

Dongbin HU, Huiwu LIU, Xiaohong CHEN, Yang CHEN

Research on the ecological compensation standard of the basin pollution control project based on evolutionary game theory and by taking Xiangjiang River as a case

© Higher Education Press 2019

Abstract Ecological compensation is a new resource and environment management model. As one of the main areas for implementing ecological compensation policies, basin ecological compensation has become an important measure for encouraging basin pollution control projects and improving the quality of regional economic development. By applying the basic game analysis of evolutionary game theory and building an evolutionary game model with a “reward–punishment” mechanism, this paper compares the interest-related decision-making behaviors of the upstream and downstream stakeholders of basin ecological compensation. By using data on the water quality of Xiangjiang River Basin, this paper calculates the rewards and penalties in different intervals by building a parametric regression mathematical model and employing the local linear regression method. Results show that a decline in water quality should be fined RMB 925500 yuan, an improvement in water quality should be awarded RMB 1227800

yuan, and a deteriorating water quality should be severely fined RMB 5087600 yuan.

Keywords evolutionary game, ecological compensation standard, Xiangjiang River Basin

1 Introduction

The contradiction between the economic society and the natural environment continues to increase along with the development of the economy and society. As the main link that connects natural and social systems, the basin ecosystem hosts the largest social population and the most intensive economic activities. In May 2016, the State Council implemented relevant measures for the ecological compensation of grasslands, farmlands, watersheds, water resources, and soil and established a criteria for identifying “those who benefit from and who are responsible for compensation” to accelerate the establishment of a compensation mechanism wherein the beneficiaries pay a certain sum and the protectors receive compensation (Du et al., 2017). As a policy that involves ecology, economics, and sociology, ecological compensation aims to repair the damaged parts of the ecological environment and conserve what is left unspoiled. By measuring the ecosystem service value, conservation cost, and development opportunity cost among others, this policy mainly adopts a two-pronged approach that combines government administrative means with market regulations to coordinate the social and economic relations among the surrounding economic entities and stockholders in both upstream and downstream regions (Du et al., 2017). The logic of game theory is to maximize the ultimate benefit and to balance the interests of both parties by establishing a reasonable “incentive-constraint” mechanism based on the “*visible hand*” (Du et al., 2017). Both sides of this evolutionary game improve their strategy according to

Received March 6, 2019; accepted April 27, 2019

Dongbin HU, Yang CHEN
School of Business, Resource-Conserving & Environment-Friendly Society and Ecological Civilization 2011 Collaborative Innovation Center of Hunan Province, Central South University, Changsha 410083, China

Huiwu LIU
School of Business, Central South University, Changsha 410083, China

Xiaohong CHEN (✉)
School of Business, Resource-Conserving & Environment-Friendly Society and Ecological Civilization 2011 Collaborative Innovation Center of Hunan Province, Central South University, Changsha 410083, China; Institute of Big Data and Internet Innovation, Hunan University of Technology and Business, Changsha 410205, China
E-mail: cxhcsu@126.com

This work was funded by the Key Project of the National Natural Science Foundation of China (Grant No. 70431006) and the Key Project of Philosophy and Social Sciences Research, Ministry of Education of China (Grant No. 16JZD0013).

different trends and the stability of their environment, among others. The optimal strategy that can maximize the interests of both parties is formulated in a continuous process of decision-making adjustment. By using certain administrative means, the ecological compensation policy internalizes the exterior costs of ecological conservation, induces the beneficiaries of ecological conservation to pay a certain fee, and provides the suppliers of ecological products with a reasonable bonus (Kong, 2010).

Establishing a basin ecological compensation policy not only rationalizes the economy–benefit relationship and the ownership of ecological products in both the upstream and downstream but also propels the upstream regions to develop a green and ecological economic model. However, the formulation of an ecological compensation standard, the evaluation of the compensation effect, and the selection of compensation modes face some key challenges, including the high liquidity of the basin ecological system, the vast coverage area, the number of involved entities, the complex inter-interest relations, and the asymmetry between regional rationality degree and information integrity. As a result, oriented to interest analysis and specific water quality data of the basin, this paper applies evolutionary game theory to study the game process of implementing an ecological compensation policy in the upstream and downstream areas of the Xiangjiang River Basin. This theory and setup can reflect how two game parties adjust their game strategies and seek optimization under practical and non-rational conditions. Moreover, by using the interest income matrix and dynamic replication equation theory, this paper aims to define the condition of the optimized strategy that can provide a theoretical foundation for formulating an ecological compensation standard. This paper also empirically analyzes the key issues faced by the ecological compensation standard of the basin ecological compensation policy.

