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Sensitive Factors Identification and Scenario Simulation of Water Demand in the Arid Agricultural Area Based on the Socio-Economic-Environment Nexus

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Abstract: Water scarcity has seriously threatened the sustainable development of Zhangjiakou City, an arid agricultural area in North China, and the ecological security of its neighboring areas. In this study, a system dynamics model is established based on variable sensitivity analysis and is employed to simulate water demand (2015–2035) in four designed alternative development scenarios in Zhangjiakou City. The results show that: (1) the variables related to irrigation farmland are the main driving factors of water demand, especially the area and water use quota. (2) The total water demand will rise continually in the current development scenario and economic priority scenario, and the proportion of agricultural water demand will drop to 67% and 63%, respectively. It will decline continually in the water-saving priority scenario and balanced development scenario, and the proportion of agricultural water demand will drop to 56% and 57%, respectively. (3) Water consumption per ten thousand yuan of GDP will fall to around 20 m³ in 2035 in each scenario, indicating that the reduction of water demand only by slowing down economic growth cannot improve the efficiency of water use. The research results will be beneficial to extract feasible strategies and policies for balancing economic development and water conservation.

Keywords: water demand; sensitivity analysis; system dynamics; scenarios simulation; Zhangjiakou city

1. Introduction

The relationships between human and natural systems are bi-directional [1]. The impact of human activities on natural systems is changing the way we view and manage the earth's resources [2,3]. With the challenges of population expansion, rapid urbanization, and climate change, water resources, as irreplaceable resources for human-nature systems, are becoming increasingly scarce [4]. This will not only significantly affect regional sustainable development but also poses a serious threat to the well-being of future generations [5–7]. The contradiction between water supply and water demand has become a global challenge facing human beings for a long time and will continue to be so in the future—especially in developing countries and regions with large population sizes and dry climates [8].

The research on water resources can be roughly summarized into two categories [9]: surface and ground hydrology, and sustainable utilization of water resources [10–12]. First, studies of surface water and groundwater are mostly related to climate change, overexploitation of groundwater, and the impact of water supply projects on the hydrological environment. Hagemann, et al. [13] studied the Colorado River basin using a model of multiple global climate-hydrological and found that climate change was not the only factor affecting the hydrological cycle. Hashemy Shahdany, et al. [14], taking the Zayandeh-Rud River basin in Iran as a case, discussed the effect of improving operational performance in irrigation canals to overcome groundwater overexploitation. Zhang [15] evaluated the environmental impacts of the South-to-North Water Diversion Project and concluded that it is necessary for the Chinese government to establish a long-term environmental monitoring network. Second, the evaluation methods of sustainable use of water resources mainly include water poverty index (WPI), water stress index (WSI), and water resources carrying capacity (WRCC). WPI, first used by Sullivan [16], is measured using five components “resources”, “access”, “capacity”, “use”, and “environment”. It has been widely used as a holistic tool to assess water resources available at different scales from countries [17–19] to districts and basins [20,21]. WSI can be used to assess the extent of water scarcity faced by the region’s society, economy, and environment systems. Utilizing this tool, Han and Ruan [22] selected nine indicators from these three systems and conducted a comparative analysis of the water resources pressure in 31 administrative regions of mainland China. WRCC refers to the maximum human activity level that available water resources can support without causing ecological and environmental degradation while maintaining an adequate standard of living [23]. A number of studies have been carried out in this aspect, especially in areas where there is a negative gap between water supply and water demand [24–26].

In recent years, the interaction of social, environmental, and water systems has become more intense and complex due to the explosive water demand [5,27–29]. In this context, to better understand the dynamic relationships of the coupled human-environmental system, the system dynamics (SD) model is becoming more and more popular in water resources planning and management as many other models based on linear causality cannot provide the mental and structural framework to solve complex problems in multiple systems [30–32]. SD was initially proposed by Forrester [33] for simulating industrial and urban dynamics. It not only enables users to understand the extent to which each variable affects the system and subsystem but also has the ability to capture the interaction of various model components [34]. According to Zomorodian, Lai, Homayounfar, Ibrahim, Fatemi, and El-Shafie [34], the application of SD in water resources mainly falls into two categories: predictive simulation models and descriptive integrated models. The former focuses on the water resources system itself but lacks mutual feedback from economic, ecological, and social subsystems [35–37]. The latter focuses on the impact of factors from various subsystems on the water supply and demand systems, such as climate change, urbanization, economic development, and population growth [13,38,39].

There has been a body of studies on the SD model in water resources simulation at various scales, from regional [6,40–44] to national and global [9,30,45]. However, most of the studies have not been closely integrated with the policies and plans of local governments, resulting in poor feasibility of the research results and weak guidance for local sustainable development practices. Therefore, Zhangjiakou, a city with extremely scarce water resources, was selected as the case area in this study to make up this gap.

Zhangjiakou City has less than 400 m³ of water per capita per year, which has not only severely constrained the economic development but also threatened regional ecological security, due to it is the geo-ecological barrier and water sources for the capital Beijing. In 2017, it was identified as “the water conservation function zone and ecological environment support zone of the capital city (two zones)” by the central government of China. In 2019, the Chinese government further formulated a medium-term plan for the development of Zhangjiakou City (2019–2035), referred to as the “Two Zones Planning”, which placed strict and specific restrictions on water consumption and water use efficiency in various sectors, including agriculture, industry, and households. Moreover, the 2022 Winter Olympic Games

will be jointly held in Beijing and Zhangjiakou, making the task of water-saving and water efficiency improvement more important and urgent for the local policymakers. Therefore, the research objectives of this study are as follows: (1) Identify and analyze the impact of different factors on the water demand of Zhangjiakou City. (2) Establish a system dynamics model to simulate the water demand of various departments in Zhangjiakou City from 2020 to 2035 under the four development scenarios. (3) Estimate the pressure on water resources under the four development scenarios. The research results are expected to provide specific and feasible guidance for the implementation of the “Two Zones Planning”, and to contribute to the sustainable use of water resources in Zhangjiakou City and its surrounding areas. In addition, the research also aims to increase researchers’ awareness of integrating with local development policies when simulating water demand, thereby enhancing the practicality of the research results.

2. Study Area and Data Sources

2.1. Study Area

Shown in Figure 1, Zhangjiakou is a prefecture-level city in northwestern Hebei province, China, with a population of 4.69 million on 36,862 km², divided into 16 counties (districts), and twelve of them are poverty-stricken areas, with a poverty population of 113,700, accounting for 28.5% of Hebei province. In 2015, the city’s gross domestic product (GDP) was 135.85 billion yuan, ranking the eighth of eleven cities in Hebei Province, and the per capita GDP was 23.6% lower than the provincial average level.

