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Agricultural irrigation water price apportionment and sharing

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ABSTRACT

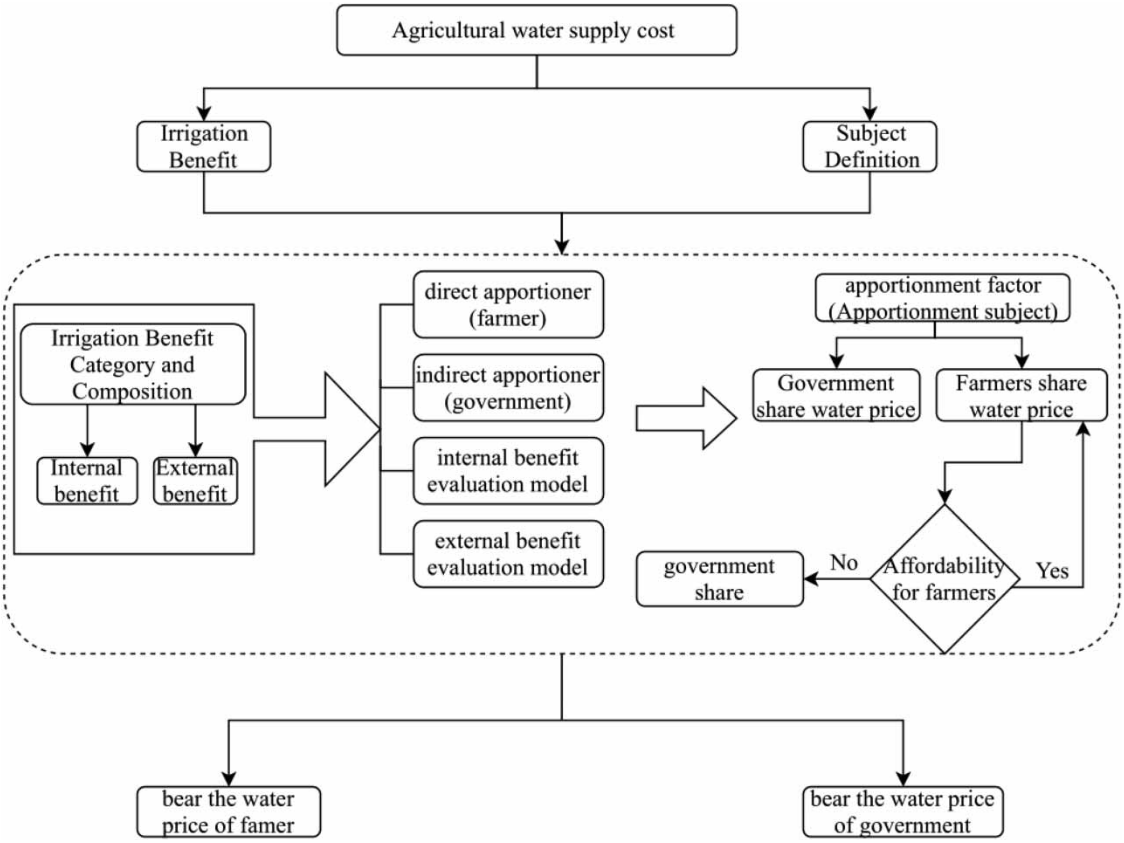
Studying the apportionment and sharing of agricultural water prices is necessary for clarifying the relationship between agricultural water price apportionment and government responsibility and ensuring the benign operation of irrigated areas. From the perspective of the versatility of irrigation water, irrigation benefits are classified as internal or external; the degree of benefit is measured using the proportion of irrigation water per cubic metre of internal and external benefits. This is used as an allocation coefficient to reasonably share prices based on farmers' water price tolerance, build agricultural water price apportionment and sharing models, and calculate the range of water prices borne by farmers and the government in the Baojixia Irrigation District in the Shaanxi Province of China. Results showed that the apportionment coefficients of farmers and government were 0.85 and 0.15, respectively. For grain crops, the farmers' price range was 0.115–0.508 yuan/m^3, while that of the government was 0.516–0.909 yuan/m^3; for cash crops, these values were 0.566–3.009 and 0.154–0.458 yuan/m^3, respectively. The results of this study support the formulation of agricultural water prices and provide a theoretical reference for reducing the water burden of farmers and promoting the high-quality development of the regional economy

Key words: Agricultural water price, Apportionment and sharing, Baojixia Irrigation District, China, Emergy theory, Irrigation benefit

