Impact of Water Rights Transaction in the Beijing-Tianjin-Hebei Region in China Based on an Improved Computable General Equilibrium Model

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Abstract: Water shortages in the Beijing-Tianjin-Hebei (BTH) region in China have constrained the region’s coordinated development. A feasible solution is introducing water rights transactions through the middle route of the South-to-North Water Diversion Project (SNWDP). However, there are few methods available for systematically simulating and evaluating the impact of inter-regional water rights transactions. In this study, an improved computable general equilibrium (CGE) model was developed to simulate the water rights transactions. Different water resources were integrated as intermediate inputs, and the model includes a substitution mechanism between different water resources. The water stress index (WSI) was used to evaluate the impact on the economy and water resources simulated by the model. The study proposes and evaluates different scenarios with different water-saving levels and transaction volumes. Water rights transactions have a positive effect on the overall economic growth of the BTH region, reducing the local water resource stress in Beijing and Tianjin; the transactions have a limited impact on the economy and water usage of Hebei Province. Compared with the general water-saving intensity scenario without water rights transactions, the recommended scenario adopts ultra water-saving intensity, along with the transfer of 100 hm$^3$ of water rights from Hebei to Beijing and Tianjin. This leads to an increase in the overall gross domestic product (GDP) of the BTH region by CNY 0.587 trillion (USD 99.6 billion); a decrease in local water usage in Beijing and Tianjin of 197 hm$^3$; and a relief in the regional imbalance of water resources stress. This study provides a quantitative analysis tool for evaluating the impact of water rights transactions and optimizing water resources allocations in the BTH region, providing a reference for simulating and evaluating water rights transactions in other regions.

Keywords: water rights transaction; quantitative analysis; CGE model; water stress index; Beijing-Tianjin-Hebei region

1. Introduction

The water resources of China are poorly distributed in space and time. The fast pace of China’s urbanization and economic growth has led to a conflict between water supply and demand, which has increased public awareness. Meanwhile, the options for water conservation and water savings have not been fully explored, aggravating the conflict. In light of the severe water shortage situation, President Xi proposed the policy of “conservation first, spatial balance, systematic management, government-market twod-handed approach”, which addresses the role of the market in resource allocation. Adopting economic means to optimize water resources allocation has become a developing trend in water resources management [1]. Establishing water right systems and implementing water...
Many previous studies have researched water rights transactions. In the 1980s, the water market that developed in Australia, America, and Chile was recognized as a representative water right system [2]. In the 1990s, Rosegrant [3] proposed that the tradable water rights market has significant potential in developing countries. Bauer [4] analyzed water market practices in Chile. Studies on the water rights system in China started in the 2000s, and since then, the institutions, benefits, and costs of the water rights market have been widely discussed [5].

Current theories and techniques on water rights involve property rights theory, water rights definition and allocation, transaction models and pricing, and water rights transaction simulations and evaluation [6,7]. For example, Peterson et al. [8] adopted the TERM water model to examine the likely economic impacts of expanding water trade in the southern Murray–Darling Basin in Australia. The results indicate that water trading systems reduce the impact of water shortages on gross domestic product (GDP). Long et al. [9] applied the game theory to evaluate the efficiency and benefits of water rights transactions for Zhangye city in the Heihe River basin. The results showed that water rights transactions can optimize the allocation of limited water resources, achieving a maximum economic benefit of 133.85 million CNY/year in a complete market. Yue et al. [10] developed a water rights transaction model, using interval parameter programming to analyze benefit expectations and the water-use efficiency of different scenarios. Zhao et al. [11] proposed a two-level water rights transaction model that optimized the social and economic efficiency of the river basin. The results indicated that the total GDP of the Shayin River Basin increased by 2.6%, without adding water consumption, after two levels of transactions. Wu [12] established a water rights transaction model of an irrigation area; the model combined a supply-demand relationship and Nash equilibrium price and water quantities to determine the transaction volume and transaction income. Mai et al. [13] developed a conceptual model for a generalized water trade system for Australia’s Murray–Darling Basin. The model then visualized the basin’s water trade systems as a whole, and identified the feedback mechanisms likely to influence trade development and endurance. Zhang et al. [14] developed a multi-objective optimization model for water rights trading, based on the “single-double water source mutual feedback mechanism.” This approach applied the economic benefit and the ecological benefit as the objective function. The results showed that water rights trading can achieve considerable economic and ecological benefits, with economic benefits increasing by 5.77%.

Current studies on water rights transactions are mainly intra-regional and intra-industry. Few studies have analyzed inter-regional or inter-industry transactions. Many studies have adopted multi-objective optimization methodologies, which generally do not include an economic mechanism or systems-level approach, making it difficult to reflect the impact of a whole economic system [12]. In terms of evaluation metrics, the impacts of water rights transactions are mostly measured by economic output, and few studies have applied an index system to quantitatively evaluate economic systems and water resources.