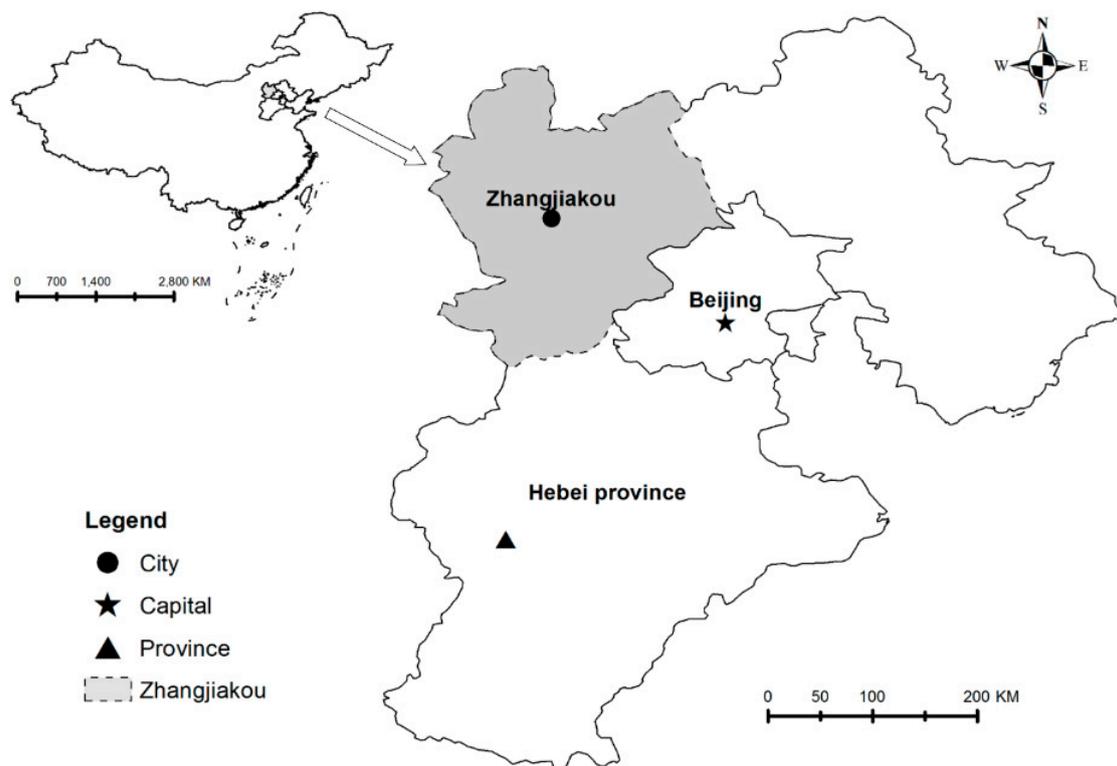


Figure 1. The location of Zhangjiakou City.

It is also an arid and semiarid region with an average annual precipitation of only 409 mm, while the annual average evaporation is as high as 1315 mm. The per capita water resources are about 350 m³, less than one-fifth of the national level, making it one of the most severe water scarcity cities in China, which is seriously threatening regional sustainable development. In addition, in terms of wind and water, Zhangjiakou City is located upstream of the capital Beijing. More than 50%

water of the Miyun Reservoir (the drinking water source) and more than 90% water of the Guanting Reservoir (former drinking water source) in Beijing come from the Chaobai River and Yongding River. The upstream of these two rivers is in Zhangjiakou City. That is, the area of about 25,000 km² located in Zhangjiakou and Beijing is considered a complete ecological unit, sharing groundwater, surface water, and atmospheric circulation, which cannot be divided by administrative divisions. Therefore, the ecological environment protection of Zhangjiakou City, especially water conservation, is also crucial to the sustainable development of Beijing.

In 2015, the city's total water consumption was 938 million m³, of which agricultural water was 703 million m³, accounting for 75%, which is 10% higher than the national average level. In the meantime, irrigation farmland increased by 50,167 ha from 2005 to 2015, with an increase of 28%, resulting in a rising demand for agricultural water, which is inconsistent with the urgent need for water-saving. The irrigation water use of different farmland in 2015 can be seen in Table 1. It is obvious that irrigated land used the most water, accounting for 53% of the total water consumption in Zhangjiakou City.

Table 1. Irrigation water use of Zhangjiakou City in 2015.

Farmland Type	Area (hm ²)	Water Use		Water Consumption per Unit Area (m ³ /hm ²)
		Water Use (10 ⁸ m ³)	Percentage of Total Water Use (%)	
Paddy field	2733	0.15	2%	5535
Irrigated land	178,467	4.98	53%	2790
Vegetable field	37,533	1.29	14%	3450

2.2. Data Sources

The basic socio-economic data mainly come from the Zhangjiakou Economic Yearbooks (2006–2016) [46], including urban and rural populations, output values of various sectors, and so on. Water resources, irrigation farmland, and livestock are collected from the Water Resources Bulletins (2005–2016) [47], including water supply, water consumption and water efficiency in various sectors, and the areas of different irrigation land. In addition, the data required for the simulation phase (2015–2035), except the initial values same as 2015, such as urbanization rates, economic development rates, and water quotas for various departments involved in the model, are set according to government reports, “Two Zones Planning” and local standards “Norm of water intake (2016)” of Hebei Province.

3. Methodology

3.1. System Dynamics Simulation

The SD model consists of four types of variables: state variables, rate variables, auxiliary variables and constants, and a series of equations reflecting the relationship between these variables. As shown in Figure 2, the simulation process can be summarized as five steps: (1) determine the research objective; (2) establish the model, determine the system boundary and the causal relationship between the variables; (3) model validation, qualitative and quantitative test; (4) scenario simulation, determine the control variables (sensitivity analysis) and set different development scenarios; (5) analysis of results.

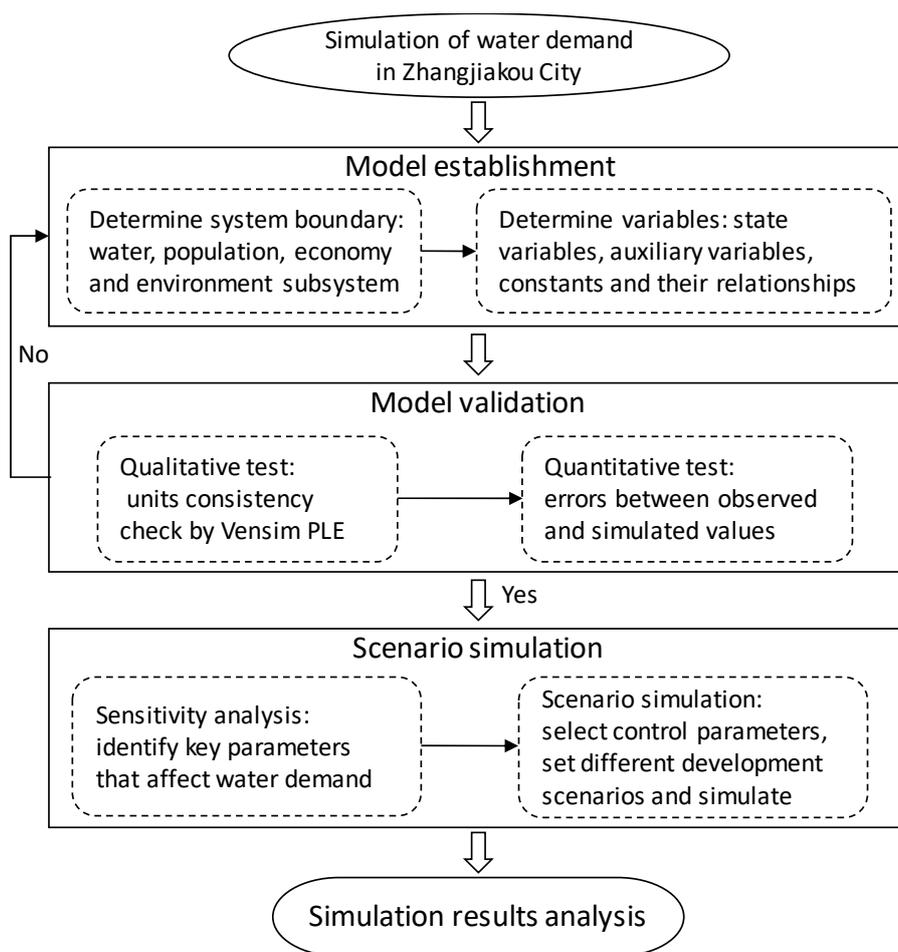


Figure 2. The modeling process of system dynamics.