2 Literature review

The formulation of a compensation standard has become an important topic in ecological compensation research given its direct relationship with the effect of implementing an ecological compensation policy. Previous studies on the ecological compensation standard have mainly focused on determining and quantifying the compensation basis. This basis can be divided into several categories, including the cost, willingness to pay (WTP), value of ecosystem services, environmental resource capacity, and water quality and quantity.

Apart from focusing on a single basis, many scholars have integrated several bases and adopted various methods to examine the ecological compensation standard. In terms of cost, Li and Hu (2007) used the ecological reconstruction equalization cost method to calculate the ecological compensation standard based on the opportunity cost in the

cities of Nanping and Fuzhou, which are located at the upper and lower reaches of Minjiang River, respectively. Meanwhile, Li et al. (2012) obtained the direct cost inputs of water resource improvement in the Dongjiang River Basin by analyzing the water environment restoration and treatment, environmental maintenance, and input costs of ecological construction. In terms of WTP, Amigues et al. (2002) thoroughly examined the residential and governmental WTP and the governmental willingness to accept in the Caronne River basin, whereas Biénabe et al. (2006) proposed a mathematical regression model based on the results of a CE analysis and a questionnaire survey on the WTP of residents of the Costa Rica Basin. By performing a questionnaire survey on the ecological compensation in the Scottish Basin system, Moran et al. (2007) found that residents tend to pay in the form of income taxes when environmental value and social welfare are considered. Villarroya and Puig (2010) found that the ecological compensation standard in a Spanish watershed is much smaller than the damage caused by environmental pollution. In terms of ecosystem service value, Costanza et al. (1997) classified the functions of the Earth's ecosystems into 17 categories, which served as bases for measuring the annual ecological service value generated by the Earth's biosphere. Daily (1997) performed a systematic and comprehensive study on the ecosystem service function that provides a theoretical foundation for investigating ecosystem service value. In terms of environmental resource capacity, Guan et al. (2016) formulated an ecological compensation standard based on total pollutant control. In terms of water quality and quantity, Chen and Zhou (2016) argued that the impact of the dynamic adjustment of hydrological indicators, including water velocity, water quality, and water volume, on the compensation standard must be considered when constructing a basin ecological compensation model. Based on their SWAT model, Yang et al. (2016) formulated an ecological compensation standard from the perspective of green water management. In terms of building a comprehensive standard, Robert and Stenger (2013) discovered that the cost of ecological compensation is nearly similar to the opportunity cost of the corresponding service in a region where a large economic gap is observed within the basin and added that the total compensation cannot make up for the total costs; therefore, the interaction among different ecosystem services must be considered in the assessment.

Although a solid basis for examining ecological compensation standards has been established, previous studies on the formulation of a scientific and effective compensation standard are mostly based on a single theory and have only adopted a single perspective without comprehensively considering all factors related to compensation. Following the compensation policy with a “constraint–reward” mechanism that has been implemented in some regions, this study considers both the

“constraints” and the “rewards” at the same time in evaluating the conditions of a highly accurate ecological compensation optimal strategy in order to provide a scientific basis for formulating an ecological compensation standard.

3 Model construction of ecological compensation evolutionary game theory

3.1 Scenarios and assumptions

This evolutionary game scenario involves two groups of stakeholders, namely, the people from the upper and lower reaches. By taking the actual implementation of ecological compensation into account, the local government, on behalf of the residents in this region, is also regarded as a stakeholder in this scenario. The following assumptions are observed in the analysis:

(1) Under the vigorous macroeconomic regulation and coordination of the provincial government, the local governments of the upper and lower reaches reach an agreement.

(2) By conserving the ecological environment and bearing both the conservation and opportunity costs, the local governments of the upper and lower reaches are directly responsible for the changes in water quality within their jurisdictions and commit themselves to maintaining the water ecological environment of the basin.

(3) When the inspection indicators regulated by the provincial government exceed the standard, the local governments of the upper and lower reaches must pay a fine that is not limited to monetary compensation. Doing so will encourage these local governments to select an optimal strategy in their game of economic development and environment conservation.

The decline in the value of ecosystem service as a result of the fluctuations (or deterioration) in water quality has a lower impact on the economic and social development of the upper reaches compared with those of the lower reaches given that the upper reaches are nestled in upstream areas with a better water quality. Therefore, the upper reaches have great potential to experience economic development at the price of polluting their environment. Meanwhile, the demands of the lower reaches for improving their water resources and ecological environments are significantly higher than those of the upper reaches given that the local life and production in the lower

reaches are closely tied to water security. However, even if conserving the watershed ecological environment has a high economic compensation value, the demand of the lower reaches for improving their ecological environment at the expense of their resources and opportunities is significantly lower than that of the upper reaches. The lower reaches are also inclined to pay economic compensation for environment conservation products to the upper reaches as a way of encouraging the latter to conserve the water environment through economic means. Therefore, the upper reaches have two options to conserve the water environment, namely, the “conservation” and “non-conservation” strategies. The lower reaches also have these two options when planning to conserve the water ecological environment at the expense of their economic development prospects.