HIGHLIGHTS

- Study on the apportionment and sharing of agricultural water prices
- The agricultural irrigation benefit is divided into direct benefit and indirect benefit according to the degree of influence.
- The emergy theory method was used to calculate the benefit value of agricultural irrigation.
- Using the benefit apportionment method, the apportionment ratio of different subjects was calculated, and the apportionment model of agricultural water price was constructed.
- Considering farmers' water bearability, research on agricultural water sharing models and analysis of agricultural water price share the scale.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The particularity of agriculture in China shows that the price of agricultural water affects the overall scenario of national food security, social stability, benign operation of farmland water conservancy projects, increase in farmers' yields and incomes, and implementation of rural revitalisation strategies. China's agricultural water price reform has achieved remarkable results, but an urgent solution is required for a prominent problem: currently, farmers' incomes are generally low, and water affordability is minimal. Thus, the established agricultural water price is lower than the cost of agricultural water supplied in irrigated areas, which hinders proper operations therein (Zhang *et al.*, 2016; Wang *et al.*, 2018). The academic consensus is that governments must achieve certain social goals through agricultural irrigation and water supply (Mahmoud, 2001; Suren, 2002). Therefore, water prices far above farmers' abilities to pay should be set taking into account public welfare and, therefore, be borne by the government (D'Odorico *et al.*, 2020). As a beneficiary of farmland irrigation and the manager of the country, the government must intervene in the formulation of agricultural water prices through allocation and reasonable sharing. The apportionment of agricultural water prices refers to sharing of the cost of agricultural water supply by apportionment subjects, including the state, local government, water pipe units, and farmers (Bhattarai *et al.*, 2007; Feng, 2018; Feng & Jiang, 2018). Based on apportioning, agricultural water price sharing means determining each subject's potential to bear as per ability to pay such that a common reasonable burden of agricultural water supply cost can be realised. It is vital to clarify the relationship vis-à-vis the apportionment of agricultural water costs, establish the responsibility of the government, and reduce the water cost burden of farmers.

In recent years, most studies have focused on the selection of agricultural water price sharing modes in different countries and regions and the necessity of establishing reasonable agricultural water price sharing models (Cao *et al*., 2015; Jiang *et al*., 2015).

When agricultural water price sharing is undertaken, it often focuses on the construction and maintenance of agricultural water conservancy projects, but the benefits generated by farmland irrigation are not considered. At present, governments share the price of agricultural water mainly through investment in the construction of farmland water conservancy projects, subsidising project operations and maintenance costs and other aspects (Li & Liu, 2016; Qiu, 2016). In the construction of irrigation and water conservancy projects in Japan, the shares of the central government, local governments, and farmers are clear, and the proportion borne by the government is more than 80% (Jamesen & Ogurac, 2010). In Israel, investment and construction funds for national farmland water conservancy projects are provided by the state, while project operations and maintenance costs are shared between the government (70%) and farmers (30%). For projects built by farmers, the government subsidises the underfunded construction and management (OECD, 2010; Li & Liu, 2016). The Indian government shares the price of water for agriculture by investing in projects, subsidising operations and maintenance costs as well as oil and electricity expenses of farmers, and providing low-interest loans (Sidhu *et al*., 2020). Economic (increased production and income of farmers) and environmental (climate regulation, water conservation, etc.) benefits from farmland irrigation are availed by the entire region; however, they are not reflected in the process of agricultural water price formulation (D'Odorico *et al*., 2020; Sanabria & Torres, 2020; Tsur, 2020). Therefore, this study aims to identify and determine the subject, object, and mode of the reasonable sharing of agricultural water prices through qualitative and quantitative research methods and to determine the share of agricultural water prices of irrigation beneficiaries via quantitative methods – from the perspective of farmland irrigation benefits. Thus, we aim to supplement and improve the theory of reasonable sharing of agricultural water prices.

2. IDEA AND METHODS

2.1. Research idea

Based on the current agricultural water supply cost water price, this paper begins with the farmland irrigation water supply process, irrigation benefits were classified as internal and external, and an evaluation model of internal and external benefits was established under the guidance of the emergy theory. Based on the degree of benefits accruing to the apportioned subjects, apportionment and sharing models of agricultural water prices were constructed using the proportion of internal and external benefits per cubic metre of irrigation water and the ability to pay farmers. The research concept is illustrated in Figure 1.

First, the subject and object of agricultural water price apportionment and sharing should be clarified. In this study, the irrigation benefits from agricultural irrigation water supply are classified based on the principle of benefit. Stakeholder theory is used to clarify and define the allocation subject, and the ability to pay is employed to define the sharing subject. Subsequently, a quantitative study on sharing is conducted.

2.2. Research methods

Since sharing is followed by apportionment, apportionment is the basis of sharing; therefore, the key objectives of this study are presented as follows: (1) calculation of the apportionment coefficient. Based on the classification of irrigation benefits, an evaluation model for the internal and external benefits of farmland irrigation was constructed guided by the emergy theory to achieve unified measurement of the benefit value of farmland

