Working Paper for

Southern Agricultural Economics Association (SAEA) 52nd Annual Meeting, February 1-4, 2020, Louisville, Kentucky.

Innovating Ecological Compensation System for Water Resources Management Reform

Qiongxia Qin Michael Reed Sayed Saghaian

(Agricultural Economics University of Kentucky)

Abstract: The goal of this research is to construct a new transboundary ecological compensation system in order to achieve three objectives: increase participant's welfare improvement, upgrade the ecological environment, and provide effective financial support. This system is a hybrid of two transboundary compensation models that involves local government: the bidirectional dynamic compensation model and the chain ecological compensation model. These models are used to match the incentive mechanism of compensation and punishment according to dynamic classified water quality, which is a hierarchical compensation mechanism. The effectiveness of this new theoretical compensation system is demonstrated by a theoretical proof and a numerical simulation from a cross-border compensation practice of the Zhejiang Xin'an River in China. The study finds that: (1) compared with the traditional two-way static compensation mechanism, the hybrid transboundary ecological compensation mechanisms have obvious Pareto welfare improvements. (2) The dynamic bidirectional compensation mechanism can stimulate the protection of water resources and achieve continuous improvement of water quality. (3) The chain ecological compensation system enhances the downstream ecological compensation payment capacity and can further extend the water protection chain. This research extends the cross-border ecological compensation mechanism and promotes the development of the compensation system design.

Key words: Transboundary; Dynamic Bidirectional; Chain; Ecological Compensation

JEL Codes: Q57 D23 H23 D04

Contact: Qiongxia Qin (Jenny)

Email:qiongxiaqin@uky.edu; jttqqx@163.com

Mobil: 859-699-2505; 00886-13675858029

University of Kentucky; Zhejiang Sci-tech University, Hangzhou, China

1. Introduction

Innovating ecological compensation systems are an important part of water resources management reform. Water pollution and shortages in river basins have become a serious challenge faced by many countries of the world. These problems have been particularly prominent in China's rapid economic development. Fortunately, China is ready to promote the construction of a comprehensive ecological scheme to deal with water pollution and shortages throughout the country（http://english.www.gov.cn/19thcpccongress/）. However, budget shortages and inertia in the current water management system have slowed the practice of ecological compensation in China. There are three development trends in ecological compensation theory that are relevant to cross-border systems: First, it follows the Pigou model to internalize cross-border issues by optimizing administrative jurisdiction. Second, it follows the principal of "polluters-pay and beneficiaries-compensate" to constitute a market-oriented governance system. Third, it tries to transcend the Coase and Pigou model to construct a voluntary governance model with conditional compensation for environmental benefit service providers (Muradian et al., 2010; Tacconi, 2012)

Ecological compensation has been implemented in accordance with the traditional Pigou or Coase model to correct externalities. The Pigou model follows a government-led path and focuses on the government compensating or taxing resource stakeholders based on their behaviors. The Coase model specifies that ecological compensation follows the principle of "polluters-pay and beneficiaries-compensate" to constitute a market-oriented governance system. There are also two paths in the corresponding pilot reforms launched in China: one is to internalize the cross-border problems by optimizing the administrative jurisdiction with Pigou-style compensation; the other is to combine "who benefits, who compensates" and "who damages, who compensates" into a compound rule to form the governance system.

The implementation of many cross-border ecological compensation pilot projects by the first path is not going smoothly, such as the pilot project of Qiantang River, Dong River, Yangzi River, Yellow River and Tai Lake Basin. It is true that the internalization of cross-border issues by using the jurisdiction of higher administrative governance can effectively promote the construction of a cross-border ecological compensation system. But there are still problems in establishing a broad and efficient ecological compensation system under the leadership of the higher government. Watershed management is often unable to deal with problems such as pollution punishment because of the lack of administrative jurisdiction. Therefore, government administrative intervention or watershed management on the first reform path does not necessarily achieve extensive and effective institutional arrangements.

The second path of reform seems much better than the first in achieving some preliminary positive results. The ecological compensation mechanism for the Xin'an River along the Zhejiang and Anhui border is based on the compound rule. Cross-border ecological compensation began in 2011 and is led by the Ministry of Finance and the Ministry of Environmental Protection, Zhejiang and Anhui provinces formally signed the first trans-provincial river basin ecological compensation agreement in October 2011 with a term of three years. Compensation funds were mainly from the central government but were supplemented by local government funding. The total annual compensation fund was 500 million Yuan (1.5 billion Yuan in total), with 300 million Yuan from the central government and 100 million Yuan from Zhejiang and Anhui provinces.

The compensation mechanism stipulated that if the annual water quality of the transboundary section met the designated standard, Zhejiang would compensate 100 million Yuan to Anhui Province, otherwise Anhui would pay 100 million Yuan to Zhejiang Province. Regardless of the above situation, the central government would allocate all 300 million Yuan to Anhui Province for the adjustment of its industrial structure, the optimization of its industrial layout, and the comprehensive management of its basin, water pollution control and ecological environment protection. This static compensation agreement, which was launched by the central government, satisfies the compound rules of "who benefits, who compensates" and "who damages, who compensates" -- a bidirectional static compensation model. Since the beginning of the project in 2012, the overall water quality of the Xin'an River Basin has improved every year, and the water quality in the cross-border area has reached the designated standards, so the compensation conditions have been reached each year.

The second round of this project continued in 2015 under the higher standard of ecosystem improvement. The three-year compensation fund continued at 1.5 billion Yuan, but the central fund was 400 million for the first year, 300 million for the second year and 200 million for the third year. The annual fund of the two provinces increased to 200 million Yuan. Meanwhile, the standard of water quality assessment was raised by 7%. During these two rounds of agreement, the transboundary water quality met standards fully and Anhui received its full compensation. The third round of the project was officially implemented at the end of 2018, and the water quality standard increased further.

Because the Xin'an River pilot project involves central government and local government funding, it is not a real Coase model, but a hybrid mechanism combining the Pigou model. Muradian et al. (2010) holds that the ecological compensation mechanism under Coase model is too theoretical and when market uncertainty, information costs, unclear property rights and other factors are considered, the public goods management model should be used to deal with the ecological compensation problem. In fact, the public goods management model is a mixture of Coase and Pigou models.

There is also a third type of classical ecological compensation theory that states that ecological compensation should be a payment for environmental services (PES) as a market transaction. Yet under state-ownership of water resources in China, this traditional western theoretical framework is inconsistent with the Chinese reality. The Xin'an River pilot project is a two-way static compensation under the control of local and central governments and is confined to the cross-border part of the watershed. As a static compensation system, it does not effectively combine the scale of ecological compensation with the state of ecological protection, and has a ceiling effect on water quality improvement. Thus, these compensation practices are still too simple, fragmented and static at the local and provincial borders.

The basin is a complete ecosystem with strong integrity and high connection that transcends the local boundary and even the provincial boundary. Fragmented ecological compensation fundamentally break the integrity of the basin. The simplicity and static nature of ecological compensation cannot effectively solve the complex ecological environment problems of the upper and lower reaches of the whole basin. Therefore, the difficulty in solving the ecological compensation problem within the whole watershed has become the focus of concern for Chinese governments at all levels. It is an urgent topic to be studied because the original static and fragemented ecological compensation system is flawed and needs change.

This gives rise to two important theoretical and practical problems: how can an effective hybrid mechanism be constructed with ecological compensation with incomplete markets? How can the practice of cross-border ecological compensation in China be combined and optimize and improve the existing compensation mechanism? The complexity of the whole watershed environment makes the innovation of a diversified ecological compensation mechanism especially necessary. Therefore, according to the theory of cross-border ecological compensation and the two-way static compensation practice of the Xinanjiang River in Zhejiang and Anhui provinces in China, this paper designs two kinds of hybrid mechanisms for ecological compensation between transboundary local governments in order to achieve the triple objectives of increasing participant's welfare, upgrading the ecological environment, and improving financial support.

The remainder of the paper is organized as follows: section 2 reviews the literature and clarifies to marginal contribution of the present study. The basic theoretical models and basic hypothesis of the bidirectional dynamic and chain ecological compensation mechanism are presented in section 3. Section 4 focuses on the theoretical analysis and proof of the basic hypothesis. A numerical simulation analysis based on the cross-border compensation practice of Xinan River is used to verify the basic hypothesis proposed in the theoretical model. The final section is the conclusions.

2. Literature review

The study of ecological compensation can be traced to the market externality theory put forward by Marshal (1890). The existence of an externality is the key to understanding ecological compensation in the river basin. The strategies to overcome the externality include two types of models which are attributed to Pigou (1920) and Coase (1960). Pigou proposed taxation to solve externalities, and Coase preferred to use property right transactions. The Pigou model emphasizes a government-led mechanism to internalizes the externalities through taxation, while the Coase model uses market negotiations to govern the externalities. However, in the framework of the Pigou tax, if there is information asymmetry, this method has limitations due to the inability to accurately set the tax rate (Ng, 2016; Guoqiang Tian, 2016). In Coase model, voluntary negotiation based on the externality will lead to Pareto optimal results, while in cross-border ecological compensation, the approach which combines "who benefits, who compensates" and "who damages, who compensates" (the two-way compound mechanism), can achieve more effective institutional arrangements (Manhong Shen, 2015).

This research focuses on the mechanism of PES (Payment for Environmental Services) and its optimization (Muradian et al., 2010; Tacconi, 2012). Westman (1977) brought ecosystem function into a utilitarian analysis framework for the first time, so that ecological compensation entered the functional ecosystem service stage characterized by utilitarianism

(Ehrlich et al., 1981). Costanza et al. (1997) further introduced the monetization of ecosystem functions which marks the beginning of the study on the value of ecosystem services (Daily, 1997). The theory of ecosystem service value, which developed at the beginning of the 21st century, began to regard ecosystem services as a commodity and cross-border ecological compensation was advocated through the market mechanism. Thus, the PES mechanism was born. (Wunder, 2006; Knetsch, 2007; Engel et al., 2008). Since the 2010s, academic circles have carried on optimization research on the PES mechanism (Muradian et al., 2010; Gastineau & Taugourdeau, 2014; Chan et al., 2017; Smith & Day，2018).