3.2. Zhangjiakou System Dynamics Model

3.2.1. Water Use Structure

The water cycle usually consists of water supply, water use, as well as wastewater treatment and reuse. Figure 3 simply shows the causal relationship between them in Zhangjiakou City. Water resources include local water and inbound water, while the available water resources need to be reduced by outbound water and environmental flows. Environmental flow refers to the amount of water that is necessary to maintain the ecological and environmental services of rivers and lakes. In this study, it is estimated by introducing the environmental flow coefficient based on relevant statistical data from previous years, that is, what percentage of the total water needs to be reserved for the river’s own ecological environment. The environmental flow coefficient is set to 0.20 for the extremely wet year, 0.25 for the average climatic year, and 0.30 for the extremely wet year, as shown in Table S1. Water use mainly includes five sectors from the three subsystems of population, economy, and ecological environment, that is, domestic, agriculture, industry, urban public, and eco-environment. Finally, some of the wastewater from the population and economic subsystems can be reused after treatment. All of these components are dynamically interrelated with each other.

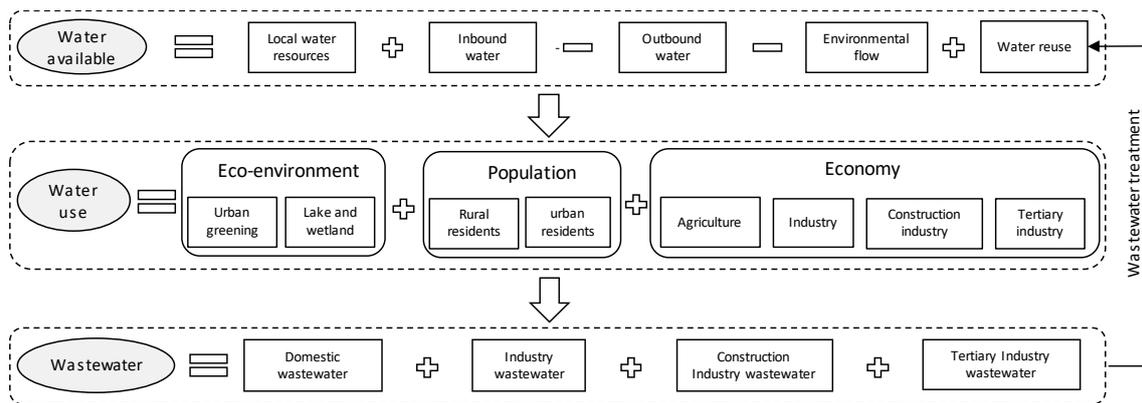


Figure 3. Relationships of water resource subsystem and other subsystems in Zhangjiakou City.

3.2.2. Establishment of Model

Based on the development status and “Two Zones Planning”, Vensim-PLE, a classical software of system dynamics, is used to establish the simulation model of water demand in Zhangjiakou City (abbreviated as ZSD), as shown in Figure 4. The simulation is from 2005 to 2035, and the modeling time step is 1 year, where the strategic planning time is from 2015–2035. It consists of four subsystems: population, economic, agriculture (irrigation land, forestry and animal husbandry) and water (water supply, water demand, and water pollution and reuse), including 8 status variables, 7 rate variables, 39 auxiliary variables, 8 table functions (lookup) and 30 constants, as well as 54 equations. The variables and their relationships can be found in Table S1.

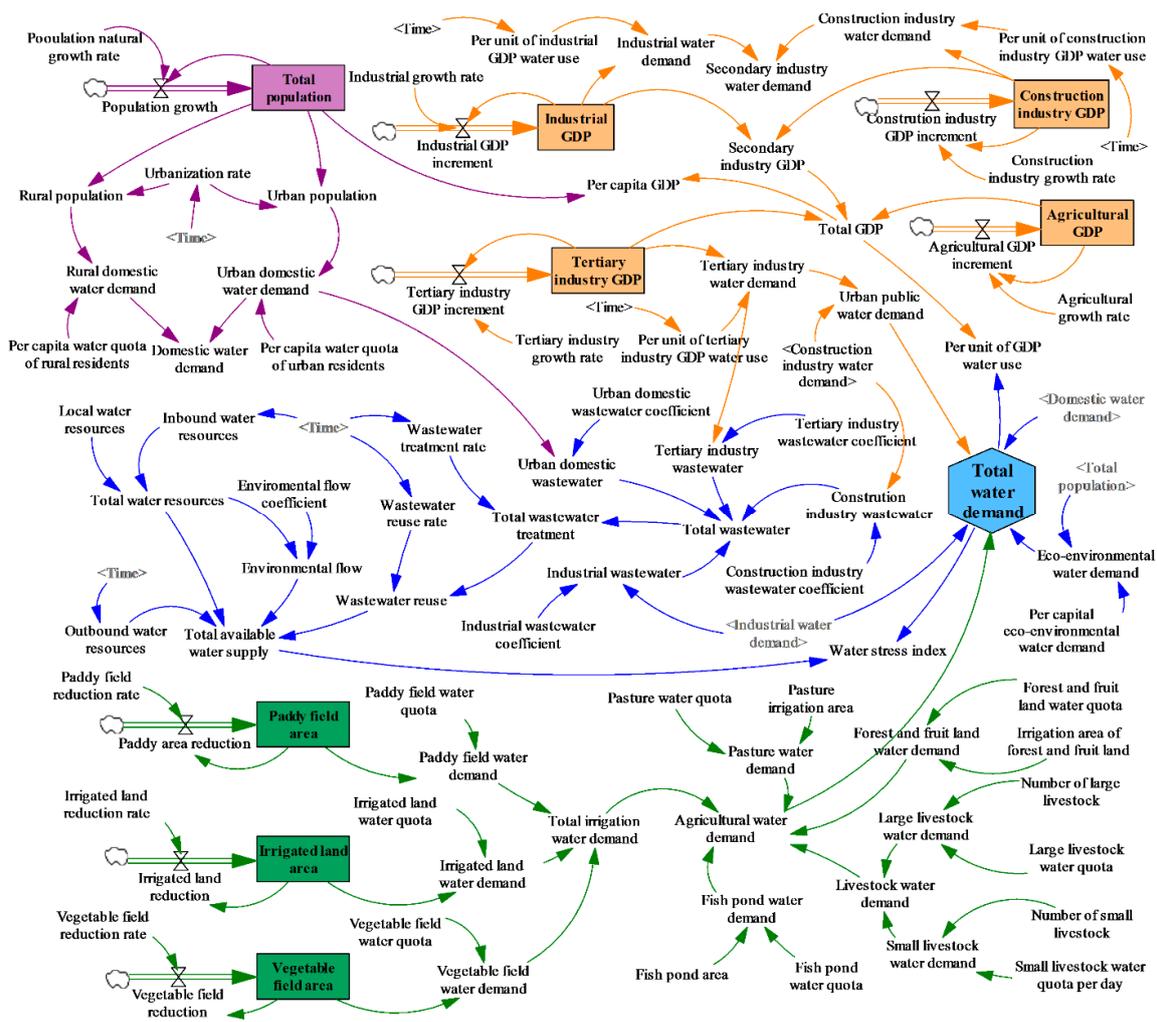


Figure 4. System dynamics model of Zhangjiakou City.

