A revenue function-based simulation model to calculate ecological compensation during a water use dispute in Guanting Reservoir Basin

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Abstract

Guanting Reservoir is one of the main sources of water to Beijing, and has had poor water quality since 1997. This has to some extent been due to a water-use dispute between Zhangjiakou (upstream) and Beijing (downstream) in the Guanting Reservoir Basin. Ecological compensation is a powerful economic incentive, and was thus chosen in this study as a model to settle the dispute. We established a model which consisted of revenue functions of Beijing and Zhangjiakou, respectively, to calculate the ecological compensation under various situations. The revenue functions included socio-economic benefits of water, pollution control cost, and environmental externalities in the downstream area. The environmental externalities included both financial and ecological losses when water sharing of the upstream area was outside the initial property distribution. Based on the revenue functions, we calculated the exact payment in a dispute, considering the profit of both the upstream and downstream areas.

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1. Introduction

1.1. Review of previous work

Rivers are among the water bodies most vulnerable to pollution. In China, the overall quality of the water of seven major rivers is subject to intermediate pollution. Excessive water consumption as a result of market ineffectiveness leads to water shortage and pollution, and so river basin environmental protections remain inefficient. Nowadays, ecological compensation is an economic incentive widely utilized in river basin environmental protection worldwide[1], including China[2]. Internationally, it has been applied as ‘Payment for Ecological Services (PES)’ and ‘Payment for Ecological Benefit’ [3]. The World Bank has carried out PES projects in Costa Rica,

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Mexico, Ecuador and Bolivia, mainly by increasing forest cover to improve the water service [4, 5]. In China, ecological compensation practice is still in a preliminary stage.

There is no accepted definition of river basin ecological compensation. Some take it as payments for the ecological services of water trading [3, 4, 6, 7], while others take it for institutional arrangements provided by governments using economic incentives to maintain and improve the ecological services of a drainage basin [8]. Ecological compensation can be calculated in various ways [9]. On one hand, it can be calculated based on ecological benefits provided by environmental protections. Ecuador established a Trust Compensation Fund in 1998 to collect finance from water users, based on the revenue functions of each stakeholder [10]. Due to increased soil salinization of the Murray–Darling Basin in Australia caused by deforestation, the upstream farmers should pay AU$17/1000 m³ of water or AU$85/ha to compensate for the standard payment over a ten-year period [11]. On the other hand, ecological compensation can also be determined by the environmental protection cost. In the Forest Environmental Services Compensation in Costa Rica, the compensation standard is 30US$/ha/y, based on the opportunity cost of land-use instead of the value of hydrological services [12]. The Perrier Vittel Company paid 75% of the disposable income of affected farms in France as compensation, based on the opportunity cost of arable land-use to get high water-quality [13].

From the macro perspective, the water-compensation accounting based on either the environmental protection cost or environmental benefits provided by protections in upstream can eliminate the downstream ‘free-rider’ phenomenon. However, research on each stakeholder is inadequate. Some studies have announced that compensation accounting should include the ecosystem service changes and impacts on stakeholders [14], and others have claimed that it should include the estimated cost, willingness to pay and capability to pay [15]. However, an accounting system meeting both the rational preferences of upstream and downstream has not yet been established and is still in a phase of qualitative description. In this case, the payments will not be acceptable to either upstream or downstream area because of lack of full consideration of each other’s position, and this leads to inefficient implementation of ecological compensation.

1.2. Study area

Beijing, the capital of China, is suffering a water shortage. Guanting Reservoir, one of the main sources of water to Beijing, has had poor water quality since 1997. Ninety-seven percent of the water entering into Guanting Reservoir comes from Zhangjiakou City. With rapid socio-economic development, the contradiction between water supply and demand in Beijing has become increasingly pronounced. For this reason, ‘The plan for sustainable use of water resources of the capital in early 21st Century (2001–2005)’ (‘21st plan’) was approved by the State Council to restore the drinking water supply function of the Guanting Reservoir. Thus, a fair and sustainable solution to water use disputes in the Guanting Reservoir Basin has become a common concern.