Assume that the opportunity cost to conserve the ecological environment in the upper reaches is C , the ecological benefit obtained by conserving the environment in the upper reaches is S , the value of compensation paid by the lower reaches to the upper reaches is P , the total revenue obtained by the upper reaches by conserving the environment is Q_1 , and the total revenue obtained by the upper reaches without conserving the environment is Q_2 . The local governments in the upper and lower reaches that adopt the conservation strategy will receive the reward J from the upper government, while those governments that do not adopt such strategy will be fined F by the upper government. The revenue payment matrix for the local governments of the upper and lower reaches in this context is shown in Table 1.

3.2 Static game analysis

In the static game, both the upper and lower reaches are completely rational and independent about their potential strategies and the current situation of their counterparts. The revenue function in the game process can be known from the revenue payment matrix, but both parties make transparent decisions, that is, one side cannot learn the decision of the other in advance. Therefore, according to the revenue payment matrix, for the local government of the upper reaches, when $2(S - C) + J + F > 0$ or $J + F + 2(S - C) > 0$, the conservation strategy is the optimal option. Similarly, for the local government of the lower reaches, when $Q_1 < Q_2$, the conservation strategy is the optimal option. In this case, when the components of revenue are changed, the optimal strategy will change accordingly,

Table 1 Revenue payment matrix for the local governments of the upper and lower reaches

Upper reaches	Lower reaches	
	Conservation	Non-conservation
Conservation	$(P + S - S + J, Q_1 - P + J)$	$(S - C + J, Q_1 - F)$
Non-conservation	$(C + P - S - F, Q_2 - P - J)$	$(C - S - F, Q_2 - F)$

thereby breaking the balance of the game strategy and failing to realize social benefits. Under such circumstance, the upper government must conduct a macro control to coordinate and encourage the local governments of the upper and lower reaches to seek the most optimal environment conservation strategy.

3.3 Evolutionary dynamic game analysis of basin ecological compensation under the “reward–penalty” mechanism

The proportions of conservation and non-conservations made by the local government of the upper reaches are assumed to be x and $1-x$, respectively. When x is 1, the local government of the upper reaches decides to “conserve”; otherwise, the local government decides to “non-serve”. Meanwhile, y and $1-y$ denote the proportions of compensation and non-compensation made by the local government of the lower reaches, respectively. When y is 1, the local government decides to “compensate”; otherwise, the local government decides to “non-compensate.” U_{11} and U_{12} denote the expected return values when the local government of the upper reaches adopts conservation and non-conservation strategies, respectively. The average return of the local government of the upper reaches is recorded as \bar{U}_1 . Therefore,

$$U_{11} = y(p + s - c + J) + (1 - y)(s - c + J), \quad (1)$$

$$U_{12} = y(c + p - s - F) + (1 - y)(c - s), \quad (2)$$

$$\bar{U}_1 = xU_{11} + (1 - x)U_{12} = x(1 - x)(U_{11} - U_{12}). \quad (3)$$

The decision making of the local government of the upper reaches for basin environment conservation can then be expressed as

$$F(x) = \frac{dx}{dt} = x(U_{11} - \bar{U}_1) = x(1 - x)(yF + 2(s - c) + J). \quad (4)$$

The function of this strategy is illustrated in Fig. 1. When x ranges from 0 to 1, the function has a 0 point, which indicates that two stable states are available regardless of the strategy adopted by the local government of the upper reaches. However, the trend of this function is liable to non-conservation strategy; when the value x is 1, the whole system is in a highly stable state.

In addition, provided that

$$\frac{dF(x)}{dx} = (1 - 2x)(yF + 2(s - c) + J) < 0, \quad (5)$$

when $x \in (0.5, 1)$, $(yF + 2(s - c) + J) > 0$, and we have $y > \frac{2(c - s) - J}{F}$. Therefore, when the local government of

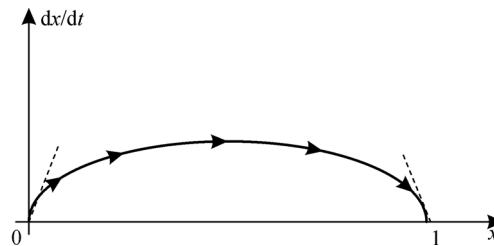


Fig. 1 Dynamic replication function of the decision strategy.

the upper reaches is inclined to adopt the conservation strategy, then the probability for the local government of the lower reaches to adopt the conservation strategy will be greater than $\frac{2(c - s) - J}{F}$. When the values of F and J increase, that is, when the degree of the reward and penalty increases, the probability for the local government of lower reaches to adopt a conservation strategy increases as well. Therefore, the game between the local governments of the upper and of lower reaches shifts toward the (conservation, conservation) strategy combination.

