A STUDY ON CROSS-REGIONAL ECOLOGICAL COMPENSATION STANDARDS IN THE WEIHE RIVER BASIN: A DUAL-BENEFIT AND SIGNALING GAME PERSPECTIVE

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Abstract. The spatial mismatch between ecological responsibility and benefits across provinces, caused by watershed ecological continuity and administrative fragmentation, presents a core challenge in determining fair cross-regional compensation standards. Focusing on the Weihe River Basin, this study introduces a "dual-benefit perspective" framework. It defines the compensation upper limit (5.168 billion CNY) based on downstream willingness to pay (WTP) and alternative governance costs, while the lower limit (2.369 billion CNY) is derived from upstream ecological protection costs. This creates a compensation negotiation range (2.369–5.168 billion CNY). Additionally, a signaling game model addresses information asymmetry in negotiations, simulating how upstream governments convey their benefits and how downstream governments adjust their strategies. Results show that public awareness can encourage high-benefit upstream governments to invest more in ecological governance, promoting a separating equilibrium. This research offers an integrated solution for scientifically determining compensation standards and designing incentive-compatible mechanisms in cross-regional watershed governance.
Keywords: *ecological compensation standards, dual-benefit perspective, signaling game model, Weihe River Basin, cross-provincial region*

Introduction

The spatial flow of watershed ecosystem services and the rigid segmentation imposed by administrative boundaries constitute a fundamental contradiction in modern watershed governance. Against the backdrop of deepening ecological civilization initiatives, watershed ecological protection is closely linked to national ecological security and regional sustainable development capacity. However, the positive externalities of ecological protection result in a spatial separation between those who bear the costs and those who benefit. This gives rise to a dilemma of mismatched rights and responsibilities: protectors struggle to receive benefits, while beneficiaries offer little compensation. This institutional imbalance is especially acute in large river basins that span multiple provinces—upstream regions bear the costs of ecological protection and forgo development opportunities, while downstream regions enjoy improved water quality and water conservation without bearing the corresponding ecological costs. Establishing a scientifically grounded and incentive-compatible horizontal ecological compensation mechanism has become key to resolving the "tragedy of the commons" in watershed management, and enabling the transformation of “lucid waters and lush mountains” into “mountains of gold and silver” (Zhang et al., 2023; Guan et al., 2024; Shao et al., 2025).

At the national strategic level, the need for quantitative ecological compensation standards has been clearly articulated. Policy documents such as the Action Plan for Establishing Market-Oriented and Diversified Ecological Protection Compensation Mechanisms, the 14th Five-Year Plan for Ecological and Environmental Protection, and

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the Outline of the Plan for Ecological Protection and High-Quality Development of the Yellow River Basin all emphasize the establishment of "scientific compensation standards based on cost–benefit analysis" to coordinate ecological interests between upstream and downstream regions, as well as across both riverbanks. The practical difficulties faced in the Yellow River Basin highlight the concentration of this challenge. As the largest tributary of the Yellow River, the Weihe River Basin plays a critical role in supporting the Guanzhong–Tianshui Economic Zone, yet it suffers from severe ecological degradation due to legacy issues from historical overdevelopment and a lack of interprovincial coordination. According to the Gansu Provincial Water Resources Bulletin (2022), 23.1% of monitored river sections in the basin consistently fall below Class IV water quality standards, which is far from meeting the targeted Class II standards, thereby directly threatening drinking water security and agricultural irrigation for over ten million people in the middle and lower reaches.

In response to the above challenges, the Chinese government has successively introduced several reform documents on ecological compensation systems, explicitly calling for the improvement of horizontal compensation mechanisms to ensure the equitable distribution of interests among upstream and downstream areas, both riverbanks, and between main and tributary streams. The Action Plan for Establishing Market-Oriented and Diversified Ecological Protection Compensation Mechanisms, the 14th Five-Year Plan for Ecological and Environmental Protection, and the Outline for Ecological Protection and High-Quality Development in the Yellow River Basin all explicitly call for quantifiable cross-regional ecological compensation standards (Kazemi et al., 2022; Niu et al., 2024). Meanwhile, upstream regions such as Dingxi and Tianshui have imposed strict industrial restrictions to protect water sources, sacrificing over one billion yuan in annual secondary industry growth potential, while downstream beneficiary areas have not fully borne the associated costs. This disconnect between "protector" and "beneficiary" roles urgently calls for fair and efficient compensation standards to close the institutional loop, whereby protectors are rewarded and beneficiaries pay (Selva et al., 2019; Costanza, 2020; Verde Zhang and Zhang, 2023).

Current ecological compensation standard calculations primarily rely on two methodological paradigms: the cost-based approach and the benefit-based approach. The cost-based approach focuses on the expenditures incurred by the protection side, such as Chen and Cheng (2018), who calculated compensation amounts in the Ningxia Basin based on water quality and quantity metrics. Although this method is operationally simple, it systematically underestimates the value of ecosystem services, and fails to address the difficulty of quantifying opportunity costs, such as the implicit loss of development rights (Duan et al., 2010; Yu et al., 2017; Xu et al., 2018). As a result, it leads to insufficient compensation and weakened incentives. The benefit-based approach is grounded in the willingness to pay (WTP) of the beneficiaries, and typically evaluates downstream gains using contingent valuation methods (CVM) or gross ecosystem product (GEP) (Ge et al., 2009; Xu et al., 2012; Su et al., 2017). However, WTP is prone to strategic bias, and GEP estimates are often model-dependent and may fail to reflect actual market value (Zhao and Wang, 2010; Yao et al., 2017). Although the choice experiment (CE) method improves WTP estimation through multi-attribute decision modeling (Yao et al., 2017), both approaches suffer from fundamental limitations: a unidimensional perspective that severs the cost–benefit linkage, failing to integrate the cost burden of compensators with the benefit gains of recipients (Costanza, 2020); and static valuation approaches that ignore behavioral interactions, particularly the strategic behavior of governments under

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asymmetric information (Liu et al., 2022), resulting in a persistent fairness–efficiency trade-off in standard-setting.

To overcome the aforementioned limitations, this study proposes an innovative "dual-benefit perspective" framework. The lower bound of compensation is anchored to the net protection cost borne by upstream regions (i.e., direct costs + opportunity costs − ecological co-benefits), ensuring the basic rights and interests of ecological protectors. The upper bound is determined by the total benefit received by downstream regions (i.e., willingness to pay + avoided governance costs), thereby constraining the payment responsibilities of beneficiaries. By coupling the value chains of both supply and demand sides, the framework delineates a negotiable compensation interval for the first time, rather than relying on a single-point estimate. This provides a scientifically grounded reference point for cross-regional negotiation.

However, the implementation of compensation standards faces a core institutional challenge: incentive distortion under asymmetric information. Upstream actors may exaggerate their costs or reduce their actual effort levels, while downstream parties, unable to verify true ecological performance, tend to suppress compensation levels. Traditional command-and-control regulatory approaches entail prohibitively high transaction costs in cross-provincial contexts (Deng and Chen, 2022). To address this, the study introduces a signaling game framework to unpack the behavioral black box. It models upstream governments as either high- or low-return types within a typological strategy space, and characterizes their private information through two observable signals: effort level and compensation request. A Bayesian updating mechanism is designed for downstream governments, enabling them to adjust compensation strategies dynamically in response to upstream signals. The model reveals the catalytic role of public awareness in achieving separating equilibrium, thus facilitating the evolution of the compensation mechanism toward incentive compatibility.

Overview of the study area and data sources

Overview of the study area

As shown in *Figure 1.*, the Weihe River originates from Niaoshu Mountain in Weiyuan County, Dingxi City, Gansu Province. Its main stream flows west to east across Gansu, Ningxia, and Shaanxi provinces (or autonomous region). It finally joins the Yellow River at Tongguan County, Weinan City, Shaanxi Province. The river has a total length of 818 kilometers and a drainage area of 134,000 square kilometers. It is the largest primary tributary of the Yellow River. The spatial distribution of the basin exhibits notable interprovincial disparities 49.8% of the basin lies within Shaanxi, 44.1% in Gansu, and only 6.1% in the Ningxia Hui Autonomous Region. As the "mother river" of the Guanzhong Plain, the Weihe River flows through 22 counties and districts across five major cities in Shaanxi: Baoji, Yangling, Xianyang, Xi'an, and Weinan This forms the economic core corridor of the province. This region hosts 64% of Shaanxi's permanent population, and contributes 65% of its regional GDP. Agricultural irrigation, industrial use, and urban water supply in the region are heavily dependent on Weihe River resources. Particularly within the framework of the Guanzhong–Tianshui Economic Zone, the Weihe serves as a foundational water source and ecological corridor, directly supporting the sustainable development of this national-level economic belt.

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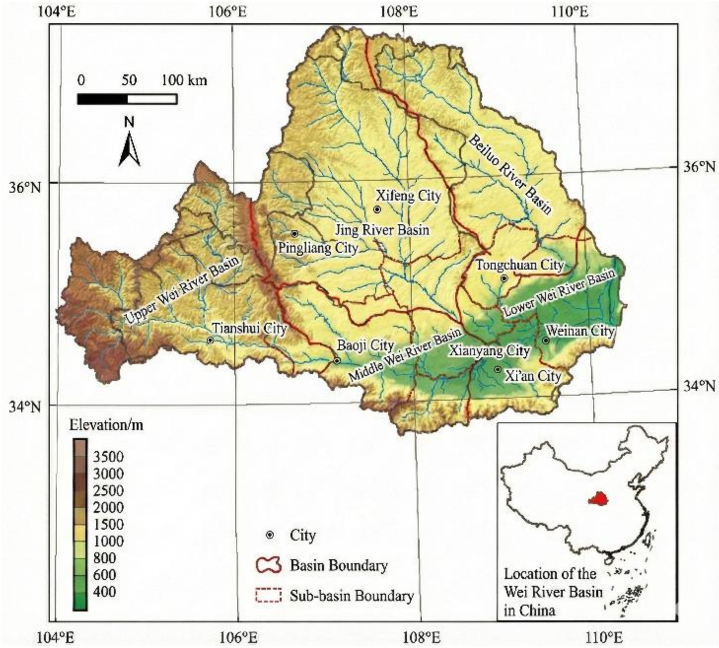

Figure 1. *Location map of the Weihe River Basin*

Data sources

The data used in this study consist mainly of questionnaire survey data and statistical and environmental monitoring data. The questionnaire data come from a stratified household survey of residents in the Weihe River Basin. The survey covered residents across the upper, middle, and lower reaches of the basin. After screening, 669 valid questionnaires were obtained, covering respondents' basic socio-demographic characteristics and their preferences for ecological improvement scenarios, with 154 respondents (23.0%) from the upper reaches (Gansu section: Dingxi and Tianshui), 217 respondents (32.4%) from the middle reaches (Shaanxi section: Baoji and Yangling), and 298 respondents (44.6%) from the lower reaches (Shaanxi section: Xianyang, Xi'an, and Weinan). These data are used to estimate the Random Parameter Logit (RPL) model and the willingness to pay of midstream and downstream residents. Statistical and environmental data are mainly drawn from the Environmental Protection Database, the Gansu Statistical Yearbook, the Shaanxi Statistical Yearbook, and municipal statistical yearbooks, covering the period 2001–2022. GDP and land-area data for 2001–2022 are used to construct the economic density index R1; data for 2019–2022 are used to calculate ecological support and ecological pressure and to construct the environmental carrying capacity index R2; and data on environmental governance investment and pollutant emissions for 2010–2022 are used to construct the historical accumulation index R3. Unless otherwise specified, the classification of city types and the ecological compensation standards are benchmarked to the year 2022. Hydrological and water-quality data are taken from the 2022 Water Resources Bulletin and related sources, evaluated in accordance with the Environmental Quality Standards for Surface Water (GB 3838–2002; MEE, 2002) using an improved Nemerow Pollution Index (Wu et al., 2018), and are used to quantify the indirect benefits of upstream ecological protection in terms of water-quality improvements in the midstream and downstream reaches. Ecosystem service value data are taken from the 2022 ecosystem assessment results for

Dingxi and Tianshui in the study area, and are used to estimate the ecosystem service values generated by upstream ecological protection and the lower bound of the compensation standard.

