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Sustainable Hydropower Development Research in China – based on Tripartite Evolutionary Game

Zeng Sheng*[,1], Bu Zheng[+], and Tao Qingmei[+]

Abstract – *As a clean and renewable energy source, hydropower benefits the sustainable economic growth. But in the process of hydropower development, it causes migration and environment problems among hydropower developers, immigrants and ecological environment. To solve the interest conflict of all three parties, this paper first applies the replication dynamics analysis methods of evolutionary game theory to study the relationship among parties involved; secondly establishes a tripartite payment matrix and analytical dynamic equations to solve stability strategies of three parties in different conditions; finally, based on the stabilization strategy of game results, it proposes three suggestions for the sustainable hydropower development.*

Keywords – *ecological compensation, evolutionary stability strategy, hydropower development, resettlement compensation, tripartite evolutionary game.*

1. INTRODUCTION

As a clean and renewable energy resources, hydropower is a widely chosen method when constructing the cyclic development of the natural. It plays an important role in continuation of human survival, because that developing hydropower projects is an effective way to solve energy crisis, reduce carbon emissions, curb global warming, governance haze weather. Nowadays, 20% of the world's electricity supply is in the form of hydropower. The hydropower construction has mushroomed worldwide ever since France piloted hydropower in 1878 [1]. In 1910, China launched its first hydropower station, Shilongba Hydropower Station, which is based in Kunming, Yunnan Province. Started in 1950, more investment has been put into hydropower resources leading to increased hydropower utilization in China [2]. In 2014, the total electricity production in China reached to 5,545.9 billion KWh, of which 19.22% was contributed by hydropower that was 1,066.1 billion KWh. Nevertheless this number barely accounts for 20% of the world hydropower utilization. Comparing with China's economic weight in the world, there is still great potential to explore in terms of the development, investment and construction of hydropower.

However, some ecological and social side effects arose during China's hydropower projects construction. The main theme of China's hydropower development in new era should focus on ecological civilization, which based on the protection of ecological harmony and sustainable development [3]. Hydropower development therefore needs to deal with two important problems: how to integrate the relationship among economic interests, environmental and social benefits of hydropower development; how to rationally allocate the economic benefits to different stakeholders of hydropower development. As the above problems have strong impact on environment, economy, and society, ignoring them would lead severe consequences such as: local citizens barely benefit from hydropower and local economic development [4]; reservoir immigrates issue worsened; ecological environment in urgent need of protection [5]–[6]; to improve economy and to maximize government's benefit without considering environment and individual interest will intensify social conflict, cause mass events, affect social stability and harmony.

In order to keep the hydropower project can sustainable development, how to balance the interests between all parties in the process of hydropower development has become an urgent problem.

2. LITERATURE REVIEW

At present, there are many literature studies on the game relations among the stakeholders in hydropower development.

In order to achieve sustainable hydropower development and social environment development, Sheng in 2009 used the evolutionary game model to study the relationship between the hydropower developer and the ecological environment and immigrants, seeking the coordination between the hydropower developer, ecological environment and the immigrants [7]. In a study by Xin in 2007, proposed that China should grant more importance to integrating environmental protection and social benefits into the hydropower development. Adhering to principle "develop in protecting and protect in developing" requires enhancing environment protection strength and improving environment protection methods [8]. The ultimate dilemma of hydropower development, according to the world hydropower development pattern, is the eco-migration. Applying the analysis and exploration of "watershed psychology", Yang in 2008, constructed the "basin's dilemma" game model on

*Research Center for Economy of Upper Reaches of the Yangtse River, Chongqing Technology and Business University, Chongqing 400067, China.

[+]School of Finance and Fiscal Affairs, Chongqing Technology and Business University, Chongqing 400067, China.

[1] Corresponding author;
Tel: + 86 130 083 938 05, Fax: + 86 023 627 693 77.
E-mail: cqzs2002@163.com.

ecological environment protection solving the interest conflict among the upstream, middle and lower reaches, and discusses how to protect the ecological environment [9]. Xi in 2006, gave a qualitative analysis on the interests of hydropower participants that includes local government, hydropower companies, reservoir eco-migrations, non-governmental environmentalists [10]. Jiansheng in 2008 worked out a qualitative analysis on interest conflict and interest game among proprietor (eco-migration institute), local government and migration. The only way to maximize one nation's interest is through professionally managed competent authority to associate with good relationship establishment among stakeholders [11].

