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A comprehensive model of basin ecological compensation funds—A case study of the Yellow River Basin in China

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The key issue in the ecological compensation mechanism in the Yellow River Basin (YRB) is the allocation of ecological compensation funds, which need to be optimized to maximize the comprehensive benefits of compensation. In this study, a comprehensive allocation model for ecological compensation funds in the YRB was constructed using the "doughnut" framework. A pre-allocation model was used to enhance the ecological benefits and quantifies the ecological value created by the compensated subjects. A pre-allocation scheme was then determined using the pre-allocation model. The optimal allocation model focuses on benefit sharing and sets a socioeconomic discrimination index system to optimize the pre-allocation scheme. Then, an empirical analysis was conducted using data from 28 regions in the upstream YRB from 2016 to 2020. The results showed that in the pre-allocation scheme, the proportion of funds was low in the west and high in the east. Each region received compensation funds based on the ecological benefits they provide. In the optimal allocation scheme, the proportion of funds received by the central and western regions in the upstream YRB should be higher, while the proportion of funds received by provincial capitals and economically strong cities should be lower, which is in line with the actual development situation in the upstream YRB. The final scheme can effectively meet the objectives of basin-wide sustainable development, ecological benefits enhancement, and benefit sharing in the YRB. This can help achieve basin-wide sustainable development and provide a reference for determining ecological compensation fund allocation schemes in other basins.

KEYWORDS

basin ecological compensation, fund allocation model, Yellow River Basin, doughnut framework, sustainable development

1 Introduction

The basin ecological compensation mechanism is based on the principles of "who benefits, who compensates" and "who pollutes, who pays" (Li and Wang, 2018). This implies that basin ecological beneficiaries or polluters should compensate the ecological protectors to achieve ecological protection and sustainable development. As payment for ecosystem services programs, the basin ecological compensation mechanism is a prominent way to address the economic externalities of ecological resource production and extraction, thus improving both ecological and social outcomes (Chan et al., 2017). Several beneficial cases in the world are available to explore the balance between environmental protection and economic development in basin ecosystem fields, such as the Birris sub-watershed in Costa Rica, where downstream hydropower company provides financial compensation to upstream farmers for soil conservation and sedimentation reduction (Vignola et al., 2012); the Tijuana River, a transboundary river, where the USA provides basin management funds to Mexico for pollutant reduction (Fernandez, 2009); and the Northern watershed in Nepal, where ecosystem services paid by downstream to upstream are determined based on land use type, combined with input from local residents and experts (Bhandari et al., 2016).

The Yellow River Basin (YRB) is an important ecological barrier and economic development area in China and is thus directly related to the achievement of China's sustainable development goals (Li et al., 2021). Due to drought, water scarcity, and human interference, the YRB, especially its upper reaches, has a fragile ecological environment (Zhang et al., 2022), leading to slower socioeconomic development in this region. Therefore, China has considered the YRB as a typical area for basin ecological compensation. The pilot ecological compensation mechanism for the YRB began in 2007. Currently, the implementation scheme of the mechanism within each province has been promulgated, and the horizontal ecological compensation between some provinces has been carried out gradually (Zhang et al., 2021). In 2020, the Chinese government promoted the mechanism to the whole basin level, setting up a basin-wide horizontal ecological compensation mechanism for the nine provinces along the Yellow River. In 2022, the "Law of the People's Republic of China on the Protection of the Yellow River" implemented a basin-wide mechanism as a legal requirement. While designing this mechanism, the allocation of ecological compensation funds is the key. It is important to fairly distribute the compensation funds paid by the ecological beneficiaries or polluters to the ecological protectors. Moreover, the ecological protectors should be encouraged to protect the basin's ecological environment, thereby obtaining greater ecological service value from them. Though the upstream provinces, such as Qinghai, Sichuan, Gansu, Ningxia, and Inner Mongolia, have plenty of water resources, they have fragile ecological environments and are thus ecological protection areas of the YRB. However, due to less economic development, it is difficult to balance the limited resources between ecological protection and economical construction. (Chang et al., 2014). Moreover, reaching a unified opinion on the fund allocation scheme is difficult because all nine provinces have the same administrative level, and each wants its own interests to be met. Therefore, determining a scientific and reasonable basin-wide fund allocation scheme is an urgent problem that needs to be solved to establish a comprehensive ecological compensation mechanism in the YRB.

Existing studies on the allocation of basin ecological compensation funds have explored the allocation criteria and allocation amounts. The allocation scheme of ecological compensation funds should both reflect the ecological value created by the compensated subjects and be acceptable to all parties to adjust the economic relationship within the region. Currently, most basin ecological compensation funds are distributed using a single criterion for allocation. Two important fund allocation criteria are the input cost method and ecosystem services value method. (1) The input cost method mainly considers the cost of implementing measures from the perspective of ecological protectors and allocates compensation funds according to their input costs. Scholars have defined input costs differently, mainly in terms of opportunity and direct costs. Opportunity costs are the benefits that upstream areas sacrifice to limit economic development for ecological and environmental protection (Zhang et al., 2013; Cheng et al., 2020). Direct costs are the actual costs incurred when implementing specific conservation measures, such as water pollution treatment costs (Wang et al., 2018). Dong et al. (2011) calculated the amount of ecological compensation funds allocated in Shiyan, a water source for the middle route of the South-to-North Water Diversion Project in China, by subtracting state compensation and internal effects from the sum of the opportunity and direct costs of ecological protection. (2) The ecosystem services value method, which mainly considers the ecological protectors providing ecological services, allocates compensation funds according to the value of the ecological services they provide (Ling et al., 2019). Some scholars have measured the ecological service values provided by the upstream region through models such as the Ecological Element (Zhang et al., 2020) and InVEST (Yan et al., 2021), then used them as criteria for allocating funds. Other scholars have combined ecological service values with GIS and remote sensing technology to calculate the ecological service values of different land use types and enhanced the scientific nature of ecological compensation criteria by improving the accuracy of land data (Gao et al., 2019; Gao et al., 2021). However, allocation based only on ecological protection alone cannot consider the goal of basin-wide common development since the socioeconomic base of each compensated subject differs, and the human and material resources that each compensated subject can invest in ecological protection also differ.