Research design

This study is grounded in the theoretical framework of ecological compensation. It constructs an analytical framework for ecological compensation standards that integrates dual-benefit estimation and a signaling game mechanism. First, drawing on ecosystem service valuation methods, the model considers the downstream region's willingness to pay and governance substitution benefits, as well as the upstream region's ecosystem service value, direct costs, and opportunity costs, to estimate the theoretical upper and lower bounds of compensation and define the feasible negotiation range. Next, to address the issue of information asymmetry in the compensation process, a signaling game model is introduced. It simulates how the upstream government sends type signals through compensation requests and effort levels, and how the downstream government updates its beliefs accordingly and formulates compensation strategies.

Dual-benefit accounting

Maximum benefits for downstream regions

The maximum benefits that downstream regions derive from upstream ecological protection include both the direct gains from improved environmental quality and the indirect benefits from reduced investment in environmental governance. These benefits reflect the maximum amount downstream beneficiaries are willing to pay for ecological improvements (Pedroso and Biu Kung'u, 2019; Lu et al., 2021), and serve as the theoretical upper bound in the compensation standard framework. This study applies the choice experiment method to quantitatively assess the direct benefits of upstream ecological protection for midstream and downstream regions. Furthermore, based on the water quality restoration cost method, it estimates the indirect benefits generated by upstream ecological compensation for downstream areas.

(1) Accounting for direct benefits in midstream and downstream regions

To accurately assess the benefit level received by downstream regions through ecological compensation, this study constructs ecological improvement scenarios using the choice experiment method. It further employs a random parameter Logit model to estimate respondents' willingness to pay (Torres-Miralles et al., 2017; Li et al., 2022).

Suppose a respondent selects from J available alternatives. The utility derived from choosing alternative i is expressed as follows:

$$U_{ni} = V_{ni} + \varepsilon_{ni} \quad \text{(Eq.1)}$$

Here, V_{ni} represents the observable component of utility, reflecting the influence of different attributes on the respondent's choice. ε_{ni} denotes the unobservable component of utility. The probability that alternative i chosen over other alternatives j among J options can be expressed as follows:

$$P_{ni} = P\left(U_{ni} > U_{nj},\ \forall i \neq j\right) = P\left(V_{ni} + \varepsilon_{ni} > V_{nj} + \varepsilon_{nj},\ \forall i \neq j\right) \quad \text{(Eq.2)}$$

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The utility function U_{ni} can be further specified as follows:

$$U_{ni} = \alpha_n\, ASC_{ni} + \beta_n\, X_{ni} + \gamma_n\, WTP_{ni} + \varepsilon_{ni} \quad \text{(Eq.3)}$$

Here, ASC_{ni} denotes the alternative–specific constant, representing the baseline utility when no management or protection measures are taken. X_{ni} represents the vector of attribute levels associated with alternative i for individual n. WTP_{ni} denotes the monetary payment associated with alternative i in the choice scenarios, that is, the cost that respondent n would have to bear when selecting this alternative. ε_{ni} is the stochastic error term capturing unobserved influences. β_n and γ_n denote the preference parameters for attributes and cost, respectively. The probability density function of the Random Parameter Logit (RPL) model for a respondent is defined as follows:

$$P_{ni} = \frac{e^{\alpha_n ASC_{ni} + \beta_n X_{ni} + \gamma_n WTP_{ni}}}{\sum_j e^{\alpha_n ASC_{nj} + \beta_n X_{nj} + \gamma_n WTP_{nj}}} = \int \frac{e^{V_{ni}(\phi_n)}}{\sum_j e^{V_{nj}(\phi_n)}}\, \phi_n f(\phi_n)\, d\phi_n \quad \text{(Eq.4)}$$

By maximizing the simulated likelihood function using the method of maximum likelihood estimation (MLE), the coefficients and standard deviations of each attribute in the preference function can be estimated. Subsequently, the compensating surplus can be calculated. The formula for calculating the compensating surplus is as follows:

$$CS_i = \frac{1}{\gamma}[(\alpha + \beta X_0) - \beta X_i] = \frac{1}{r}(V_0 - V_i) \quad \text{(Eq.5)}$$

Here, CS_i represents the respondent's total willingness to pay (WTP) for alternative i. α , β and γ denote the mean coefficients of the attribute and cost variables, respectively. V_0 and V_i represent the attribute levels under the baseline (no management) scenario and under the implementation of alternative i, respectively.

To capture individual-level preference heterogeneity, this study employs the Random Parameter Logit (RPL) model, estimated using Stata 17.0. The model is specified as follows:

The coefficients for water quality improvement, water resource abundance, biodiversity, and ecological benefits are specified as random parameters to estimate both their means and standard deviations.

The coefficient for the affordability attribute is treated as a fixed parameter to estimate its mean value.

The alternative-specific constants (ASCs) are specified as fixed parameters and their mean values are estimated.

To better characterize preference heterogeneity, separate estimations are conducted for urban and rural respondents.

1) Sample characteristics

In this study, extensive data were collected through a questionnaire survey conducted among residents in the Shaanxi section of the Weihe River Basin. To ensure the accuracy and reliability of the survey results, all enumerators involved in the study received detailed and targeted training, in order to minimize misunderstandings of the questionnaire items. In addition, a two-enumerator-per-respondent interview model was adopted to ensure the quality and consistency of questionnaire responses. A total of 713 questionnaires were distributed during the survey. After rigorous screening, questionnaires with missing key information or logical inconsistencies were excluded. In the end, 669 valid questionnaires were obtained, yielding a valid response rate of 93.83%.

As shown in *Table 1.*, the sample covers a wide range of household income, family size, age, and education levels, reflecting the diversity of respondents' socio-economic backgrounds. These data capture the basic demographic characteristics of most residents and provide a solid empirical basis for the subsequent analysis.

Table 1. *Descriptive statistics of sample and indicators*

Variable	Urban	Rural
Gender (male-to-female ratio)	0.785	0.386
Average age	37.6	48.3
Years of residence	18.9	44.8
Education level		
Illiterate	0.00	6.31
Primary school	0.07	26.88
Junior high school	11.32	43.24
Vocational school / High school	21.86	12.35
Junior college	31.78	10.44
Bachelor's degree or above	34.97	0.78
Marital status (proportion married)	0.43	0.85
Annual household income (10000 yuan)	11.634	8.519
Average household size	2.69	5.68

2) Attribute selection

In selecting the experimental attributes, this study adopts the framework of ecosystem service functions as its theoretical foundation and draws on the experimental design of Ni (2020). It incorporates the cognitive preferences of residents in the Weihe River Basin regarding ecological and environmental issues. Prior to questionnaire design, field investigations and expert interviews were conducted. The selection of experimental attributes was guided by key policy documents, including the Key Management Plan for the Weihe River Basin, the Gansu Province Water Pollution Control Program (2015–2050), and the Annual Water Pollution Control Plan of Dingxi City. This ensures that the attributes are both contextually relevant and aligned with policy priorities (see *Table 2.* for detailed attributes).

3) Questionnaire design

In designing the Choice Experiment (CE) questionnaire, five key attributes were identified. For each attribute, three level sets were assigned. Each level set was further divided into three alternative scenarios. The experimental design was optimized using Ngene 1.1.1 software through an orthogonal design approach (Ni et al., 2020), This process yielded 12 representative choice sets, totaling 36 alternatives. Validity testing indicated a D-error of 0.0040 and an A-error of 0.0531, suggesting a high level of reliability in the questionnaire design. After minor adjustments, the final version of the questionnaire was confirmed.

(2) Accounting for indirect benefits in midstream and downstream regions

1) This study adopts an improved version of the Nemerow Pollution Index method, using dissolved oxygen (DO), permanganate index (CODMn), and ammonia nitrogen (NH_3-N) as evaluation indicators to assess water quality at the Shaanxi–Gansu junction of the Weihe River Basin (Wu et al., 2018).

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$$R_i = \frac{S_{max}}{S_i} \quad W_i = \frac{R_i}{\sum_{i=1}^{n} R_i} \tag{Eq.6}$$

where W_i is the weight of the i-th pollutant factor, n is the number of pollutant factors, S_i is the evaluation standard for the i-th pollutant factor, and S_{max} is the maximum evaluation standard among the n pollutant factors.

Table 2. *Evaluation indicators for ecosystem value in the Weihe River Basin*

Evaluation Attribute	Attribute Description	Source	Attribute Levels
Water Quality Improvement	The goal is to raise the average water quality category at monitoring sections to Class II or above, indicating significant improvement in water quality.	Gansu Province Water Pollution Control Program (2015–2050)	No improvement* Improved
Water Resource Abundance	Annual average increase in runoff entering Shaanxi Province, reflecting the improvement and stability of regional water resources.	Key Management Plan for the Weihe River Basin	No increase* +100 million m³ +200 million m³
Biodiversity	The number of fish species in the Weihe River Basin is expected to increase significantly in the next five years, highlighting biodiversity enhancement and ecosystem health.	Expert interviews	No improvement* +3 species +5 species
Ecological Benefits	Within the next five years, the proportion of ecological tourism and landscape areas in the mid- and downstream regions of the Weihe River Basin is expected to increase, reflecting environmental improvement and growing attractiveness for recreation.	Expert interviews	No improvement* 5% 10%
Affordability (Cost Attribute)	Five years from now, households' willingness to pay for different ecological improvement scenarios will be measured by the annual payment amount, reflecting both support for environmental improvement and project affordability.	Questionnaire survey	¥0 ¥200 ¥400 ¥600

Attributes marked with * indicate the baseline status, representing the expected condition in five years under a scenario without any additional management or protection measures

An increase in the Nemerow Index generally indicates a trend of water quality deterioration. By applying *Equations (7), (8), and (9)*, the modified Nemerow Index for each evaluation parameter can be calculated, and the corresponding water quality category can be determined based on predefined pollution classification standards.

$$P = \sqrt{\frac{F'^2_{max} + F^2_{ave}}{2}} \tag{Eq.7}$$

$$F_i = \frac{D_i}{S_i} \tag{Eq.8}$$

$$F'_{max} = \frac{F_{max} + F_w}{2} \tag{Eq.9}$$

where D_i is the measured value of the i-th pollutant factor; F_{max} is the maximum value of F_i; $\overline{F_i}$ is the average value of F_i; F_w is the F value of the pollutant factor with the

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largest weight; P is the improved Nemerow pollution index; and S_i has the same meaning as above.

