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Evolution of water resource allocation in the river basin between administrators and managers

Zuliang Lu[a,b,*], Fei Cai[a], Jinkui Liu[a], Jiayuan Yang[a], Shuhua Zhang[b] and Shuang Wu[a]
[a] Key Laboratory for Nonlinear Science and System Structure, Chongqing Three Gorges University, Chongqing 404000, China
[b] Research Center for Mathematics and Economics, Tianjin University of Finance and Economics, Tianjin 300222, China
*Corresponding author. E-mail: zulianglux@126.com

ABSTRACT

The reasonable allocation of water resources runs through the main links of regional water resource planning and management, which is a complex decision-making issue, ensures the sustainable development and utilization of water resources, and makes a greater contribution to the sustainable development of social economy. In this paper, evolutionary game theory is applied to the allocation of watershed water resources in a river basin. Also, the analysis of the replication dynamics and evolutionary stability strategies of water resource allocation among water resource manufacturers was done. It was found that the evolutionary game among the water resource manufacturers has only an evolutionary stability strategy. Considering the evolutionary game between water resource managers and water resource manufacturers, the evolutionary stability strategy is analyzed. This study suggests that there are two evolutionary stability strategies (**N**: normal water intake, **H**: high level of regulation) and (**E**: excess water intake, **L**: low level of regulation) between the water resource manufacturers and the administrative water resource regulators, where the strategy (**N**: normal water intake, **H**: high level of regulation) is the expected direction. The evolution factors of the strategy (**N**: normal water intake, **H**: high level of regulation) were analyzed. Furthermore, it also suggested that an effective reward and punishment mechanism will help to draw up excessive water, dismantle the conflicts between the water resource manufacturers and the administrative water resource regulators, and increase the benefits of both sides.

Key words: administrative regulators, evolutionary game, manufacturers, water resource allocation, water security

HIGHLIGHTS

- The evolutionary game theory is applied to the problem of water resource allocation.
- The strategy choice of game subjects is analyzed, and the effective reward and punishment mechanism is introduced to solve the conflict between game subjects and increase the interests of both sides.

GRAPHICAL ABSTRACT

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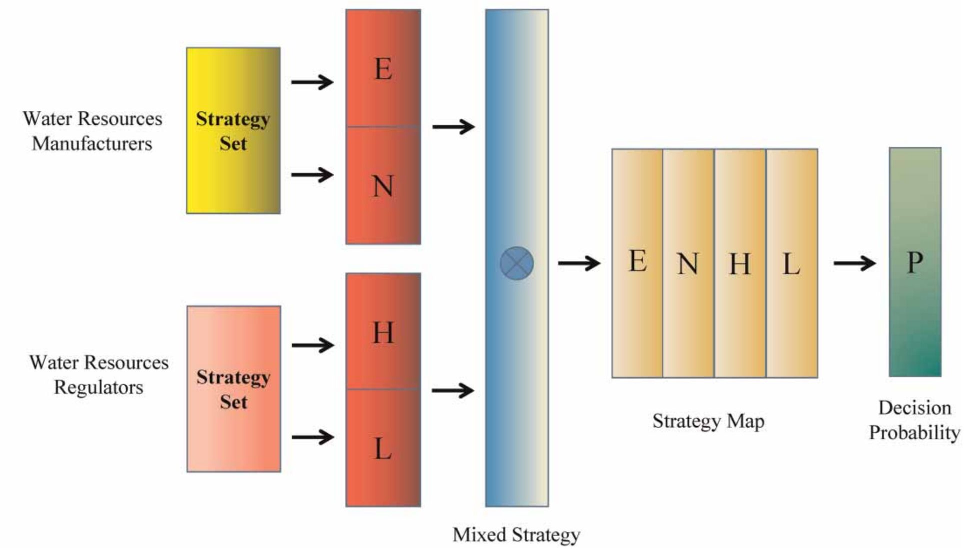

1. INTRODUCTION

In an era of rapid economic development, people's demand for water resources is increasing day by day. An increase in the frequency, duration, and severity of regional drought poses major threats to the health and integrity of downstream ecosystems (Petes *et al.* 2012). Water resources are becoming increasingly scarce. The shortage of water resources has seriously, in some ways, restricted the development of national economy. These are related to water security issues. Water security refers to the capacity of water resources at a guaranteed quantity and quality to meet requirements for human survival and development, which can maintain the basin sustainability and the human and ecological environment health and protect people's life and property from water disasters (Yao *et al.* 2020). However, in recent years, frequent floods, water shortage, pollution, and water ecological damage have become serious global challenges (Han *et al.* 2018). The reasonable allocation of water resources is proposed for the shortage of water resources and competition, and its implementation is realized through the water resource allocation system. From the current situation, there are some problems in water allocation decisions due to technical and management limitations.

Firstly, there exists a gap between planning objectives and the actual management operation. Generally speaking, in China, the planning of a river basin has drawn conclusions on water resource allocation, but there are still insufficient annual and short term combined with real-time hydrological conditions and water demand information to ensure a reasonable implementation plan. Secondly, the pre-alarm system is inadequate for the combination of water resource allocation and forecasting. Water resource decision-making is mainly based on static information of water resources and current water resource allocation. Although this method is easy for different water intake subjects to recognize, it is not conducive to dynamic management and cannot fully adapt to the ever-changing reality. Thirdly, there is a lack of overall analysis and consideration in the actual operation process. In addition to the joint operation of some key projects, the project operations under the normal management system and water demand lack the framework and mechanism for the overall optimal allocation of water resources in the basin. Finally, water-supply emergency management and crisis management mechanisms are lacking. There are operational water resource allocation and scheduling schemes in the conventional state, but the water resource allocation mechanism and effect evaluation methods in the emergency state are lacking. Therefore, the reasonable allocation of water resources is a complex decision-making problem, which runs through the links of water resource planning and management in a river basin.

The nature of water resource systems depends on economy and society (Li *et al.* 2018). One of the basic issues of optimal allocation of water resources is that different interest groups prefer different objectives and these objectives may conflict with each other (Tian *et al.* 2019). How to effectively allocate water resources and make corresponding institutional arrangements to eliminate conflicts and achieve win-win results has become a hot topic for experts and scholars. Eleftheriadou & Mylopoulos (2008) applied cooperative game theoretical concepts in the case study on the Nestos-Mesta transboundary river. Rowland (2006) used game theory and Nash bargaining theory to analyze the allocation and conflict of water resources and realized the optimal allocation and conflict resolution of water resources. The authors studied the bankruptcy game models of water resource allocation by using the theory of bankruptcy and bargaining (Mianabadi *et al.* 2014; Sechi & Zucca 2015). There were some experts and scholars who used advanced computer technology such as an intelligent algorithm to study water resource allocation (Gopalakrishnan *et al.* 2005; Karamouz *et al.* 2005; Nandalal & Hipel 2007).

To the best of our knowledge, the fairness of water resource allocation is the key to sustainable utilization of water resources, which is closely related to social stability (D'Exelle *et al.* 2012). Hipel *et al.* (2013) considered the multi-objective attribute of each player. The result showed that, often, there are conflicts between individuals in the negotiation process because water is regarded as a public good which should be used fairly. Giordano & Wolf (2001) thought that, in the process of negotiation, players in each region, based on their initial position on rights, have raised the most fundamental issue of how to allocate water resources fairly. Therefore, there is an urgent need for a fair and systematic approach to provide a reasonable decision-making method for water resource allocations to reflect the value systems and concerns of all players.

