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Feasibility analysis of water resources market transaction of water diversion project based on evolutionary game

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ABSTRACT

Water diversion projects realize the change of water rights ownership by diverting water resources, but most of the water diversion projects are dominated by the government in the operation stage, which can't realize complete market-oriented transaction of resources. In this study, the water source area, project management department and users involved in water resources trading of a water diversion project are regarded as stakeholders, and an evolutionary game model is established to analyze the feasibility and restrictive conditions of the free trading of water resources in the water diversion project. The research results show that the three parties can realize the balance and stability of interests (the water source area supplies good water, the project management department supplies sufficient water, users take water according to the supply), which means that the water market transactions are feasible. Meanwhile, it also gives clear restrictions on the water price of the three parties transaction: the project management department water price for purchase is less than P_e on the premise of lower than $(N_e)/\ Q_c - Q_i\ + P_e$, the sale water price is not higher than $(N_u + (1-\gamma)G)/Q_c - Q_a$. The free trading of water resources in the water diversion project under the market mechanism is of great significance for clarifying the water rights and reducing the financial pressure of the government.

Key words: evolutionary game, water diversion project, water price, water resources trading

HIGHLIGHTS

- Establish an evolutionary game model of three stakeholders involved in the water resources transaction of a water diversion project.
- Analyze the feasibility of the water resources market transaction.
- Restrict the water selling price of the water source area and project management department.
- Promotion of market-oriented trading of water resources is of supporting significance to clarify water rights and reduce government financial pressure.

1. INTRODUCTION

1.1. Research background

The Middle Route Project of the South-to-North Water Diversion Project in China, with a total length of 1,432 km, and the whole route was put into operation in December 2014, providing domestic water for more than 20 large and medium-sized cities and 131 counties (Construction & Administration Bureau of South-to North Water Diversion Middle Route Project 2021) along the route, it has supplied 37.9 billion m^3 of water to the water-receiving areas, and directly benefits 75 million people. After the project enters the operation stage, the water quality becomes an important factor affecting the success or failure of the project, and the water supply area of the middle route of the South-to-North Water Diversion Project is also divided into drinking water source areas. In order to promote water quality protection, ecological compensation is often used to guide and motivate. Government financial subsidy and market-oriented fund-raising are the two main channels of China's current water resources compensation mechanism (Ge *et al.* 2006); among them, market-oriented fund-raising follows the principle of 'who benefits who compensates'. The establishment of the ecological compensation mode of government paid compensation will involve the improvement of the whole country's legal, financial and resource management system, which needs a long-term development process. At the same time, it will also cause certain financial pressure on the government. In order to alleviate the financial payment pressure of the government, some studies have pointed out that ecological compensation can be considered from the water price accounting to form a market trading mechanism of who uses who compensates; among them, Jin & Chen (2009) proposed that the composition of water price should include six parts: water resource value, normal cost of water resource production, environmental cost, reasonable profit of enterprises, ecological compensation value and tax; Du (2020) designed the guiding technology of single boundary Contingent Valuation Method to estimate farmers' willingness to pay for ecological compensation in water source area by increasing agricultural water price in Northern Jiangsu Province.

Therefore, the water price of a water diversion project is very critical in the operation stage. In terms of the water price formation mechanism, China's general water price system mainly includes three parts: water price of resource, water price of project, water price of environment. Li & Jiang (2019) and Ma (2014) pointed out that due to the fact that the actual collected water price of China's water diversion project is lower than the operating water price, the project is difficult to operate. Therefore, they proposed to increase the water diversion price from the perspective of user affordability and government subsidies. Noll (1993) pointed out that due to the time limit of water trading contract, the old contract was based on fixed price and did not take into account the expansion of operation and maintenance costs. Based on this, the federal government subsidizes the increased operating costs and capital costs of the Central Valley Water Diversion Project. Sun (2021) established the non-cooperative game model and cooperative game model under government subsidies, and proved that with the increase of government subsidies, the optimal water supply and optimal income are also increasing, and meanwhile, the operation cost of the project can be reduced. Besides, Anderson (1998) mentioned that the water cost of the central Jewish state project is $\$24.3/m^3$, while farmers only need to pay $\$0.65/m^3$. Lasserre (2005) states that the intermediate price difference is subsidized by the government. From the study of water price of water transfer project, we can see that the preferential and subsidy policies provided by the government are one of the ways to solve the problem of water price of water diversion project.

However, water resources, as a kind of resource, has economic externality. As far as water diversion project is concerned, water resources for water diversion have the characteristics of commodity trading, and water resources trading has become one of the important directions of water resources management reform and development. In the field of resource use and management, Edward (2003) analyzed the effect of property rights behavior of the governments of Sweden and New Zealand through case studies, and found that reducing the control of forest land could achieve win-win economic and environmental benefits, pointed out that the government could not be an effective manager of public land. In terms of the use of water resources, Rogers *et al.* (2002) pointed out that water resource pricing can be used to promote equity, efficiency and sustainability of the water sector, but its use pricing policy requires large-scale government intervention to ensure full coverage of equity and public goods issues. When Randall (1981) studied the current water pricing and distribution policy in Australia, he believed that it suffered a great loss of efficiency. After comprehensively considering the relevant theories of welfare economics, management price theory, market property rights theory and some reform suggestions of the United States, he proposed and developed a transferable water rights system and carried out market-oriented trading. Li (2009) mentioned that the transformation of the environmental management mode and reasonably introducing the market mechanism are the innovative demands of the ecological environment management system for the construction of an environment-friendly society in the new era. In water resources transaction, each stakeholder has the characteristics of the game, which has a certain influence on the transaction price.

