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A Market-Based Payment Study for Forest Water Purification Service in Loess Plateau of Yellow River Basin, China

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Abstract: Freshwater scarcity is increasingly threatening social development and human survival, and more effective watershed environmental management measures are yet to be developed. Market-based payment is an innovative tool to coordinate the relationship between ecosystem services' supply and demand sides in watersheds, emphasizing the market (rather than government intervention) as the main means to regulate and control the behavior of interest-related subjects. We proposed a marked-based plan for forestry water purification service and stimulate the potential benefits of this plan under the zero transaction cost assumption. We applied and demonstrated the approach in the Loess Plateau of the Yellow River Basin (LPB) in China. By constructing the relationship between the higher reaches of annual forestry investment and the corresponding lower reaches of sediment concentration, we established forestry water purification service supply function (R^2 = 0.956). Then, connecting the agents' cost function of water treatment plants in the lower reaches with the forest water purification service, we obtained the forestry water purification service demand function (R^2 = 0.943). Combining both the service supply and demand functions, we stimulated the market equilibrium state. The results show that higher reaches will provide 13.164 kg/m^3 of water purification service by afforestation, and lower reaches can save RMB 2.131 billion annually via this service. This study suggests that marked-based payment between areas is feasible for a watershed ecosystem service, and promoting the establishment of watershed compensation market is a rewarding development direction. All of these insights provide a valuable reference point for Chinese horizontal ecological compensation practice.

Keywords: ecosystem service; forest water purification; horizontal ecological compensation; marked-based payment

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1. Introduction

Freshwater scarcity is one of the main challenges that humans will face this century [1]. Presently, about 66% of the global population experiences severe water scarcity for at least one month each year, and approximately 500 million people endure chronic water scarcity throughout the entire year [2]. Though China has large water resources, it also faces water deficiency, low-quality water, and other problems. The transportation of fine sediment through rivers can lead to significant negative impacts on aquatic ecosystem health, downstream infrastructure, and community water supply [3]. The forest ecosystem can effectively prevent the transportation to provide higher-quality water to people in lower reaches [4]. This function is called the forest water purification service. Within the scope of a basin, it is common that downstream areas enjoy a large amount of water purification services without paying for them, resulting in externalities and giving rise to shortage of supply and unfairness.

Payment for ecosystem services (PES, or payment for environmental services) is a conservation program that uses economic incentives for service providers to ensure a sustainable supply of ecosystem services [5,6]. In order to correct externalities, the Chinese government has propelled many watershed payment for ecosystem service (PES) projects [7];

these projects are mainly driven by government funding and are usually called vertical ecological compensation projects [8,9]. These projects have worked effectively in many places but still have faced some problems. Since vertical ecological compensation projects are mainly supported by government transfer payments, in some areas, the compensation efficiency is low, and it is considered insufficient to truly compensate for the economic losses in the affected areas [9]. Moreover, when the period of compensation project ends, the ecological environment of some areas may deteriorate again. To avoid such situation, the new central document has put forward the initiative of diversified ecological compensation [10]. It also has emphasized the horizonal ecological compensation mechanism as an important development direction in the future. Horizontal eco-compensation refers to a system that directly transfers payments for ecosystem services between local governments and interest-related subjects [9]; therefore, for an ideal horizontal eco-compensation project, the market has vital importance in regulating the supply and demand of the service, and the lack of perfect transaction mechanism hinders the realization of horizontal compensation.

Studies involving watershed water purification or freshwater supply value assessment are relatively common, but these studies often only estimate the value from the perspective of service supply [11,12], without considering the specific benefit that the downstream really receives. When propelling horizontal basin compensation projects, such studies pose difficulty for forming the basis for compensation by the downstream [13]. In particular, some studies have established econometric models based on the actual benefits of service beneficiaries [14,15]. Applying the panel dataset of Malaysia, Vincent J R et al. [16] developed econometric models that reflect the relationship between water treatment costs and forest cover change, suggesting that forest protection can reduce water treatment costs, especially for virgin forests. With the bioeconomic model estimated by the generalized method of moments, Fiquepron J. et al. [17] used the effect of the operating costs on drinking water price to calculate the benefit of water purification services provided by forests in France. These studies have answered the economic benefits of downstream from the upstream supply of services under certain conditions in the corresponding study area, but they lack the measurement of supply costs and the mechanism analysis in the decision-making process of upstream and downstream compensation participants. In addition, these studies do not contain the cost-benefit analysis of transactions, so it is difficult to measure the social benefits of horizontal basin compensation projects, which has important reference significance for deciding whether to promote this kind of project.

The Loess Plateau of Yellow River basin (LPB), located in the middle reaches of the Yellow River, has played a crucial role in the nation's social and economic progress and is an important drinking water source for around 200 million people in the lower reaches; however, the severe issue of soil erosion has been a longstanding challenge in this region, which has posed a significant threat to the livelihoods of people in the lower reaches for thousands of years [18]. LPB has been responsible for approximately 90% of the sediment load carried by the Yellow River [19], so its forest purification service significantly affects the quality of downstream water. In this paper, a market-based analytical framework is proposed to stimulate the service trade mechanism between an upper-reaches supplier and a lower-reaches demander in a horizontal compensation program. The framework was applied to the LPB to predict the potential economic benefits of horizontal compensation there, which helps to fill the knowledge gap and is conducive to the realization of horizontal ecological compensation. The remainder of the paper is organized as follows. In Section 2, we construct our analysis framework, mainly including basic elements, essential hypothesis, mathematical derivation process, and derivation result. In Section 3, we apply the analysis framework on our study area and acquire the potential trade surplus there, the main process can be described as the flowchart of Figure 1. In Section 4, we conclude our study and discuss its policy implications.