A few studies have also used dual criteria for the allocation of ecological compensation funds, such as water quantity and water quality in transboundary rivers, ecological restoration costs, and ecosystem services. Hao et al. (2021) and Chen and Zhou, 2016 built a two-way compensation mechanism between upstream and downstream by starting from the water consumption in upstream areas and the water quality of transboundary river crossings, with upstream areas compensating downstream areas when water quantity is less or water quality is poor, and downstream areas compensating upstream areas when water quantity is surplus or water quality is improved. Tu et al. (2022) combined water quality restoration costs and ecosystem service flows to develop a fund allocation standard in terms of both costs and benefits. However, whether it is a single standard or a dual standard, the existing fund allocation standards are only considered from the perspective of environmental protection, failing to simultaneously involve the common prosperity and balanced development of the whole basin and cannot meet the basic requirements of the current basin ecological compensation (Guan et al., 2016).

Specifically, for ecological compensation in the YRB, existing studies have mainly dealt with factors influencing ecological compensation (Wang et al., 2022), coordinated regional ecological and economic development (Li et al., 2021; Ren et al., 2022), and ecological compensation policy effects (Chen et al., 2020; Zhao et al., 2021), but less on ecological compensation fund allocation. Hu et al. (2022) determined the amount of ecological compensation funds allocated to 32 counties in the middle of the YRB based on the overflow values of runoff management and soil erosion control. Zhou et al. (2022) measured the value of ecosystem services in nine provinces of the YRB using the equivalence factor method and suggested that the value of ecosystem services in each region was positively and negatively correlated with the level of economic development and ecological compensation priority, respectively. In the ecological practice of the YRB, the basin-wide level horizontal ecological compensation mechanism has not been established, while the cross-provincial-level fund allocation is mostly seen between two neighboring provinces, and the signed agreements include the Sichuan-Gansu and Henan-Shandong sections (Si and Zhang, 2022). This shows that the allocation of ecological compensation funds for the whole YRB is open to question, both for academic research and ecological practice.

Previous studies on the allocation of basin ecological compensation funds are abundant: single criteria (input cost method; ecosystem services value method) and dual criteria (water quantity and quality in transboundary rivers; ecological restoration costs and ecosystem services) for fund allocation have been proposed while preliminary research and practice on ecological compensation fund allocation in the YRB have been conducted. Nevertheless, some issues are worth exploring: (1) Most existing ecological compensation fund allocation standards have been considered from the perspective of ecological protection. However, allocation only based on ecological protection cannot consider the goal of basin-wide common development because the socioeconomic base of each compensated subject differs, and the human and material resources that each compensated subject can invest in ecological protection differ. (2) As a typical area of ecological compensation in China, the current ecological compensation mechanism in the YRB is still mainly restricted to some regions or between neighboring provinces, and a lack of discussion exists on the allocation standard of ecological compensation funds at the basin-wide level.

Based on the above discussion, we have constructed a comprehensive allocation model for ecological compensation funds in the YRB, in which a pre-allocation model is used to simulate the ecological value creation of compensated subjects, and an optimal allocation model is used to regulate the relationship between the fund allocation scheme and the socioeconomic status of compensated subjects. Then, an empirical study was carried out in the upstream YRB to determine the ecological compensation fund allocation scheme that simultaneously meets the requirements of environmental protection and economic development. Compared with previous literature, this paper has the following contributions: (1) Based on the basin ecological and economic sharing mechanism, this study considers the compensation fund allocation criteria in terms of both ecological benefit enhancement and economic development sharing, instead of merely considering the former, which can effectively realize the common beauty of the environment and common prosperity of the people in the entire basin. (2) Taking the YRB, the key area of ecological compensation in China, as the research object, this study refines the precision of the research area to the prefectural level, thus making the research typical, and it provides a reference for other basins to conduct horizontal ecological compensation work.

The remainder of this paper is organized as follows. Section 2 introduces the data sources, presents an analysis of the fund-allocation mechanism, and describes the comprehensive fund allocation model. Section 3 presents and discusses the empirical results, including those of the pre-allocation and optimal allocation schemes. Section 4 summarizes the conclusions and provides policy suggestions.

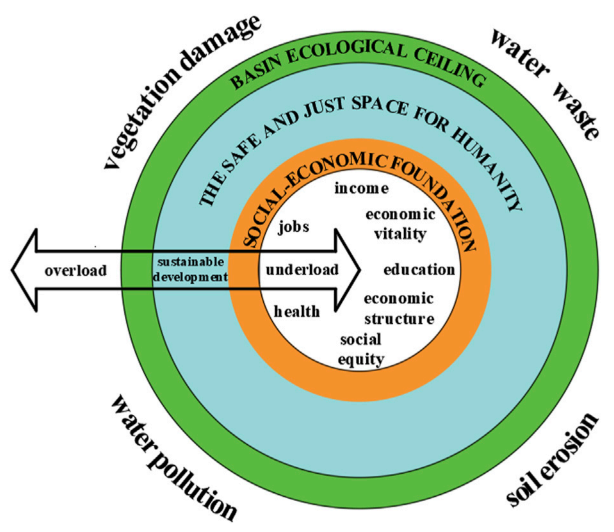

FIGURE 1
"Doughnut" theoretical framework for basin ecological compensation fund allocation.

2 Materials and methods

2.1 Data sources

The Yellow River originates from the Bayankara Mountain Range in Qinghai Province, China, with a total length of 5,464 km, flowing from west to east through the nine provinces of Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong, controlling a watershed area of 682,200 square kilometers. As the water source of the Yellow River, the upstream YRB bears the difficult task of ecological protection and is the main compensated subject in horizontal ecological compensation; therefore, it was chosen as the study object in this study. The *Flood Control Plan of the Yellow River Basin* defines the upstream YRB as the area from the source to the town of Hekou, Inner Mongolia. Combined with the experience of Zhang and Zhang (2020), this study follows the principles of taking the natural YRB as the basis, maintaining the integrity of the prefectural administrative units, and considering the regional socioeconomic relevance to the Yellow River when selecting the research object. Therefore, the current research was carried out in 28 areas from five provinces in the upstream YRB, using the average data from 2016 to 2020. The eco-efficiency-related data used in the pre-allocation model were mainly from the *Environmental Status Bulletin*, *Soil and Water Conservation Bulletin*, *Water Conservancy Statistics Bulletin*, and *Water Resources Bulletin* of each province and city. The socioeconomic data used in the optimal allocation model were from statistical yearbooks, national economic and social development statistical bulletins, and government work reports of relevant provinces and cities.