The computable general equilibrium (CGE) model has a distinct advantage when quantifying the economic impacts of water rights transactions. The model reflects the “input-output” relationship between economic sectors and changes in the commodity market, factor market, and economic structure under the condition of equilibrium. Introducing the water resources sector into the CGE model enables the exploration of interactions between water resources and the social economy. Coupling a CGE model and the water stress index is a viable way to quantify the detailed water resources and economic impact of water rights transactions.

This study coupled a multi-regional CGE model with the water stress index to evaluate different water rights transaction scenarios and support decision-making regarding the management of water resources. The study included: (1) constructing a multi-regional CGE model for the BTH region, with an extended water resources module; (2) proposing feasible water
rights transaction scenarios, based on water-savings level and water transaction volumes, and simulating the economic and water resources impact; and (3) adopting the water stress index to assess the impact of the transaction, generating a recommended scenario. This study provides a quantitative analysis tool for evaluating the impact of water rights transactions and optimizing water resource allocations in the BTH region. It also provides a reference for simulating and evaluating water rights transactions in other regions.

2. Materials and Methods

2.1. Study Area

The Beijing-Tianjin-Hebei (BTH) region is located in the north coastal area of China, and includes Beijing, Tianjin Municipalities, and Hebei Province. The location of the BTH region is shown in Figure 1. The BTH region forms China’s third largest economy after the Yangtze River delta region and the Pearl River delta region [15]. The gross domestic product of the BTH region reached CNY 8458 billion (USD 1227 billion due to the exchange rate of 2019, similarly hereinafter) in 2019 with a population of 110 million and 218,000 km² in land area. The BTH region is located in the Haihe River basin, which is characterized by a warm temperate continental monsoon climate. The BTH region is a typical resource-based area, with water shortages. The total water resources of the region have been reduced from 28 to 29 billion m³ in the late 1950s to about 15 billion m³ in 2019 [16], and the level of per capita water resources is far below the international warning line [16]. The BTH region has a high intensity level with respect to human activities; this disturbs the water cycle, places great stress on water resources, increases the degree of risk, and makes it difficult to ensure water safety [17].

To alleviate water shortages in the region, the South-to-North Water Diversion Project (SNWDP) was built to provide an important water source in Beijing, Tianjin, and Hebei.
China proposed the Beijing-Tianjin-Hebei Cooperative Development Strategy as a major national strategy to advance the coordination of the population, economy, resources, and environment of the region. An important part of this strategy is optimizing the inter-regional allocation of limited water resources, especially the allocation of SNWDP water through water rights transactions. This highlights the urgent need for simulation and evaluation methods to assess the impacts of possible water rights transaction schemes.

2.2. Model Framework

This study establishes a CGE model with an extended water resources module of the BTH region. The schematic of the model structure is shown in Figure 2, the original CGE model modules are shown in black boxes, and the extended water resources module is shown in dashed boxes.

![Figure 2. Schematic of model structure.](image)

2.2.1. CGE Model

The computable general equilibrium (CGE) model originated from Walras’ general equilibrium theory, which covers a large set of simultaneous equations of different economic activities in the economic system, including production, demand, consumption, and income [18]. The CGE model accurately describes linkages in economic systems, making it a powerful policy analysis tool.

The CGE model includes a production module, investment module, household consumption module, export module, price module, supply and demand balance module, and other modules [19]. The production module reflects the input and output processes of the industrial sector. It solves for commodity (such as water) and factor inputs under the principle of optimal decision-making (cost minimization), based on a given industry’s output level. The trade module reflects the process of regional distributions of a commodity output. The household consumption module solves for the demand for goods under utility maximization conditions subject to budget constraints. The module is based on a linear expenditure system, where the expenditure on each good is a linear function of the price of
the good and the income level. The investment module reflects the process of producing new fixed capital. The relationship between new fixed capital and commodity inputs is depicted using the Leontief function. In the export module, the export demand for domestic produced goods is inversely proportional to foreign currency prices. The price module reflects the linkage between base prices and consumer prices. The supply and demand balance module adopts the market clearing equation.

The enormous regional model (TERM) is a framework for CGE modeling of multiple regions within a single country [19]. TERM includes not only the full theory of the CGE model, but also small-region representation and inter-regional trade matrices [19]. This study adopts TERM to establish the CGE model.

2.2.2. Water Resources Module

Based on the CGE model, this study extended a water resources module to explore the interactions between water resources and the social economy. Several methods can be adopted to integrate water resources into the CGE model: placing water resources as constraints, production factors, and intermediate inputs. The constraints method is relatively simple but does not introduce a price mechanism. The production factors method and intermediate input method introduce the price mechanism, but makes the production function and model structure more complex [20]. To simulate water rights transactions, the intermediate input method effectively reflects the relationship of the water supply industry and water commodities in the economy. This method was also adopted by Muhammad et al. [21] to establish the TERM Water model and to analyze the economic impact of increased water demand in Australia. The limitation of this method is that the CGE model assumes a perfect water market, where different types of water flow freely between different sectors, and water is fully utilized without waste [22].

The study adopted the intermediate input method to integrate different water resources into the CGE model. The research also further refines the “water” commodity into “local conventional water”, “local non-conventional water”, and “SNWDP water”, as shown in Figure 2. Substitution relationships among these three types of water were also considered.

