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Analysis of agriculture water pricing reform in a water-deficit area of Northwest China

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ABSTRACT

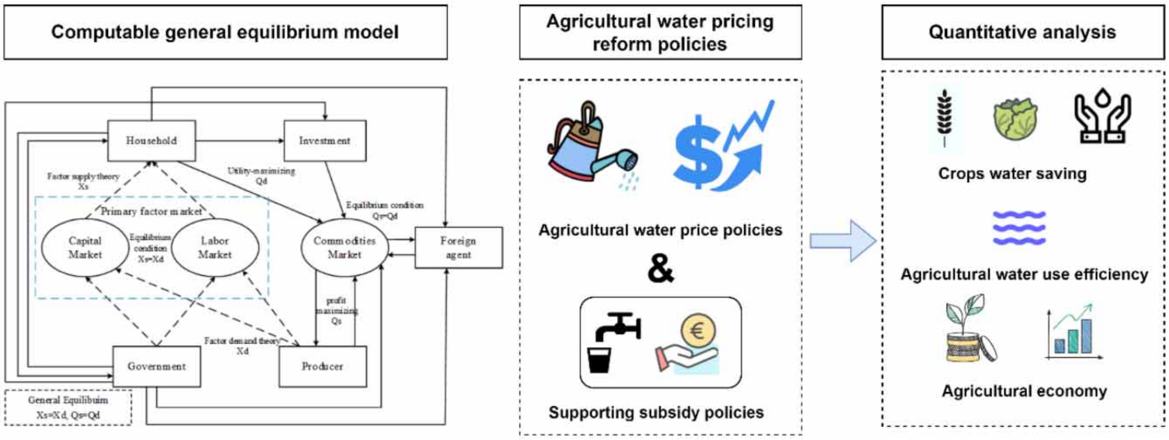
Northwest China frequently experiences significant droughts and water shortages. To better balance the supply and demand, and provide sufficient funds for water resource projects, this study applied a computable general equilibrium model to construct an agricultural water pricing policy model that depends on the crops' economic value and regional water use characteristics. Wuwei City in Gansu Province was used as a case study to test the model. Three agricultural water price increase policies and three supporting subsidy policies were developed. The study quantitatively investigated the impact of these policies on the agricultural economy, water use, and efficiency of water use from different water sources. The results indicated that water pricing reform promotes water conservation and improves water use efficiency. Subsidies can reduce the negative impact of water pricing policies on the agricultural economy. Economic crops (e.g. vegetables) are more sensitive to water prices compared to food crops (e.g. wheat). Finally, to the best of our knowledge, this study provided the best water pricing reform scenario expected to be the most effective for local development.

Key words: Agricultural economic impact, Agricultural water pricing policy, CGE model, Subsidization, Water conservation impact, Water use efficiency

HIGHLIGHTS

- The impact of agricultural water pricing reform on water uses and economics was quantitatively analyzed using the CGE model.
- Three agricultural water price policies and three supporting subsidy policies were developed, based on local farmers' water price bearing capacity.
- Water was subdivided into various sources and different elasticities were substituted. The agriculture was subdivided into three crops.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Water waste is a significant challenge in China, partly because of the relatively low price of agricultural water and negligible difference in the prices of water between different sources (Wang, 2007). These problems also lead to significant challenges in ensuring the efficient operation of water supply projects (Liao, 2004). One practical approach is to regulate water prices through market mechanisms. While the privatization of water services has become a massive market worldwide (Chaisse, 2017), it remains a much-debated issue in China, where the need for an increase in water price is reviewed independently of investment injections and return demand at the Price Bureau. As a result, the potential of water pricing to improve resource allocation and water conservation has not been fully exploited (Qian, 2018). Additionally, as agricultural water projects expand, governments must develop water-related policies consistent with investment agreements and international principles for water services to avoid additional costs (Chaisse & Marine, 2015). To coordinate the above issues, China has worked since 2016 to reform agricultural water prices comprehensively using adjustments and subsidies. (General Office of the State Council of the People's Republic of China, 2016). In 2018, the National Development and Reform Commission (2018) jointly multi-departmentallly issued a circular on *Further Promoting Comprehensive Reform of Agricultural Water Prices*. It required that reform plans and designs consider local water resources, planting structures, economic development levels, and other factors. In 2020, the National Development and Reform Commission (2020) issued an updated *Notice on Further Promoting Comprehensive Agricultural Water Price Reform*, which emphasized studying the comprehensive impact of water price reform on agricultural production, and assessing the extent of water price adjustments with concerning famers' affordability. However, due to the absence of a scientific water price adjustment model and insufficient financial subsidies, reform of agricultural water prices in China has been slow and inefficient. There are also challenges in assessing the economic impact of agricultural water pricing reform and water conservation effects. Furthermore, the choice of subsidy targets is controversial. Therefore, effectively adjusting water prices is fundamental to ensuring the sustainable operation of water supply projects. This highlights the need for an appropriate water price adjustment model to analyze the comprehensive impact of water price adjustments and to develop related supporting policies. Key topics include agricultural water use; water efficiency; regional economics, such as agricultural value added; and regional welfare, such as the Consumer Price Index (CPI) in arid areas. Previous studies on this topic have focused on qualitative analysis approaches (Willis *et al.*, 2013; Zuo *et al.*, 2014). However, recently, more quantitative studies have emerged in the literature.

Previous empirical studies mainly discussed whether the water price is a significant determinant of saving water in water-scarce areas and analyzed the impact of water prices, subsidies, and technologies of water use. For example, Schoengold *et al.* (2006) estimated the price elasticity of irrigation water in arid areas of the Western United States using the empirical method. Dagnino & Frank (2012) integrated the microeconomic theory of crop water demand and observed crop water use data into a framework that is suitable for empirical analysis. Zhou *et al.* (2015) explored whether the price will effectively restrain the increase in demand for agricultural irrigation water in the Heihe River Basin using the empirical method. However, the abovementioned studies lack descriptions of the linkages between agriculture and other sectors, resulting in the overestimated water price effect. Besides, the empirical model cannot set policies by year or forecast future changes in policy and economic conditions. Compared with an empirical model, (1) the computable general equilibrium (CGE) model establishes a comprehensive quantitative relationship among various components, enabling researchers to analyze the impacts of disturbances from a particular sector of the economy on the effects of the entire economic system, both favorable and unfavorable; (2) the policy of the CGE model can flexibly set and can accurately adjust the number of subsidies and years; (3) the CGE model can comprehensively analyze the regional macro impact of water pricing policy and subsidy policies such as gross domestic product (GDP), investment, and CPI. Berck *et al.* (1991) first applied the CGE model to address the agricultural water problems of San Joaquin Valley; since then, CGE models have been continuously refined and improved. For example, Gomez *et al.* (2004) applied the CGE model to analyze the water rights trading impact on the Balearic Islands' social economy. That study established a 'water market' that improved the efficiency of water resource allocation, positively and significantly impacting agricultural income. The Global Trade Analysis Project-Water (GTAP-W) model was applied by Calzadilla *et al.* (2011) to analyze the macroeconomic implications of increasing irrigation efficiency. The study found that a water policy directed at improving irrigation efficiency led to global and regional water savings, but it is not beneficial for all regions. In contrast, Decaluwe *et al.* (1999) applied the CGE model to explore the implications of different water policies in various sectors, including agriculture. That study focused on water distribution, population growth, and urbanization in Morocco. Cardenete & Hewings (2011) applied a static CGE model to study the impact of increasing water prices on water resources protection, water use efficiency, and water redistribution in the agricultural sector in Andalusia, Spain; Fang *et al.* (2016) developed an environmental CGE model to simulate the regional economic and environmental effects of discharge fees. The simulation results revealed that increased fees harmed GDP, but effectively controlled wastewater. These studies have collectively demonstrated the feasibility of applying the CGE model to study water pricing problems.