2) Furthermore, the indirect benefits of upstream ecological compensation for midstream and downstream regions are estimated using the water quality restoration cost method. Water quality restoration cost refers to the financial input required to restore a polluted water body to a good ecological status. The model is constructed based on the direct treatment costs of wastewater treatment plants (Pang et al., 2010), and integrates the change in per-unit water restoration cost over a given time with the volume of water in each region, thereby deriving the model for estimating indirect benefits in the midstream and downstream areas of the Weihe River Basin:

$$Y = \beta_0 + \beta_1 x_1^2 + \beta_2 \log(x_2) + \beta_3 \log(x_3) + \beta_4 x_1 x_3 + \beta_5 x_2 x_3 + \beta_6 x_2 x_4 + \beta_7 x_3 x_4 + \mu \quad \text{(Eq.10)}$$

In the equation: Y represents the unit cost of wastewater treatment, measured in yuan per ton (¥/t); x_1, x_2, x_3, x_4 represent the influent concentrations (mg/L) of BOD, COD, NH_3-N, and TP, respectively; β_0 through β_7 are the parameters to be estimated; μ is the random error term.

Using data from 327 domestic wastewater treatment plants, Li et al. (2023) modeled the functional relationship between major pollutants and treatment costs:

$$\begin{aligned} Y = 4.31 &+ 3.6 \times 10^{-5} x_1^2 - 0.41 \log(x_2) - 0.488 \log(x_3) \\ &- 3.269 \times 10^{-4} x_1 x_3 + 1.3 \times 10^{-4} x_2 x_3 \\ &- 4.397 \times 10^{-4} x_2 x_4 + 5.2214 \times 10^{-3} x_3 x_4 + \mu \end{aligned} \quad \text{(Eq.11)}$$

The expression for estimating the indirect benefits of ecological compensation in the midstream and downstream regions of the Weihe River Basin is as follows:

$$L_2 = \Delta Y \cdot V_{\text{Weihe}} \quad \text{(Eq.12)}$$

where V_{Weihe} represents the annual runoff volume of the Weihe River in the Shaanxi section.

Net ecological protection benefits in upstream regions

The net ecological protection benefits refer to the direct economic gains obtained by upstream regions—such as government subsidies and ecological tourism revenues—minus the direct costs and indirect opportunity costs incurred during the ecological protection process. This value serves as the lower bound of the ecological compensation standard, representing the minimum economic incentive necessary for upstream regions to engage in ecological protection activities.

(1) Aggregation of direct costs

The direct costs of ecological protection are categorized into four components: resource depletion cost, environmental degradation cost, pollution control cost, and environmental protection cost (Yuan, 2022). The calculation methods for each cost component are as follows:

Resource depletion cost C_{1k}: calculated by multiplying the water supply quantity of Dingxi and Tianshui with the unit price of urban water supply.

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$$C_{1\text{water}} = X_{\text{water}} \times P_{\text{water}} \quad \text{(Eq.13)}$$

Here, X_{water} denotes the quantity of water resources supplied, and P_{water} represents the unit price of water resources.

Environmental degradation cost C_2: proxied by local fiscal expenditures on the operation and maintenance of water conservancy projects.

Pollution control cost C_3: represented by the annual water pollution control expenditures of environmental protection authorities (Ni et al., 2020).

Environmental protection cost C_4: estimated using the cost substitution method, based on expenditures for soil and water conservation.

Considering regional differences in ecological carrying capacity, economic development level, and governance history, an ecological compensation adjustment coefficient (R) is constructed, incorporating the economic development coefficient (R_1), ecological carrying capacity coefficient (R_2), and historical accumulation coefficient (Yuan, 2022). That is:

$$R = R_1 * R_2 * R_3 \quad \text{(Eq.14)}$$

The compensation amount should be determined based on the priority level of regional ecological urgency. However, the range of adjustment should remain within a defined limit, and a minimum threshold should be set. In other words, the value of R must be bounded by upper and lower limits, allowing for upward adjustment in certain cases or merely covering the direct damage costs in others. This approach reflects and respects interregional equity and disparities arising from natural endowment differences. Therefore, the adjusted direct ecological compensation cost is calculated as follows:

$$C_D = \sum_{i=1}^{L} C_i * R, \quad R \in [1, L] \quad \text{(Eq.15)}$$

1) Economic development coefficient (R1)

Based on economic density data (i.e., the ratio of regional GDP to land area) from six cities and prefectures in the Weihe River Basin between 2001 and 2022, corresponding R1 values are assigned accordingly. The economic density levels of the Weihe River Basin are presented in *Table 3.*.

Table 3. *Economic density of cities in the Weihe River Basin*

Region	Description	Average Economic Density	Assigned Range of R1
Dingxi	Headwaters of the Weihe River; low economic density; underdeveloped	11.74	1
Tianshui	Upper reaches; relatively low economic density; underdeveloped	26.15	1
Baoji	Midstream; moderate economic density; average development	68.25	1<R1<1.08
Xianyang	Downstream; high economic density; well developed	1,621.02	1.16<R1<1.24
Xi'an	Downstream; very high economic density; highly developed	5,678.14	1.24<R1<1.32
Weinan	Downstream; relatively high economic density; moderately developed	789.01	1.08<R1<1.16

Data Source: Gansu Statistical Yearbook; Shaanxi Statistical Yearbook

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2) Environmental carrying capacity coefficient (R2)

Environmental carrying capacity refers to the maximum number of individuals that an ecosystem can sustain under specific environmental conditions. Drawing on existing literature, this study constructed an index system to assess ecological carrying capacity (see *Table 4.*) Based on data from six cities in the Weihe River Basin from 2019 to 2022, we calculated both ecological support capacity and ecological stress levels for each city. The cities were then classified into four categories accordingly (see *Table 5.*).

Table 4. *Influencing Factors of River Basin Environmental Carrying Capacity*

Indicator	Ecological Carrying Capacity Dimension		Calculation Formula
Water Consumption per Unit GDP	Development Capacity	Ecological Stress P	$P = \sum_{i=1}^{4} p_i * w_i$, where w_i is the weight
Domestic Water Use per Capita			
Pollutant Emissions per Unit of Industrial Output			
Domestic Sewage Discharge per Capita			
Urban Domestic Sewage Treatment Rate	Ecological Regulation Capacity	Ecological Support S	$S = \sum_{i=1}^{5} p_i * w_i$, where w_i is the weight
Industrial Wastewater Treatment Rate			
Proportion of GDP Invested in Sewage Treatment			
Utilization Rate of Water Environmental Capacity	Environmental Carrying Utilization Capacity		
Vegetation Coverage Rate			

Table 5. *Assigned values of environmental carrying capacity coefficient (R_2) for cities in the Weihe River Basin*

Type	Characteristics Description	Ecological Support	Ecological Pressure	R_2 Value Range	Region(s)
1	Low support, high pressure	66.9543	75.5239	$1.08 \leq R2 \leq 1.13$	Dingxi, Baoji
2	High support, high pressure	75.6250	75.4013	$1.06 \leq R2 < 1.08$	Xi'an, Xianyang
3	Low support, low pressure	68.0425	72.4613	$1 < R2 < 1.06$	Tianshui
4	High support, low pressure	72.3457	72.2783	$R2 = 1$	Weinan

Note: Data are derived from the Gansu Statistical Yearbook, Shaanxi Statistical Yearbook, and the Environmental Protection Database. All indicators were processed using the efficacy coefficient method, and indicator weights were adjusted based on the principle of variance

The “high/low” categories of ecological support (S) and ecological pressure (P) are defined relative to the sample mean. Specifically, for 2019–2022, the mean ecological support index across the cities in the Weihe River Basin is 70.7414 and the mean ecological pressure index is 73.9162. Cities with $S \geq 70.7414$ are classified as having high ecological support, and those with $S < 70.7414$ as having low ecological support. Similarly, cities with $P \geq 73.9162$ are classified as having high ecological pressure, and those with $P < 73.9162$ as having low ecological pressure.

3) Historical accumulation coefficient (R3)

Based on data from 2010 to 2022 obtained from the Environmental Protection Database, Gansu Statistical Yearbook, Shaanxi Statistical Yearbook, and municipal yearbooks, this study calculated the annual average environmental governance investment and pollutant discharge in the Weihe River Basin.Based on these metrics, different types of governance and pollution profiles were identified (see *Table 6.*).

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***Table 6.** Assignment of historical accumulation coefficient R₃ in the Weihe River Basin*

Type	Characteristics Description	Governance Investment	Pollutant Discharge	R3 Value Range	Region(s)
1	High pollution, high investment	171,672.09	79,578.75	1.15≤R3<1.5	Xi'an, Xianyang
2	Low pollution, high investment	153,802.93	30,834.11	R3=1	Weinan, Baoji
3	Low pollution, low investment	42,759.93	26,517.16	1≤R3<1.05	Dingxi
4	Moderate pollution, moderate investment	65,723.90	45,439.83	1.05≤R3<1.15	Tianshui

(2) Opportunity cost

To assess the industrial development constraints caused by ecological conservation, this study adopts the Opportunity Cost Approach, selecting comparable regions without ecological engineering as the control group. By comparing the per capita value added of the secondary industry, we estimate the opportunity cost of development in ecological service areas (Duan et al., 2010; Adhikari et al., 2017). Specifically, the industrial opportunity cost in year n is derived by comparing the difference in industrial growth rates between protected and unprotected areas. In the calculation process, the gap in per capita value added of the secondary industry between the two areas leads to the following opportunity cost formula for the service-providing region:

$$C_I = |G_{cn} - G_{mn}| \cdot N_n \cdot M_n \quad \text{(Eq.16)}$$

where, G_{cn} and G_{mn} represent the per capita value added of the secondary industry in the control region and the ecological service region, respectively, in year n. $N_n$denotes the total population in the service region at the end of year n, while $M_n$is the benefit adjustment coefficient, determined by the ratio of GDP after n years of ecological governance to the GDP of the corresponding year (Yu et al., 2017).