Game theory is a methodology to study the decision-making of different decision-makers when they interact with each other directly under the condition of interdependence and to seek this kind of decision-making equilibrium (Loaiciga 2004). The purpose of the game analysis was to establish appropriate incentive mechanisms and rules to achieve a stable equilibrium. The traditional game theory was based on the assumption of complete rationality and has strict requirements. Compared with the traditional game theory, the evolutionary game theory has relaxed the assumption conditions, but also belonged to bounded rationality (Gintis 2000). The sole aim of evolutionary game model analysis was the dynamic change rate of the proportion of individuals that the game players take a certain strategy, which can be expressed by a dynamic differential equation (Taylor & Konker 1978). With the development of game theory, it has been applied in many aspects. For example, Liu *et al.* (2015) developed an evolutionary game of two enterprise populations' dynamics and stability in the decision-making process of the river basin's sustainable development. Chen & Wu (2010) built an evolutionary game model between regions with excessive water right groups and regions with too few water right groups. They analyzed the replicator dynamics and evolutionary stable strategy (ESS) of each group.

In addition, based on the evolutionary game theory, Xiao and Peng (Xiao *et al.* 2021) constructed an evolutionary game model involving water-supply companies and water-consuming companies with a systematic analysis of the interaction process between the policy formulation related to water pricing by water-supply companies and the decision-making related to water consumption by water-consuming companies. Chen & Hu (2018) developed an evolutionary game theory model of the interaction between governments and manufacturers based on static carbon taxes and subsidies. Yuan (Yuan *et al.* 2019) and Arjoon and Tilmant (Arjoon *et al.* 2016) attempted to fill the transboundary water-sharing problem by combining the evolutionary game and the system dynamic model to predict the equilibrium outcomes of different strategic scenarios. To resolve a variety of conflicts over water resources, Yang and Zeng (Yang *et al.* 2008) developed a two-person game theory-based model for water resource management in the transboundary regions of a river basin. Varouchakis *et al.* (2018) proposed a two-person zero-sum game, involving a conflict of interest between the Municipal Enterprise for Water and Sewage of Chania (Player 1) and the city's approximately 108,000 residents (Player 2). Parsapour Moghaddam *et al.* (2015) applied a new heuristic evolutionary game to determine evolutionary stable equilibrium strategies for conjunctive surface and groundwater allocation to water users with conflicting objectives. Gao (Gao *et al.* 2019) investigated the interactions among upstream government, downstream government, and central government by applying evolutionary game in the Easter Route of the South-to-North Water Transfer Project in China. Lu (Lu *et al.* 2020) established a trilateral game model using an evolutionary game of the users in the upper, middle, and lower reaches of a river basin, extending the traditional game and carrying out the simulation of the evolution behaviors of the main game subjects.

However, the existing evolutionary game research on water resource allocation is relatively abstract and does not take into account the role of the water resource administrative regulators in water resource allocation, although the above studies have a lot of reference significance for us to do the following. Hence, this paper uses the evolutionary game theory to analyze the replication dynamics and evolutionary stability strategies between water resource manufacturers without government control and under government control, and between water resource managers and water resource manufacturers in the river basin water resource allocation, seeking an optimal stable strategy between the water resource manufacturers and water resource administrative regulators in order to solve the contradiction between them. Finally, a numerical example is used to simulate the evolutionary behavior of each player under different parameter values, which provides some suggestions for the reasonable allocation of water resources between the water resource manufacturers and the water resource administrative regulators.

In this paper, the theory of evolutionary game is used to allocate water resources in a river basin. Section 2 introduces the relevant materials and methods of evolutionary game theory. In Section 3, describing the construction and analysis of the model, the evolutionary game between two water resource manufacturers without administrative water resource regulators is discussed, and the administrative water resource regulation in evolutionary game is considered and their ESS is analyzed. The results are discussed and analyzed in Section 4. In Section 5, this paper is summarized.

2. MATERIALS AND METHODS

2.1. Research methodology

Evolutionary game theory combines game theory and dynamic evolutionary analysis, and holds that when the economy is in a stable equilibrium state, economic agents have finite rationality to continuously imitate and learn favorable strategies and finally reach a stable strategy, namely an ESS (Smith 1974). Replication dynamics refers to a dynamic differential equation that describes the proportion of a particular strategy adopted in a population as follows (Xu *et al.* 2018):

$$F(x_S) = \frac{dx_S}{dt} = x_S[E(x_S) - \bar{E}] \tag{1}$$

where dx_S/dt is the rate of change in the proportion of game participants adopting strategy S over time. x_S is the proportion of the S strategy participants in the whole process. $E(x_S)$ is the expected return value of the S strategy in the game system, and the $\bar{E}$ is the average expected return. The stability points of the ESS should have the following properties: when the evolution reaches a stable state, the derivative of the differential equation of the replicator dynamics should be less than 0, namely, $F'(x_s^*) < 0$.

2.2. Bounded rationality and strategy

2.2.1. Bounded rationality

This means that the game subjects cannot find the best strategy at the beginning of the game (Xu *et al.* 2019). Nash equilibrium is not important to them, because they may not have the ability to find Nash equilibrium; the game subjects may adopt any strategy, so the process of the evolutionary game is gradual, which means that equilibrium is the result of one-time choice.

2.2.2. Strategy

In an uncertain decision-making environment, different people may exhibit very different behaviors (Wang *et al.* 2017). Water resource manufacturers will adjust its strategy according to the strategies of other water resource manufacturers and the administrative water resource regulator in the process of water resource allocation. The behavioral strategies are as follows: (1) there are two options for water resource manufacturers: {excess water intake **E**, normal water intake **N**}. (2) There are two options for administrative water resource regulator: {high level of regulation **H**, low level of regulation **L**}.

In order to analyze the replicator dynamics and its ESS among the water resource manufacturers, and between the water resource manufacturers and the water resource administrative regulators, the following concepts were first introduced:

	Water intake	**Regulation**
Strategy	Excess water intake **E**	High level of regulation **H**
	Normal water intake **N**	Low level of regulation **L**

According to the theory of water rights, it is known that water rights, which are the property rights of water resources, are the decision-making power, which are related to the use of water resources (Wang 2005). The water right is a kind of property right around a certain amount of water resources under the condition of scarcity. Water resources have the characteristics of fluidity and recycling. The object of the water rights is a certain amount of water resources allocated intuitively. In the initial allocation of water rights in each cycle, the water intake of each party is given. This given water intake is marked as the intake threshold q^T. In this paper, M water intake subjects are considered. Then we have the following definitions:

(1) *Excess water intake* **E**: In each cycle, the quantity of water intake $q_j > q^T$ of each party as excess water intake is defined. Let $q_j^{\mathbf{E}},\ j = 1, 2$ be the quantity of excess water intake.
(2) *Normal water intake* **N**: In each cycle, the quantity of water intake $q_j \le q^T$ of each party as normal water intake is also defined. Let $q_j^{\mathbf{N}},\ j = 1, 2$ be the quantity of normal water intake.

According to the regulation theory, the basin administrative regulation of water resource allocation is also an important part of social regulation (Guo & Niu 2012). There are also differences in the level of administrative control over water resource allocation, which leads to the following definitions:

(3) *High level of regulation* **H**: The administrative water resource regulators can give a timely and effective response, which acts as a reward or punishment to the different water intake strategies adopted by each water intake subject, rewarding the water intake subject for normal water intake strategy **N** and punishing the water intake subject for excessive water intake strategy **E**.
(4) *Low level of regulation* **L**: The administrative water resource regulators fail to give a timely and effective response to the different water intake strategies adopted by each party's water intake subjects.