To sum up, in the allowable stage of the water diversion project, in order to reduce the degree of government intervention and financial pressure, the water resources of the water diversion project can promote better pricing of water resources by clarifying the water rights and conducting trading. Therefore, based on the ownership of water rights of the water diversion project, this paper analyzes the decision-making strategies of buyers and sellers from the perspective of water resources trading, and adopts the evolutionary game method to explore the operational feasibility of the water rights trading market mechanism, to provide support for water price pricing of the water diversion project.The research idea of this paper is shown in Figure 1.

1.2. Research method

Evolutionary game theory originated from the game analysis of conflict and cooperation behavior of animals and plants by genetic ecologists such as Fisher (1930), Hamilton (1967) and Trivers (1971). Lewontin (1961) explicitly applied the concept of game theory to evolutionary biology for the first time in 1961. Mayanard & Price (1973) introduced the idea of game theory into the analysis of biological evolution and proposed the concept of the evolutionary stable strategy (ESS) for the first time. Taylor & Jonker (1978) put forward the basic dynamic concept of evolutionary game theory – Replicator Dynamics – when they investigated the phenomenon of ecological evolution. Evolutionary stability strategy and replicator dynamics constitute the

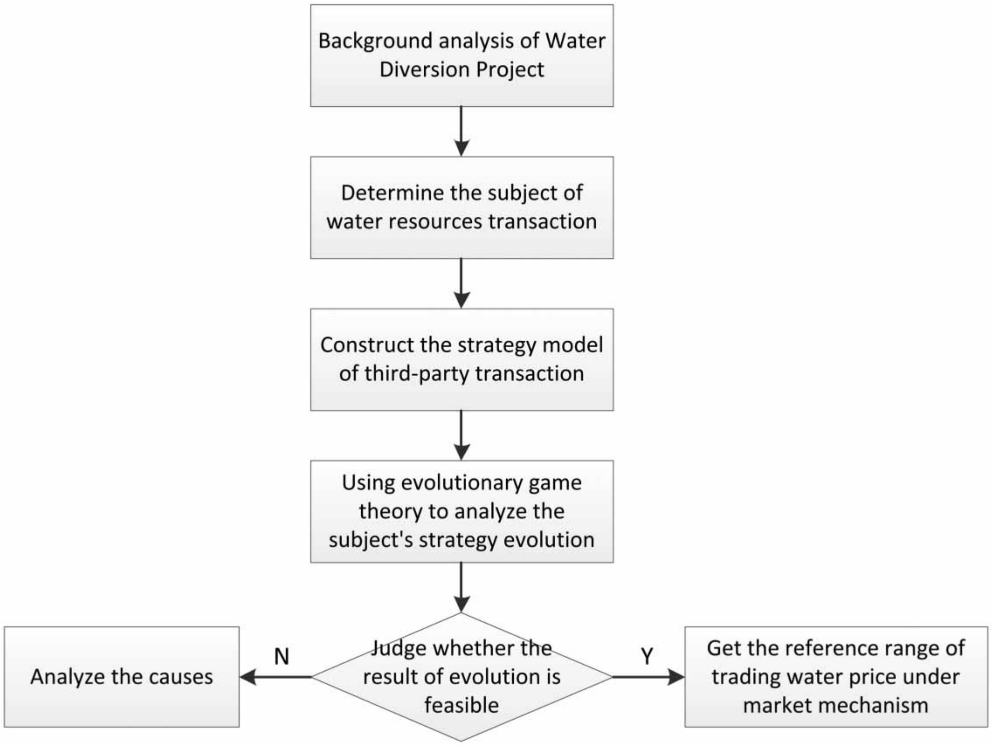

Figure 1 | Research roadmap.

core basic concepts of evolutionary game theory. They represent the stable state of the evolutionary game and the dynamic convergence process to this stable state respectively. The steps of the evolutionary game method are shown in Figure 2.

ESS emphasizes the evolutionary process of the strategy, and the replicator dynamic equation describes the evolutionary stable state under the possibility of variation. The ESS under different evolutionary paths can be calculated by the fitness function and Jacobian matrix.