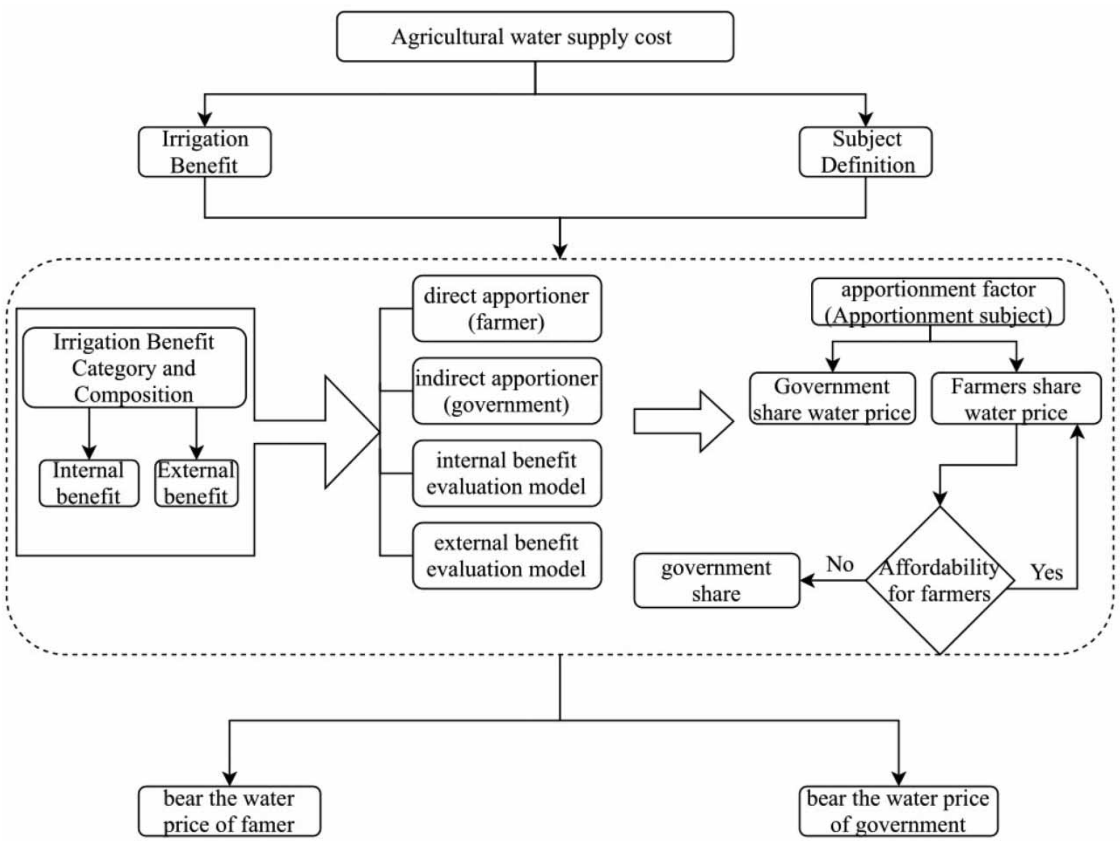


Fig. 1 | Research concept.

irrigation. The proportion of internal and external benefits of irrigation water per cubic metre was used as the apportionment coefficient. (2) Analysis of farmers' ability to afford. The water price bearing index analysis method was used to analyse the water price bearing capacity of farmers and lay the foundation for the reasonable sharing of water prices.

2.2.1. Emergy theory

Emergy theory (Odum, 1996) is a relatively scientific and reasonable theory for the quantitative assessment of natural resources and their socioeconomic activities. The theory is based on the emergy of solar energy and uses the energy value conversion rate to convert different types of energy that cannot be directly compared into uniform standard emergy value for analysis. It measures resources, the environment, and a series of economic activities at a deeper level to calculate the real value. The conversion formula is as follows:

$$E = \tau B \tag{1}$$

where E is the emergy (sej), τ is the emergy conversion rate (sej/J or sej/g), and B is the amount of energy or substance (J or g).

A quantitative relationship between the benefit from energy value and its corresponding monetary price is used to quantify the benefit value (Lü *et al.*, 2013), and the conversion formula is:

$$P = E \times \frac{1}{\mathrm{EDR}} \quad (2)$$

where P is the value (yuan) and EDR is the emergy currency ratio (sej/yuan), which has a specific value in the literature (He *et al.*, 2020).

2.2.2. Analysis method of water charge bearing index

Currently, the classified water price is widely implemented in China. The water charge bearing index is used to truly reflect farmers' tolerance in connection to the current water price (Wang *et al.*, 2019; Huang *et al.*, 2022b) and evaluate the water price tolerance of farmers growing food and cash crops in an irrigated area. Currently, the index analysis method is commonly used to calculate water price affordability in China, and its mathematical model is as follows:

$$P_{\mathrm{C}} = \frac{\alpha V}{W} \quad (3)$$

where P_{C} is the water price tolerance (yuan/m^3); α is the expenditure coefficient of the water cost, the proportion of water cost to production cost, output value, or net income; W is water consumption per unit of irrigation ($\mathrm{m}^3/\mathrm{hm}^2$); and V is the cost, output value, or net income (yuan).

2.3. Model building

2.3.1. Classification of irrigation benefits

Beginning with the process of agricultural irrigation water supply and based on the function of irrigation water, irrigation benefits can be classified as internal and external. The internal benefits of farmland irrigation primarily manifest in satisfying crop growth demands and promoting an increase in yield through agricultural production (Wang *et al.*, 2018; Ziolkowska, 2018; Chen *et al.*, 2021). Moreover, irrigation has a certain impact on the microclimate and environment of irrigated areas (Valipour, 2017; El-Shirbeny *et al.*, 2021). This study primarily discusses the regulation of farmland climate through irrigation, while considering that plant transpiration and inter-tree evaporation absorb a large amount of latent heat, thereby reducing surface temperature and increasing air humidity (Albaladejo-Garcia *et al.*, 2020; He *et al.*, 2020).

The inter- and intra-annual variations in groundwater level in an irrigation area are significantly affected by irrigation. Groundwater level rises significantly after irrigation begins and declines after irrigation stops. This increase is proportional to the amount of irrigation water applied (Scanlon *et al.*, 2006). China has a wide agricultural territory with different crops in the north and south, and the functions of water conservation produced by farmland irrigation differ slightly. For irrigated areas dominated by dry crops, the function of water conservation via irrigation is primarily reflected in the infiltration effect of agricultural water supply process channels (Guoliang *et al.*, 2016), and the amount of newly conserved water sources is represented by the infiltration of channels. For irrigated areas dominated by paddy fields, water conservation generated via irrigation includes the channels in the water supply process and the infiltration effect of paddy fields during irrigation. Therefore, increased water conservation is represented by channels and paddy fields (Cong *et al.*, 2018).

