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Accounting of Transboundary Ecocompensation Standards Based on Water Quantity Allocation and Water Quality Control Targets

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Abstract
In China, under the premise that the water quantity allocation and water quality control targets for transboundary rivers have been determined, ecocompensation between upstream and downstream areas is urgently needed in management practice when targets cannot be met in the transboundary section. A dynamic accounting method for ecocompensation standards needs to be established at the scientific level. However, the accounting method of the existing ecocompensation standards is not sufficient. The purpose of this study is to propose a transboundary compensation standard accounting method based on water quantity allocation and water quality control targets and to establish ecocompensation standard accounting formulas for the Shaying River watershed. The accounting process is as follows: the water quantity compensation standard in different water quantity scenarios is calculated from the perspective of the water resource value. By using the comprehensive pollution index method, the water quality compensation standard is calculated in different water quality scenarios, and the ecocompensation standard calculation formulas for watersheds are determined. As an application, 27 types of ecocompensation standard formulas for the Shaying River watershed were determined for 3 hydrological frequencies (50%, 75% and 95%), 3 water quantity scenarios (equal-quantity, excess-quantity and reduced-quantity discharging) and 3 water quality levels (equal-quality, inferior-quality and better-quality discharging). The results not only provide a compensation standard for the Shaying River but also provide a reference for the calculation of ecocompensation standards for other transboundary rivers in China with definite water quantity and water quality management objectives.

Keywords Transboundary compensation standard · Water resources value · Comprehensive pollution index method (CPI) · Water quantity compensation standard · Water quality compensation standard · Dynamic accounting method · Shaying River

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1 Introduction

In China, under the construction of an ecological civilization and strict management of water resources, many transboundary rivers have allocated water quantities, and the water quality targets of transboundary sections have been determined. However, in daily management, if the water quantity and quality of a transboundary section cannot meet the water quantity allocation and water quality targets, implementing ecological compensation measures in upstream and downstream areas is an urgent problem that must be solved in management practice. The water resource value forms the basis of transboundary ecological compensation standards (Li et al. 2010; Liu and Lv 2012; Tang et al. 2018). Therefore, at the scientific level, the value of water resources needs to be determined, and a dynamic accounting method for ecocompensation standards needs to be established accordingly.

At present, the methods used to calculate river ecocompensation standards (which can also be regarded as watershed ecocompensation standards) locally or globally are mainly based on ecosystem service values (Pagiola et al. 2005; Pimentel et al. 1997; Liu et al. 2017; Xu et al. 2019; Wang and Li 2019), the water footprint method (Tian 2006; Qi 2009; Wei and Xia 2012; Geng and Zhang 2009; Lu and Ke 2016; Li 2018), the opportunity cost (kosoy et al. 2007; Ferraro 2008; Roland and Leon 2009; Liu et al. 2006; Huang 2013; Zhang 2009), water quality monitoring (Pang et al. 2010; Wu et al. 2018; Yang et al. 2018; Xie et al. 2013; Wang et al. 2012; Liu et al. 2016; Qin et al. 2018), willingness to pay (Bienabe and Hearne 2006; Arlene et al. 2007; Moreno et al. 2012; Zhao 2013; Chen and Ma 2017; Peng et al. 2010), and water quality and quantity (Xu et al. 2008; Fu et al. 2012; Guo et al. 2013; Chen and Zhou 2016). These six ecocompensation standard calculation methods have different compensation bases and application scopes. The compensation focuses are also different for each method since each has distinct advantages and disadvantages (Table 1). In addition, none of these six calculation methods for ecocompensation standards take into account both the dynamic changes in water resource values and the dynamic changes in water quality and quantity, thus influencing the calculation results.

The objectives of this paper are to propose a transboundary river compensation standard accounting method based on water quantity allocation and water quality control targets and to determine the ecocompensation standard accounting formulas of the Shaying River as an example. To achieve these objectives, shadow price models, assessment methods of the water resource value, accounting methods for water quantity compensation standards, comprehensive pollution index (CPI) methods, accounting methods for water quality compensation standards, and accounting methods for transboundary ecocompensation standards are utilized in this study. The models and methods are described in detail in Section 2. Then, the study area is described briefly in Section 3. Next, the results and discussion are provided in Section 4 and Section 5. Finally, the conclusions are presented in Section 6.

2 Methodology

We hold the opinion that the ecocompensation standard for transboundary rivers should consider both water quantity and water quality. Since the water quantity allocation and water

Table 1 Summary of the accounting methods for watershed ecocompensation standards

Accounting methods	Method introduction	Advantages	Disadvantages
Watershed ecocompensation standards based on ecosystem service value	The economic value of watershed ecosystem services is used as the watershed ecocompensation standard	The economic value of water resources can be comprehensively calculated at the watershed scale; this approach has a broad application scope and is commonly used	1) Computing process is complex, extensive data are needed, and the implementation is difficult. 2) The final compensation standard is too high to be accepted by the compensation subject.
Watershed ecocompensation standards based on the water footprint method	The water footprint method is used to calculate the regional water resource usage, the economic value of which is used as the watershed ecocompensation standard	The direct use value of water resources, which is easy to quantify, is regarded as the compensation standard. The operation steps are easy to implement, the relevant data are easy to obtain and analyze, the scope of use is broad and the method is commonly applied	Considers only the quantity of water resources, and the quality of water resources is not considered.
Watershed ecocompensation standards based on opportunity cost	The lost opportunity cost in the headwater region is considered in the watershed eco-compensation standard	This method takes full account of the cost of ecological constructors in upstream areas and has good practical feasibility.	The subjectivity of data is high, and the accuracy of the accounting results is not sufficient
Watershed ecocompensation standards based on water quality monitoring	The control cost of water quality changes (improvement or reduction) is considered in the watershed eco- compensation standard	The basis of compensation is clear, and this approach has been applied in many provinces.	Only considers the influence of upstream water quality changes on compensation standards and ignores the impact of upstream water savings or water use on compensation standards.
Watershed ecocompensation standards based on willingness to pay	The specific amount of compensation that residents are willing to receive or money they will pay is considered in the watershed eco-compensation standard	This method involves simple operations and fully considers the beneficiary's willingness to pay	The data are from surveys, so the calculation results are subjective.
Watershed ecocompensation standards based on water quality and quantity	Based on the determination of standard water quantity and quality, the eco-compensation standard is calculated from the perspectives of water quantity and quality	The calculation method takes into account the water quality and quantity. In addition, It is much more complete and realistic than methods that only consider one of the two factors.	The compensation relationship between upstream and downstream is not clear, and the water resources value is not scientifically established

quality management objectives of transboundary rivers have been determined, there are conflicts related to water resource utilization in both water quantity and water quality between upstream and downstream areas (Figs. 1 and 2).

2.1 Water Quantity Compensation Standard from the Perspective of Water Resources Value

2.1.1 Assessment of Water Resource Value

The value of water resources includes the economic and ecological value of water resources. The accounting formula is:

$$V = V_J + V_S \tag{1}$$

where V is the value of water resources (yuan); V_J is the economic value of water resources (yuan); and V_S is the ecological value of water resources (yuan).