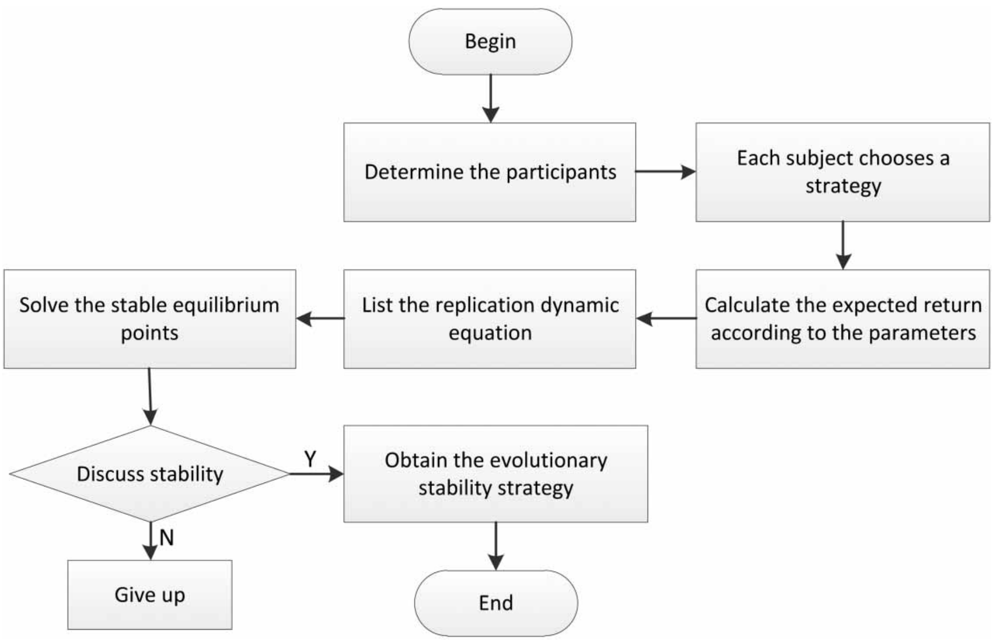

Figure 2 | Steps diagram of evolutionary game method.

Suppose there are k populations playing against each other, and each population $k(k = 0,1\ldots n)$ has n strategies. Population k corresponds to the n dimensional vector sets $s_k = \{x = (x_1,x_2,\ldots, x_n)|x_i \geq 0, x_1 + x_2 + \ldots + x_n = 1\}$. The vector s_k represents the proportion of individuals in population k that adopt each strategy in that population. The fitness function represents the payment (benefit) of each population under the game strategy. Individual fitness is expressed as a function of the individual strategy and the current state, and the state is continuously differentiable with respect to time. Fitness function: $f(r,s) = \{f_1(r_1,s), f_2(r_2,s),\ldots,f_k (r_k,s)\}$. r_k represents the mixed strategy of any individual in population k, and s represents the state. Replication dynamics is a dynamic differential equation that describes the frequency or frequency of a specific strategy in a population. It means that the growth rate of the proportion of individuals using a pure strategy in the population is equal to the difference between the payment obtained when using the strategy and the average payment of the group. Replication dynamics reflects the basic dynamics of evolutionary game theory, which is expressed as:

$$\frac{dx_m}{dt} = x_m[u(m, s) - u(s, s)](m = 1, 2, \ldots, n) \quad (1)$$

where x_m is the proportion of adopting strategy m in a population, u(m,s) represents the fitness (expected return) when adopting strategy m, u(s,s) represents the average fitness (average expected return), and m represents different strategies. The process of strategy ESS is to calculate the average fitness by fitness function, and multiply the difference between it and the return of a strategy by the strategy's probability of obtaining the replication dynamic equation of the specific strategy growth rate, and multiply the difference between it and the return of a strategy by the strategy's probability of obtaining the replication dynamic equation of the specific strategy growth rate. Finally, according to the determinant value of the Jacobian matrix and the eigenvalue of the matrix it is judged whether the specific strategy is ESS.

In recent years, evolutionary game theory, as a tool to analyze the evolution process of strategic subjects, has been widely used in the fields of economics, ecology and environmental science. At present, evolutionary game theory has made some progress in the study of related issues in the field of water. Most scholars use evolutionary game theory to focus on solving the ecological compensation model of water resources (Hu & Liu 2019), trans-boundary water resources conflict (Lu *et al.* 2021), water environment governance (Xv *et al.* 2017), and so on. However, there are few studies on the strategic evolution of stakeholders in water rights trading of water projects. Therefore, from the perspective of the evolution of the strategy of water resources trading subjects, this paper seeks the stable equilibrium point to maximize the interests of each subject in the process of water resources trading, and it is reasonable to use the evolutionary game method.

2. THE BASIC HYPOTHESIS AND CONSTRUCTION OF THE TRIPARTITE INTEREST EVOLUTIONARY GAME MODEL UNDER THE MARKET TRADING MECHANISM

2.1. Basic hypothesis and description of the model

Under the market trading mechanism, the water resource transaction entities of the water diversion project include the water resource transferor, namely the water source area, the water resource transferee, namely the water receiving area composed of many users along the project. The construction and management sectors of the water diversion project act as middlemen to realize the transfer of resources. The trading relationship among the three parties involved in water resource trading of the Middle Route Project of South-to-North Water Diversion is shown in Figure 3.

It can be seen that under the effect of the market mechanism, the water source area and the project management department, as well as the project management department and the users, need to sign a water resource trading contract in line with the interests of the three parties through negotiation and consultation. The content of the contract is mainly about the restriction of water quality and quantity on the behavior of the three parties. The water source area transfers the high-quality water source, and the project management department needs to pay for the good water source. The project management department shall deliver the water resources from the water source area to the water households in a timely way, appropriately and with good quality. Users can sign a contract with the project management department according to their own water consumption, and pay the corresponding fees for obtaining the water quantity specified in the contract. It is assumed that the demand of water resources for water transfer in the receiving area is mainly for drinking water, which requires high water quality, and the current water quality in the source area meets this requirement. Based on this, the three parties formulate the basic terms of basic water quality and quantity. If any party violates the agreement of water quality and quantity due to its own subjective intention during the execution of the contract, it needs to bear the corresponding penalty according to the contract.