Considering this background, the following topics need to be studied in the future: (1) the subdivision of agricultural crop types, according to their economic characteristics; (2) the subdivision of different water sources and their differential pricing; and (3) the subsidization impact on agricultural water pricing. To address these topics and assess China's agricultural water pricing reform policies, we extended the (State Information Center General Equilibrium) SICGE model, a recursive dynamic CGE model of the Chinese economy, by introducing a subdivided agricultural module, based on the economic characteristics of different agricultural crops. Water was subdivided into surface water, groundwater, and unconventional water and substitutions were done using different elasticities to investigate the impact of water pricing reform on different water sources. To increase the flexibility of the water pricing reform policy, we also established a subsidy policy based on the local farmers' agricultural water price bearing capacity. This paper explored the combined impacts of water pricing and subsidy policies on water use, water use efficiency by different crops, and the regional economy in agricultural water pricing reform in water-scarce areas of northwest China. This study aims to provide the best water pricing reform scenario which will be most effective for local development. This study also provides a reliable policy analysis tool for examining the effects of China's agricultural water price reforms, which can help managers formulate appropriate water price reform policies. The study's baseline scenarios span 19 years (2012–2030). The water pricing policy increasing prices started in 2017, and the model results focus on expected deviations in agricultural water use, agricultural water use efficiency, and agricultural economy from 2021 to 2030.

2. MATERIALS AND METHODS

2.1. Study area

This study analyzes water resource dynamics in Wuwei City, Gansu Province, China, which has a total area of 32,347.07 km^2 (Figure 1). The climate is dry, with an annual precipitation of 156–256 mm, and an annual evaporation rate exceeding 2,000 mm. Wuwei City receives significant economic benefits from agriculture. The city has a high ratio of agricultural (including agriculture, forestry, animal husbandry, and fishery) value added income to the total GDP. Its agricultural water use accounts for a large proportion of total water use (Figure 2). The scarcity of water resources has become a constraint on the region's economic development. These conditions highlight why this area is an effective representative case to analyze the impact of agricultural water pricing

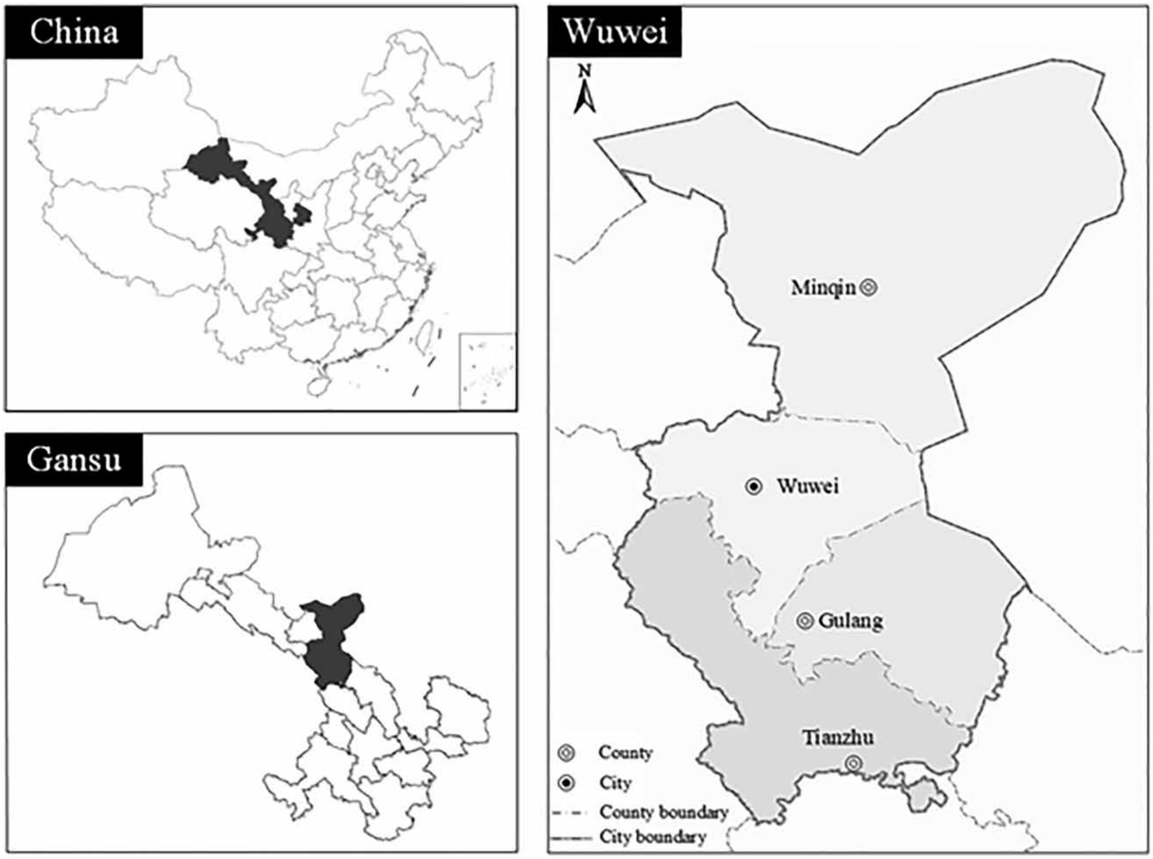


Fig. 1 | The geographical location of Wuwei City.

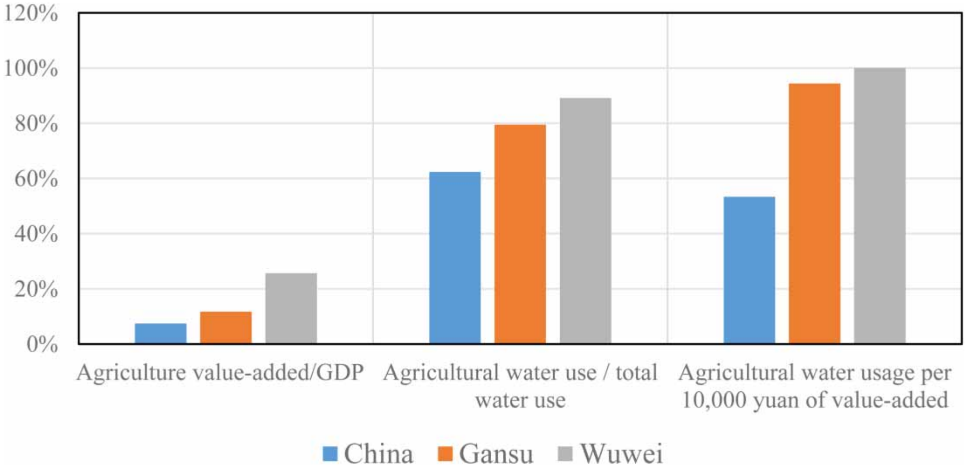


Fig. 2 | The agricultural economy and water use in Wuwei City in 2017. *Source: China, Gansu and Wuwei Statistics Yearbook. Note*: The agricultural water use per 10,000 yuan of value added is set as 1 in Wuwei, China; Gansu and Wuwei values are shown to illustrate relative values.

reforms. Crops grown in Wuwei City include food crops, such as wheat, corn, and potatoes; and economic crops, such as fiber, vegetables, and medicinal herbs. Compared with food crops, most economic crops use water-saving irrigation. This means that both the planting cost and output value per unit area of economic crops are higher compared to food crops. The water use per unit area is higher for economic crops compared to food crops, due to the long irrigation cycle and large water use (Table 1).