At present, the research on the PES mechanism focuses on the subject and object of compensation, compensation method, compensation efficiency and evaluation. In the study of compensation subject, some literature advocate the implementation of a market-orientated PES mechanism (Wunder, 2006; Engel, et al., 2008). However, Muradian et al. (2010) think that the compensation mechanism for pure market subjects is not feasible and even consider it a "PES fantasy" (Robert & Bram, 2017). Thus, some scholars have explored the hybrid compensation model with government-led and market-oriented elements (Hecken et al., 2015; Hauskcost, 2017). Manhong Shen et al. (2016) take the cross-border ecological compensation of the Xin'an River as an example to design a two-way static compensation mechanism. Smith and Day (2018) further propose the concept of a sharing mechanism between the compensation entities.

In the study of compensation object, the traditional PES mechanism emphasizes that the object of ecological compensation is the provider of environmental services. However, from the perspective of environmental damage compensation, the object of ecological compensation includes all the stakeholders (such as relevant governments, residents, enterprises and ecosystems)which are involved in environmental damage (Engel et al., 2008). In addition, traditional ecological compensation often only considers overall compensation or non-differential compensation (Cole, 2012), while the Gastineu & Tageourdeau (2014) distinguishes between preference and wealth heterogeneity.

Research on compensation methods includes environmental compensation and monetary compensation (Kermagoret et al., 2016). Rocio et al. (2015) argue that the compensation methods corresponding to different ecological compensation practices are not the same. More and more scholars have proposed state-contingent compensation (Derissen & Quaas, 2013; Rocio et al., 2015). The compensation evaluation includes two aspects: one is the focus on the trade-off between equity and efficiency in ecological compensation (Pascal et al., 2010), and the second is about efficiency analysis (Vatn, 2010; Borner et al., 2017). Ecological compensation efficiency pays attention to the problem of optimal compensation. Jones and Pease (1997) argue that unless individual preferences are homogenous, environmental compensation cannot compensate for each individual and only provides compensation at the aggregate level. Cole (2012) discusses the equilibrium efficiency of an ecological compensation system from the perspective of a representative public. Gastineau & Taigourdeau (2014) analyzes the welfare level of environmental compensation from the angle of individual heterogeneity and investigates the optimal compensation system with individual preference heterogeneity and individual wealth differences. In addition, the specification of the ecological compensation standard of the cross-border basin is also considered as the key factor that influences the efficiency of compensation (Guangming Shi et al., 2014).

Although research on the details of ecological compensation is relatively rich, the systematic research on the mechanism itself is still insufficient. Wunder (2006) points out that PES are voluntary, quantifiable, flexible and diverse. The PES mechanism is widely promoted all over the world, but because water resources are state-owned in China, the PES mechanism under the Coase model is not effective in implementing ecological compensation, especially in cross-border situations, which are prone to cause collective rational conflicts (Wei Qian and Jie Zhang, 2014). There are not many studies on diversified ecological compensation for a whole watershed. Most of the existing studies are limited to the design of ecological compensation mechanism in small watersheds and the pilot project on cross-border ecological compensation (Junfeng Wang et al., 2011; Guangming Shi and Jinnan Wang, 2014; Guihuan Liu et al., 2016; Yiyuan Hu et al., 2016; Hongwei Guo et al., 2017). Transboundary water ecological protection and ecological compensation need to be not only completed between the governments or watershed management agencies, but also led by the higher level government of the basin (Ring, 2008; Shi Guangming and Jinnan Wang, 2014).

Since cross-border watershed ecological compensation involves multiple administrative regions, there are cross-administrative or cross-basin issues. In order to make up for the above defects and to realize the dynamic continuous Pareto improvement of the ecological compensation system, this paper intends to adopt the compound rules of the polluters-pay and beneficiaries-compensate to construct a cross-boundary, two-way dynamic compensation system based on the characteristics of classified water quality and hierarchical compensation, which combines Pigou model and Coase model. Based on the idea of an ecological compensation sharing mechanism (Smith and Day, 2018), this new system is a bidirectional dynamic compensation model and a chain ecological compensation model. These models are used to match the incentive mechanism of compensation and punishment according to dynamic water quality, which is a hierarchical compensation mechanism.

The contribution of this paper lies with the following points: First, based on the two-way static compensation system, dynamic water quality and dynamic compensation are introduced into the ecological compensation mechanism to achieve the optimization of water quality and compensation level. The second is to show that the two-way dynamic compensation system and the cross-border ecological compensation system designed in this paper are a Pareto improvement over the traditional cross-border ecological compensation system from a theoretical perspective that is corroborated through numerical simulation analysis. The third is to effectively combine the government mechanism and the market mechanism to construct two types of cross-border ecological compensation systems based on cross-basin local governments. The construction of cross-border ecological compensation system is incentive compatibility, so it involves no government regulation and lowers the financial compensation burden on the higher level of government.

3. Basic Theoretical Framework and Hypothesis

3.1. Benchmark models

The one-way static compensation model based on Pigou model is a benchmark model for this study. The basic structure has two cross-basin administrative areas, with the initial water quality of the upper and lower reaches of the basin interface, X_0 , which is lower than the water quality requirement, X_1 , of the downstream administrative area. For this reason, the upstream and downstream administrative region governments carry out negotiations on water ecological protection and ecological compensation on behalf of the stakeholders in their respective regions. The negotiation stipulates that if the water quality during the contract period is no lower than X_1 , the downstream government will pay the number of M ecological compensation to the upstream government.

At this point, the expected utility of the downstream is:

$$EU_{b1} = p(M)U(\Delta X, -M) + (1 - p(M))U(X_0) \tag{1}$$

The expected return of the upstream ER_{b1} is:

$$ER_{b1} = p(M)M - c(\Delta X) \tag{2}$$

Here, $p \in [0,1]$ is the implementation probability of the water quality X_1 on the intersection during the contract period. The implementation rate, p , is affected by the degree of ecological protection efforts, but the degree of effort is unobservable. We use the compensation amount M as a proxy variable for the degree of effort. We define $p = p(M)$, $\frac{dp}{dM} > 0$, $\frac{d^2 p}{dM^2} > 0$. $U(\cdot)$ is the utility function of the downstream, $\Delta X = X_1 - X_0$ is the degree of improvement in water quality. In equation (1) $U(\Delta X, -M)$ indicates the downstream utility when the water quality is up to X_1 . $U(X_0)$ denotes the downstream utility when the water quality dos not reach X_1 . $c(\cdot)$ is the cost of improved water quality ΔX in the upstream region. The optimal reaction function is obtained from equations (1) and (2):

$$M = f_{b1}(\Delta X) \tag{3}$$

$$\Delta X = \phi_{b1}(M) \tag{4}$$

Equation (3) gives the maximum amount of ecological compensation that the downstream area is willing to pay at a given level of water quality improvement. Equation (4) gives the maximum water quality improvement level that the upstream region is willing to promote given the amount of ecological compensation from downstream. Assuming that the above reaction functions have the characteristics of continuity and quasiconvexity, then the game space, Θ , based on the two optimal reaction functions is the core of the equilibrium solution in thef one-way static compensation model. [1] The ecological compensation amount,

[1] This core may be a closed or an open core, which is determined by the characteristics of the optimal reflection function. If it is open, it can be defined as quasi-vertebra.

M^*, and water quality X_1 at the equilibrium state are determined under the bargaining strategy of the upper and lower reaches of the watershed, where $X_1 = \Delta X^* + X_0$. In order to improve the execution of the contract, a third party can be invited to join, such as the superior administrative organization, to supervise the implementation of the agreement.

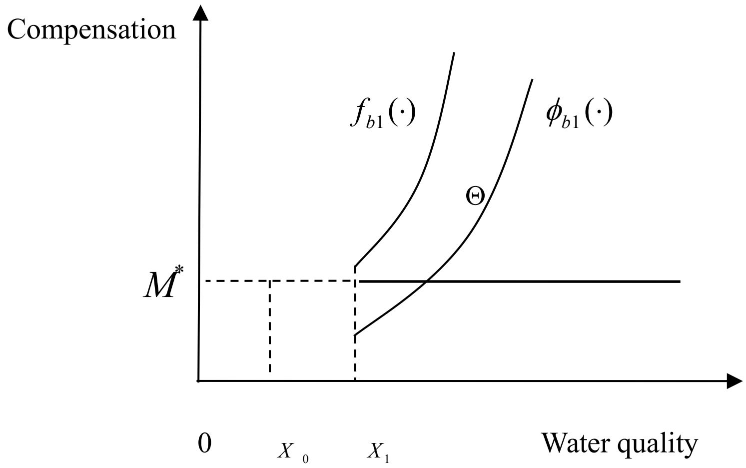

Figure 1 One-way static compensation model

This benchmark model only follows the beneficiary-compensating rule. It does not implement the polluters-paying rule for ecological damages committed in the upper administrative region. Therefore, this benchmark model only has an incentive effect for the upper administrative district, but no binding on the ecological damage carried out in the upstream administrative region. In addition, as what can be seen from figure 1, when the water quality reaches X_1, the downstream ecological compensation is maintained at M^*. The upstream administrative region has no incentive to continuously improve the water quality beyond X_1 due to incentive compatibility. Furthermore, in order to make the compensation model more implementable a third-party monitoring mechanism must be added, normally by the superior government.

In order to make up for defects in the one-way static model, second benchmark model is introduced which is a bidirectional static compensation model. The two-way static compensation model combines the two single compensation principles which are polluters-pay and beneficiaries-compensate to form a compound rule. This model abandons the superior government-led system in the Pigou model and introduces the quasi-market mechanism of local intergovernmental transactions in order to achieve more flexible and effective ecological compensation.

The two-way static compensation model has two transboundary watershed administrative areas and the initial water quality of the junction sections, X_0, is lower than the water quality requirements of the downstream administrative areas X_1. The governments of the upstream and downstream administrative regions carry out negotiations on water ecological protection and ecological compensation on behalf of their respective regions stipulating that when the water quality during the contract period is at level X_1 or above, the downstream will compensation the upstream by M. If the water quality is lower than X_1, the upstream grants damages to the downstream M quota.