3.3. Model Evaluation and Sensitive Factors Identification

3.3.1. Model Evaluation

In this study, the absolute relative error (ARE) is employed for model performance validation.

$$ARE = \left| \frac{(S_i - R_i)}{R_i} \right| \tag{1}$$

where R_i and S_i represent the observed value and the simulated value of variable i , respectively.

3.3.2. Sensitive Factors Identification

In order to identify which variables (constants) in the ZSD model have greater impacts on the water demand, we use the “univariate” method in the sensitivity analysis function of Vensim DSS, that is, the value of each variable is changed independently, while the values of others are held constant. Sensitivity analysis not only helps us to select key variables for scenario setting scientifically but also to improve the understanding of the relationships between input and output variables in the SD model, which will contribute to the formulation of policies [43].

3.4. Water Stress Index (WSI)

There have been many methods for regional water stress assessment. The ratio of water demand to water availability can be a relatively straightforward reflection of whether the amount of water resources is surplus or deficit. Therefore, it is used in this study to measure the pressure of water resources in different development scenarios. The formula is:

$$WSI = \frac{TWD}{TAW} \quad (2)$$

where *TWD* and *TAW* represent the total water demand and the total available water, respectively. When *WSI* is greater than 1, it means water resources are in a state of deficiency; when *WSI* is less than 1, it means water resources are in the surplus state; when *WSI* is equal to 1, it means water resources supply and demand are just balanced.

4. Results

4.1. Model Validation

In order to conduct the model validation, the water demand from 2005–2015 is simulated, with 2005 as the base year. Table 2 shows the absolute relative errors (AREs) between the simulated and observed values for 2010 and 2015. The AREs of most variables are within 10%, indicating that the ZSD model has a good performance to reflect the behavior of the simulated system. Here, the ARE of industrial GDP is greater than 10% in 2015, which is because the industrial GDP used in the Zhangjiakou Economic Yearbook (2016) is very likely a mistake. According to the annual government report, the industrial growth rate in 2015 was 4.2%, however, the industrial GDP in the Zhangjiakou Economic Yearbook (2016) was 44.17 billion yuan, even lower than 47.56 billion yuan in 2014. If this is adjusted according to the industrial growth rate in the government report, the industrial GDP in 2015 should be 49.56 billion yuan.

Table 2. Absolute relative errors of the main variables between the simulated and observed values.

Variables	2010			2015		
	Simulated Value	Observed Value	ARE	Simulated Value	Observed Value	ARE
Total population (10 ⁴ persons)	462	466	0.9%	474	469	1.0%
Rural population (10 ⁴ persons)	309	314	1.4%	303	298	1.6%
Urban population (10 ⁴ persons)	152	152	0.2%	171	171	0.1%
Total GDP (10 ⁸ yuan)	961.3	966.4	0.5%	1495.3	1363.5	9.7%
Agricultural GDP (10 ⁸ yuan)	143.1	152.9	6.4%	250.2	243.7	2.7%
Secondary industry GDP (10 ⁸ yuan)	399.3	415.2	3.8%	655.2	545.6	20.1%
Industrial GDP (10 ⁸ Yuan)	338.9	352.5	3.9%	544.1	441.7	23.2%
Construction industry GDP (10 ⁸ yuan)	60.5	62.7	3.6%	111.1	104.9	5.9%
Tertiary industry GDP (10 ⁸ yuan)	418.8	398.3	5.1%	589.8	574.3	2.7%
Domestic water demand (10 ⁸ m ³)	0.8132	0.8144	0.2%	1.0435	1.0323	1.1%
Rural domestic water demand (10 ⁸ m ³)	0.4405	0.4426	0.5%	0.4647	0.4583	1.4%
Urban domestic water demand (10 ⁸ m ³)	0.3727	0.3718	0.2%	0.5788	0.5768	0.4%
Agriculture water demand (10 ⁸ m ³)	8.2422	8.2465	0.1%	7.0342	7.0282	0.1%
Industrial water demand (10 ⁸ m ³)	1.2031	1.2500	3.8%	1.0882	1.0074	8.0%
Construction water demand (10 ⁸ m ³)	0.0357	0.0372	4.1%	0.0255	0.0244	4.7%
Tertiary water demand (10 ⁸ m ³)	0.0712	0.0683	4.2%	0.1475	0.1455	1.3%
Environment water demand (10 ⁸ m ³)	0.0623	0.0628	0.7%	0.1483	0.1469	0.9%
Urban public water demand (10 ⁸ m ³)	0.1069	0.1056	1.2%	0.1730	0.1699	1.8%
Total water demand (10 ⁸ m ³)	10.4276	10.4794	0.5%	9.4872	9.3848	1.1%
Total wastewater discharge (10 ⁸ m ³)	0.8228	0.8420	2.3%	0.9862	0.9357	5.4%

4.2. Sensitivity Analysis

Based on the ZSD model and other studies on water demand simulation [9,48,49], twelve constant variables that may have the largest impacts on the total water demand are selected, as shown in Figure 5.

To identify the extent of the impacts, these 12 variables are further analyzed using the sensitivity analysis function in Vensim DSS. The initial value of each variable is the same as the observed value in 2015, and its value range is determined through historical data and relevant plannings (especially the “Two Zones planning”). The results are shown in Figure 5, where yellow, green, blue, and gray represent confidence intervals of 0–50%, 50–75%, 75–95%, and 95–100%, respectively. The greater the bandwidth in the graph, the more sensitive the total water demand is to the variables.