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2.2 Fund allocation mechanism analysis

In the basin-wide ecological compensation mechanism, even though the total amount of compensation funds is limited, multiple subjects are compensated. To share the value of ecological services and socioeconomic welfare in the basin, these ecological compensation funds are allocated to obtain the allocation scheme accepted by each compensated subject. Raworth (2012), Raworth (2017) combined socioeconomic systems with biophysical processes and proposed a theory of boundary between them, emphasizing the mutual equilibrium and inclusion of environmental protection with social equity and economic development. Based on this theory, this study constructs a "doughnut" theoretical framework for allocating basin ecological compensation funds, as shown in Figure 1.

This theoretical framework shows that the allocation of ecological compensation funds should meet the environmental, social, and economic requirements of sustainable development and seek a balance between ecological environment protection and human needs (Olawumi and Chan, 2018). The underloaded areas within the inner circle of the "doughnut" have excellent environmental protection and a weak socioeconomic foundation, whereas the overloaded areas outside the outer circle experience serious environmental damage and high socioeconomic development. The proportion of compensation funds for both needs to be adjusted in the opposite direction to help them move toward sustainable development. Therefore, the fund allocation scheme needs to balance the environment and socioeconomics of each area and simultaneously reduce underload and overload to promote basin-wide sustainable development. The "doughnut" theoretical framework requires the fund allocation scheme to motivate the creation of ecological value as well as ensure shared socioeconomic development.

Owing to the unidirectional mobility of rivers, ecological damage and water pollution in the upstream regions inevitably threaten the water safety of the downstream regions. The upstream regions cannot spontaneously restrict their own economic development and strengthen basin ecological protection, whereas the downstream regions cannot obtain the extra quality water provided by the former without compensation. For the former, its economic sacrifice is essentially an internal diseconomy that requires corresponding financial compensation to continue implementation; for the latter, its willingness to pay compensation funds is related to the external economy obtained from the former, i.e., greater the ecological value, the more compensation funds it pays. Therefore, when allocating basin ecological compensation funds, ecological benefits should be considered as the main criterion, and the general principle of "who protects, who is compensated" should be followed. This will stimulate the enthusiasm of upstream areas for environment and water resources protection, as well as increase the willingness of downstream areas to pay compensation funds, thus forming a positive cycle of ecological benefits enhancement. Thus, the allocation of basin ecological compensation funds should contribute to improving ecological benefits.

The allocation of basin ecological compensation funds should also advocate shared socioeconomic development. Compared with other regions in China, the overall economic development of the YRB lags and is uneven across regions. From the perspective of basin-wide shared development, the fund allocation scheme must consider balancing the socioeconomic development of the region along with ecological benefits. The sustainable development of the whole basin depends on the region with the lowest socioeconomic development, so the areas with higher levels of socioeconomic development should support and drive the lower areas to develop together. Thus, when allocating ecological compensation funds, it is necessary to consider the economic development, social stability, livelihood protection, and other factors of each compensated subject and facilitate the relative equity of regional development by adjusting the proportion of compensation funds to promote the basin-wide sharing of development opportunities and prosperity of all people.

2.3 Comprehensive fund allocation model

2.3.1 Model construction ideas

In the context of building a basin-wide ecological compensation mechanism for the YRB in China, ecological compensation fund allocation needs to focus on achieving the goals of basin-wide sustainable development, ecological benefit enhancement, and regional shared development. Considering these objectives, fund allocation should follow the principles of basin-wide sustainability, fund allocation effectiveness, and fund allocation sharedness. The main difficulties were as follows: (1) how to weigh the relationship between ecological incentives and shared development to construct the fund allocation model? (2) how to design an index system to achieve a positive cycle of ecological benefits? (3) how to optimize the pre-allocation scheme to promote the sharing of regional development opportunities?

The above problems were solved using the following steps: (1) the sustainable development requirements of the YRB were analyzed based on the "doughnut" theory, and a two-tier allocation model of ecological compensation funds by combining ecological value creation incentives with shared socioeconomic development was constructed; (2) a pre-allocation model was constructed based on the idea of "who protects, who is compensated," and an index system was built based on this; (3) the optimal allocation model focuses on regional shared development, balances the degree of socioeconomic development of each region, improves the pre-allocation scheme through regional shared discrimination, and determines the optimal allocation scheme for ecological compensation funds. The specific ideas for constructing a comprehensive allocation model for basin ecological compensation funds are shown in Figure 2.

2.3.2 Pre-allocation model

The principle of fund allocation effectiveness mainly focuses on the improvement of ecological benefits and requires that the ecological benefits created by the compensated subjects be taken as the basic measurement standard for fund allocation. In terms of ecological benefit evaluation, the pressure-state-response (PSR) framework is a widely used tool that depicts a panorama of environmental problems from an anthropocentric perspective, including the human damage pressure, impact, and protection response to the environment, thereby enabling a comprehensive evaluation of the ecological benefits created by a region (Bernhard and Harald, 2008; Sun et al., 2016; Zhang et al., 2020). By sorting through relevant government documents and combining the problems in the YRB, such as environmental deterioration, serious water pollution, and wastewater, the PSR framework was used to construct a pre-allocation index system for ecological compensation funds. In this framework, P denotes the direct