Wuwei City is part of the Shiyang and Yellow River Basins, with average total multi-year water resources of 1.22 billion m^3 (1956–2000 series). Wuwei's agricultural water supply projects (irrigation districts) are led by the government primarily for investment and construction purposes. The water supply sectors are responsible for the projects' operation and maintenance (O&M). Wuwei's agricultural water prices currently barely recover the operation and maintenance costs. New irrigation projects increase water supply costs, so the agricultural water prices need to be further increased. Based on field research data, the annual operational cost of new water conservancy projects is approximately 40.58 million yuan, equivalent to 19.14% of the current agricultural water supply cost (2.12 billion yuan). The annual water supply in Wuwei City is 1.59 billion m^3; water sources

Table 1 | Cultivation of food and economic crops in Wuwei City.

			Year		
Agricultural crop types	**Item**	**Unit**	**2015**	**2016**	**2017**
Food crops	Planting area	km^2	1,880	1,851	1,804
	Average water use per unit area	m^3/hm^2	34.5	32.2	32.6
	Output value per unit area	yuan/hm^2	22,335.0	21,690.0	20,820.0
Economic crops	Planting area	km^2	639	684	721
	Average water use per unit area	m^3/hm^2	97.0	106.4	99.2
	Output value per unit area	yuan/hm^2	124,784.9	129,959.9	141,044.9

Source: Wuwei Statistics Yearbook and Water Resources communiqué.

include surface water (including external water transfers), groundwater, and recycle water (for example, sewage and rainwater reuse).

Table 2 presents the water use by different sectors from 2013 to 2017. Wuwei's current recycled water supply capacity accounts for 0.68% of the total water supply, currently unavailable for agriculture. Different irrigation districts depend on distinct water sources. Generally, the surface water is priced by volume and area, while groundwater is priced based on electricity bills. The terminal water price for each irrigation district ranged from 0.04 to 0.25 yuan/m^3 in 2019, as listed in Supplementary material, Table S1.

2.2. Modeling framework

The CGE model analyzes the relationships and influences among agents, evaluates the correlation effect of policy changes, and allows the flexible modification of simulated policies based on changes in the research problem. Therefore, it can be effectively applied to measure the transmission of water pricing policies. The model includes multiple equations that explain the balanced interaction between demand and supply in any economic system. The equations are based on the optimal conditions of import profits, consumer benefits, export costs, and producer profits. By solving the equations, the model generates relative quantities and prices that correspond with the entire economy's general equilibrium.

The model includes the following six economic agents: producers, investors, households, the government, foreign agents, and an inventory agent or accountant (Horridge, 2006). Each producer minimizes costs for a given input and implements a constant return to scale (CRS) production function. Consumer demand is modeled using a representative utility-maximizing household. Consumers receive payments and use the income to consume commodities and services. When facing budget constraints, consumers maximize their benefit or utility by selecting the best combination of commodities and services. Government revenues are generated by taxes and fees, and government expenditures include subsidies, transfers, and other public utilities. The model assumes that aggregate government demand is consistent with aggregate household consumption. The model applies a flexible linkage approach.

To describe the optimal allocation of domestic commodities, domestic markets, and exports, a constant elasticity of transformation (CET) equation is adopted to achieve optimal profits. In addition, the incomplete substitutability between imported and domestic goods is modeled using Constant Elasticity of Substitution (CES) (Dixon & Jorgenson, 2012). Sectoral production requires intermediates and the three primary factors of labor, capital, and land. Capital and labor are fully mobile domestic factors, while the land is sector-specific. Figure 3 shows the linkages between the agents and the general equilibrium of commodities and factors.

Table 2 | Water use by sectors and sources in Wuwei City (10^8 m^3).

	Agriculture		Industry			Service	
Year	Surface water	Ground water	Surface Water	Ground water	Recycled Water	Surface water	Ground water
2013	10.36	3.71	0.07	0.90	0.03	0.02	0.16
2014	10.34	3.92	0.02	0.90	0.08	0.02	0.15
2015	10.70	3.63	0.01	0.95	0.08	0.02	0.15
2016	10.36	3.56	0.05	1.00	0.10	0.02	0.15
2017	8.94	3.88	0.11	0.61	0.10	0.02	0.17

Source: Wuwei Water Resources communiqué.

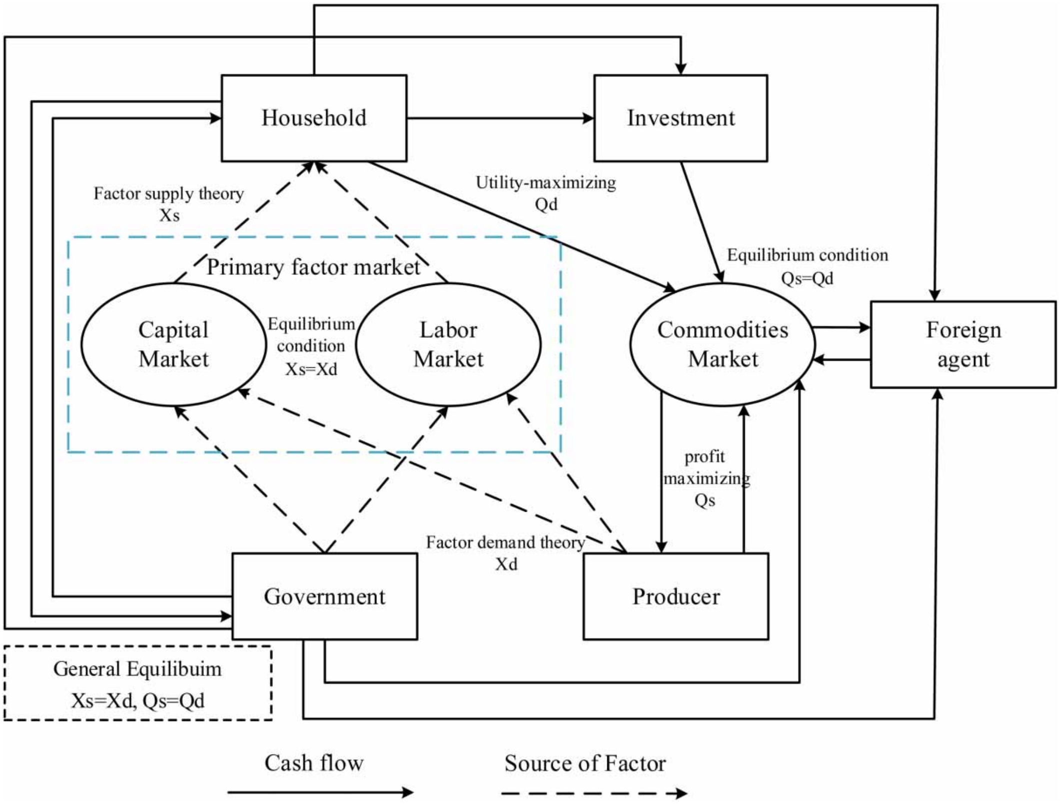


Fig. 3 | Model of the intrinsic linkages of agents and the general equilibrium of commodities.