3. MODEL CONSTRUCTION AND ANALYSIS

3.1. The game

A river basin water resource allocation area with $m \in M$ water intake subjects is considered. Maximum available water resources in the area are regarded as Q. The quantity of water intake subject is defined as$q_i,\ i \in M$. Then, the total quantity of all water intake subjects can be seen as follows:

$$q = \sum_{j \in M} q_j, \quad j \in M \tag{2}$$

It is assumed that the cost of unit water is a constant c, the average pollution rate of unit water is λ, and the abatement cost of unit waste water is c_0. The output per unit of water resources is set as p, the maximum available water resources as Q and the total water intake q of all water intake subjects. Let $\alpha > 0$ be the marginal negative effect of water intake per unit on the water resource output. Then, the output per unit of water resources is as follows (Chen *et al.* 2008):

$$p = p(q) = \alpha(Q - q), \quad q \le Q \tag{3}$$

According to Chen *et al.* (2008) and Anand & Giraud-Carrier (2020), the profit function of water intake subject i is defined by

$$u_i = \alpha(Q - \sum_{j=1}^{n} q_j)q_i - cq_i - \lambda c_0 q_i, \quad i = 1, 2, \cdots, n, \tag{4}$$

where $\alpha(Q - \sum_{j=1}^{n} q_j)q_i$ is the income of water intake q_i, and cq_i and $\lambda c_0 q_i$ are the production cost and pollution abatement cost of producing q_i output, respectively.

Next, a stochastic game among a large population of water resource manufacturers is considered. Suppose that the population of n water intake subjects consists of two parties **A** and **B**. Party **A** presents the water resource manufacturers which adopted excess water intake strategy **E** and the proportion of party **A** which adopted excess water intake strategy **E** is σ. It is taken for granted that party **B** presents the water resource manufacturers which have chosen normal water intake strategy **N** and the proportion of party **B** which adopted excess water intake strategy **E** is $1-\sigma$. Then we have the following payoff functions:

$$u_1^{\mathbf{EE}} = \alpha[Q-(q_1^{\mathbf{E}}+q_2^{\mathbf{E}})]q_1^{\mathbf{E}} - (c+\lambda c_0)q_1^{\mathbf{E}}, \tag{5}$$

$$u_2^{\mathbf{EE}} = \alpha[Q-(q_1^{\mathbf{E}}+q_2^{\mathbf{E}})]q_2^{\mathbf{E}} - (c+\lambda c_0)q_2^{\mathbf{E}}, \tag{6}$$

$$u_1^{\mathbf{EN}} = \alpha[Q-(q_1^{\mathbf{E}}+q_2^{\mathbf{N}})]q_1^{\mathbf{E}} - (c+\lambda c_0)q_1^{\mathbf{E}}, \tag{7}$$

$$u_2^{\mathbf{EN}} = \alpha[Q-(q_1^{\mathbf{E}}+q_2^{\mathbf{N}})]q_2^{\mathbf{N}} - (c+\lambda c_0)q_2^{\mathbf{N}}, \tag{8}$$

$$u_1^{\mathbf{NE}} = \alpha[Q-(q_1^{\mathbf{N}}+q_2^{\mathbf{E}})]q_1^{\mathbf{N}} - (c+\lambda c_0)q_1^{\mathbf{N}}, \tag{9}$$

$$u_2^{\mathbf{NE}} = \alpha[Q-(q_1^{\mathbf{N}}+q_2^{\mathbf{E}})]q_2^{\mathbf{E}} - (c+\lambda c_0)q_2^{\mathbf{E}}, \tag{10}$$

$$u_1^{\mathbf{NN}} = \alpha[Q-(q_1^{\mathbf{N}}+q_2^{\mathbf{N}})]q_1^{\mathbf{N}} - (c+\lambda c_0)q_1^{\mathbf{N}}, \tag{11}$$

$$u_2^{\mathbf{NN}} = \alpha[Q-(q_1^{\mathbf{N}}+q_2^{\mathbf{N}})]q_2^{\mathbf{N}} - (c+\lambda c_0)q_2^{\mathbf{N}} \tag{12}$$

where the subscript 1 represents party **A** and the subscript 2 represents party **B**. $u_1^{\mathbf{EE}}$ is the payoff of party **A** when party **A** chooses strategy **E** and party **B** chooses strategy **E**, $u_2^{\mathbf{EE}}$ is the payoff of party **B** when party **A** chooses strategy **E** and party **B** chooses strategy **E**, the rest of the explanation is similar. $q_1^{\mathbf{E}}$ and $q_2^{\mathbf{E}}$ are the quantities of excess water intake of parties **A** and **B**, respectively, and $q_1^{\mathbf{N}}$ and $q_2^{\mathbf{N}}$ are the quantities of normal water intake of parties **A** and **B**, respectively.

Therefore, the payoff matrix of evolutionary game between two water resource manufacturers can be as expressed in Table 1.

According to the principle of symmetry (Gintis 2000), there exists $q_1^{\mathbf{E}} = q_2^{\mathbf{E}},\ q_1^{\mathbf{N}} = q_2^{\mathbf{N}}$. Hence,

$$u_1^{\mathbf{EE}} = u_2^{\mathbf{EE}}, \quad u_1^{\mathbf{NN}} = u_2^{\mathbf{NN}}, \quad u_1^{\mathbf{EN}} = u_2^{\mathbf{NE}}, \quad u_1^{\mathbf{NE}} = u_2^{\mathbf{EN}} \tag{13}$$

Without loss of generality, the expected values u_1, u_2 and the population average expected values $\bar{u}$ of two kinds of game players, those who adopted excess water intake strategy **E** and normal water intake strategy **N** (Friedman 1991, 1998), are as follows:

$$u_1 = \sigma u_1^{\mathbf{EE}} + (1-\sigma)u_1^{\mathbf{EN}}, \tag{14}$$

$$u_2 = \sigma u_1^{\mathbf{NE}} + (1-\sigma)u_1^{\mathbf{NN}}, \tag{15}$$

$$\bar{u} = \sigma u_1 + (1-\sigma)u_2 \tag{16}$$

According to the principle of evolution, if the adaptability or payoff of a strategy is higher than the average adaptability of the population, the strategy will develop in the population, which shows that the growth rate of the proportion of individuals using a strategy in the population is greater than zero (Carlos *et al.* 2009). However, the replicator dynamic equation is a dynamic differential equation that describes the frequency of a specific strategy used in a population (Cressman & Apaloo

Table 1 | Payoff matrix for evolutionary game of the water resource manufacturers

			Party B	
			σ **E strategy**	**1 − σ** **N strategy**
Party **A**	σ	**E** strategy	$(u_1^{\mathbf{EE}}, u_2^{\mathbf{EE}})$	$(u_1^{\mathbf{EN}}, u_2^{\mathbf{EN}})$
	$1-\sigma$	**N** strategy	$(u_1^{\mathbf{NE}}, u_2^{\mathbf{NE}})$	$(u_1^{\mathbf{NN}}, u_2^{\mathbf{NN}})$