At this point, the expected utility of the downstream is:

$$EU_{b2} = p(M)U(\Delta X, -M) + (1 - p(M))U(X_0, M) \quad (5)$$

The expected return from the upstream ER_{b2} is:

$$ER_{b2} = p(M)M - (1 - p(M))M - c(\Delta X) \quad (6)$$

In equation (5) $U(X_0, M)$ shows the downstream utility when the necessary water quality is not reached. The non-negative requirement of the participation constraint condition for the downstream is easy to meet under the constraints of participation. But the non-negative requirement of the expected benefit for the upstream in equation (6) needs to consider the impact of the probability of implementation $p(\cdot)$, the ecological compensation amount M and the cost of the improvement $c(\cdot)$. We already have

$$\frac{dp}{dM} > 0 \quad (7)$$

If $p > 0.5$ and M is large enough, the non-negative requirement of equation (6) can be satisfied.

The optimal reaction functions are obtained from equations (5) and (6):

$$M = f_d(\Delta X) \quad (8)$$

$$\Delta X = \phi_d(M) \quad (9)$$

There is a break point at level X_1 in the reaction equations (8) and (9), that is

$$f_d(\Delta X) = 0 \ , \ \phi(M) < 0 \ \text{when} \ X \leq X_1 \quad (10)$$

which means when the water quality is not reached at X_1 the maximum compensation that the downstream is willing to pay is zero, but the upstream is willing to pay the damage. The decision space based on equations(8), (9) and (10) is shown in figure 2.

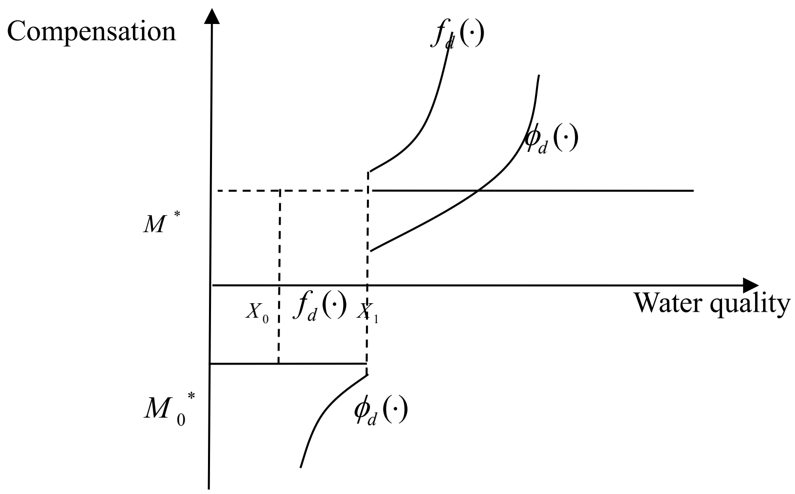

Figure 2 Bidirectional static compensation model

Comparing equation (5) and (1), the downstream expected utility in the two-way static compensation model is significantly larger than that in the one-way static compensation model because the utility function of equation (5) compensate damages M . Further, comparing equations (6) and (2), the upstream expected benefit in the two-way static compensation model is strictly less than that in the one-way static compensation model, even if the downstream compensation amount M is increased, it cannot change $ER_{b2} < ER_{b1}$. Therefore, the two-way static compensation model without third-party intervention does not achieve Pareto improvement of welfare compared with the one-way static compensation model, so the practicability of the compensation protocol has not been enhanced. One improvement is to introduce third-party entities, such as the higher-level government, to inject additional ecological compensation funds into the two-way static compensation contract. In this case, the total amount of ecological compensation is composed of the compensation amount of the downstream administrative area M and the external compensation amount M', that is

$$M_t = M + M' \tag{11}$$

At this point, the expected revenue of the upstream administrative district becomes

$$ER'_{b2} = p(M_t)M + M' - (1 - p(M_t))M - c(\Delta X) \tag{12}$$

The expected return of the upstream administrative district represented in equation (12) is obviously larger than the original income shown in equation (6), and it is easier to achieve non-negative conditions, especially when the external compensation amount M' reaches a certain amount, $ER'_{b2} > ER_{b1}$ could be achieved. The cross-border ecological compensation practice implemented for the Xin'an River by Anhui Province and Zhejiang Province is the specific case of this two-way static compensation model. The two-way static compensation model represented by equations (5) and (6) does not achieve Pareto improvement of the overall welfare compared with the ecological compensation baseline model, but it is possible for Pareto improvement by adding a third-party mechanism. However, in this way the mechanism is really a government-led Pigou model, so many of the drawbacks of the Pigou model will follow.

Therefore, compared with the one-way static compensation model, the bidirectional static compensation model has two major defects. First, it requires intervention from a third party, and cannot escape the government-led trajectory under the Pigou model, which also limits the promotion and application of the model; second, the static characteristics of the model will also lead to a threshold problem or a glass ceiling effect for water resource protection. Once the water quality of the intersection reaches the target requirement, the upstream cannot obtain more compensation and will lack motivation to further improve environment protection. In order to solve the above defects of the static compensation models, it is necessary to introduce a hierarchical compensation mechanism that reflects the dynamic water quality characteristics. Therefore, we further expand the above two models and construct a two-way (bidirectional) dynamic compensation model and chain compensation model.

3.2 Extended model

(1) Extended Model 1 - Bidirectional Dynamic Compensation Model

We add to the two-way static compensation model with the following assumptions: (1) Water quality will divided into different level with respect to the different requirements which is called dynamic classification structure of water quality; (2) Hierarchical ecological compensation corresponding to the classification structure of water quality which means different water quality will get different level of ecological compensation. Thus, a two-way dynamic compensation model can be constructed to realize the goal of sustainable improvements in water quality within a cross-border watersheds. The model combines the intensity of ecological protection, the continuous improvement of water quality and hierarchical ecological compensation, in order to alleviate the tradeoff between ecological protection and ecological compensation. The formulation is more likely to result in a win-win situation for stakeholders while constantly improving the ecological environment.

The bidirectional dynamic compensation model is a composite contract structure designed based on the two-way static compensation model. The water quality of the watershed boundary section can be divided into several levels according to the ladder structure, such as class I, class II, class III, class IV, class V and inferior V-type water. When the water quality of the section reaches Class I, Class II, and Class III standards, respectively, the differential matching ecological compensation amount is given; and when the water quality is lower than Class III, there is damage compensation from the upstream. As for the specification of water quality we also can construct a similar composite contract for more detailed types and concentrations of some vital contaminants.[2]

A more general assumption is that the water quality requirements are presented in n incremental levels with an initial water quality X_0 which is below the downstream water quality requirements $X_i \cdot i \in [1, n]$. The upstream and downstream governments negotiate the protection of water resources in the basin, stipulating that when the water quality at the junction of different administration areas along the samethe basin is at least X_i during the contract period, the downstream stream will compensate M_i to the upstream. If the water quality is lower than the level X_i , the upstream will pay the downstream M_0 . There is a negotiation contract on the X_1 , and in the other water quality requirements above X_1 , the upstream pays the corresponding compensation M_i .

Thus, the dynamic expected utility of the downstream EU_d is:

$$EU_d = \sum_{i=1}^{n} p_i(M_i)U(\Delta X_i, -M_i) + (1 - \sum_{i=1}^{n} p_i(M_i))U(X_0, M_0) \qquad (13)$$

The dynamic expected return of the upstream ER_d is:

$$ER_d = \sum_{i=1}^{n} p_i(M_i)M_i - (1 - \sum_{i=1}^{n} p_i(M_i))M_0 - \sum_{i=1}^{n} p_i(M_i)c(\Delta X_i) \qquad (14)$$

n is the number of water quality classifications. $U(\Delta X_i, -M_i)$ is a utility function for improved water quality with hierarchical ecological compensation, $U(X_0, M_0)$ is a utility function when the lowest class water quality target is not achieved. Equation (13) also describes downstream expected benefits as a combination of hierarchical compensation

[2] In fact, the compensation mechanism can also be designed as a more detailed hierarchical mechanism, but the transaction cost of reaching an agreement is higher. Some ecological compensation agreements also measure water quality and water quantity. This measure is suitable for water shortage areas with water source and water quality. In fact, the annual average water quality level can replace the measure standard of water quality and quantity. In addition, the serious water pollution problem can even be directly taken as illegal events to be enforced.

M_i and water quality improvement costs $c(\Delta X_i)$. The two-way dynamic compensation model encourages upstream stakeholders to implement effective water quality improvement with the hierarchical compensation system.

Based on equations (13) and (14) we can build response $2n+2$ response functions:

$$M_i = f_d(\Delta X_i) \quad i = 0,1,2,\cdots n \tag{15}$$

$$\Delta X_i = \phi_d(M_i) \quad i = 0,1,2,\cdots n \tag{16}$$

The corresponding response functions and bargaining decision equilibria are shown in figure 3. In each classified water quality range, the two sides determine the corresponding amount of ecological compensation which must be in the feasible region between the two reaction functions. The optimal degree of water quality protection is selected to obtain the corresponding compensation instead of being limited to the lowest compensation degree in the static compensation model. The upstream has the intention of continuous water improvement through the optimization of ecological protection.