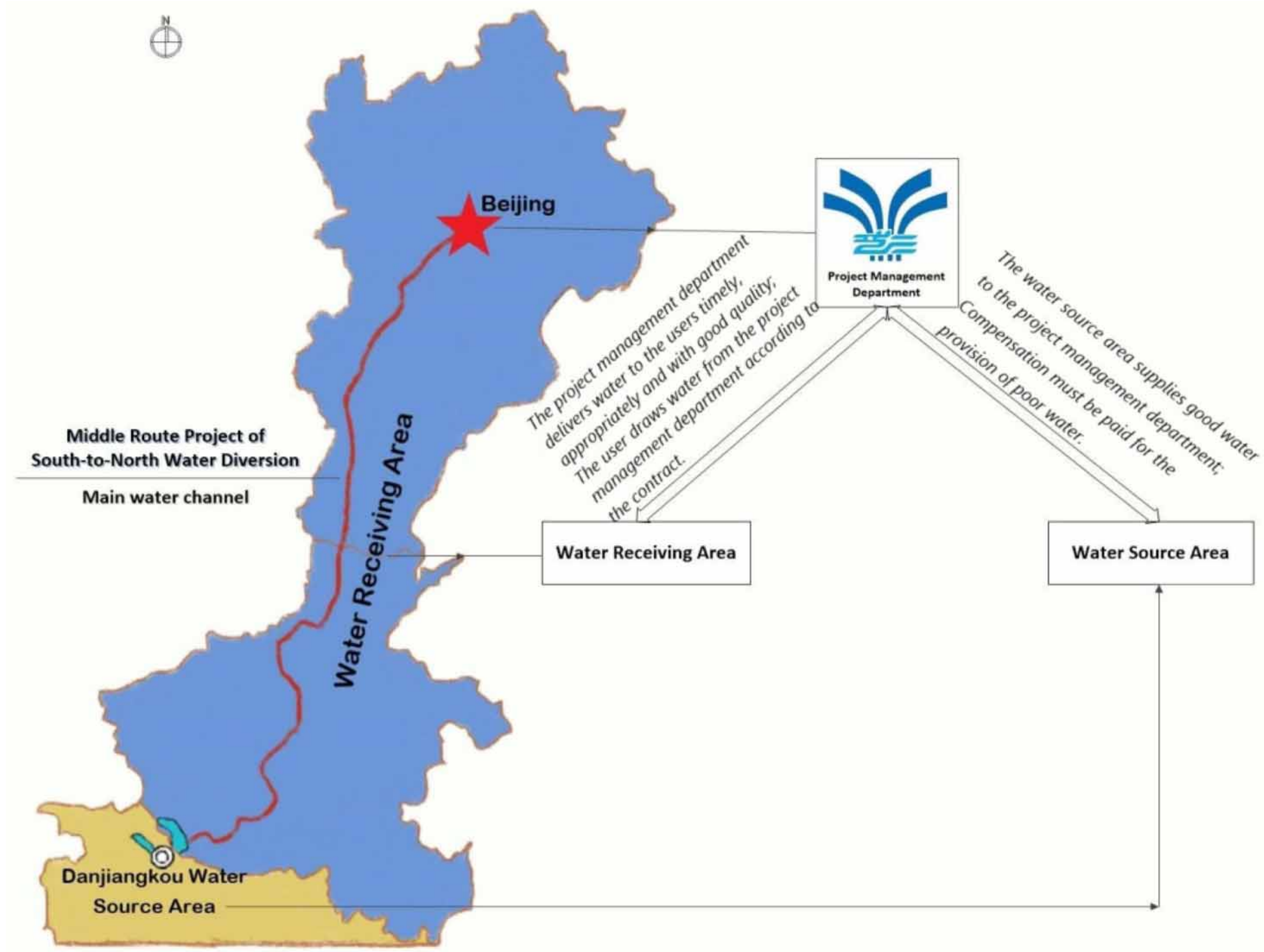

Figure 3 | Schematic diagram of trading relationship between water resources entities.

2.2. Model building

The strategy selection of water source area, project management department and users is shown in Figure 4.

The water source area can provide the project management department with two choices: good water and poor water. The project management department can choose to provide sufficient water and insufficient water to users. Users can choose to accept the amount of water supplied by the project management department, or they can take water from the project management department according to their actual need in a certain period of time.

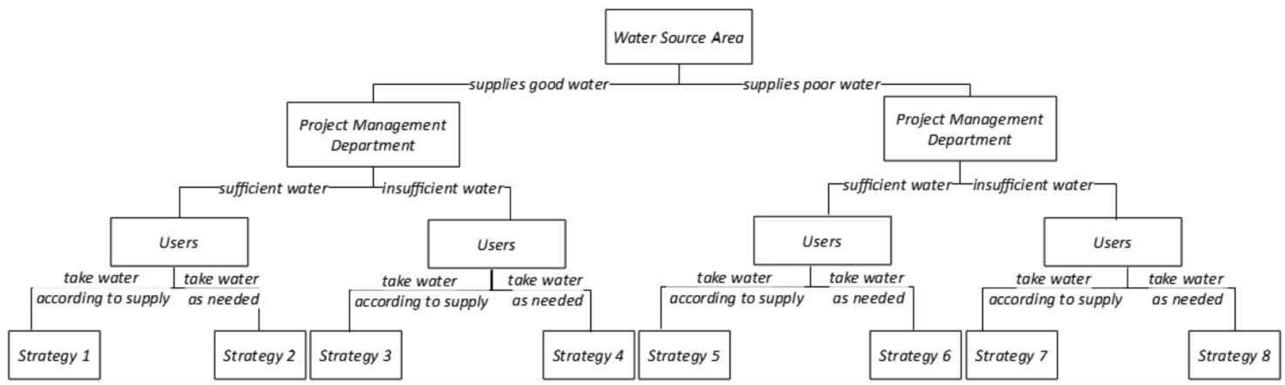

Figure 4 | Behavior strategy selection of water source area, project management department and users.