2016). Hence, from (14) and (16), it is obtained that

$$\begin{aligned}\frac{d\sigma}{dt} &= \sigma(u_1 - \bar{u}) = \sigma(1-\sigma)(u_1 - u_2) \\ &= \sigma(1-\sigma)\{[(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})](q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \sigma\alpha(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})^2\}\end{aligned} \tag{17}$$

By means of the first-order optimal condition, it is not difficult to find three fixed points of (17). Therefore, the possible stable state points are the following:

$$\sigma_1^* = 0 \tag{18}$$

$$\sigma_2^* = 1 \tag{19}$$

$$\sigma_3^* = \frac{(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})}{\alpha(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})} \tag{20}$$

where σ_3^* if and only if

$$\frac{(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})}{\alpha(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})} \in [0, 1]$$

This is because $q_1^{\mathbf{E}} > q_1^{\mathbf{N}}$ and $0 \le \sigma_3^* \le 1$, so that

$$(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}}) \ge 0 \tag{21}$$

and

$$(\alpha Q - c - \lambda c_0) - \alpha(2q_1^{\mathbf{E}} + q_1^{\mathbf{N}}) \le 0 \tag{22}$$

such that

$$\alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}}) \le \alpha Q - c - \lambda c_0 \le \alpha(2q_1^{\mathbf{E}} + q_1^{\mathbf{N}}) \tag{23}$$

Let $F(\sigma) = d\sigma/dt$, then the first derivative of $F(\sigma)$ is obtained as follows:

$$F'(\sigma) = (1-2\sigma)[(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})](q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha\sigma(2-3\sigma)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})^2 \tag{24}$$

According to the stability theorem of ordinary differential equation and the property of evolutionary stability strategy, if $F'(\sigma^*) < 0$, σ^* is the ESS of replicator dynamics in the corresponding evolutionary game (Friedman 1991), bringing $\sigma_1^*, \sigma_2^*, \sigma_3^*$ into (24), it is known that

$$F'(\sigma_1^*) = [(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})](q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) > 0 \tag{25}$$

$$F'(\sigma_2^*) = -[(\alpha Q - c - \lambda c_0) - \alpha(2q_1^{\mathbf{E}} + q_1^{\mathbf{N}})](q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) \ge 0 \tag{26}$$

$$F'(\sigma_3^*) = \frac{1}{\alpha}[(\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})][(\alpha Q - c - \lambda c_0) - \alpha(2q_1^{\mathbf{E}} + q_1^{\mathbf{N}})] < 0 \tag{27}$$

Hence, σ_3^* is the point of the ESS.

3.2. Evolution factors

The phase diagram of the replicator dynamic equation is plotted in Figure 1. Obviously, the point that intersects the horizontal axis and the tangent slope at the intersection is the evolutionary stability strategy of the evolutionary game.

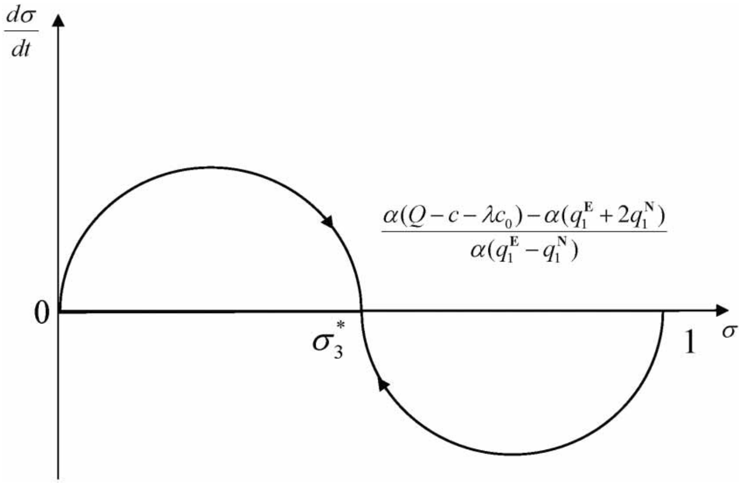

Figure 1 | Phase diagram for evolutionary game of the water resource populations.

The choice of individual proportion σ^* of excess water intake strategy **E** is smaller. However, from $\sigma_3^* = (\alpha Q - c - \lambda c_0) - \alpha(q_1^{\mathbf{E}} + 2q_1^{\mathbf{N}})/\alpha(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})$, it decreases with the decrease of Q and decreases with the increase of c, λ, c_0. It shows that the smaller the Q of the maximum available water resources, the smaller the proportion of individuals who adopt the strategy of excessive water intake **E**, and the larger the unit production cost c, the average pollution rate λ, and the unit abatement cost c_0, the smaller the individual proportion of water resource manufacturers adopting the strategy of excess water intake **E**.

3.3. Within administrative regulators

Another subject, the administrative water resource regulator in water resource allocation, is now introduced. The administrative water resource regulator is responsible for monitoring whether the water resource manufacturers take excessive water or not.

If water resource manufacturers adopt excess water intake strategy **E**, the penalty c_p, which is regarded as the value for the administrative water resource regulators, will be charged per unit of water exceeding the threshold q^T. On the contrary, if water resource manufacturers adopt normal water intake strategy **N**, the reward c_r, which is provided by the administrative water resource regulators, will be obtained per unit of water less than the threshold q^T.

Suppose that the regulated cost is c_h if the administrative water resource regulators choose the high level of regulation strategy **H**, and the regulated cost is c_l if the administrative water resource regulators choose the low level of regulation strategy **L**. If the administrative water resource regulators apply the high level of regulation strategy **H**, regardless of whether the water resource manufacturers adopt the excess water intake strategy **E** or the normal water intake strategy **N**, the administrative water resource regulators will obtain the reward r from the administrative water resource regulators per unit water that exceeds or is less than the threshold q^T, which is obtained from the upper administrative regulators. Otherwise, if the administrative water resource regulators choose the low level of regulation strategy **L**, the administrative water resource regulators will be charged by the upper administrative regulators for a fixed penalty c_f. As long as the water resource manufacturers adopt the excess water intake strategy **E**, the upper administrative regulators will punish the administrative water resource regulators with penalty c_a per unit water more than the threshold q^T.

3.3.1. Game between the water resource manufacturers and the water resource regulators

The proportion of players who adopt the strategy of excess water intake **E** is set as x in game of the water resource manufacturers, and then $1 - x$ represents the proportion of the water resource manufacturers who choose the normal water intake strategy **N**. Meanwhile, it is assumed that the proportion of players who adopt the strategy of high-level regulation **H** is y in the game of the administrative water resource regulators, and then $1 - y$ presents the proportion of the administrative water resource regulators who adopt the low-level regulation strategy **L**. Then, the following payoff functions are obtained:

$$v_1^{\mathbf{EH}} = \alpha(Q - q_1^{\mathbf{E}})q_1^{\mathbf{E}} - (c + \lambda c_0)q_1^{\mathbf{E}} - c_p(q_1^{\mathbf{E}} - q^T) \tag{28}$$

$$v_2^{\mathbf{EH}} = (r + c_p)(q_1^{\mathbf{E}} - q^T) - c_h \tag{29}$$

$$v_1^{\mathbf{EL}} = \alpha(Q - q_1^{\mathbf{E}})q_1^{\mathbf{E}} - (c + \lambda c_0)q_1^{\mathbf{E}} \tag{30}$$

$$v_2^{\mathbf{EL}} = -c_f - c_l - c_a(q_1^{\mathbf{E}} - q^T) \tag{31}$$

$$v_1^{\mathbf{NH}} = \alpha(Q - q_1^{\mathbf{N}})q_1^{\mathbf{N}} - (c + \lambda c_0)q_1^{\mathbf{N}} + c_r(q^T - q_1^{\mathbf{N}}) \tag{32}$$

$$v_2^{\mathbf{NH}} = (r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h \tag{33}$$

$$v_1^{\mathbf{NL}} = \alpha(Q - q_1^{\mathbf{N}})q_1^{\mathbf{N}} - (c + \lambda c_0)q_1^{\mathbf{N}} \tag{34}$$

$$v_2^{\mathbf{NL}} = -c_f - c_l \tag{35}$$

where the subscript 1 represents water resource manufacturers and the subscript 2 represents administrative water resource regulators. Therefore, the payoff matrix of evolutionary game between the water resource manufacturers and the administrative water resource regulators is as shown in Table 2.