The expected returns of the local government when adopting the conservation and non-conservation strategies are denoted by U_{21} and U_{22} , respectively, while the average expected return value is denoted by \bar{U}_2 .

$$U_{21} = x(Q_1 - p + J) + (1 - x)(Q_2 - p + J), \quad (6)$$

$$U_{22} = x(Q_1 - F) + (1 - x)Q_2, \quad (7)$$

$$\bar{U}_2 = yU_{21} + (1 - y)U_{22} = y(1 - y)(U_{21} - U_{22}). \quad (8)$$

The dynamic replication equation for the decision making of this local government on basin environment conservation can be expressed as

$$F(y) = \frac{dy}{dt} = y(U_{21} - \bar{U}_2) = y(1 - y)(xF - p + J). \quad (9)$$

Let $F(y) = 0 \Rightarrow y = 0, 1$. A steady state can be observed at 0, 1, and let

$$\frac{dF(y)}{dy} = (1 - 2y)(xF - p + J) < 0. \quad (10)$$

When $y \in (0.5, 1)$, $(xF - p + J) > 0$, and we have $x > \frac{p - J}{F}$. When F is greater than J , that is, when the penalty is greater, $\frac{p - J}{F}$ tends to decrease. Meanwhile, when J is greater than F , that is, when the reward is greater, $\frac{p - J}{F}$ tends to increase. This variation trend implies that reward plays an active role in shifting the game toward the (conservation, conservation) strategy combination. When F and J are in a reasonable state, this strategy combination

can approach or even reach the optimal state of social benefits.

By using the Jacobi matrix local equilibrium point proposed by Friedman, the replication dynamic equations of the local governments of the upper and of lower reaches constitute the replication dynamic system of evolutionary game, which Jacobi matrix B can be expressed as

$$\begin{aligned}
 B &= \begin{bmatrix} \frac{\partial F(x)}{\partial x} & \frac{\partial F(x)}{\partial y} \\ \frac{\partial F(y)}{\partial x} & \frac{\partial F(y)}{\partial y} \end{bmatrix} \\
 &= \begin{bmatrix} (1-2x)(yF + 2(s-c) + J) & x(1-x)F \\ y(1-y)F & (1-2y)(xF - p + J) \end{bmatrix}.
 \end{aligned} \tag{11}$$

The determinant of matrix B is

$$\begin{aligned}
 \det(B) &= (1-2x)(1-2y)(yF + 2(s-c) + J) \\
 &\quad \times (xF - p + J) - xyF^2(1-x)(1-y),
 \end{aligned} \tag{12}$$

while its trace is

$$\begin{aligned}
 tr.B &= (1-2x)(yF + 2(s-c) + J) + (1-2y) \\
 &\quad \times (xF - p + J).
 \end{aligned} \tag{13}$$

Friedman argued that if the strategy (x, y) is a stable equilibrium strategy, then its Jacobi matrix B satisfies $\det B > 0$ and $tr.B < 0$. If the optimal strategy reaches a relatively stable state, then both x and y take the value of 1, and the following conditions must be met:

$$\begin{cases} \det.B = (F + 2(s-c) + J)(F - p - J) > 0 \\ tr.B = F + 2(s-c) + 2J - p > 0 \end{cases} \\
 \Rightarrow \begin{cases} F + J > p \\ F + J > 2(c-s) \end{cases}.$$

A smaller critical value for the sum of penalty and reward can be derived from these two equations. After the interest game between the local governments of the upper and of lower reaches, the above critical value is the same as the critical value obtained under the existence condition, thereby providing not only the basis for formulating an ecological compensation standard but also for identifying its effects. This trend also implies that when formulating the ecological compensation standard, impartial reward and penalty can influence the strategies of the local governments of the upper and of lower reaches when formulating an ecological compensation standard and then influence their implementation of ecological compensation policies.

4 Case study of Xiangjiang River Basin

4.1 Heavy metals comprehensive control project and ecological compensation status

Located in the southcentral part of China, the Xiangjiang River Basin is the largest river in the Hunan Province and is considered an important tributary of the Yangtze River. The upper reaches of this basin is underdeveloped, while its lower reaches, specifically the Changsha–Zhuzhou–Xiangtan region where the urbanization rate reaches over 70%, is moderately developed. However, along with the continued development of the economy and society, the Xiangjiang River Basin confronts an increasing rate of heavy metal contamination and decreasing ecosystem services value given the unreasonable layout of its surrounding industries. The damage to the ecological environment also hinders the harmonious and healthy development of the society and economy in the region. Therefore, a reasonable compensation plan and a scientific compensation standard must be formulated to encourage the launch of a comprehensive heavy metals control project in various areas of the Xiangjiang River Basin. Further improving the ecological compensation mechanism of the Xiangjiang River Basin plays a pivotal role not only in controlling the heavy metals pollution and improving the ecosystem environment of this basin but also in meeting the demands for a harmonious and unified development between the economy and society.

