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Water transfer projects and "Water-Energy-Food Nexus" governance from the perspective of game theory

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ABSTRACT

The "water-energy-food nexus" governance depends on the strategic interaction of multiple stakeholders. However, existing research on this particular aspect is very limited. Water is needed in industry and agriculture, and in all aspects of life, and the availability of water resources is the top priority for water, energy, and food security. However, water shortages and uneven spatial and temporal distribution require water transfer projects to adjust the distribution of water resources and to consider "water-energy-food nexus" governance. This paper investigates water transfer projects and "water-energy-food nexus" governance by using the game theory, building game models and analyzing the strategic interaction of multiple stakeholders. The solution of the Nash equilibrium supports the formulation of policy recommendations and implementation paths for the sustainable development of water transfer projects governance. The results indicate that water transfer projects can be used as a solution for the "water-energy-food nexus" governance.

Keywords: Game theory; Nash equilibrium; Water transfer projects; Water, energy and food nexus; Sustainable development

1. Introduction

The "water-energy-food nexus" (WEF Nexus) governance depends on the strategic interaction of multiple stakeholders. Water is needed in industry and agriculture, and in all aspects of life, and the availability of water resources is the top priority for water, energy, and food security. The Background Paper of the Bonn 2011 Conference "The Water, Energy and Food Security Nexus", prepared by Hoff [1], showed how the "Nexus" perspective, as a basis for policy recommendations, can contribute towards the achievement of water, energy, and food security by improving efficiency, reducing trade-offs, creating synergies, and improving cross-sectoral governance. Especially, water transfer projects should reduce water shortages and uneven spatial and temporal distribution by considering WEF Nexus governance.

Several previous studies focused on the WEF Nexus [2–14]. Rapid population growth and increased urbanization have contributed towards increasing pressures on global water, energy, and food resource systems. Therefore, there is an imperative need for resilient and effective resource management that considers the societal, environmental, and economic components of sustainable development, by modelling approaches for dynamic decision-making within the WEF Nexus, focusing on mathematical optimization, agent-based modelling, and game theory [15]. There are currently a limited number of studies focusing on water transfer projects and WEF Nexus governance [16]. This paper aims to fill this gap, investigating water transfer projects and the WEF Nexus by using game theory, building game models, and analyzing the strategic interactions of multiple stakeholders.

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2. Methodology

2.1. Assumptions

Rationality. It was assumed that all players within the game are rational and will strive to maximize their payoffs in the game.

Complete information. It was assumed that each player knows the other player's utility function and the rules of the game.

2.2. Pure strategy Nash equilibrium

Definitions:

- *Players*: the governments in water source areas, and the governments in water receiving areas.
- *Strategy space*:
  Pure strategy of the government in water source areas: S_1 = {governing, not governing};
  Pure strategy of the government in water receiving areas: S_2 = {compensating, not compensating};
  The strategy space is: $S_1 \times S_2$, where
  $S_1 \times S_2$ = {(governing, compensating), (governing, not compensating), (not governing, compensating), (not governing, not compensating)}

- *Utility*:

C_1 = Cost of the government in water source areas when it chooses to govern (i.e., human, financial, and material resources investments);

R_1 = Benefits of the government in water source areas when it chooses to govern; this includes tangible benefits (i.e., tax reduction or government subsidies) and intangible benefits related to pollution treatment (i.e., the improvement in government's image due to pollution treatment), where $R_1 > C_1$ or $R_1 = C_1$ or $R_1 < C_1$;

C_1' = Cost of the government in water source areas when it chooses not to govern (i.e., fines for exceeding the standard to be paid), $C_1' = C_1$ or $C_1' > C_1$ or $C_1' < C_1$;

R_1' = Benefits of the government in water source areas when it chooses not to govern, $R_1' = R_1$ or $R_1' > R_1$ or $R_1' < R_1$;

C_2 = Sunk cost of the government investment in the construction of water transfer projects in water receiving areas;

R_2 = Benefits obtained by the government in water receiving areas through water transfer projects, generally $R_2 > C_2$;

B = Compensation for water source areas chosen by the government in water receiving areas; $R_2 - C_2 > B$, otherwise it will be null.

When the government in water source areas chooses not to govern, the payoff of the receiving area is 0;

R_3 = Additional benefits for the normal implementation of the project obtained by the central government as representative of national interests;

R = Total benefits from the project, $R = R_1 + R_2 + R_3$.