To ensure the robustness of the comparison, this study carefully considered the similarity between the ecological service areas and the selected control regions in terms of geographic location, natural resource endowments, and industrial structure. Accordingly, Baiyin City was selected as the control group for Dingxi City, and Pingliang City for Tianshui City, to facilitate the estimation of opportunity costs.

(3) Ecosystem service value

This study employs the equivalent factor method of ecosystem service value to quantitatively estimate the ecological functional value of different land types (Gao et al., 2021). Drawing on the research of Xie et al. (2015), we use the ratio of average grain yield per unit area as a correction coefficient (Costanza et al., 1998).

$$\text{Correction coefficient} = \frac{\sum_i a_i Q_i}{\sum_i A_i Q_i} \quad \text{(Eq.17)}$$

Here, a_i denotes the per–unit–area yield of a specific crop in the Weihe River Basin, A_i represents the national per-unit-area yield of the same crop, Q_i is the national market price per unit of that crop. Based on these, the correction coefficient and the per-unit-area ecosystem service value equivalent for the Weihe River Basin can be derived.

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Based on research needs and by drawing on existing studies, the land in the Weihe River Basin is categorized into cultivated land, forest land, grassland, wetlands, water bodies, built-up areas, and unused land. After consulting with the statistical bureaus of Gansu and Shaanxi provinces, as well as relevant city and county forestry and grassland authorities, it was found that complete data are currently unavailable. Therefore, following the methodology of Sun et al., Landsat imagery data from the Google Earth Engine remote sensing platform were utilized. Annual land use and land cover (LULC) data from 2001 to 2022 for the Weihe River Basin were obtained. A spatiotemporal feature model was then constructed, and a Random Forest (RF) classifier was applied to perform unsupervised classification of remote sensing images within the basin. As a result, land type area distributions were obtained for six cities within the Weihe River Basin, (based on 6,677 manually interpreted sample points, with accuracy validation showing an overall classification accuracy of 92% for the land use dataset).

Signaling game

In ecological compensation mechanisms, upper and lower bound estimates help define a preliminary reasonable compensation range. However, the final implementation still depends on the bargaining and strategic interaction between upstream and downstream governments (Deng and Chen, 2022). In practice, the upstream side holds private information, such as its environmental governance costs and the effectiveness of conservation efforts. The downstream side, on the other hand, cannot directly verify this information. This creates a clear information asymmetry between the two parties. Such asymmetry may lead the upstream to exaggerate its compensation demands, while the downstream suppresses its willingness to pay. This undermines both the fairness and efficiency of the compensation mechanism. To better capture the strategic behavior in the compensation process, this paper introduces a signaling game model. In the model, compensation requests and governance efforts are viewed as signals sent by the upstream government to convey its type. The downstream government is assumed to adjust its compensation strategy based on these observed signals. This helps design an ecologically sound compensation mechanism that aligns incentives between the two parties.

Model assumptions

The upstream and downstream government actors in the game are assumed to follow the rational economic man hypothesis. They weigh potential risks and benefits, and choose strategies that maximize their own interests.

The compensation mechanism involves significant information asymmetry. Differences in information access between upstream and downstream governments lead to opacity regarding intentions and payoffs.

Ecological compensation is a continuous and dynamically evolving process. Previous interactions influence future strategic decisions.

The model assumes the game process is free from external shocks. This is intended to ensure the objectivity of the outcomes (Geng, 2020).

Fundamental elements of the model

The upstream government engages in ecological protection, which may yield either high (v_H) or low (v_L) ecological returns. In this section, the type of upstream government (S) is defined as either high-return or low-return, i.e., $S \in \{H, L\}$. The implementation of

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ecological protection incurs a policy execution cost (c_s) for the upstream government. The upstream government's return-generating capacity is private information. The downstream government only knows the probability distribution of this type through prior information. Specifically, $\mu_0 = P(S = H)$ and $1 - \mu_0 = P(S = L)$ .The upstream government requests ecological compensation from the downstream government at a price (w). In addition, the upstream government can signal its return type by means such as implementation efforts or policy localization. This signaling variable is defined as the level of additional effort (t). Without loss of generality, we assume that different types of upstream governments incur different marginal costs (a_i,), where ($i \in \{H, L\}$).

After observing the upstream government's behavioral strategy, the downstream government updates its posterior belief, where $\mu = P(S = H \mid t)$ and $1 - \mu = P(S = L \mid t)$.It then determines the price (p) to be charged to the public, which reflects the total cost including taxes, fees, and other charges In addition, during policy implementation, the downstream government also incurs an execution cost (c_r).

The public's willingness to cooperate with ecological protection follows a uniform distribution over the interval [0,1]. Given the upstream government's type (high or low return), the public's expected efficiency of upstream ecological protection is given by $v(\mu) = \mu\, v_H + (1 - \mu)\, v_L$.

If the public contributes an investment of p per unit to support the policy, then the expected net benefit of ecological protection for the public is $E(U) = \delta\, v(\mu) - p$. The public will only be willing to pay taxes to the government if and only if $E(U) > 0$. Accordingly, the total public investment is given by $d(\mu) = 1 - \frac{p}{v(\mu)}$. Let λ denote the proportion of upstream investment efficiency that can be inferred by the public, and $1 - \lambda$ represent the proportion that remains unobservable.

On the one hand, for an upstream government with high return capability, the expected amount of ecological funding supplied by the public is given by:

$$q_H(\mu, p) = \lambda \left(1 - \frac{p}{V_H}\right) + (1 - \lambda) \left(1 - \frac{p}{V_L}\right) \quad \text{(Eq.18)}$$

On the other hand, for an upstream government with low return capability, the expected amount of ecological funding supplied by the public is given by:

$$q_L(\mu, p) = \lambda \left(1 - \frac{p}{V_L}\right) + (1 - \lambda) \left(1 - \frac{p}{V_H}\right) \quad \text{(Eq.19)}$$

The decision variables and parameters of the game-theoretic model are presented in *Table 7.*.

Based on its type of environmental protection behavior, the upstream government sends an effort-level signal t in (tH, tL) and a compensation request signal M in (MH, ML). Here, tH and MH denote high effort and high compensation request, respectively, while tL and ML represent low effort and low compensation request. Under proactive environmental behavior, the upstream government tends to send the MH signal. When effort is insufficient, it may send a mimicked high-effort signal MH, or a low-effort signal ML. There are eight possible combinations of upstream government behaviors and signaling strategies, as detailed in *Table 8.*.

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Table 7. *Parameters and decision variables of the game-theoretic model*

Decision Variables	Definition
t	Additional effort level by the upstream government, where $i \in \{H, L\}$
w	Ecological compensation requested by the upstream government from the downstream government
p	Average price charged by the downstream government to the public, including taxes, fees, and other charges
Parameters	**Definition**
q_i	Ecological funding supply from the public
v_i	Ecological protection benefit, where $i \in \{H, L\}$
λ	Proportion of upstream government's return efficiency that can be inferred by the public
δ	Public's willingness to cooperate with ecological protection, $\delta \sim U(0,1)$
μ	Prior probability distribution known by the downstream government
a_i	Marginal cost of ecological protection for different types of upstream governments
c_r	Policy implementation cost, where $r \in \{s, r\}$

Table 8. *Behavioral strategy combinations of upstream governments in ecological compensation*

Upstream Government / Type	High Compensation (MH)	Low Compensation (ML)
High-return, High-effort Government (SH, tH)	SH,tH,MH	SH,tH,ML
High-return, Low-effort Government (SH, tL)	SH,tL,MH	SH,tL,ML
Low-return, High-effort Government (SL, tH)	SL,tH,MH	SL,tH,ML
Low-return, Low-effort Government (SL, tL)	SL,tL,MH	SL,tL,ML

Model construction

(1) Game sequence

Based on the declaration submitted by the upstream government, the downstream government faces two possible decisions: either making a direct decision without verification, or conducting verification before deciding whether to compensate. For the upstream government, it may choose to genuinely protect the ecological environment and request compensation, or act perfunctorily in pursuit of economic gain, seeking compensation through false declarations. Therefore, when receiving signals from declarations, the government needs to consider various factors, including compensation amount, protection cost, camouflage cost, penalty amount, verification cost, and social loss. By applying Bayes' theorem, it aims to accurately assess the authenticity of the signals and make an optimal decision accordingly.

Stage One: The upstream government determines its policy effort level t and requests ecological compensation w from the downstream government, in order to maximize its expected utility.

$$\pi_s = (W - C_s)\, q_i(\mu, p) \; - \; a_i\, t \qquad \text{(Eq.20)}$$

Stage Two: The downstream government, based on its posterior belief $\mu = P(S = H \mid t)$, determines the total charge p imposed on the public, in order to maximize its expected utility.

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$$\pi_r = (P - W - C_r)\,[\mu\, q_H(\mu, p) + (1 - \mu)\, q_L(\mu, p)] \quad \text{(Eq.21)}$$

(2) Benchmark model: Symmetric information scenario

This study uses the symmetric information scenario as the benchmark for strategic analysis. Two cases are considered: the equilibrium under the high-return government and the equilibrium under the low-return government.

First, under the high-return government, assume $\mu_0 = \mu = 1$ and $v = v_H$.

The total funding supplied by the public is denoted as q_H.

$$q_H(1, p) = 1 - \frac{p}{v_H} \quad \text{(Eq.22)}$$

The profit function of the upstream government is denoted as π_s:

$$\pi_s = (w - c_s)\, q_i(\mu, p) - a_i\, t \quad \text{(Eq.23)}$$

The profit function of the downstream government is denoted as π_r:

$$\pi_r = (p - w - c_r)\left(1 - \frac{p}{v_H}\right) \quad \text{(Eq.24)}$$

The following result can thus be derived:

Proposition 1: Under complete information, the market equilibrium outcome for the high-return upstream government is as follows:

$$t_H^* = 0, w_H^* = \frac{v_H + c_s - c_r}{2}, q_H^* = \frac{v_H - c_s - c_r}{4v_H}$$
$$\pi_{sH}^* = \frac{(v_H - C_r - C_s)^2}{8v_H}, \pi_r^* = \frac{(v_H - C_r - C_s)^2}{16v_H}$$

Proof: First, derive the downstream government's best response function p(w) with respect to the compensation request w made by the upstream government. Then substitute this function into the upstream government's profit function. Next, solve the first-order conditions of the profit function with respect to w and the additional effort t: That is,

$$\frac{\partial \pi_s}{\partial w} = 0, \quad \frac{\partial \pi_s}{\partial t} = 0$$

This yields the optimal compensation request w_H^*. Substituting it back into the downstream government's best response function gives the equilibrium outcome.

Second, for the low-return government, let $\mu_0 = \mu = 0$.