The lower reaches of the Xiangjiang River Basin (Changsha–Zhuzhou–Xiangtan region and Yueyang City) are more developed than its upper reaches (Chenzhou City and Yongzhou City). This ecological compensation model is in line with the basin ecological compensation model where “the lower reaches are beneficiaries while the upper reaches are victims”. To address the heavy metals pollution and facilitate the implementation of a comprehensive control project for heavy metals in the area, in 2014, the Hunan provincial government explored a lateral basin compensation to improve the water environment of the Xiangjiang River Basin and then rewarded or fined the relevant parties according to the water quantity and quality assessment results collected from various cities and counties of the basin. In 2015 and 2016, the sum of these rewards and penalties has reached 60 million yuan (Wang and Liu, 2017). After the implementation of this policy, the water quality monitoring data for the Xiangjiang River Basin show that the heavy metals pollution is gradually alleviating and that the ecological carrying capacity of the basin is gradually recovering. As reflected in its ecological compensation benefit scores, the Xiangjiang River Basin has greatly benefitted from the implementation of this policy in 2014 (Tian and Dai, 2016). After the promulgation of this policy, the comprehensive control project for heavy metals has

yielded remarkable outcomes and the ecological compensation benefits for the Xiangjiang River Basin have significantly increased. The present ecological compensation scenarios in this region are mainly concentrated on basin ecological compensation while the compensation method is limited to monetary compensation. Given the lack of fund channels, the compensation is often made by different government levels through fiscal transfer payments. By referring to the water quality monitoring data and some economic indicators of the Xiangjiang River Basin from 2005 to 2016, this paper calculates the economic costs of various water quality scenarios based on the environmental and economic cost conversion relationship and then formulates some incentives or penalties to provide a scientific and effective basis for formulating an ecological compensation standard in the region.

4.2 Parametric local regression econometric mathematical model

Based on the evolutionary game theory model of river basin ecological compensation with the “reward–punishment” mechanism, this paper uses the water quality data of the upper reaches of the Xiangjiang River Basin to construct a parametric local regression econometric mathematical model for the local regression parameter measurement of the ecological compensation of the basin. The local linear regression method is applied to study the intrinsic relationship between the water quality of the Xiangjiang River Basin and its key social and economic development indicators. This approach can reveal the

marginal effects of the water quality and economic development of the region, and the findings can be used to analyze the relationship between water quality index and economic indicators and to calculate the cost criteria relationship between the environment and economy. To facilitate the analysis, the water quality evaluation categories are initially quantified before performing a comprehensive evaluation. Following the “a better water quality means a smaller monitoring value” principle of the method for calculating water quality, the five water quality classifications are weighted as shown in Table 2. By using the water quality monitoring data of the Xiangjiang River Basin from 2005 to 2016, the quarterly average water quality of the upper reaches is calculated and the water quality changes in the entire area are then determined. Figure 2 shows that the water quality of the Xiangjiang River Basin has rapidly improved in recent years and that the rate of improvement has accelerated every year. Following a short-term period of stabilization in 2014, the year-on-year growth rates in water quality improvement have significantly increased in 2015 and 2016. These findings show that the ecological compensation policy, which was implemented in Hunan Province in 2014, has a significant positive impact on the water quality of the Xiangjiang River Basin.

If the parametric regression model contains only one basic variable, then the basic analytical expression of the mathematical model is