In the water resources module extended by this study, sector output is a CRESH production function, with different intermediate inputs, water commodities, and primary factors. To reflect the substitution relationships between the different types of water sources, we set a hierarchical structure (from bottom-to-top) [22]: “local water” is a CES production function of “local conventional water” and “local non-conventional water”, while “composite water” is a CES production function of “local water” and “SNWDP water.”

The demand for “local water” is represented as a CES equation as follows:

$$X_{locwt,i,d}^{(1)} = \frac{X_{locwt,s,i,d}^{(1)}}{A_{locwt,s,i,d}} f_{locwt,i}^{(1)} b_{locwt,s,i,d}^{(1)} \left( i = 1, \ldots, n; s = 1, 2; d = B, T, H \right)$$ (1)

Equation (1) shows that intermediate input of local water $X_{locwt,i,d}^{(1)}$ used in sector $i$ region $d$ is the CES composite of local conventional and non-conventional water. The variable $X_{locwt,s,i,d}^{(1)}$ represents the different sources of local water used in sector $i$ region $d$. The variable $s$ represents the source ($s = 1$ is conventional water; $s = 2$ is non-conventional water). The variable $A_{locwt,s,i,d}^{(1)}$ represents the technological parameters; $b_{locwt,s,i,d}^{(1)}$ represents the shares of different local water sources in sector $i$ region $d$; and $f_{locwt,i}^{(1)}$ represents the constant elasticity of substitution between conventional and non-conventional water.

As the water division infrastructure develops and as there is ongoing demand for SNWDP water, local water may be replaced. The demand for composite water, consisting of local water and SNWDP water, is represented as the following CES equation.

$$X_{water,i,d}^{(1)} = \frac{X_{water,s,i,d}^{(1)}}{A_{water,s,i,d}} f_{water,i}^{(1)} b_{water,s,i,d}^{(1)} \left( i = 1, \ldots, n; s = 1, 2; d = B, T, H \right)$$ (2)
Similar to Equation (1), Equation (2) shows that intermediate input water $X^{(1)}_{\text{water},i,d}$ used in sector $i$ region $d$ is the CES composite of local water and SNWDP water. The variable $X^{(1)}_{\text{(water,s),i,d}}$ represents the different sources of water used in sector $i$ region $d$; and $s$ represents the source ($s = 1$ is local water; $s = 2$ is SNWDP water). The variable $A^{(1)}_{\text{(water,s),i,d}}$ represents the technological parameters; $b^{(1)}_{\text{(water,s),i,d}}$ represents the shares of different water sources in sector $i$ region $d$; and $\rho^{(1)}_{\text{water,i}}$ is the constant elasticity of substitution between local water and SNWDP water.

2.2.3. Water Stress Index

The water stress index (WSI) measures the scarcity of water resources [23] and provides a rough indication of the water security degree in a country or region. Based on the past literature [23] and CGE model, this study adopted the water quantity stress index ($P_q$), water economic stress index ($P_e$), and water ecological stress index ($P_c$) to construct a water stress index system for the BTH region. The impacts of water rights transactions are evaluated using the index.

The water quantity stress index ($P_q$) reflects the available water resources to meet the water demands of the region’s population; the amount of available water resources per capita serves as the indicator. The water economic stress index ($P_e$) reflects the ability of water resources to support the regional economic development. A higher index is associated with more available water resources to support social development. The amount of water used per GDP of CNY 10,000 was chosen as indicator. The water ecological stress index ($P_c$) represents the ability of water resources to support the regional ecological environment. A higher degree of water resources development and utilization is associated with greater amounts of crowding with respect to the ecological use of water by humans, which also generates higher levels of ecological stress. The ratio of local water usage to local water resources available was chosen as an indicator. The corresponding calculation formulas are as follows.

$$ P_q = \frac{W_F}{NPOP} $$

$$ P_e = \frac{W_F}{V_{GDP}} $$

$$ P_c = \frac{W_L}{W_D} $$

In Equations (3)–(5), $P_q$ is the water quantity stress index; $W_F$ is the regional water availability; $NPOP$ is the regional population; $P_e$ is the water economic stress index; $V_{GDP}$ is the regional GDP; $P_c$ is the water ecological stress index, and $W_L$ is the amount of water supplied by local water sources to support the region’s total social production water usage; and $W_D$ is the regional local water availability.