In farmland ecosystems, irrigation can increase nitrogen content in soils and regulate soil moisture (Zhou *et al.*, 2020). Nitrogen in irrigation water is primarily in the form of nitrated nitrogen, which is conducive to soil health and is directly absorbed by crops as a nutrient (Liang *et al.*, 2017). Under suitable moisture conditions, the number and activity of soil microorganisms increase, the transformation and decomposition of minerals and organic matter are accelerated, and the available nutrients in the soil increase, thereby improving soil fertility (Chunmei *et al.*, 2020; Girsang *et al.*, 2020).

In summary, the benefits of irrigation can be categorised as internal, such as an increase in agricultural yield, and external/environmental, such as climate regulation, conservation of water sources, and soil ripening.

2.3.2. Definition of subject and object

As the most direct users of irrigation water and direct beneficiaries of an increase in agricultural yield, farmers should bear a portion of the cost of agricultural water supply (Bhattarai *et al.*, 2007; Feng & Jiang, 2018). Additionally, agricultural water supply has environmental benefits, such as climate regulation, water source conservation, ecological balance maintenance, and soil ripening, which are enjoyed by the entire region; this implies that the government, which is the representative of the social beneficiary, should participate in the apportionment (Feng, 2018; Feng & Jiang, 2018). Owing to the limited water price tolerance of farmers, the government must share water costs to generate an agricultural water price that does not increase the burden on farmers.

Therefore, farmers enjoy internal benefits as the direct apportionment subject; the government, as the representative of social benefits, is the indirect apportionment subject. As farmers are a socially vulnerable group, they generally have low incomes and a weak ability to pay. Thus, the government, as the national manager, should share the water price when it is far above what farmers can afford. Therefore, the government is the subject of water price sharing.

In summary, the subjects of apportionment are the farmers and the government, whereas the subject of sharing is the government. The object of apportionment is the cost of agricultural water supply, while the object of sharing is the part of the water price above the farmers' ability to pay.

2.3.3. Apportionment model

2.3.3.1. Benefit assessment model

(1) . Internal benefit model

. The agricultural production process is complex and requires irrigation inputs and other agricultural production materials. Therefore, the irrigation–benefit–apportionment coefficient multiplied by the total value of increase in farmland was used to evaluate internal benefits (Wang *et al.*, 2018). First, the increase in yield of each agricultural product is obtained based on the actual irrigated area and the increase in yield per unit area using the following formula:

$$AP_I = AI_S \times \beta \tag{4}$$

where AP_I is the increase in yield (kg), AI_S is the actual irrigated area (hm^2), and β is the increase in the yield per unit area (*kg/hm*).

Based on the increase in yield, the emergy analysis method is used to calculate the increased yield emergy value of agricultural products, which is the sum of the energy values for increasing the yield of each agricultural product:

$$E_{CO} = \sum_{n=1}^{n} \tau_n \cdot NB_{Cn} \tag{5}$$

where E_{CO} is the gross emergy value of the increase in farmland yield (sej), τ_n is the emergy conversion rate of each agricultural product (sej/J), and NB_{Cn} is the energy from an increase in the production of each agricultural product (J).

The internal benefit of farmland irrigation is equal to the allocation coefficient of the irrigation benefit multiplied by the total output value of the farmland. The internal benefit model for farmland irrigation can be obtained using Equations (1) and (2).

$$P_N = \frac{\delta \times E_{CO}}{EDR} \tag{6}$$

where P_N is the internal benefit of irrigation (yuan) and δ is the allocation coefficient of the irrigation benefit.

(2) External benefit model

(1) Climate regulation benefit

Climate regulation is primarily reflected in water evapotranspiration; water in plants and soil diffuses into the air in the form of gas during crop growth. This process consumes heat and, therefore, reduces the temperature and increases humidity. For irrigated areas dominated by dry crops, evapotranspiration (ET) is the net irrigation water consumption (I). For irrigated areas dominated by paddy fields, evapotranspiration is equal to the net irrigation water consumption minus field leakage (F_d) and displacement (D) (He *et al.*, 2020). That is,

$$ET \approx I \tag{7}$$

$$ET \approx I - \sum 10(F_d + D) \cdot A_{\text{paddy field}} \tag{8}$$

where $A_{\text{paddy field}}$ is the irrigated area of the paddy field (hm^2).

The evaporative energy of irrigation (EB) is calculated using the energy conversion rate of irrigation water as follows:

$$EB = 10^6 L \cdot ET \tag{9}$$

where L is the latent heat of evaporation (J/g; $L = 2{,}500–2.2\,T$) and T is the annual average temperature.

By combining Equations (1) and (2), the climate regulation benefit model can be obtained as follows:

$$P_E = \frac{E_B \cdot \tau_S}{EDR} \tag{10}$$

where P_E is the climate regulation benefit (yuan), and τ_S is the emergy conversion rate of evaporation (sej/J).