Although interest game between two stakeholders in hydropower development is well documented, no previous literature studies the situation with three stakeholders from the game theory point of view. This paper lays originality on the tripartite evolutionary game model, which is applied to analyze the interest conflict among multi-stakeholders involved in hydropower development. By quantitatively analyzing the interest game of hydropower developers, migration and ecological environment, this paper proposes win-win suggestions on how hydropower develops in protecting and protects in developing.

3. ANALYSIS OF TRIPARTITE GAME IN HYDROPOWER DEVELOPMENT

This paper constructs a game model of the hydropower development, and by solving the dynamic equation it obtains a stability strategy of the game model.

3.1 Evolutionary Game Theory (EGT)

Evolutionary game theory is a multi-player game with many competitors, it is a theory that adapts game theory into dynamic evolution process analysis. Firstly, as the research object is changing over time, the purpose of evolutionary game theory is to achieve an understanding on the dynamic evolution of the group, and to explain why and how the group comes into being its current status.

Secondly, the factors affecting the group are featured by both a randomness and, mutation in disturbance. There is some regularity to follow for selection mechanism during evolution process. Group's selection process determines EGT's ability of prediction and interpretation. Usually the selection process of the group has a certain inertia, and this process lurks the dynamics of the mutation, thus constantly generating new varieties and new features [12].

3.2 The Participants in the Model

This tripartite evolutionary game model involves three participants: hydropower developer, ecological environment, and migration.

The hydropower developer refers to the hydropower development enterprise or government representatives. The ecological environment is not conscious will response hydropower developers on an objective reality (for simplicity, ignore the delay of the environment impact). Successful migration is of essential for hydropower project implementation. To maximize benefit, hydropower developers turn to reduce compensation to migrants. But low compensation cannot achieve successful migration. Failure to solve the interest conflict between hydropower developers and migrants may induce serious social problems.

3.3 Participants Strategies

In the tripartite game process, each group has two strategy choices. In the strategy selection of this model, hydropower developers can choose either to launch development or to abandon development. Migrants can relocate either voluntarily or reluctantly. The ecological environment may respond in either degradation or improved situations.

Figure 1 illustrates the process of tripartite game that is based on the above conditions. According to Figure 1, there are 8 outcomes represented by set St (t = 1,2,3, ..., 8), where S1 = (launch development, voluntary relocation, environmental degradation); S2 = (launch development, voluntary relocation, environment improved); S3 = (launch development, involuntary relocation, environmental degradation); S4 = (launch development, involuntary relocation, environmental improved); S5 = (abandon development, Voluntary relocation, environmental degradation); S6 = (abandon development, voluntary relocation, environment well improved); S7 = (abandon development, involuntary relocation, environmental degradation); S8 = (abandon development, involuntary relocation, environment improved).

3.4 Variables and Hypothesis

The probability of the successful development by a hydropower developer is assumed to be x, which represents the feasibility of hydropower project development. If x is larger, the probability of project success is higher, and the probability of the abandonment is $1-x$. The probability of voluntary relocation is y, and the probability of involuntary resettlement is $1-y$. The probability of environmental deterioration is z, it value represents the fragility of ecological environment, that is, if the ecological environment is more fragile, The probability of deterioration is higher, the probability of environment well is $1-z$.

If a hydropower project is launched, hydropower developer will earn income A, migrants will get compensation B from hydropower developer. Voluntary migrants pay relocation cost C. Under involuntary relocation, the cost C will be transferred from migrants to a hydropower developer. All migrations, voluntary or involuntary, forgo the environment benefit D from their original hometown after relocation.

When implement hydropower project causes environment deterioration, hydropower developer will bear the environmental maintenance cost E, and the environment will be harmed by F. If the environment is improved, *i.e.* the environmental damage is 0, a hydropower developer bears no environmental maintenance cost.