Using WSI calculations from the literature [24], the standardized equations and weights of the index are as follows.

$$ WSI = W_q * P_q + W_e * P_e + W_c * P_c $$

$$ Y'_i = \frac{Y_i - Y_{\min}}{Y_{\max} - Y_{\min}} \quad (i = q, e) $$

$$ Y'_c = \frac{Y_i - Y_{\min}}{Y_{\max} - Y_{\min}} \quad (i = c) $$

$$ \sigma(Y'_i) = \sqrt{\frac{1}{n-1} \sum (Y'_i - Y'_\bar{i})^2} \quad (i = q, e, c) $$

$$ W_i = \frac{\sigma(Y'_i)}{\sigma(Y'_q) + \sigma(Y'_e) + \sigma(Y'_c)} \quad (i = q, e, c) $$
In Equations (6)–(10), WSI represents the water stress index; \( W_q, W_e \) and \( W_c \) represent the corresponding weights of water quantity stress index, water economic stress index, and water ecological stress index, respectively; \( W_q + W_e + W_c = 1 \). The variables \( Y_i \) and \( Y'_i \) represent the original and standardized values of each water stress index, respectively; and \( Y_{min} \) and \( Y_{max} \) represent the minimum and maximum values of each index, respectively. Equation (7) calculates the water resources quantity stress index and water resources economic stress index. Equation (8) calculates the water resources ecological stress index. The variable \( \sigma(Y'_i) \) is the mean squared deviation of \( Y'_i \); \( \overline{Y'_i} \) is the expectation of \( Y'_i \); and \( n \) is the number of each WSI value.

Previous literature [24] indicates that a WSI ranging from 0.0 to 0.1 represents low stress; in this case, water resources and economic and environmental development are reasonably balanced. A WSI ranging from 0.1 to 0.2 represents medium stress; in this case, water resources, economic and environmental development remain within the threshold of the water resources carrying capacity, and are acceptable in the short term. A WSI index ranging from 0.2 to 1.0 represents high stress; in this case, water resources and the economy and environment are mismatched, and the water crisis is serious.

2.3. Database

Water usage and economic data from Beijing, Tianjin, Hebei and other regions of China are used to construct the model database. Model parameters are assigned based on a survey and analysis.

For water usage data, the study collected the 2019 water resources bulletin of China, Beijing, Tianjin, and Hebei published by the department of water resources, which contains detailed water usage information. The water supply data of SNWDP was collected from China Water Rights Exchange Co., Ltd. (Beijing, China). The water utilization structure classified by water source and sector was derived. For water sources, the water usage data were divided into “local conventional water,” “local non-conventional water,” and “SNWDP water.” The data for “local conventional water” were derived from the combination of “surface water” and “groundwater” in the water resources bulletin. The data for “local unconventional water” were derived from the combination of “recycled water,” “desalinated water,” and other items. The data for “SNWDP water” were derived from statistical data. Water usage data were divided into “Beijing”, “Tianjin”, “Hebei” and “other regions”. The data on industry level classifications were based on reference literature and general research.

For economic data, the study collected the 42-sector input-output tables of China, Beijing, Tianjin, and Hebei for 2017 from the department of national accounts, and the 2020 Statistical Yearbook published by the bureau of statistics. Input-output tables were updated using the bi-proportional scaling method, based on data from the 2020 Statistical Yearbook. The 42 sectors were merged into 13 sectors based on sector attributes, as shown in Table 1. The sectors include agriculture, general light industry, general heavy industry, water intensive light industry, water intensive heavy industry, conventional water supply industry, non-conventional water supply industry, SNWDP water supply industry, construction, trade, transport, general services, and water intensive services.

Model parameters were assigned based on literature and references, as follows. The labor elasticity of the demand coefficient (SLAB) is 0.243, using an estimate from the Chinese Academy of Social Sciences [25]. The consumer price elasticity is 4, using data from the PRCGEM model [26]. The industry Armington elasticity, factor substitution elasticity, and household consumption elasticity are adopted from ORANIG model results and are treated as a weighted average. Based on the literature [27,28], the Frisch parameters were assigned values of \(-2.0\) to \(-0.7\), according to the per capita income level of Beijing, Tianjin, Hebei, and other regions. Other model parameters were adopted from the ORANIG model database.
### Table 1. Model sectors merged from 42 sectors national economy industry classification.

| Sector Classification | 13 Sectors | 42 Sectors Based on the National Economy Industry Classification |
|-----------------------|------------|---------------------------------------------------------------|
| **Primary Sector**    | Agriculture | Agriculture, Forestry, Animal Husbandry, and Fishery          |
| General light industry | Comprehensive use of waste resources; manufacture of communication equipment, computers, and other electronic equipment; manufacture of electrical machinery and equipment; manufacture of leather, fur, feather, and related products; manufacture of measuring instruments; manufacture of metal products; other manufacturing; processing of timber and furniture; repair of metal products, machinery, and equipment |
| General heavy industry | Extraction of petroleum and natural gas; manufacture of general purpose machinery; manufacture of special purpose machinery; manufacture of transport equipment; mining and washing of coal; production and distribution of gas |
| Water intensive light industry | Food and tobacco processing; manufacture of paper, printing and articles for culture, education and sport activity; textile industry |
| Water intensive heavy industry | Manufacture of non-metallic mineral products; manufacture of chemical products; mining and processing of metal ores; mining and processing of nonmetal and other ores; processing of petroleum, coking, processing of nuclear fuel; production and distribution of electric power and heat power; smelting and processing of metals |
| Conventional water supply industry | Production and distribution of tap water |
| Non-conventional water supply industry | Production and distribution of tap water |
| SNWDP water supply industry | Production and distribution of tap water |
| **Tertiary Sector**   | Construction | Construction |
| Trade                 | Wholesale and retail trades |
| Transport             | Transport, storage, and postal services |
| General services      | Administration of water, environment, and public facilities; finance; information transfer, software and information technology services; leasing and commercial services; real estate; scientific research and polytechnic services |
| Water intensive services | Accommodation and catering; culture, sports, and entertainment; education; health care and social work; public administration, social insurance, and social organizations; resident, repair and other services |