1) Economic value of water resources (V_J)

The economic value of water resources is calculated according to the theoretical value of the water use amounts required for domestic, industry, and agriculture. The accounting formula is given as:

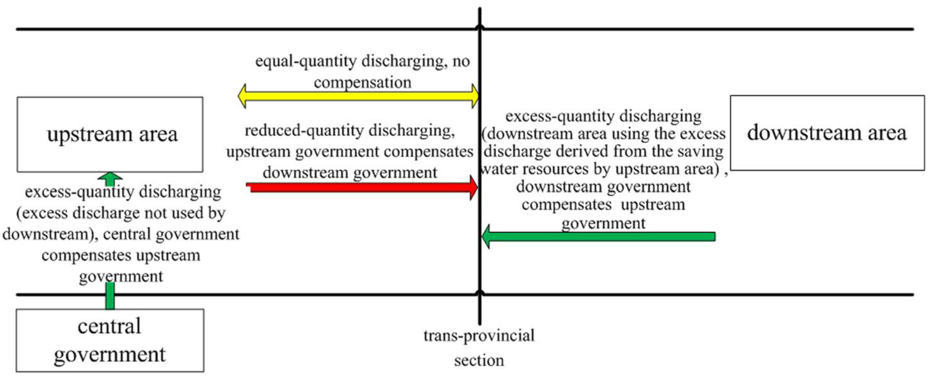

Fig. 1 Principle of water quantity compensation standard accounting. 1) Compared with the standard discharge from the water quantity allocation agreement in a transboundary section, when the upstream area discharges an equal quantity of water resources, there is no compensation relationship between the upstream and downstream governments. 2) When the upstream area overuses the allocated water resources, resulting in the reduction of discharge, the available water in the downstream area will be reduced, and the upstream government should compensate the downstream government. 3) When the upstream area saves water resources and discharges excessively, the upstream area should be compensated for the value of the saving water resource. The downstream government and the central government may be the compensation subjects. The compensation standard and the principles for determining the compensation subjects are as follows: first, according to the value of water resources created by the downstream area using the excess drainage derived from the saving water resources by upstream area, the compensation standard is used to determine the appropriate compensation paid from the downstream government to the upstream government, and the surplus is borne by the central government

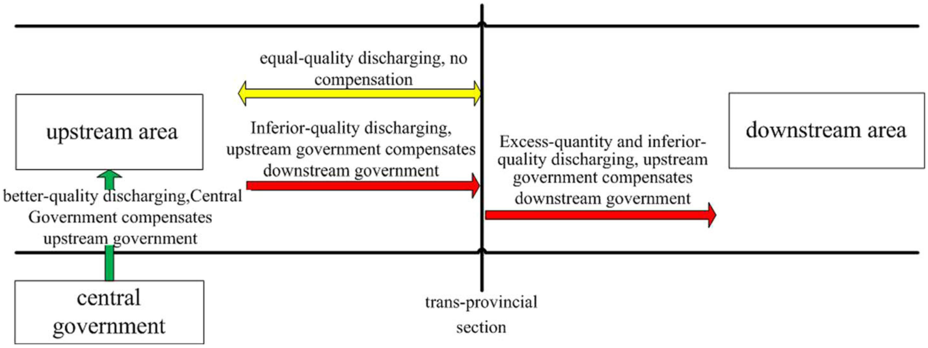

Fig. 2 Principle of water quality compensation standard accounting. 1) Considering the water quality targets in the transboundary section, when the upstream area discharges equal-quality water resources, there is no compensation relationship between the upstream and downstream governments. 2) When the upstream area discharges inferior-quality water resources, the water quality downstream will deteriorate, and the upstream government should compensate the downstream government. In addition, when the upstream area discharges inferior-quality and excess-quantity water resources, the upstream government should bear the treatment costs of meeting water quality targets. 3) When the upstream area discharges high-quality water resources, it is clear that the upstream area has made efforts to protect the water quality and has produced positive externalities. Therefore, the upstream area should be compensated. However, it is not necessary for downstream areas to use high-quality water resources for their own interests. Therefore, the compensation subject is the central government which encourage the upstream to maintain high-quality water resources

$$V_J = \sum_{i=1}^{n} C_{iL} Q_{iL} + \sum_{i=1}^{n} C_{iI} Q_{iI} + \sum_{i=1}^{n} C_{iA} Q_{iA} \tag{2}$$

where V_J is the value of water resources (yuan); Q_{iL}, Q_{iI} andQ_{iA} are the water use amounts for domestic, industry, and agriculture for the reach-i region(m^3), respectively, and these data can be obtained generally from water quantity allocation schemes; and C_{iL}, C_{iI} andC_{iA} are the theoretical values of water resources for domestic, industry, and agriculture for the reach-i region (yuan/m^3), respectively, which are calculated by a shadow price model.

- We refer to previous studies that used the shadow pricing method to calculate the value of water resources (Yuan et al. 2002; Mao and Yuan 2003; Zhu et al. 2005; Sun et al. 2007; Tang et al. 2018). The shadow price model is specifically:

a) Watershed partitioning involves dividing a watershed into administrative regions at the same level based on the transboundary section of the river.
b) The maximum net benefit of water use in a watershed is used to establish the objective function, and the upper and lower limits of various water use departments and the amount of available water in the watershed are used as constraints. The optimal allocation model for water resources is established as follows:

$$\max R = \sum_{i=1}^{n} e_{i\mathrm{I}}\, q_{i\mathrm{I}} + \sum_{i=1}^{n} e_{i\mathrm{A}}\, q_{i\mathrm{A}} + \sum_{i=1}^{n} e_{i\mathrm{L}}\, q_{i\mathrm{L}} + \sum_{i=1}^{n} e_{i\mathrm{O}}\, q_{i\mathrm{O}}$$

$$\mathrm{S.T.}\ \mathrm{A}_{i\mathrm{Imin}} \le q_{i\mathrm{I}} \le \mathrm{A}_{i\mathrm{Imax}}$$

$$\mathrm{A}_{i\mathrm{Amin}} \le q_{iA} \le \mathrm{A}_{i\mathrm{Amax}}$$

$$\mathrm{A}_{i\mathrm{Lmin}} \le q_{i\mathrm{L}} \le \mathrm{A}_{i\mathrm{Lmax}}$$

$$\mathrm{A}_{i\mathrm{Omin}} \le q_{i\mathrm{O}} \le \mathrm{A}_{iO\mathrm{max}}$$

$$q_{i\mathrm{I}} + q_{i\mathrm{A}} + q_{i\mathrm{L}} + q_{i\mathrm{O}} \le \mathrm{Q}_i$$

$$q_{i\mathrm{I}}, q_{i\mathrm{A}}, q_{i\mathrm{L}}, q_{i\mathrm{O}} \ge 0 \qquad \text{其中} i = 1，2，\ldots\ldots n;$$

where R is the net social benefit from the use of water resources and n is the number of reaches. $\mathrm{A}_{i\mathrm{Imin}}$and $\mathrm{A}_{i\mathrm{Imax}}$ are the upper and lower limits of industrial water use for the reach-i region; $\mathrm{A}_{i\mathrm{Amin}}$ and $\mathrm{A}_{i\mathrm{Amax}}$ are the upper and lower limits of agricultural water use for the reach-i region; $\mathrm{A}_{i\mathrm{Lmin}}$ and $\mathrm{A}_{i\mathrm{Lmax}}$ are the upper and lower limits of domestic water use for the reach-i region; $\mathrm{A}_{i\mathrm{Omin}}$ and $\mathrm{A}_{i\mathrm{Omax}}$ are the upper and lower limits of outside-stream ecological water use for the reach-i region; Q_i *is* the amount of available water supplied for the reach-i region; $e_{i\mathrm{I}}$, $e_{i\mathrm{A}}$, $e_{i\mathrm{L}}$ and $e_{i\mathrm{O}}$ are the net benefit coefficients of water use for industry, agriculture, domestic and the outside-stream ecological environment, respectively, for the reach-i region; and $q_{i\mathrm{I}}$, $q_{i\mathrm{A}}$, $q_{i\mathrm{L}}$ and $q_{i\mathrm{O}}$ are the water use amounts for industry, agriculture, domestic and the outside-stream ecological environment for the reach-i region under the maximum net benefit.

c) Computation of the dual solutions of the model

According to the connotation of the shadow price method, the shadow price of water resources (i.e., the theoretical value of water resources) for different water use departments is actually determined through a dual solution of the optimal allocation model of water resources discussed above.