Ecological compensation, although still in a preliminary stage in China, was chosen in this research to solve this problem due to its powerful incentive effect as described above. How to establish an accounting system which can be accepted by both cities remains crucial. In this study, we established an ecological compensation accounting system based on the revenue functions of Beijing and Zhangjiakou. This accounting system includes estimates of environmental externality (to Beijing caused by Zhangjiakou) of both finance and ecology. In this way, we obtained payments that considered the profit of both stakeholders of water use disputes. Ecological compensation that supports the ecological service transactions between Beijing and Zhangjiakou would greatly improve the development of fairness and sustainability in the Guanting Reservoir Basin.

Guanting Reservoir watershed (41°14.2′–38°51′N, 112°8.3′–116°20.6′E) is located on the Yongding River, about 80 km northwest of Beijing. It is one of the main sources of water to Beijing. The large amount of water use for agriculture in the upstream city of Zhangjiakou has resulted in water consumption exceeding the capacity of Yongding River. Guanting Reservoir ceased providing water to Beijing in 1997 as a result of continual deterioration in water quality [16]. With the increasing water demand of Beijing, restoration of Guanting Reservoir has become urgent. It is an important task of the ‘21st plan’ to restore the drinking water supply function of Guanting Reservoir. The water quality measured across the Bridge Eight section, which is the Hebei–Beijing provincial trans-boundary section of the Yongding River, is expected to have reached Grade III of GB 3838-2002 (Environmental quality standards for surface water of China) by 2010. It is assumed that the water inflow to Guanting will be 120 million m³ at 75% assuring probabilities in 2010. However, the inflow quality of Guanting Reservoir remains worse than
Grade V, and the reservoir water quality at Grade V. Additionally, the average inflow was only 113 million m$^3$ during 2000–2006. All these facts indicate that management of powerful incentives toward environmental protection in this area is needed.

2. Methodology

We attempted to establish a market for water ecological service transactions between Beijing and Zhangjiakou. The optimal allocation of resources would work through the market transactions, leading to sustainable water use in this basin instead of over-consumption. Two elements are required to run these transactions. One is the clarity of water property rights of the two regions in Guanting Reservoir Basin, and the other is accurate payments supporting the transactions which are acceptable to both stakeholders. The payments can be calculated with an accounting system which can quantify the profit of each city during a water-use dispute in the Guanting Reservoir Basin. Followings are two parts to explain the clarity and the accounting system.

2.1. Clarity of Property Rights

To safeguard the water resources and sustainable development of regional economies in Beijing and its upstream area, the State Council approved the ‘21st plan’ in 2001. This plan was compiled by Beijing, Zhangjiakou, Chende and Datong. It forecasts the particular emissions and water share of the upstream area above Beijing in Guanting Reservoir Basin in 2010. Based on that, it designed the objectives, i.e. by the year 2010 the water quality across Bridge Eight section will have reached Grade III, and the inflow to Guanting is 120 million m$^3$ at 75% assuring probabilities. This plan is equated to an agreement in law signed by Beijing and the upstream cities. Thus, in this study we took the planning objectives, the quality and quantity of inflow to Guanting, as the initial water rights and emission permit allocations between Zhangjiakou and Beijing. Based on the clarity of property, we calculated the cost of behavior beyond the initial property boundaries of each city through the market. In this way, the ecological services transactions may work.

2.2. Model of The Accounting System

We established a model of the accounting system which consisted of revenue functions of Beijing and Zhangjiakou, respectively, to quantify the profit of each city during water use in the Guanting Reservoir Basin. The revenue function of Zhangjiakou consisted of benefits from water use and cost for environmental protection. The revenue function of Beijing, consisted of water use benefit and the environmental externalities, financial loss, and ecological loss or benefit, caused by water pollution or protection in the upstream area. The ecological compensation between the two cities could be determined by the rational choices of each stakeholder, which were quantified through the established revenue functions.