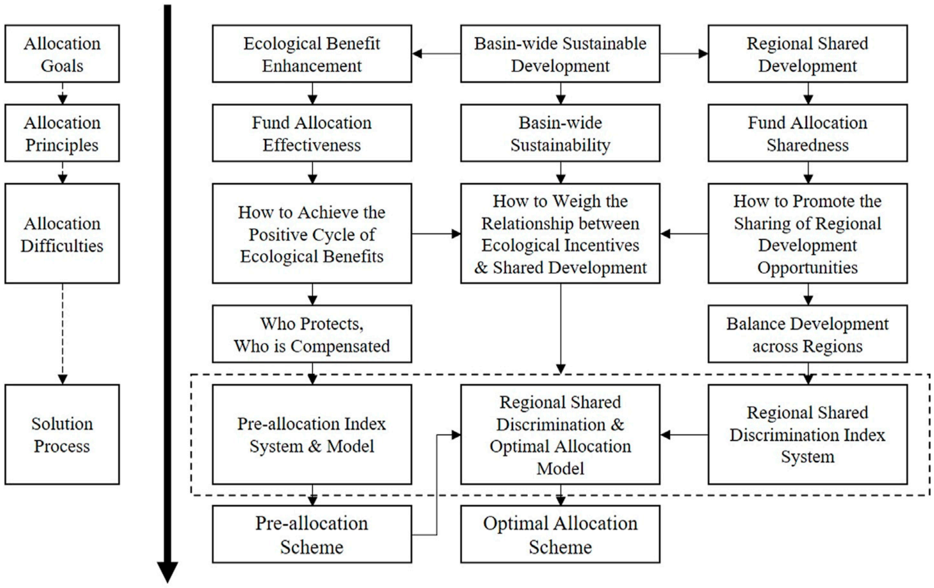

FIGURE 2
Ideas for constructing the comprehensive allocation model of basin ecological compensation funds.

TABLE 1 Pre-allocation index system of basin ecological compensation funds.

Evaluation dimension	Evaluation index	Unit	Attribute
Environmental pollution (P)	Total sewage discharge	kt	–
Ecological state (S)	Water quality compliance rate of important rivers and lakes water function zones	%	+
Environmental governance (R)	Afforestation area	hm^2	+
	Water consumption intensity	%	–
	Soil erosion control area	km^2	+

pressure on the ecological environment caused by industrial production and residential life, and it represents the driver of change in the basin ecological status, i.e., environmental pollution. In many developing countries, untreated or partially treated sewage is the main pressure affecting the water environment (de Almeida et al., 2021), therefore we used the "total sewage discharge" to represent environmental pollution. S denotes the impact of stress on the environmental status and represents the current state of the basin ecological environment, i.e., ecological state. Ji et al. (2022) pointed out that pollution control to improve water quality is the key to water environment maintenance; therefore, the "water quality compliance rate of important rivers and lakes water function zones" was used as a measure. R denotes the improvement measures taken by the government in response to the current environmental pressure and status, and it represents the ecological management of the watershed, i.e., environmental governance. Rimal et al. (2021), Xu et al. (2022a), and Zhang et al. (2010) considered that restoration of degraded forests, water conservation, and soil erosion control are essential to reduce ecological pressures from humans, respectively; therefore, we chose "afforestation area", "water consumption intensity", and "soil erosion control area" for R. The pre-allocation index system of the basin ecological compensation funds is presented in Table 1.

The entropy weight method was used to determine the objective weights based on the magnitude of the variability of the indicators so that the funds can be pre-allocated (Guan et al., 2016). The process of constructing the pre-allocation model using the entropy weight method is as follows:

(a) Standardization of indicators.

$$x_{ij} = \begin{cases} \dfrac{r_{ij} - \min\limits_{1\le j\le n}\left(r_{ij}\right)}{\max\limits_{1\le j\le n}\left(r_{ij}\right) - \min\limits_{1\le j\le n}\left(r_{ij}\right)} & \text{positive indicators} \\[2ex] \dfrac{\max\limits_{1\le j\le n}\left(r_{ij}\right) - r_{ij}}{\max\limits_{1\le j\le n}\left(r_{ij}\right) - \min\limits_{1\le j\le n}\left(r_{ij}\right)} & \text{negative indicators,} \end{cases} \tag{1}$$

where n and m represent the number of regions and indicators, respectively, and x_{ij} and r_{ij} represent the standardized and original data value, respectively, of indicator i of region j.

TABLE 2 Regional shared discrimination index system.

Discrimination criterion	Discrimination index	Unit	Attribute
Social equity	Urban registered unemployment rate	%	+
	Urban-rural consumer spending ratio	–	+
	Urban-rural disposable income ratio	–	+
Livelihood security	Expenditure on education *per capita*	Yuan	–
	Number of beds in health facilities for 10,000 people	–	–
Economic structure	GDP *per capita*	Yuan	–
	Proportion of tertiary industry in GDP	%	–
Economic vitality	Total retail sales of consumer goods	100 million Yuan	–
	Total tourism income	100 million Yuan	–

(b) Entropy is defined. The entropy value h_i of indicator i is as follows:

$$\begin{cases} h_i = -\frac{1}{\ln n}\sum_{j=1}^{n} f_{ij}\ln f_{ij} \\ f_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \end{cases} \tag{2}$$

(c) Entropy weights are defined. The entropy weight u_i of indicator i is as follows:

$$u_i = \frac{1-h_i}{m-\sum_{j=1}^{m} h_i}, \left(0 \le u_i \le 1, \sum_{i=1}^{m} u_i = 1\right) \tag{3}$$

The proportion of fund pre-allocation is determined. The fund pre-allocation proportion p_j for region j is as follows:

$$\begin{cases} p_j = \frac{S_j}{\sum_{j=1}^{n} S_j} \\ S_j = \sum_{i=1}^{m} x_{ij} u_i, \\ \sum_{j=1}^{n} p_j = 1 \end{cases} \tag{4}$$

where S_j is the total eco-efficiency score of the region.

2.3.3 Optimal allocation model

The principle of fund allocation sharedness focuses on regional shared development and requires that the proportion of basin ecological compensation funds allocated to each compensated subject match its socioeconomic development status. Based on this, combined with the official requirements for the socioeconomic development of the YRB, the main criteria for regional shared discrimination are social equity, livelihood security, economic structure, and economic vitality (Guan et al., 2016). Many factors were considered in the process of selecting specific indicators for fund allocation.