(2) Water conservation benefit

Recharging the groundwater table in irrigation areas is the main function of conserving water sources. For irrigated areas dominated by dry crops, the total amount of water conserved (W_{gr}) is primarily the channel conservation amount ($Q_{\text{channel supplement}}$). For irrigated areas dominated by paddy fields, it is primarily composed of the channel and paddy field conservation amounts ($Q_{\text{field supplement}}$). The formula is as follows:

$$W_{gr} = Q_{\text{channel supplement}} = mQ_{\text{Canal head water diversion}} \quad m = \gamma(1-\eta) \tag{11}$$

$$W_{gr} = Q_{\text{channel supplement}} + Q_{\text{field supplement}} \quad Q_{\text{field supplement}} = \chi \sum 10 F_d A_{\text{paddy field}} \tag{12}$$

where $Q_{\text{Canal head water diversion}}$ is the water diversion of the canal head (m^3), m is the leakage coefficient of the canal system, γ is the correction coefficient (reflecting the amount of water consumed in the humid soil layer and lost by evaporation in the process of water transmission through channels), η is the channel water utilisation coefficient, and χ is the coefficient of infiltration recharge.

Gibbs free energy of groundwater at the regional mean temperature (ΔG_{gr}) was used to convert the amount of conserved water resources into conserved water energy (E_G):

$$E_G = 10^6 \Delta G_{gr} \cdot W_{gr} \tag{13}$$

The water source benefit model for farmland irrigation conservation is obtained by combining Equations (1) and (2).

$$P_G = \frac{E_G \cdot \tau_G}{\text{EDR}} \tag{14}$$

where P_G is the benefit arising from water source conservation (yuan) and τ_G is the conversion rate of groundwater emergy (sej/J).

(3) Soil ripening benefit

In this study, the benefit of farmland irrigation soil maturation refers to the direct input of nitrogen into the soil via irrigation water, which increases the value of nutrients in the soil. The irrigated input nitrogen nutrient content (NB) in the region in question is calculated as follows:

$$\text{NB} = \text{NB}_{ph} \times A_{\text{actual irrigation}} \tag{15}$$

where NB_{ph} is the input nitrogen content of irrigation water per unit irrigation area (g/hm^2) and $A_{\text{actual irrigation}}$ is the actual irrigation area of the region (hm^2).

Using the input nitrogen amount multiplied by the specific emergy conversion ratio of nitrogen (τ_N), the soil ripening benefit model can be obtained by combining Equations (1) and (2).

$$P_N = \frac{\text{NB} \cdot \tau_N}{\text{EDR}} \tag{16}$$

where P_N is the benefit value of regional soil maturation (yuan), and τ_N is the conversion rate of the nitrogen energy value (sej/J).

In summary, the external benefit model of farmland irrigation is

$$P_W = P_E + P_G + P_S \tag{17}$$

2.3.3.2. Apportionment factor. The apportionment coefficient method was adopted for apportionment based on the agricultural water supply costs, and the proportion of internal and external benefits provided per cubic metre of irrigation water was used to reflect the allocation coefficient. Specifically,

$$\varepsilon_i = \frac{P_{P_N}}{P_{P_N} + P_{P_W}} \tag{18}$$

$$\omega_i = \frac{P_{P_W}}{P_{P_N} + P_{P_W}} \tag{19}$$

where P_{P_N} and P_{P_W} are the internal and external benefits per cubic metre of irrigation water (yuan/m^3), respectively; ε_i is the farmers' apportionment coefficient; and ω_i is the government's apportionment coefficient.

The apportioned water price can be obtained by combining the water price of the agricultural water supply cost with the apportionment coefficient using the following formula:

$$\mathrm{FSP_W} = \varepsilon_i \cdot \mathrm{ASCP_W} \tag{20}$$

$$\mathrm{GSP_W} = \omega_i \cdot \mathrm{ASCP_W} \tag{21}$$

where $\mathrm{ASCP_W}$ is the water price of agricultural water supply cost (yuan/m^3), $\mathrm{FSP_W}$ is the apportionment of water price for farmers (yuan/m^3), and $\mathrm{GSP_W}$ is the apportionment of water price for the government (yuan/m^3).

2.3.4. Sharing model

The water price bearing index (α) is a key indicator when calculating water price tolerance; however, it is generally set to a certain value in use and a certain subjectivity and error occur (Huang *et al.*, 2022a, 2022b). This index is used as an interval to measure the ability of farmers to pay the water price with a certain proportion of the water fee in agricultural production cost, output value, and net benefit; its maximum value is used to constitute the water price tolerance range of farmers.

$$P_C = \left[min\left(\frac{V\alpha_1}{W}, \frac{V_1\varphi_1}{W}, \frac{V_2\theta_1}{W}\right), \quad \max\left(\frac{V\alpha_2}{W}, \frac{V_1\varphi_2}{W}, \frac{V_2\theta_2}{W}\right)\right] \tag{22}$$

where P_C is the water price tolerance range of farmers (yuan/m^3); V is the production cost (yuan); V_1 is the average output value per hectare (yuan); V_2 is the net income (yuan); α_1 and α_2 are the minimum and maximum value proportions of water cost to production cost, respectively; φ_1 and φ_2 are the minimum and maximum values of the proportions of the water cost to the output value, respectively; and θ_1 and θ_2 are the minimum and maximum values of the proportion of the water cost to net income, respectively.

The government is responsible for taking into account the ability of farmers to pay the water price, therefore, if $\mathrm{FSP_W} > P_C$, the water price that farmers should be apportioned exceeds what they can afford. Governments should implement economic measures to address this problem. Therefore, the range of water prices shared by the government is as follows:

$$\mathrm{GRSP_W} = \mathrm{FSP_W} - P_C \tag{23}$$

where $\mathrm{GRSP_W}$ is the water price shared by the government (yuan/m^3).