Assuming that the probability of good water supply to the project management department is x, then the probability of poor water supply is 1-x. The probability that the project management department provides the users with sufficient water (i.e., approximately equal to the contracted water quantity) is y, then the probability of insufficient water is 1-y. The probability of the users taking water by supplying is z, then the probability of taking water by demanding is 1-z (where $0 < x < 1$, $0 < y < 1$, $0 < Z < 1$).

According to the analysis of the possible behavioral choices of the tripartite stakeholders in Figure 4, it can be determined that there are a total of 8 strategies. The following 16 parameters can be assumed based on the strategy selection of each subject and the contract terms signed. These parameters can reflect the amount that the water source area, the project management department and the user have compensated or been compensated for, also reflect the amount of water traded between the project management department and the users. Finally, the benefits obtained by the water source area, the project management department and the users in the process of water right trading can be calculated. Specific parameter settings and meaning are shown in Table 1.

Based on the above basic assumptions and parameter analysis, the income matrix of the tripartite game model is obtained, as shown in Table 2.

2.3. Replicative dynamic equations of evolutionary game

(1) For the water source area, the expected return of good water supply is U_g, and the expected return of poor water supply is U_p:

$$\begin{cases} U_g = yz(P_sQ_c - A) + y(1-z)(P_sQ_a - A) + (1-y)z(P_sQ_i - A) + (1-y)(1-z)(P_sQ_a - A) \\ U_p = yz(P_sQ_c + A - B - C) + y(1-z)(P_sQ_a + A - B - C) + (1-y)z(P_sQ_i + A - B - C) + \\ \qquad (1-y)(1-z)(P_sQ_a + A - B - C) \end{cases} \tag{2}$$

Table 1 | Parameter settings and representations

Parameters	Representations
Q_c	The contracted water volume between water source area, project management department and users;
Q_i	The project management department cannot provide sufficient water supply to many users of the society due to its own reasons (such as the reduction of water flow caused by the destruction of the project structure);
Q_a	Users take water from the project management department according to actual needs;
P_s	The price of water when water source area transfers water resources to the project management department;
A	When the water source area supplies water to the project management department, it gives up the opportunity cost of putting water resources into other projects;
B	The compensation paid by the water source area when it supplies poor water to the project management department;
C	Water resources are used to develop other industrial economic projects in the water source area, resulting in water pollution and deterioration of water quality, resulting in environmental losses;
P_e	The price of water when the project management department sells water resources to users;
D	Operation costs incurred by the project management department during the operation period, including project maintenance costs, staff salaries, water resources transportation costs and other management costs;
αB	The compensation that should be paid by the project management department to the users when they provide poor water ($0 < \alpha < 1$);
N_e	If the project management department fails to supply sufficient water as stipulated in the contract to the users due to its own reasons, it shall compensate users for the liquidated damages;
N_u	When the project management department supplies users with sufficient water, the users take the water according to need due to their own reasons (such as increased rainfall), the penalty shall be paid to the project management department;
E	The treatment cost for users to treat the poor water supplied by the project management department to reach the level of drinkable water;
F	The operating cost of many users at the social level;
G	The total benefits obtained by the users when the project management department supplies sufficient water to users and users take water according to the supply;
γG	The total benefits of users when the project management cannot supply sufficient water or when the users take water according to demand ($0 < \gamma < 1$).

Note: The above parameters are involved in algebraic operation in the model. It is assumed that the parameters themselves are all greater than 0, and the relevant losses takes the opposite number of corresponding benefits.

Table 2 | Income matrix of three parties

Strategy	Subject strategy combination	Water source area	Project management department	Users
1	(Supply good water, Supply sufficient water, Take water according to supply)	P_sQ_c-A	P_eQ_c-P_sQ_c-D	G-P_eQ_c-F
2	(Supply good water, Supply sufficient water, Take water as needed)	P_sQ_a-A	P_eQ_a-P_sQ_a-D + N_u	γ G-P_eQ_a-F-N_u
3	(Supply good water, Supply insufficient water, Take water according to supply)	P_sQ_i-A	P_eQ_i-P_sQ_i-D-N_e	γ G-P_eQ_i-F + N_e
4	(Supply good water, Supply insufficient water, Take water as needed)	P_sQ_a-A	P_eQ_a-P_sQ_a-D	γ G-P_eQ_a-F
5	(Supply poor water, Supply sufficient water, Take water according to supply)	P_sQ_c + A-B-C	P_eQ_c-P_sQ_c-D + (1-α)B	G-P_eQ_c-F + αB-E
6	(Supply poor water, Supply sufficient water, Take water as needed)	P_sQ_a + A-B-C	P_eQ_a-P_sQ_a-D + (1-α)B + N_u	γ G-P_eQ_a-F + αB-E-N_u
7	(Supply poor water, Supply insufficient water, Take water according to supply)	P_sQ_i + A-B-C	P_eQ_i-P_sQ_i-D + (1-α)B-N_e	γ G-P_eQ_i-F + αB-E + N_e
8	(Supply poor water, Supply insufficient water, Take water as needed)	P_sQ_a + A-B-C	P_eQ_c-P_sQ_c-D + (1-α)B	γ G-P_eQ_a-F + αB-E