2.2.1. General Structure of The Model

The allocation of water between the two cities was set up according to the prediction of water share between the two areas in Guanting Reservoir Basin in the ‘21st plan’. For each area, the use of water resource was divided into three parts: for agriculture, industry, and living. The proportion of the three parts depends on the features of each area, and is modified by the coefficient of each part. The sector’s structure is displayed in Fig 1.

2.2.1.1. Case I

Case I assumed that excessive sewage was produced in Zhangjiakou, and the quality of water across the Bridge Eight section in the Yongding River was Grade IV or V, which is worse than the Grade III objective. In this case, Zhangjiakou caused negative environmental externalities to Beijing, including financial and ecological losses. Thus, Zhangjiakou should pay ecological compensation to Beijing.

2.2.1.1.1. Revenue of Upstream Area Sector
In Case I, the revenue function of Zhangjiakou consisted of two parameters, the benefit of water use and the ecological compensation for Beijing. The benefit of water use comprised three parts: for agriculture, industry and living (indicating economic and social benefits of water use in Zhangjiakou).

Fig. 1. The model of water resource allocation

2.2.1.2. Revenue of Downstream Area Sector

In Case I the revenue function of Beijing consisted of four parameters: the benefit of water use, the financial and the ecological loss caused by excessive sewage produced in Zhangjiakou, and the compensation paid by Zhangjiakou for its excessive sewage emission as clarified above. The benefit of water use comprised three parts: for agriculture, industry and living (indicating the economic and social benefits of water use in Beijing). The ecological loss comprised four parts: biological diversity, habitat, landscape and historical culture, and recreation losses. We used the contingent valuation method (CVM), involving 300 questionnaires to estimate the value of these ecological services. The result was shown in detail below (in the parameters section 3.2.2.2). The financial loss comprised three parts: agriculture, industry and social losses. The ecological compensation was equal to financial loss plus ecological loss of the downstream area, Beijing, when the upstream area’s additional socio-economic benefits of water use are greater than the financial and ecological losses. Otherwise, it is equal to the additional socio-economic benefits of the upstream area.

2.2.1.2. Case II

Case II assumed that the environmental protection worked well in the upstream area, Zhangjiakou, and the quality of water across the Bridge Eight section was Grade II, better than the planning objective of Grade III. In that case, Zhangjiakou caused advantageous environmental externalities to Beijing, including financial and ecological benefits. In other words, the water right Beijing received was beyond the initial property boundaries as previously clarified. Thus, Beijing should pay ecological compensation to Zhangjiakou for its extra pollution control costs. There are separate sectors for upstream and downstream revenue functions.

2.2.1.2.1. Revenue of Upstream Area Sector

In Case II, the revenue function of Zhangjiakou consisted of three parameters: the benefit of water use, the extra cost for pollution control, and the ecological compensation paid by Beijing. The benefit of water use comprised three parts: water use for agriculture, industry and living (i.e. economic and social benefits during water use in
Zhangjiakou. The extra cost for pollution control in Zhangjiakou depended on the quality of the water in Yongding River. The formula of the ‘water quality–economic losses’ was displayed in the parameters section 3.2.2.1, and was constructed using the results of previous studies.

2.2.1.2.2. Revenue of Downstream Area Sector

In Case II the revenue function of Beijing consisted of three parameters: the benefit of water use, the ecological benefit caused by extra pollution control in Zhangjiakou, and the compensation paid to Zhangjiakou for the water right Beijing received which was beyond the initial property boundaries as clarified previously. The benefit of water use comprised three parts: water use for agriculture, industry and living (i.e. economic and social benefits during water use in Beijing). The ecological benefit comprised four parts: biological diversity, habitat, landscape and historical culture, and recreation benefits. We used the CVM method, involving 300 questionnaires to estimate the value of these ecological services. The result was shown in detail below (in the parameter section 3.2.2.2). The ecological compensation is equal to the pollution control cost to upstream area (Zhangjiakou) when the downstream area’s (Beijing) additional ecological benefit is greater than the cost. Otherwise, it is equal to the additional ecological benefit to the downstream area.