Table 2 Weights of the water quality classifications

Classification	Class I	Class II	Class III	Class IV	Class V
Weights	1	2	3	4	5

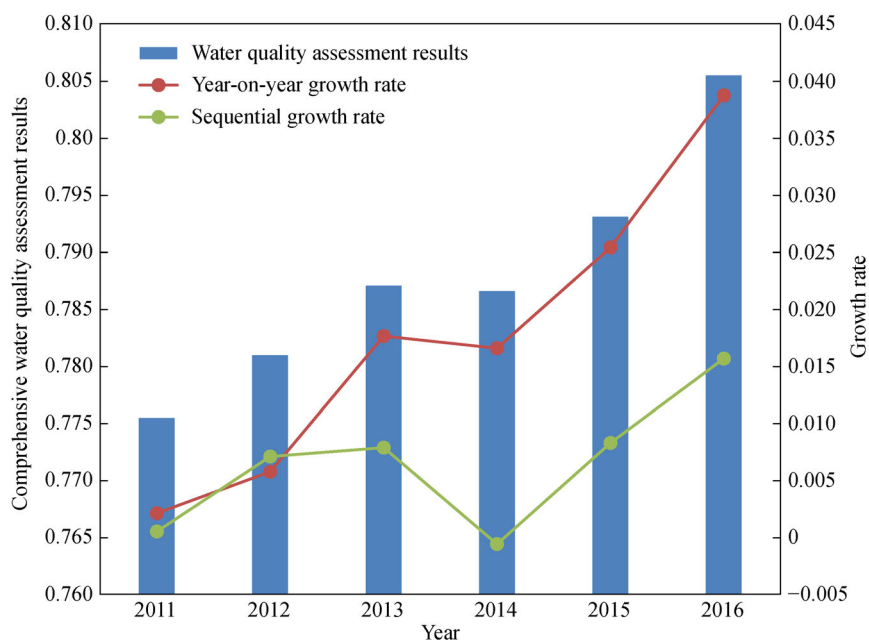


Fig. 2 Variation in water quality in the upper reaches of the Xiangjiang River Basin.

$$G = f(x) + \varepsilon.$$

The parameter regression model for water quality and GDP can be expressed as

$$G = f(WQ) + \varepsilon.$$

According to previous studies, the economic and social development and environmental pollution levels of China generally show an inverted U-shape relationship. Given that the cubic function demonstrates the best fit to the data, this function is employed to fit the aforementioned U-shaped relationship. The mathematical model is built as follows:

$$G = f(WQ) = aWQ^3 + bWQ^2 + cWQ + d + \delta$$

(a, b, c, d are coefficients, δ is error parameter),

where $G = f(WQ)$ and WQ denote the quarterly GDP and average annual water quality of the upper reaches (Chenzhou and Yongzhou) from 2005 to 2016 and are treated as the dependent and independent variables in the cubic function, respectively. The graph of the function after fitting is shown in Fig. 3. The strength of the relationship between $G = f(WQ)$ and WQ can be seen in its marginal effect, which mainly reflects the cost relationship between the environmental (represented by water quality) and economic indicators (represented by GDP). Therefore, following opportunity cost theory, this paper adopts the local linear regression method to calculate the marginal effect of average water quality on the quarterly GDP of the upper reaches and to determine the relationship between the water quality and economic development of the Xiangjiang River Basin.

4.3 Analysis of the regression results of the ecological compensation model

Given that the marginal effect follows the changes in the independent variables, a local linear regression is

performed based on a point-by-point sample estimation. A total of 10 to 20 monitoring sites are available in the upper reaches of the Xiangjiang River Basin. To accurately reflect the marginal utility of water quality for GDP at a certain level, the marginal effect value for a single sample point is obtained before computing the average marker effect values for the sample points at all monitoring sites. According to the fitting function, the relations between water quality and local GDP show different directions and strengths across different intervals. The marginal effect value in interval (0, 3) represents the economic cost of reducing the water quality score or the amount of penalty for a decline in water quality. In a more segmented way, the water quality in interval (1, 2) denotes that the water quality has improved and that the reward factor produces the greatest impact. Different kernel functions are used to find the marginal effect values in intervals (1, 2), (2, 3), (0, 3), and so on. However, given its relatively poor water quality, interval mainly exceeds the standard penalty, and its marginal utility value is taken as the excess penalty amount.

Table 3 shows that the marginal effect value of water quality for GDP is 925500 yuan, which means that when the average water quality is reduced by one unit, then the upper reaches lose 925500 yuan of their GDP for conserving or treating their water bodies. This amount represents the opportunity cost of conserving or harnessing water bodies in this interval. From the perspective of subdivision, when the water quality is at interval (1, 2), the a one unit reduction in water quality corresponds to a 1.22728 million yuan loss in the GDP of the upper reaches for conserving or treating water bodies. Table 3 also shows

Table 3 Marginal utility of water quality for GDP at different intervals

Interval	Marginal effect value (in 10000 yuan)
(1, 2)	122.728
(2, 3)	-508.76
(0, 3)	-92.55

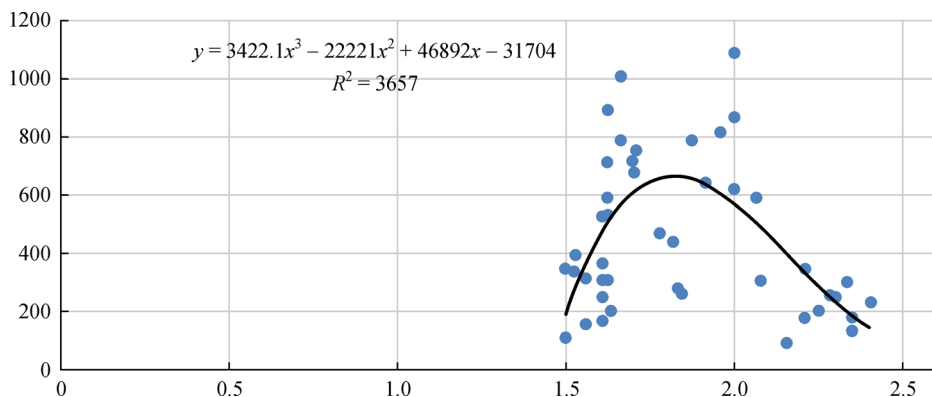


Fig. 3 Function graph of $f(WQ)$.