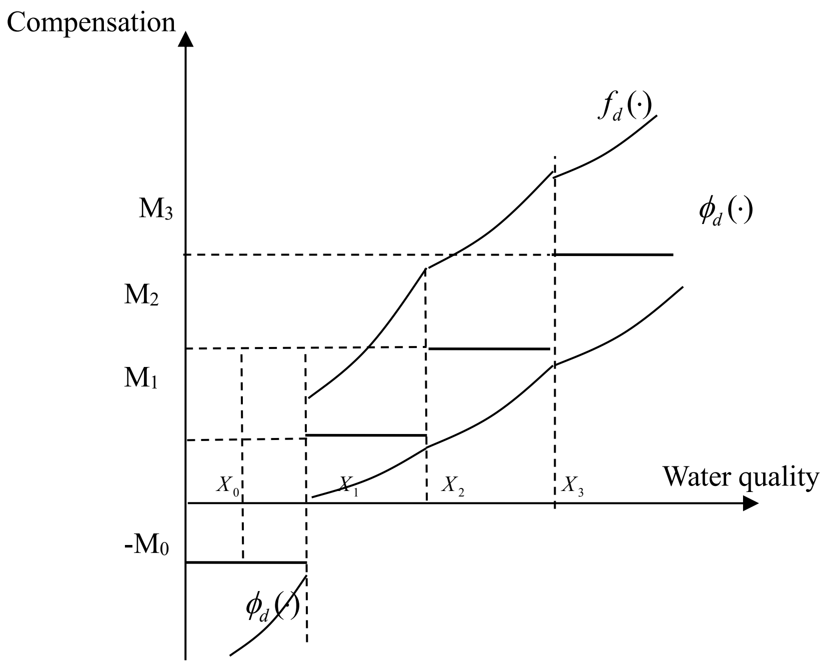

Figure 3 Bidirectional dynamic compensation model

(2) Extended Model 2 - Chain Compensation Model

The chain compensation model is another extension of the bidirectional dynamic compensation model. The prototype for this compensation model comes from the ecological compensation system for the Dong River Basin along Hong Kong-Guangdong-Jiangxi provinces. The chain compensation model also stems from one-way chain compensation system. We extend the one-way chain compensation system to the bidirectional dynamic chain ecological compensation model based on a two-way dynamic model to further investigate the two-way ecological compensation situation covering multiple administrative regions. The basic assumptions of the chain compensation model are as follows: There is one upstream administrative region and m downstream administrative districts along a watershed. The distribution of those downstream administrative regions is a monotonic chain. The problem is one of ecological compensation sharing and water protection in the chain. Assuming that the downstream administrative districts can establish a chain ecological compensation sharing mechanism with the upstream administrative region. This sharing mechanism takes the watershed as the link, the adjacent administrative regions as the boundary, and the cross-section water quality as the standard. The downstream administrative regions need to compensate the upstream areas for water quality improvement or effective protection of water resources, and then implement a cross-border chain-sharing mechanism for ecological compensation along the basin. Each region faces a negotiation agreement on "benefit compensation" and "damage compensation" for water quality protection. In the above chain ecological compensation system, the expected return of the upstream ecological protection zone ER_c remains,

$$ER_c = \sum_{i=1}^{n} p_{1,i}(M_{1,i})M_{1,i} - (1 - \sum_{i=1}^{n} p_{1,i}(M_{1,i}))M_{1,0} - \sum_{i=1}^{n} p_{1,i}(M_{1,i})c(\Delta X_{1,i}) \quad (17)$$

Where $M_{1,i}$ is the ecological compensation for the upstream when the water quality meets classification requirements X_i . $M_{1,0}$ is the amount of compensation paid by the upstream for water quality that does not meet the minimum classification requirements. From equation (17), the expected benefit function of the first upstream administrative region is similar to that in equation (14). If the m downstream administrative areas follow a monotonous chain structure, there are not only chain-based compensation and damage compensation mechanisms, but also chain-type water environmental protection problems. The expected utility of the j administrative district EU_j is,

$$\begin{aligned} EU_{cj} = & \underbrace{\sum_{i=1}^{n} p_{j,i}(M_{j,i})U(\Delta X_{j,i}, -M_{j,i}) + (1 - \sum_{i=1}^{n} p_{j,i}(M_{j,i}))U(X_{j,0}, M_{j,0})}_{\text{upstream agreement utility}} \\ & \underbrace{+U(\sum_{i=1}^{n} p_{j+1,i}(M_{j+1i})M_{j+1,i} - (1 - \sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i}))M_{j+1,0} - \sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i})c(\Delta X_{j+1,i}))}_{\text{downstream agreement return}}, \quad (18) \\ & j = 2, \cdots m \end{aligned}$$

Equation (18) shows that the expected utility of the administrative region j is composed of the utility of the upper stream agreement and the return from the downstream agreement. The upper stream protocol utility is similar to that in the equation (13) of the two-way dynamic compensation model, where, $U(\Delta X_{j,i}, -M_{j,i})$ is the utility of the administrative region j when the water quality of the upstream section reaches the classification requirements X_i . $U(X_{j,0}, M_{j,0})$ is for the case when the water quality of the upstream section does not meet the minimum classification requirements. . The utility of downstream agreements, $M_{j+1,i}$ is the amount of ecological compensation from downstream ecological compensation obtained by the j administrative district when the downstream section water quality meets the classification requirements. $M_{j+1,0}$ is for the case when the water quality of the downstream section does not meet the minimum classification requirement.

The $n+1$ reaction functions can be obtained by equation (17) and $(n+1)\times(m-1)$ reaction functions come from equation (18). Thus, there are $(n+1)\times m$ combinations of equilibrium strategies $(M_{ij}, \Delta X_i)$ that can be obtained from the corresponding bargaining strategy between the upstream and the downstream. Assume that a unified compensation standard is implemented among the administrative regions corresponding to the same water quality, the strategic balance of the above bargaining can still be simplified to $n+1$

equilibrium solutions. For simplicity, the watershed district in figure 4 is divided into only three areas, and the water quality is also divided into three classes. The basic structure of the simplified chain model is shown in figure 4.

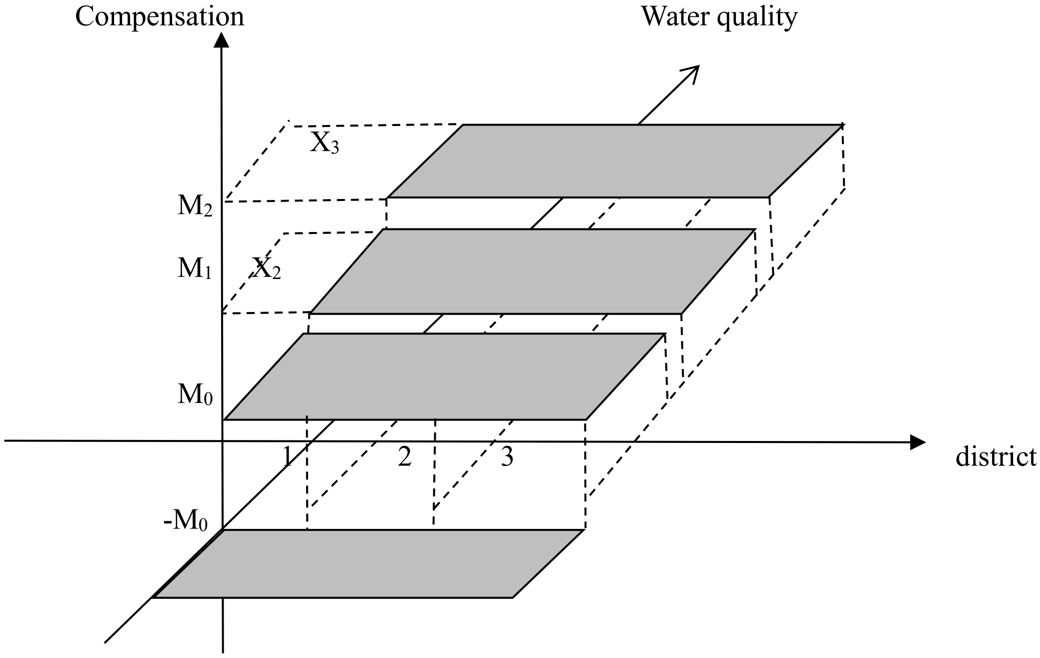

Figure 4 Chain ecological compensation model

3.3 Hypothesis

Based on the above analysis, the following hypothesis are proposed:

Hypothesis 1: Compared with a bidirectional static compensation model, both bidirectional dynamic compensation model and chain compensation model have Pareto improvement effects when certain conditions are satisfied. This hypothesis is aimed at the welfare analysis between different cross-border ecological compensation models.

Hypothesis 2: The dynamic matching mechanism of classified water quality and hierarchical ecological compensation in the two-way dynamic ecological compensation model can stimulate the upstream region to implement more stringent water conservation behavior, thus contributing to the continuous improvement of water resources protection. This hypothesis is the most important issue of the ecological compensation mechanism; that is, an efficient ecological compensation mechanism must realize water environmental protection.

Hypothesis 3: The chain ecological compensation model further enhances the overall payment capacity of the downstream, prolongs the length of the water ecological protection chain, and helps to achieve full coverage of transboundary watershed ecological protection. Hypothesis 3 indicates that chain compensation can improve the overall payment capacity for ecological protection.

4 Theoretical Proof of Hypothesis

4.1 Theoretical proof of hypothesis 1

Section 3 showsthere is Pareto improvement in the two-way static compensation model with the intervention of a third party compared with the one-way static model. In order to prove that there is a Pareto improvement in the bidirectional dynamic compensation model and chain compensation model compared with the bidirectional static compensation model, it is necessary to prove that the expected utility and expected return in the extended models are no lower than those in the bidirectional static compensation model. First, we check the expected return of the upstream in the bidirectional dynamic compensation model, and compare equations (14) and (6). If $ER_d \geq ER_{b2}$ then the following condition must hold

$$\left[\sum_{i=1}^{n} p_i(M_i)M_i - (1-\sum_{i=1}^{n} p_i(M_i))M_0\right] - \left[p(M)M - (1-p(M))M\right] \geq \sum_{i=1}^{n} p_i(M_i)c(\Delta X_i) - c(\Delta X) \quad (19)$$

Assuming that the damage compensation $M = M_0$ and the initial water quality X_0 is the same for both circumstances, then

$$\sum_{i=1}^{n} p_i(M_i)M_i \geq p(M)M \quad (20)$$

$$(1-\sum_{i=1}^{n} p_i(M_i))M_0 \leq (1-p(M))M \quad (21)$$

And

$$\sum_{i=1}^{n} p_i(M_i)c(\Delta X_i) \geq c(\Delta X) \quad (22)$$

Obviously, both sides of equation (19) are positive. Therefore, when equation (19) is satisfied, there is a Pareto improvement for the upstream in the bidirectional dynamic compensation model.