2.2.2. Parameters of The Model

2.2.2.1. The Benefits of Water Use – W (q, L)

The accounting of socio-economic benefits of different water quality and quantity for use was divided into two parts. The benefit was calculated at the same quantity as used for water quality of Grade III. In addition, the socio-economic system losses caused by water pollution under the present situation were calculated. Econometric methods were used to account the economic losses, and used as a correction term for the benefits of water use under different water qualities. Therefore, the social and economic benefit of water use was as below.

\[ W(q,L) = f(q) - g(q,L) \] (1)

where \( q \) is regional water consumption, and \( L \) is water quality.

(A) The benefits of production and living water-use – \( f(q) \)

\[ f(q) = f_1 + f_2 + f_3 = \left[ \varepsilon(Y - Y_i)W/M - C\right][(1 + r)^f q^1 + \left(\frac{10000}{q^1}\right)\times \beta \times f][(1 + r)^f q^2 + S_1(1 + r)^f q^3 \] (2)

where \( f_1 \) is the benefit of water for agriculture; \( f_2 \) for industry; \( f_3 \) for life; \( q \) is the total water consumption in the region; \( x_1 \) is the water quantity coefficient of water for agriculture in the region; \( x_2 \) water quantity coefficient of water for industry in the region; \( x_3 \) water quantity coefficient of water for life in the region; \( \varepsilon \) is the sharing coefficient for the benefits of irrigation; \( Y_i \) is the yield of irrigation crops (kg/ha); \( Y_oi \) is the yield of dry-land crops (kg/ha); \( V \) is the crop prices (CNY/kg); \( M \) is the irrigation quota (m3/ha); \( C \) is the costs of water supply in irrigated areas (CNY/m3); \( q_i \) is the water consumption of 10 000 CNY output value (m3/10 000 CNY); \( \beta \) is the sharing coefficient for industrial water supply; \( f \) is the net rate of output; \( S_1 \) is the price of water for life (yuan /m3); and \( r \) is the annual interest rate (%).

(B) The correction term of water quality – \( g(q, L) \)

Accounting the loss in a socio-economic system caused by pollution, as a correction term, is as follows \[^{18} \].

\[ g(q,L) = \sum_{i=1}^{3} \Delta F_i = \sum_{i=1}^{3} \left[ F_i (1+r)^f \gamma_i \right] = \sum_{i=1}^{3} \left[ F_i \left( \frac{K_i \varepsilon^{a(l-LTH)}}{\varepsilon^{a(l-LTH)}} - 1 + M_i \right) (1 + r)^f \right] \] (3)

where \( \Delta F_i (i = 1, 2, 3) \) is the loss of water for agriculture, industry and life; \( K_i \) is the largest potential economic loss coefficient of water pollution for each category of water use; \( M_i \) is the symmetrical turning point of the economic loss for categories of water quality; \( \alpha \) is the price factor of water pollution for each category of water use; \( L \) is the level of water quality, and \( LTH \) is the level of water quality at the inflection point in the ‘water quality-economic losses’ curve. Other parameters are the same as in Formula (2).

2.2.2.2. Aquatic Ecosystem Service Value Changes Depend On Water Quality – E(q, L)
Using the CVM method, involving 300 questionnaires concerning Guanting Reservoir, this study estimated the aquatic ecosystem service values for biodiversity, species habitat, recreation, and landscape and historical culture, in the Guanting Reservoir (Fig 2).

![Biological Diversity](image1)

![Habitat](image2)

![landscape and historical culture](image3)

![landscape and historical culture](image4)

Fig.2. Willingness to pay for ecosystem services value.

In this study, the relationship between water quality and ecological services value was simulated as the S-curve of environmental economics. Different values of ecosystem services (E) from the Guanting Reservoir were obtained when the level of water quality in the section was better or worse than Grade III.

\[
E = d(q, L) = LE^{\frac{1}{\gamma E} - 3} \left( \frac{e^{\alpha (L - LTH)} - 1}{1 + e^{\alpha (L - LTH)}} + M \right) \frac{1}{1 + e^{\frac{1}{(1 + e^{\alpha (L - LTH)} - 3)}}}
\]

(4)

Where \(1/(1 + e^{\alpha (L - LTH)} - 3)\) is the correction factor for willingness to pay for the ecosystem services for t years later \(^{19}\); e is the natural logarithm; and \(E\) is the Engel coefficient. Other parameters are the same as in the former types.