2.3. The improvement of the SICGE model

This study uses the core module of the Agricultural Water Pricing SICGE (AWPSICGE) model, which is based on the SICGE model, jointly developed by the State Information Center (SIC) and the China Institute of Water Resources and Hydropower Research (IWHR). The dynamic mechanism of the model is based on the MONASH model, which is a dynamic general equilibrium model for Australian economic development. It addresses the stock/flow accumulation relationships between capital stocks and investments, and between foreign debt and trade deficits (Siddig & Grethe, 2014). The existing SICGE model includes only one agricultural sector and water sector, which is insufficient for analyzing agricultural water pricing policies in China. To analyze the response of different crops to water pricing policies, this study subdivided the agriculture sector into three sub-sectors, each of which produces a specific set of commodities. This study also subdivided the water sector into three sub-sectors, and established an alternative relationship among different water sources.

2.3.1. Agricultural subdivision module

As noted above, given the significant differences between food crops and economic crops relating to cultivation practices, value added, and water use per area, this study divided the agriculture sector into the following three sectors: food crops sector, economic crops sector, and other agriculture sectors. This facilitated an analysis of the impact of increased water pricing and subsidy policies. Data were collected from the Wuwei City Statistical

Yearbook and Water Resources communiqué. The bottom of the model in Figure 4 shows that local and non-local commodities satisfy the CES substitution relationship.

$$X_{i,j}^{(1)} = CES\left\{\frac{X_{(is)j}^{(1)}}{A_{(is)j}^{(1)}};\rho_{ij}^{(1)}, b_{(is)j}^{(1)}\right\}(i, j = 1, \ldots, n) \tag{1}$$

Equation (1) shows that intermediate input $X_{i,j}^{(1)}$ is the CES function compound of local and non-local commodities. Input $X_{(is)j}^{(1)}$ represents the input of i commodity from source s ($s = 1$ for local commodities; $s = 2$ for non-local commodities) to sector j. The parameters $A_{(is)j}^{(1)}$ and $b_{(is)j}^{(1)}$ are technical progress parameters and share parameters, respectively. The parameter ρ is the constant substitution elastic coefficient.

The form of the CES function used in the formula is as follows:

$$\underset{s}{CES}\{f_s;\rho, b_s\} = \left(\sum_s f_s^{-\rho} b_s\right) \tag{2}$$

At the middle of the model, three kinds of agricultural commodities, the value added, water, and other intermediate inputs are associated with the total output using the Leontief function. The Leontief function has the same form as the CES function, but its substitution elasticity is equal to 0. Figure 4 shows the logic structure diagram.

2.3.2. Water sources substitution module

Multi-layer nesting was applied to reflect the substitution effect of different water sources. The hierarchy and corresponding substitution elasticity were set based on an analysis of the strength and possibility of the substitution relationship. To analyze the economic impact of water pricing reforms, this study subdivided the water sector into the surface water sector, groundwater sector, and recycled water sector. Different substitution relationships were established among these water types. Figure 5 shows the logic structure diagram. The improved model simulates changes in the water source structure, triggered by changes in the prices for different water sources. After improving the model, the total output from each sector was still included in the Leontief production function. That function assumes no substitution relationship between total water use (the three kinds of water) and other

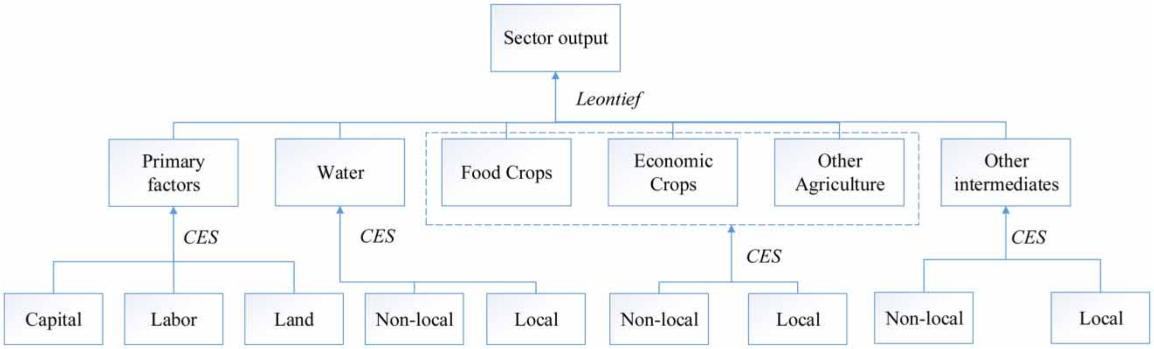


Fig. 4 | The sectoral output structure in the agricultural subdivision module.

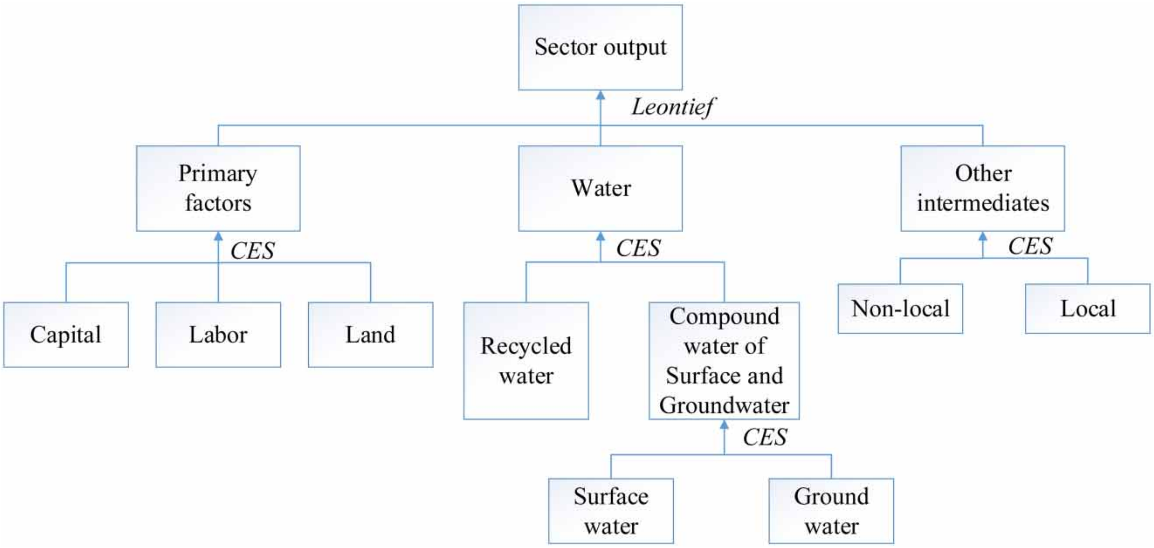


Fig. 5 | The water sources substitution module.

intermediate inputs.

$$X_{Sur\_Grou,j}^{(1)} = CES\left\{\frac{X_{Surf,j}^{(1)}}{A_{Surf,j}^{(1)}}, \frac{X_{Grou,j}^{(1)}}{A_{Grou,j}^{(1)}}; \rho_j^{Surf\_Grou}, b_{Surf,j}^{(1)}, b_{Grou,j}^{(1)}\right\} \quad (j = 1, \ldots, n) \tag{3}$$

The variables $X_{Surf,j}^{(1)}$ and $X_{\mathrm{Grou},j}^{(1)}$ represent the amount of surface water and groundwater, respectively, used by sector j in the production process. The parameters $A_{\mathrm{Surf},j}^{(1)}$, $A_{\mathrm{Grou},j}^{(1)}$, $b_{Surf,j}^{(1)}$, and $b_{Grou,j}^{(1)}$ represent the technological progress parameters and share parameters, respectively, of sector j. The parameter $\rho_j^{Surf\_Grou}$ is the constant substitution elastic coefficient, with a substitution elasticity of approximately 0.8, based on Zhao *et al.* (2016).