And given $v = v_L$, the total funding from the public is $q_L(0, p) = 1 - \frac{p}{v_L}$.

The upstream government's profit function is $\pi_s = (w - c_s)q_i(\mu, p) - a_i t$.

The downstream government's profit function is $\pi_r = (p - w - c_r)(1 - \frac{p}{v_L})$.

Proposition 2: Under complete information, the market equilibrium outcome for the low-return upstream government is as follows:

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$$t_L^* = 0, w_L^* = \frac{v_L + c_s - c_r}{2}, q_L^* = \frac{v_L - c_s - c_r}{4v_L}$$
$$\pi_{sL}^* = \frac{(v_L - C_r - C_s)^2}{8v_L}, \quad \pi_r^* = \frac{(v_L - C_r - C_s)^2}{16v_L}$$

Proof: First, derive the downstream government's best response function p(w) with respect to the compensation request made by the upstream government. Substitute this response function into the upstream government's objective profit function. Then solve the first-order condition of the profit function with respect to the compensation price w and additional effort level t.

That is, $\frac{\partial \pi_s}{\partial w} = 0$,This yields the optimal compensation level w_L^*. Substituting it back into the downstream government's best response function gives the equilibrium outcome.

Propositions 1 and 2 indicate that regardless of whether the upstream government is of high or low capability type, there is no incentive to exert additional effort in ecological protection under conditions of complete information.

Results and analysis

Analysis of dual-benefit accounting results

Quantifying the maximum benefit in the downstream region of the basin

(1) Direct benefits

Based on the estimation results of the previously constructed Random Parameter Logit (RPL) model, this study further analyzes the payment preference characteristics of urban and rural residents regarding various ecological service attributes. Accordingly, the annual average willingness to pay (WTP) under typical ecological improvement scenarios is estimated. This is then used to project the annual scale of direct ecological benefits in the middle and lower reaches of the basin.

Table 9. presents the estimated preference coefficients of urban and rural residents across various ecological attributes. The overall model fits well, with the RPL models for both groups passing the likelihood ratio test at the 1% significance level, indicating sound model specification and strong joint explanatory power of the variables. For water quality improvement, the preference coefficient is 1.052 for urban residents (significant at the 5% level) and 0.857 for rural residents (significant at the 10% level). Both groups exhibit positive preferences, suggesting high acceptability of this attribute, with urban residents showing a stronger preference. Regarding water resource abundance, rural residents exhibit a significantly higher coefficient of 1.231 (significant at the 1% level), compared to 0.731 for urban residents (significant at the 5% level), highlighting the critical role of water security in rural livelihoods. For biodiversity, the urban coefficient is 0.235 (significant at the 10% level), while the rural coefficient is 0.355 but not statistically significant, possibly due to a larger standard error. As for ecological environmental benefits, the attribute is significantly preferred by the urban group (coefficient of 0.521, significant at the 1% level), whereas the rural coefficient of 0.132 is not statistically significant, suggesting this attribute is more appealing to urban residents. The coefficient for affordability is 0.002 for urban (significant at the 5% level) and 0.003 for rural samples (significant at the 10% level), both positive, indicating some degree of price sensitivity in willingness to pay, with rural respondents being more responsive. In addition, the

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standard deviations (S.D.) of all attributes are statistically significant at the 1% level, implying substantial internal heterogeneity in preferences and confirming the appropriateness of the RPL model in capturing individual-level variation.

Table 9. *Estimation results of the random parameter logit (RPL) model*

Estimated Parameter	Urban		Rural	
	Coefficient	Std. Error	Coefficient	Std. Error
M. (Water Quality Improvement)	1.052**	0.147	0.857*	0.123
M. (Water Resource Abundance)	0.731**	0.104	1.231***	0.099
M. (Biodiversity)	0.235*	0.042	0.355	0.043
M. (Ecological Environmental Benefits)	0.521***	0.017	0.132	0.019
M. (Affordability)	0.002**	0.002	0.003*	0.0007
M. (ASC)	1.580***	0.354	1.439***	0.432
S.D. (Water Quality Improvement)	1.188***	0.282	1.601***	0.285
S.D. (Water Resource Abundance)	0.716***	0.169	0.685***	0.177
S.D. (Biodiversity)	0.323***	0.055	0.421***	0.060
S.D. (Ecological Environmental Benefits)	0.159***	0.039	0.198***	0.039
LR chi2(4)	82.20		113.99	
Log likelihood	-809.146		-881.557	

Note: *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively. M. denotes the mean estimate, and S.D. denotes the standard deviation

The compensating surplus reflects the average willingness to pay (WTP) of basin residents for ecological improvement. Assuming that Gansu Province, located in the upper reaches of the Weihe River Basin, implements ecological restoration measures and that all environmental indicators reach the optimal levels designed in this study within five years, the estimated results in Table 9 suggest that, over the following five years, the average annual WTP per household would be ¥1,269.50 for urban residents and ¥858.33 for rural residents. According to the Statistical Yearbook of Shaanxi Province, in 2022, the four cities located in the Weihe River Basin had approximately 2.5877 million urban households and 0.9267 million rural households. Survey results show that 88.63% of urban and 81.96% of rural respondents expressed a willingness to pay a certain amount for ecological improvements in the Weihe River Basin. Based on these figures, the total external benefit (denoted as L1) of ecosystem service improvement in the Weihe River Basin is estimated at 356,349.51 ten thousand.

$L_1 = 1{,}269.50 \times 2{,}587{,}700 \times 0.8863 + 858.33 \times 926{,}700 \times 0.8196$
$= 291{,}174.89 + 65{,}174.62$
$= 356{,}349.51$ ten thousand yuan

(2) Indirect benefits

According to the Environmental Quality Standards for Surface Water, surface water is classified into five quality levels, and the corresponding Nemerow pollution indices are determined for each category. See *Table 10.* for details.

Based on Class II water standards, the calculated P-value range for upgrading from Class I water is: $P < 0.625$. According to Class III standards, the P-value range for upgrading from Class I water is: $P < 0.431$; for Class II water: $0.431 \le P < 0.625$; and for Class III water: $0.625 \le P < 1$.

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Table 10. *Limit values of basic items in surface water quality standards (mg/L)*

Indicator	Class I	Class II	Class III	Class IV	Class V
COD	15	15	20	30	40
BOD	3	3	4	6	10
NH_3-N	0.15	0.5	1.0	1.5	2
TP	0.02	0.1	0.2	0.3	0.4

According to the Weihe River Basin Management Regulation of Shaanxi Province, the water quality target for the basin is set as Class II. Assuming no ecological protection in the upstream region, the water flowing into Shaanxi would be of Class III quality.

According to *Equation (11)*, the marginal benefit of quality improvement is $\triangle Y = 0.191$ yuan/ton.

As reported in the 2022 Water Resources Bulletin of Shaanxi Province, the annual runoff volume of the Weihe River was 8.402 billion cubic meters.

The indirect benefit L_2 from ecological compensation in the middle and lower reaches of the Weihe River Basin is calculated as: $L_2 = 0.191 \times 84.02 \times 10^8 = 160{,}478.2$ yuan or ¥160,478.2 ten thousand.

Quantification of net ecological benefits in the upstream region of the basin

(1) Direct costs

1) Water resource consumption costs

Given the public nature of water resources and the government-regulated pricing system, this study uses urban water prices to represent the unit value of water resources. According to the minutes of the third executive meeting of the Dingxi Municipal Government and the official document Ding Fa Gai Shang Jia [2017] No. 80, issued by the Dingxi Development and Reform Commission, the basic urban water price in Dingxi is ¥2.25 per cubic meter. According to the official website of the Tianshui Municipal Government, the urban water price in Tianshui is ¥2.05 per cubic meter. According to the *Gansu Province Water Resources Bulletin*, the total water supply in Dingxi in 2022 was 387.85 million cubic meters. The water supply in Tianshui was 336.353 million cubic meters.

In 2022, the water resource consumption cost for Dingxi City was: $C_{1Dingxi}=3.8785 \times 2.25=76{,}218.75$ ten thousand yuan.

The corresponding cost for Tianshui City was: $C_{1Tianshui}=3.36353 \times 2.05=68{,}952.37$ ten thousand yuan.

Therefore, the total water resource consumption cost is: $C_{1Water}= C_{1Dingxi} + C_{1Tianshui} =76{,}218.75+68{,}952.37=145{,}171.12$ ten thousand yuan.

2) Water resource degradation cost

According to the 2022 General Public Budget Final Accounts of Dingxi City, the expenditure on water conservancy infrastructure construction was ¥37.90 million. According to the 2022 General Public Budget Final Accounts of Tianshui City, the expenditure on the operation and maintenance of water conservancy projects was ¥205.34 million.

Therefore, the water resource degradation cost is estimated as: $C_{2Water}=243.24$ million yuan.

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3) Water pollution control cost

According to the 2022 final accounts of the Dingxi Municipal Bureau of Ecology and Environment, Dingxi's expenditure on water pollution control was ¥371.84 million. According to the 2022 final accounts of the Tianshui Municipal Bureau of Ecology and Environment, Tianshui's expenditure on water pollution control was ¥369.99 million.

Therefore, the total water pollution control cost is: C_{3Water}=741.83 million yuan.

4) Water environmental protection cost

According to the 2022 General Public Budget Final Accounts of Dingxi and Tianshui, the expenditure on soil and water conservation in Dingxi was ¥6.02 million, and in Tianshui it was ¥6.64 million.

Therefore, the total water environmental protection cost is: C_{4Water}=12.66 million yuan.

The direct costs of ecological protection in the Weihe River Basin are summarized in *Table 11.*.

Table 11. *Direct costs of ecological damage in the Weihe River Basin*

Region	Cost Item	Accounting Basis	Investment Amount (10,000 yuan/year)
Dingxi	Water resource consumption cost	$C_{1\text{Water}} = X_{\text{Water}} \times P_{\text{Water}}$	76,218.7
	Water resource degradation cost	O&M expenditure on water conservancy	3,790
	Water pollution control cost	Water pollution control expenditure	37,184
	Water environmental protection cost	Soil and water conservation	602
	Total	Total direct cost in Dingxi	117,794.7
Tianshui	Water resource consumption cost	$C_{1\text{Water}} = X_{\text{Water}} \times P_{\text{Water}}$	68,952.37
	Water resource degradation cost	O&M expenditure on water conservancy	20,534
	Water pollution control cost	Water pollution control expenditure	36,999
	Water environmental protection cost	Soil and water conservation	644
	Total	Total direct cost in Tianshui	127,149.37
Total			244,944.07

The ecological compensation coefficient for Dingxi is: $R_{Dingxi}=R_{1Dingxi}\times R_{2Dingxi}\times R_{3Dingxi}=1 \times 1.13 \times 1.05=1.1865$

The ecological compensation coefficient for Tianshui is: $R_{Tianshui}=R_{1Tianshui}\times R_{2Tianshui}\times R_{3Tianshui}=1 \times 1.06 \times 1.15=1.219$

The adjusted direct cost for Dingxi is: 1.1865 × 117,794.7=139,763.41 ten thousand yuan.