If the hydropower developer abandons the current project, the cost of this hydropower project will be saved for other projects that will generate benefit G. If the environment is improved after the abandonment of hydropower project, the hydropower developer bears no environmental maintenance cost. Since no hydropower is launched in this place, the untouched environment gains benefit H. If the environment is worsened after the abandonment of hydropower project, hydropower developer will pay the environment maintenance cost I and the environment loss is J.

If migrant moves voluntarily and the ecological environment is good, migrant will get positive benefits K from the ecological environment, and the ecological environment is compensated L by the good treatment of the voluntary migrant. On the other hand, if the ecological environment is worsened, migrant will not get the positive benefits from the ecological environment, and the ecological environment gets no ecological compensation. For involuntary relocation, migrant gets no benefit and will still bear cost J if environment is worsened.

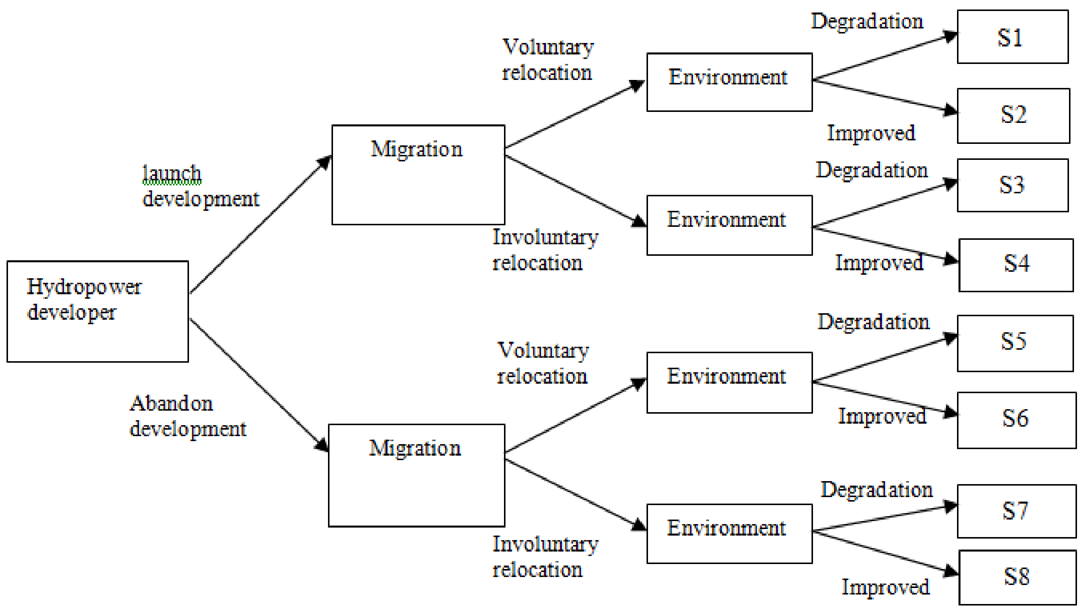


Fig. 1. Tripartite strategy in hydropower development process.

3.5 Payment Matrix and Expected Utility Analysis

According to the set parameters and hypotheses, we can get the payment matrix of the tripartite game.

Hydropower developers get expected return function U_{11} when project is successfully launched; U_{12} when project is abandoned. The average expected return function of hydropower developers is $\overline{U_1}$. According to the payment matrix of Table 1:

$$U_{11} = yz(A-B-E)+y(1-z)(A-B)+z(1-y)(A-B-C-E)+(1-y)(1-z)(A-B-C) \quad (1)$$

$$U_{12} = yz(G-B-I)+y(1-z)(G-B)+z(1-y)(G-B-C-I)+(1-y)(1-z)(G-B-C) \quad (2)$$

$$\overline{U_1} = xU_{11}+(1-x)U_{12} \quad (3)$$

Migrants get expected return function U_{21} under voluntary relocation; U_{22} under involuntary relocation. The average expected return function of immigrants is $\overline{U_2}$. According to the payment matrix of Table 1:

$$U_{21} = xz(B-C-D)+x(1-z)(B-C-D+K)+z(1-x)(B-C-D)+(1-x)(1-z)(B-C-D+K) \quad (4)$$