In summary, the ranges of water prices borne by farmers and the governments are as follows:

$$\mathrm{FBP_W} = P_C \tag{24}$$

$$\mathrm{GBP_W} = \mathrm{GSP_W} + \mathrm{GRSP_W} \tag{25}$$

3. CASE STUDIES

3.1. Study area overview

Baojixia Irrigation District, which is located in the western part of the Guanzhong Plain, Shaanxi Province, China, is one of the top 10 irrigation districts in China. It is responsible for the irrigation spread over

188,600 hm^2 of farmland in 14 counties (cities and districts) of Baoji, Yangling, Xianyang, and Xi'an, Shaanxi Province. It mainly cultivates wheat, corn, vegetables, melons and fruits and other cash crops, and mainly cultivates dry crops. The current agricultural water supply full cost water price is 1.024 yuan/m^3.

3.2. Data sources

Economic data were obtained from the 2009 to 2019 Shaanxi Provincial Statistical Yearbook and the Statistical Bulletin of National Economic and Social Development of All Cities (districts) in Shaanxi Province for the 2008–2018 period. Data on irrigation water consumption in farmlands were derived from the Water Resources Bulletin of Shaanxi Province for the 2008–2018 period. Data on agricultural water supply cost and irrigation water consumption in the irrigation area were obtained from the Baojixia Yinwei Irrigation Management Center in Shaanxi Province. The management centre of the irrigated areas investigated the production costs and output values of typical crops in the area (Table 1).

4. APPORTIONMENT OF WATER PRICE

4.1. Internal benefit estimation

The analysis of the benefit from an increase in agricultural yield was based on the actual irrigated area. Investigation of the irrigated area and a review of the relevant literature revealed that the yield of grain and cash crops increased by 2,250 and 3,000 kg/ha, respectively, after irrigation. In this study, the allocation coefficient of the irrigation benefit (β) was set as 0.45, and the emergy conversion rate of each agricultural product (τ_n) was obtained from the literature (Lü *et al.*, 2013). According to Equations (4)–(6), the average benefit from farmland irrigation in the Baojixia irrigation area from 2008 to 2018 was 531×10^6 yuan. Combined with the average annual agricultural irrigation water consumption of 271×10^6 m^3 in the irrigation area, the average internal benefit per cubic metre of irrigation water in the Baojixia irrigation area was calculated to be 1.98 yuan/m^3 (Table 2).

4.2. External benefit estimation

(1) Estimation of climate regulation benefits

Using relevant data on farmland irrigation water in the Guanzhong region, the annual average farmland irrigation evapotranspiration in the Guanzhong area from 2008 to 2018 was estimated to be $1,604 \times 10^6$ m^3, and the conversion rate of evaporative energy value (τ_S) was 12.2 sej/J (Lü *et al.*, 2013; He *et al.*, 2020). Substituting this into Equations (7)–(10), the annual average climatic benefit value of farmland irrigation in the Guanzhong area of Shaanxi Province from 2008 to 2018 was 920×10^6 yuan.

(2) Estimation of the benefits of conserving water sources

The utilisation coefficient of canal water in each irrigation area in Guanzhong changes annually. Therefore, Equation (11) was transformed, and the amount of canal loss was replaced by the approximate consumption

Table 1 | Investigation of typical crops in the irrigated area.

Crop type	Production cost (yuan/hectare)	Yield (kg/hectare)	Unit price (yuan/kg)	Net profit (yuan/hectare)
Wheat	155 25	6,750	2.52	1,485
Corn	134 70	7,500	2.52	5,430
Fruit tree	666 00	375 00	2.4	234 00

Table 2 | Internal benefits per cubic metre of irrigation water in irrigation areas.

Item	Internal benefits (10^6 yuan)	Water for irrigation (10^6 m^3)	Water benefit per cubic metre (yuan/m^3)
2008	492	258	1.9
2009	407	387	1.05
2010	465	231	2.01
2011	442	307	1.44
2012	482	354	1.36
2013	423	348	1.22
2014	481	216	2.22
2015	535	212	2.53
2016	638	200	3.18
2017	687	176	3.89
2018	786	296	0.93
Mean value	531	271	1.98

of farmland irrigation water minus the amount of water consumed and then multiplied by the correction factor (γ) to obtain the channel conservation value. The average annual water loss of the canal system in the Guanzhong region from 2008 to 2018 was $1,018 \times 10^6$ m^3, and the correction factor (γ) was set as 0.35, resulting in an average annual channel conservation value of 356×10^6 m^3. In this study, the average annual groundwater emergy conversion rate (τ_G) of the Guanzhong area from 2008 to 2018 was calculated by referring to the calculation method of the natural water solar energy conversion rate (Lü *et al.*, 2013), where τ_G was 0.127×10^6 sej/J. The average annual benefit value of farmland irrigation water source conservation in the Guanzhong area from 2008 to 2018 was calculated as 459×10^6 yuan by substituting into Equations (11)–(14).