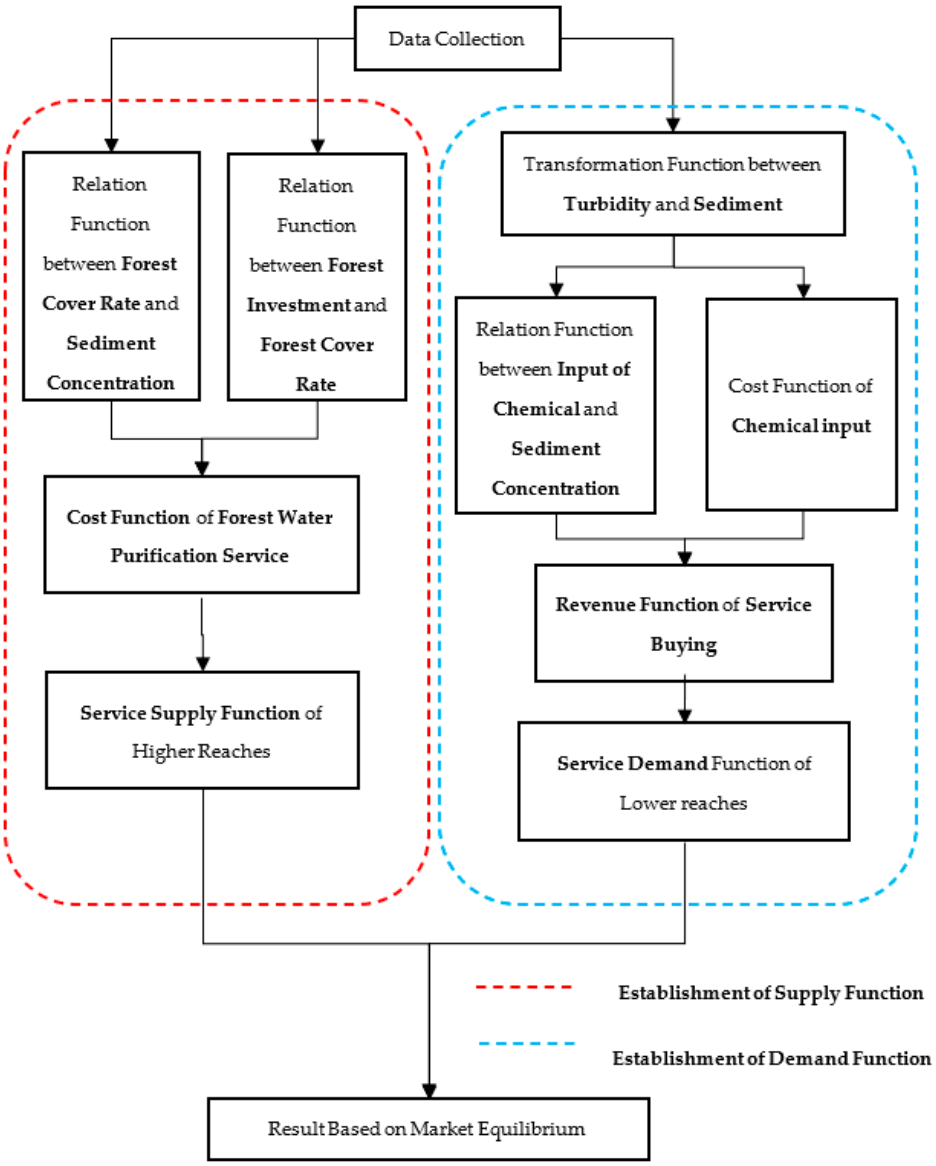


Figure 1. Flowchart of the empirical study process.

2. Modeling

2.1. Basic Elements

The analysis framework mainly contains three elements: the service being traded, the service provider, and the service demander. The improvement of raw water quality is the measurement of forest purification service. We adopted the sediment load concentration as the proxy of water quality, because on one hand, high sediment load is the most representative problem in the LPB in terms of water quality [19], and on another hand, most water quality problems are strongly correlated with sediment load [20].

Water treatment plants in the lower reaches are the demanders of the service. They are willing to participate in this market because purchasing water purification services from the higher reaches is a potentially profitable choice. These water treatment plants are obligated to produce water that meets the drinking water standards of downstream residents. They can use water treatment technology, purchase water purification services from the higher reaches, or combine both choices with different rates to achieve this obligation. The rate depends on whether they pay the lowest cost. And the amount of the service depends on the amount of money they are willing to pay for this service. Water treatment plants also

face limitations because they, as service buyers, can gain true financial benefits only if the service services provide the services they have sold [5].