The payoff matrix is shown in Table 1.

Game analysis:

When the benefits obtained by the government in water receiving areas through the water transfer project are lower than the compensation for the water source areas chosen by them, then $R_2 - C_2 - B < R_2 - C_2$ and $-C_2 - B < -C_2$; therefore, choosing not to compensate is their strictly dominant strategy.

- If $R_1' = R_1$ and $C_1' < C_1$, then the benefits of the government in water source areas for choosing not to govern are not lower than those of the government in water source areas for choosing to govern, and the cost of the government in water source areas for choosing not to govern is lower than that of the government in water source areas for choosing to govern. At this time, $R_1 - C_1 < R_1 - C_1' = R_1' - C_1'$. Therefore, the choice of not governing is the strictly dominant strategy of the government in water source areas, and the choice of not compensating is the strictly dominant strategy of the government in water receiving areas. Hence, the Nash equilibrium is (not governing, not compensating).
- If $R_1' > R_1$ and $C_1' < C_1$, then the benefits of the government in water source areas for choosing not to govern are greater than those of the government in water source areas for choosing to govern, and the cost of the government in water source areas for choosing not to govern is lower than that of the government in water source areas for choosing to govern. At this time, $R_1 - C_1 < R_1' - C_1'$. Therefore, the choice of not governing is the strictly dominant strategy of the government in water source areas, and the choice of not compensating is the strictly dominant strategy of the government in water receiving areas. Hence, the Nash equilibrium is (not governing, not compensating).
- If $R_1' < R_1$ and $C_1' > C_1$, then the benefits of the government in water source areas for choosing not to govern are lower than those of the government in water source areas for choosing to govern, and the cost of the government in water source areas for choosing not to govern is far greater than that of the government in water source areas for choosing to govern. At this time, $R_1 - C_1 > R_1 - C_1' > R_1' - C_1'$, and the government in water source areas will have an incentive to choose to govern.

It is clear that only when $R_1 > C_1$ such that $R_1 - C_1 + B > R_1' - C_1'$, the government in water source areas will have an

Table 1
Payoff matrix

		Water receiving areas	
		Compensating	Not compensating
Water source areas	Governing	$(R_1 - C_1 + B, R_2 - C_2 - B)$	$(R_1 - C_1, R_2 - C_2)$
	Not governing	$(R_1' - C_1' + B, -C_2 - B)$	$(R_1' - C_1', -C_2)$

incentive to choose to govern. Therefore, without external constraints, neither side has enough motivation to work hard to protect the environment. The situation is clearly characterized as a prisoner's dilemma.

Independently from whether or not the project has benefits, the sunk cost C_2 will exist, leading to $R_2 - C_2 - B > -C_2$ or $R_2 - C_2 > -C_2$, that is, $R_2 > B > 0$. Without external constraints, the government in water receiving areas usually takes the initiative to propose a compensation, and then negotiates with the local government in water source areas, thus forming the dynamic game illustrated in Fig. 1.

Game analysis:

In this case, if $R_1 - C_1 + B > R_1' - C_1'$, then governing the environment will be a rational choice of the government in water source areas, that is, the compensation for the water source areas by the government in the water receiving areas can be greater than the investment saved by the government in the water source areas when it chooses not to govern. Then the Nash equilibrium is (compensating, governing), which depends on the benefits R_2 generated by the project to the water receiving areas. If $R_2 - C_2 - B < -C_2$, that is, the benefits R_2 to water receiving areas are lower than the compensation B to water source areas, then the water receiving areas will choose to reject the project. As long as $R_2 - C_2 - B \geq -C_2$, that is, the benefits R_2 to water receiving area are not lower than the compensation B to water source areas, then the government in water receiving areas will have an incentive to negotiate with the government in water source areas and provide the benefit compensation until $R_1 - C_1 + B > R_1' - C_1'$, so that the government in water source areas decides to choose the strategy of governing, and the dynamic game reaches the optimal steady state of (compensating, governing).

In addition, if $R_1' < R_1$, $C_1' > C_1$, that is, if the benefits to the government in water source areas when it chooses not to govern are lower than those when it chooses to govern, and the cost when it chooses not to govern is far greater than that when it chooses to govern, that is, $R_1 - C_1 > R_1 - C_1' > R_1' - C_1'$, then the government will have an incentive to choose to govern.