From Table 2, the game matrixes of the water resource manufacturer A and the administrative water resource regulator B are given in the following equation:

$$\begin{aligned} A &= \begin{pmatrix} \alpha(Q - q_1^{\mathbf{E}})q_1^{\mathbf{E}} - (c + \lambda c_0)q_1^{\mathbf{E}} - c_p(q_1^{\mathbf{E}} - q^T) & \alpha(Q - q_1^{\mathbf{E}})q_1^{\mathbf{E}} - (c + \lambda c_0)q_1^{\mathbf{E}} \\ \alpha(Q - q_1^{\mathbf{N}})q_1^{\mathbf{N}} - (c + \lambda c_0)q_1^{\mathbf{N}} + c_r(q^T - q_1^{\mathbf{N}}) & \alpha(Q - q_1^{\mathbf{N}})q_1^{\mathbf{N}} - (c + \lambda c_0)q_1^{\mathbf{N}} \end{pmatrix}, \\ B &= \begin{pmatrix} (r + c_p)(q_1^{\mathbf{E}} - q^T) - c_h & (r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h \\ -c_f - c_l - c_a(q_1^{\mathbf{E}} - q^T) & -c_f - c_l \end{pmatrix}. \end{aligned} \tag{36}$$

The water resource manufacturers and the administrative water resource regulators both have the same pure strategies as follows:

$$x_1 = \mathbf{E}, \quad y_1 = \mathbf{H}, \quad x_2 = \mathbf{N}, \quad y_2 = \mathbf{L} \tag{37}$$

and the mixed strategies

$$X = (x, 1 - x), \quad Y = (y, 1 - y) \tag{38}$$

According to the water resource manufacturers, it is obtained that

$$\begin{aligned} E(x_1, Y) &= (1, 0)A\begin{pmatrix} y \\ 1 - y \end{pmatrix} \\ &= yv_1^{\mathbf{EH}} + (1 - y)v_1^{\mathbf{EL}}, \end{aligned} \tag{39}$$

and

$$\begin{aligned} E(X, Y) &= (x, 1 - x)A\begin{pmatrix} y \\ 1 - y \end{pmatrix} \\ &= x(1 - x)(yv_1^{\mathbf{EH}} + (1 - y)v_1^{\mathbf{EL}} - yv_1^{\mathbf{NH}} - (1 - y)v_1^{\mathbf{NL}}). \end{aligned} \tag{40}$$

Table 2 | Payoff matrix for evolutionary game between the water resources manufacturers and the administrative water resources regulators

			Administrative regulators	
			y **H strategy**	**1 –** ***y*** **L strategy**
Manufacturers	x	**E** strategy	$(v_1^{\mathbf{EH}}, v_2^{\mathbf{EH}})$	$(v_1^{\mathbf{EL}}, v_2^{\mathbf{EL}})$
	$1 - x$	**N** strategy	$(v_1^{\mathbf{NH}}, v_2^{\mathbf{NH}})$	$(v_1^{\mathbf{NL}}, v_2^{\mathbf{NL}})$

Then

$$\begin{aligned} E(x_1, Y) - E(X, Y) &= x(1-x)\{(\alpha Q - c - \lambda c_0)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) \\ &\quad -y[c_p(q_1^{\mathbf{E}} - q_1^{T}) + c_r(q^T - q_1^{\mathbf{N}})]\}. \end{aligned} \tag{41}$$

Similarly, as for the administrative water resource regulators,

$$\begin{aligned} E(y_1, X) &= (1, 0)B\begin{pmatrix} x \\ 1-x \end{pmatrix} \\ &= xv_2^{\mathbf{EH}} + (1-x)v_2^{\mathbf{NH}}, \end{aligned} \tag{42}$$

and

$$\begin{aligned} E(Y, X) &= (y, 1-y)B\begin{pmatrix} x \\ 1-x \end{pmatrix} \\ &= y(1-y)(xv_2^{\mathbf{EH}} + (1-x)v_2^{\mathbf{NH}} - xv_2^{\mathbf{EL}} - (1-x)v_2^{\mathbf{NL}}). \end{aligned} \tag{43}$$

Then

$$\begin{aligned} E(y_1, X) - E(Y, X) &= y(1-y)\{(r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h + c_f + c_l \\ &\quad -x[(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^{\mathbf{T}})]\}. \end{aligned} \tag{44}$$

Evolutionary game theory considers the evolutionary process as a dynamic system; therefore, from (41) and 44), an ordinary differential equation group is obtained as follows:

$$\begin{cases} \dfrac{dx}{dt} = & x(1-x)\{(\alpha Q - c - \lambda c_0)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})\} \\ & -y[c_p(q_1^{\mathbf{E}} - q_1^{T}) + c_r(q^T - q_1^{\mathbf{L}})] \\ \dfrac{dy}{dt} = & y(1-y)\{(r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h + c_f + c_l \\ & -x[(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^{T})]\}. \end{cases} \tag{45}$$

For the first-order condition, five equilibrium points are obtained as

$E_1(0, 0),\ E_2(0, 1),\ E_3(1, 1),\ E_4(1, 0)$

and

$$E_5\left(\frac{(\alpha Q - c - \lambda c_0)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})}{c_p(q_1^{\mathbf{E}} - q_1^{T}) + c_r(q^T - q_1^{\mathbf{N}})}, \frac{(r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h + c_f + c_l}{(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^{T})}\right)$$

As Friedman (1998) wrote in his paper, Jacobian matrix can be used to find the local equilibrium points. Let $F_1(x) = dx/dt$ and $F_2(y) = dy/dt$. Hence, the Jacobian matrix J, the determinant $det\,(J)$, and the trace $tr\,(J)$ of (45) are obtained, showing

$$J = \begin{pmatrix} \dfrac{\partial F_1}{\partial x} & \dfrac{\partial F_1}{\partial y} \\ \dfrac{\partial F_2}{\partial x} & \dfrac{\partial F_2}{\partial y} \end{pmatrix} \tag{46}$$

$$det(J) = \begin{vmatrix} \dfrac{\partial F_1}{\partial x} & \dfrac{\partial F_1}{\partial y} \\ \dfrac{\partial F_2}{\partial x} & \dfrac{\partial F_2}{\partial y} \end{vmatrix} \tag{47}$$

$$tr(J) = \frac{\partial F_1}{\partial x} + \frac{\partial F_2}{\partial y} \tag{48}$$

where

$$\begin{aligned}\frac{\partial F_1}{\partial x} &= (1-2x)\{\alpha Q - c - \lambda c_0)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) \\ &\quad -y[c_p(q_1^{\mathbf{E}} - q_1^{T}) + c_r(q^T - q_1^{\mathbf{N}})]\}, \\ \frac{\partial F_1}{\partial y} &= -x(1-x)[c_p(q_1^{\mathbf{E}} - q^T) + c_r(q^T - q_1^{\mathbf{N}})], \\ \frac{\partial F_2}{\partial x} &= -y(1-y)[(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^T)], \\ \frac{\partial F_2}{\partial y} &= (1-2y)\{(r - c_r)(q^T - q_1^{\mathbf{N}}) - c_h + c_f + c_l \\ &\quad -x[(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^T)]\}.\end{aligned}$$

Let ESS represent the evolutionary stable strategy. According to the local stability analysis method, the stability analysis of five equilibrium points is carried out, and the results are shown in Table 3.