$$U_{22} = xz(B-D)+x(1-z)(B-D)+z(1-x)(B-D)+(1-x)(1-z)(B-D) \quad (5)$$

$$\overline{U_2} = yU_{21}+(1-y)U_{22} \quad (6)$$

Ecological environment gets expected return function U_{31} if suffered from environmental deterioration; U_{32} if environment is improved. The average expected return function of ecological environment is $\overline{U_3}$. According to the payment matrix:

$$U_{31} = xy(-F)+x(1-y)(-F)+y(1-x)(-J)+(1-x)(1-y)(-J) \quad (7)$$

$$U_{32} = xy\cdot L+x(1-y)\cdot 0+y(1-x)\cdot(H+L)+(1-x)(1-y)\cdot H \quad (8)$$

$$\overline{U_3} = zU_{31}+(1-z)U_{32} \quad (9)$$

Table 1. Tripartite payment matrix for hydropower developers, migrants and ecological environment.

strategy	hydropower developer	Immigration	ecological environment
x, y, z	A-B-E	B-C-D	-F
x, y, $1-z$	A-B	B-C-D+K	L
x, $1-y$, z	A-B-C-E	B-D	-F
x, $1-y$, $1-z$	A-B-C	B-D	0
$1-x$, y, z	G-B-I	B-C-D	-J
$1-x$, y, $1-z$	G-B	B-C-D+K	H+L
$1-x$, $1-y$, z	G-B-C-I	B-D	-J
$1-x$, $1-y$, $1-z$	G-B-C	B-D	H

3.5 Tripartite Game Replicated Dynamic Equation and Its Stability Analysis

In order to implement hydropower, developers choose the following replicated dynamic equation:

$$F(x)=\frac{dx}{dt}=x(U_{11}-\overline{U}_1)=x(1-x)\left[A-G+z(I-E)\right] \tag{10}$$

According to Equation 10, when $z=\frac{G-A}{I-E}$, then $F(x)=\frac{dx}{dt}=0$, then x is stable. When $z\neq\frac{G-A}{I-E}$, let $F(x)=\frac{dx}{dt}=0$, there are two possible equilibrium solutions: $x=0$ or $x=1$. As evolutionarily stable strategy (ESS) requires the derivative of replicated dynamic equation, F'(x), be negative at stability points, differentiate F(x):

$$\frac{dF(x)}{dx}=(1-2x)\left[A-G+z(I-E)\right] \tag{11}$$

According to Equation 11, when $\left[A-G+z(I-E)\right]>0$, then $z<\frac{G-A}{I-E}$. Considering E is the environmental maintenance cost developers should pay if there is any damage caused by hydropower project implementation, while I is the environmental maintenance cost paid by developers after abandoning the hydropower project, surely untouched environment would suffer less damage, therefore I<E, $I-E<0$. If x=0, $F'(0)>0$; if x=1, $F'(1)<0$. Hence, $x=1$ is the solution of evolutionary stable strategy (ESS).

When $\left[A-G+z(I-E)\right]<0$, then $z>\frac{G-A}{I-E}$, $F'(0)<0$, $F'(1)>0$, $x=0$ is the solution of evolutionary stable strategy (ESS).

Because $\frac{G-A}{I-E}$ will affect the evolutionarily stable strategy, it is necessary to find out how $\frac{G-A}{I-E}$ affects ESS. When $0<\frac{G-A}{I-E}<1$, there is no impact on ESS;

When $\frac{G-A}{I-E}<0$, because $z\geq 0$, $x=0$ is the only solution of ESS;

When $\frac{G-A}{I-E}>1$, because $z\leq 1$, $x=1$ is the only solution of ESS.

According to the above analysis, we can obtain hydropower developers with the value of z and $\frac{G-A}{I-E}$ in different value, the dynamic trend and stability of the phase diagram (Figure 2).