The complex of combination surface water, groundwater, and recycled water is assumed to satisfy the CES function, as follows:

$$X_{Surf\_Grou\_Uncv,j}^{(1)} = CES\left\{\frac{X_{Surf\_Grou,j}^{(1)}}{A_{Surf\_Grou,j}^{(1)}}, \frac{X_{Uncv,j}^{(1)}}{A_{Uncv,j}^{(1)}}; \rho_j^{Surf\_Grou\_Uncv}, b_{Surf\_Grou,j}^{(1)}, b_{Uncv,j}^{(1)}\right\} \quad (j = 1, \ldots, n) \tag{4}$$

where $X_{Surf\_Grou\_Uncv,j}^{(1)}$ is the number of water source composite products used by sector j in the production process; and the parameters $X_{Uncv,j}^{(1)}$ and $A_{Uncv,j}^{(1)}$ represent the volume of recycled water and technological progress used by sector j, respectively. The meanings of other variables and parameters are the same as in Equation (4). The substitution elasticity of $\rho_j^{Surf\_Grou\_Uncv}$ is approximately 0.2 (Zhao *et al.*, 2016).

2.4. Model parameters

The study model applied parameters from the Chinese version of the ORANI-G model, which is a generic single-country CGE model, including CES element substitution elasticity, CET elasticity, and the expenditure elasticity of residents' demand (Horridge, 2006). The ORANI-G model is a 122-sector model based on the SICGE model of the Chinese economy (Supplementary material, Table S2). Due to a lack of data, the production function parameters of other sectors were assigned the value of 2, based on the Chinese version of the ORANI-G model. In this study, the labor demand elasticity for all sectors was set at 0.243 according to Zhao *et al.* (2019). This model used data from the People's Republic of China General Equilibrium Model (PRCGEM), setting the consumer price elasticity at 4 (Zhao *et al.*, 2016). The CES elasticity in this study adopted the value of the SICGE model from the China National Information Center (Li & Zhang, 2012).

The Frisch parameter is defined as the ratio of total income to the sum of total income minus basic demand in the linear expenditure system (LES) demand function model. Previous research data indicate that when the income of residents increases, the absolute value of the Frisch parameter tends to decrease. For example, when the per capita income increased from \$100 to \$3,000 (1970 price), the Frisch parameter increased from −7.5 to −2.0 (Dervis *et al.*, 1982). Based on the parameter values of the China Version of the ORANI-G Model-4, the per capita disposable income of Wuwei City in 2017 was 18,667 yuan, which was lower than the Chinese average. As such, the Frisch parameter value was set at −3.

2.5. Baseline scenario

Using data from Wuwei City's 2012 Statistical Yearbook, Gansu's 2012 input–output table, and Gansu's Hydrological Yearbook, we calculated Wuwei's 2012 input–output table using the Biproportional Scaling Method (Schneider & Zenios, 1990). This ensured that the total output and value added of different sectors remained unchanged. To accurately reflect the main economic characteristics of Wuwei, this study analyzed the main and key impacts of policies based on national statistics. Using national economic sector classification field codes, the 42 sectors in the input–output table were merged into 10 sectors (Supplementary material, Table S3). Then, the water sector was subdivided into three sub-sectors (surface water, groundwater, and recycled water), and the agriculture sector was subdivided into three sub-sectors (food crops, economic crops, and other agriculture). The result was an input–output table of 15 sectors in Wuwei City.

To ensure the reliability of the model, we conducted both historical and forecast simulations. First, we performed a historical simulation of the baseline scenario to simulate the economic changes in Wuwei City from 2012 to 2016. We compared the simulated value with the real value (Supplementary material, Table S4). Then, according to Wuwei City's future economic and social development plan, and assuming that the water supply price system remains unchanged, we predicted future economic development changes (Table 3). The

Table 3 | Value added growth of the macro economy in the baseline scenario in Wuwei City.

Categories	2017–2020	2021–2030 (simulation results)
GDP	6%	5%
Agriculture	4%	3%
Industry	5%	3.5%
Service industry	8%	6%

Source: Wuwei's Statistics Yearbook and the 13th Five-Year Plan.

growth rate of sectoral value added was set based on the region's annual growth rate and the *13th Five-Year Plan of Wuwei City*.

According to the *National Water-Saving Action Plan of Wuwei City*, the total use amounts of surface water and groundwater sources are expected to decrease by approximately 10 and 20%, respectively, by 2030 compared to 2017. The baseline scenario forecast results are presented in Table 4.

2.6. Policy scenarios

The studied policy scenarios focus on the deviations of endogenous variables (the unknown variables in the equation, obtained by solving the model) from their baseline levels caused by exogenous shocks (the known variables in the equation, set by people). From an economic perspective, to maintain the normal operation of water supply projects, agricultural water prices should be at or above operational costs (Bontems & Nauges, 2019). Hence, we assumed for modeling purposes that the future agricultural water price level should be increased by 19.14%. Based on field investigation results and consultation opinions of management sectors and experts, the modeled annual adjustment rate should not exceed, as was therefore constrained at, 10%.

Given this background, three water pricing reform scenarios were established. Scenario 1 (S01) adjusts the water price to meet operating costs in 2021, then adjusts it to meet a low-profit water price, and then adjusts it to meet a full-cost water price (for government-invested water conservancy projects, the full-cost water price includes project operating costs, environmental costs, water resources tax, and business tax). In 2030, Scenario 2 (S02) adjusts the water price to meet operating costs in 2025, then adjusts it to meet the low-profit water price. Scenario 3 (S03) adjusts the water price to meet operating costs in 2030. The water price adjustments for the three scenarios are listed in Table 5.

Part of China's water pricing reforms includes the practice that the agricultural water charges are collected by water supply sectors and placed into a special account for water conservancy expenses. In China, most irrigation projects are invested in and constructed by the government; as such, there are disputes about allocating the increased water charge caused by new projects. The government has expressed concern that farmers cannot

Table 4 | The deviation in water use in the baseline scenario in Wuwei City (simulation results).

Year	2021	2025	2030
Surface water	−2.3%	−6.3%	−10.0%
Groundwater	−5.3%	−13.4%	−20.4%

Table 5 | Calculation of agricultural water pricing adjustment schemes (increase rate %).

	Operating and maintenance cost water pricing target year								
	2021			2025			2030		
Year	SW	GW	RW	SW	GW	RW	SW	GW	RW
2017–2020	5	9	0	1.5	4	0	1.5	2	0
2021–2025	4	6	0	1.5	4	0	1	2	0
2026–2030	3.5	5	0	1.3	2.5	0	1	2	0
Total	57.5	91	0	20	48.5	0	16	28	0

Note: SW, surface water; GW, groundwater; RW, recycled water.

afford water charges caused by the price increases (National Development and Reform Commission, 2019). As such, they indirectly subsidize farmers, either by providing subsidies to supplement agricultural income, or by directly subsidizing the water supply sectors for the operation and maintenance of the systems.