(2) The project management department chooses M_s as the expected revenue of sufficient water supply, M_i as the expected revenue of insufficient water supply:

$$\begin{cases} M_s = xz(P_eQ_c - P_sQ_c - D) + x(1-z)(P_eQ_a - P_sQ_a - D + N_u) + (1-x)z(P_eQ_c - P_sQ_c - D + (1-\alpha)B) \\ +(1-x)(1-z)[P_eQ_a - P_sQ_a - D + (1-\alpha)B + N_u] \\ M_i = xz(P_eQ_i - P_sQ_i - D - N_e) + x(1-z)(P_eQ_a - P_sQ_a - D) + (1-x)z\,[P_eQ_i - P_sQ_i - D + (1-\alpha)B - N_e] \\ +(1-x)(1-z)[P_eQ_a - P_sQ_a - D + (1-\alpha)B] \end{cases} \tag{3}$$

(3) The expected revenue of users choose to take water according to supply is S_p, and the expected revenue of water drawn by demand is S_n:

$$\begin{cases} S_p = xy(G - P_eQ_c - F) + x(1-y)(\gamma G - P_eQ_i - F + N_e) + (1-x)y\,(G - P_eQ_c - F + \alpha B - E) \\ +(1-x)(1-y)(\gamma G - P_eQ_i - F + \alpha B - E + N_e) \\ S_n = xy(\gamma G - P_eQ_a - F - N_u) + x(1-y)(\gamma G - P_eQ_a - F) + (1-x)y\,(\gamma G - P_eQ_a - F + \alpha B - E - N_u) \\ +(1-x)(1-y)(\gamma G - P_eQ_a - F + \alpha B - E) \end{cases} \tag{4}$$

Based on the above equations, the replication dynamic equations of each game subject can be obtained as:

$$\begin{aligned} F(x) &= \frac{dx}{dt} = x(1-x)(U_g - U_p) \\ &= x(1-x)(B + C - 2A) \end{aligned} \tag{5}$$

$$\begin{aligned} F(y) &= \frac{dy}{dt} = y(1-y)(M_s - M_i) \\ &= y(1-y)[z(P_eQ_c - P_sQ_c - P_eQ_i + P_sQ_i + N_e) + (1-z)N_u] \end{aligned} \tag{6}$$

$$\begin{aligned} F(z) &= \frac{dz}{dt} = z(1-z)(S_p - S_n) \\ &= z(1-z)\{y[(1-\gamma)G + P_eQ_a - P_eQ_c + N_u] + (1-y)(P_eQ_a - P_eQ_i + N_e)\} \end{aligned} \tag{7}$$

3. ANALYSIS OF STABLE POINT AND STABLE STRATEGY OF SYSTEM EVOLUTION

3.1. Evolutionary stable point

The Jacobian matrix of the above three-dimensional dynamic equations can be obtained as follows:

$$\begin{cases} F(x) = \dfrac{dx}{dt} = x(1-x)(U_g - U_p) = 0 \\ F(y) = \dfrac{dy}{dt} = y(1-y)(M_s - M_i) = 0 \\ F(z) = \dfrac{dz}{dt} = z(1-z)(S_p - S_n) = 0 \end{cases} \tag{8}$$

To solve the evolutionary equilibrium point of the tripartite game system, considering that the asymptotically stable solution of the replication dynamic system of the multi group evolutionary game must be a strict Nash equilibrium solution (Zeng 2012), only the following equilibrium points E_1[0,0,0], E_2[0,0,1], E_3[1,0,0], E_4[0,1,0], E_5[1,1,0], E_6[0,1,1], E_7[1,0,1], E_8[1,1,1,1] need to be considered.

Then the simplified Jacobian matrix is obtained as follows:

$$D_et(J) = \begin{bmatrix} \dfrac{dF(x)}{dx} & \dfrac{dF(x)}{dy} & \dfrac{dF(x)}{dz} \\ \dfrac{dF(y)}{dx} & \dfrac{dF(y)}{dy} & \dfrac{dF(y)}{dz} \\ \dfrac{dF(z)}{dx} & \dfrac{dF(z)}{dy} & \dfrac{dF(z)}{dz} \end{bmatrix} = \begin{bmatrix} a_{11}a_{12}a_{13} \\ a_{21}a_{22}a_{23} \\ a_{31}a_{32}a_{33} \end{bmatrix} \tag{9}$$

$a_{11} = (1-2x)(B+C-2A)$; $a_{12} = 0$; $a_{13} = 0$; $a_{21} = 0$; $a_{22} = (1-2y)[z(P_eQ_c - P_sQ_c - P_eQ_i + P_eQ_i + N_e) + (1-z)N_u]$; $a_{23} = y(1-y)[P_eQ_c - P_sQ_c - P_eQ_i + P_sQ_i + N_e - N_u]$; $a_{31} = 0$; $a_{32} = z(1-z)\{[(1-\gamma)G + P_eQ_a - P_eQ_c + N_u] - (P_eQ_a - P_eQ_i + N_e)\}$; $a_{33} = (1-2z)\{[y(1-y)G + P_eQ_a - P_eQ_c + N_u] + (1-y)\ (P_eQ_a - P_eQ_i + N_e)\}$.