Forest farmers are willing to participate in the market because they can earn more rewards via their forest protection behavior. They are regarded as the suppliers of forest water purification services in this study, and the amount of the service varies depending on the amount of money they offered in exchange for this service. Expanding the planting area of trees and vegetation, regularly pruning, clearing, thinning, strengthening patrol, preventing illegal logging, and other activities, the work of forest farmers in the higher reaches strengthens the prevention and control of forest diseases, pests, and fires, and promotes the ecological restoration and the restoration of damaged trees effectively slowing down the speed of water and soil loss and desertification in the basin. For forest farmers, market-based payment can really be an effective financial incentive only if they have general knowledge about the services they supply [21].

2.2. Model Hypothesis

Hypothesis 1. *The property rights of the forest purification service are clearly defined.*

It means the service belongs to the supplier who generates it and cannot be used by demanders without paying for it. According to the Coase theorem, well-defined property rights are the prerequisite for the optimal allocation of resources [22]. In the real world, however, the properties of many forestry ecosystem services are usually not defined, which can give rise to externality [19].

Hypothesis 2. *The supply of forest purification service in the upper reaches increases with the marginal cost.*

Although the area of the LBP is huge, its suitable area for afforestation is limited with its special physical geographical condition [23], and according to the China Forestry Statistical Yearbook, the number of forest farmers in the LBP varies little from year to year. Due to the limitations of the available land area and the number of people who can nurture the forest, the cost of supplying forest hydrological services in the upper areas is increasing at the margin [24].

The cost function of forest water purification service supply is represented as $C_S(q)$, in which q means amount of service supply by the upper reaches annually in our study area. The marginal cost function is presented as follows:

$$MC(q) = \frac{\partial C_S(q)}{\partial q} > 0 \quad (1)$$

According to Hypothesis 2, we can obtain:

$$\frac{\partial MC}{\partial q} = \frac{\partial^2 C_S(q)}{\partial q^2} > 0 \quad (2)$$

Hypothesis 3. *The water treatment of plants (WTPs) in the upper reaches is with increasing marginal cost.*

Let the cost function of water treatment be $C_T(x)$, where x represents the concentration of water been purified by WTPs; then, we have the water treatment marginal cost for WTPs:

$$MC_T(x) = \frac{\partial C_T(x)}{\partial x} > 0 \quad (3)$$

According to Hypothesis 3, we have:

$$\frac{\partial MC_T(x)}{\partial x} = \frac{\partial^2 C_T(x)}{\partial x^2} > 0 \tag{4}$$

Hypothesis 4. *The amount of water demanded in lower reaches is constant.*

The amount water demanded in the lower reaches is mainly used to maintain the life of its habitants and is decided to a large extent by its population. According to the Yellow River Almanac, the population in the lower reaches of the Yellow River changes little in a short period of time. To simplify the modeling, the amount of water demanded is assumed to be a constant value, defined as N.

Hypothesis 5. *The water pollutant concentration to be treated is constant.*

The water pollutant concentration to be treated is the difference of the water pollutant concentration between raw water that cannot be directly used by lower-reaches residents (also do not receive forest water purification services) and water treated by plants that meets the residents' domestic water standards. The concentration to be treated is determined jointly by the initial water quality of the upper reaches and the water quality standard of residential water. The latter is determined by the water quality standard of the study area and is generally fixed for a specific study area, while the former fluctuates with geology, climate, and other factors. Hypothesis 5 determines that it is a fixed value, so the treated water pollutant concentration is fixed. We define the treated water pollutant concentration as D_T; apparently, the water purification service q cannot surpass D_T.

Hypothesis 6. *The initial marginal cost is less than the initial marginal benefit.*

According to Hypothesis 3, $C_T(x)$ represents the cost to provide hydrologic service to residents in downstream areas, then $C_T(D_T)$ refers to the cost of the lower-reaches WTPs that apply water treatment technology independently to meet the consumption of water for local residents' living, without the supply of forest purification services generated by the upper reaches. $C_T(D_T - q)$ refers to cost of the lower-reaches WTPs using water treatment technology dependently, buying q units of purification service from the upper reaches. We define the revenue function of purchasing forest water purification services as $C_D(q)$; apparently, it can be represented as:

$$C_D(q) = C_T(D_T) - C_T(D_T - q) \tag{5}$$

Taking the derivative of both sides of Equation (5), we can obtain the marginal revenue function as:

$$MR(q) = \frac{\partial C_D(q)}{\partial q} = -\frac{\partial C_T(D_r - q)}{\partial q} > 0 \tag{6}$$

According to Equation (4),

$$\frac{\partial MR(q)}{\partial q} = \frac{\partial^2 C_D(q)}{\partial q^2} = -\frac{\partial^2 C_T(D_r - q)}{\partial q^2} > 0 \tag{7}$$

According to Hypothesis 6, we have:

$$MC_T(0) < MR(0) \tag{8}$$

Hypothesis 7. *Zero transaction cost between the upper and lower reaches.*

In reality, the transaction costs exist in many respects [25]. The possible costs include not only the cost of information searching and negotiation but also the cost of measuring service volume, as well as the cost of maintaining market order, building the conflict–resolution mechanism, and others. These costs are common but hard to measure. This study focuses mainly on the benefits of the trade, so in most parts of this paper, the transaction cost is assumed to be zero.