From Table 3, only two of the five local equilibrium points are evolutionary stable strategies. In addition, the system has two unstable equilibrium points and one saddle point. Then, the simulation diagram of the evolutionary stability strategy for the water resource manufacturers and the administrative water resource regulators is plotted in Figure 2. From Table 3 and Figure 2, the probability of taking excessive water intake strategy **E** is decreasing to zero, while the probability of taking high-level regulation strategy **H** is increasing to one and finally stable at$E_2(0, 1)$. This also proves that the (**N**, **H**) strategy is the expected ESS.

3.3.2. Analysis of evolution factors

Based on Table 3, the phase diagram is plotted as shown in Figure 3. Figure 3 shows the replicator dynamics between the water resource manufacturers and the administrative water resource regulators. It is known that E_2 and E_4 are the points of evolutionary stable strategies corresponding to strategies (**N**, **H**) and (**E**, **L**) adopted by the water resource manufacturers and the administrative water resource regulators, respectively. The points E_1 and E_3 are unstable, and E_5 is the saddle point. The broken line $E_1E_5E_3$ is the critical line of the system converging to different states. According to the property of saddle point (Duersch *et al.* 2012), the system will converge to point $E_2(0, 1)$ when the initial state is in the upper left region-$E_1E_5E_3E_2E_1$, that is, the water resource manufacturers and the administrative water resource regulators will adopt the strategy (**N**, **H**). Similarly, the system will converge to point $E_4(1, 0)$, while the initial state is in the lower right region-$E_1E_5E_3E_4E_1$, that is, the water resource manufacturers and the administrative water resource regulators will adopt the strategy (**E**, **L**).

From Figure 3, if $x^* = y^*$, then the area of $E_1E_5E_3E_2E_1$ is equal to the area of $E_1E_5E_3E_4E_1$. This shows that the probabilities of the systems converging to two evolutionary stable strategies are equal. But, in fact, $E_2(0, 1)$ is the dream direction of system evolution, where the water resource manufacturers and the administrative water resource regulators will adopt the strategy of normal water intake and a high level of regulation (**N**, **H**). Under the circumstances of the above ESS, the water resource manufacturers can consciously abide by relevant rules to choose excess water intake strategy without breaking through

Table 3 | Equilibrium points and local stability

Equilibrium points	*det*(*J*)	*tr*(*J*)	Stability
$E_1(0, 0)$	+	+	Instable
$E_2(0, 1)$	+	−	ESS
$E_3(1, 1)$	+	+	Instable
$E_4(1, 0)$	+	−	ESS
$E_5(x^*, y^*)$	−	0	Saddle point

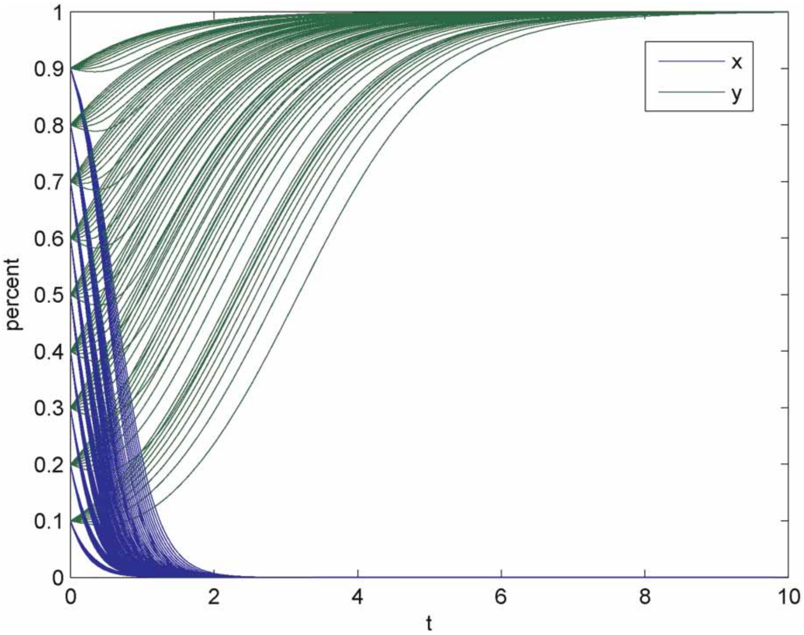

Figure 2 | Simulation diagram of the evolutionary stability strategy for the water resource manufacturers and the administrative water resource regulators. *x* is the evolution curve of the water resource manufacturers's strategy over time, *y* is the evolution curve of the administrative water resource regulators's strategy over time, *t* is time and 'percent' is the initial probability of participants choosing evolutionary stable strategies.

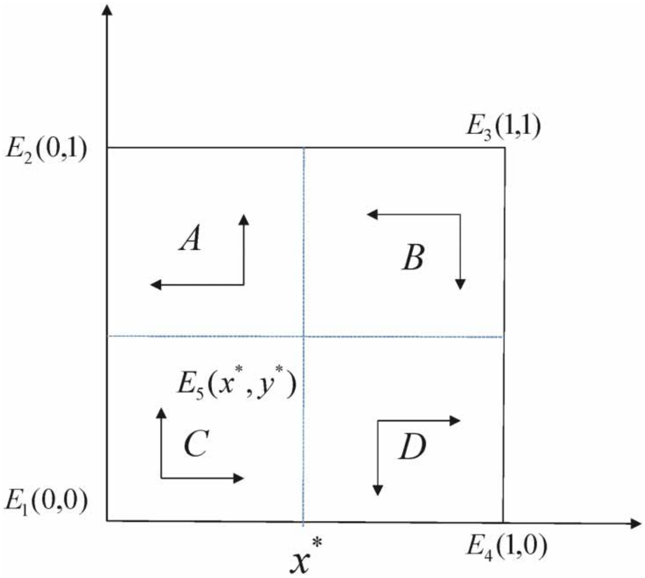

Figure 3 | Phase diagram for evolutionary game between the water resource manufacturers and the administrative water resource regulators.

the threshold q^T. Meanwhile, the administrative water resource regulators will do their best to supervise, so as to achieve the effective allocation and utilization of water resources.