Take 8 equilibrium points into the Jacobian matrix and get the eigenvalues of each equilibrium point, as shown in Table 3. Only the equilibrium point with negative real part of eigenvalues could be called a stable evolution strategy.

Equilibrium E_1[0,0,0] and E_5[1,0,0] are due to $\lambda_2 = N_u > 0$, and become unstable points; equilibrium point E_2[0,0,1] and equilibrium point E_6[1,0,1] are caused by $\lambda_2 = (P_e - P_s)\ (Q_c - Q_i) + N_e > 0$, and become unstable points. The equilibrium points E_3[0,1,0], E_4[0,1,1], E_7[1,1,0] and E_8[1,1,1] can become evolutionary stability strategies when the eigenvalue algebra satisfies certain inequality conditions. Because the conditions are stable, as to which one or more strategies can be called stability strategies, it is necessary to analyze the inequality of the eigenvalue algebra according to the actual engineering situation.

3.2. Determination of evolutionary stability strategy

3.2.1. Background of interest subjects

Taking the Middle Route Project of the South-to-North water diversion as an example, its water source area has been designated as a state-level poverty-stricken county for 7 consecutive years, and the overall level of economic and social development is low. According to relevant statistics (Guo 2021), from 2014 to 2016, the national per capita annual income was 21,321.5 yuan, and the per capita annual income of the water source area was 17,137 yuan, which was 19.63% lower than the national per capita annual income in the same period, and the social and economic development lagged behind.

The middle route of the South-to-North Water Diversion Project has supplied water to the Beijing-Tianjin-Hebei regions for 7 consecutive years. Taking Beijing as an example, by May this year, nearly 6.5 billion m^3 of water had been transferred to them. Since the continuous drought in 1999, the groundwater level in Beijing has declined by 0.82 meters annually. The river water has stopped falling and rebounded after entering Beijing. From the end of 2015 to the end of 2020, the groundwater level has rebounded for 5 consecutive years, with a total rise of 3.72 meters, which has greatly improved the water ecological environment and alleviated the water source pressure. Therefore, in order to ensure the social and economic development of the water receiving area, it is necessary to divert water continuously.

Table 3 | Equilibrium points and eigenvalue of Jacobian matrix

		Eigenvalue			
Strategy	Equilibrium point	λ_1	λ_2	λ_3	Asymptotic stability
1	$E_1(0,0,0)$	$B+C-2A$	N_u	$P_e(Q_a-Q_i)+N_e$	No
2	$E_2(0,0,1)$	$B+C-2A$	$(P_e-P_s)(Q_c-Q_i)+N_e$	$-[P_e(Q_a-Q_i)+N_e]$	No
3	$E_3(0,1,0)$	$B+C-2A$	$-N_u$	$(1-\gamma)G+P_e(Q_a-Q_c)+N_u$	Condition 1
4	$E_4(0,1,1)$	$B+C-2A$	$-[(P_e-P_s)(Q_c-Q_i)+N_e]$	$-[(1-\gamma)G+P_e(Q_a-Q_c)+N_u]$	Condition 2
5	$E_5(1,0,0)$	$-(B+C-2A)$	N_u	$P_e(Q_a-Q_i)+N_e$	No
6	$E_6(1,0,1)$	$-(B+C-2A)$	$(P_e-P_s)(Q_c-Q_i)+N_e$	$-[P_e(Q_a-Q_i)+N_e]$	No
7	$E_7(1,1,0)$	$-(B+C-2A)$	$-N_u$	$(1-\gamma)G+P_e(Q_a-Q_c)+N_u$	Condition 3
8	$E_8(1,1,1)$	$-(B+C-2A)$	$-[(P_e-P_s)(Q_c-Q_i)+N_e]$	$-[(1-\gamma)G+P_e(Q_a-Q_c)+N_u]$	Condition 4

To sum up, in order to achieve economic development in the water source area, it is imperative to seize the opportunity of the middle route of the South-to-North Water Diversion Project, take ecological economy as the main line, and continue to deliver high-quality water to the water receiving area, so as to promote the economic stability and rapid development of both sides.

3.2.2. Determine the stability strategy

According to Table 3, to judge the positive and negative of the conditional stable equilibrium solution, it is mainly related to the positive and negative of the following three algebraic expressions.

(1) $B+C-2A$;

The water source area has been in a state of backward economic development for a long time, and the opportunity cost of development in a certain period of time is small. At the same time, the development and utilization of the water source area would destroy the water environment and ecology of Danjiangkou reservoir area, and even affect the drinking water safety of several drinking water intakes in the reservoir area. So, we think that A is small enough, C is large enough, inequality $B+C-2A>0$ always holds.