2.3. Model Equilibrium

According to Equations (4), (7) and (8), with $MC(q)$ and $MB(q)$ as continuous functions, there must be $\exists\alpha \in [0, D_T]$ so that $\forall q \in [0, \alpha]$. Therefore, we always have:

$$MR(q) \geq MC(q) \tag{9}$$

We define $q^* = \max\alpha$. The maximum of α means the threshold that market participants cannot obtain more revenue if they make more deals, so q^* represents the threshold at the equilibrium state. With the zero transaction hypothesis, the rational lower-reaches WTPs are willing to participate in the transaction and pay for each unit service as long as the price of each unit is less than the marginal revenue. The same is true for the foresters in the upper reaches: they, as rational persons, are willing to trade and supply the service with a higher payment than the marginal payment for each unit of service. Based on these, q^* units of service could be the equilibrium in their transaction; as for the price P, we have:

$$MR(q) \geq P \geq MC(q) \tag{10}$$

Equation (10) is important because it represents that the trade is acceptable for both the demander and supplier. When the trade reaches equilibrium, there is a surplus of the transaction of forest water purification services:

$$TS = \int_0^{q*} (MR(q) - MC(q))dq \tag{11}$$

TS refers to the trade surplus. It is an important economic conception, which measures the total returning of the trading for society under zero transaction cost conditions. Equation (11) represents the trade revenue from the difference between the marginal revenue of the lower reaches and the marginal cost of the higher reaches. Furthermore, if we conceal the zero transaction cost assumption and define transaction costs as F_{TC}, then we can obtain the net trade surplus as:

$$NTS = TS - F_{TC} \tag{12}$$

Transaction costs are a famous economic term first proposed by Coase, which reveals that market operations come with costs [26].The costs include the cost of clarifying and protecting service property rights, information searching cost, negotiation cost, supervision cost, and others [27]. Therefore, transaction costs could be thought as the main impediment for the realization of trade beneficial in a service transaction between higher and lower reaches. NTS (i.e., Net Trade Surplus) is the conception based on TS, bringing the transaction costs into consideration. The trade can only happen if the net trade surplus is greater than. Based on forementioned Hypotheses 1–6, with the zero transaction of Hypothesis 7, the reward of the trade is TS. And without Hypothesis 7, this trade exists only if the trade surplus is more than the transaction costs, i.e., $NTS \geq 0$.

3. Empirical Study

Based on the forementioned model analysis framework, this paper takes the LPB and the lower reaches of the Yellow River as the study area, and we constructed the service supply and service demand function of forest water purification service based on the

relevant statistical and geographic information data in the study area from 2000 to 2019. Applying both models, we obtained the eventual result in a marked equilibrium state.

3.1. Study Area and Database

3.1.1. Study Area

The studied watershed mainly contains two parts: the LPB, which is located in the middle reaches of the Yellow River, and the lower reaches of Yellow River. These areas have a typical continental climate, which is cold, dry, and seasonally variable. The topography of the LPB varies greatly, with altitude between 800 m and 3000 m; it is also the most severe area of soil and water loss on earth [28]. In recent years, the vegetation cover (Figure 1) of the LPB has increased largely, and its sediment transport has reduced with the propulsion of afforestation [29]. The lower reaches of the Yellow River are mainly located in Henan and Shandong Province; there are around 200 million citizens living there, part of whose water is fetched from Yellow River.

3.1.2. Database

The annual forest cover data of Shaanxi and Shanxi in LP during 2000–2019 were calculated based on Huang's 30 m spatial resolution land use data [30]. Monthly precipitation data during 2000–2019 were acquired from the Historical Data Set of Surface Meteorological Observation in China collected by the China Meteorological Data Service Centre. The annual forestry investment data during 2000–2019 were referenced from the China Forestry Statistical Yearbook or the China Forestry and Grassland Statistical Yearbook; the value we used only includes afforestation and forest tending terms, and other investment terms, like forestry industry development, are exempt in this study. The annual river sediment concentration data of the lower reaches were from the Longmen hydrological station, obtained from the Bulletin of River Sediment in China. The Henan Province and Shandong Province are located on the lower reaches, and the people there are the main consumers of the forest water purification. The population of these provinces was obtained from Yellow River Almanac in 2022. The water plant water treatment chemical data were referenced from the Study of Zhao Rong et al. [31], and water treatment chemical price was based on market investigation.

3.2. Supply Model of Forestry Water Purification Service

An ecosystem service supply model is a function of service quantity with respect to supply cost; however, there is no function model directly linking those two variables in relevant studies, so intermediate variables are needed. Studies have suggested that afforestation significantly mitigates soil erosion and reduces sediment yield [32,33], so the forest water purification service is largely decided by the forest area which can be measured by the forest cover rate. And in China, the change of forest coverage in the study area is, to a large extent, determined by the forestry investment for afforestation and forest tending. Therefore, we established two functions, including the relation function of forest cover and sediment yield, and the relation function of forest investment and forest cover rate. Then, we took the forest cover rate as the intermediate variable connecting forest investment and water purification service to construct the forest water purification service supply function.

3.2.1. Relation Function between Forest Cover Rate and Sediment Concentration

The forest cover rate was mainly calculated based on geographic information data. First, we extracted the land use data of the LPB area (Figure 2) from Huang's 30 m resolution land use data of China [30]. Then, we divided the forest cover area of the LPB by the total area of the LPB to obtain the forest coverage rate. We conducted this operation year by year from 2000 to 2019 to obtain annual forest cover rate data. All of the above calculation processes are based on the software ArcGIS 10.8.