Without loss of generality, we assume that when studying the effect of one parameter on strategy selection, the other parameters are fixed. If the initial state is in area A, then the water resource manufacturers and the administrative water resource regulators must adopt the strategy (**N**, **H**). Therefore, the area of A is as follows:

$$\begin{aligned} S_A &= x^*(1-y^*) \\ &= \frac{(\alpha Q - c - \lambda c_0)(q_1^{\mathbf{E}} - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q_1^{\mathbf{E}} - q_1^{\mathbf{N}})}{c_p(q_1^{\mathbf{E}} - q^T) + c_r(q^{\mathbf{E}} - q_1^{\mathbf{N}})} \\ &\quad \cdot \left(1 - \frac{(r - c_r)(q^T - q_1^{\mathbf{L}}) - c_h + c_f + c_l}{(r - c_r)(q^T - q_1^{\mathbf{L}}) - (r + c_p + c_a)(q_1^{\mathbf{H}} - q^T)}\right) \\ &= \frac{[(\alpha Q - c - \lambda c_0)(q^T - q_1^{\mathbf{N}}) - \alpha(q_1^{\mathbf{E}} + q_1^{\mathbf{N}})(q^T + q_1^{\mathbf{N}})][(r + c_p + c_a)(q_1^{\mathbf{E}} - q^T) - c_h + c_f + c_l]}{[c_p(q_1^{\mathbf{E}} - q^T) + c_r(q^T - q_1^{\mathbf{N}})][(r - c_r)(q^T - q_1^{\mathbf{N}}) - (r + c_p + c_a)(q_1^{\mathbf{E}} - q^T)]}. \end{aligned} \tag{49}$$

To analyze the influence of parameters on the initial state in area A, we assign values to these parameters (Table 4), which are arbitrarily given and stable and satisfy the two evolutionary stability points in Table 3. From Figure 4, the influence of parameters on the strategy selections are analyzed.

The relations between the marginal negative effect α and the area S_A of A, and the relations between the average pollution rate of unit water λ and the area S_A of A are plotted in Figure 4(a) and 4(b), respectively. It is easy to say that α and S_A have a positive correlation, but λ and S_A have a negative correlation. This shows that it will tend to equilibrium point $E_2(0, 1)$ if the marginal negative effect is increasing. However, if the water is polluted seriously, it will be difficult to reach equilibrium point $E_2(0, 1)$. From Figure 4(c) and 4(d), regardless of the cost of unit water c and the enhancement level of abatement cost of unit sewage, it will be difficult to reach equilibrium point $E_2(0, 1)$.

From Figure 4(e) and 4(f), $S_A$is a decreasing function of c_p, and it is also a decreasing function of c_a. However, both c_p and c_a decreased the fastest in a short time and then tended to a fixed value of zero. Therefore, as long as the values of c_p and c_a are guaranteed to increase within a small range, the probability of reaching equilibrium point $E_2(0, 1)$ will be increased. From Figure 4(h) and 4(i), $S_A$is an increasing function of c_r, and it is an increasing function of r, too. Hence, in order to increase S_A, it is necessary to increase the value of c_r and r in a small range to increase the probability of reaching equilibrium point$E_2(0, 1)$. Later, it is going to be balanced. Comparing Figure 4(e), 4(f) and Figure 4(g), 4(h), it is not difficult to find that the changes of c_p and c_a are in [2, 4], the change of c_r is in [0, 1], and the change of r is in [0, 2]. Numerically, c_p and c_a are more influential than c_r and r. That is to say, punishment is faster to reach equilibrium point $E_2(0, 1)$ than reward.

From Figure 4(i) and 4(j), $S_A$is the inverse function of c_h, and it is the linear increasing function of c_l. This shows that increasing the high regulated cost c_h will reduce the probability of reaching equilibrium point $E_2(0, 1)$ and, on the contrary, increasing the low regulated cost will increase the probability of reaching equilibrium point $E_2(0, 1)$. From Figure 4(k), a fixed penalty c_f contributes to reaching equilibrium point $E_2(0, 1)$.

4. RESULTS AND DISCUSSION

Based on the above analysis, in the main results, it was found that

(1) Only one ESS $(\sigma_3^*, 0)$ was among the water resource manufacturers. This showed the larger the unit production cost c, the average pollution rate λ, and the unit abatement cost c_0, the smaller the individual proportion of water resource manufacturers adopting the strategy of excess water intake **E**.

(2) There existed two evolutionary strategies between the water resource manufacturers and the administrative water resource regulators: the (**N**, **H**) and (**E**, **L**), where the strategy (**N**, **H**) is the expected direction. However, the strategy

Table 4 | Parameters: $Q, q^T, q_1^{\mathbf{E}}, q_1^{\mathbf{N}}$ (thousand/m^3) and $c, c_0, c_p, c_a, c_r, c_h, c_l, r, c_f$ (CNY/m^3)

α	Q	c	λ	c_0	c_p	c_a	c_r	c_h	c_l	r	c_f	q^T	$q_1^{\mathbf{E}}$	$q_1^{\mathbf{N}}$
1	20	2	1	0.4	1	1	1	1	0	3	5	10	10.1	9

α is the marginal negative effect, λ is the average pollution rate of unit water, c is the cost of unit water, c_0 is the abatement cost of unit waste water, the penalty c_p and c_a are water resource manufacturers and administrative water resource regulators, respectively, c_r is the reward of water resource manufacturers, r is the reward for the administrative water resource regulators, c_h and c_l are the regulated costs, c_f is a fixed penalty for administrative water resource regulator, q^T is the threshold of water intake, $q_1^{\mathbf{E}}$ is the quantity of excess water intake of party **A** and $q_1^{\mathbf{N}}$ is the quantity of normal water intake of party **A**.