(3) Estimation of soil ripening benefits

The amount of nitrogen carried in irrigation water depends on the nitrogen content of the irrigation water and the amount of irrigation water used. The amount of nitrogen brought in by irrigation water in this study was set as 7.7 kg/hm (Lü *et al.*, 2013; He, 2021), and by substituting its value into Equation (15), the average annual nitrogen input of farmland irrigation was estimated to be 5.82×10^6 kg. The nitrogen energy conversion rate (τ_N) was 3.8×10^6 sej/kg. Using Equation (16), the average annual farmland irrigation soil ripening benefit in the Guanzhong area from 2008 to 2018 was calculated to be 392×10^6 yuan.

(4) External benefit result analysis

The climatic regulation, water source conservation, and soil ripening benefits of farmland irrigation in the Guanzhong area are summarised. The results are shown in Table 3, and the external benefit values of farmland irrigation in the Guanzhong area from 2008 to 2018 are shown in Figure 2.

Figure 2 shows that the value of the external benefit of irrigation in the Guanzhong area is ranked in descending order of benefits arising from the conservation of water source exceed those from soil ripening, which in turn are greater than climate regulation benefit – indicating that farmland irrigation in irrigated areas is of great significance in preventing groundwater subsidence and maintaining soil fertility. Based on the estimated results of the external benefits of farmland irrigation over the past 11 years, the benefit in terms of climate regulation is the least, accounting for approximately 10%. However, in terms of the total amount, taking 2018 as an example,

Table 3 | Estimation results of external benefit of farmland irrigation in the Guanzhong area.

Year	Benefit of climate (10^6 yuan)	Benefit of conserving water sources (10^6 yuan)	Benefit of soil ripening (10^6 yuan)	Benefit of total (10^6 yuan)
2008	93	454	400	946
2009	91	455	391	937
2010	86	456	389	931
2011	81	457	356	893
2012	76	458	325	859
2013	77	459	335	871
2014	85	460	349	894
2015	90	461	357	908
2016	103	462	426	990
2017	110	463	465	1,038
2018	117	464	520	1,100
Average	92	459	392	942

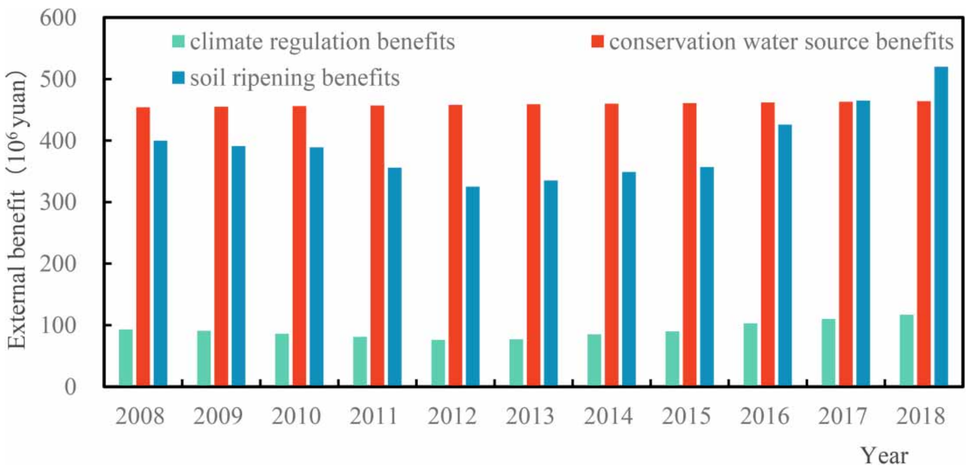


Fig. 2 | External benefit values of farmland irrigation in the Guanzhong area (2008–2018).

the benefit value of climate regulation in the Guanzhong area is 117×10^8 yuan; its ecological benefit cannot be ignored. Accordingly, the total value of the external benefit of farmland irrigation in the Guanzhong area shows an overall increasing trend, which indicates that the utilisation value of farmland irrigation water resources in the Guanzhong area is increasing, and its contribution to the ecological environment is constantly improving.

4.3. Apportionment of water price

In this study, the external benefits to the irrigation area were calculated based on the proportion of agricultural irrigation water. The proportion of the irrigation area was calculated to be 9.97%, the external benefit of agricultural irrigation in the Baojixia irrigation area was 94×10^6 yuan, and the external benefit per cubic metre of irrigation water was 0.35 yuan/m^3 (Table 4).

For the Baojixia irrigation area, the internal benefit per cubic metre of irrigation water was 1.98 yuan/m^3, and the external benefit was 0.35 yuan/m^3. Substituting the data into Equations (18) and (19), the average apportionment coefficients for farmers and the government over the years were 0.85 and 0.15, respectively (Table 5).

The project water supply cost data for the irrigated area in the final year were obtained from the Agricultural Water Supply Cost Supervision and Examination Report, supervised and examined by the Shaanxi Provincial Price Bureau in 2014. This study used the complete cost of agricultural water supply in the irrigation area (1.024 yuan/m^3). Combined with the apportionment coefficient of the irrigation area and substituting it into Equations (20) and (21), the water price apportionments paid by the farmers and the government in the irrigation area were 0.870 and 0.154 yuan/m^3, respectively.

4.4. Share of water price

Based on the analysis of domestic research results and the irrigation area scenario, the water fee accounted for 10–15% of the average output cost per mu and 5–10% of the output value, and the specific proportion of income per mu was 5–10%. Additionally, combined with the unit irrigation water consumption, water price ranges of grain and cash crops, based on the water price tolerance index, were 0.115–0.508 and 0.566–3.009 yuan/m^3, respectively. Comparing the water apportionment price of farmers with the affordable water price of different

Table 4 | External benefits per cubic metre of irrigation water in the Baojixia irrigation area.