that when the marginal effect value is positive, the reward factor greatly affects the decision making. When the water quality is at interval (2, 3) and the marginal effect value is negative, a one unit reduction in water quality corresponds to a 5.087 million yuan loss in the GDP of the upper reaches. Under such circumstance, the excessive penalty factor can greatly affect the decision making. According to the latest ecological compensation standard for the Xiangjiang River main stream based on monthly calculation of Hunan Province, a region whose assessment factors for all exit assessment sections reach the second category will be awarded 500000 yuan. Therefore, when the WQ is at interval (1, 2), the reward amount will be lower than the theoretical reward compensation amount proposed in this study. Meanwhile, when the water quality of the water exit section is higher by only one grade compared with that of the entry section, the reward will be 1 million yuan. If this grade is lowered, then the corresponding penalty will be 1.5 million yuan. In sum, the penalty and reward intensities are greater than the theoretical reward compensation amount of 925500 yuan. If the water quality deterioration level is high, then from the better water quality interval (the upstream water quality is generally better) to the poor water quality interval, the penalty will be 5 million yuan. Compared with the marginal utility value of the interval (2,3) that corresponds to the deterioration in water quality, the policy demonstrates a better reward behavior, except for the lack of incentives in the excellent water quality range. The intensity of the interval reward and punishment is consistent with the experimental results. Figure 2 shows that the latest water quality assessment results for the Xiangjiang River Basin have maintained a steady and positive change, thereby indicating that the environmental conservation and quality measures of the basin have begun to stand out. According to relevant data, the total amount of rewards and punishments for the Xiangjiang River Basin in 2015 and 2016 have exceeded 60 million yuan, and the ecological compensation policy has increasingly played a pivotal role in recovering and conserving its water environment.

5 Conclusions and policy recommendations

In light of the opportunity cost, externality, and synergy compensation of the upper and lower reaches, a mathematical model with a “reward–penalty” mechanism is developed based on evolutionary game theory to formulate an ecological compensation standard for the Xiangjiang River Basin. A similar water quality assessment system is also introduced for both the upper and lower reaches of the basin. If the water quality of a certain area reaches a specified level, then rewards will be given. Otherwise, the area will be given an “economic penalty.” The entire ecological compensation process is coordinated and macro-controlled by the higher-level government. This

process differs from the traditional ecological compensation model of “the lower reaches compensate the upper reaches”. Holding both reaches accountable for the water quality in the region can further highlight the identity and fairness of ecological compensation policies and encourage the local governments of these reaches to adopt practical measures when implementing a comprehensive control project for heavy metals pollution in the Xiangjiang River Basin to effectively address its heavy metals pollution problem.

Given that both the comprehensive control project for heavy metals pollution and the formulation of an ecological compensation policy for Xiangjiang River Basin are systematic in nature, the ecological environment conservation in this area depends on the implementation of various policies. The ecological compensation policy is an important part of the current green system enforced by the government. Therefore, the following points warrant further attention:

(1) The ecological compensation policy implementation needs not only the practical work of the local governments of the upper and lower reaches but also the dynamic supervision of the higher-level government. The effectiveness of the conservation and governance efforts in these reaches also needs to be evaluated. Those areas that obtain poor assessment results may be given economic penalties by the higher-level government by following a combination of different approaches, while those areas that receive excellent assessment results need to be given some economic rewards. This “reward–penalty” coordinated compensation mechanism carries great significance in effectively promoting social equity and implementing ecological compensation policies in both the upper and lower reaches.

(2) Under the “reward–penalty” coordinated supervision mechanism, the local governments of the upper and of lower reaches must optimize their policy making and strive to improve the chances for a conservation strategy to be implemented within their areas. The theoretical model of ecological compensation basin based on evolutionary game theory strikes a balance when both reaches adopt a conservation strategy. Together with the reward–penalty scheme of the higher-level government, such dynamic system shifts toward the equilibrium point of the “conservation–conservation” strategy. In sum, adopting the conservation strategy will alleviate the economic costs and accelerate a green and harmonious development in the region.