In terms of social equity, the increase in unemployment, and income and expenditure disparities can cause social unrest and affect the stability of regional economic development (Badimon, 2013; Kurian 2007). Hence, the "urban registered unemployment rate," "urban-rural consumer spending ratio," and "urban-rural disposable income ratio" were selected. With respect to livelihood security, educational resources and medical conditions help improve the basic living standards of people and promote sustainable livelihood security (Singh and Hiremath, 2010). Thus, "expenditure on education *per capita*" and "number of beds in health facilities for 10,000 people" were selected as indicators. As for the economic structure, industrial reform is used to channel financial inputs, stimulate overall economic growth, and increase personal income (Asano and Tyers, 2019); therefore, "GDP *per capita*" and "proportion of tertiary industry in GDP" were used as indicators. Regarding economic dynamism, "total retail sales of consumer goods" and "total tourism income" were chosen to promote consumption and tourism, so as to absorb foreign capital, increase employment, revitalize the regional economy, and share development opportunities (Xu et al., 2022b). Finally, the regional shared discrimination index system is shown in Table 2, which balances the development degree of each compensated subject, compensates the regions with fewer development opportunities, and correspondingly reduces the compensation funds for regions with more development opportunities.

Wu et al. (2010) proposed the idea of harmony diagnosis for basin initial water rights allocation, limiting the amount of water allocation in each region to socioeconomic development indicators within a designed range, so as to maintain the harmony of water rights allocation scheme. Drawing on this idea, this study built an optimal allocation model to discern the regional sharedness of the pre-allocation scheme and optimize and adjust the scheme to realize the sharing of regional development opportunities.

Let D be the regional set, $D = \{d_1, d_2, \cdots, d_n\}$, and the set of pre-allocation proportion of ecological compensation funds for each compensated subject is $P = \{p_1, p_2, \cdots, p_n\}$, that is, the fund proportion of region d_a is p_a. Then the "regional pair" $(d_a, d_b), a, b = 1, 2, \cdots, n, a \neq b$, indicating a two-by-two comparison between region d_a and region d_b was set. The specific steps of the regional shared discrimination and the optimal allocation model are as follows:

The regional shared discriminant coefficient of the "region pair" (d_a, d_b) was defined as:

$$\gamma_{(d_a,d_b)} = \sum_{i=1}^{m} u_i \frac{r_{ia}}{r_{ib}}, \tag{5}$$

where the entropy weight method was used to preprocess the regional shared discriminators, and r_{ia}, r_{ib}, and u_i were calculated using Eqs.1–3.

The ratio between the fund allocation proportion p_a of region d_a and the fund allocation proportion p_b of region d_b should maintain a matching relationship with the regional shared discriminant coefficient $\gamma_{(d_a,d_b)}$, i.e., the shared discrimination criterion is:

$$\begin{cases} \eta_{min}\gamma_{(d_a,d_b)} \le \dfrac{p_a}{p_b} \le \eta_{max}\gamma_{(d_a,d_b)} \\ a, b = 1, 2, \cdots, n; a \ne b, \\ 0 < \eta_{min} < 1; \eta_{max} > 1 \end{cases} \tag{6}$$

where $\eta_{min}\gamma_{(d_a,d_b)}$ and $\eta_{max}\gamma_{(d_a,d_b)}$ are the lower and upper limits of the fund allocation ratio of the "region pair" (d_a, d_b), respectively; η_{min} and η_{max} are the lower and upper limit coefficients, respectively, which limit the fluctuation range of the fund allocation ratio of the regions d_a and d_b relative to the ratio of their socioeconomic conditions, respectively. This study improves the selection method of the lower and upper limit coefficients, thereby controlling the fund allocation ratio within a certain range so that the proportion of ecological compensation funds received by each region matches its socioeconomic development status. Thus, it helps in regulating the economic relationship of the whole basin and promotes basin-wide balanced and shared development. Because the regional shared discrimination index system reversely reflects the regional socioeconomic situation of the upstream YRB, this study adjusts its positive and negative attributes and uses the entropy weight method to calculate the total socioeconomic score S_j of each region. Then, the ratio of the maximum score to the average score is taken as the upper limit coefficient, whereas the ratio of the minimum score to the average score is taken as the lower limit coefficient, that is, $\eta_{max} = \frac{S_{max}}{Save} = 1.804$ and $\eta_{min} = \frac{S_{min}}{Save} = 0.597$.

For any "region pair" (d_a, d_b) that satisfies Eq. 6, the current scheme has valid regional shared discrimination and can be used as the final fund allocation scheme. If there is a "region pair" that dissatisfies Eq. 6, the current scheme falls short of the shared requirements, and the failed "region pair" needs to be optimized. For the "region pair" (d_a, d_b) that does not pass the regional shared discrimination, its fund proportion should be adjusted optimally. When $\frac{p_a}{p_b} > \eta_{max}\gamma_{(d_a,d_b)}$, the ratio breaks through the upper limit, and the fund proportion of region d_a should be reduced. When $\frac{p_a}{p_b} < \eta_{min}\gamma_{(d_a,d_b)}$, the ratio does not reach the lower limit, and the fund proportion of region d_a should be increased. In the case of fixed total fund allocation, the sum of the regional adjustment quantity should be 0. The adjusted fund proportion of region d_a is as follows:

$$\begin{cases} p_a^{'} = \begin{cases} \min\limits_{a \ne b} \left\{\eta_{max}\gamma_{(d_a,d_b)}p_b\right\}, \dfrac{p_a}{p_b} > \eta_{max}\gamma_{(d_a,d_b)} \\ \max\limits_{a \ne b} \left\{\eta_{min}\gamma_{(d_a,d_b)}p_b\right\}, \dfrac{p_a}{p_b} < \eta_{min}\gamma_{(d_a,d_b)} \end{cases} \\ \Delta p_a = p_a^{'} - p_a \\ \sum\limits_{a=1}^{n} \Delta p_a = 0 \end{cases} \tag{7}$$

The adjusted fund allocation ratio was then used in Eq. 6 for optimal regional shared discrimination until the optimal scheme was determined.