The adjusted direct cost for Tianshui is: 1.219 × 127,149.37=152,995.08 ten thousand yuan.

The total direct cost of upstream ecological damage in the Weihe River Basin is: C_D=139,763.41+152,995.08=292,758.49 ten thousand yuan.

(2) Opportunity cost calculation

Table 12. presents the 2022 secondary industry output, per capita industrial output, total population, and benefit adjustment coefficients for Dingxi and Tianshui (as

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ecological service zones), along with their corresponding control cities, Baiyin and Pingliang. Accordingly, the industrial opportunity cost in 2022 is estimated to be ¥38,497.64 million for Dingxi and ¥62,172.63 million for Tianshui. Therefore, the indirect cost of ecosystem service improvement in the upstream region of the Weihe River Basin is calculated as: C_I=100,670.27 ten thousand yuan.

Table 12. *Opportunity costs associated with ecological compensation in the upstream Weihe River Basin*

Region	Secondary Industry Output (10,000 yuan)	Total Population (10,000 people)	Per Capita Output (yuan)	Benefit Adjustment Coefficient	Industrial Opportunity Cost (10,000 yuan)
Dingxi	966,000	250.58	3,855.056269	0.04	38,497.6368
Baiyin	1,315,000	170.87	7,695.909171		
Tianshui	2,203,200	295.44	7,457.351747	0.07	62,172.62881
Pingliang	1,907,000	182.25	1,0463.64883		

(3) Ecological protection benefits in the upstream region

This study draws on the approach developed by Sun Bingqing et al. It uses Landsat imagery from the Google Earth Engine remote sensing platform. A spatiotemporal feature model was constructed. A Random Forest (RF) classifier was applied to perform unsupervised classification of remote sensing images across the Weihe River Basin. This produced land use area distribution data for six municipalities within the basin (Sun et al., 2023). The method of Xie et al. (2015) was also referenced. The ratio of grain yield per unit area was used as a correction factor. Based on this, the 2022 ecosystem service value in Dingxi was estimated at ¥72,961.6 ten thousand yuan. That of Tianshui was ¥83,536.63 ten thousand yuan. Therefore, the total ecological protection benefit in the upstream region of the Weihe River Basin amounted to ¥156,498.23 ten thousand yuan.

Defining the negotiation range for compensation based on benefit disparities

The quantitative analysis above reveals that the cost of providing upstream ecological services exceeds the direct benefits received by upstream regions, but remains lower than the benefits accrued by downstream areas from those services. Therefore, internal ecological compensation arrangements within the basin are both reasonable and feasible. The compensation standard should be jointly determined by upstream and downstream parties through negotiation based on the ecological improvements achieved. During this process, the following principles should be observed: The compensation amount should not exceed the benefits derived by the middle and lower reaches from ecological service improvements, that is, ¥5,168.28 million per year. The compensation should at least cover the losses borne by the upstream region due to ecological protection efforts, which amount to ¥2,369.31 million per year. Within the range of ¥2,369.31 million to ¥5,168.28 million, both parties have significant room for negotiation. This indicates that upstream environmental efforts have generated an additional net benefit of ¥2,798.97 million per year. To achieve the optimal overall benefit for the basin, upstream and downstream stakeholders should negotiate the allocation of the ¥2,798.97 million in annual net gains.

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Signaling game equilibrium and behavioral mechanism simulation

Model analysis

Under asymmetric information in this model, there exist two types of Perfect Bayesian Equilibria: separating equilibrium and pooling equilibrium. In a separating equilibrium, the high-return and low-return upstream governments choose different levels of ecological compensation w, allowing the public to infer the true type of the upstream government. In a pooling equilibrium, both types of upstream governments choose the same compensation level w and effort level t, and the public's posterior belief remains equal to its prior.

(1) Separating equilibrium

Proposition 3: A separating equilibrium exists if $t_L^* = 0$,, $t_H^* > 0$, and $\mu(t_L^*) = 0$, $\mu(t_H^*) = 1$. Under these conditions, the following statements hold:

When $t_H^* > t_1$, the low-return upstream government has no incentive to deviate from the equilibrium, that is, it will not mimic the high-return type.

When $t_H^* < t_2$, the high-return upstream government also has no incentive to deviate from the equilibrium, meaning it will not mimic the low-return type.

Proof: The proof consists of two parts.

Part one examines the incentive compatibility condition for the low-return government. For Proposition 3(i), it is shown that the profit from mimicking the high-return type, $\pi_{sL}(1, w, t)$, is less than the profit from truthfully revealing its type, $\pi_{sL}(0, w, t)$. This yields the incentive-compatible decision range for the low-return type.

Part two focuses on the incentive compatibility condition for the high-return government. For Proposition 3(ii), it is shown that the profit from mimicking the low-return type, $\pi_{sH}(1, w, t)$, is less than the profit from honest signaling, $\pi_{sH}(0, w, t)$. This defines the stable strategy region for the high-return government.

Part One:

1) When the low-return upstream government exerts effort level t_H, i.e., when $\mu = 1$, the expected total funding from the public is given by:

$$q_L(1, p) = \lambda\left(1 - \frac{p}{v_L}\right) + (1 - \lambda)\left(1 - \frac{p}{v_H}\right)$$

The downstream government's objective profit function can thus be written as: $\pi_{rL}(1, w, t_H) = (p - w - c_r)\, q_L(1, p)$, where the downstream government's best response function with respect to p can be derived from the first-order condition:

$$p(w) = \frac{(1-\lambda)\,(w + c_r)\,v_L + v_H\,(\lambda\,(w + c_r) + v_L)}{2\,\lambda\,v_H - 2\,(-1+\lambda)\,v_L}$$

Substituting $p(w)$ into the upstream government's profit function $\pi_{sL}(1, p(w), t_H)$, and solving the first-order condition yields:

$$w_L^* = \frac{\lambda\,(-c_r + c_s)\,v_H + \big((-1+\lambda)(c_r - c_s) + v_H\big)\,v_L}{2\,\lambda\,v_H - 2\,(-1+\lambda)\,v_L}$$

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$$\pi_{sL}^*(1,w_L^*,t_H)=\frac{1}{8}\left(2c_r\left(c_s\left(\frac{1-\lambda}{v_H}+\frac{\lambda}{v_L}\right)-1\right)-2c_s-8a_Lt_H+c_r^2\left(\frac{1-\lambda}{v_H}+\frac{\lambda}{v_L}\right)+c_s^2\left(\frac{1-\lambda}{v_H}+\frac{\lambda}{v_L}\right)+\frac{\lambda}{v_L}\right)+\frac{v_Hv_L}{\lambda v_H+v_L-\lambda v_L}.$$

2) When the low-return upstream government chooses effort level t_L, i.e., when $\mu = 0$, the best response function $p(w)$ of the downstream government with respect to the compensation request is derived, and is substituted into the upstream government's objective profit function. The first-order conditions of the upstream profit function with respect to w and t are then solved.

Specifically, solving $\frac{\partial \pi_s}{\partial w}=0$, yields the optimal compensation request w_L^*.

Substituting w_L^* back into the downstream best response function leads to the equilibrium outcomes:

$$w_L^*=\frac{v_L+c_s-c_r}{2},\quad q_L^*=\frac{v_L-c_s-c_r}{4\,v_L},\quad \pi_{sL}^*=\frac{(v_L-c_s-c_r)^2}{8\,v_L}$$

3) By comparing the equilibrium profits under mimicking and truthful reporting, the threshold effort level,

$$t_H>t_1=\frac{\left(\frac{1-\lambda}{v_H}+\frac{\lambda}{v_L}\right)\left(c_r+c_s-\frac{v_Hv_L}{\lambda v_H+v_L-\lambda v_L}\right)^2-\frac{(c_r+c_s-v_L)^2}{v_L}}{8a_L}$$

can be derived from the inequality $\pi_{sL}^*(1,w_L^*,t_H)>\pi_{sL}^*(0,w_L^*,t_H)$.

Part Two:

1) When the high-return upstream government exerts effort level t_L, that is, when $\mu = 0$, the expected total public funding is given by:

$$q_H(0,p)=\lambda\left(1-\frac{p}{v_H}\right)+(1-\lambda)\left(1-\frac{p}{v_L}\right)$$

The downstream government's objective profit function is thus: $\pi_{rH}(0,w,t_H)=(p-w-c_r)\,q_H(1,p)$, where the downstream government's best response function with respect to p is obtained from the first-order condition:

$$p(w)=\frac{w\lambda v_H-wv_H-c_rv_H+\lambda c_rv_H-w\lambda v_L-\lambda c_rv_L-v_Hv_L}{2(-v_H+\lambda v_H-\lambda v_L)}$$

Substituting $p(w)$ into the upstream government's profit function $\pi_{sH}(1,p(w),t_H)$, and solving the first-order condition yields:

$$w_L^*=\frac{(1-\lambda)(c_r-c_s)v_H+(\lambda c_s-\lambda c_r+v_H)v_L}{2(-1+\lambda)v_H-2\lambda v_L}$$

$$\pi_{sL}^*(1,w_L^*,t_H)=\frac{1}{8}\left(\frac{\lambda(c_r+c_s)^2}{v_H}+\frac{v_H}{\lambda}-2(c_r+c_s+4a_Ht_H)+\frac{(1-\lambda)(c_r+c_s)^2}{v_L}-\frac{(1-\lambda)v_H^2}{\lambda((1-\lambda)v_H+\lambda v_L)}\right).$$

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2) When the high-return upstream government exerts effort level t_H, i.e., when $\mu = 1$, the optimal response function $p(w)$ of the downstream government with respect to the compensation request is derived, and substituted into the upstream government's objective profit function. The first-order conditions with respect to w and t are then solved.

Specifically, solving $\frac{\partial \pi_s}{\partial w} = 0$, yields the optimal compensation request w_L^*.

Substituting w_L^* back into the downstream best response function gives the equilibrium outcomes:

$$w_H^* = \frac{v_H + c_s - c_r}{2}, \qquad q_H^* = \frac{v_H - c_s - c_r}{4\, v_H}, \quad \pi_{sH}^* = \frac{(v_H - c_s - c_r)^2}{8\, v_H}$$

3) By comparing equilibrium profits under mimicking and truthful reporting, the threshold effort level

$$t_H > t_1 = \frac{(\pm 1)\left(\frac{(c_r + c_s)^2}{v_H} - \frac{v_H}{\lambda} - \frac{(c_r + c_s)^2}{v_L} + \frac{v_H^2}{\lambda\big((1-\lambda)v_H + \lambda v_L\big)}\right)}{8 a_L}$$

can be derived from the inequality $\pi_{sH}^*(1, w_L^*, t_H) > \pi_{sH}^*(0, w_L^*, t_H)$.