(3) By taking the Xiangjiang River Basin as an example, the theoretical model of ecological compensation based on evolutionary game theory performs a parameter estimation for the empirical analysis. Based on the water quality and GDP of the Xiangjiang River Basin from 2010 to 2016, the marginal cost across different intervals is calculated and the following conclusions are drawn. Under the simple interval, the amount of reward and penalty is close to the

current ecological compensation standard of Hunan Province. One huge difference is that the interval whose water quality reaches the second category will be awarded 500000 yuan in the current ecological compensation standard but will be awarded 1227280 yuan according to the equilibrium stability point calculated in this work. Therefore, the extant incentive program for water quality in Hunan Province warrants further improvement, and the role of such incentives in the implementation of ecological compensation policies must be further amplified.

The basin pollution control project research is a relatively rigorous and complex project that involves economic, social cost, and environmental perspectives given the interaction between the human social and natural environment systems. The formulation of a compensation standard for the upper and lower reaches is linked to a wide range of aspects, and the available options for compensation are equally wide ranging. Therefore, future studies must focus on other factors that may affect the ecological compensation standard, optimize the theoretical model of such standard, and enrich the dependent variable in an empirical analysis to formulate a highly effective, comprehensive, and reasonable ecological compensation standard for the Xiangjiang River Basin.

References

- Amigues J P, Boulatoff C, Desaignes B, Gauthier C, Keith J E (2002). The benefits and costs of riparian analysis habitat preservation: a willingness to accept/willingness to pay contingent valuation approach. *Ecological Economics*, 43(1): 17–31
- Biénabe E, Hearne R R (2006). Public preferences for biodiversity conservation and scenic beauty within a framework of environmental services payments. *Forest Policy and Economics*, 9(4): 335–348
- Chen Y P, Zhou Y (2016). Estimation of watershed ecological compensation standard based on water quality and water volume: Taking Ningxia Hui Autonomous Region in the Yellow River Basin as an example. *Chinese Journal of Agricultural Resources and Regional Planning*, 37(4): 119–126
- Costanza R, D'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neil R V, Paruelo J, Raskin R G, Sutton P, van den Belt M (1997). The value of the world's ecosystem services and natural capital. *Nature*, 387(15): 253–260
- Daily G C (1997). *Nature's Services: Societal Dependence on Natural Ecosystems*. Washington DC: Island Press
- Du Q Q, Zhang R H, Ma B (2017). Study on the estimation of ecosystem service value and ecological compensation mechanism: Taking Huairou District of Beijing as an example. *Ecological Economics*, 33(11): 146–152, 176
- Guan X J, Liu W K, Chen M Y (2016). Study on the ecological compensation standard for river basin water environment based on total pollutants control. *Ecological Indicators*, 69: 446–452
- Kong F B (2010). *China's Ecological Compensation Mechanism: Theory, Practice and Policy Design*. Beijing: China Environmental Science Press
- Li C F, Zhang Y Y, Zhao G C, Mo L J (2014). Study on watershed ecological compensation based on evolutionary game theory: taking Taihu Lake Basin as an example. *China Population Resources and Environment*, 24(1): 171–176
- Li Y, Peng X C, Zhou L X (2012). *Exploration of Watershed Ecological Compensation and Pollution Compensation Policies and Mechanisms: Taking Dongjiang River Basin as An Example*. Beijing: Economy & Management Publishing House
- Li Y S, Hu Y (2007). Analysis of interregional ecological benefit compensation standard in Minjiang River Basin. *Research of Agricultural Modernization*, 28(3): 327–329 (in Chinese)
- Moran D, Mcvittie A, Allcroft D J, Elston D A (2007). Quantifying public preferences for agri-environmental policy in Scotland: a comparison of methods. *Ecological Economics*, 63(1): 42–53
- Robert N, Stenger A (2013). Can payments solve the problem of undersupply of ecosystem services? *Forest Policy and Economics*, 35(4): 83–91
- Tian Y X, Dai Y (2016). Research on performance evaluation of watershed ecological compensation mechanism: taking Xiangjiang River as an Example. *Business (Atlanta, GA)*, 2016(28): 104–105
- Villarroya A, Puig J (2010). Ecological compensation and environmental impact assessment in Spain. *Environmental Impact Assessment Review*, 30(6): 357–362
- Wang L, Liu T (2017). Research on compensation of ecological protection in Dongting Lake. *China Economic and Trade Guide (Theoretical Edition)*, 2017(35): 15–17
- Xu D W, Chang L, Hou T S, Zhao Y F (2012). Calculation of watershed ecological compensation standard based on WTP and WTA: a case study in Liaohe River Basin. *Journal of Resources Science*, 34(7): 1354–1361
- Yang G S, Huang J S, Li J, Yin W (2016). Study on ecological compensation standard of green water management based on SWAT model. *Journal of Hydraulic Engineering*, 47(6): 809–815