Voluntary migrants have the following replicated dynamic equation:

$$F(y)=\frac{dy}{dt}=y(U_{21}-\overline{U}_2)=y(1-y)\left[(1-z)K-C\right] \tag{12}$$

According to Equation 12, when $z=1-\frac{C}{K}$, $F(y)=\frac{dy}{dt}=0$, then y is stable. When $z\neq 1-\frac{C}{K}$, let $F(y)=\frac{dy}{dt}=0$, there are two possible equilibrium solutions: $y=0$, $y=1$.) ESS requires the derivative of replicated dynamic equation, F'(y), be negative at stability points, differentiate F(y):

$$\frac{dF(y)}{dx}=(1-2y)\left[(1-z)K-C\right] \tag{13}$$

According to Equation 13, when $\left[(1-z)K-C\right]>0$, $z<1-\frac{C}{K}$, $F'(0)>0$, $F'(1)<0$. So $y=1$ the solution of ESS.

When $\left[(1-z)K-C\right]<0$, $z>1-\frac{C}{K}$, $F'(0)<0$, $F'(1)>0$. Then, $y=0$ is the solution of ESS.

Because that $1-\frac{C}{K}$ will affect ESS, it is necessary to find out $1-\frac{C}{K}$ affects ESS.

When $0<1-\frac{C}{K}<1$, there is no impact on ESS;

When $1-\frac{C}{K}<0$, because $z\geq 0$, $y=0$ is the only solution of ESS;

When $1-\frac{C}{K}>1$, because $z\le 1$, $y=1$ is the only solution of ESS.

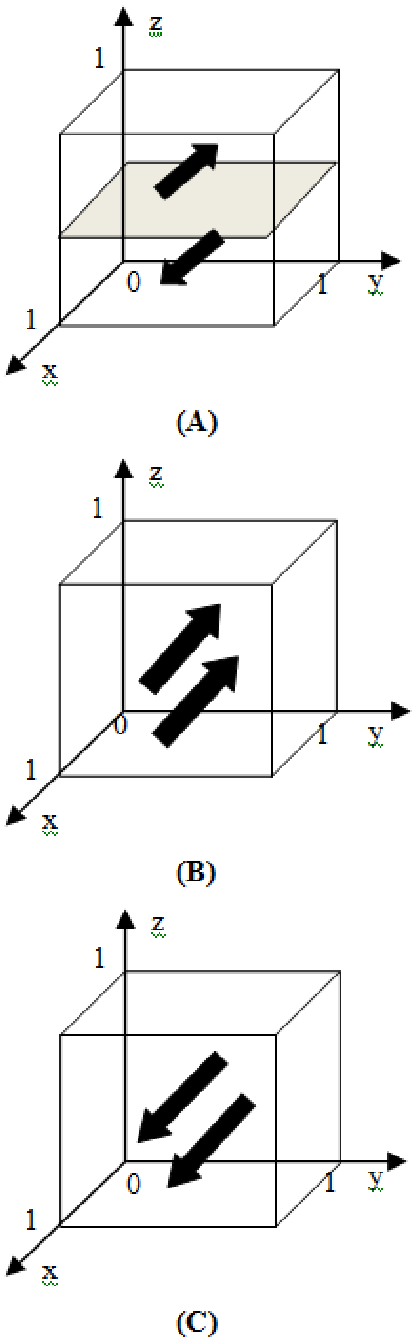


Fig. 2. Trend phase diagram of hydropower developers.

(A) when $0<\frac{G-A}{I-E}<1$**, (B) when** $\frac{G-A}{I-E}<0$**, (C) when** $\frac{G-A}{I-E}>1$

The above analysis gives the following dynamic trend stereograms of migrants (Figure 3):