Year	Guanzhong external benefit (10^6 yuan)	Baojixia external benefit (10^6 yuan)	Irrigation water consumption of Baojixia (10^6 m^3)	Proportion (%)	Water benefit of per cubic metre (yuan/m^3)
2008	946	65	258	6.84	0.25
2009	937	131	387	14	0.34
2010	931	82	231	8.76	0.35
2011	893	105	307	11.73	0.34
2012	859	115	354	13.4	0.33
2013	871	116	348	13.33	0.33
2014	894	73	216	8.14	0.34
2015	908	74	212	8.12	0.35
2016	990	78	200	7.85	0.39
2017	1,038	71	176	6.85	0.4
2018	1,100	132	296	12.01	0.45
Average	942	94	271	9.97	0.35

Table 5 | Apportionment coefficients of irrigation districts over the years.

Project	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	Mean
Farmer	0.88	0.76	0.85	0.81	0.81	0.79	0.87	0.88	0.89	0.91	0.68	0.85
Government	0.12	0.24	0.15	0.19	0.19	0.21	0.13	0.12	0.11	0.09	0.32	0.15

Table 6 | Reasonable undertaking of water price.

Crop type	Water apportionment (yuan/m^3)		Share water price (yuan/m^3)	Bear the water price (yuan/m^3)	
	Farmer	Government	Government	Farmer	Government
Food crop	0.87	0.154	0.362–0.755	0.115–0.508	0.516–0.909
Cash crop			0–0.304	0.566–3.009	0.154–0.458

crops, we observe that for farmers who grow food crops, the apportionment water price exceeds their water price tolerance. For farmers who grow cash crops, the apportionment water price is within their tolerance range, but they cannot carry the cost in full.

Based on the calculation results of the apportioned water price and government sharing, the water price ranges of apportioned subjects for food and cash crops were obtained using Equations (24) and (25): those of the farmers were 0.115–0.508 and 0.566–3.009 yuan/m^3, respectively, and those of the government were 0.516–0.909 and 0.154–0.458 yuan/m^3, respectively (Table 6).

5. DISCUSSION

This paper focuses on the benefit of agricultural irrigation water to study the allocation and sharing of agricultural irrigation water price. The established allocation and sharing model of agricultural irrigation water price can lay a foundation for the study of agricultural water price in irrigation area and can expand the limited thinking of reasonable sharing method of water price mainly focusing on the investment and cost of agricultural water conservancy project construction and maintenance. The identification of beneficiaries is conducive to clarifying the allocation relationship of agricultural irrigation water price, clarifying government responsibilities, and promoting the benign operation of irrigation areas and food security production.

It should be mentioned that owing to the availability of data, the above-stated agricultural water price apportionment and water price sharing models of agricultural areas only considered the benefits of increase in irrigation yield and the part of the ecological benefit (positive external benefits) classified under farmland irrigation benefits; the positive external benefits generated by farmland irrigation are not fully covered, and the negative external benefits are not classified. It also does not take into account the social benefits of irrigation (such as food security and employment); therefore, further research is needed to refine the findings. Additionally, indirect beneficiaries are inevitably attributed to the government, which has some limitations. In future research, the farmland irrigation stakeholders need to be further refined to provide a scientific basis for agricultural water price sharing. In addition, it is worth noting that planting structures vary in different natural environments/regions, which limit the universality of this model. The main direction of the follow-up research to this study will focus on the apportionment and sharing of agricultural water prices based on economic, environmental, and social benefits. The composition of agricultural irrigation benefits and stakeholders should be further investigated to provide a theoretical basis for the formulation of agricultural water prices.

6. CONCLUSION

In this study, two typical agricultural irrigation benefits were analysed, and the agricultural water price apportionment and sharing subjects were defined. The agricultural water supply cost apportionment coefficient was reasonably determined. Water price tolerance of farmers was analysed, agricultural water price apportionment and reasonable sharing models in irrigation areas were established, and the agricultural water prices of the apportionment subjects were quantitatively shared. The main conclusions of this study are as follows:

(1) Based on the versatility of farmland irrigation water, irrigation benefits can be classified as internal and external from the perspective of agricultural irrigation water supply. Internal benefits include increase in agricultural yield, whereas external benefits include climate regulation, water source conservation, and soil ripening.
(2) Based on the principle of benefit, farmers and the government are determined to be the subjects of apportionment. Using emergy analysis theory, an internal and external benefit evaluation model was constructed to calculate the proportion of internal and external benefits per cubic metre of irrigation water and reasonably determine the apportionment coefficient. Farmers' water price tolerance and government water sharing prices were determined quantitatively according to the local agricultural water use scenario and economic development status of the irrigation area.
(3) The model was applied to the Baojixia Irrigation District in Shaanxi Province, and farmers and the government were the main subjects of apportionment, with apportionment ratios of 0.85 and 0.15, respectively. Based on the agricultural water supply cost water price of the irrigation area, combined with the water price tolerance of farmers, the range of water prices borne by each was obtained. For grain crops, the farmers should bear water prices in the range of 0.115–0.508 yuan/m^3, and the government 0.516–0.909 yuan/m^3; for cash crops, the farmers' price was 0.566–3.009 yuan/m^3, and the government's price was 0.154–0.458 yuan/m^3.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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