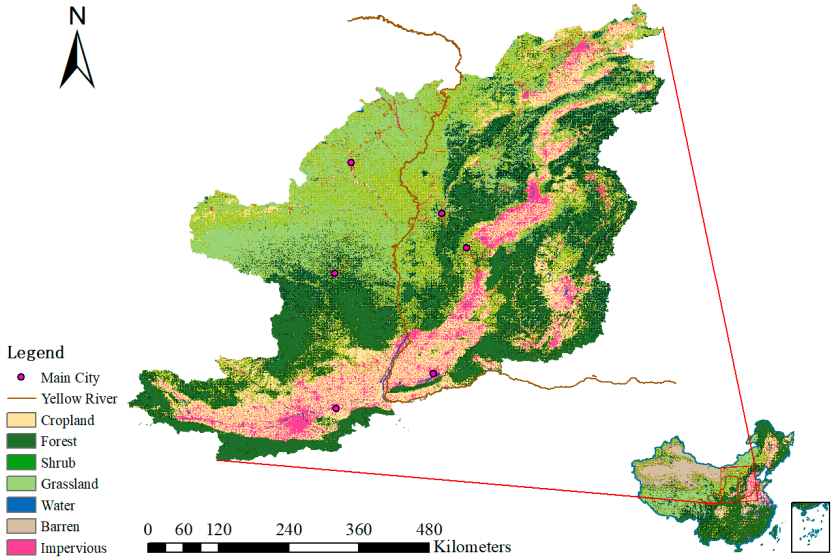


Figure 2. Studied area in the LPB.

We do not have specific prior quantitative knowledge about how forest cover rate affects sediment concentration, so we regressed the available data with different function forms and then selected the best fit. The relevance of the influence of forest cover on sediment concentration is thought to be an empirical problem [14]. Therefore, we referred to relevant papers about function form [16,34,35] and eventually sorted out seven forms of equations (Table 1). We regressed sediment yield data, forest cover rate data, monthly precipitation data, and monthly summit precipitation data in these function form, and the result is shown in Table 2.

Table 1. Forms of the regression function of Sc and Fc.

The Form of the Regression Equation
$Sc1 = a + b \times Fc + c \times Pa + d \times Ps$
$Sc2 = e^{a+b\times Fc+c\times Pa}$
$Sc3 = e^{a+b\times Fc+d\times Ps}$
$Sc4 = e^{a+b\times Fc+c\times Pa+d\times Ps}$
$Sc5 = e^{a+b\times Fc} + c \times Pa$
$Sc6 = e^{a+b\times Fc} + d \times Ps$
$Sc7 = e^{a+b\times Fc} + c \times Pa + d \times Ps$

where Sc refers to sediment concentration, Fc means forest cover rate, Pa is the annual precipitation. And Ps refers to month summit precipitation month summit precipitation annually.

According to the regression result, function (6) gains the highest R square value, and all coefficients are significant (with $p < 0.05$); according to statistical methodology, we choose it as the eventual function:

$$Sc = e^{35.577-158.586Fc} + 0.003Ps \quad (13)$$

Equation (13) reveals the quantitative relation between the forest cover rates of the upper reaches and the raw water sediment concentration of the lower reaches.

Table 2. Regression results of Fc and Sc.

	(1) Sc1	(2) Sc2	(3) Sc3	(4) Sc4	(5) Sc5	(6) Sc6	(7) Sc7
Con							
_cons	79.661 ***	13.307 ***	13.119 ***	14.982 ***	36.123 **	35.577 **	34.984 **
	(19.211)	(2.307)	(2.435)	(2.783)	(14.645)	(12.816)	(13.245)
Fc							
_cons	−278.033 ***	−47.203 ***	−49.913 ***	−54.981 ***	−161.375 **	−158.586 **	−155.675 **
	(86.713)	(11.340)	(12.194)	(13.713)	(70.391)	(61.559)	(63.682)
Pa							
_cons	−0.002	−0.000		−0.000	0.001 ***		−0.000
	(0.002)	(0.000)		(0.000)	(0.000)		(0.001)
Ps							
_cons	0.002		−0.000	0.001		0.003 ***	0.004
	(0.004)		(0.000)	(0.001)		(0.001)	(0.003)
N	20	20	20	20	20	20	20
adj. R^2	0.366	0.864	0.857	0.868	0.895	0.906	0.901

Standard errors in parentheses. ** $p < 0.05$, *** $p < 0.01$.

3.2.2. Relation Function between Forest Cover Rate and Forestry Investment

Forests provide a variety of ecosystem services. Referencing the relevant literature [36], we acknowledge that the value of water purification services in the upper reaches of the Yellow River accounts for about 5% of the total value of forest ecosystem services. Based on this, we calculated the forestry investment of forest water purification services in the LPB.

Forestry investment in the study area is continuous annually, and the annual increase in forest cover is logically related not only to the many forestry tending and planting supported by forestry investment in the current year but also to the forestry investment in previous years, especially in the recent past. Because those seedlings planted with the support of forestry investments in previous years go through a phase of rapid growth, they contribute more forest cover growth in subsequent years. For the consideration of this mechanism, we construct a linear regression model with time lag term to better reveal the quantitative relationship between forestry investment and forest cover rate.