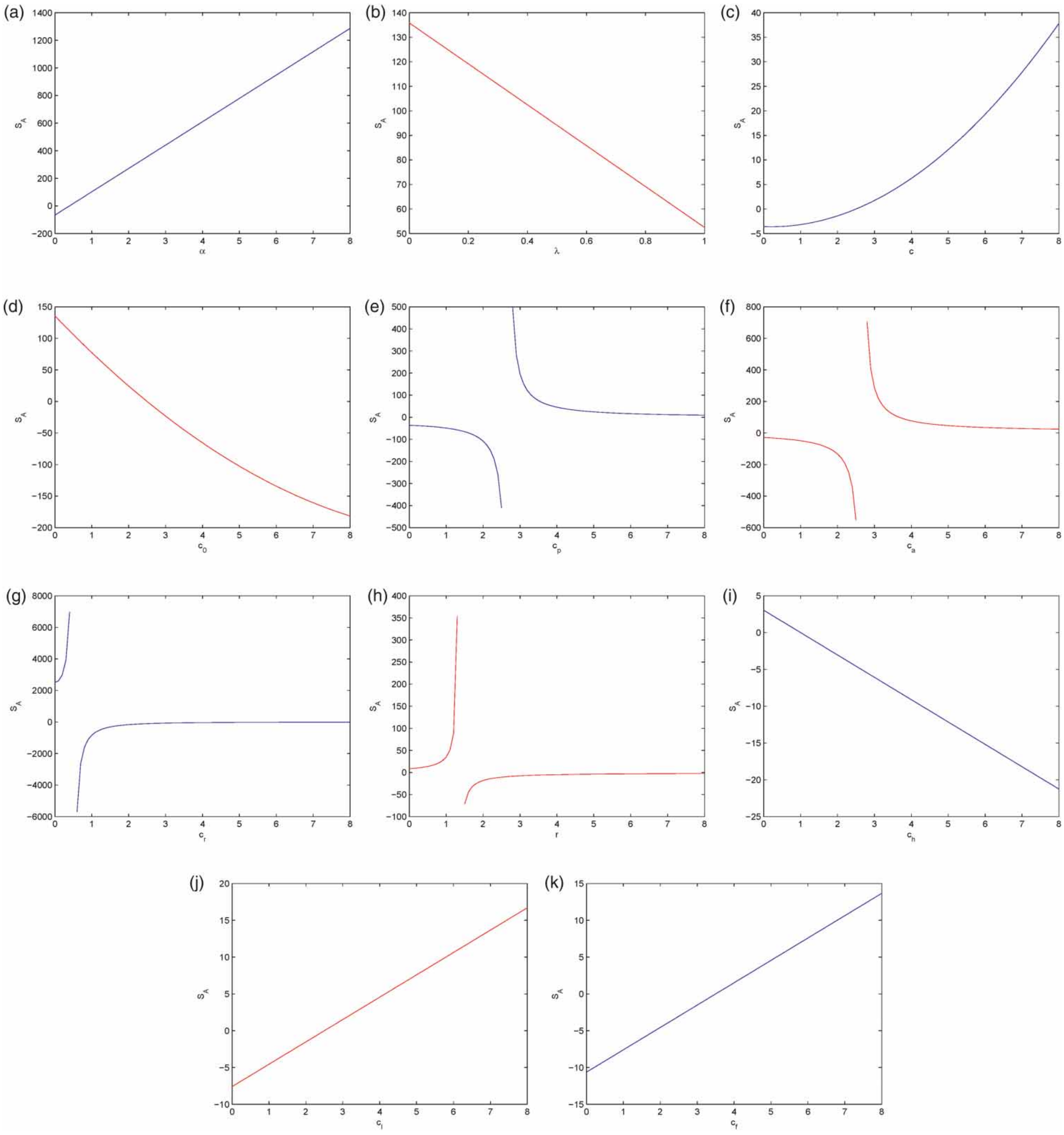

Figure 4 | The influence of parameters (the marginal negative effect α, the average pollution rate of unit water λ, cost of unit water c, abatement cost of unit waste water c_0, the penalty c_p for water resource manufacturers and c_a for administrative water resource regulators, the reward of water resource manufacturers c_r, the reward for the administrative water resource regulator r, the regulated cost c_h and c_l, a fixed penalty for administrative water resource regulators (c_f) on the strategy selections.

(**N**, **H**) is that in which the water resource manufacturers who adopted the strategy of normal water intake **N** and the administrative water resource regulators who applied correspondingly the strategy of high level of regulation **H**.

(3) The initial probabilities of water intake strategies or regulation levels will affect the final stable state directly.
(4) When the group which applied normal water intake strategies becomes smaller, the group which adopted excess water intake strategies is closer to the threshold q^T, and the proportion of group chosen excess water intake strategies becomes

larger, the profits of each participating subjects become smaller which leads to conflicts in water resource allocation. It suggests that water resource manufacturers should positively adopt normal water intake strategy for increasing the expected profits of both sides.

(5) The water resource regulators should firmly implement the supervision and take the incentive mechanism with both rewards and punishments in a way which can effectively inhibit the growth of group that applies excess water intake strategies, dismantle conflicts and increase profits.

(6) The unit water resource output is a linearly decreasing function of total water intake. The model is mainly applicable to analyzing the evolution process and the evolution trend of water resource allocation and conflict in a river basin, so as to effectively dismantle the conflict of water resource allocation and achieve the situation of multi-party coordination and win-win situation.

Based on the data in Table 5, we next discuss the impact of the following three reward and punishment mechanisms on the evolutionary stability strategy (0,1), such as heavy reward and light punishment (reward c_r increases and penalty c_p remain unchanged), light reward and heavy punishment (reward c_r remains unchanged and penalty c_p increases), and heavy reward and heavy punishment (reward c_r increases and penalty c_p increases), and compare them.

It can be seen from the table that when the administrative water resource regulators pay more attention to heavy rewards and light punishment (reward r_c increases and punishment c_p remains unchanged), S_A decreases first and then increases, the average expected benefit of the water resource manufacturers increases, and the average expected benefit of the administrative water resource regulators decreases. When the administrative water resource regulators pay more attention to light rewards and heavy punishment (reward r_c remains unchanged and punishment c_p increases), S_A decreases, the average expected benefit of the water resource manufacturers decreases, and the average expected benefit of the administrative water resource regulators decreases. When the administrative water resource regulators pay more attention to heavy rewards and heavy punishment (reward r_c increases and punishment c_p increases), S_A decreases first and then increases, the average expected benefit of the water resource manufacturers decreases, and the average expected benefit of the administrative water resource regulators decreases.

According to the expected system evolution direction (0,1), three incentive strategies are compared. The heavy reward and light punishment strategy and the heavy reward and heavy punishment strategy are better strategies. Compared with the heavy reward and heavy punishment strategy, the expected benefit of the regulatory department is higher. Therefore, the heavy reward and heavy punishment incentive is an effective strategy, which can effectively restrain excessive water intake, so as to solve the conflict in water resource allocation.

5. CONCLUSIONS

In this paper, evolutionary game theory was used to allocate water resources in a river basin. Based on an assumption background, the replicator dynamics and its stable strategy among the water resource manufacturers were first analyzed. Later, the administrative water resource regulators in the evolutionary game were considered and their evolutionary stable strategies were analyzed. The results show that only one ESS (σ_3^*, 0) was among the water resource manufacturers and there are two evolutionary stability strategies (**N**: normal water intake, **H**: high level of regulation) and (**E**: excess water intake, **L**:

Table 5 | Evolutionary stability strategy and expected benefit of evolutionary game between water resource manufacturers and administrative water resource regulators

	Punishment mechanisms 1					Punishment mechanisms 2					Punishment mechanisms 3				
	c_r	c_p	S_A	$\bar{v}_1$	$\bar{v}_2$	c_r	c_p	S_A	$\bar{v}_1$	$\bar{v}_2$	c_r	c_p	S_A	$\bar{v}_1$	$\bar{v}_2$
1	1	1	1.5588	80.7044	−5.8235	1	1	1.5588	80.7044	−5.8235	1	1	1.5588	80.7044	−5.8235
2	1.2	1	1.4949	80.8416	−5.8369	1	1.2	1.5075	79.0829	−5.8866	1.2	1.2	1.4474	79.2426	−5.8947
3	1.4	1	1.4949	80.9732	−5.8800	1	1.4	1.4585	77.0740	−5.9458	1.4	1.4	1.4019	77.4845	−5.9851
4	1.6	1	1.5588	81.0995	−5.9583	1	1.6	1.4116	74.4453	−6.0012	1.6	1.6	1.4116	75.2615	−6.1034
5	1.8	1	1.7047	81.2207	−6.0877	1	1.8	1.3689	70.7692	−6.0531	1.8	1.8	1.4796	72.2615	−6.2653
6	2	1	1.9830	81.3373	−6.3061	1	2	1.2241	65.1359	−6.1019	2	2	1.6250	68.1625	−6.5000

low level of regulation) between water resource manufacturing industry and administrative water resource management organization, where the strategy (**N**: normal water intake, **H**: high level of regulation) is the expected direction. Moreover, the incentive strategy of heavy reward and punishment can effectively restrain excessive water intake, thus solving the conflict in water resource allocation.

The reasonable allocation of water resources runs through the main links of regional water resource planning and management, which is a complex decision-making issue. Thus, in allocation of water resources, it is necessary to consider the allocation factors comprehensively and formulate an overall, fair, reasonable, efficient and flexible allocation plan of water resources. This is so as to ensure the sustainable development and utilization of water resources and make a greater contribution to the sustainable development of social economy.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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