2.2.2.3. The Cost of Water Pollution Control – I (L, Ls)

The formula of water pollution control cost was listed below \(^{20}\).

\[
I = 0.4976 \times e^{-0.0074 \times \text{COD}}
\]

(5)
where I is total cost of water pollution control (CNY); and COD is the value of chemical oxygen demand content (mg).

3. Results and discussion

The model ran with a time-step of one stage spanning four stages with Stage 1 being the base stage and Stage 4 the target stage. The water quantity across the Bridge Eight section was set according to the prediction of the particular water-share of the upstream area above Beijing in Guanting Reservoir Basin in the ‘21st plan’. The coefficients of each parameter (e.g. sharing coefficients of irrigation and of industry) in the model were set according to results of previous studies.

3.1. Case I

The inflow quality to Guanting Reservoir was still worse than Grade V. Case I assumed that the quality of the inflow was Grade V in Stage 1, Grade V in Stage 2, Grade IV in Stage 3, and Grade III in Stage 4. The ecological compensation was equal to the extra socio-economic benefits Zhangjiakou received from excessive water use and releasing sewage beyond the initial property boundaries as clarified in the ‘21st plan’. The exact ecological compensation Zhangjiakou should pay Beijing in Stage 1 with inflow of Grade V quality was 2,215,685,134.67 CNY; in Stage 2 with Grade V inflow was 2,215,859,808.61 CNY; in Stage 3 with Grade IV inflow was 1,704,114,033.96 CNY; and in Stage 4 with Grade III inflow was 0.

In the first three stages, when the water quality across the Bridge Eight section was worse than the planning objective of Grade III, Zhangjiakou should pay Beijing ecological compensation since it would cause negative environmental externalities to Beijing. The payments were the exact extra socio-economic benefits it received by excessive water use and releasing sewage beyond the initial property boundaries as clarified in the ‘21st plan’. Thus the net revenue of Zhangjiakou in Stages 1–2 did not increase. In this condition, being censured for pollution and getting no extra financial benefit, Zhangjiakou no longer had any motivation for excessive water consumption. As a result, the illegal water rights of Zhangjiakou would be gradually transferred back to Beijing. This reached a balance in Stage 4, and by that time, the ecological compensation was 0, and the net revenues of both Beijing and Zhangjiakou were at a maximum.

As the ecological compensation was the extra benefit Zhangjiakou received, not the environmental externalities caused in Beijing during this water dispute, the payments were always less than the financial and ecological losses. This shows that the accounting system was always based on the revenue, not losses, of each city. In other words, the payments were always within the capability of Zhangjiakou, since the accounting system considered the profit and supported the rational choice of Zhangjiakou.

In fact, the water allocation between Zhangjiakou and Beijing in the first three stages deviated from the condition of efficiency in the Guanting Reservoir Basin. The inefficient resource allocation could not satisfy the qualification of market transactions. In this case, the payments between the two stakeholders could not cover the real value of the ecological services. However, without the motivation for excessive consumption by Zhangjiakou as discussed above, water resource allocation between the two cities would return to the initial distribution of water use and emission rights as required in the ‘21st plan’. By that time, there would be optimal water resource allocation between Beijing and Zhangjiakou. Under the conditions of optimal water allocation between Beijing and Zhangjiakou, the ecological services transactions would cease, and the ecological compensation decrease to zero. This ensures efficient development of the basin and with efficient development, each area obtains maximum profit. The rational choice by each area is to maximize profit and the accounting system supports this process through ecological compensation. Thus, the accounting system supported the rational choices by both stakeholders, and as a result, this accounting system should be acceptable to each area during the water dispute.