The expected utility for the downstream, which involves equations (5) and (13), is

$$\sum_{i=1}^{n} p_i(M_i)U(\Delta X_i, -M_i) \geq p(M)U(\Delta X, -M) \quad (23)$$

$$(1-\sum_{i=1}^{n} p_i(M_i)) \leq (1-p(M)) \quad (24)$$

Then

$$EU_d \geq EU_{b2} \quad (25)$$

And because

$$EU_{b2} \geq EU_{b1} \quad (26)$$

then

$$EU_d \geq EU_{b2} \geq EU_{b1} \qquad (27)$$

Therefore, under the premise of equation (19), the bidirectional dynamic compensation model has improved welfare for all parties compared with the bidirectional static compensation model.

Because the total compensation amount in the equation (17) for the chain compensation model, $M_{1,i}$ is greater than or equal to the total compensation amount in the equation (14), then

$$ER_c \geq ER_d \qquad (28)$$

Then we can say under the premise that the equation (19) is satisfied,

$$ER_c \geq ER_d \geq ER_{b2} \qquad (29)$$

Recall the expected utility of a single downstream administrative area EU_{cj} in the chain compensation model is composed of the upstream protocol utility and downstream agreement return represented by equation (18). This means each downstream administrative area j received additional downstream agreement return compared with the same situation in the bidirectional dynamic model. Therefore, $EU_{cj} \geq EU_d$. and combining this result with equation (27):

$$EU_c \geq EU_d \geq EU_{b2} \geq EU_{b1} \qquad (30)$$

Thus, it can be seen from the equations (29) and (30) that the chain compensation model is a Pareto improvement compared with the two-way dynamic compensation model. Also, under certain conditions, both the bidirectional dynamic model and the chain compensation model have a Pareto improvement compared with the two-way static compensation model.

4.2 Theoretical proof of hypothesis 2

Hypothesis 2 states that the two-way dynamic compensation model the matching mechanism between the change of water quality ΔX_i and the hierarchical ecological compensation M_i can promote higher water quality protection actions in upstream areas. This means that ecological compensation can significantly promote water quality improvement:

$$\frac{\partial \Delta X_i}{\partial M_i} > 0 \qquad (31)$$

The proof of the equation (31) is based on the objective function of the upstream administrative region. It is easy to obtain the complete differential equation of the equation (14)

$$\begin{aligned} dER_d = &\sum_{i=1}^{n} \left(\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i)\right)dM_i \\ &- \sum_{i=1}^{n} p_i(M_i)\frac{dc(\Delta X_i)}{d\Delta X_i}d\Delta X_i \end{aligned} \qquad (32)$$

In the hierarchical compensation structure of the bidirectional dynamic compensation model, the compensation hierarchy optimization means that in the structure of the equation (32), when $dER_d = 0$, we can get $dM_{i-1} = 0$ and $d\Delta X_{i-1} = 0$, According to this, equation (32) is simplified to

$$dER_d = (\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i))dM_i - p_i(M_i)\frac{dc(\Delta X_i)}{d\Delta X_i}d\Delta X_i \qquad (33)$$

among them

$$\frac{dp_i(M_i)}{dM_i} > 0 \qquad (34)$$

$$\frac{dc(\Delta X_i)}{d\Delta X_i} > 0 \qquad (35)$$

According to the assumptions, equations (34) and (35) are naturally established, and at the same time, equation (36) needs to be satisfied.

$$\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i) > 0 \qquad (36)$$

Further, from equation (33), to make dM_i and $d\Delta X_i$ increase without decreasing dER_d. The constraint is

$$(\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i))dM_i \geq p_i(M_i)\frac{dc(\Delta X_i)}{d\Delta X_i}d\Delta X_{ii} \qquad (37)$$

Adjust it,

$$\frac{d\Delta X_i}{dM_i} \leq \frac{\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i)}{p_i(M_i)\frac{dc}{d\Delta X_i}} \qquad (38)$$

Equation (38) is the incentive compatibility condition of bidirectional dynamic compensation effect in upstream administrative region. In addition, equation (39) can be obtained by the participation constraint. That is,

$$\frac{d\Delta X_i}{dM_i} \geq 0 \qquad (39)$$

Therefore, the combination of equation (38) and equation (39) can be further changed into,

$$0 \le \frac{d\Delta X_i}{dM_i} \le \frac{\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i)}{p_i(M_i)\frac{dc}{d\Delta X_i}} \qquad (40)$$

If the condition of the equation (36) is satisfied, the feasibility interval defined by the above equation (40) exists, which also means that the existence condition of $\frac{d\Delta X_i}{dM_i}$ is satisfied in this interval. Of course, equation (40) is only a necessary condition for the establishment of hypothesis 2. To conform to a necessary and sufficient condition, it is also necessary to meet the requirements of $dEU_d > 0$ when dM_i and $d\Delta X_i$ increase. In fact, this condition can be easily satisfied, and obtained by the complete differential of equation of equation (13) that,

$$\begin{aligned} dEU_d = & \sum_{i=1}^{n} \frac{dp}{dM_i}(U(\Delta X_i, -M_i) - U(X_0, M_0))dM_i - \sum_{i=1}^{n} p(M_i)\frac{dU_1}{dM_i}dM_i \\ & + \sum_{i=1}^{n} p(M_i)\frac{dU_1}{d\Delta x_i}d\Delta X_i \\ & + (1 - \sum_{i=1}^{n} p(M_i))\left[\frac{\partial U(X_0, M_0)}{\partial X_0}dX_0 + \frac{\partial U(X_0, M_0)}{\partial M_0}dM_0\right] \end{aligned} \qquad (41)$$

Because of $dX_0 = 0$, $dM_0 = 0$ then equation (41) is simplified to

$$\begin{aligned} dEU_{d1} = & \sum_{i=1}^{n} \frac{dp_i}{dM_i}(U(\Delta X_i, -M_i) - U(X_0, M_0))dM_i - \sum_{i=1}^{n} p_i(M_i)\frac{dU_1}{dM_i}dM_i \\ & + \sum_{i=1}^{n} p_i(M_i)\frac{dU_1}{d\Delta x_i}d\Delta X_i \end{aligned} \qquad (42)$$

Also because $\frac{dp_i}{dM_i} > 0$, $(U_1 - U_o) > 0$, $p(M_i) \ge 0$, $\frac{dU_1}{dM_i} < 0$, we can get a conclusion that when dM_i and $d\Delta X_i$ increase, $dEU_d > 0$.

Therefore, under the condition of satisfying equation (36) and (40), the bidirectional dynamic compensation model can stimulate the water resources protection behavior of the upstream administrative district to improve the water quality continuously under the positive incentive of hierarchical ecological compensation.

4.3 Theoretical proof of hypothesis 3

The ecological compensation to be paid by the downstream administrative area in the bidirectional dynamic compensation model will be converted into a chain sharing mechanism and undertaken by several downstream administrative regions. Taking the jth administrative district as an example, in the two-way dynamic compensation model, the downstream participant needs to be paid directly, but in the chain structure, the jth administrative district can obtain the downstream payment as a upstream participant through the chain structure. The benefit should satisfy the participation constraint:

$$\Delta M_j = \sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i})M_{j+1,i} - (1-\sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i}))M_{j+1,0} - \sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i})c(\Delta X_{j+1,i}) \geq 0 \quad (43)$$

Equation (43) shows that in addition to having the capacity for an upstream payment for $M_{j,i}$ quota, the administrative district jth can also get extra ecological compensation from the downstream to enhance its ability to pay. In the chain compensation model, the ability to pay for the jth administrative district is

$$M_{j,i} + \Delta M_j \geq 0 \quad (44)$$

The payment capacity of the jth administrative district is enhanced. Since the utility function is a monotonically increasing function of income, the utility level of the jth administrative region can be obtained from equation (43):

$$\begin{aligned} EU_{j,i} &= \sum_{i=1}^{n} p_{j,i}(M_{j,i})U(\Delta X_{j,i}, -M_{j,i}) + (1-\sum_{i=1}^{n} p_{j,i}(M_{j,i}))U(X_{j,0}, M_{j,0}) \\ &+ U(\sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i})M_{j+1,i} - (1-\sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i}))M_{j+1,0} - \sum_{i=1}^{n} p_{j+1,i}(M_{j+1,i})c(\Delta X_{j+1,i})) \\ &\geq \sum_{i=1}^{n} p_{j,i}(M_{j,i})U(\Delta X_{j,i}, -M_{j,i}) + (1-\sum_{i=1}^{n} p_{j,i}(M_{j,i}))U(X_{j,0}, M_{j,0}) \end{aligned} \quad (45)$$

As a result, the expected utility level of the jth administrative district in the chain compensation model has increased from the original upstream protocol utility to the sum of the upstream protocol utility and the downstream protocol utility; and the overall expected utility level has increased significantly. This means that all administrative districts in the chain compensation model are more motivated to implement ecological compensation, which further ensures the length of the water ecological protection chain. These incentives help the transboundary watershed to achieve full ecological protection.

5. Numerical simulation of relevant hypotheses

In order to support the theoretical propositions and hypotheses, we use numerical simulation analysis. The simulation is based on the practice of cross-border ecological compensation for the Xin'an River in Zhejiang and Anhui province. As mentioned above, the Xin'an cross-border ecological compensation practice is a two-way static compensation model with the intervention of the central government as a third party. Therefore the numerical simulation is based on these basic facts to demonstrate the hypotheses of that the bidirectional dynamic compensation and the chain compensation models are superior over static models.