3 Results and discussion

3.1 Pre-allocation scheme

Following the principle of fund allocation effectiveness, ecological compensation funds were allocated to the compensated subjects according to the ecological benefits they create. The pre-allocation scheme in the upstream YRB is shown in Figure 3. The ecological benefits created by each region were different; therefore, the pre-allocation fund proportion was unevenly distributed in space, showing an overall trend of low in the west and high in the east. Moreover, the provincial capitals, Yinchuan and Lanzhou, and their nearby areas are significantly low points, while the up-midstream junction Erdos and Ulanqab are significantly high points.

Erdos and Ulanqab are located close to the junction of the middle and upper reaches; thus, they are committed to soil erosion control to reduce the river sand content and prevent the imbalance of water and sand in the downstream areas. Moreover, in these regions, grasslands are widely distributed, forest and grass restoration work is in place, and the grassland vegetation cover is over 40%, maintaining a high level of ecological management. Among the regions with mid-high pre-allocation funds, the ecologically fragile area of Alax accounts for 94% of the total area. In this area, industrial development is restricted because the focus is on land greening and sand control. As a result, the environment has improved significantly, and Alax has become a national model for sand control. Longnan, Guyuan, and Wuwei are some other regions with strong ecological beliefs. These are restricted by mountainous terrain, with insufficient development of traditional industries, thus giving importance to the development of the ecological economy and tourism economy.

Other areas with medium pre-allocated funds, such as Bayannur, Baotou, and Hohhot, are located at the end of the upstream YRB, but their human-water relationship lacks coordination, and the water resources needed for regional economic development are close to or even exceed the total amount of local water resources, resulting in a high degree of ecological resource consumption. Linxia, Dingxi, Hainan, Gannan, and Haidong have backward economic levels, with *per capita* GDP below the national average. Hence, the government work in them is still focused on economic development, with relatively little investment in ecological protection work.

Yushu, Haixi, Aba, and Guoluo are minority autonomous prefectures that are relatively vast and sparsely populated. The publicity and education on ecological protection are insufficient, nor can they provide sufficient human and material resources for environmental management, so the ecological benefits are lacking, and the pre-allocated funds are medium-low. The rest of the region is in the Urban Agglomeration along the Yellow River in Ningxia and Lanzhou-Xining Urban Agglomeration, which are key economic construction areas of the country. Thus, industrial enterprises and populations are relatively dense, environmental pollution is induced while the economy is driven, and the basin environment is damaged by sewage discharge, leading to the lowest pre-allocation funds.

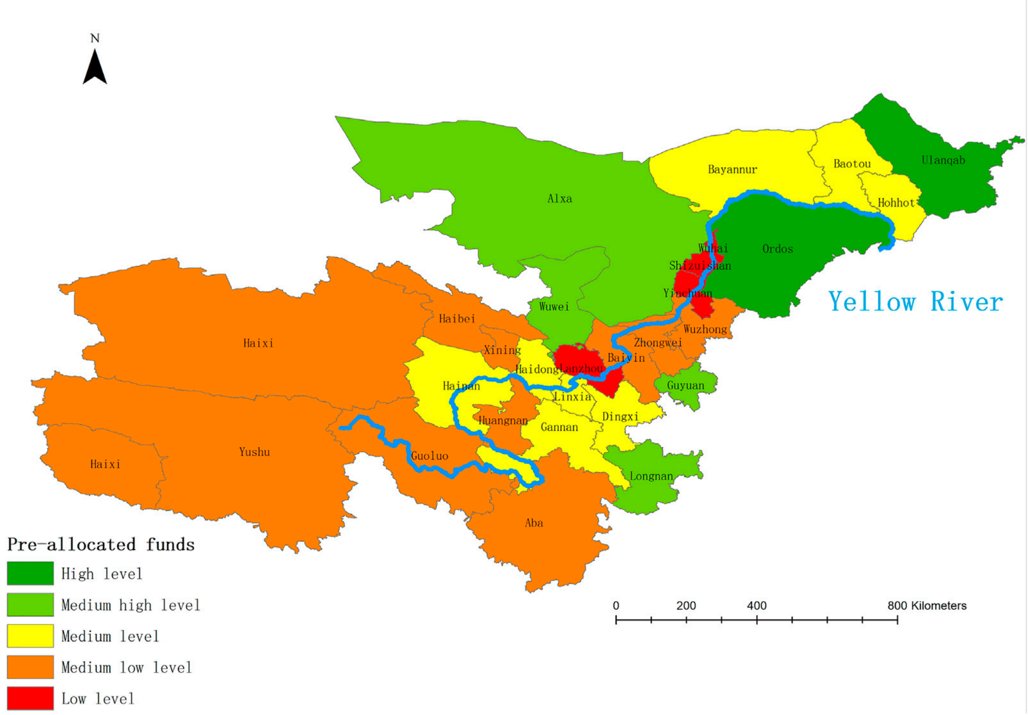

FIGURE 3
Pre-allocation scheme in the upstream YRB.

The pre-allocation scheme is based on the ecological benefits created by the compensated subjects, which is in line with the basic idea of "who protects, who benefits" but does not achieve the sharing of regional development. For example, although Yushu, Guoluo, and Hainan are located on the Qinghai-Tibet Plateau with harsh production and living conditions, minority populations, and backward socioeconomic development, their pre-allocated funds are only medium-low and do not support development. In contrast, Erdos is located at the end of the upstream YRB and has access to high-quality water. It has also developed a tourism and livestock industry by virtue of its excellent and wide pastureland. Thus, its economic vitality is relatively strong, and its *per capita* GDP is the highest in the upstream areas, but the pre-allocated funds are of the highest grade, which does not reflect efforts for regional shared economic development. Consequently, in order to achieve overall regional sustainable development, we should also consider balanced regional development opportunities and the realization of common regional development.

3.2 Optimal allocation scheme

The original index data related to the principle of fund allocation sharedness was entered into Eq. 5 to calculate the regional shared discriminant coefficient of each regional pair. Then, the initial discrimination result was calculated using Eq. 6, and the regional pairs were optimized and adjusted pairs using Eq. 7. Finally, the optimal fund allocation scheme for the upstream YRB was obtained, as shown in Figure 4.