The model is repeatedly run with the MATLAB program, and multiple optimization schemes are considered in the calculation. Taking the net social benefit of each scheme as the weight, the shadow price of each water use department in each reach can be calculated by the weighted averaging method, that is, the theoretical water resource value of water use for domestic (C_{iL}), industry (C_{iI}), agriculture (C_{iA}) and the outside-stream ecological environment (C_{iO}) in each reach in a watershed (yuan/m^3).

2) Ecological value of water resources (V_S)

The ecological value of water resources includes the ecological value of outside-stream and in-stream water resources. Therefore, the accounting formula for the ecological value of water resources is:

$$V_S = V_W + V_\mathrm{E} \tag{4}$$

where V_S is the ecological value of water resources (yuan); V_W is the ecological value of outside-stream water resources (yuan); and V_E is the ecological value of in-stream water resources (yuan).

- The ecological value of outside-stream water resources (V_W) is calculated by the following formula:

$$V_W = \sum_{i=1}^{n} C_{iO} Q_{i0} \tag{5}$$

where V_W is the ecological value of outside-stream water resources (yuan) and Q_{iO} is the outside-stream ecological water-use amount in the reach-i region. These data can be obtained from water quantity allocation schemes. C_{iO} is the theoretical water resource value of water use in the outside-stream ecological environment of each reach in the watershed (yuan/m^3), which is calculated from the shadow price model.

- The ecological value of in-stream water resources (V_E) is calculated by the following formula:

$$V_E = \sum_{i=1}^{n} P_{iE} Q_{iE}; \tag{6}$$

$$P_{iE} = \omega_{iL} C_{iL} + \omega_{iI} C_{iI} + \omega_{iA} C_{iA} \tag{7}$$

where V_E is the ecological value of in-stream water resources (yuan); $P_{iE}$is the unit value of in-stream water resources in reach-i of a river (yuan/m^3); Q_{iE} is the runoff in reach-i of a river (m^3); C_{iL}, $C_{iI}$and C_{iA} are the theoretical values of water resources for societal, industrial and agricultural water use (yuan/m^3), respectively; and ω_{iL}, ω_{iI} and ω_{iA} are the weighting factors for the theoretical value of water resources associated with domestic, industry, and agriculture. The proportions of the water use amounts for domestic, industry and agriculture to the total amount are considered the weighting factors.

2.1.2 Water Price in Water Quantity Compensation (Also Called the Unit Value of Water Resources)

The water price in water quantity compensation (also called the unit value of water resources) is calculated according to the water resource value and water resource amount for the watershed (water consumption + runoff). The accounting formula is given as:

$$C = \frac{V}{\sum_{\mathrm{i}}^{\mathrm{n}} Q_{\mathrm{i}H} + \sum_{\mathrm{i}}^{\mathrm{n}} Q_{\mathrm{i}E}} \tag{8}$$

where C is the water price in water quantity compensation (also called the unit value of water resources) (yuan/m^3); V is the value of water resources (yuan); $Q_{\mathrm{i}H}$ is the water consumption of different water-use departments in the reach-i region (m^3); and Q_{iE} is the runoff in reach-i (m^3).

2.1.3 Water Quantity Compensation Standard for a Transboundary Section

Based on the standard discharge from the water quantity allocation agreement in a transboundary section, different water quantity scenarios (equal-quantity, excess-quantity and reduced-quantity discharging) are established. Then, the calculation formula for the water quantity compensation standard in the transboundary section is:

$$M_{K_1}=\begin{cases}-C\times|Q-Q^{'}| & Q<Q^{'} & UP\rightarrow DOWN\\ C\times|Q-Q^{'}| & Q=Q^{'} & UP\leftrightarrow DOWN\\ \begin{cases}C\times\left(U_D-U_D^{'}\right)\\ C\times\left(U_U^{'}-U_U\right)-C\times\left(U_D-U_D^{'}\right)\end{cases} & \begin{matrix}Q>Q^{'},U_D>U_D^{'},and\\ U_U^{'}-U_U>U_D-U_D^{'}\end{matrix} & \begin{matrix}UP\leftarrow DOWN\\ CEN\rightarrow UP\end{matrix}\\ C\times\left(U_U^{'}-U_U\right) & \begin{matrix}Q>Q^{'},U_D>U_D^{'},and\\ U_U^{'}-U_U\le U_D-U_D^{'}\end{matrix} & UP\leftarrow DOWN\end{cases} \tag{9}$$

where M_{K_1} is the water quantity compensation standard (100 million yuan); C is the water price in water quantity compensation (yuan/m^3); Q and $Q'$are the actual discharge and the standard discharge from the water quantity allocation agreement in a transboundary section (100 million m^3), respectively; U_U and $U_U^{'}$ are the actual water use amount and the standard water use amount from the water quantity allocation agreement for the upstream area (the area above the transboundary section) (100 million m^3), respectively; and U_D and $U_D^{'}$ are the actual water withdrawal from rivers and the standard water withdrawal from rivers from the water quantity allocation agreement for the downstream area (the area below the transboundary section) (100 million m^3), respectively. The compensation stakeholders are the upstream, downstream and central governments. The one-way arrows indicate the compensation direction, and the two-way arrows represent no compensation behaviors.

The above formula, however, is flawed in that it assumes that the excess water used downstream comes only from upstream savings. However, in addition to come from upstream savings, the excess water used downstream also may come from the floods and the local water resources. Therefore, when the upstream area saves water resources and discharges excessively, the upstream area should be compensated for the value of the saving water resource, and the central government is the compensation subject. Even if the downstream government overuses the water, the source of the excess water is indistinguishable, so the downstream government does not participate in upstream ecological compensation. Then, Formula 9 is modified to Formula 10:

$$M_{K_1}=\begin{cases}-C\times|Q-Q^{'}| & Q<Q^{'} & UP\rightarrow DOWN\\ C\times|Q-Q^{'}| & Q=Q^{'} & UP\leftrightarrow DOWN\\ C\times\left(U_U^{'}-U_U\right) & Q>Q^{'},and\ U_U^{'}>U_U & CEN\rightarrow UP\end{cases} \tag{10}$$

2.2 Water Quality Compensation Standard Based on the Comprehensive Pollution Index Method

2.2.1 Comprehensive Pollution Index (CPI) Method

The comprehensive pollution index (CPI) is a quantitative indicator that reflects the degree of comprehensive pollution for various pollutants in water bodies. The specific formula is:

$$P_K = \sum_{j=1}^{n} \frac{C_j}{C} \times C_k \tag{11}$$

where P_K is the CPI of water quality for section k in a watershed; the higher the value is, the more serious the water pollution problem; n is the type of pollutant; C_j is the measured concentration of the pollutant; C_{oj} is the evaluation criterion for the pollutant, which can be obtained from the Environmental Quality Standard for Surface Water (GB3838–2002); and C_k is the uniform maximum allowable index for various pollutants in surface water. In this study, the value of C_k is 0.1.