5.1 Numerical simulation analysis of hypothesis 1

(1) Simulation framework

Equation (15) shows the prerequisite for a two-way dynamic compensation model to have a Pareto welfare improvement. From the basic structure of equation (15), it is possible to define a distance function, d:

$$d = \left[\sum_{i=1}^{n} p_i(M_i)M_i - (1 - \sum_{i=1}^{n} p_i(M_i))M_0 \right] - \left[p(M)M - (1 - p(M))M \right] - \left[\sum_{i=1}^{n} p_i(M_i)c(\Delta X_i) - c(\Delta X) \right] \tag{46}$$

Based on this function d, we may specify the number of water quality classifications, the probability function, the cost function and the range of related variables in equation (46), and then analyze the variation characteristics of the distance d with respect to the relevant parameters, in particular, ecological compensation amount M and water quality variables ΔX. Special attention is paid to the critical condition where values of d go from negative to positive values. First, according to the classification characteristics of water quality in practice, set $n = 3$, which means high water quality class I, class II and class III. Establish the probability function of realization the corresponding water quality needs to meet the following three conditions:

① Under the premise that the given parameters are unchanged, the greater the ecological compensation M, the greater the probability of achieving the water quality goal (this is the compensation incentive effect).

② The larger the parameter is, with the given unchanged M, and the water quality target realization probability is smaller, this is the water quality target effect).

③ Meet the basic probability constraint

$$\sum_{i=1}^{n} p_i(M_i) \le 1 \tag{47}$$

Based on the above specification, we choose the following probability density function:

$$p_\lambda(M) = Me^{-\lambda M} \tag{48}$$

Where λ is a parameter related to the water quality target. The first order condition of equation (48) satisfies the following

$$\frac{\partial p_\lambda(M)}{\partial M} = (1 - \lambda M)e^{-\lambda M} > 0\text{, given, } \lambda M < 1 \tag{49}$$

$$\frac{\partial p_\lambda(M)}{\partial \lambda} = -M^2 e^{-\lambda M} < 0 \tag{50}$$

The value of M_λ is given as

$$M_\lambda = 0.1\lambda + 0.1M \quad , \quad M \in [2,5] \tag{51}$$

Define the cost function as

$$c(\Delta X_i) = \Delta X_i^2 \qquad (52)$$

which meets the increasing cost conditions . The water quality change is presented as equation (53).

$$\Delta X_\lambda = 0.5\lambda + 0.1\Delta X \text{，} \quad \Delta X \in [2,5] \qquad (53)$$

(2) Simulation results and analysis

We want to investigate the influence of changes in M and ΔX_i on d, and the critical condition of changes in positive and negative value of d. First, let's look at the influence of a change in M on d. Assume that the value of ΔX_i is chosen to be $\Delta X_i = [2,3,4,5]$, and the other conditions are unchanged. The simulation results are shown in Figure 5.

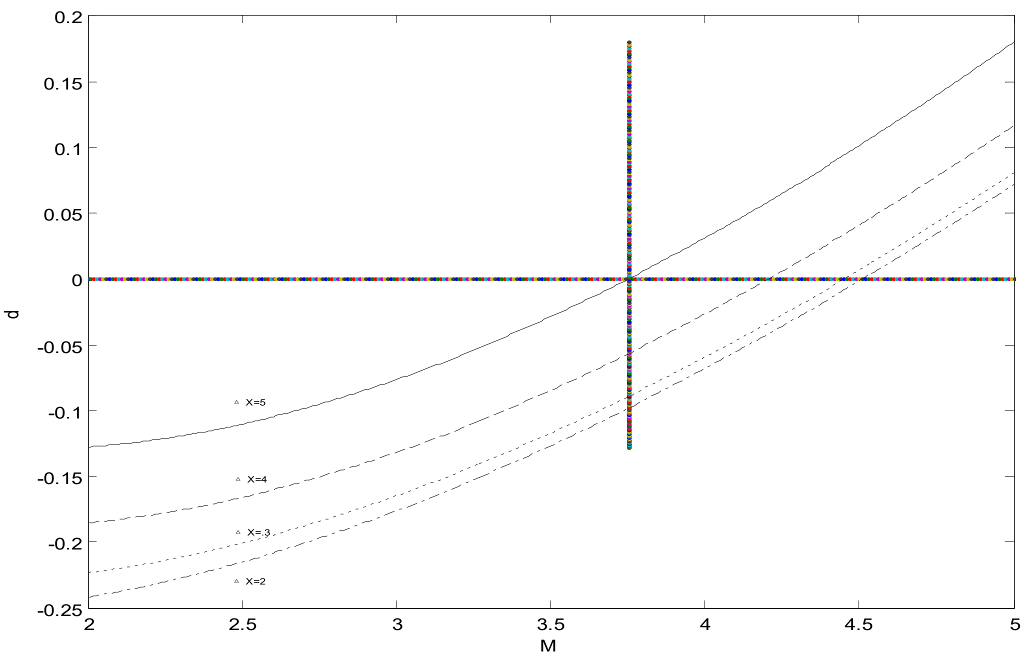

Figure 5 Effect of ecological compensation on the distance function d

The simulation results show that there is a critical point of positive and negative values for d as the ecological compensation changes. This means that at the upper right of the critical point, the bidirectional dynamic compensation model is better than the two-way static compensation model, and vice versa. In addition, the critical point is affected by the value of ΔX_i . Larger values for ΔX_i generate smaller values for M at the critical point. **This shows that the higher the required water quality improvement, the greater the advantage of bidirectional dynamic compensation model. As water quality improvement requirements are lowered, the more suitable the bidirectional static model. So we need to take the advantage of bidirectional dynamic compensation model to achieve higher water quality.**

The influence of ΔX_i on d can be obtained in a similar manner. Select $M = \{2,3,4,5\}$, $\Delta X_i \in [2,5]$, and assume that other conditions are unchanged. Figure 6 shows the effect of

ΔX_i change on d.

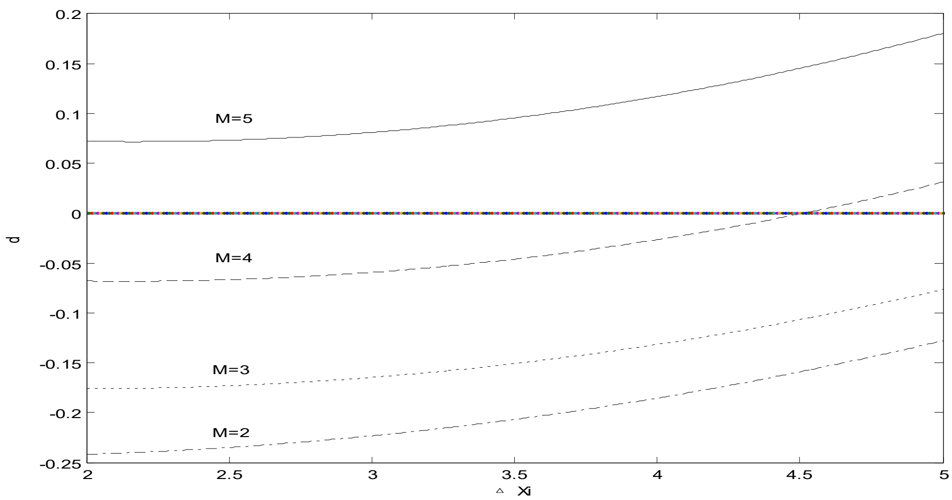

Figure 6 The effect of ΔX_i on the distance function d

Figure 6 shows that d increases with increasing ΔX_i at all ecological compensation levels. However, when M is smaller, d is displayed as negative within the range of ΔX_i. Only when M takes on larger values does d become positive. The above simulation results show that when the compensation amount is small, the bidirectional static compensation model has more advantages. When M is large, the bidirectional dynamic compensation model is superior to the bidirectional static compensation model. So if the static compensation model is in place, the bidirectional dynamic mechanism should be introduced if compensation is increased.

The two numerical simulation results show the influence of M and ΔX_i on the distance function d. They provide insights into the scope of application for the two-way dynamic compensation mechanism and the basic conditions and existence nodes that satisfy the Pareto improvement. The simulation results also fully show that the two-way dynamic compensation system is feasible in order to further improve water quality and the ecological protection of upstream water under current ecological compensation practice for Xinanjiang River. Furthermore, the two-way dynamic compensation mechanism does not require external compensation to meet the incentive compatibility and participation conditions. Thus it can be widely promoted for cross-border ecological compensation.

5.2 Numerical simulation of hypothesis 2

At present, the ecological compensation of Xinanjiang is a two-way static compensation system. The water quality assessment standard is a two-way static standard: when the target is achieved, the compensation is implemented by the downstream; when the target is not met, the compensation is paid by the upstream. This mechanism will lead to a glass-ceiling effect for where water quality improvement is limited to the target standard. Once water quality meets the standard, there is no incentive to improve water quality and promote ecological protection. This glass-ceiling effect is inconsistent with the requirements for a continuous improvement of the downstream water quality and the goal of ecological protection of the whole society. The two-way dynamic compensation system can encourage the upstream areas to implement ecological protection actions for continuous improvement of water quality through the classification of the water quality and the grading compensation mechanism.

(1) Simulation framework construction

For the hypothesis 2, the corresponding numerical simulation analysis is to show the existence of a feasibility interval (as defined in equation (40), the interval size and how the interval changes as factors in equation (40) change. Define the interval as

$$T = \frac{\frac{dp_i(M_i)}{dM_i}(M_i + M_0 - c(\Delta X_i)) + p_i(M_i)}{p_i(M_i)\frac{dc}{d\Delta X_i}} \quad (54)$$

①Interval existence simulation. Interval existence simulation refers to whether the interval value T exists under the premise of giving various function forms and parameter values, i.e.

$$T > 0 \quad (55)$$

② Simulation of interval size and its influencing factors. Analyze the influencing factors on the interval value T and simulate the effects of variations in T with respect to Mi and ΔX_i .