Assuming multiple local governments, there are n local governments, then the game will become more interesting, that is, the government in water source areas has two choices (i.e., governing or not governing) after the government in water receiving areas chooses to compensate, which will lead to the "free-rider" problem (Table 2).

Assumption: G_i and G_j are two local governments in water source areas.

Game analysis:

Without external constraints, if G_i chooses not to govern and still can obtain a compensation, then G_i will choose not to govern; the same applies for G_j.

Obviously, in this model there are two Nash equilibriums: (governing, not governing) and (not governing, governing). When the local government in water receiving areas chooses to compensate, the bargaining result of both parties is $R_1 - C_1 + B > R_1' - C_1'$. Therefore, when G_j chooses to govern, for G_i the benefits of choosing not to govern will be greater than those of choosing to govern. On the contrary, when G_j chooses not to govern, for G_i the benefits of choosing to govern will be greater than those of choosing not to govern; the same applies for G_j.

In a game with n local governments, without external constraints, the Nash equilibrium of local governments in water source areas will be (not governing, not governing, ..., not governing). Hence, the "free-rider" problem will lead to a "Tragedy of the Commons". Therefore, the supervision of the central government is necessary.

Furthermore, if $R_1' < R_1$, $C_1' > C_1$, that is, if the benefits of the government in water source areas when it chooses not

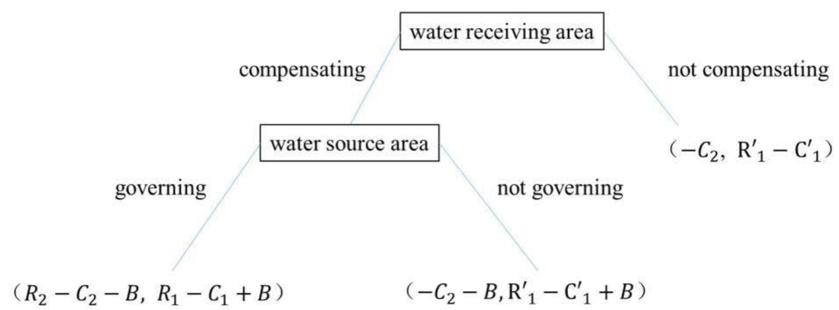

Fig. 1. Dynamic game between governments in water source and water receiving areas.

Table 2
Payoff matrix between local governments in water source areas

		Local government in water source areas G_j	
		Governing	Not governing
Local government in water source areas G_i	Governing	$(R_{i1} - C_{i1} + B_i, R_{j1} - C_{j1} + B_j)$	$(R_{i1} - C_{i1} + B_i, R'_{j1} - C'_{j1} + B_j)$
	Not governing	$(R'_{i1} - C'_{i1} + B_i, R_{j1} - C_{j1} + B_j)$	$(R'_{i1} - C'_{i1}, R'_{j1} - C'_{j1})$

to govern are lower than those when it chooses to govern, and the cost when it chooses not to govern is far greater than that when it chooses to govern, then $R_1 - C_1 > R_1 - C_1' > R_1' - C_1'$, and the government in water source areas will also have an incentive to choose to govern.

2.3. Mixed strategy Nash equilibrium

Assumptions:

In order to protect local governments in water source areas from the "free-rider" problem, the central government and the local governments in water receiving areas should be considered as a community of interests. Accordingly, it was assumed that the central government plays a role of supervision, and its benefits are reflected by the local government in water source areas.

It was assumed that the government in water source areas chooses not to govern with a probability α.

Definitions:

- Participants: G_i, the local government in water source areas.
- *Strategy space*:
  Pure strategy of the government in water source areas: T_1 = {governing, not governing};
  Pure strategy of the government in water receiving areas: T_2 = {supervising, not supervising};
  The strategy space is: $T_1 \times T_2$, where

$T_1 \times T_2$ = {(governing, supervising), (governing, not supervising), (not governing, supervising), (not governing, not supervising)}

- *Utility*:

f = Expenses needed by the government in water receiving areas to choose supervision in exchange for the information on whether the government in water source areas chooses to govern. Once it is found that the local government in water source areas has not chosen to govern, the interest compensation B_i will be cancelled.