#### 2.4. Water Rights Transaction Scenarios

Ni et al. [29] discussed the definition of tradable water rights and concluded that tradable water rights usually include water saved through technology and management; unused water due to mismatched water infrastructure; and water from usage conversion due to land use changes (e.g., abandonment due to urbanization). The water usage efficiency is relatively low in Hebei, which means there is a large potential for water saving. Meanwhile, Hebei has not fully used its SNWDP water rights [30]. This highlights the feasibility of water rights transactions from Hebei to Beijing and Tianjin through SNWDP.

Based on historical economic and water usage data of the BTH region, Zhang [30] analyzed the tendency between the socio-economic index, and proposed using the water quota and water demand under different water-saving intensities of the region in 2025. General water-saving intensity means a business-as-usual intensity of water savings; extreme
water-saving intensity means water-saving investments are 1% of the total investment of the entire society; and ultra water-saving intensity means water-saving investments are 2% of the total investment of the entire society [31,32]. The maximum water transaction volume is determined by the water right surplus of Hebei and the water demand deficit of Beijing and Tianjin.

This study adopted the results of Zhang [31] and combined different water-saving intensities with water transaction volumes to form different scenarios. The non-transaction scenarios are the baseline scenarios, and the transaction scenarios are the policy scenarios, as shown in Table 2. The scenario numbers T1, T2 and T3 indicate the water-saving intensities as general, extreme, and ultra water saving, respectively. Scenario numbers P0 to P3 indicate the water transaction volumes.

Table 2. Water rights transaction scenarios.

| Scenario       | Scenario No. | Water-Saving Intensity | Water Transaction Volume (hm$^3$) | Beijing (hm$^3$) | Tianjin (hm$^3$) | Hebei (hm$^3$) |
|----------------|--------------|------------------------|-----------------------------------|------------------|------------------|----------------|
| Baseline Scenario |              |                        |                                   |                  |                  |                |
| T1P0           | General Water Saving | 0                      | 0                                | 0                | 0                | 0              |
| T2P0           | Extreme Water Saving    | 0                      | 0                                | 0                | 0                | 0              |
| T3P0           | Ultra Water Saving       | 0                      | 0                                | 0                | 0                | 0              |
| Policy Scenario |              |                        |                                   |                  |                  |                |
| T1P1           | General Water Saving     | 100                    | 71                               | 29               | −100             |                |
| T1P2           | General Water Saving     | 200                    | 141                              | 59               | −200             |                |
| T1P3           | General Water Saving     | 300                    | 212                              | 88               | −300             |                |
| T2P1           | Extreme Water Saving     | 100                    | 71                               | 29               | −100             |                |
| T2P2           | Extreme Water Saving     | 200                    | 141                              | 59               | −200             |                |
| T3P1           | Ultra Water Saving       | 100                    | 71                               | 29               | −100             |                |

3. Results and Discussion

The WSI is used to simulate and evaluate scenarios with different water-saving intensities and water transaction volumes. Table 3 shows the water usage and GDP in different scenarios.

Table 3. Water usage and GDP in different scenarios.

| Scenario No. | T1P0  | T2P0  | T3P0  | T1P1  | T1P2  | T1P3  | T2P1  | T2P2  | T3P1  |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Total Water Usage (hm$^3$) |       |       |       |       |       |       |       |       |       |
| Beijing      | 1354  | 1317  | 1289  | 1407  | 1461  | 1517  | 1372  | 1427  | 1344  |
| Tianjin      | 1732  | 1671  | 1623  | 1752  | 1774  | 1797  | 1692  | 1714  | 1645  |
| Hebei        | 13,010 | 12,548 | 12,190 | 12,921 | 12,832 | 12,743 | 12,457 | 12,366 | 12,097 |
| BTH          | 16,096 | 15,536 | 15,102 | 16,080 | 16,057 | 15,520 | 15,057 | 15,086 |        |
| Local Water Usage (hm$^3$) |       |       |       |       |       |       |       |       |       |
| Beijing      | 937   | 900   | 872   | 919   | 903   | 889   | 884   | 870   | 857   |
| Tianjin      | 1559  | 1498  | 1451  | 1550  | 1542  | 1535  | 1489  | 1482  | 1442  |
| Hebei        | 11,761 | 11,299 | 10,940 | 11,772 | 11,783 | 11,794 | 11,308 | 11,316 | 10,948 |
| BTH          | 14,257 | 13,697 | 13,263 | 14,241 | 14,228 | 14,218 | 13,681 | 13,668 | 13,247 |
| GDP (CNY Trillion) |       |       |       |       |       |       |       |       |       |
| Beijing      | 4.457 | 4.447 | 4.416 | 4.850 | 5.267 | 5.673 | 4.858 | 5.290 | 4.840 |
| Tianjin      | 1.922 | 1.917 | 1.904 | 2.214 | 2.455 | 2.664 | 2.217 | 2.463 | 2.209 |
| Hebei        | 4.466 | 4.455 | 4.424 | 4.429 | 4.410 | 4.390 | 4.415 | 4.395 | 4.383 |
| BTH          | 10.844 | 10.819 | 10.744 | 11.493 | 12.133 | 12.727 | 11.490 | 12.148 | 11.431 |
3.1. Water Usage