2.2.2 Water Quality Compensation Standard for a Transboundary Section

Based on the water quality target for a transboundary section, different water quality scenarios (equal-quality, inferior-quality and better-quality discharging) are established. Then, the formula for the water quality compensation standard in the transboundary section is:

$$M_{K_2} = \begin{cases} (P_k{}^{o} - P_k{}^{out}) \times Q_P \times C_{k_2} & P_k{}^{o} < P_k{}^{out} \quad UP \rightarrow DOWN \\ (P_k{}^{o} - P_k{}^{out}) \times Q_P \times C_{k_2} & P_k{}^{o} = P_k{}^{out} \quad UP \leftrightarrow DOWN \\ (P_k{}^{o} - P_k{}^{out}) \times Q_P \times C_{k_2} & P_k{}^{o} > P_k{}^{out} \quad CEN \rightarrow UP \end{cases} \tag{12}$$

where M_{K_2} is the water quality compensation standard in the transboundary section (100 million yuan); $P_k{}^{out}$ and $P_k{}^{o}$ are the CPIs of actual water quality and standard water quality (water quality target) in the transboundary section, respectively; Q_P is the amount of water discharged into rivers in upstream areas (100 million m^3); and C_{k_2} is the unit cost of maintaining water quality, which can be regarded as the unit cost of sewage treatment (yuan/m^3).

2.2.3 Sewage Treatment Costs in the Combined Scenario of Excess-Quantity and Inferior-Quality Discharging

In the combined scenario of excess-quantity and inferior-quality discharging, upstream areas should bear the treatment cost, which enables water quality target to be met in the transboundary section. The corresponding accounting formula is:

$$M_{K2}{}' = (P_k{}^{o} - P_k{}^{out}) \times \left(U_U{}' - U_U\right) \times C_{k_2} \tag{13}$$

where $M_{K2}{}'$ is the sewage treatment cost in the combined scenario of excess-quantity and inferior-quality discharging (100 million yuan). The definitions of the other parameters are given above.

2.3 Transboundary River Ecocompensation Standard

The transboundary river ecocompensation standard (M) includes the water quantity compensation standard in the transboundary section (M_{K_1}), the water quality compensation standard in the transboundary section (M_{K2}) and the sewage treatment cost in the combined scenario of excess-quantity and inferior-quality discharging ($M_{K2}{}'$); the accounting formula is:

$$M = M_{K1} + M_{K2} + M_{K2}{'} \tag{14}$$

Furthermore, Table 2 shows the detailed formulas for calculating the transboundary river ecocompensation standard.

3 Case Study

The Shaying River is the largest tributary of the Huaihe River, and it originates in the Funiu Mountain area of Henan Province and flows to the Huaihe River in Yingshang County, Anhui Province, with a total length of 561 km. The Shaying River watershed is located in the middle and upper reaches of the Huai River, between 112°45′ ~ 113°E and 34°20′ ~ 34°34′N, as shown in Fig. 3. The Shaying River watershed covers 32 counties (cities) in Henan Province and Anhui Province.

In January 2018, a water quantity allocation agreement for seven important transprovincial rivers in the Huaihe River watershed, including the Shaying River, was approved. In the water quantity allocation agreement for the Shaying River watershed, the standard discharge for the transprovincial section, the standard water-use amount in Henan Province and the standard water withdrawal from the river in Anhui Province were identified (Table 3). In addition, the basic ecological water demand of the Shaying River watershed was also stipulated as 5.5 m^3/s from October to March, 5.8 m^3/s April to May, and 20.4 m^3/s June to September. According to the Water Function Zoning of Major Rivers and Lakes in China (2012–2030), the water quality target of the transprovincial section is Class III. At present, the main over-standard pollutants are total phosphorus, COD, ammonia nitrogen, BOD_5 and the permanganate index in the trans-provincial section.

Table 2 Detailed formulas for calculating the transboundary river ecocompensation standard

Discharging scenario			River ecocompensation standard (M)	Compensation subject and object
equal-quality	reduced-quantity	$Q<Q'$	$-C\times \mid Q-Q' \mid$	$UP \rightarrow DOWN$
	equal-quantity	$Q=Q'$	0	$UP \leftrightarrow DOWN$
	excess-quantity	$Q>Q'$ and $U_U' > U_U$	$C\times(U_U'-U_U)$	$CEN \rightarrow UP$
inferior-quality	reduced-quantity	$Q<Q'$	$-C \times \lvert Q-Q' \rvert + (P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2}$	$UP \rightarrow DOWN$
	equal-quantity	$Q=Q'$	$(P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2}$	$UP \rightarrow DOWN$
	excess-quantity	$Q>Q'$ and $U_U' > U_U$	$C\times(U_U'-U_U)$	$CEN \rightarrow UP$
			$(P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2} + (P_k{}^{o}-P_k{}^{out}) \times (U_U{'}-U_U) \times C_{k_2}$	$UP \rightarrow DOWN$
better-quality	reduced-quantity	$Q<Q'$	$-C\times \mid Q-Q' \mid$	$UP \rightarrow DOWN$
			$(P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2}$	$CEN \rightarrow UP$
	equal-quantity	$Q=Q'$	$(P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2}$	$CEN \rightarrow UP$
	excess-quantity	$Q>Q'$ and $U_U' > U_U$	$C \times (U_U{'}-U_U) + (P_k{}^{o}-P_k{}^{out}) \times Q_p \times C_{k_2}$	$CEN \rightarrow UP$

The one-way arrows indicate the compensation direction, and the two-way arrows represent no compensation behaviors