$R_{i1} - C_{i1} + B_i$ = Benefits of G_i under the strategy (governing, supervising);

$R_2 - C_2 - B - f$ = Benefits of the government in water receiving areas under the strategy (governing, supervising);

$R_{i1} - C_{i1} + B_i$ = Benefits of G_i under the strategy (governing, not supervising);

$R_2 - C_2 - B$ = Benefits of the government in water receiving areas under the strategy (governing, not supervising);

$R_{i1}' - C_{i1}'$ = Benefits of G_i under the strategy (not governing, supervising);

$R_2 - C_2 - B - f + B_i$ = Benefits of the government in water receiving areas under the strategy (not governing, supervising); the local government in water receiving areas faces the "free-rider" problem in water source areas and takes corresponding measures;

$R_{i1}' - C_{i1}' + B_i$ = Benefits of G_i under the strategy (not governing, not supervising). The final result of the repetition of the game among the actors is that all local governments in water source areas choose the strategy of not governing.

$-C_2 - B$ = Benefits of the government in water receiving areas under the strategy (not governing, not supervising);

α = Probability that G_i chooses not to govern;

β = Probability that the local government in water receiving areas chooses to supervise.

When $R_{i1}' - C_{i1}' < R_{i1} - C_{i1} + B_i < R_{i1}' - C_{i1}' + B_i$, there is only a mixed strategy Nash equilibrium. Assuming that G_i plays with a mixed strategy $\sigma_1 = (\alpha, 1 - \alpha)$, that is, it chooses not to govern with a probability of α, and chooses to govern with a probability of $1 - \alpha$, then the government in water receiving areas plays with the mixed strategy $\sigma_2 = (\beta, 1 - \beta)$, that is, it chooses to supervise with a probability of β, and chooses not to supervise with a probability of 1 – β (Table 3).

The expected utility function of G_i is:

$$\begin{aligned} v_1(\sigma_1,\sigma_2) &= \alpha\left[\beta\left(R_{i1}' - C_{i1}'\right) + (1-\beta)\left(R_{i1}' - C_{i1}' + B_i\right)\right] \\ &+ (1-\alpha)\left[\beta\left(R_{i1} - C_{i1} + B_i\right) + (1-\beta)\left(R_{i1} - C_{i1} + B_i\right)\right] \\ &= \alpha\left(R_{i1}' - C_{i1}' + B_i - \beta B_i\right) + (1-\alpha)\left(R_{i1} - C_{i1} + B_i\right) \end{aligned} \quad (1)$$

In order to reach the Nash equilibrium, the mixed strategy (β, 1 – β) of the government in water receiving areas must make the expected benefits of G_i have no difference between the choices of governing and not governing. According to the definition of the Nash equilibrium, under the premise of the given mixed strategy (β, 1 – β) of the local government in water receiving areas, the maximum value of $v_1(\sigma_1, \sigma_2)$ is solved. In Eq. (1), the derivative of α was obtained, the derivative zero was calculated, and the first order condition for the optimization of G_i was obtained as follows:

$$\frac{\partial V_1}{\partial \alpha} = R_{i1}' - C_{i1}' + B_i - \beta B_i = R_{i1} - C_{i1} + B_i \quad (2)$$

The left side of Eq. (2) indicates the expected benefits of G_i when it chooses not to govern, while the right side indicates its expected benefits when it chooses to govern. When G_i is indifferent between these two strategies, the optimal probability β^* of choosing supervision by the local government in water receiving areas in the Nash equilibrium is obtained. Based on Eq. (2), the solution is the following:

Table 3
Payoff matrix for the mixed strategy Nash equilibrium

		Government in water receiving areas	
		Supervising (probability β)	Not supervising
Government in water source areas G_i	Governing	$(R_{i1} - C_{i1} + B_i, R_2 - C_2 - B - f)$	$(R_{i1} - C_{i1} + B_i, R_2 - C_2 - B)$
	Not governing (probability α)	$(R_{i1}' - C_{i1}', R_2 - C_2 - B - f + B_i)$	$(R_{i1}' - C_{i1}' + B_i, -C_2 - B)$

$$\beta = \frac{\left(R_{i1} - C_{i1}\right) - \left(R'_{i1} - C'_{i1}\right)}{B_i} \tag{3}$$

Namely:

$$\beta^* = \frac{\left(R_{i1} - C_{i1}\right) - \left(R'_{i1} - C'_{i1}\right)}{B_i} \tag{4}$$