For modeling purposes, we needed to determine the farmers' bearing capacity of agricultural water prices, to select optimal subsidy policies and optimize the water charge allocations. To do this, we calculated the local farmers' bearing capacity of the agricultural water price, by calculating the proportion of water expenses to the cost of agricultural output (Chen, 2007), and determined whether a demand-side subsidy is required. Studies in China have shown that it is reasonable for agricultural water expenses to account for 5–15% of the ratio of the output value to the area (Development Research Center of the Ministry of Water Resources of P.R.C, 2003). Based on this, Table 6 shows the agricultural water price bearing capacity, according to the agricultural output value and the agricultural irrigation water use of Wuwei City in 2017. Based on this, the price of surface water in Wuwei was set at 0.2 yuan/m^3, and the price of groundwater was set at 0.05 yuan/m^3 (Supplementary material, Table S1), based on 2017 values. In Scenario 1, costs are recovered in 2021, and then profits are generated. Consequently, the scenario's water price in 2030 may increase to approximately 0.35 yuan/m^3 for surface water and 0.12 yuan/m^3 for groundwater. The average water price associated with the largest water price adjustment, Scenario 1, in this study is lower than the lowest value that local farmers can afford. This indicates it is appropriate to subsidize the water charges for water supply sectors in Scenarios 4–6.

Based on the water price adjustments, we introduced three additional policy scenarios, focused on subsidies: Scenario 4 (S04), Scenario 5 (S05), and Scenario 6 (S06), which set 2021, 2025, and 2030, respectively, as the target years of setting the agricultural water price to cover operational costs. These new subsidy policies also assume the government subsidizes the additional water charges (40.58 million yuan) levied in the water price policies to the water sectors by reducing production taxes from 2021. This further reduces the sector's production costs.

3. RESULTS

3.1. Impact on water use of surface water and groundwater

An increase in agricultural water prices generally leads to an increase in the cost of agricultural water use. In the modeled output, as the process unfolded, the demand for agricultural water began to decline. The water use for food and economic crops is expected to decrease compared with the baseline scenario (Figure 6(a) and 6(b)). The three scenarios projected different rates of decreasing water use due to different price increases: the decreased water use was greatest for S01, followed by S02, and then S03. In S01, surface water use for food and economic crops is expected to decrease by 1.47% (food) and 1.51% (economic), or 5.97 million m^3 and 6.23 million m^3, respectively, of water conserved in 2030. The groundwater use for food and economic crops is expected to

Table 6 | Calculation of farmers' bearing capacity of agricultural water price in Wuwei City (comparable price).

Unit	Output value of agriculture 10^9 yuan	5% of the output 10^9 yuan	15% of the output 10^9 yuan	Agricultural irrigation water 10^9 m^3	Affordable water price 5% yuan/m^3	Affordable water price 15% yuan/m^3
Food crops	3.75	0.19	0.56	0.63	0.30	0.89
Economic crops	10.17	0.51	1.53	0.65	0.78	2.34

Source: Wuwei's Statistical Yearbook and Water Resources communiqué.

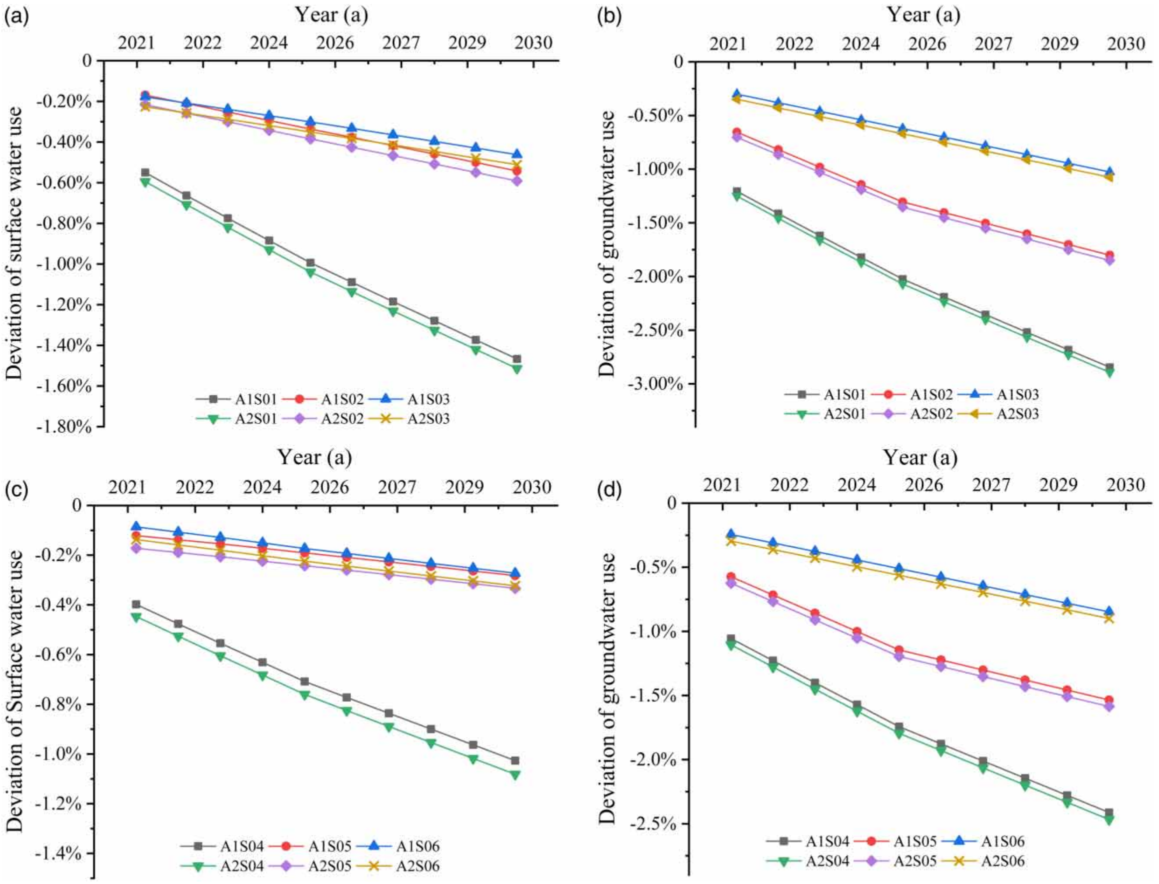


Fig. 6 | The expected deviation of water use for food crops and economic crops in S01, S02, and S03 scenarios compared to the baseline scenario. (a) Surface water use under the increased water pricing policy, (b) groundwater use under the increased water pricing policy, (c) surface water use under the supporting subsidy policies, and (d) groundwater in the supporting subsidy policies. *Note:* A1S01 indicates the year-on-year change in the water use of food crops relative to the baseline scenario under S01; A2S01 represents the year-on-year change in the water use of economic crops relative to the baseline scenario under S01. Others are similar.

decrease by 2.85% (food) and 2.89% (economic), or 4.33 million m^3 and 4.45 million m^3, respectively, of water conserved in 2030 compared to the baseline scenario.