The impact of forestry investment on forest cover on a specific area is, to a large extent, an empirical problem. The impact of the forestry investment on the forest cover in different countries or regions shows great heterogeneity [37], and since we have no predetermined experience within the LPB, we carried out linear regression for the forestry investment from the current period to the ninth stage of lag one by one. The results are as follows; we applied statistical methodology and chose a higher goodness-of-fit as the criterion to select the final model:

The result (Table 3) shows that the fourth-order lag term has the best fitting effect (with $R^2 = 0.956$). We used it as our final regression result and constructed the regression function of forest cover on forestry investment; the specific function is as follows:

$$Fc = 0.20781 + 0.00106 \times Invest(t) + 0.00177 \times Invest(t-4) \quad (14)$$

where the unit of Invest in Equation (14) is RMB one billion, and for the convenience of subsequent processing, we convert the lag term to current period at an annual interest rate of 5%; the converted formula is as follows:

$$Fc = 0.20781 + 0.00321 \times Invest(t) \quad (15)$$

Table 3. Regression results of the forest cover rate and forestry investment.

	(1) Fc0	(2) Fc1	(3) Fc2	(4) Fc3	(5) Fc4	(6) Fc5	(7) Fc6	(8) Fc7	(9) Fc8	(10) Fc9
Invest	0.00296 ***	0.00086	0.00091	0.00093 **	0.00106 ***	0.00005 ***	0.001 ***	0.00111 ***	0.00129 ***	0.00101 ***
	(0.0003)	(0.00104)	(0.00066)	(0.00042)	(0.0002)	(0.00001)	(0.0003)	(0.0003)	(0.0003)	(0.0003)
L1.Invest		0.00206 * (0.00099)								
L2.Invest			0.00198 *** (0.00058)							
L3.Invest				0.00191 *** (0.0004)						
L4.Invest					0.00177 *** (0.0002)					
L5.Invest						0.00170 *** (0.0002)				
L6.Invest							0.00185 *** (0.0002)			
L7.Invest								0.00194 *** (0.0002)		
L8.Invest									0.00216 *** (0.0002)	
L9.Invest										0.00262 *** (0.0002)
_cons	0.20396 ***	0.20513 ***	0.20630 ***	0.20781 ***	0.20891 ***	0.21059 ***	0.21200 ***	0.21195 ***	0.21048 ***	0.21298 ***
	(0.00239)	(0.00251)	(0.00248)	(0.00205)	(0.00146)	(0.00153)	(0.00195)	(0.0023)	(0.00263)	(0.00269)
N	20	19	18	17	16	15	14	13	12	11
adj. R^2	0.833	0.842	0.868	0.913	0.956	0.955	0.938	0.933	0.944	0.952

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Equation (15) is the eventual equation to reveal the relation between the forest cover rate and forest investment.

3.2.3. Supply of Forest Water Purification Service

According to Equations (13) and (15), we obtained the supply function of forest water purification service as:

$$Sc = e^{2.621-0.509\times Invest} + 0.003 \times Ps \quad (16)$$

It can be obtained from Equation (16) that without the forest investment for the upper reaches (i.e., $Invest = 0$) and depending merely on upper reaches natural endowments, the lower-reaches sediment concentration would have $Sc_0 = 13.749 + 0.003Ps$.

We define the reduction of sediment concentration provided by upper reaches from forest farmers' afforestation and forest tending behavior as forest water purification services, and we define the amount of forest water purification services provided by upper foresters as q. Therefore, we can obtain:

$$q(Invest) = Sc(0) - Sc(Invest) \quad (17)$$

Furthermore, $Invest$ can be represented as the function of q:

$$Invest = 0.5149 - 0.1965 \times \ln(13.749 - q) \tag{18}$$

Taking the derivative of both sides, we obtain the marginal cost of the forestry water purification service of the upper-reaches forester:

$$MC = \frac{\partial Invest}{\partial q} = \frac{0.1965}{13.749 - q}, 0 < q < 13.749 \tag{19}$$

Apparently, the marginal cost of upper reaches is increasing, in agreement with Hypothesis 2. Also, Equation (19) refers to the upper-reaches supply function of the forest water purification service.

3.3. Demand of Forest Water Purification Service

The water quality of the upper reaches in this study was mainly measured by its sediment concentration, while, for most lower-reaches water treatment plants, turbidity is used much more frequently as a sediment load measurement index in their database, so the unit must be converted. According to relevant study [38], their relation function is as follows:

$$Tb = 357.143 \times Sc + 4 \tag{20}$$

where Tb refers to the turbidity of water, and Sc means water sediment concentration.

In the wastewater treatment industry, PAC and PAM are widely used as coagulant and flocculation in the water plant process. Here, we used them as the main indices to measure the treatment cost of water plants. First, we performed a regression for water turbidity and the input of chemical.

The regression result (Table 4) is significant, so we can obtain:

$$\ln \frac{Tbr}{Tbt} = y = 0.023 \times Pac + 7.080 \times Pam \tag{21}$$

where Tbr means the turbidity of raw water, Tbt refers to the turbidity of treated water, and Pac and Pam represent the unit input of PAC and PAM as coagulant and flocculation, respectively. Since D_T refers to treated water pollutant concentration, we can obtain:

$$Tbr = Tbt + D_T \tag{22}$$

Table 4. Regression results of the turbidity and chemical input.