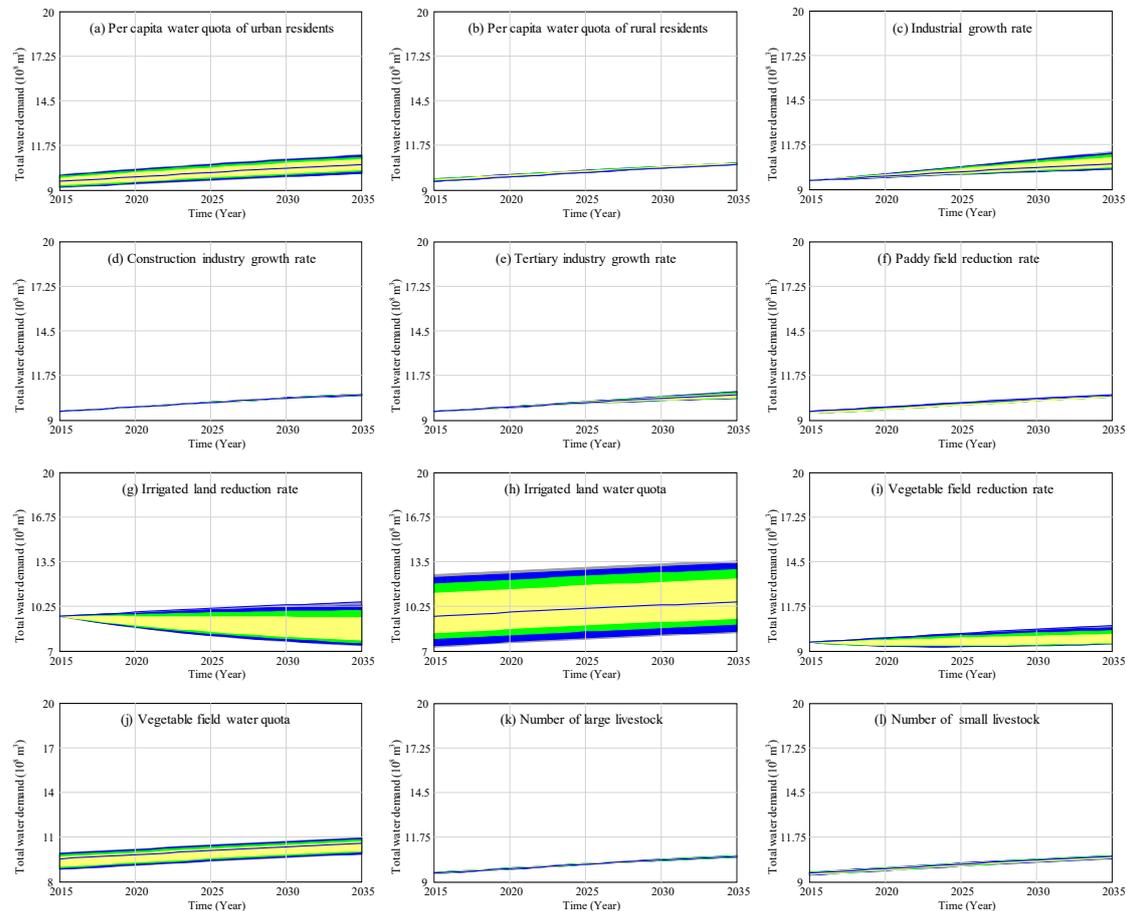


Figure 5. Sensitivity analysis for twelve constant variables.

It is obvious that these variables have very different impacts on total water demand, which can be divided into four categories:

(1) Per capita water quota. The urbanization rate of Zhangjiakou City was 52% in 2015, and the proportion of the urban population will further increase as the urbanization process continues. In addition, the per capita water quota for urban residents is 50–140 m³/day, while it is only 40–60 m³/day for rural residents. Therefore, the total water demand is more sensitive to the per capita water quota of urban residents than to that of rural residents.

(2) GDP growth rate. The sensitivities of total water demand to the growth rate of GDP of different sectors from large to small are industry, tertiary industry, and construction. There are two main reasons: First, the output values are significantly different, and the output value of the construction industry is much smaller than that of the industrial and tertiary industry. Second, the water consumption per unit of industrial output value is 12–23 m³ per 10,000 yuan, while it is less than 3 m³ per 10,000 yuan for the tertiary industry and construction industry.

(3) Irrigation area and water quota. Although the irrigated land and the vegetable field have the same ranges of water quota, both are 1500–4500 m³/ha, and the irrigated land area reduction rate range (−0.05, 0) is smaller than the vegetable field area reduction rate range (−0.1, 0), but the total water

demand is more sensitive to the area reduction rate and water quota of irrigated land than to those of the vegetable field. This is because the area of irrigated land is much larger than that of the vegetable field. In 2015, the area of irrigated land was 4.8 times that of vegetable fields.

(4) The number of livestock. The proportion of livestock water consumption is relatively small, which was only 3.4% in 2015, so the total water demand is less sensitive to the number of livestock, whether it is large livestock or small livestock.

In general, irrigated land has the greatest impact on total water demand due to the large amount of water use of irrigated land, which was 497 million m³ in 2015, accounting for 53%, resulting in the total demand for water resources being most sensitive to the two variables related to it.

4.3. Scenarios Simulation

4.3.1. Scenarios Setting

In line with the planning period of the two districts of Zhangjiakou City, the simulation time of water demand is 2015–2035, with 2015 as the base year. For most variables, the initial values are derived from the Economic Yearbooks and the Water Resources Bulletins, and for the rest of the variables, they are set based on historical data or reference to relevant government plans, as shown in Table S1.

Based on the sensitivity analysis, the 15 variables shown in Table 3 are selected as control variables to set four development scenarios: current development scenario (CDS), economic priority scenario (EPS), water-saving priority scenario (WPS), and balanced development scenarios (BDS). The main characteristics of each scenario are as follows: (1) In CDS, except for the urbanization rate and industrial GDP water quota, the other variables are consistent with 2015. (2) In EPS, the economic growth rates are higher than the CDS. Moreover, due to the current low per capita water use and inadequate irrigation of farmland, the per capita water quota and the water quota for all types of irrigated farmland are also set higher than the current situation. (3) In WPS, the economic growth rates and urbanization rates are lower than CDS, and the areas of the three types of irrigated farmland are rapidly reduced. (4) In BDS, the economic growth rates are between EPS and WPS, and the reduction rates of the three types of irrigated farmland are lower than WPS. The values of these 15 variables in each scenario are shown in Table 3.

Table 3. Values of control variables in four development scenarios.

Variables	Units	Time	CDS	EPS	WPS	BDS
Per capita water quota of urban residents	L/person/day	–	93	120	100	110
Per capita water quota of rural residents	L/person/day	–	42	60	50	60
Industrial growth rate	%	–	4.6	5.6	3.6	5.1
Construction industry growth rate	%	–	7.3	8.3	6.3	7.3
Tertiary industry growth rate	%	–	8.1	9.1	7.1	8.1
Agriculture growth rate	%	–	3.3	4.3	2.3	3.3
Paddy field reduction rate	%	–	0	0	–50	–25
Irrigated land reduction rate	%	–	0	0	–2	–1
Irrigated land water quota	m ³ /ha	–	2790	3240	2340	2565
Vegetable field reduction rate	%	–	0	0	–3	–1.5
Vegetable field water quota	m ³ /ha	–	3450	3900	3000	3150
Number of large livestock	Million	–	0.75	0.95	0.65	0.85
Number of small livestock	Million	–	11.59	13.59	10.59	12.59
Urbanization rate	%	2015	52	52	52	52
		2020	60	62	58	60
		2022	62	65	60	62
		2025	65	68	62	65
		2030	70	73	67	70
		2035	72	75	69	72
Per unit of industrial gross domestic product (GDP) water use	m ³ *10 ^{–4} yuan ^{–1}	2015	22.8	22.8	22.8	22.8
		2025	18	20	15	18
		2035	12	15	10	12

Note: CDS: current development scenario; EPS: economic priority scenario; WPS: water-saving priority scenario; BDS: balanced development scenario.

4.3.2. Simulation Results

(1) Population subsystem

With a natural population growth rate of 3.07%, the total population of Zhangjiakou City will increase from 4.69 million in 2015 to 4.99 million in 2035. Meanwhile, the urbanization rate is also rising, resulting in domestic water use will increase in every scenario. Domestic water demands from large to small in 2035 are EPS (191 million m³), BDS (174 million m³), WPS (154 million m³), and CDS (143 million m³), as shown in Figure 6a. The gap in domestic water demand between urban and rural will further expand, and the ratio of them will increase from 2.0–2.4 in 2015 to 4.5–6.0 in 2035, as shown in Figure 6b.