Figure 3 shows the total water usage in different scenarios. The ranking of regional total water usage in ascending order is T1P0, T1P1, T1P2, T1P3, T2P0, T2P1, T2P2, T3P0, and T3P1. The results indicate that water rights transactions decrease the total water usage of the BTH region.

Figure 3. Total water usage in different scenarios.

Figure 4 shows the changes in total water usage in T1P1 relative to T1P0.

At the regional level, the total water usage increases in Beijing and Tianjin, and decreases in Hebei after the transactions. For example, compared with the T1P0 scenario, the total water usage amounts in the T1P1 scenario increases in Beijing and Tianjin, by 53 $\text{hm}^3$ and 20 $\text{hm}^3$, and decreases in Hebei, by 89 $\text{hm}^3$, accounting for 3.90%, 1.15% and (−)0.68% of their original total water usage amounts respectively.

At the sector level, the increased water usage is mainly by the tertiary sector of Beijing and Tianjin, where the water rights are granted, followed by their secondary and primary sectors. Because of the forward linkages experienced by the tertiary sector, water usage in both the secondary and primary sectors simultaneously increase. The decreased water usage is mainly in the primary sector, followed by the secondary and tertiary sectors. This is because Hebei has the largest surplus of water rights in the primary sector, which is the main component of the transaction volume. The implementation of water rights transactions leads to a shift in the water utilization structure in Beijing, Tianjin, and Hebei; the water utilization structure moves from the less efficient primary sector to the secondary and tertiary sectors.
At the water source level, the regional local water usage decreases after the transactions. The ranking of regional local water usage in ascending order is T1P0, T1P1, T1P2, T1P3, T2P0, T2P1, T2P2, T3P0, and T3P1. For example, compared with the T1P0 scenario, the local water usage in the T1P1 scenario decreases in Beijing and Tianjin, by 18 hm$^3$ and 9 hm$^3$, accounting for $(−)1.88\%$ and $(−)0.61\%$ of their original local water usage amounts, respectively. This is because local water sources are replaced by SNWDP water. In addition, local water usage in the primary and secondary sectors increases slightly. Beijing’s water utilization structure is most affected by the transactions; this is because Beijing has a relatively small water usage in the tertiary sectors and obtains more water rights from SNWDP. The local water usage in the T1P1 scenario increases in Hebei, by 11 hm$^3$, accounting for 0.10% of the original local water usage amounts respectively. The primary sector is affected most significantly, followed by the secondary sectors and then the tertiary sectors. This is because the primary sector’s water rights are the main component of the transaction volume. Water rights transactions place some stress on Hebei’s local water sources; however, the proportion of the transaction water volume to the total water usage of Hebei Province is relatively small.

In general, water rights transactions decrease total water usage and optimize the regional water allocation pattern and utilization structure. At the cost of increased local water usage in Hebei, the local water usage is relieved in Beijing and Tianjin, where water resources are under stress. This results in a more balanced water usage pattern across the full BTH region. The negative impact of the transactions is limited, because of the large total water usage by Hebei Province.

### 3.2. Sector Output

Figure 5 shows the sector output in different scenarios. The ranking of regional GDP in ascending order is T1P3, T2P2, T1P2, T1P1, T2P1, T3P1, T1P0, T2P0, and T3P0. Results indicate that water rights transactions increase the overall GDP of the BTH region.
Figure 5. Sector output in different scenarios.

At the regional level, the GDP increases in Beijing and Tianjin after the transactions. For example, compared with the T1P0 scenario, the GDP in the T1P1 scenario increases in Beijing and Tianjin, by CNY 0.393 trillion and CNY 0.292 trillion, and decreases in Hebei by CNY 0.037 trillion, accounting for 8.83%, 15.19% and (−)0.83% of their original GDP, respectively. This is mainly because of the higher water use efficiencies in Beijing and Tianjin, which can support a larger economic scale per unit of water resources. The water efficiency in Hebei is relatively low. Compared with the primary sector, water resources allocated in the secondary and tertiary sectors have a stronger driving effect on the economy.

At the sector level, water rights transactions lead to a direct increase in GDP for Beijing and Tianjin, mainly in the tertiary sectors, where water rights are granted. The increase is lower in the secondary sectors, and is smallest in the primary sector. This is because the development of the tertiary sectors indirectly advances the development of secondary and primary sectors. In Hebei Province, water rights transactions negatively impact the tertiary, secondary, and primary sectors. The primary sector in Hebei Province cedes the most water, but the decline in sector output is not significant. This is because of the low share of the primary sector in industrial structure; with a relatively low output per unit of water.