	Y
Pac	0.023 ***
	(0.003)
Pam	7.080 ***
	(1.067)
N	23
adj. R^2	0.943

Standard errors in parentheses. *** $p < 0.01$.

Using the corresponding data, the precipitation data from 2000 to 2019 was calculated as 1409 mm, i.e., $Ps = 1409$, so we have the original sediment concentration Sc_0:

$$Sc_0 = 13.749 + 0.003 \times Ps = 17.978 \tag{23}$$

The water treatment cost function of the lower-reaches plant is presented as follows:

$$C_T = (P_{Pac} \times Pac + P_{Pam} \times Pam) \times W_{demand} \tag{24}$$

where W_{demand} represents the total amount of water demanded by the lower reaches, and P_{Pac} and P_{Pam} are the price of PAC and PAM, respectively. According to Equations (22) and (24), Hypothesis 3 is satisfied. Then, we can obtain the total revenue of the lower reaches with ecosystem service supply. Obviously, it is the function of the service provided by the upper reaches:

$$TR(q) = C_{T0} - C_{T1} = C_T(Tbr_0) - C_T(Tbr_0 - Tb(q)) \tag{25}$$

where C_{T0} represents the water treatment cost of the lower reaches without upper-reaches forestry investment, and C_{T1} represents the cost of the lower reaches when the upper reaches provide forestry investment.

According to the Chinese Standards for Drinking Water [39], the water turbidity should not exceed 3NTU; therefore, in this study, $Tbt = 3$. According to the Yellow River almanac in 2022, the number of people in the lower reaches in the Henan and Shandong Provinces are 99.37 million and 101.53 million, respectively, and each of them consumed 239 m^3 and 219.5 m^3 of water, respectively, in one year. Based on these data, the amount of water needed in lower reaches was calculated to be around 46 billion m^3. Based on the market investigation, the average price of PAC and PAM are RMB 1000/t and RMB 10,000/t, i.e., RMB 0.001/g and RMB 0.01/g. Appling these data, the marginal revenue was calculated as follows:

$$MR(q) = \frac{\partial TR(q)}{\partial q} = \frac{577.500}{6420.715 - 357.143 \times q} \tag{26}$$

Upward revenue curve is unusual, the main reason is that the water purification service we adopt is not a standardized commodity. For example, reducing the concentration of the unit from 200 g/m^3 to 150 g/m^3 will cost less than reducing the concentration from 150 g/m^3 to 100 g/m^3, although they are same in the reduction of sand, which means that the same reduction of sediment in the upper reaches for cleaner water will bring more benefits to the lower reaches, which indicates the increment of marginal return.

3.4. Result

Equations (19) and (26) form a trade system. The upper-reaches supplier and lower-reaches demander, as rational agents, will bargain with each other until the system reaches an equilibrium. Then, we can obtain the equilibrium intersection point (p, q^*), where $q^* = 13.164$ and $p = 0.336$. In the equilibrium state, the TS will reach its summit (Figure 3), and social welfare reaches its optimal state.

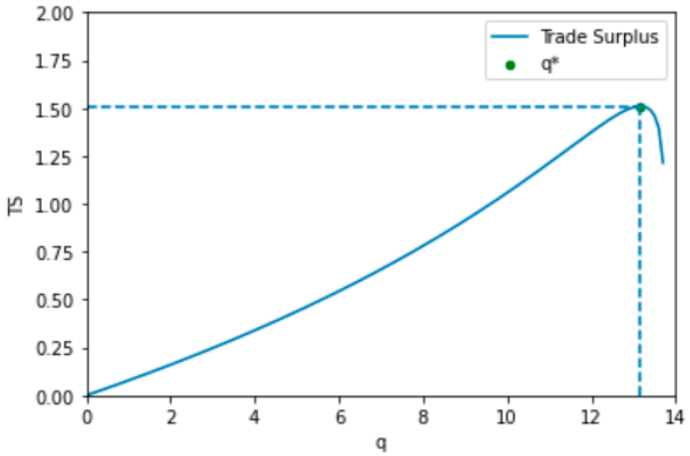


Figure 3. Change of the TS with the service amount.

The equilibrium point is helpful to ensure the efficient allocation of social resources, and it is also meaningful for both the upper and lower reaches. For the lower reaches, it indicates their actual demand for forest water purification services under current technical constraints. For the upper reaches, it reveals the real demand of the society for this service, and that can lead to their optimization of production processes and the more efficient use of funds. The total social benefit of this trade, which is measured by the trade surplus (TS), is calculated as:

$$TS = \int_0^{q^*} [MR(q) - MC(q)]dq = \int_0^{13.164} [\frac{577.500}{6420.715 - 357.143 * q} - \frac{0.1965}{13.749 - q}]dq \quad (27)$$

The eventual value $TS = 1.510$, i.e., the total transaction surplus, is RMB 1.510 billion. In the equilibrium state, the forest investment is calculated as:

$$Invest^* = \int_0^{q^*} MC(q)dq = \int_0^{13.164} \frac{0.1965}{13.749 - q}dq = 0.620 \quad (28)$$