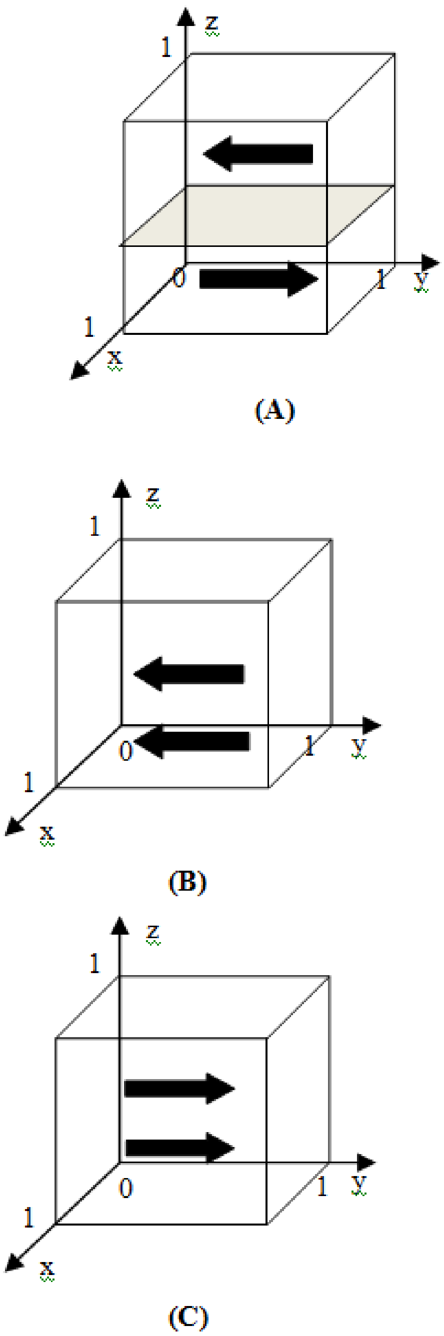


Fig. 3. Trend phase diagram of migrantiong trend.

(A) when $0<1-\frac{C}{K}<1$**, (B) when** $1-\frac{C}{K}<0$**, (C) when** $1-\frac{C}{K}>1$

The replicated dynamic equation of the ecological environment deterioration is given as follows:

$$F(z)=\frac{dz}{dt}=z(U_{31}-\overline{U}_3)=z(1-z)\left[(x-1)(J+H)-xF\right] \qquad (14)$$

According to Equation 14, when $\left[(x-1)(J+H)-xF\right]=0$, $F(z)=0$, then z is stable. When there are two possible equilibrium solutions: $z=0$, $z=1$. Taking the derivative of $F(z)$:

$$\frac{dF(z)}{dx} = (1-2z)\left[(x-1)(J+H) - xF\right] \quad (15)$$

According to Equation 15, when $\left[(x-1)(J+H) - xF\right] > 0$, which means that $x > \frac{J+H}{J+H-F}$, $F'(0) > 0$ and $F'(1) < 0$, so $z = 1$ is the solution of ESS.

When $\left[(x-1)(J+H) - xF\right] < 0$, which means that $x < \frac{J+H}{J+H-F}$, $F'(0) < 0$ and $F'(1) > 0$, so $z = 0$ is the solution of ESS.

Because $\frac{J+H}{J+H-F}$ will affect ESS, it is necessary to find out $\frac{J+H}{J+H-F}$ affects ESS.

When $0 < \frac{J+H}{J+H-F} < 1$, there is no impact on ESS;

When $\frac{J+H}{J+H-F} < 0$, because $x \geq 0$, then $z = 1$ is the only solution of ESS;

When $\frac{J+H}{J+H-F} > 1$, because $x \leq 1$, then $z = 0$ is the only solution of ESS;

The above analysis gives the following dynamic trend stereograms of ecological environment (Figure 4):

The whole system's game equilibrium states can thus be achieved by combining the above tripartite replicated dynamic equations. Given the initial states of parameters, the dynamic trend and the evolutionary game system stable strategy of hydropower developers, migrants and ecological environment are shown in Figure 5.

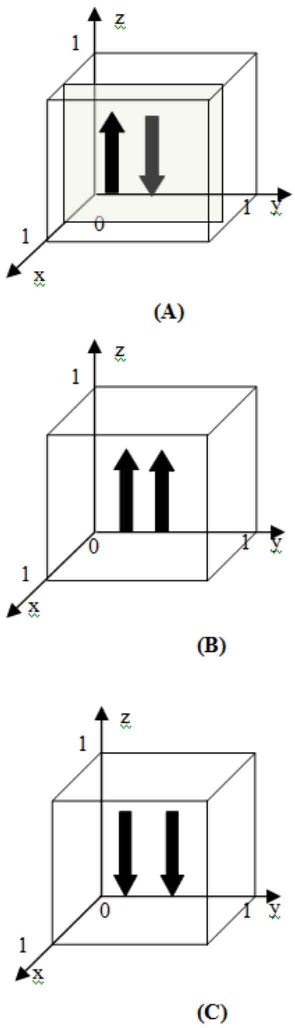
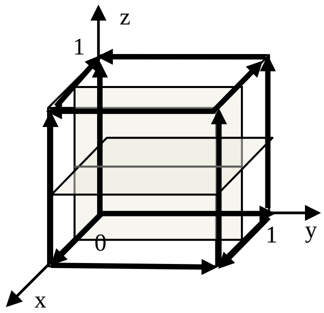