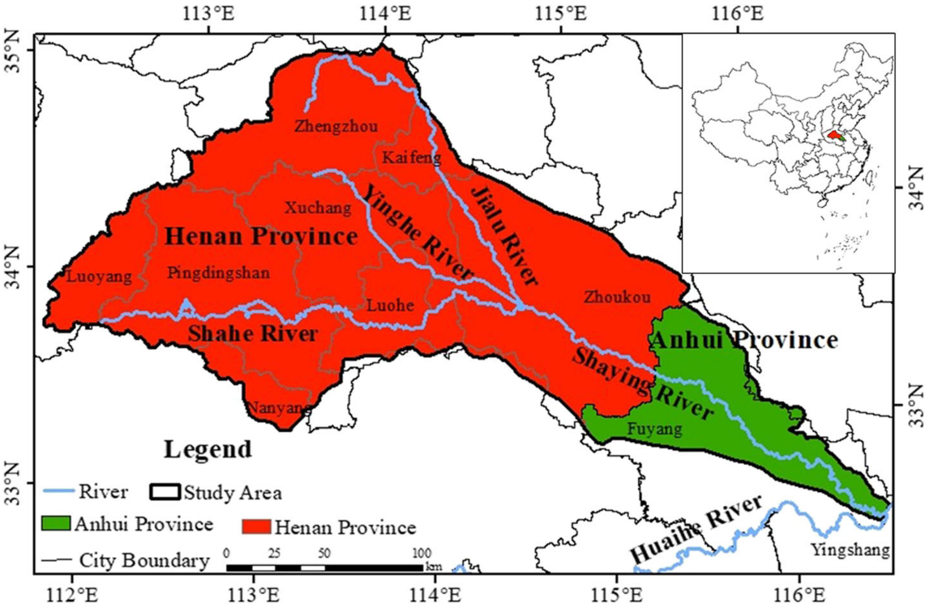

Fig. 3 Location of the Shaying River watershed

4 Results

4.1 Water Quantity Compensation Standard for the Transprovincial Section of the Shaying River

4.1.1 Value of Water Resources in the Shaying River Watershed

The calculation process for the shadow price model of the Shaying River watershed is as follows. 1) The Shaying River is divided into reach 1 and reach 2. Correspondingly, the Shaying River watershed in Henan Province above the province boundary is called the upstream area, and the Shaying River watershed in Anhui Province below the province boundary is called the downstream area. 2) The optimal allocation model of water resources for the Shaying River watershed is established. The relevant data used in the model are shown

Table 3 The standard water quantity indexes for 2030 in the water quantity allocation agreement for the Shaying River watershed (100 million m^3)

Hydrological frequencies	Standard discharge in the transprovincial section	Standard discharge from basin outlet section	Standard water use amount in Henan Province	Water consumption/ Water usage	Standard water withdrawals from rivers in Anhui Province
50%	35.45	39.23	73.18	0.84	7.59
75%	15.24	16.73	82.79	0.84	10.09
95%	7.66	8.47	76.81	0.84	8.85

Standard discharge is equivalent to the Standard runoff

Table 4 The net benefit coefficient and the upper and lower limits of various water use departments in each reach in the Shaying River watershed

Hydrological frequencies	Reach	Industrial water use			Agricultural water use			Domestic water use			Outside-stream ecological water use			Amount of available water
		Net benefit coefficient (yuan/m^3)	Upper limit (100 million m^3)	Lower limit (100 million m^3)	Net benefit coefficient (yuan/m^3)	Upper limit (100 million m^3)	Lower limit (100 million m^3)	Net benefit coefficient (yuan/m^3)	Upper limit (100 million m^3)	Lower limit (100 million m^3)	Net benefit coefficient (yuan/m^3)	Upper limit (100 million m^3)	Lower limit (100 million m^3)	(100 million m^3)
50%	Reach 1	0.366	18.08	16.27	0.293	17.91	10.75	0.366	16.88	7.66	0.178	2.49	2.24	46.14
	Reach 2	0.366	3.26	2.93	0.293	3.25	1.95	0.366	2.59	0.94	0.178	0.14	0.12	7.59
75%	Reach 1	0.366	18.08	16.27	0.293	23.35	14.01	0.366	22.39	7.66	0.178	2.49	1.99	54.66
	Reach 2	0.366	3.26	2.93	0.293	5.71	3.43	0.366	3.62	0.94	0.178	0.14	0.11	10.09
95%	Reach 1	0.366	18.08	16.27	0.293	19.96	11.98	0.366	10.91	7.66	0.178	2.49	1.24	40.4
	Reach 2	0.366	3.26	2.93	0.293	4.73	2.84	0.366	3.01	0.94	0.178	0.14	0.07	8.85

The upper limits of the water use amounts for industry, agriculture, outside-stream ecological environment and the lower limit of the domestic water use amount are calculated by the water-use amount stipulated by the water-quantity allocation agreement and the proportions of the water use amounts for industry, agriculture, outside-stream ecological environment, domestic water-use to the total amount under the current situation. The lower limit of the industrial water use amount is 90% of the upper limit. The lower limit of the agricultural water use amount is 60% of the upper limit. The lower limit of the outside-stream ecological water use amount is 90%, 80% and 50% of the upper limits for hydrological frequencies of 50%, 75%, and 95%, respectively. The net benefit coefficients of various water use departments are from the data presented by Zhu et al. (2005). The amount of available water is obtained from the allocation agreement

Table 5 Theoretical water resource values of different water use departments in the Shaying River watershed (yuan/m^3)

Hydrological frequencies	Reach	Industrial water use	Agricultural water use	Domestic water use	Outside-stream ecological water use
50%	Reach 1	0.379	0.295	0.362	0.184
	Reach 2	0.379	0.295	0.358	0.184
75%	Reach 1	0.393	0.304	0.362	0.189
	Reach 2	0.393	0.304	0.357	0.189
95%	Reach 1	0.357	0.278	0.353	0.167
	Reach 2	0.357	0.278	0.343	0.167

Table 6 Economic value of water resources in the Shaying River watershed (100 million yuan)

Hydrological frequencies	Reach	Industrial water use	Agricultural water use	Domestic water use	Sum
50%	Reach 1	6.848	5.280	2.773	17.43
	Reach 2	1.234	0.958	0.338	
75%	Reach 1	7.099	7.093	2.775	20.32
	Reach 2	1.280	1.736	0.337	
95%	Reach 1	6.450	5.555	2.703	17.51
	Reach 2	1.163	1.317	0.323	

in Table 4. 3) The dual solution of the model is calculated, and the theoretical water resource value of each reach is obtained (Table 5).

The economic value of water resources in the Shaying River watershed is 1.743 billion yuan, 2.032 billion yuan and 1.751 billion yuan for hydrological frequencies of 50%, 75% and 95%, respectively (Table 6).

The results indicate that the ecological values of outside-stream water resources for the Shaying River watershed corresponding to hydrological frequencies of 50%, 75% and 95% are 48 million yuan, 50 million yuan and 44 million yuan, respectively (Table 7).

After calculating the unit value of in-stream water resources (Table 8), combined with runoff, the ecological value of in-stream water resources for hydrological frequencies of 50%, 75% and 95% is 1.271 billion yuan, 0.551 billion yuan and 0.259 billion yuan, respectively (Table 9).

Table 7 Ecological value of outside-stream water resources for the Shaying River watershed

Hydrological frequencies	Reach	Outside-stream ecological water use amount (100 million m^3)	Theoretical water resource value (yuan/m^3)	Ecological value of outside-stream water resources (100 million yuan)
50%	Reach 1	2.49	0.184	0.48
	Reach 2	0.14	0.184	
75%	Reach 1	2.49	0.189	0.50
	Reach 2	0.14	0.189	
95%	Reach 1	2.49	0.167	0.44
	Reach 2	0.14	0.167	

Table 8 Unit value of in-stream water resources for the Shaying River

Hydrological frequencies	Reach	Theoretical water resource value for outside streams (yuan/m^3)			Weighting factors			Unit value of in-stream water resources (yuan/m^3)
		Industrial water use	Agricultural water use	Domestic water use	Industrial water use	Agricultural water use	Domestic water use	
50%	Reach 1	0.379	0.295	0.362	0.39	0.39	0.17	0.323
	Reach 2	0.379	0.295	0.358	0.43	0.43	0.12	0.333
75%	Reach 1	0.393	0.304	0.362	0.35	0.45	0.15	0.329
	Reach 2	0.393	0.304	0.357	0.32	0.57	0.09	0.333
95%	Reach 1	0.357	0.278	0.353	0.38	0.41	0.16	0.305
	Reach 2	0.357	0.278	0.343	0.36	0.52	0.10	0.309

Table 9 Ecological value of in-stream water resources for hydrological frequencies of 50%, 75% and 95% in the Shaying River watershed

Hydrological frequencies	Runoff (100 million m^3)	Unit value of in-stream water resources (yuan/m^3)	Ecological value of in-stream water resources (100 million yuan)
50%	39.23	0.324	12.71
75%	16.73	0.329	5.51
95%	8.47	0.306	2.59

In summary, according to the economic value of water resources and the ecological value of water resources in the Shaying River watershed, the value of water resources at hydrological frequencies of 50%, 75% and 95% is 3.062 billion yuan, 2.633 billion yuan and 2.054 billion yuan, respectively (Table 10).