In general, water rights transactions promote the regional economy and improve the regional industrial structure. The tertiary sectors’ output in Beijing and Tianjin increases significantly, while all sectors’ output in Hebei Province somewhat decreases. Industrial structures are upgraded to higher water efficiencies. From a fairness perspective, the areas receiving water rights should compensate the economic losses of the area providing the rights.
3.3. Water Stress Index

Based on the model simulation results, the WSI of the current situation, the baseline scenarios, and the policy scenarios were calculated. The WSI values in different scenarios are shown in Table 4. The WSI values and its portion are shown in Figure 6.

Table 4. Water stress index in different scenarios.

| Scenario No. | Current | T1P0  | T2P0  | T3P0  | T1P1  | T1P2  | T1P3  | T2P1  | T2P2  | T3P1  |
|--------------|---------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|              | Water Quantity Stress Index Portion (Wq * Pq) |       |       |       |       |       |       |       |       |       |
| Beijing      | 0.272   | 0.342 | 0.342 | 0.342 | 0.319 | 0.295 | 0.272 | 0.319 | 0.295 | 0.319 |
| Tianjin      | 0.304   | 0.342 | 0.342 | 0.342 | 0.329 | 0.315 | 0.301 | 0.329 | 0.315 | 0.329 |
| Hebei        | 0.000   | 0.074 | 0.074 | 0.074 | 0.084 | 0.093 | 0.103 | 0.084 | 0.093 | 0.084 |
| BTH          | 0.094   | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 | 0.162 |
|              | Water Economic Stress Index Portion (We * Pe) |       |       |       |       |       |       |       |       |       |
| Beijing      | 0.281   | 0.310 | 0.310 | 0.309 | 0.315 | 0.319 | 0.322 | 0.315 | 0.319 | 0.314 |
| Tianjin      | 0.223   | 0.264 | 0.264 | 0.263 | 0.278 | 0.288 | 0.294 | 0.278 | 0.288 | 0.278 |
| Hebei        | 0.000   | 0.090 | 0.089 | 0.087 | 0.089 | 0.089 | 0.089 | 0.088 | 0.088 | 0.086 |
| BTH          | 0.151   | 0.211 | 0.211 | 0.209 | 0.221 | 0.229 | 0.236 | 0.221 | 0.229 | 0.220 |
|              | Water Ecological Stress Index Portion (Wc * Pc) |       |       |       |       |       |       |       |       |       |
| Beijing      | 0.026   | 0.027 | 0.015 | 0.005 | 0.021 | 0.016 | 0.011 | 0.009 | 0.004 | 0.000 |
| Tianjin      | 0.335   | 0.329 | 0.305 | 0.286 | 0.326 | 0.323 | 0.320 | 0.302 | 0.299 | 0.283 |
| Hebei        | 0.254   | 0.175 | 0.156 | 0.142 | 0.175 | 0.176 | 0.176 | 0.157 | 0.157 | 0.143 |
| BTH          | 0.239   | 0.173 | 0.155 | 0.141 | 0.173 | 0.172 | 0.172 | 0.155 | 0.154 | 0.140 |
|              | Water Stress Index |       |       |       |       |       |       |       |       |       |
| Beijing      | 0.579   | 0.679 | 0.667 | 0.657 | 0.655 | 0.630 | 0.605 | 0.643 | 0.619 | 0.633 |
| Tianjin      | 0.862   | 0.936 | 0.911 | 0.891 | 0.933 | 0.925 | 0.915 | 0.909 | 0.901 | 0.890 |
| Hebei        | 0.254   | 0.339 | 0.320 | 0.304 | 0.348 | 0.358 | 0.368 | 0.329 | 0.339 | 0.312 |
| BTH          | 0.484   | 0.547 | 0.528 | 0.513 | 0.556 | 0.564 | 0.570 | 0.537 | 0.546 | 0.522 |

The BTH region is currently in a high stress zone, with Tianjin having the highest water stress, followed by Beijing and Hebei. Tianjin has a high level of water quantity, economic, and ecological stress. Beijing has high levels of water quantity and economic stress. Hebei Province has a high level of water-ecological stress. The WSI values in Beijing, Tianjin and Hebei are all increasing over time. When comparing different baseline scenarios, a higher water-savings intensity is associated with a slower increase in WSI values.

Comparing the policy scenarios with the baseline scenarios, the WSI values decrease for Beijing and Tianjin, which have higher water stress levels. The WSI values increase slightly for Hebei under each policy scenario. The overall water stress of the BTH region increases slightly, but the distribution pattern among regions is more balanced. For Beijing, the scenario with the lowest water stress is T1P3, followed by T2P2, T1P2, and T3P1. For Tianjin, the scenario with the lowest water stress is T3P1, followed by T3P0 and T2P2. For Hebei, the scenario with the lowest water stress is T3P0, followed by T3P1 and T2P0.