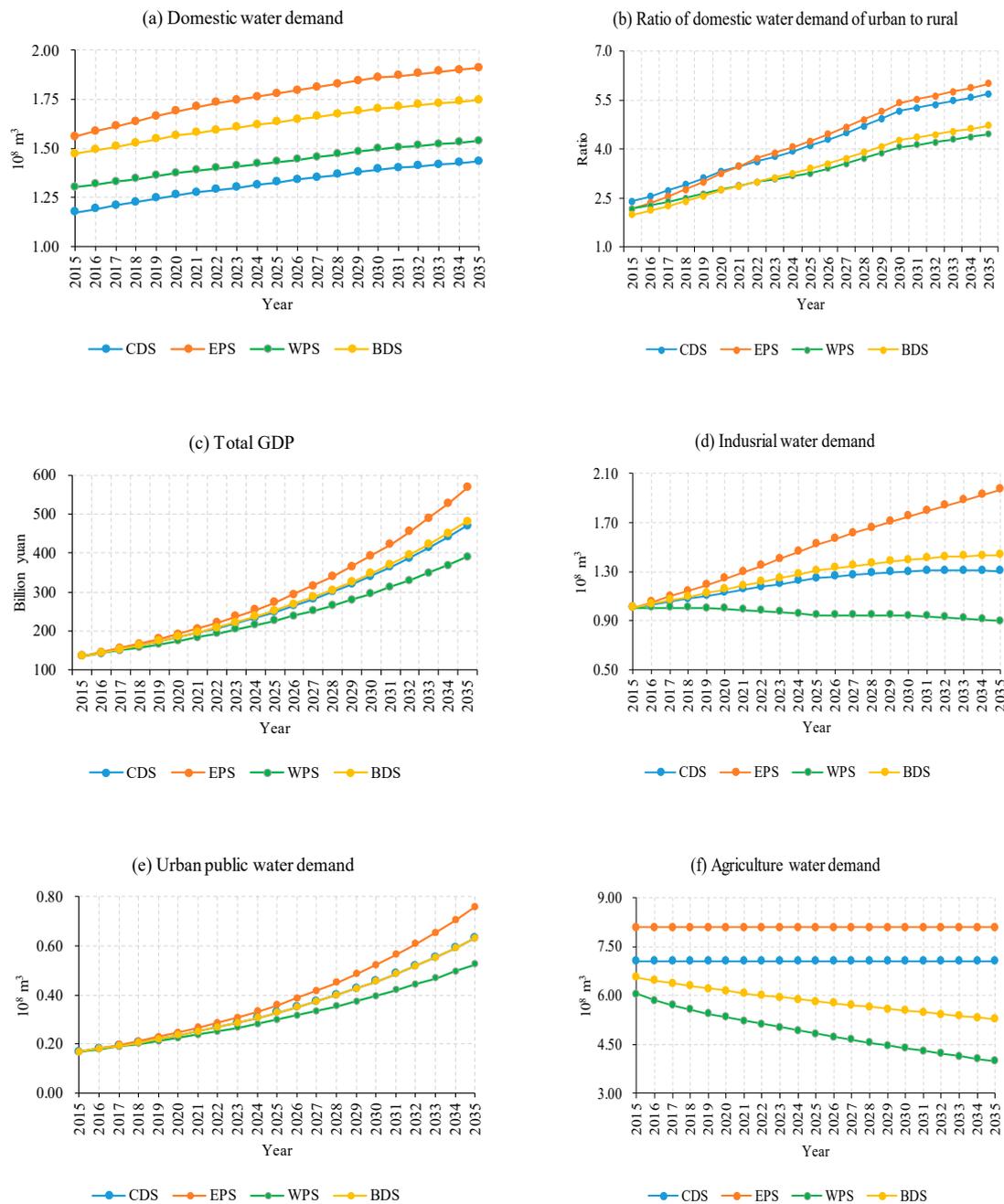


Figure 6. Cont.

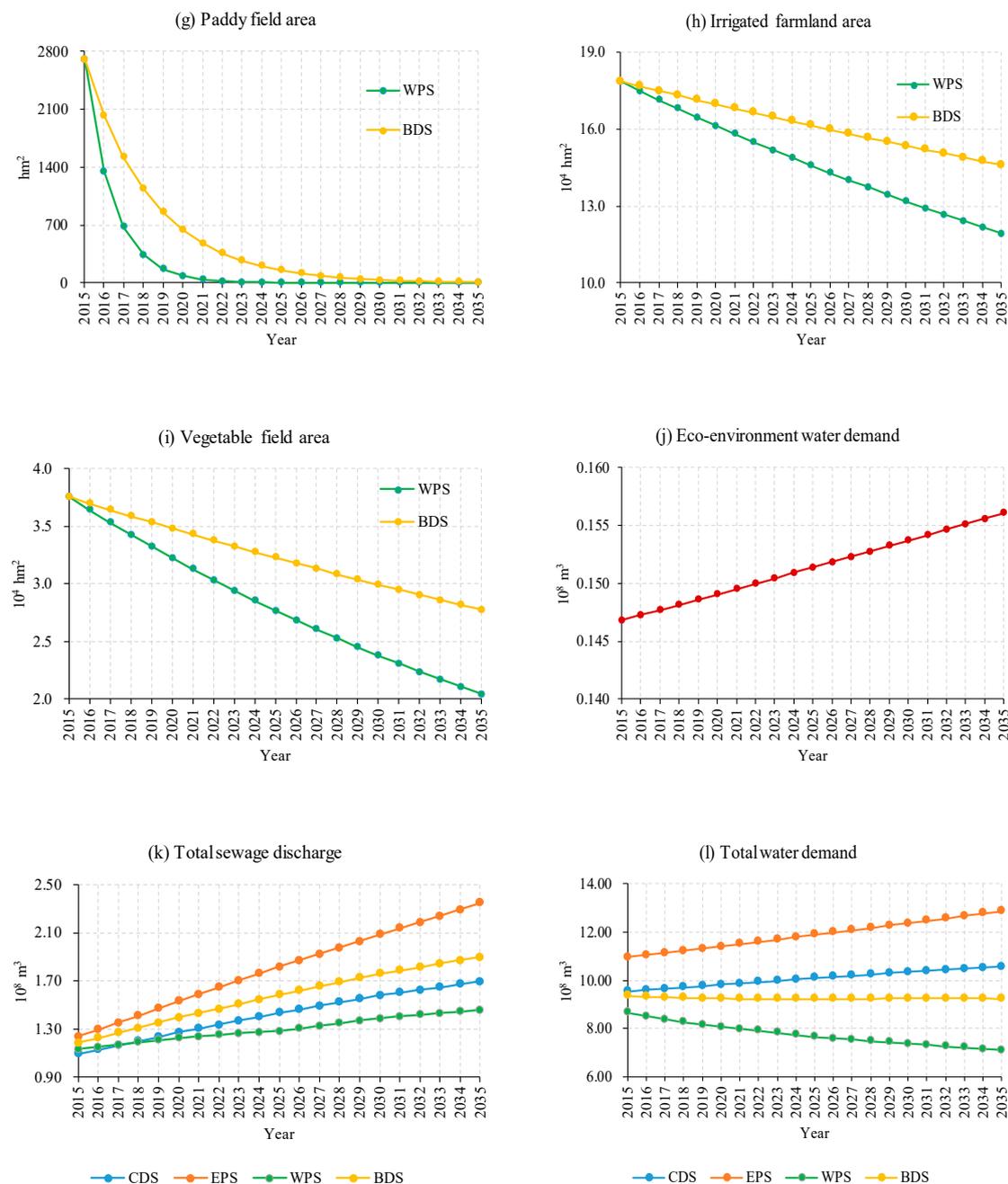


Figure 6. The simulation results of four development scenarios.

(2) Economic subsystem

The growth rates of total GDP from high to low are EPS (7.4%), BDS (6.5%), CDS (6.4%) and WPS (5.4%), resulting the total GDP will reach 567 billion yuan, 482 billion yuan, 471 billion yuan, and 390 billion yuan, respectively, as shown in Figure 6c. The structure of contribution rates of primary, secondary and tertiary industries to GDP will change from 18%:40%:42% in 2015 to 10%:32%:58% (CDS, EPS, and WPS) and 10%:34%:56% (BDS) in 2035.

The industrial water demands from high to low are EPS (197 million m³), BDS (143 million m³), CDS (130 million m³), and WPS (90 million m³) in 2035, as shown in Figure 6d. It shows a declining trend only in WPS. The urban public water demands increase in each scenario, from high to low are EPS (76 million m³), BDS (63 million m³), CDS (63 million m³), and WPS (52 million m³) in 2035, as shown in Figure 6e.