Similarly, given the mixed strategy (α, 1 – α) of G_i, the expected utility function of the government in water receiving areas is as follows:

$$\begin{aligned} v_2\left(\sigma_1,\sigma_2\right) &= \beta\left[\left(1-\alpha\right)\left(R_2 - C_2 - B - f\right) + \alpha\left(R_2 - C_2 - B - f + B_i\right)\right] \\ &\quad + \left(1-\beta\right)\left[\left(1-\alpha\right)\left(R_2 - C_2 - B\right) + \alpha\left(-C_2 - B\right)\right] \\ &= \beta\left(\alpha B_i + R_2 - C_2 - B - f\right) + (1-\beta)\left(R_2 - C_2 - B - \alpha R_2\right) \end{aligned} \tag{5}$$

According to the definition of the Nash equilibrium, under the premise of the given mixed strategy (α, 1 – α) of G_i, the maximum value of $v_2(\sigma_1, \sigma_2)$ is solved. In Eq. (5), the derivative of β was obtained, the derivative zero was calculated, and the first order condition for optimization of the government in water receiving areas was obtained as follows:

$$\frac{\partial V_2}{\partial \beta} = \alpha B_i + R_2 - C_2 - B - f = R_2 - C_2 - B - \alpha R_2 \tag{6}$$

The left side of Eq. (6) indicates the expected benefits of the government in water receiving areas when it chooses to supervise, while the right side indicates its expected benefits when it chooses not to supervise. When the government in water receiving areas is indifferent between these two strategies, the optimal probability α^* of not governing by G_i in the Nash equilibrium is obtained. Based on Eq. (6), the solution is as follows:

$$\alpha = \frac{f}{B_i + R_2} \tag{7}$$

namely:

$$\alpha^* = \frac{f}{B_i + R_2} \tag{8}$$

Therefore, the mixed Nash equilibrium of this game is as follows:

$$\alpha^* = \frac{f}{B_i + R_2}, \quad \beta^* = \frac{\left(R_{i1} - C_{i1}\right) - \left(R'_{i1} - C'_{i1}\right)}{B_i} \tag{9}$$

3. Results and discussion

3.1. Improving national laws

If the central government strengthens its supervision and increases punishment, that is, if the value of C'_1 increases such that $C'_1 > C_1$ and $R'_1 < R_1$, $(R_{i1} - C_{i1}) > (R'_{i1} - C'_{i1})$, then the local government in water source areas will have no opportunity to choose not to govern; instead, it will try to bring pollution under control. Due to the sunk cost C_2, the local government in water receiving areas will actively negotiate and cooperate with those in water source areas during the operation of the project on the benefit compensation value B, although the final result of the negotiation is determined by the benefit value R_2 of the local government in water receiving areas. The "WEF Nexus" should be taken into full account in the top-level design with innovation in national policies and laws on water, energy, and agriculture, so as to avoid the prisoner's dilemma, the "free-rider" problem, and the "Tragedy of the Commons". A coordination mechanism among multiple stakeholders should be established and improved to address the "WEF Nexus" in a coherent and sustainable way. Since the main bottleneck of sustainable development in relation to the "WEF Nexus" lies in the shortage of water resources, the efficiency of water resources utilization and the level of water resources recycling should be improved. A water resources management platform should be built, by using Internet, big data, artificial intelligence, blockchain, and digital twin technologies to integrate comprehensive water resources data and information. Horizontal and vertical evolutionary learning should be adopted not only to promote the realization of knowledge dynamic and optimized management from data to information, from information to knowledge, and from knowledge to wisdom but also to build a "Smart WEF Nexus" with data as the key element, break the information island, realize interconnection, promote the modernization of governance capacity and of the governance system, achieve connectivity, and promote sustainable development.

The Nash equilibrium indicates that the local government in water receiving areas will choose the strategy of supervising with an optimal probability of β^*. If the local government in water receiving areas supervises with a probability of $\beta > \beta^*$, then the best strategy for the local government in water source areas will be to choose governing; otherwise, it will be not governing. If the local government in water source areas supervises with a probability of $\beta = \beta^*$, then the local government in water source areas will randomly choose to govern or not. In the mixed strategy Nash equilibrium, the optimal probability $\beta^* = \frac{\left(R_{i1} - C_{i1}\right) - \left(R'_{i1} - C'_{i1}\right)}{B_i}$ of the local government in water receiving areas that chooses to supervise depends on five variables: R_{i1}, R'_{i1}, C_{i1}, C'_{i1}, and B_i. If $R_{i1} = R'_{i1}$ and $\beta^* = \frac{C'_{i1} - C_{i1}}{B_i}$, then the optimal probability depends on three variables: C_{i1}, C'_{i1}, and B_i. For the local government in water receiving areas, the governance costs of the local government in water source areas C_{i1} and C'_{i1} are exogenous variables, and β^* is inversely proportional to B_i. Therefore, increasing the compensation of benefits to the local government in water source areas can effectively reduce the frequency of supervision by local government. In addition, B_i is also the punishment for the "free-rider" problem. Therefore, increasing the punishment to local governments in water source areas and improving the supervision quality of the central government will also effectively reduce the optimal supervision probability of local governments in water receiving areas.