3.2. Case II

The inflow quality to Guanting Reservoir was below Grade V. Case II assumed that the quality of the inflow was Grade III in Stage 1, Grade II in Stage 2, Grade III in Stage 3, and Grade III in Stage 4. The ecological
compensation was equal to the additional ecological benefit to the downstream area (Beijing) due to extra pollution control carried out upstream (Zhangjiakou). The ecological compensation Beijing should pay Zhangjiakou in Stage 2 when the inflow quality was Grade II was 588,234,347.94 CNY; however, in Stages 1, 2 and 4 when the inflow quality was Grade III, the compensation was 0 in each scenario.

In Stage 2, Beijing paid Zhangjiakou the extra ecological benefit it got as ecological compensation. That means to get extra ecological services beyond the initial property distribution in the ‘21st plan’, Beijing has to pay money equal to the additional ecological services value which was estimated by 300 questionnaires in this study. That is why the net revenue of Beijing increased slowly and continually instead of reaching a maximum in Stage 2. On the other hand, Zhangjiakou spent significant amounts on extra pollution control, which was more than the ecological compensation Beijing paid. Thus the revenue of Zhangjiakou declined sharply in Stage 2.

As the ecological compensation was the extra ecological benefit Beijing received, not the pollution control cost that Zhangjiakou spent, the payments were less than the environmental protection cost in Zhangjiakou. This shows that the accounting system was always based on the revenues of each city instead of the environmental protection cost. Thus, the payments were always within the capability of Beijing, as the accounting system considered the profit and supported the rational choice of Beijing.

In fact, when the environmental protection cost in the upstream area was more than the additional ecological benefit accrued in the downstream area, it indicated that the relationship between environmental protection and socio-economic development in the Guanting Reservoir Basin had deviated from the comprehensive, coordinated and sustainable development principles and should be amended. In this condition, without sufficient economic incentives and following the rational choice, Zhangjiakou would cut pollution control costs. Thus water quality would decline to Grade III, and remain at the balance of the initial property distribution. Then, the ecological services transactions would cease, and the ecological compensation decrease to zero. This would ensure efficient development of this basin, and with efficient development each area would get maximum profit. The rational choice of each area is to maximize profit and the accounting system supports this process through ecological compensation. Thus, this accounting system supports the rational choice of each stakeholder, and so this accounting should be acceptable by each area during this water dispute.

4. Conclusion

The clarity of water rights and emission rights between regions in the upstream and downstream is the basis of ecological compensation accounting. Compensation mode is bidirectional. In this study, the planning objective of "21st Century (2001-2005), the capital of sustainable water resources planning" was taken as the initial water right allocation. In CASE I, as the entry worse than target water quality, Zhangjiakou should pay ecological compensation to Beijing; in CASE II, as the entry better than water quality objectives, Beijing should pay ecological compensation to Zhangjiakou conversely.

Indirect environmental externalities (ecological damage or eco-efficiency) should be into the accounting system of compensation. Using of CVM, this paper assessed the value of water ecosystem services in the Guanting reservoir areas. Based on assessment results, by drawing the S curve in “water quality - economic losses”, the difference value between of ecosystem services varies water quality were accounted to characterization the indirect environmental externalities of water activities of Zhangjiakou to Beijing.

We tried to establish a model which consisted of revenue functions of Beijing and Zhangjiakou respectively to quantify the profit of each city during water use. Considering the profit of each stakeholder, we calculated the exact payment when the water quality and quantity of the provincial trans-boundary section were in various situations. In that way, a market for water ecological service transactions, supported by ecological compensation, between Beijing and Zhangjiakou was established. The optimal allocation of water resources would work through the market transactions, leading to sustainable water use in this basin. The results indicated that: when the water quality of inflow to Beijing, was worse than National Water Quality Standard III, Zhangjiakou needed to pay Beijing the extra socio-economic water use benefits comparing to the initial right instead of the financial and ecological loss in Beijing under poor water quality; when the water quality of inflow was better than National Water Quality Standard III, Beijing needed to pay Zhangjiakou the additional ecological benefit comparing to the initial right instead of the pollution control cost spend in Zhangjiakou.
References