4.1.2 Water Price in Water Quantity Compensation for the Shaying River Watershed (Also Called the Unit Value of Water Resources in the Shaying River Watershed)

Table 11 shows the water prices in water quantity compensation for the Shaying River watershed at hydrological frequencies of 50%, 75% and 95%, which are 0.36 yuan/m^3, 0.39 yuan/m^3 and 0.37 yuan/m^{3,} respectively.

4.1.3 Water Quantity Compensation Standard for the Transprovincial Section of the Shaying River

The accounting formulas of the water quantity compensation standard for the transprovincial section at hydrological frequencies of 50%, 75% and 95% were determined (see formulas 15–17 for details).

$$M_{\mathrm{K}_1 50\%}=\begin{cases}-0.36\times|Q_{50\%}-35.45| & 15.24<Q_{50\%}<35.45 & UP\rightarrow DOWN\\ 0.36\times|Q_{50\%}-35.45| & Q_{50\%}=35.45 & UP\leftrightarrow DOWN\\ 0.36\times(73.18-U_{U50\%}) & Q_{50\%}>35.45, and 73.18>U_{U50\%} & CEN\rightarrow UP\end{cases} \tag{15}$$

$$M_{\mathrm{K}_1 75\%}=\begin{cases}-0.39\times|Q_{75\%}-15.24| & 6.99<Q_{75\%}<15.24 & UP\rightarrow DOWN\\ 0.39\times|Q_{75\%}-15.24| & Q_{75\%}=15.24 & UP\leftrightarrow DOWN\\ 0.39\times(82.79-U_{U75\%}) & 15.24<Q_{75\%}<35.45, and\ 82.79>U_{U75\%} & CEN\rightarrow UP\end{cases} \tag{16}$$

Table 10 Value of water resources in the Shaying River watershed (100 million yuan)

Hydrological frequencies	Economic value of water resources	Ecological value of water resources			Value of water resources
		Sum	Outside stream	In-stream	
50%	17.43	13.19	0.48	12.71	30.62
75%	20.32	6.01	0.50	5.51	26.33
95%	17.51	3.03	0.44	2.59	20.54

Table 11 Water price in water quantity compensation for the Shaying River watershed at hydrological frequencies of 50%, 75% and 95%

Hydrological frequencies	Value of water resources (100 million yuan)	Total water consumption of water use departments (100 million m^3)	Runoff (100 million m^3)	Price of water quantity compensation (yuan/m^3)
50%	30.62	44.93	39.23	0.36
75%	26.33	51.56	16.73	0.39
95%	20.54	47.91	8.47	0.37

$$M_{K_1 95\%} = \begin{cases} -0.37 \times \lvert Q_{95\%} - 6.99 \rvert & 3.76 < Q_{95\%} < 6.99 & UP \rightarrow DOWN \\ 0.37 \times \lvert Q_{95\%} - 6.99 \rvert & Q_{95\%} = 6.99 & UP \leftrightarrow DOWN \\ 0.37 \times (76.81 - U_{U95\%}) & 6.99 < Q_{95\%} < 15.24, and 76.81 > U_{U95\%} & CEN \rightarrow UP \end{cases} \quad (17)$$

where $M_{K_1 50\%}$,$M_{K_1 75\%}$ and $M_{K_1 95\%}$ are the water quantity compensation standards for the transprovincial section corresponding to hydrological frequencies of 50%, 75% and 95%, separately (100 million yuan); $Q_{50\%}$, $Q_{50\%}$and $Q_{95\%}$ are the actual discharge values in the transprovincial section at hydrological frequencies of 50%, 75% and 95%, respectively (100 million m^3), which can be obtained through Corresponding hydrologic station set by the state; and $U_{U50\%}$, $U_{U75\%}$ and $U_{U95\%}$ are the actual water-use amounts in the upstream area at hydrological frequencies of 50%, 75% and 95%, respectively (100 million m^3). The meanings of the remaining variables are given in Table 3. "UP", "DOWN" and "CEN" represent the upstream government, downstream government and central government, respectively.

4.2 Water Quality Compensation Standard for the Shaying River Watershed

4.2.1 Water Quality Compensation Standard for the Transprovincial Section of the Shaying River

Five pollutants, including total phosphorus, COD, NH_3-N, BOD and the permanganate index, were selected to calculate the CPI. The CPI of the water quality target (Class III) in the transprovincial section is 0.5. Additionally, the unit cost of sewage treatment is 1.38 (yuan/m^3) (Tan et al. 2015), and the amount of water discharged into rivers from upstream areas at hydrological frequencies of 50%, 75% and 95% is 2.82, 3.63 and 1.19 (100 million m^3), respectively. Therefore, the accounting formulas for the water quality compensation standard in the transprovincial section at hydrological frequencies of 50%, 75% and 95% can be determined (see formulas 18–20 for details).

$$M_{K_2 50\%} = \begin{cases} (0.5 - P_{k50\%}{}^{out}) \times 2.82 \times 1.38 & P_{k50\%}{}^{out} > 0.5 & UP \rightarrow DOWN \\ (0.5 - P_{k50\%}{}^{out}) \times 2.82 \times 1.38 & P_{k50\%}{}^{out} = 0.5 & UP \leftrightarrow DOWN \\ (0.5 - P_{k50\%}{}^{out}) \times 2.82 \times 1.38 & P_{k50\%}{}^{out} < 0.5 & CEN \rightarrow UP \end{cases} \quad (18)$$

$$M_{K_2 75\%} = \begin{cases} (0.5 - P_{k75\%}{}^{out}) \times 3.63 \times 1.38 & P_{k75\%}{}^{out} > 0.5 & UP \rightarrow DOWN \\ (0.5 - P_{k75\%}{}^{out}) \times 3.63 \times 1.38 & P_{k75\%}{}^{out} = 0.5 & UP \leftrightarrow DOWN \\ (0.5 - P_{k75\%}{}^{out}) \times 3.63 \times 1.38 & P_{k75\%}{}^{out} < 0.5 & CEN \rightarrow UP \end{cases} \quad (19)$$

$$M_{K_2 95\%} = \begin{cases} (0.5 - P_{k95\%}{}^{out}) \times 1.19 \times 1.38 & P_{k95\%}{}^{out} > 0.5 \quad UP \rightarrow DOWN \\ (0.5 - P_{k95\%}{}^{out}) \times 1.19 \times 1.38 & P_{k95\%}{}^{out} = 0.5 \quad UP \leftrightarrow DOWN \\ (0.5 - P_{k95\%}{}^{out}) \times 1.19 \times 1.38 & P_{k95\%}{}^{out} < 0.5 \quad CEN \rightarrow UP \end{cases} \quad (20)$$

where $M_{K_2 50\%}$, $M_{K_2 75\%}$ and $M_{K_2 95\%}$ are the water quality compensation standards for the transprovincial section at hydrological frequencies of 50%, 75% and 95%, respectively (100 million yuan), and $P_{k50\%}{}^{out}$, $P_{k75\%}{}^{out}$ and $P_{k95\%}{}^{out}$ are the CPIs of actual water quality in the transboundary section at hydrological frequencies of 50%, 75% and 95%, respectively.