(2) $[(P_e-P_s)(Q_c-Q_i)+N_e]$;

As a middleman, the difference between the purchase price P_e and the selling price P_s of water resources is the benefits of the project management department, which must be $P_e-P_s>0$ for the maintenance of the project construction loan, project maintenance and operation. At present, there is still a shortage of water resources in the water receiving area of the South-to-North Middle Route Project, and there is a large demand for water transfer, which has accepted 37.9 billion m^3. Therefore, we think that when the project operation meets the requirement of sufficient water source, the contracted water volume of the three parties is large, and Q_i is the situation where the water delivery flow of the project management department is reduced due to force majeure (such as structural damage of the project) during the execution of the contract, so the inequality $(Q_c-Q_i)>0$, $(P_e-P_s)(Q_c-Q_i)+N_e>0$. And $P_s<(N_e)/(Q_c-Q_i)+P_e$ can be obtained, because $P_e>P_s$; therefore, it can be concluded that the water price in the water source area should meet $P_s<P_e<(N_e)/(Q_c-Q_i)+P_e$.

(3) $[(1-\gamma)G+P_e(Q_a-Q_c)+N_u]$;

Once the users change the actual water quantity in the process of using water, instead of taking water according to the contract, it will cause very passive problems such as hidden danger of operation safety to the project management department. As mentioned above, the middle route of the South-to-North Water Diversion Project has been in operation for nearly 7 years, running safely and smoothly, and users have a great demand for water. Generally, the actual water intake will not be less than the contracted water quantity. On the contrary, with the social and economic development of the water receiving area, the urgency of water resources demand in the water receiving area increases, and there will be a risk that Q_a exceeds Q_c. Therefore, we consider that the inequality $(1-\gamma)G+P_e(Q_a-Q_c)+N_u>0$ is always true. However, from a theoretical point of view, in the process of water resource transaction of the water diversion project, we think that the $Q_a<Q_c$, and the penalty N_u is large

Table 4 | Positive and negative conditions of stable equilibrium points

Strategy	Equilibrium point	Eigenvalue λ_1	λ_2	λ_3
3	$E_3(0,1,0)$	$B + C - 2A > 0$	$-N_u < 0$	$(1-\gamma)G + P_e(Q_a - Q_c) + N_u > 0$
4	$E_4(0,1,1)$	$B + C - 2A > 0$	$-[(P_e - P_s)(Q_c - Q_i) + N_e] < 0$	$-[(1-\gamma)G + P_e(Q_a - Q_c) + N_u] < 0$
7	$E_7(1,1,0)$	$-(B + C - 2A) < 0$	$-N_u < 0$	$(1-\gamma)G + P_e(Q_a - Q_c) + N_u > 0$
8	$E_8(1,1,1)$	$-(B + C - 2A) < 0$	$-[(P_e - P_s)(Q_c - Q_i) + N_e] < 0$	$-[(1-\gamma)G + P_e(Q_a - Q_c) + N_u] < 0$

enough, and the inequality $(1-\gamma)G + P_e(Q_a - Q_c) + N_u > 0$ is established, so the water price sets by the project management department should meet the requirements of $P_e < (N_u + (1-\gamma)G)/(Q_c - Q_a)$.

In summary, the positive and negative conditions of stable equilibrium points are shown in Table 4. $E_8(1,1,1)$ is the optimal evolutionary stability strategy. At the same time, among the four possible stability strategies discussed, the project management department should provide sufficient water. It can be seen that, as a trading link, the project management department must have a complete and effective operation safety guarantee system and technology to improve the safety of the project operation and scheduling flexibility.

In addition, the analysis shows that the water price P_e of the project management department is determined by the difference between the actual water demand of the users and the contracted water demand, the total benefit of users, and the default payment to be paid. These parameters should also be considered in the water price formulation of the water source area. Therefore, in the aspect of water resources trading, each stakeholder should pay special attention to the formulation of liquidated damages and the negotiation of the amount of water used.

4. CONCLUSIONS

Based on the evolutionary game theory, this study establishes an evolutionary game model from the three main levels of the water source area, project management department and users of the water diversion project. Through the analysis of the system evolution equilibrium state, it shows that the water resources market-oriented operation mechanism of the water diversion project is feasible, and the optimal strategy adopted by the three parties is as follows: (the water source area supplies good water, the project management department supplies sufficient water, the users take water according to supply), which can ensure the interests of each subject as well as meeting the maximization. Therefore, in order to better promote the formation of the optimal strategy state, the water pricing of the project management department should meet $P_e < (N_u + (1-\gamma)G)/(Q_c - Q_a)$, the water price of the water source area should meet the requirements of $P_s < P_e < (N_e)/(Q_c - Q_i) + P_e$.

In order to jointly promote the marketization of water resources trading in water diversion projects, all parties need to strengthen relevant construction:

1. Establish and strengthen the negotiation mechanism of contract contents between both parties. In the process of transaction of water resources, each subject should be in line with the principles of fairness, voluntariness and good faith to restrain the behavior of water rights trading and create a good trading atmosphere.
2. Users should improve the accounting ability of water demand; combined with the actual situation of water consumption, with the help of mathematical methods or a model to predict the water demand in a certain period in the future.
3. The project management department should pay attention to the operation safety of the project, improve its own technical level, and flexibly schedule water resources according to the change of user needs.

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DATA AVAILABILITY STATEMENT

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

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