From the overall spatial distribution, the areas with high allocation funds are concentrated in the first half of the upstream YRB, forming a green central circle, whereas the areas with low allocation funds are located in the provincial capitals, shown as red dots within the green circle. The overall trend is high in the west and low in the east and interspersed in the low areas of the provincial capital. With this allocation model, the areas with increased allocation funds are concentrated in the western and central parts of the upstream YRB, and the areas with reduced allocation funds are mainly provincial capitals and strong economic cities.

For an area with increased allocation funds, such as Yushu, the compensation funds received in the pre-allocation scheme are at a low–medium level because it lacks sufficient human and material resources to invest in environmental protection and, therefore, fails to provide relatively high ecological benefits. However, Yushu is remote and has a weak socioeconomic development base, which justifies its insufficient ecological investment. Allocating ecological compensation funds based on ecological benefits is unfair. The optimal allocation scheme takes considers and raises the compensation funds allocated to Yushu to a high level to support its socioeconomic development.

Ordos, an area with reduced allocation funds, has a large area of high-quality grassland and can invest more resources into ecological protection based on its strong economic foundation, thus creating significant ecological benefits, leading to a high level of compensation funds in the pre-allocation scheme. However, to realize regional shared development, the regions with leading socioeconomic development should drive and help the development of the lagging regions. Therefore, the optimal

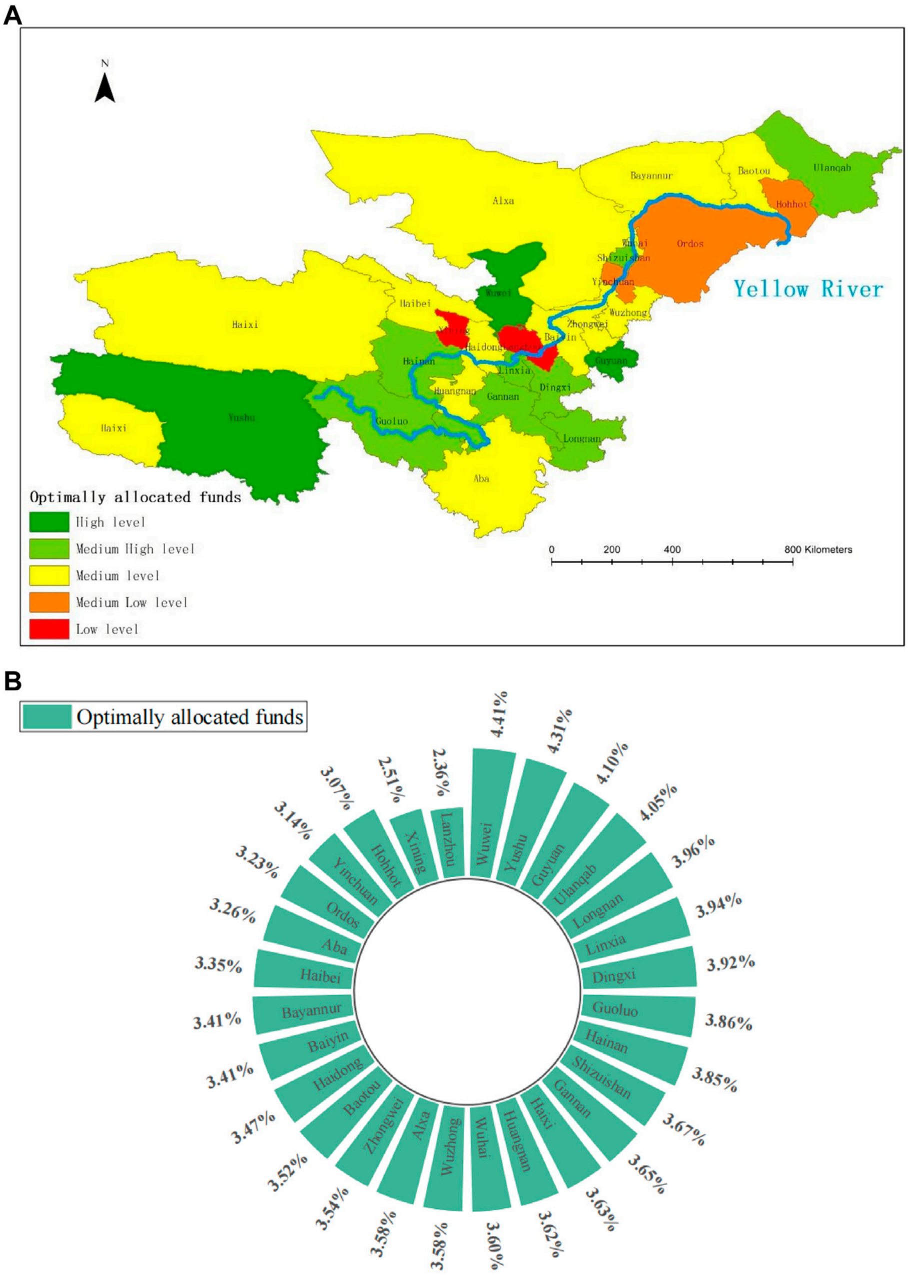

FIGURE 4
Optimal fund allocation scheme for upstream YRB: **(A)** spatial distribution; **(B)** fund proportions.

allocation scheme reduces the compensation funds of Ordos to a medium–low level, and this change is in line with the principle of fund allocation sharedness and can promote the sustainable development of the entire YRB.