The Nash equilibrium of the government in water receiving areas indicates that the local government in water source areas will choose not to govern with an optimal probability of $\alpha^* = \frac{f}{B_i + R_2}$, that is, to act as "free-rider" in order to obtain additional benefits. If the local government in water source areas chooses not to govern with a probability of $\alpha > \alpha^*$, then the optimal strategy of the local government in water receiving areas is to choose to supervise; otherwise, it will choose not to supervise. If the local government in water source areas chooses not to govern with a probability of $\alpha = \alpha^*$, then the optimal choice of the local government in water receiving areas is to randomly choose either to supervise or not. From $\alpha^* = \frac{f}{B_i + R_2}$, we can see that the optimal probability of the local government in water source areas choosing not to govern is directly proportional to the check cost f of the local government in water receiving areas, and inversely proportional to the benefits R_2 from the project and the compensation value B_i provided by the local government in water receiving areas. Since R_2 is independent, f and B_i will affect the probability of the local government in water source areas to choose not to govern, that is, to act as "free-rider".

$$\frac{\partial \alpha^*}{\partial f} > 0 \tag{10}$$

$$\frac{\partial \alpha^*}{\partial B_i} < 0 \tag{11}$$

Therefore, the probability that the local governments in water source areas choose not to govern, that is, to play the "free-rider", could be reduced by decreasing the supervision cost f, improving the supervision quality of the central government, and increasing the benefit compensation value of water source areas B_i.

3.2. Focusing on long-term interests

When the game is only played once, each player only cares about their one-time payoff. If the game is repeated several times, players may seek long-term future interests instead of immediate interests, so as to escape from the prisoner's dilemma and achieve cooperation. Therefore, the number of times the game will be repeated will affect the results of the game equilibrium. The intangible benefits (i.e., enhanced government image) derived from environment protection to local governments in water source areas, and those derived from the supervision of the central government (governments in water receiving areas), will be highlighted over time; this can encourage players to cooperate, so as to achieve common long-term interests.

3.3. Reaching a cultural consensus

There is a general consensus on the seriousness of environmental problems. As stated in Agenda 21, it is our common responsibility to protect our living environment. Apart from law, morality is also a punishment mechanism for uncooperative actions, which helps human beings to escape from the prisoner's dilemma. The sense of morality naturally encourages people to condemn immoral or unjust behaviors or to avoid cooperation with immoral subjects, so that these suffer losses and the immoral behaviors in society will be restrained. Therefore, as long as the dual concepts of morality/immorality and justice/injustice are formed in a society, they will automatically produce a regulatory role. Through education, training, cooperation, and exchange, the public's awareness of "WEF Nexus" security should be enhanced; moreover, their awareness of water conservation and environmental protection innovation should be raised, and the strategic interaction of all stakeholders should be promoted to realize the overall optimization of societal efforts. Only by reaching a societal consensus around an ecological culture, can a moral society with an endogenous force be really built, so that morality is institutionalized and self-conscious.

4. Conclusion

Using the game theory, this paper investigated water transfer projects and "WEF Nexus" governance, building game models and analyzing the strategic interaction of multiple stakeholders. The following conclusions can be drawn from this study.

This paper investigates water transfer projects and "water-energy-food nexus" governance by using the game theory, building game models and analyzing the strategic interaction of multiple stakeholders. The solution of the Nash equilibrium supports the formulation of policy recommendations and implementation paths for the sustainable development of water transfer projects governance. The results indicate that water transfer projects governance can be used as a solution for the "water-energy-food nexus" governance by improving national laws, focusing on long-term interests and reaching a cultural consensus. That is, by achieving "harmony between humankind", then we can achieve "harmony between humankind and nature" for sustainable development of resources, environment and human society. This research opens up new path for theoretical research on sustainability science, "water-energy-food nexus" governance and sustainable development of water transfer projects governance.

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