4.2.2 Sewage Treatment Costs in the Combined Scenario of Excess-Quantity and Inferior-Quality Discharging in the Shaying River Watershed

The accounting formulas for the sewage treatment costs in the combined scenario of excess-quantity and inferior-quality discharging at hydrological frequencies of 50%, 75% and 95% were determined (see formulas 21–23 for details).

$$M_{K_2 75\%}{}' = (0.5 - P_{k75\%}{}^{out}) \times (73.18 - U_{U50\%}) \times 1.38 \quad (21)$$

$$M_{K_2 75\%}{}' = (0.5 - P_{k75\%}{}^{out}) \times (82.79 - U_{U75\%}) \times 1.38 \quad (22)$$

$$M_{K_2 95\%}{}' = (0.5 - P_{k95\%}{}^{out}) \times (76.81 - U_{U95\%}) \times 1.38 \quad (23)$$

where $M_{K_2 50\%}{}'$, $M_{K_2 75\%}{}'$ and $M_{K_2 95\%}{}'$ are the sewage treatment costs for hydrological frequencies of 50%, 75% and 95%, respectively (100 million yuan), and the other parameters are defined above.

4.3 Ecocompensation Standard for the Shaying River Watershed

Tables 12, 13 and 14 show the accounting formulas for the ecocompensation standard at hydrological frequencies of 50%, 75% and 95% in the Shaying River watershed.

5 Discussion

We present a new method for calculating the ecocompensation standards of transboundary rivers. This approach has several specific characteristics: 1) The problems of the existing watershed ecocompensation methods based on water quality and quantity, e.g., the compensation relationship between upstream and downstream is not clear, and the water resources value is not scientifically established, are mitigated. 2) Our ecocompensation standard accounting method can determine the best ecocompensation standard in different water quality (equal-quality, inferior-quality and better-quality discharging) and water quantity (equal-quantity, excess-quantity and reduced-quantity discharging) scenarios. Moreover, the method can also aid in identifying the corresponding compensation subject and object. 3) Our ecocompensation standard accounting method can determine the unit value of water resources for different hydrological frequencies and provide key and dynamic parameters for the

Table 12 Accounting formulas for the ecocompensation standard in the Shaying River watershed at a hydrological frequency of 50%

Discharge scenarios			Ecocompensation standard for the Shaying River watershed ($M_{50\%}$)	Compensation subject and object
equal-quality	reduced-quantity	$15.24<Q_{50\%}<35.45$	$-0.36\times\mid Q_{50\%}-35.45\mid$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{50\%}=35.45$	0	$UP\leftrightarrow DOWN$
	excess-quantity	$Q_{50\%}>35.45$, and$U_{U50\%}<73.18$	$0.36\times(73.18-U_{U50\%})$	$CEN\rightarrow UP$
inferior-quality	reduced-quantity	$15.24<Q_{50\%}<35.45$	$-0.36\times\mid Q_{50\%}-35.45\mid+(0.5-P_{k50\%}{}^{out})\times 3.89$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{50\%}=35.45$	$(0.5-P_{k50\%}{}^{out})\times 3.89$	$UP\rightarrow DOWN$
	excess-quantity	$Q_{50\%}>35.45$, and$U_{U50\%}<73.18$	$0.36\times(73.18-U_{U50\%})$	$CEN\rightarrow UP$
			$(0.5-P_{k50\%}{}^{out})\times 3.89+(0.5-P_{k50\%}{}^{out})\times(73.18-U_{U50\%})\times 1.38$	$UP\rightarrow DOWN$
better-quality	reduced-quantity	$15.24<Q_{50\%}<35.45$	$-0.36\times\mid Q_{50\%}-35.45\mid$	$UP\rightarrow DOWN$
			$(0.5-P_{k50\%}{}^{out})\times 3.89$	$CEN\rightarrow UP$
	equal-quantity	$Q_{50\%}=35.45$	$(0.5-P_{k50\%}{}^{out})\times 3.89$	$CEN\rightarrow UP$
	excess-quantity	$Q_{50\%}>35.45$, and$U_{U50\%}<73.18$	$0.36\times(73.18-U_{U50\%})+(0.5-P_{k50\%}{}^{out})\times 3.89$	$CEN\rightarrow UP$

Table 13 Accounting formulas for the ecocompensation standard in the Shaying River watershed at a hydrological frequency of 75%

Discharge scenarios			Ecocompensation standard for the Shaying River watershed ($M_{75\%}$)	Compensation subject and object
equal-quality	reduced-quantity	$6.99<Q_{75\%}<15.24$	$-0.39\times\mid Q_{75\%}-15.24\mid$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{75\%}=15.24$	0	$UP\leftrightarrow DOWN$
	excess-quantity	$15.24<Q_{75\%}<35.45$, and$U_{U50\%}<82.79$	$0.39\times(82.79-U_{U75\%})$	$CEN\rightarrow UP$
inferior-quality	reduced-quantity	$6.99<Q_{75\%}<15.24$	$-0.39\times\mid Q_{75\%}-15.24\mid+(0.5-P_{k75\%}{}^{out})\times 5.01$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{75\%}=15.24$	$(0.5-P_{k75\%}{}^{out})\times 5.01$	$UP\rightarrow DOWN$
	excess-quantity	$15.24<Q_{75\%}<35.45$, and$U_{U50\%}<82.79$	$0.39\times(82.79-U_{U75\%})$	$CEN\rightarrow UP$
			$(0.5-P_{k75\%}{}^{out})\times 5.01+(0.5-P_{k75\%}{}^{out})\times(82.79-U_{U75\%})\times 1.38$	$UP\rightarrow DOWN$
better-quality	reduced-quantity	$6.99<Q_{75\%}<15.24$	$-0.39\times\mid Q_{75\%}-15.24\mid$	$UP\rightarrow DOWN$
			$(0.5-P_{k75\%}{}^{out})\times 5.01$	$CEN\rightarrow UP$
	equal-quantity	$Q_{75\%}=15.24$	$(0.5-P_{k75\%}{}^{out})\times 5.01$	$CEN\rightarrow UP$
	excess-quantity	$15.24<Q_{75\%}<35.45$, and$U_{U50\%}<82.79$	$0.39\times(82.79-U_{U75\%})+(0.5-P_{k75\%}{}^{out})\times 5.01$	$CEN\rightarrow UP$

Table 14 Accounting formulas for the ecocompensation standard in the Shaying River watershed at a hydrological frequency of 95%