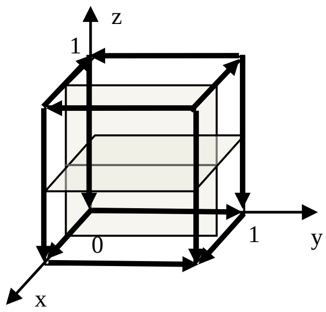
Fig. 4. Trend phase diagram of ecological environment

(A) when $0 < \frac{J+H}{J+H-F} < 1$ **, (B) when** $\frac{J+H}{J+H-F} < 0$ **, (C) when** $\frac{J+H}{J+H-F} > 1$



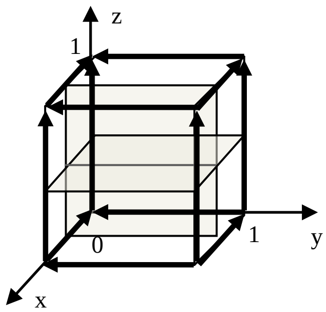
$0<\frac{G-A}{I-E}<1$, $0<1-\frac{C}{K}<1$, $\frac{J+H}{J+H-F}<0$

(1) **Equilibrium point: (0, 0, 1)**



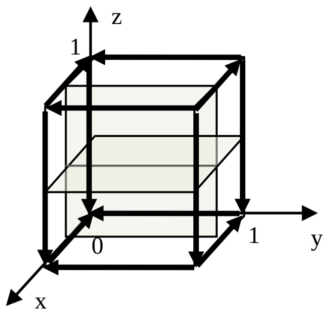
$0<\frac{G-A}{I-E}<1$, $0<1-\frac{C}{K}<1$, $\frac{J+H}{J+H-F}>1$

(2) **Equilibrium point: (1, 1, 0)**



$\frac{G-A}{I-E}<0$, $1-\frac{C}{K}<0$, $\frac{J+H}{J+H-F}<0$

(3) **Equilibrium point: (0, 0, 1)**



$\frac{G-A}{I-E}<0$, $1-\frac{C}{K}<0$, $\frac{J+H}{J+H-F}>1$

(4) **Equilibrium point: (0, 0, 0)**

Fig. 5. Tripartite evolutionary game group replicated dynamic trend stereogram.

According to the diagram, when all three arrows turn into the same point, the tripartite game system reaches equilibrium, *i.e.* achieves stable status, hence find the following three equilibrium conditions for ESS:

The first equilibrium set for ESS is $\frac{G-A}{I-E}<1$, $1-\frac{C}{K}<1$ and $\frac{J+H}{J+H-F}<0$.

In this equilibrium we first have $A-G<E-I$, which indicates that hydropower project will be abandoned because that the excessive return developers obtained from hydropower project (A-G) is not able to cover the environmental maintenance cost developers have to pay (E-I).

Secondly, $K>0$ and $K<C$ there arise involuntary relocation because the compensation migrants get is not enough for resettlement cost.

Third, $J+H<F$. The overall environment is worsened as the compensation for environment is not enough to cover the damage.

Therefore, (0, 0, 1) is the evolutionary stability strategy (ESS) of the evolutionary game system. The trajectory is shown in (1) and (3) of Figure 5. That is S7 (abandonment development, involuntary relocation, environmental degradation), is the final choice for hydropower developers, migration and ecological environment.

The second equilibrium set for ESS is $0<\frac{G-A}{I-E}<1$, $0<1-\frac{C}{K}<1$ and $\frac{J+H}{J+H-F}>1$

In this equilibrium we first have $A>G$, indicating that the current hydropower project provides higher return, A, to developer than other project, which is G. Developer thus will choose to launch this hydropower project.