Proposition 3 suggests that under a separating equilibrium: First, the low-return upstream government has no incentive to exert additional effort, whereas the high-return upstream government is motivated to do so. This divergence in effort levels between different government types enables the public to clearly distinguish between the two types. Second, to prevent the low-return type from mimicking the high-return type, the high-return upstream government must set a minimum effort level $t_H^* > t_1$, thereby establishing a credible separation threshold. Third, to prevent the high-return government from mimicking the low-return type, the additional effort level must be constrained from above, i.e., $t_H^* < t_2$. This echoes an old Chinese saying: “Those who overdo will fail; those who cling too tightly will lose.”

(2) Sensitivity analysis

Proposition 4: The following statements hold:

The incentive range for the low-return upstream government to deviate from the equilibrium decreases as λ and a_L increase, that is, t_1 is a decreasing function of λ and a_L.

The profit of the low-return upstream government also decreases with higher values of λ and a_L, meaning that π_{sL} is a decreasing function of λ and a_L.

Proof: Taking the first derivatives of t_1 with respect to λ and a_L, we obtain:

$$\frac{\partial t_1}{\partial \lambda} < 0, \quad \frac{\partial t_1}{\partial a_L} < 0$$

In addition, taking the second derivatives of π_{SL} with respect to λ and a_L yields:

$$\frac{\partial^2 \pi_{SL}}{\partial \lambda^2} < 0, \quad \frac{\partial^2 \pi_{SL}}{\partial \alpha_L^2} < 0$$

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This indicates that the first derivatives of π_{sL} are decreasing functions of λ and a_L.Given that $\left.\frac{\partial\pi_L}{\partial\lambda}\right|_{\lambda=1} > 0$, $\left.\frac{\partial\pi_L}{\partial\alpha_L}\right|_{\alpha_L=1} > 0$, Proposition 4 is thus proven.

Proposition 4 indicates that as public awareness of government type improves, the feasible range for a low-type government to mimic a high-type one becomes more limited. Furthermore, Proposition 4 indirectly suggests that the profit of a low-return government is uncorrelated with the policy implementation cost c_H of a high-return government.

Proposition 5: The following statements hold:

The incentive range for the high-return upstream government to deviate from the equilibrium increases with rising λ and a_L, that is, t_2 is an increasing function of λ and a_L.

The profit of the high-return upstream government increases with higher λ, meaning that π_{sL} is an increasing function of λ. Meanwhile, its profit decreases as a_L increases, indicating that π_{sL} is a decreasing function of a_L.

Proof: Taking the first derivatives of t_2 with respect to λ and a_L, we obtain:

$$\frac{\partial t_2}{\partial\lambda} < 0, \quad \frac{\partial t_2}{\partial a_L} < 0$$

In addition, taking the second derivatives of π_{SH} with respect to λ and a_L yields:

$$\frac{\partial^2\pi_{SH}}{\partial\lambda^2} < 0, \quad \frac{\partial^2\pi_{SH}}{\partial\alpha_L^2} < 0$$

Therefore, the first derivatives of π_{SH} are decreasing functions of λ and a_L.Given that $\left.\frac{\partial\pi_{SH}}{\partial\lambda}\right|_{\lambda=1} > 0$, $\left.\frac{\partial\pi_{SH}}{\partial\alpha_L}\right|_{\alpha_L=1} > 0$, Proposition 5 is thus proven.

Proposition 5 implies that as public awareness of government type increases, the feasible range for a high-return government to mimic a low-return type becomes increasingly limited, making its additional effort level more meaningful and credible. Proposition 5 also indirectly suggests that the profit of the high-return government is uncorrelated with the policy implementation cost c_L of the low-return government.

Simulation analysis

To verify the effectiveness of the method proposed in this paper, a series of rigorous numerical simulations were conducted. These experiments were implemented using the Matlab2023b software platform, aiming to solve the signaling game model under asymmetric information, and to obtain corresponding equilibrium results. During the simulation, the threshold constraints of the ecological compensation standard were strictly followed, and the following parameter values were adopted: $v_H = 5000000$, $v_L = 3000000$, $c_f = 11000$, $c_s = 10000$, $t_H = 0.7$. These parameter settings help to more accurately assess the strategic interactions between upstream and downstream regions within the ecological compensation framework, thereby providing scientific guidance for policymakers.

(1) Sensitivity simulation of equilibrium profits

As shown in ***Hiba! A hivatkozási forrás nem található.*** and *Figure 3.*, Propositions 4 and 5 reveal the effects of the proportion of informed public, as well as the marginal social

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responsibility costs of low- and high-quality upstream governments, on the minimum required additional effort level. First, according to the numerical simulation results, when the effort level is fixed at $t_H = 0.7$, as the public's awareness ratio λ increases, the profit of the high-return government increases, while the profit of the low-return government decreases. On one hand, the reduction in information costs leads to higher equilibrium profits for high-return upstream governments. On the other hand, because of greater separation clarity, low-return governments are placed at a disadvantage. This is because low-return upstream governments exert no additional effort under any separating equilibrium, and all members of the public are aware of their low-return nature, resulting in a negative correlation between public awareness and their profits. Second, regardless of government type, simulation results suggest that their profits consistently remain within the range [334561,494519], indicating that ecological protection gains have both upper and lower bounds. The specific outcomes depend on the public's sectoral insight or their awareness of ecological investment performance. For instance, when $\lambda = 0.7$, the profits for high- and low-return governments are ¥4,104.26 million and ¥3,584.34 million, respectively. When $\lambda = 0.3$, the profits are ¥3,584.34 million and ¥4,104.26 million, respectively.

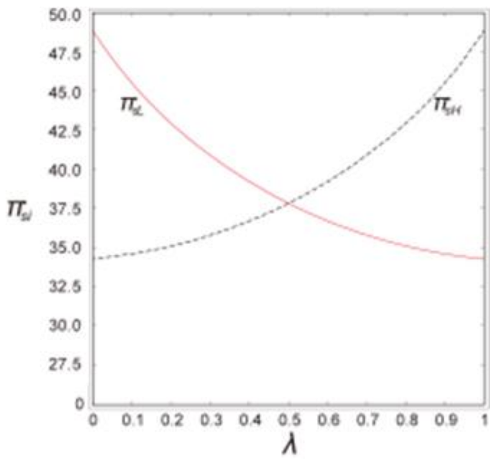
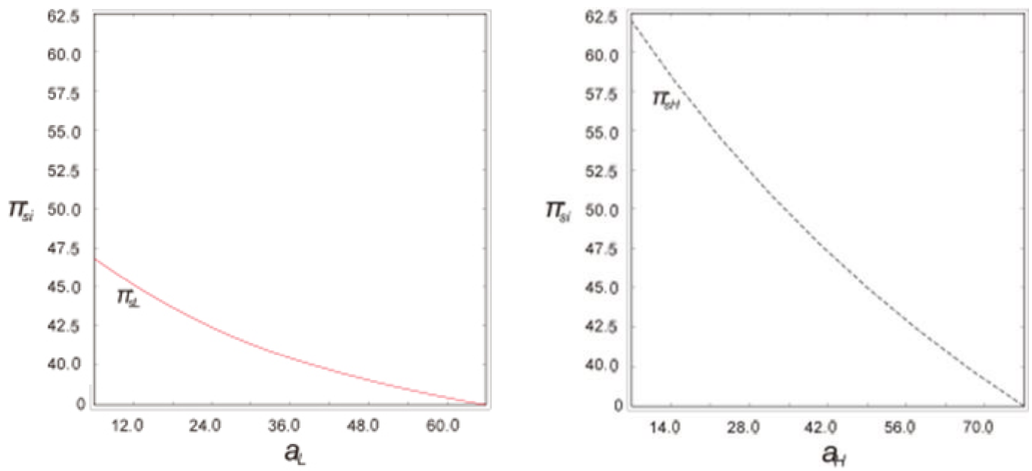


Figure 2. *Profit π_{si} of upstream governments under varying public awareness levels λ*



(a) Variation in π_{sL} with respect to a_L **(b)** Variation in π_{sH} with respect to a_H

Figure 3. *Upstream government profit π_{si} under varying marginal ecological protection costs*

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a_i

(2) Stability region of the separating equilibrium

As illustrated in ***Hiba! A hivatkozási forrás nem található.*** and *Figure 3.*, Propositions 4 and 5 reveal how the proportion of informed public, as well as the marginal social responsibility costs of low- and high-quality upstream governments, affect the minimum level of additional effort required to maintain separation. When information asymmetry among the public decreases, the profit gained by low-return upstream governments from mimicking high-return types declines, thereby weakening their incentive to mimic. Furthermore, the higher the marginal cost of ecological protection for low-return upstream governments, the weaker their motivation to mimic becomes. In such cases, the stability region of the separating equilibrium expands, ensuring that the efforts and contributions of high-return governments are better protected.

Conclusion and implications

Research conclusions

This study finds that if the upstream region of the Weihe River Basin in Gansu Province carries out ecological restoration and reaches the expected ideal ecological condition within the next five years, then, over the following five years, the average annual willingness to pay will be ¥1269.50 for urban residents and ¥858.33 for rural residents. Based on the number of households in the Weihe River Basin of Shaanxi Province in 2022, the total social willingness to pay could reach ¥3563495100. If no ecological protection measures are implemented in the upstream area, the estimated indirect benefits for the downstream area would be ¥1604782000. The calculated upper bound of the ecological compensation standard is ¥5168277100. By accounting for the ecological compensation costs and direct returns in the upstream region, the lower bound of the ecological compensation standard is determined to be ¥2369305300.

Under asymmetric information, the analysis based on a signaling game model reveals that regardless of the upstream government's capability type, there is no incentive to exert additional efforts in ecological protection under full information. However, as downstream governments and the public become more aware of the upstream government's capability type, the room for low-capability governments to disguise themselves narrows significantly, and even high-capability governments face constraints in disguise. Moreover, greater transparency improves the profit of high-capability governments while reducing that of low-capability ones. The study also finds that the cost of policy implementation has no significant effect on the returns of different government types. The returns across all types of governments generally remain within the range of 3.34561 to 4.94519 billion yuan. This indicates that the ecological protection benefits have a clear upper and lower bound. When public awareness λ equals 0.7, the compensation returns are 4.10426 billion yuan for high-capability governments and 3.58434 billion yuan for low-capability governments. When λ drops to 0.3, the respective returns are reversed: 3.58434 billion yuan and 4.10426 billion yuan.