Discharge scenarios			Ecocompensation standard for the Shaying River watershed ($M_{95\%}$)	Compensation subject and object
equal-quality	reduced-quantity	$3.76<Q_{95\%}<6.99$	$-0.37\times\mid Q_{95\%}-6.99\mid$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{95\%}=6.99$	0	$UP\leftrightarrow DOWN$
	excess-quantity	$6.99<Q_{95\%}<15.24$, and$76.81>U_{U95\%}$	$0.37\times(76.81-U_{U95\%})$	$CEN\rightarrow UP$
inferior-quality	reduced-quantity	$3.76<Q_{95\%}<6.99$	$-0.37\times\mid Q_{95\%}-6.99\mid+(0.5-P_{k95\%}{}^{out})\times 1.64$	$UP\rightarrow DOWN$
	equal-quantity	$Q_{95\%}=6.99$	$(0.5-P_{k95\%}{}^{out})\times 1.64$	$UP\rightarrow DOWN$
	excess-quantity	$6.99<Q_{95\%}<15.24$,and$76.81>U_{U95\%}$	$0.37\times(76.81-U_{U95\%})$	$CEN\rightarrow UP$
			$(0.5-P_{k95\%}{}^{out})\times 1.64+(0.5-P_{k95\%}{}^{out})\times(76.81-U_{U95\%})\times 1.38$	$UP\rightarrow DOWN$
better-quality	reduced-quantity	$3.76<Q_{95\%}<6.99$	$-0.37\times\mid Q_{95\%}-6.99\mid$	$UP\rightarrow DOWN$
			$(0.5-P_{k95\%}{}^{out})\times 1.64$	$CEN\rightarrow UP$
	equal-quantity	$Q_{95\%}=6.99$	$(0.5-P_{k95\%}{}^{out})\times 1.64$	$CEN\rightarrow UP$
	excess-quantity	$6.99<Q_{95\%}<15.24$,and$76.81>U_{U95\%}$	$0.37\times(76.81-U_{U95\%})+(0.5-P_{k95\%}{}^{out})\times 1.64$	$CEN\rightarrow UP$

calculation of the water quantity compensation standard and watershed ecocompensation standard under different hydrological frequencies. 4) There is no time-scale limit to our ecocompensation standard accounting method. This method can be used to calculate the ecocompensation standards of transboundary rivers when a set of data for water quantity allocation and water quality objectives is available for a given segment.

We have determined the ecocompensation standard accounting formulas for the Shaying River watershed but not fixed values. Notably, the actual discharges, concentrations of major pollutants, water use amounts in upstream Henan Province and water withdrawals from the river in downstream Anhui Province have not been determined. These parameters need to be monitored over a long period of time by specialized agencies. It is suggested that a Shaying River ecocompensation consultation platform be established by watershed management institutions, namely, the Huai River Water Resources Commission. The consultation platform for ecological compensation should be responsible for monitoring the parameters discussed above.

In this case, it is difficult to verify the rationality of Shaying River ecocompensation standard formulas. However, the unit value of water resources in the Shaying River watershed has been calculated for hydrological frequencies of 50%, 75% and 95%, with estimated values of 0.36 yuan/m^3, 0.39 yuan/m^3 and 0.37 yuan/m^3, respectively.

The unit value of water resources in the Shaying River watershed was close to that obtained by Zhu et al. (2005) in 2000. However, compared with the water resource values of 0.71 yuan/m^3 in the Xin'an River Basin (Sun et al. 2007), 3.10 yuan/m^3 in the intake area of the South-to-North Water Diversion Project (Tang et al. 2018), and 4.58 yuan/m^3 in China (He and Chen 2005), although the water resource values in different hydrological scenarios are separately calculated in our research, they are generally much lower than those in other studies. As a crucial parameter, the net benefit coefficient of various water use departments in this study may have been inappropriate due to data limitations; Zhu et al. (2005) adopted the net benefit coefficient to obtain the water resource value for the Huaihe River basin in 2000. The net benefit coefficients of various water use departments are time constrained, and those in our research are much lower than those in other regions. Therefore, the net benefit coefficients of various water use departments should be updated based on the year of transboundary ecocompensation in the next step. Table 15 shows the net benefit coefficients and water resource values in different studies.

6 Conclusions

In this paper, a transboundary river ecocompensation standard accounting method based on water quantity allocation and water quality control targets is proposed, and the corresponding ecocompensation standard accounting formulas are determined by taking the Shaying River watershed as the study area. The following conclusions were drawn from the study.

1) The transboundary river ecocompensation standard accounting method includes a) an accounting method for water quantity compensation standards from the perspective of water resources value and b) an accounting method for water quality compensation standards based on the comprehensive pollution index method. c) Ecocompensation standards are calculated for different water quantity and water quality scenarios at the

Table 15 The net benefit coefficients and water resource values in different studies

Data source	Net benefit coefficient (yuan/m^3)	Water resource value (yuan/m^3)	Study area	The accounting year
Zhu et al. (2005)	Industrial water-use:0.366 Agriculture water-use:0.293 Domestic water-use:0.366 Outside-stream ecological water-use:0.178	Industrial water-use: 0.206 Agriculture water-use: 0.212 Domestic water-use: 0.206 Outside-stream ecological water-use: 0.115	Huaihe River watershed (including Shaying River watershed)	2000
Our research	Industrial water-use:0.366 Agriculture water-use:0.293 Domestic water-use:0.366 Outside-stream ecological water-use:0.178	0.36 (P=50%) 0.39 (P=75%) 0.37 (P=95%)	Shaying River watershed	–
Sun et al. (2007)	Industrial water-use:2.1 Domestic water-use:2.1 Agriculture water-use:0.06 Tertiary industry water-use:3.61	0.71	Xin'an River Basin	2006
Tang et al. (2018)	Agriculture water-use:3.55 Industrial water-use:116.41	3.10	the intake area of the South-to-North Water Diversion Project	2012
He and Chen (2005)	–	4.58	China	2020

watershed scale. Therefore, in the transboundary river ecocompensation standard accounting method, the effects of dynamic changes in the water resource value, water quality and water quantity on the ecocompensation standards are simultaneously considered.

2) The unit values of water resources in the Shaying River watershed are 0.36 yuan/m^3, 0.39 yuan/m^3 and 0.37 yuan/m^3 at hydrological frequencies of 50%, 75% and 95%, respectively. These values are generally much lower than those in other studies. As a crucial parameter, the net benefit coefficients of various water use departments in this study are much lower than those in other studies. Therefore, the net benefit coefficients should be updated based on the year of transboundary ecocompensation in the future.
3) In this study, 27 types of ecocompensation standard formulas for the Shaying River watershed were determined for different hydrological frequencies (50%, 75% and 95%), water quantity scenarios (equal quantity, excess quantity and reduced quantity discharging) and water quality scenarios (equal quality, inferior quality and better-quality discharging).
4) The establishment of online monitoring points for water consumption/use should be prioritized, the national water resource monitoring capacity should be improved, and the implementation of transboundary ecocompensation should be promoted.

Although most of the conclusions are drawn from the case study of the Shaying River watershed, the methodology and results of this study are objective and rational. Therefore, the findings of this study provide a compensation standard for the Shaying River and a reference for the calculation of ecocompensation standards for other transboundary rivers in China with definite water quantity and water quality management objectives.

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Declarations

Conflict of Interest The authors declare that they have no competing interests.

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