③Selection of various functions, variables and parameters. Considering the constraints equations (36) and (48), the functional forms and value ranges for the probability density function $p_\lambda(M)$, ecological compensation value M and cost function $c(\Delta X_i)$ the selected values are the same as the numerical simulations for Hypothesis 1. Substituting the corresponding functional forms into equation (54） and simplifying we

$$T = \frac{(1-\lambda M_i)(M_i + M_0 - \Delta X_i^2) + M_i}{2M_i \Delta X_i} \quad (56)$$

Furthermore, the parameter values in formula (56) need to satisfy the similar condition of formula (49), that is,

$$\lambda M_i < 1 \quad (57)$$

(2) Simulation results and analysis

To satisfy equation (57), we define the range of values as $\lambda \in [0.6, 1]$ $M_i = 0.1\lambda + 0.1M$ $M \in [2, 5]$ We examine the change in T at five levels of $\lambda = 0.6$, $\lambda = 0.7$, $\lambda = 0.8$, $\lambda = 0.9$ and $\lambda = 1.0$ respectively.

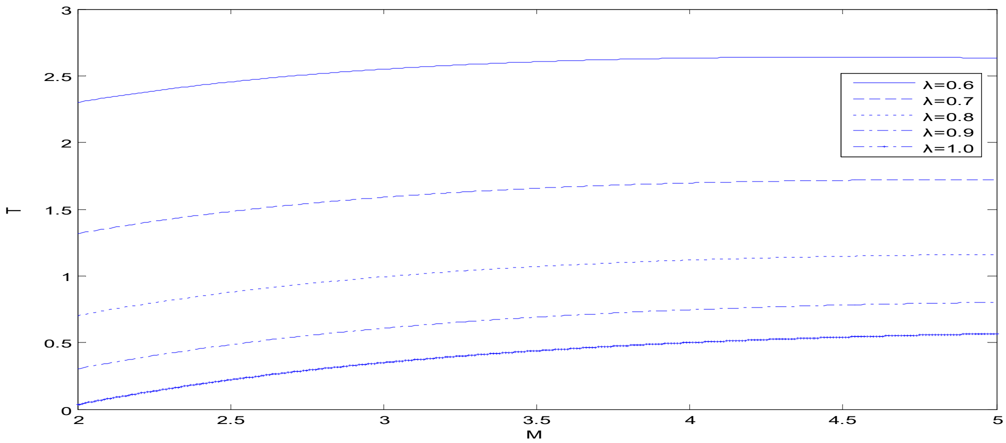

Figure 7 The Effect of M on T

Figure 7 shows that T is positive and increases as Mi increases at all levels of λ . This means that T exists objectively and there is a significant positive interval.

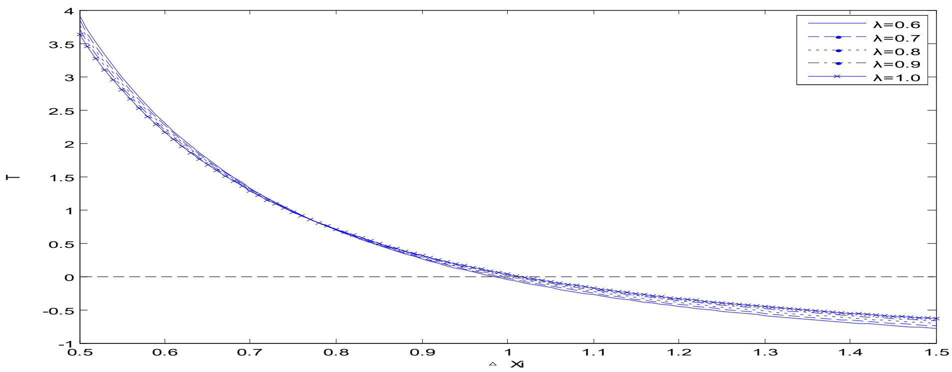

Figure 8 ΔX_{λ} Effect on T

We are also interested in the effects of adjusting the range for ΔX_{λ} . So we allow $\Delta X_{\lambda} \in [0.5, 1.5]$, and keep the values of λ the same. Figure 8 shows in this case T exists objectively and there is a significant positive interval. The above simulation results further verify the core content of Hypothesis 2, that is, in the two-way dynamic compensation system, the positive matching mechanism between the water quality variable ΔX_i and the ecological compensation variable M_i can ensure that the expected income of the upstream administrative area is positive. Thus this compensation system can provide a positive incentive constraint to promote higher water quality protection actions for the upstream administrative regions. This analysis also further clarifies that the two-way dynamic compensation system can ensure the continuous improvement of water quality in the Xin'an River Basin.

5.3 Numerical simulation of hypothesis 3

The middle and lower reaches of the Xin'an River Basin include not only Hangzhou, but also some areas of Jiaxing and Shaoxing areas, and even parts of Shanghai. Therefore, the problem is how to further build a chain compensation mechanism on the basis of the two-way dynamic compensation mechanism, and to link the water quality requirements on the upstream water resources in Hangzhou, Jiaxing and even Shaoxing through the chain compensation mechanism to achieve the dual objectives of ecological compensation and water resources protection.

(1) Simulation framework construction

Hypothesis 3 includes two important principles: First, the ability to pay for ecological compensation is enhanced; second, the length of the water ecological protection chain is extended. In view of the problem of ecological compensation payment ability, we pay attention to the establishment of equation (43); and the extension of the water ecological protection chain is derived from the ability to enhance the payment ability for the downstream parties. Therefore, only the numerical simulation of equation (43) can meet the basic requirements of the two core contents of hypothesis 3. Equation (43) is essentially a participatory condition for the implementation of water resources protection in the jth administrative region. Therefore, in the numerical simulation part, we need to demonstrate the existence of the participatory conditions described in equation (43) and their change trends. We define a distance function,

$$d' = \sum_{i=1}^{n} p_{1i}(M_i)M_{1i} - (1 - \sum_{i=1}^{n} p_{1i}(M_i))M_{j,j+1} - \sum_{i=1}^{n} p_{1i}(M_i)c(\Delta X_{1i}) \quad (58)$$

The selection of the various functions, variables and related parameters in equation (58) is still consistent with the specifications in the simulation of hypothesis 1. The numerical simulation mainly investigates the influence of the distance function d' with ecological compensation M_i and water quality changes ΔX_{1i}, and pays attention to the nodes of positive and negative transformation.

(2) Simulation results and analysis

First, examine the impact of ecological compensation M on the distance function d. Two water quality classification structures, n=2 and n=3, are selected. Given $M \in [2,5]$, the influence of changes in M on d' are analyzed assuming other conditions are unchanged. The simulation results are shown in Figure 9.

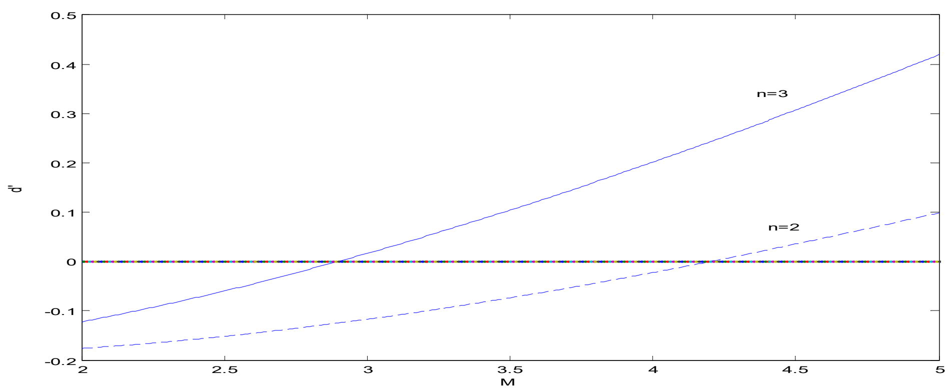

Figure 9 M impact on d'

Figure 9 shows that M continues to increase from 2, and d' also monotonically increases gradually from a negative value to a positive value. In addition, the more the water quality classifications, the earlier the positive value appears. The positive value range of d' indicates that the subject behavior satisfies the participatory condition, The simulation results for these participatory conditions also show that in a more complex water quality classification system, the compensation of the two-way dynamic model requires less compensation. After adding downstream positive ecological compensation, the distance function will move upward, so equations (44) and (45) are easier to hold.

We also demonstrate that the distance function d' gradually decreases as the water quality increases. It moves from positive to negative at ΔX_{1i} equal 4.0 as shown in figure 10. The positive value of d' indicates that the behavioral subject satisfies the participatory condition, further indicating that the chain compensation mechanism enhances the ecological compensation payment ability of the participating subjects.

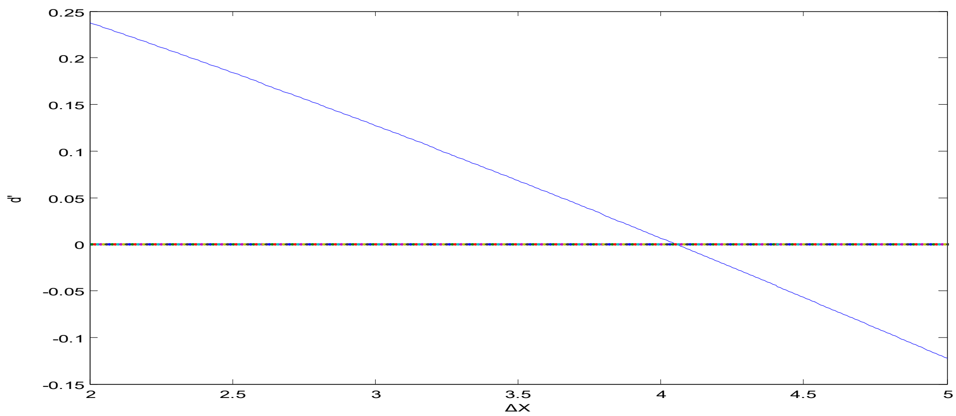

Figure 10 ΔX_{1i} **impact on** d'

The numerical simulation result of hypothesis 3 shows that equation (43) satisfies the establishment condition in specific value ranges for M_i and ΔX_{1i}. This means that within a certain interval, the chain compensation mechanism enhances the ecological compensation capacity of the j^{th} administrative region. Further, the basic logical of the extension of the water resources protection chain is further obtained by equation (43). Taking the construction of Xin'an basin chain ecological compensation system as an example, the numerical simulation results of Hypothesis 3 indicate that the chain compensation system will enhance the ecological compensation payment capacity of the middle and lower reaches of Xin'an basin such as Hangzhou, Jiaxing, Shaoxing and Shanghai. This will encourage the above-mentioned regions to join in the chain-based ecological compensation system to ensure full coverage of water resources in the basin.