Secondly, $K>C$ means voluntary relocation. Because that migrants get K as benefit from the ecological environment that is higher than resettlement cost C.

Third, $J+H>F$ indicate an environment improvement as the compensation for environment is enough to cover the damage.

Therefore, (1, 1, 0) is the evolutionary stabilization strategy (ESS) of the evolutionary game system. The trajectory is shown in (2) of Figure 5. S2 (launch development, voluntary relocation, environment improved), is the final choice for hydropower developers, migration and ecological environment.

The third equilibrium set for ESS is $\frac{G-A}{I-E}<0$, $1-\frac{C}{K}<0$ and $\frac{J+H}{J+H-F}>1$

In this equilibrium we first have $G>A$, indicating that developer has higher opportunity cost to launch current hydropower project. Developer will choose to abandon current hydropower project.

Secondly, $C>K$ means involuntary relocation, because that migrants get K as benefit from the ecological environment that is not enough to cover the resettlement cost C.

Third, $J+H>F$ indicate an environment improvement as the compensation for environment is enough to cover the damage.

So (0, 0, 0) is the evolutionary stabilization strategy (ESS) of the evolutionary game system. The trajectory is shown in (4) of Figure 5 (abandon development, involuntary relocation, environment improved), is the final choice for hydropower developers, migration and ecological environment.

4. CONCLUSION AND ENLIGHTENMENT

Through the result of the evolutionary game model of hydropower developer, migration and ecological environment in the hydropower development process, the following conclusions can be drawn:

a) Whether the hydropower developer decides to developing the hydropower project depends on the excess return, depend on the income of the hydroelectric project, the income must higher than the opportunity cost of the fund. On the other hand, whether the hydropower developer develop the hydropower projects also depends on the cost of compensating of the environment, even there is an excess return, hydropower developers will not choose to develop the project if the benefits are not enough to compensate the environment.
b) Migrant would volunteer to resettle for hydropower project only if they can have enough benefit that is higher than the cost of relocation. This benefit can either sourced from migrants moving to a better place or from the environment improvement. due to the relocation of the immigrant, the local ecological environment is protected, immigrants are able to achieve positive effects from good living conditions.
c) Environment compensation from hydropower developers would affect environment deeply. Enough compensation can contribute environment improvement, otherwise, ecological environment is suffered from deterioration brought by the hydropower project. Such ecological environment deterioration would in turn be an obstacle for the hydropower project and would do harm to the downstream residents.

Considering the above conclusion, we provide the following three suggestions:

1) Enhance the supervise force over the construction and operation of hydropower stations. Environmental monitors should be assigned during both the ecological and environmental processes. As the hydropower development process have inevitable negative impacts on the environment, should the compensation is not enough to recover the ecological damage caused by the hydropower project, environment is doomed to suffer [13]. Hence supervision and monitor during hydropower project construction and operation are essential in hydropower developers' effort to reduce the environmental damage. Ecological compensation and project improvement are required whenever hydropower project causes harm to environment. Only by this can maintain the local ecological environment and minimize the ecological damage caused by hydropower project.
2) Improve the migrants regulatory system and optimize the employment service in ecological migration area grant migrants higher economic benefit than their original place [14]. According to the previous analysis, the resettlement cost and compensation are important to achieve voluntary relocation. The higher the economic benefit granted by relocation, the lower resettlement cost, the more voluntary relocation. High economic benefit can be obtained by sound migrants regulatory system. This system should aim to livelihood reconstruction and re-employment through better employment service in ecological migration area.
3) Choose proper basin hydropower exploitation model. There are many factors that affect the environmental cost of one basin hydropower exploitation, among which geology conditions, hydropower project management, and hydropower exploitation model are strongly related to ecological environmental cost of hydropower project [15]. Therefore, an appropriate hydropower exploitation model can reduce the negative environmental effect of hydropower project and even can help to promote the restoration and to improve basin ecological environment. If chose a wrong development method vicious competition may be encouraged and leading a great destructive effect on the ecological environment.

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