In contrast, Figure 6(c) and 6(d) shows the expected impact of subsidies on agricultural surface water use and indicates that subsidies incentivize water use in agriculture. While the projected water use is expected to decrease overall under the subsidy policies, the decrease is not expected to be as large as under the water pricing policy. Compared with the baseline scenario, the surface water and groundwater use is expected to decrease for both food crops and economic crops. This is because the increases in agricultural water price directly impact agricultural water use. In contrast, subsidies for the water supply sectors have an indirect impact, leading to a reduction in agricultural water use costs. Therefore, agricultural water use is expected to continue to decline. Using S04 as an example, when operating costs are recovered in 2020 and subsidies to the water supply sector begin in 2021, the surface water use for food crops and economic crops is expected to decrease by 1.03% (food) and 1.08%

(economic), or by 4.18 million m^3 and 4.43 million m^3, respectively, of water conserved in 2030. The groundwater use for food crops and economic crops is expected to decrease by 2.41% (food) and 2.47% (economic), or by 3.67 million m^3 and 3.79 million m^3, respectively, of water conserved in 2030 compared with the baseline scenario.

3.2. Impact on water use efficiency

The previous section demonstrated that water pricing adjustments impact water use efficiency. As the cost of agricultural production increases, agricultural value is expected to be added, and water use is expected to decrease. If agricultural water use decreases more than the value added, the water use efficiency increases (Figure 7(a).

In S01, for example, water use per 10,000 yuan of added value is expected to decrease by 0.73% for food crops and 0.78% for economic crops in 2021. With the continued impact of water pricing adjustments, water use efficiency is also expected to improve, with a 1.83% decrease for food crops and a 1.88% decrease for economic crops in water use, per 10,000 yuan of value added in 2030. After subsidies, water use efficiency is expected to decline (Figure 7(b)). Using S04 as an example, the water use per 10,000 yuan of value added for food crops is expected to decrease by 1.41% in 2030, and the water use per 10,000 yuan of value added for economic crops is expected to decrease by 1.46%. The three subsidy scenarios identified an increase in water use efficiency compared to the baseline scenario, reflecting the positive effects of the subsidy policies.

3.3. Impact on agricultural economy

Figure 8(a) shows the agricultural economic impact of the water pricing policy scenarios. An increase in water prices is expected to lead to an increase in production costs and increased cost of living for both producers and consumers. Thus, other conditions being equal, the study predicted a decrease in the agricultural value added as a result of reduced household consumption. Briefly, the agricultural value added (Y) was defined as a function of technological progress A, capital K, and labor L: $Y = 1/A \times F(K, L)$. The agricultural value added in S01 in 2030 is expected to be 0.10% lower compared to in the baseline scenario. This reflects the combined effect of primary factor use and labor adjustments (−0.67% percentage change in L and −0.03% in K). Compared with the baseline scenario, the agricultural value added of S01 showed the largest expected decline.

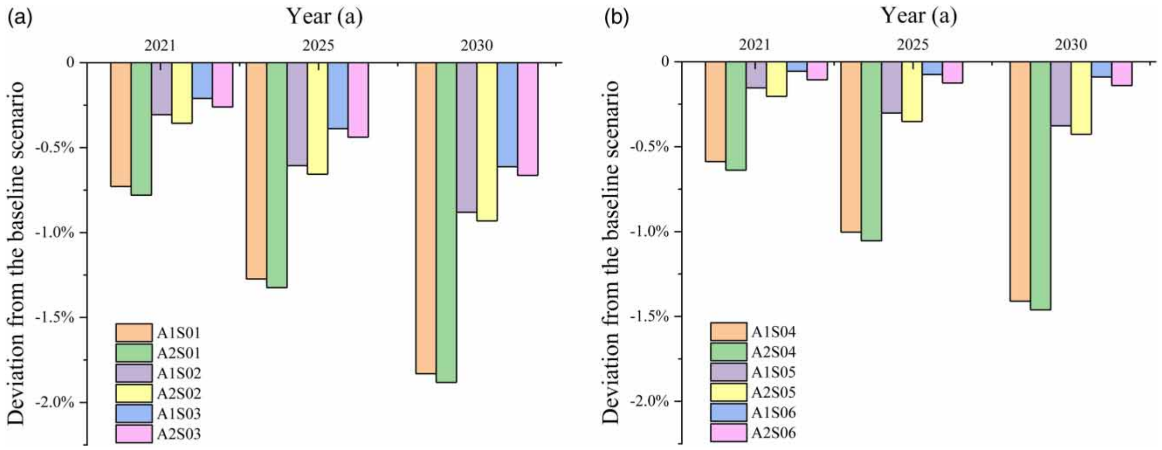


Fig. 7 | The deviation of water use per 10,000 yuan of agricultural value added from the baseline scenario. (a) Increasing water pricing policy and (b) supporting subsidization policy.

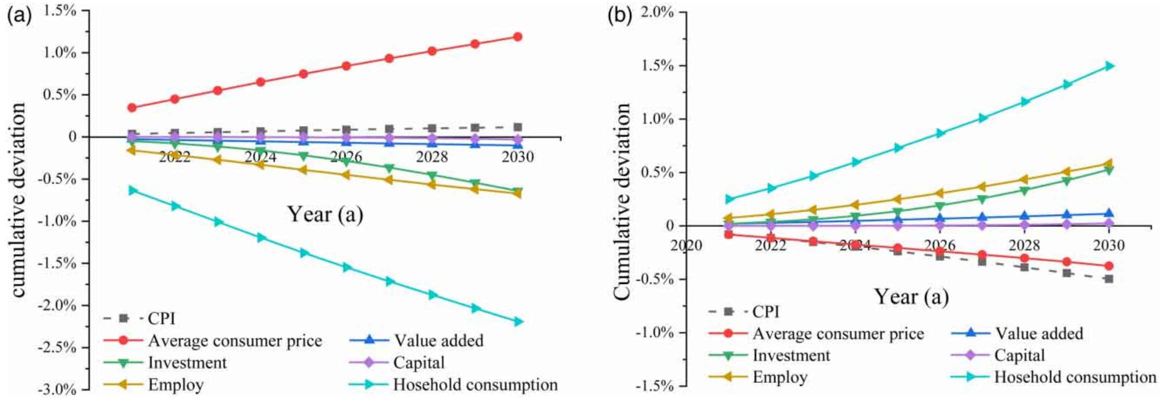


Fig. 8 | The macroeconomic impact (%, cumulative deviation of food crops from the baseline). (a) Increasing water pricing policy and (b) supporting subsidization policy.

The value added for food crops and economic crops are expected to decrease by 0.24 and 0.12%, respectively, in 2030 as shown in Table 7.

From a consumption perspective, an increase in water prices leads to an increase in the price of water-impacted commodities: the CPI in 2030 is expected to be 0.12% higher than the baseline scenario. This is due to the increase in water-impacted commodity prices, as the average price of food crops is expected to increase by 1.19%. As a result, real household consumption is expected to decrease by 2.19%, and investment is expected to decrease by 0.64% in 2030, compared to the baseline scenario.

Figure 8(b) shows the agricultural economic impact of the subsidy policy scenarios compared to the water pricing policy scenarios. The reduced production costs are expected to lead to a decrease in the price of water commodities (compared to the water pricing scenarios). Figure 8(b) shows that an increase in water prices and subsidies to the water sectors may indirectly affect the agricultural sector and may be transmitted to all sectors. This is expected to ultimately lead to a reduction in CPI, production costs, and cost of living for producers and consumers. The agricultural value added in 2030 in S04 is projected to be 0.11% higher than S01. Table 8 shows that the associated value added for food crops is expected to increase by 0.17%, and the value added of economic crops is expected to increase by 0.09% (with a change of 0.57% for L and 0.02% for K).

Turning to a demand analysis, a 0.5% lower CPI is expected in 2030 in S04 compared to in S01; this would reflect a 0.38% decrease in the average agricultural consumer price. As a result, under S04, real household

Table 7 | The cumulative deviation of agricultural value added in S01–S03 scenarios from the baseline scenario (%).