(3) Agricultural subsystem

In CDS and EPS, agricultural water demands remain at 704 million m³ and 808 million m³, of which the proportions of farmland irrigation are 91.2% and 91.5%, respectively, as shown in Figure 6f.

In WPS, the area of paddy fields, irrigated land, and vegetable fields decreased at an average annual rate of 50%, 2%, and 3%, respectively, resulting in a reduction in agricultural water demand from 604 million m³ to 399 million m³, and the proportion of water demand for farmland irrigation will drop from 90.3% to 85.3%, as shown in Figure 6g–i.

In BDS, the paddy fields, irrigated land, and vegetable fields are reduced at an average annual rate of 25%, 1%, and 1.5%, respectively, while the number of livestock is increased to ensure that the GDP growth rate of the primary industry remains unchanged. At this time, the agricultural water demand will decrease from 656 million m³ to 527 million m³, and the proportion of water demand for farmland irrigation will drop from 90.0% to 87.7%.

(4) Ecological environment subsystem

Since the per capita ecological environment water demand is set to 3.13 m³ in the four scenarios, the ecological environment water demand increased from 14.7 million m³ to 15.6 million m³ with the increase of population in each scenario, as shown in Figure 6j.

The total amount of wastewater discharged is increasing in every scenario, from high to low are EPS (235 million m³), BDS (190 million m³), CDS (169 million m³), and WPS (146 million m³) in 2035, as shown in Figure 6k. The wastewater mainly comes from urban domestic water and industry sectors, and the proportion of them will drop from 93–94% to 83–85% with the change of GDP.

(5) Total water demand

As displayed in Figure 6l, in CDS and EPS, the total water demand will increase from 954 million m³ and 1097 million m³ to 1057 million m³ and 1288 million m³, and the proportion of agricultural water demand will drop to 67% and 63%, respectively.

In WPS and BDS, the total water demand will drop from 866 million m³ and 936 million m³ to 710 million m³ and 924 million m³, and the proportion of agricultural water demand will drop to 56% and 57%, respectively.

4.3.3. Water Stress Index

In the water supply subsystem, the amount of inbound water and outbound water from 2015 to 2035 are set according to the “Two Zones Planning” of Zhangjiakou City. The total water resources of the extremely wet year, the average climatic year, and the extremely dry year were set as the maximum value of 17.01, the average value of 14.51, and the lowest value of 11.42 from 2008 to 2016, respectively. In addition, due to the over-exploitation of water resources in Zhangjiakou City, from the perspective of sustainable development, the environmental flow coefficients of the extremely wet year, the average climatic year and the extremely dry year are set to 0.2, 0.25 and 0.3, respectively, which are slightly higher than the proportion of unused water in Zhangjiakou City for many years.

As shown in Figure 7, in general, the water stress indexes in the four scenarios from high to low are EPS, CDS, BDS, and WPS. In the extremely wet year, the water stress indexes of the four development scenarios are between 0.5 and 1, indicating the water resources are in the state of surplus. In the average climatic year, the water stress indexes of CDS and EPS will rise continually, and it is going to exceed 1 in CDS and is always greater than 1 in EPS. The water stress indexes in WPS and BDS are between 0.6 and 1.0 and will decline continually. In the extremely dry year, the water stress indexes of CDS, EPS, and BDS are always greater than 1, while it is less than 1 after 2019 in WPS.

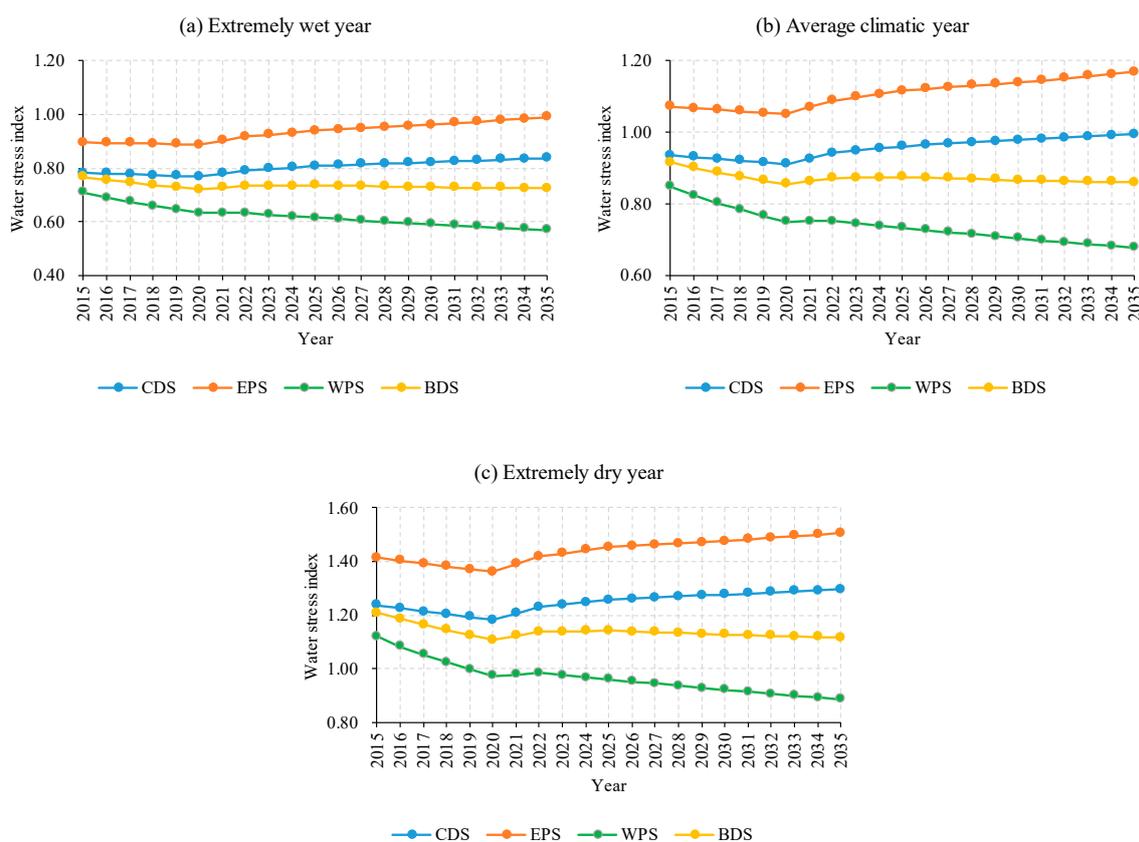


Figure 7. Water stress index of four development scenarios.

5. Discussion

5.1. Comparison with the “Two Zones Planning”

The industrial growth rates of Zhangjiakou City in this study are set between 3.6–5.6%, slightly lower than 6% in the “Two Zones Planning” as it has been declining in recent years, from 5.9% in 2014 to 2% in 2017, making it very difficult to keep an average annual growth rate of 6% until 2035. Nevertheless, considering that the current GDP of Zhangjiakou City is lagging behind in eleven cities in Hebei Province and facing the requirements of economic growth, we still set the industrial growth rate higher than 2017.

In 2015, the industrial water quota of Zhangjiakou City was 22.8 m³, while the national average level was 58.3 m³, which means that Zhangjiakou City’s industrial water efficiency has been at the leading level in the country, even exceeding some developed countries. Therefore, the average annual rate of water consumption per ten thousand yuan industrial GDP in this study is set around 3%, which is lower than that of the “Two Zones Planning” (6%). In fact, in terms of industrial water conservation, the current focus should be on how to adjust the industrial layout and structure to mitigate the contradiction of the water resources distribution and industrial water demands.