6. Conclusions

Ecological compensation is an effective means to deal with the protection of water sources and the improvement of water environment in river basins. However, the system choice for cross-border ecological compensation is a difficult problem to be solved. The PES mechanism under the simple Coase mode or the government leading system under the Pigou mode are not generally effective, and the hybrid mechanism is the main research direction of the ecological compensation mechanism reform and innovation. The traditional one-way static compensation model embodies the general characteristics of the mixed mechanism, but the operation of the system is not guaranteed without the intervention of the higher government. The bi-directional static compensation model improves the enforceability of the mechanism by using the bi-directional negotiation protocol, but it is inefficient because there is no dynamic matching between compensation and protection. Based on the traditional static two-way compensation model, we construct a two-way dynamic compensation model and chain compensation model with an inter-governmental quasi-market transaction mechanism in order to achieve an effective match between ecological compensation incentives, pollution penalties and continuous water quality improvement.

This paper proposes three theoretical hypotheses aimed at the implementation efficiency of the bidirectional dynamic compensation and chain compensation models. Theoretical proofs and numerical simulations are carried out on all three hypotheses. The theoretical results show that the bidirectional dynamic compensation model has an obvious Pareto improvement effect on benefits of the upstream and the downstream. It also has an incentive effect to promote continuous water quality improvement. The chain compensation model further extends the length of the compensation chain and the coverage of water resources protection. The numerical simulation analysis is based on the two-way static compensation practice of the Xin'an basin along the Zhejiang-Anhui border, which further demonstrates the validity of the three hypotheses. Therefore, the two types of bidirectional dynamic compensation systems proposed in this paper are effective forms of cross-border ecological compensation within a watershed.

The research in this paper has the following important policy implications: First, the reform of cross-border ecological compensation system must take the innovation of hybrid mechanism into consideration. The research results show that the two-way dynamic compensation model based on the hybrid mechanism can significantly promote the improvement of welfare level, ecological continuous improvement and ecological protection fund support. In this paper, the two-way dynamic compensation model or chain compensation model is better than the existing two-way static compensation model. Second, on the basis of the hybrid mechanism, we should re-examine the role of the government, especially the status of local government as the subjective and object of ecological compensation. The prevaled western PES mechanism based on the Coase model is based on the private ownership of property rights. Even so, many scholars have found many flaws in the PES mechanism. Under the premise of the state-owned nature of water resources, China's ecological compensation system should pay more attention to the role of the government in ecological compensation, and actively explore the hybrid mechanism of ecological compensation based on local government. Third, in the practice of ecological compensation, we should also actively promote supply-side reform. The traditional practice of ecological compensation in China overemphasizes the problem of financial support on the supply side.However, the conclusion of this paper shows that using the chain compensation model, the inter-basin ecological compensation fund can be automatically strengthened without relying on the injection of external funds. Therefore, we should pay more attention to the reform and innovation of the ecological compensation system on the supply side .

References

[1] Begossi A., May P. H., Lopes, P., Oliveira L. E.C. et al., 2011, "Compensation for Environmental Services from Artisanal Fisheries in SE Brazil: Policy and Technical Strategies", *Ecological Economics*, 71(7):25-32.

[2] Bellver-Domingo, Hernández-Sancho&Molinos-Senante., 2016, "A review of Payment for Ecosystem Services for the economic internalization of environmental externalities: A water perspective", *Geoforum,* 70(3):115-117

[3] Blackman A., and Woodward R. T., 2010, "User Financing in a National Payments for Environmental Services Program: Costa Rican Hydropower", *Ecological Economics*, 69(8):1626-1638.

[4] Borner J., Baylis K., Corbera E., et al., 2017, "The Effectiveness of Payments for Environmental Services", *World Development*, 96(C): 359-374.

[5] Chan K. M. A., Anderson, E., Chapman M., et al. 2017, "Payments for Ecosystem Services: Rife with Problems and Potential—for Transformation towards Sustainability", *Ecological Economics*, 120(8):117-125.

[6] Carson, R., Flores N. Meade N., 2001. "Contingent Valuation: Controversies and Evidence," *Environmental & Resource Economics,* 19(2):173-210.

[7] Carson R., Groves T., 2007. "Incentive and informational properties of preference questions," *Environmental & Resource Economics*, 37(1):181-210.

[8] Cole S. G., 2012, "Environmental Compensation is not for the Birds", Doctoral Theisis, Swedish University of Agricultural Sciences.

[9] Costanza R., d'Arge R., Groot R., et al., 1997, "The Value of the World's Ecosystem Services and Natural Capital", Nature, 387, 253–260.

[10] Cranford M. & Mourato S., 2011, "Community Conservation and a Two-stage Approach to Payments for Ecosystem Services", *Ecological Economics*, 71(8): 89-98.

[11] Derissen S. & Quaas M. F., 2013, "Combining Performance-Based and Action-Based Payments to Provide Environmental Goods under Uncertainty", *Ecological Economics*, 85(2):77-84.

[12] Engel S., Pagiola S., Wunder, S., 2008, "Designing Payments for Environmental Services in Theory and Practice: An Overview of the Issues", *Ecological Economics*, 65(4): 663-764.

[13] Gastineau P., Taugourdeau E., 2014, "Compensating for Environmental Damages", *Ecological Economics*, 97(3): 150-161.

[14] Guangming Shi, Jinnan Wang, 2014, "Ecological compensation Mechanism of Transboundary Watershed". Beijing: *China Environment Press* .

[15] Hausknost D. Grima N., Singh S. J., 2017, "The political dimensions of Payments for Ecosystem Services (PES): Cascade or stairway?", *Ecological Economics*, 131(8):109-118.

[16] Hecken G. V., Bastiaensen, J., Windey C., 2015, "Towards a power-sensitive and socially-informed analysis of payments for ecosystem services (PES): Addressing the gaps in the current debate", *Ecological Economics*, 120(10):117-125.

[17] Huijie Wang, Zhanfeng Dong, et al., (2016) Ecocompensation for watershed services in China, Water International, 41:2, 271-289

[18] John A. List,Charles F. Mason., 2001, "Optimal Institutional Arrangements for Transboundary Pollutants in a Second-Best World: Evidence from a Differential Game with Asymmetric Players", Journal of Environmental Economics and Management, 42(3):277-296

[19] Jones C. A., Pease K. A. 1997, "Restoration-Based Compensation Measures In Natural Resource Liability Statutes", Contemporary Economic Policy, 15(4):111-122.

[20] Kermagoret C., Levrel H., Carlier A., Jeanne D. B., 2016, "Individual preferences regarding environmental offset and welfare compensation: a choice experiment application to an offshore wind farm projectet", *Ecological Economics*, 129(5):230-240.

[21] Knetch Jack L., 2007, "Biased Valuations, Damage Assessments, and Policy Choices: the Choice of Measure Matter", *Ecological Economics*, 63(4): 684－689.

[22] Manhong Shen., 2005, " Water right Trading and Government Innovation: a case on Dongyang Yiwu Water right Trading"，*Management World* , 31(6),. pp.45－56

[23] Muradian R., Rival L., 2012, "Between markets and hierarchies: the challenge of governingecosystem services", Ecosystem Services, (7): 93-100.

[24] Muradian R., Corbera E., Pascual U., Kosoy, N., et al., 2010, "Reconciling Theory and Practice: An Alternative Conceptual Framework for Understanding Payments for Environmental Services", *Ecological Economics*, 69(6): 1202-1208.

[25] Nicolas Robertc, Anne Stenger., 2013, Can payments solve the problem of undersupply of ecosystem services, *Forest Policy and Economics,* 35(10) :83-91

[26] Pascual U., Muradian R., Rodriguez, L. C., Duralappah A., 2010, "Exploring the links between equity and efficiency in payments for environmental services: A conceptual approach", *Ecological Economic*s, 69(6): 1237-1244.

[27] Ring I., “Integrating Local Ecological Services into Intergovernmental Fiscal Transfers: The Case of the ICMS-E in Brazil”, *Land Use Policy*, 2008, 25(4):485-497.

[28] Rocio, M. S., Maldonado, J. H., Wunder, S., et al., 2015, “Heterogeneous users and willingness to pay in an ongoing payment for watershed protection initiative in the Colombian Andes”, *Ecological Economic*s, 75(3):126-134.

[29] Runmin Fu, Xiaolin Miao. 2015, “Reconstruction of Financial transfer payment system in China's Ecological functional area”, *Economic Research*, No. 3, pp. 47-61.

[30] Smith G., Day B., 2018, “Addressing the Collective Action Problem in Multiple-purchaser PES: An Experimental Investigation of Negotiated Payment Contributions”, *Ecological Economics*, 144, 36-58.

[31] Stergios Athanassoglou., 2010, "Dynamic nonpoint-source pollution control policy: Ambient transfers and uncertainty", Journal of Economic Dynamics and Control, 34(12):2494-2509

[32] Tacconi L. 2012, Redefining payments for environmental services, *Ecological Economics*, 73(1):29-36.

[33] Vatn A., 2010, “An institutional analysis of payments for environmental services”, *Ecological Economics*, 69(6):1245-1252.

[34] Vatn A., 2014, “Markets in environmental governance. From theory to practice”, *Ecological Economics*, 105(75):97-105..

[35] Wenhui Zeng, 2008, "Regulation of Transboundary pollution in Watershed: an empirical study of Water pollution across provinces in China". *Economics (Quarterly*), No. 2, . pp.447－464

[36] Wunder, S., 2005, Payments for environmental services: some nuts and bolts. CIFOR Occasional Paper, 42

[37] Wunder S.,2006, “The Efficiency of Payments for Environmental Services in Tropical Conservation”, *Conservation Biology*, 21(1):48-58.

[38] Zhanfeng Dong, Hongxiang Li, Aiyu Yi et al., 2017: "Construction of Ecological compensation Mechanism in the Yangtze River Basin: framework and key points", *China Environmental Management* No. 12