Scenarios	2021	2025	2030
A1S01	−0.07	−0.15	−0.24
A1S02	−0.02	−0.05	−0.09
A1S03	−0.02	−0.04	−0.06
A2S01	−0.03	−0.07	−0.12
A2S02	−0.01	−0.03	−0.04
A2S03	−0.01	−0.02	−0.03

Table 8 | The cumulative deviation of agricultural value added in S04–S06 scenarios from S01 to S03 scenarios (%).

Scenarios	2021	2025	2030
A1S04–A1S01	0.03	0.09	0.17
A1S05–A1S02	0.03	0.07	0.15
A1S06–A1S03	0.03	0.08	0.15
A2S04–A2S01	0.02	0.05	0.09
A2S05–A2S02	0.01	0.04	0.08
A2S06–A2S03	0.01	0.04	0.08

consumption of agricultural products is expected to increase by 1.48% and investment in agriculture is expected to increase by 0.53% compared to S01 in 2030.

4. DISCUSSION

This study found that reforms to water pricing may encourage the conservation of agricultural surface water and groundwater. However, the effect of this agricultural water pricing reform on agricultural water conservation was found to be rather limited, similar to Zhao's research results. Zhao *et al.* (2015) used the static CGE model in 2002 to determine that when the price of irrigation water increased by 15%, the irrigation water use of Qinghai, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan, and Shandong decreased by 4.02, 1.00, 8.54, 0.05, 0.72, 1.02, 0.13 and 0.16%, respectively. It occurred primarily for two prevailing reasons. First, low agricultural water prices result in a low proportion of agricultural water costs to total agricultural costs. Furthermore, farmers lack an awareness of commodity water prices. Second, farmers in underdeveloped area have a limited ability and means to conserve water for irrigation. Additionally, according to the model mechanism in our study, subsidies reduce the cost of agricultural water, and reduce the water-saving effect by increasing the water price. However, these subsidies are expected to compensate for the loss of agricultural development. Preventing the loss of agricultural labor and capital, and avoiding price increases, may positively impact the stability of agriculture and food production. Thus, the agricultural water price should at least reach the operating cost; subsidizing the water sectors can then begin. In addition, the government should maximize the coordination and management of water supply sectors to further promote agricultural water conservation.

Water use fluctuates more in economic crops compared to food crops, due to both a larger water use per unit area and higher water cost per unit of economic crops produced. When the water prices of both food and economic crops are increased to the same extent, the water charges impact economic crops more than food crops. As such, economic crop producers are more inclined to reduce water use. Therefore, economic crops are more sensitive to water prices than food crops. However, from an agricultural economy (value added) perspective, economic crops are better able to absorb higher water prices compared with food crops. This may be because the output value per unit area and the associated profit are higher for economic crops compared to food crops. Differentiated water price policies are needed based on the types of crop cultivation. For example, in the current model, the water price associated with food crops gradually reaches the level needed to just pay operating costs, while the water prices associated with the economic crops lead to profits.

The agricultural water price reform policies have less of a negative impact on the regional economy. The agricultural value added is expected to decrease by 0.10%, while the CPI is expected to increase by 0.12%. This projected range of change was consistent with Cui *et al.* (2019). Cui's study found that when the water price of the whole industry increases by 10%, the GDP of the Beijing–Tianjin–Hebei region is expected to drop by 0.039%, and the CPI is expected to increase by 0.001%. Unlike the above studies, this paper determines the impact of China's agricultural water price reform in the regional economy and discusses subsidy policies on agricultural water use for different crops. It also evaluates the possibility of harnessing different water sources for agricultural purposes in the CGE model. Moreover, the water pricing policies are developed more reasonably because we considered farmers' financial capacity to cover agricultural water expenses, together with the operating costs involved in water supply projects. There are two major reasons why the results obtained in this study differ from Cui's research results: 1. Wuwei is less-developed than the Beijing–Tianjin–Hebei region, and its ratio of agricultural value added to GDP is high. Therefore, the ramifications for an increase in agricultural water prices are more severe in the regional economy compared to the developed regions. 2. The water source substitution module introduced in this paper allows different water sources to complement each other, thus reducing the impact of agricultural water price fluctuations on the economy.

The comprehensive analysis of the six study scenarios found that S01 and S04 were significantly better than other scenarios with respect to improving water savings and water efficiency. Both are expected to have little impact on the agricultural economy and lie within the bearing capacity of farmers. Compared to S01, which covers the expenses of operating cost in 2020, S04 also includes subsidies for the water supply sectors. This is expected to reduce the negative impact of water pricing reforms on the agricultural economy, and may help the water supply sectors meet their operation and maintenance costs. Hence, S04, which recovers water supply costs and subsidizes water supply sectors in 2021, was selected as the best water price reform scenario.

5. CONCLUSIONS

This study adopted an improved CGE model to simulate agricultural water pricing policies, based on the characteristics of agricultural production and water use in Northwest China. Three water pricing scenarios and three supporting subsidy scenarios were considered to assess the impact of water pricing reform on agricultural water savings and the agricultural economy in Northwest China through perceivable quantitative change. The scenarios provide the theoretical basis for efficient use of agricultural water and adaptive water resources management.

- Agricultural water price reforms are expected to effectively reduce agricultural water use. (Surface water use and groundwater use are expected to decrease by 6.23 million m^3 and 3.79 million m^3 in 2030, respectively.) The reforms are also expected to improve agricultural water use efficiency. These approaches also showed a lower negative impact on the agriculture economy compared to other subsidy-driven scenarios (the agricultural value added is expected to decrease by 0.10% and CPI is expected to increase by 0.12%).
- From a water use perspective, economic crops were found to be more sensitive to water pricing adjustments compared to food crops. However, when considering the agricultural economics, such as the value added, economic crops were found to generally able to better adjust to water prices than food crops. Therefore, differentiated water price policies with higher water prices for economic crops than for food crops should be formulated.
- The water price policies, accompanied by subsidies, are expected to effectively save water, improve water efficiency, reduce the economic impact of water price increases, and ensure the smooth operation of water supply departments. Therefore, the scenario associated with recovering operating costs in 2020 and subsidizing the water charges incurred by the water supply sectors (S04) was considered to be the best water price reform scenario.

The findings shed light on the fact that decision-makers should make full use of pricing tools to achieve water savings with affordability for farmers. Subsidies to the water supply sectors can result in the dual benefits of saving water and attenuated negative impacts. Like all studies, this one had some limitations. For example, the study did not consider the technical progress in agricultural water conservation resulting from subsidies to the water supply sectors and the water quality of different water sources. Nevertheless, this study highlighted the positive implications of developing an effective water pricing policy in Northwest China. In addition, the model in this paper is not limited in its application in arid regions. It could also be used to assess the combined effects of water pricing policies and water rights trading, and could be applied in water environments in water-rich regions, by flexibly adjusting the model's baseline and policy variables.

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AUTHOR CONTRIBUTIONS

Y.Q. and H.N. conceptualized the study; Y.Q. and X.L. did the formal analysis; H.N. acquired funds; Y.Q. and J.K. performed the methodology; Y.Q., J.K. and X.L. were involved in software analysis; H.N. and Y.J. supervised the study; Y.Q. and X.L. validated the study; Y.Q. visualized the study; Y.Q. and J.K. wrote the original draft; Y.Q., H.N., Y.J. and G.C. wrote, reviewed and edited the article.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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