The irrigated land is planned to reduce 64,667 ha (36.2%) by 2022 in the “Two Zones Planning”. The area of irrigated land, according to the sensitivity analysis, is indeed the biggest factor affecting the demand for water resources. However, the reduction rate of irrigated land should not be so fast because it is a very important factor to guarantee food security and residents’ income. Therefore, in this study, we make a modest adjustment of the reduction rate of irrigated land. The area of irrigated land will be reduced by 59,333 ha and 32,667 ha by 2035 in WPS and BDS, respectively.

In terms of water resources efficiency, the total GDP in the “Two Zones Planning” will increase from 136.35 billion yuan in 2015 to 407.50 billion yuan in 2035, resulting in a decrease in water

consumption per ten thousand yuan GDP from 68.79 m^3 in 2015 to 21.66 m^3 in 2035. At the same time, the proportion of unused water resources will also drop from 41% in 2015 to 56% in 2035. Although it will indeed save water resources, will it cause a waste of water supply capacity? As shown in Figure 8, the water demand for per ten thousand yuan GDP in the four scenarios varied from 63 m^3 to 80 m^3 in 2015, and the difference will become smaller and smaller over time, reaching from 18 m^3 to 23 m^3 in 2035. This means no matter which scenario is chosen, the water demand per ten thousand yuan GDP will eventually fall to about 20 m^3 in 2035 as the economy grows. If lower water demand is achieved only by slowing economic growth, the water resources efficiency will not be improved, and it may also result in the waste of water supply capacity. Therefore, Zhangjiakou City should choose a coordinated development model to balance economic development and water conservation.

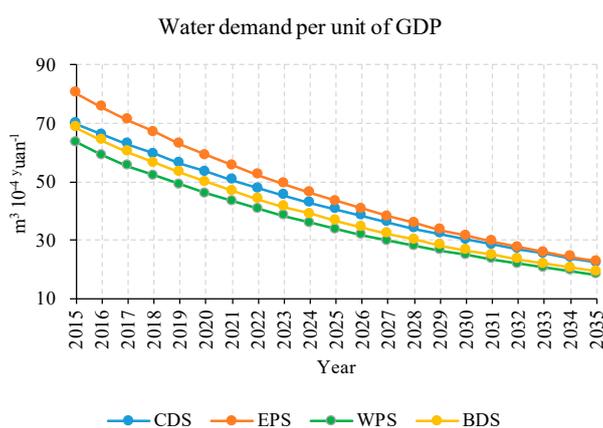


Figure 8. Water demand per unit of GDP.

5.2. Policy Suggestions for Sustainable Water Use

In general, Zhangjiakou City should take the water resources carrying capacity as the primary consideration for regional economic development and ecological security. In order to promote the structural adjustment and optimization of water use, it is vital to carry out the assessment of the current status of water resources carrying capacity on county scale from the perspectives of total water use, water use efficiency, and water pollution. In the meantime, the management concept should shift from the water supply side to the water demand side, and from extensive water use to intensive water use.

Reduction of agricultural water use. According to the sensitivity analysis, the agricultural water-related indicators are most sensitive to the total water demand in Zhangjiakou City. That is to say, the agricultural sector has the largest water-saving potential. Therefore, there is a need to reduce the area of irrigated farmland. In this process, the correlation between the crop structure, food production, and agricultural income, as well as other factors must be considered to achieve maximum benefits. In addition, it is also essential to strictly control the planting area of high-water-consumption crops, vigorously promote water-saving renovation, and develop high-efficiency water-saving irrigation measures, such as large-scale sprinkler irrigation, micro-irrigation, and high-standard pipe irrigation.

Targeted control of industrial water use. On the one hand, it is crucial to strictly limit the entry of high-water-consuming industries and enterprises, and focus on the promotion of water-saving technologies in high-water-consuming industries such as thermal power, building materials, and food, to ensure the continuous decrease of the total industrial water consumption. On the other hand, comprehensive strategies should be adopted in future water management, such as industrial transformation and upgrading, optimization of industrial layout, upgrading of water-saving technology, and strengthen long-term water consumption planning and quota management.

Urban public and ecological water conservation. First, the water-saving technological transformation of key water use sectors should be accelerated, such as schools, hospitals, hotels, restaurants, car washes, and ski resorts. Second, the government needs to actively promote the

construction of recycled water utilization projects. For example, the water recycling systems should be set up in new communities and give priority to the use of recycled water and rainwater in urban greening, municipal environmental sanitation, and ecological landscapes. In addition, it is also important to optimize the layout of urban pipeline networks, replace severely aged water supply pipeline facilities, and reduce water leakage during water supply.

5.3. Limitations of This Study

Although the system dynamics model is well-known for its nonlinear simulation, this feature is primarily reflected in the relationship between different subsystems. In most studies, only the flow variables can change the stock variables. For example, industrial GDP can only be influenced by the growth rate of industrial GDP in ZSD, and the value of the growth rate of industry GDP has to be set to a constant, making it become a linear simulation process. This is actually impossible in reality, especially in the case of a long simulation period with a lot of uncertainties. In addition, since the agriculture GDP is closely related to the area of the irrigated farmland, in theory, they should be linked in the system dynamics model, but we failed to achieve it due to lack of data, as agriculture consists of crop farming, forestry, and animal husbandry, and there are both irrigation farmland and rain-fed farmland in crop farming, and the areas of various crops are changing every year. It is very difficult to find data that can support us in obtaining contribution rates of different types of irrigation farmland to the agriculture GDP and the inherent relationship between them. Therefore, the changes in irrigation farmland areas are not linked to the agriculture GDP as in other studies [31,34]. Despite these drawbacks, however, the simulation results can still reflect the water demand relatively accurately in different development scenarios and provide a practical guide to the policymakers.

6. Conclusions

In this study, a complex system dynamics model (ZSD) reflecting the relationships between the water resources subsystem and other subsystems in Zhangjiakou City, such as population, economy, and environment subsystem, is established by using Vensim PLE, a system dynamics software. Then the ZSD model is employed to simulate water demand (2015–2035) in four designed alternative development scenarios. The main conclusions are as follows:

(1) According to the sensitivity analysis, the variables related to irrigation farmland are the main driving factors of water demand, especially the area and the average water consumption of irrigated land. Therefore, reducing the area of irrigated farmland and improving the efficiency of agricultural irrigation water will be the main direction of water-saving in Zhangjiakou City. However, it is vital to consider various factors to decide at what degree to reduce the area of irrigation farmland, such as agricultural output value and farmers' income.

(2) The total water demand will rise continually in CDS and EPS, and the proportion of agricultural water demand will drop to 67% and 63%, respectively. Meanwhile, it will decline continually in WPS and BDS, and the proportion of agricultural water demand will drop to 56% and 57%, respectively.

(3) In the extremely wet year, the water stress indexes of the four scenarios are between 0.5 and 1.0, which means that water resources are sufficient. In the average climatic year, the water stress indexes will rise continually in CDS and EPS, and it is always greater than 1.0 in EPS, while the water stress indexes will decline continually in WPS and the BDS, changing between 0.6 and 1.0. In the extremely dry year, the water stress indexes are only less than 1.0 in WPS after 2019.

(4) Regardless of which development model is chosen, the water demand for per ten thousand yuan GDP will eventually fall to around 20 m³ in 2035. Therefore, reducing water demand only by slowing down economic growth cannot improve the efficiency of water use, and even results in inefficiency of water supply capacity.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2071-1050/12/10/3996/s1>, Table S1: Variables and equations in the ZSD model.

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