When comparing T1P0–T3P0, as water-saving intensities increase, the water ecological stress levels decrease. When comparing T1P1–T1P3, as the water transaction volumes increase, the water quantity stress levels decrease. The water economic stress changes slightly under different scenarios. Overall, water savings have a stronger mitigating effect on water stress than water rights transactions. Therefore, water rights transactions should not be conducted until sufficient water-saving measures have already been implemented in the region.
Figure 6. Water stress index and its portion in different scenarios.

Figure 7 shows the water stress index in different regions. In general, compared with the non-transaction, general water-saving scenario, the T3P1 scenario is the most recommended, given the associated significant decrease in the WSI in Beijing and Tianjin, and smaller increase in WSI in Hebei. This scenario adopts the ultra water-saving intensity, and 100 hm$^3$ of water rights are transferred from Hebei: Beijing purchases 71 hm$^3$ and Tianjin purchases 29 hm$^3$.

Compared with the non-transaction scenario with ultra water savings, after adopting the transactions, the overall GDP of the BTH region increases by CNY 0.687 trillion (USD 99.6 billion). The local water usage of Beijing and Tianjin decreases by 23 hm$^3$; the local water usage of Hebei increases by 7 hm$^3$. The WSI values of Beijing and Tianjin decrease by 0.023 and 0.002, respectively; and the WSI in Hebei increases by 0.008.

Comparing the non-transaction scenario with general water-savings, after adopting the transactions, the overall GDP of the BTH region increases by CNY 0.587 trillion (USD 85.1 billion). The local water usage decreases for Beijing and Tianjin by 197 hm$^3$; the same usage decreases for Hebei by 813 hm$^3$. The WSI values in Beijing and Tianjin decrease by 0.046 and 0.046, respectively, and the WSI in Hebei decreases by 0.027.
Figure 7. Water stress index in different regions.

The results of this study are consistent with previous research. The impact on sector output is consistent with Lu’s study on inter-industry water rights transactions, indicating the economic feasibility of transferring water rights from primary sector to secondary and tertiary sectors [33]. The impact on the regional sector output and water usage is similar to Liu’s study on inter-regional industrial transfer [34]. Compared with previous research, this study refines the water resources mechanism of the model, providing a new method for simulating and evaluating inter-regional and inter-industry water rights transactions.

4. Conclusions

By simulating and evaluating inter-regional water rights transactions between Beijing, Tianjin, and Hebei, this study provides valuable insights for relieving water stress. Existing methods have difficulty systematically reflecting the relationship between water resources and economic systems, and do not effectively simulate the role of water rights transactions on the economic system and water resources to provide recommendations for decisionmakers. This study establishes a multi-regional CGE model with an extended water resources module, and explores the impact on the economy and water resources using the water stress index. The resulting model provides decision support for implementing China’s water management concept of “conservation first, spatial balance, systematic management, government-market two-handed approach.” The approach may also help realize the Beijing-Tianjin-Hebei Cooperative Development Strategy. Main conclusions are as follows:
The study integrates different water sources as intermediate inputs into a multi-regional CGE model. The model reflects the input-output relationships of water resources in an economic system, and the impacts of substitutions between water sources. This provides a more comprehensive and systematic simulation of the impact of water rights transactions compared with previous studies. The water stress index is established as a standard to reflect the degree of regional water resources security, enabling the comparison and evaluation of the impacts from water rights transactions;

(2) Water rights transactions in the BTH region positively impact the regional economy. The surplus water rights provided by the South-to-North Water Diversion Project in Hebei Province is transferred to the tertiary sectors of Beijing and Tianjin. This guides the industry’s transition to water-intensive development, directly contributing to Beijing and Tianjin’s economic development, but having a limited negative impact on Hebei’s economy;

(3) Water rights transactions in the BTH region help optimize regional water resources allocation and relieve regional water stress. Water rights transactions improve the overall water utilization efficiencies of Beijing, Tianjin, and Hebei. On the water supply side, multi-source interactions reduce the stress on local water supplies in Beijing and Tianjin, with limited impacts to water resources in Hebei Province. On the water demand side, water is used more efficiently, and the water utilization structure shifts from the less efficient primary sector to more efficient sectors;

(4) This study comprehensively evaluates the economic benefits and water stress relief effects, and provides a recommended scheme for water rights transactions. This includes adopting ultra water savings, and transferring 100 hm$^3$ of water rights from Hebei, with Beijing purchasing 71 hm$^3$ and Tianjin purchasing 29 hm$^3$. Compared with the general water-saving scenario without transactions, after adopting the transactions, the overall GDP of the BTH region increases by CNY 0.587 trillion. The local water usage of Beijing and Tianjin decreases by 197 hm$^3$, and the water usage from Hebei decreases by 813 hm$^3$. The water stress index in Beijing and Tianjin decreases by 0.046 and 0.046, respectively, and the value for Hebei decreases by 0.027.

This study has several limitations that can be addressed in future research. Due to a lack of data, the study is conducted at the provincial level, the accuracy of the results would be improved if municipalities of Hebei are refined as spatial units. The residential and ecological water usage were not considered in the model.

Despite these limitations, this study adds value to the broader field of water resources management by providing a new method for simulating and evaluating the impact of water resources transactions.

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