Therefore, in order to obtain high-quality water resources, the lower-reaches service demanders are willing to pay, at most, RMB 2.131 billion to the higher reaches, and the higher-reaches service supplier needs at least RMB 0.620 billion to cover their afforestation cost. Zhang et al. [40] estimated the value of forest purification services in the Loess Plateau region as RMB 20.900 billion; this assessment was based on these Chinese terrestrial ecosystem service value equivalent compared with their estimation. Our result may be an underestimation for forest purification services, but their result does not consider to what extent these service benefit the lower reaches; therefore, it may be hard for the lower reaches to accept and offer payment, which may make it difficult to propel a horizonal ecological compensation program. Though our estimation is lower than the relevant study, our result may be closer to the real trade market in the future. As RMB 1.510 billion of trade surplus is a substantial profit for social benefit gain in the LPB, it can bring large environmental improvement at the watershed scale with less costs. And the huge revenue can attract more social capital and related resources to participate in this market, which may further promote the effective development and utilization of new technologies for watershed ecological protection. Extensive social participation will also stimulate the gradual improvement and maturity of the relevant laws, regulations, and management systems.

4. Discussion and Conclusions

4.1. Discussion

(1) Benefits

The results have showed that, in an ideal condition, the establishment of a forest water purification service at the watershed scale is a rewarding institutional arrangement. The society will gain RMB 1.510 billion of trade surplus, and the abundant market revenue makes it possible to ensure the interests of joint agents. In traditional vertical ecological compensation, the central government has been under enormous financial pressure; at the same time, higher reaches are forced to supply forest ecosystem services but they usually do not receive enough compensation to offset their opportunity cost [9]. Based on the trade market, the lower-reaches water treatment plants can receive a higher quality of water in a more economical way via their payments to upper-reaches forest farmers. Meanwhile, the payment from the lower reaches will be a strong financial incentive for the upper reaches to invest more human and material resources to protect and restore forest ecosystems so that more water purification services are provided.

(2) Transaction Costs

Enough low transaction costs are vital for market-based payments at the watershed scale. The result of this paper can happen, of course, only with zero or low transaction costs. The costs consist of the service measurement cost, negotiation cost, conflict resolution

cost, and others. The large negotiation cost and conflict resolution cost mainly come from the lack of real service market mechanisms and the uncomplete content of relevant laws and regulations; if these problems had been solved, then it would be possible to reduce these costs possible to a low level. In fact, the Chinese government is actively searching for reform, and marked-based compensation has been formally proposed since 2018 [41]. Such policy will undoubtedly be helpful to reduce the transaction costs.

Based on relevant data of the LPB and the lower reaches of the Yellow River, this paper roughly measured the supply and demand of forest water purification service there, which partly solved the problem of high measurement cost. However, it is still far from perfect, and we consider the forest water purification service only as the saved drinking water cost for lower reaches. The service can also help to reduce or avoid the silting of downstream river and have other potential benefits; these benefits were not calculated as the payment, eventually leading to the underestimation for the service. Forest ecohydrological process is extremely complicated, and human scientific knowledge is still very limited [42]. To better measure the service, on one hand, deeper scientific research is needed, especially fundamental studies about forest ecohydrological mechanisms; on the other hand, the transformation from fundamental scientific research knowledge to service measurement must be strengthened.

(3) Potential applications

The results of this study have good reference significance for the LPB in the middle Yellow River Basin. The results show that the establishment of the forest water purification service trading market in the LPB has considerable returns, but the establishment needs to overcome a large number of transaction costs. Currently, due to the lack of relevant laws, regulations, and corresponding conflict–resolution mechanisms, we suggest the establishment of a pilot market, and the government should be the main sponsor for this establishment.

Considering that more forest ecosystem services may make it helpful to address environmental challenges more comprehensively, the analytical framework of this study may also be applied to forest water purification services in other watersheds in China, and the trade surplus value can be an instructive index to decide whether it is worthy to establish a service market there. The research paradigm of this paper may also be expanded to the forest flood reduction service trading market between higher and lower reaches, as long as the measurement can be changed from forest water purification to forest flood mitigation and downstream willingness to pay can be replaced by the potential damage caused by a flood.

The ecological impact of forest-providing services deserves further study because there may be trade-offs or synergies between different forest ecosystem services (e.g., more forests may reduce the available amount of local water to some extent, but it may have other positive effects, such as carbon sink and water purification). The research of coupling multiple ecological markets may be a direction worth exploring in the future.

4.2. Conclusions

In conclusion, we have simulated an ideal service trading market with zero transaction costs. The simulation results show that with clearly defined property rights, the trading of forest water purification services between upstream and downstream can generate considerable market returns. Based on the relevant data of the middle and lower reaches of the Yellow River in China, we conducted an empirical study, and the results show that, without considering the transaction costs, the upstream and downstream water purification service transactions can bring large market benefits. However, it is obvious that the transaction costs are still very large in reality, which is the main obstacle to higher- and lower-reaches service transactions [43]. Based on the realization of the many benefits calculated by the forementioned model, improving relevant systems, promoting the establishment of upstream and downstream forest water quality service trading markets,

and reducing transaction costs are key to optimizing the existing ecological compensation project. It is worth exploring a path to achieve win-win results and protect natural ecology.

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