To analyze the reasons for the fund allocation proportions in the final scheme, the total eco-efficiency score and the total socioeconomic score of each region are arranged clockwise in the order of the fund allocation proportions from highest to lowest, as shown in Figure 5. According to the definition in Section 2.3.2 and Section 2.3.3, a high total ecological benefit score or low total socioeconomic score leads to a higher proportion of allocated funds. These can be roughly divided into three categories. The first category is the region from Wuwei clockwise to Gannan. Most of these regions have an eco-efficiency score higher than 0.5, or even 0.7, while the total socioeconomic score fluctuates around 0.4, indicating that they both obtain a higher amount of pre-allocation funds. This is due to effective ecological management, optimizing the adjustment increase because of the weak economic foundation and insufficient development momentum, and finally obtaining a fund allocation proportion of more than 3.65%, which is the key funding target of horizontal ecological compensation. The second category is the area from Haixi clockwise to Aba. The total eco-efficiency score of these areas is within 0.3–0.5, and the total

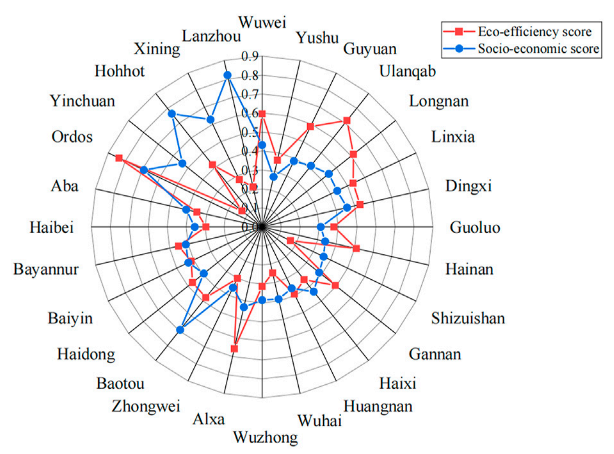

FIGURE 5
Total eco-efficiency and socioeconomic scores for upstream YRB.

socioeconomic score fluctuates around 0.4. Compared with the first category, the level of socioeconomic development is roughly comparable, but environmental management still needs to be improved, and the final fund allocation proportion obtained ranges from 3.26% to 3.63%. The third category is from Ordos clockwise to Lanzhou. The total eco-efficiency score of these regions fluctuates more, but the average socioeconomic score is 0.68, the ecological compensation funds are adjusted downward because of their excellent development advantages, and the final fund allocation proportion obtained ranges from 2.36% to 3.23%. These three regions are shown in Figure 4A as green, yellow, and red, respectively.

The optimal fund allocation scheme designed was in line with the actual situation of YRB development. The central and western regions are at the head of the upstream YRB, lag in economic development due to restrictions on industrial growth to protect the ecological environment, sacrificing certain development opportunities. Thus, they deserve more compensation funds. Provincial capitals and strong economic cities benefit from the high-quality water environment and rapid scale of urbanization and development. Thus, they should provide compensation funds to the central and western regions to promote the sharing of development opportunities.

4 Conclusion

In the context of sustainable development, ecological protection should be mutually balanced and inclusive with socioeconomic development. Based on the doughnut theory, this study constructed an allocation model of ecological compensation funds to conduct an empirical study of the upstream YRB. The three conclusions of this study are as follows:

a) A comprehensive allocation model of basin ecological compensation funds was constructed. This study considered the problems and regional characteristics of the YRB, organically combined the promotion of ecological benefits with shared development opportunities, and constructed a two-tier model for fund allocation. The pre-allocation model focuses on ecological benefit enhancement and affirms the ecological benefits of each compensated subject by quantifying the ecological environment management effectiveness. The optimal allocation model focuses on regional shared development and optimizes the pre-allocation scheme by incorporating socioeconomic conditions.
b) An empirical analysis of the upstream YRB was conducted to verify the validity of the model. In this study, the data of 28 regions in the upstream YRB from 2016 to 2020 were substituted into the model for calculation, and the resulting fund allocation scheme satisfied the development requirements of regional ecological and economic sharedness, which indicates that the two-tier model is scientific and reasonable.
c) The allocation schemes for ecological compensation funds in the upstream YRB were determined. In the pre-allocation scheme, the western regions should receive lesser funds and the eastern regions higher. Moreover, the provincial capitals, Yinchuan and Lanzhou, had lesser proportion of funds, whereas Ordos and Ulanqab received a higher proportion. The optimal allocation scheme increases the proportion of funds in the central and western regions of the upstream YRB and decreases the proportion of funds in the provincial capital and economically strong cities. This is in agreement with the actual development status of the upstream YRB and can effectively promote shared development to achieve prosperity in the entire region.

To implement the basin horizontal ecological compensation fund allocation scheme effectively, this study provides the following suggestions:

a) For the sake of local economic development, many regional governments do not consider basin ecological protection a core task and do not want to sacrifice their own interests to help economically backward regions. However, the basin is holistic in nature, and the ecological and economic conditions of each region are closely related. Therefore, it is essential to publicize the ecological compensation scheme to regional governments and make them understand that the development of the whole basin is inseparable. The willingness to share resources as well as ecological protection needs to be enhanced by each region to promote the basin-wide ecological protection fund allocation.
b) A basin-coordinating agency to manage ecological compensation funds needs to be established. The current basin ecological compensation practice is still mainly among cities within the province or among neighboring provinces. The ecological and economic linkages between upstream and downstream regions that are far apart are thus not considered. Moreover, administrative barriers between regions make it difficult to distribute funds directly to grassroots ecological protectors at the prefecture and county levels. A basin-coordinating agency can manage basin-wide ecological compensation funds, provide guidance for the common development of the whole basin, open communication channels between regions, listen to the opinions and suggestions of each region, and guarantee the formulation and implementation of the basin ecological compensation fund allocation scheme.
c) The current basin ecological compensation that relies solely on the payment of funds from downstream to upstream regions

needs to be modified. It is necessary to deepen interregional cooperation and implement diversified compensation practices. For instance, developing tourism and reaching targeted green economic exchange agreements may help to speed up the realization of ecological goals in the upstream area. Similarly, high-tech and environment-friendly enterprises in downstream areas can be encouraged to establish branches or build cooperative parks in upstream areas to promote the renewal of science and technology and the green transformation of industries. Thus, inter-regional synergistic cooperation can achieve basin-wide ecological protection along with economic development.

Data availability statement

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

Author contributions

JZh contributed to material preparation; JZh and JZo contributed to conceptualization and methodology; JZo was involved in data curation and writing—original draft; JZh was involved in writing—review and editing; KZ took part in supervision. All the authors read and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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