these problems, exploring the collaborative utilization of water resources has become an urgent need. Based on the complex network perspective and evolutionary game theory, this paper constructs a water resources collaborative utilization network and game model, analyzes the topology structure of the water resources collaborative utilization network, and studies the cooperative evolution rules of game subjects under the influence of different dynamic factors. The research results show that the construction of the evolutionary game model for collaborative utilization of water resources fully takes into account the dynamic factors affecting the evolutionary game, and the conditions for stable cooperation are obtained through the analysis of equilibrium point evolutionary dynamics. Secondly, in simulation experiments, it was found that factors such as gain-loss ratio and economic preference have a significant impact on the cooperative behavior of subjects.

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