These findings are broadly consistent with previous studies on watershed ecological compensation in China, which also report substantial downstream willingness to pay and emphasize the importance of linking compensation standards to both ecological benefits and regional economic capacity (Zhao and Wang, 2010; Xu et al., 2012). However, the implied compensation levels in the Weihe River Basin are somewhat higher than those reported for some other basins (Geng et al., 2018), which may reflect the relatively

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stronger dependence of the Guanzhong Plain on Weihe River water resources and higher perceived risks of water pollution. In addition, while earlier work on ecological compensation has mainly relied on either cost-based or benefit-based methods (Xu et al., 2012; Yu et al., 2017), our dual-benefit and signaling game framework explicitly incorporates both upstream protection costs and downstream benefits under conditions of information asymmetry. By combining RPL-based willingness-to-pay estimates with a game-theoretic analysis of intergovernmental behavior, this study helps to bridge micro-level preference heterogeneity and macro-level compensation negotiations, providing new insights for the design of cross-regional ecological compensation mechanisms in large river basins. Nevertheless, the analysis is still based on a medium-term (five-year) static framework and does not explicitly capture long-term dynamic adjustments or distributional effects among different social groups, which should be further explored in future research.

Policy implications

This study not only provides a quantitative basis for the scientific estimation of cross-provincial ecological compensation standards in the Weihe River Basin, but also offers theoretical guidance for the optimization of compensation mechanisms. Based on the findings, the following policy recommendations are proposed: First, the compensation standard should be scientifically determined: the lower bound should be based on the net ecological conservation loss borne by upstream regions, and the upper bound should reflect the comprehensive benefits received by downstream regions, ensuring a balance between fairness and efficiency. Second, the incentive and constraint mechanism should be improved by incorporating a signaling game framework, to encourage upstream governments to truthfully signal their environmental efforts. Compensation schemes should be phased and performance-linked to enhance the effectiveness of incentives. Third, information transparency and public participation should be strengthened, with the establishment of an independent third-party monitoring and evaluation system to promote data sharing and public oversight, thereby alleviating the information asymmetry between upstream and downstream stakeholders. Fourth, cross-regional collaboration should be promoted, by establishing diverse cooperative mechanisms such as joint meetings, negotiated consultations, and co-governance platforms, to foster the overall sustainable development of the watershed.

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APPENDIX

Survey Questionnaire 1
Weihe River Basin Ecological Compensation Survey

Part I Basic Information about the Respondent and Household
Your gender:
( ) Male ( ) Female
Your age:
______ years old
Your highest level of education:
( ) Primary school or below

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( ) Junior middle school
( ) Senior high school or secondary technical school
( ) Junior college or college
( ) Above college
Your health status:
( ) Good
( ) Average
( ) Poor
( ) Very poor
Your occupation is:
( ) Student
( ) Crop farming
( ) Self-employed / business owner
( ) Enterprise employee
( ) Government employee
( ) Animal husbandry
( ) Other
Your workplace is located:
( ) Locally
( ) Outside the local area
How many actual laborers are there in your household?
( ) 1 ( ) 2 ( ) 3 ( ) 4 ( ) 5 or more
Your household's annual income:
______ ten thousand yuan (RMB)
Main source of your household's annual income:
( ) Farming
( ) Migrant work (off-farm wage work)
( ) Doing business
( ) Wage/salary income
( ) Retirement pension
( ) Other
Are there any of the following information sources near your place of living or work? (Multiple choice)
( ) Mobile phone/computer with internet access
( ) Books/newspapers at bookstores or newsstands
( ) Documents/notices displayed at government information disclosure points
( ) Professional databases
( ) Books/newspapers in libraries/reading rooms
Part II Farmers' Ecological Perception
How much attention do you pay to the ecological environment of the river basin where you live?
( ) Not at all
( ) Not much
( ) Some attention
( ) Quite a lot of attention
( ) A great deal of attention
How satisfied are you with the ecological environment of the river basin where you live?
( ) Very dissatisfied
( ) Not very satisfied
( ) Satisfied
( ) Quite satisfied
( ) Very satisfied
Do you think it is necessary to improve the ecological environment of the river basin where you live?

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( ) Not necessary at all
( ) Not very necessary
( ) Indifferent
( ) Necessary
( ) Very necessary
Do you agree that protecting the ecological environment of the river basin is an unshirkable responsibility and obligation of every citizen?
( ) Strongly disagree
( ) Disagree
( ) Neutral
( ) Agree
( ) Strongly agree
Do you think the use of pesticides, chemical fertilizers, etc. will pollute the ecological environment of the river basin?
( ) Definitely not
( ) Probably not
( ) Uncertain
( ) Very likely
( ) Definitely yes
Who do you think should bear the main responsibility for protecting the ecological environment of the river basin? (Multiple choice, select up to 3 options)
( ) Local government
( ) Related enterprises
( ) Local residents
( ) Environmental protection public-interest organizations
If someone damages the ecological environment of the Weihe River Basin, will you question or challenge him/her?
( ) Definitely not
( ) Probably not
( ) Not sure
( ) Very likely
( ) Definitely yes
Do you believe that you have the ability to make some contribution to improving the ecological environment of the Weihe River Basin?
( ) Strongly do not believe
( ) Do not really believe
( ) Neutral
( ) Rather believe
( ) Strongly believe
Part III Cognition of Ecological Compensation in the Weihe River Basin
How well do you understand the ecological compensation policies in the Weihe River Basin?
( ) Not at all
( ) Not very well
( ) Generally understand
( ) Understand fairly well
( ) Understand very well
In order to improve the ecological environment of the river basin, do you think it is necessary to adopt compensation measures?
( ) Not necessary at all
( ) Not very necessary
( ) Indifferent
( ) Necessary
( ) Very necessary

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Have you participated in ecological compensation projects in the Weihe River Basin in the past three years?
( ) Yes
( ) No
If your household has received ecological compensation, what is the subsidy standard (amount)?
______ yuan
What is your psychological expectation regarding the ecological subsidy policies currently implemented by the government for the river basin?
( ) Very doubtful
( ) Somewhat doubtful
( ) Do not care
( ) Quite confident
( ) Very confident
Who do you think should mainly provide compensation for the social, economic and ecological benefits generated by ecological protection in the river basin (such as improving cultivated land fertility, increasing agricultural income, and protecting the cultivated land ecological environment)? (Multiple choice)
( ) Local government
( ) Beneficiary enterprises
( ) Non-governmental organizations (e.g. environmental organizations)
( ) Local residents
( ) General public

Survey Questionnaire 2
Willingness to Receive Ecological Compensation in the Weihe River Basin

Dear respondent:
This questionnaire aims to understand residents' willingness and attitudes toward ecological compensation, so as to provide a reference for government decision-making. Please read each question carefully and choose the option that best matches your actual situation and opinions. All your answers will be kept strictly confidential and used only for this research. Thank you for your participation!
Your age [Fill in the blank] *

Your gender [Single choice] *
( ) Male
( ) Female
Your household registration (hukou) [Single choice] *
( ) Urban
( ) Rural
Number of people currently living together with you in your household [Fill in the blank] *

Your current education level is [Single choice] *
( ) Primary school or below
( ) Junior middle school
( ) Senior high school (or secondary technical school)
( ) Junior college
( ) Bachelor's degree
( ) Master's degree
( ) Doctoral degree
Your occupation is [Single choice] *
( ) Farmer
( ) Self-employed / individual business owner

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( ) Civil servant
( ) Public institution staff
( ) Private-enterprise owner
( ) State-owned enterprise employee
( ) Private-enterprise employee
( ) Freelancer
( ) Other
Your household’s average annual disposable income (yuan) [Single choice] *
( ) 5,000 and below
( ) 5,001–10,000
( ) 10,001–20,000
( ) 20,001–30,000
( ) 30,001–40,000
( ) 40,001–50,000
( ) 50,001–60,000
( ) 60,001–70,000
( ) 70,001–80,000
( ) 80,001–90,000
( ) 90,001–100,000
( ) Above 100,000
How satisfied are you with your current health status? [Single choice] *
( ) 1 Very dissatisfied
( ) 2
( ) 3
( ) 4
( ) 5 Very satisfied
The distance from your residence to the Weihe River Basin is ______ km [Fill in the blank] *

How satisfied are you with the water quality of the Weihe River Basin? [Single choice] *
( ) 1 Very dissatisfied
( ) 2
( ) 3
( ) 4
( ) 5 Very satisfied
How satisfied are you with the water quantity of the Weihe River Basin? [Single choice] *
( ) 1 Very dissatisfied
( ) 2
( ) 3
( ) 4
( ) 5 Very satisfied
Do you know the current ecological environment status of the river basin where you live? [Single choice] *
( ) Yes
( ) No
How important is the ecological environment of the river basin where you live to you? [Single choice] *
( ) 1 Very unimportant
( ) 2
( ) 3
( ) 4
( ) 5 Very important
Do you think the current ecological environment of the Weihe River Basin needs to be improved? [Single choice] *

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( ) Very much needs improvement
( ) Needs improvement
( ) Average
( ) Does not need improvement
Because ecological protection measures are implemented in the upstream area, the ecological environment in the downstream area is ensured. Are you willing to pay a certain amount of money every year to compensate the upstream area? [Single choice] *
( ) Yes
( ) No
(Answer this question only if you chose "Yes" in Question 15)
What is the maximum amount you are willing to pay each year to compensate the upstream area (as a reward to the upstream for protecting the environment)? [Single choice] *
( ) ≤ 50
( ) 50–100
( ) 100–150
( ) 150–200
( ) 200–250
( ) 250–300
( ) 300–350
( ) 350–400
( ) 400–450
( ) 450–500
( ) 500–600
( ) 600–700
( ) 700–800
( ) 800–900
( ) 900–1,000
( ) 1,000–1,500
( ) ≥ 1,500
(Answer this question only if you chose "Yes" in Question 15)
In what way would you prefer to compensate the upstream area (as a reward to the upstream for protecting the environment)? [Single choice] *
( ) Increased water fees
( ) Ecological protection fee
( ) Donation
( ) Voluntary labor
( ) Other methods
If you are a protector of the basin's ecological environment, are you willing to receive compensation (rewards) for your protection behavior? [Single choice] *
( ) Yes
( ) No
(Answer this question only if you chose "Yes" in Question 18)
What is the maximum amount of compensation you would be willing to receive each year (as compensation for your ecological protection actions)? [Single choice] *
( ) ≤ 50
( ) 50–100
( ) 100–150
( ) 150–200
( ) 200–250
( ) 250–300
( ) 300–350
( ) 350–400
( ) 400–450

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( ) 450–500
( ) 500–600
( ) 600–700
( ) 700–800
( ) 800–900
( ) 900–1,000
( ) 1,000–1,500
( ) ≥ 1,500
(Answer this question only if you chose “Yes” in Question 18)
In what form would you prefer to receive compensation (for your ecological protection actions)? [Single choice] *
( ) Cash
( ) Skills training
( ) Preferential loans
( ) Project support (e.g. road construction, school construction, cultural facilities construction)
( ) Job opportunities
( ) Other

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