Environmental Science and Pollution Research (2024) 31:23091–23105
https://doi.org/10.1007/s11356-024-32599-1

RESEARCH ARTICLE

A system dynamics simulation-based strategic analysis of integrated water resources utilization and management in Shenzhen city

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Received: 9 August 2023 / Accepted: 19 February 2024 / Published online: 28 February 2024

Abstract
As one of the most rapidly developing cities in China, Shenzhen grapples with an increasing challenge in managing water resources due to escalating conflicts with its soaring water demand. This study established a system dynamics (SD) model based on a causal loop diagram to explore the intricate interconnections within the urban water resources system. Through simulating water supply and demand in Shenzhen from 2021 to 2035, the model identified key sensitive factors and examined various utilization scenarios for multiple water resources. Results indicated that water scarcity posed a significant obstacle to Shenzhen's development. To tackle this challenge, several effective measures should be implemented, including enhancing water conservation capabilities, developing seawater resources, promoting water reuse, optimizing the economic structure, and managing population growth. Prioritizing water conservation efforts and maximizing the utilization of seawater resources were regarded as the most impactful strategies in alleviating the water crisis. Furthermore, the relationship between water conservation capabilities and seawater utilization scale was analyzed using the SD model, contributing to the development of a comprehensive water resources management strategy. The findings from this study would provide insights into robust methods for allocating water resources, thereby enhancing sustainable water management strategies applicable to regions facing similar challenges.

Keywords Rapid urbanization · Water shortage · Multiple water sources · Integrated water resources management · System dynamics

Introduction

Water resources are fundamental for supporting social production, human life, and ecological development (Momblanch et al. 2016). However, due to rapid industrialization and urbanization processes in recent decades, water scarcity has become an increasingly severe issue in China. The conflict between high water demands and extremely limited water resources poses a serious threat to sustainable development (Dalin et al. 2015). The emergence of water resource problems can be attributed to two main factors: the widespread scarcity of freshwater resources and inadequate treatment to water-related issues (WWF 2003). Therefore, it is imperative to develop new water sources and optimize urban water resource management methods to address these challenges and achieve sustainable development.

Urban water resource management encompasses a complex system that includes multiple interrelated systems such as water resources system, economy, population, and ecology (Liu and Cheng 2010). Within this large system, there

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Responsible Editor: Xianliang Yi

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are numerous essential components and intricate variations that contribute to its complexity. Two types of complexity can be identified: detail complexity, which arises from the large number of elements within the system, and dynamic complexity, which results from the temporal or spatial separation of system effects (Zarghami and Akbariyeh 2012). The presence of these two characteristics in urban water resource systems presents significant challenges to urban water resource management, highlighting the need for careful selection of the intelligent methods to analyze system complexity and improve predictive capabilities. The system dynamics (SD), initially proposed by Forrester (1958), is a valuable approach for simulating the behavior of urban systems. SD is particularly well-suited for analyzing the intricate relationships of complex systems, as it can effectively handle nonlinearities, multi-feedback problems, and complex dynamics. It enables the identification of the specific impact of system elements on the overall system output, which is very important for modeling and analyzing social and resource-related systems. Given these characteristics, SD is considered to be particularly applicable to studies focused on water and land resources (Chen and Wei 2014, Saysel et al. 2002; Xu et al. 2002).

Currently, system dynamics models are widely applied in diverse research fields to study sustainable water resources development. In the realm of urban water management policies, for example, Armenia et al. (2023) integrated the system dynamics approach with fsQCA. They analyze the necessary and sufficient water management policies that can promote sustainable water resources development and identify key factors within water management policies. Duran-Encalada et al. (2017) utilized an analysis based on a SD model to examine the effects of global climate change on water quality and quantity. The results presented policy recommendations that the government can employ to mitigate water-related risks. In the macroeconomic regulation of urban industrial development, Xu et al. (2017) used system dynamics modeling to analyze the operation of the water system and proposed implementing the policy of converting cultivated land back to grassland, reducing the proportion of agricultural land, and achieving a 1:7 ratio of agriculture and husbandry to achieve sustainable development in the Tongliao city. Through a combination of a SD model and the Cobb–Douglas function, Li et al. (2019a) proposed adjusting investments as a means to address the imbalance between industrial water supply and demand in cities. System dynamics have also demonstrated good performance in applications within integrated social-ecological-economic-water systems. A study focusing on Jiaxing city employed a system dynamics approach to enhance water management. It emphasized the importance of improving water use efficiency, controlling population and economic growth rates, and maximizing the utilization of surface and reclaimed to alleviate water scarcity risks and promote sustainable water management (Zhou et al. 2021). Li et al. (2018) utilized the system dynamics to analyze the water supply and demand situation in Zhengzhou. Combining interval parameter two-stage stochastic programming, the study proposed an optimized water resource allocation scheme for Zhengzhou. Additionally, SD methods have been applied to watershed water resource management. Dai et al. (2022) established a system dynamics model for the Yongding River Basin, simulating water resource utilization in different regions within the basin. Development recommendations were provided for regions with varying development scenarios. System dynamics model was established to analyze the Water Pollution Emission (WPE) system in the Yangtze River Basin, elucidating the relationship between economic development and environmental health (Jia et al. 2021). However, previous studies using SD methods typically highlighted measures that should be emphasized or could alleviate water pressure but were often vague and did not quantify the specific levels these measures should achieve to form clear, quantifiable strategies. When it comes to “quantification,” existing research often combines SD methods with other approaches to determine water allocations for different water-use sectors, rather than specifying the levels at which management measures should operate. This has resulted in relatively ambiguous water resource management strategies.

In Shenzhen city, the water-related challenges and crises are particularly acute. For instance, problems such as water scarcity, water pollution, and low rates of reclaimed water recycling are prevalent, profoundly impacting the population, economic growth and sustain development (Liu et al. 2022). Therefore, it is necessary to analyze the water resources in Shenzhen using comprehensive urban water resource management methods. A SD model was established to assess the carrying capacity of water resources in Shenzhen, suggesting that adjustments to industrial structure and increased water-saving efforts could help achieve the water resource carrying capacity target by 2030 (Zhang 2010). To analyze the trends in water supply and demand in Shenzhen, Li et al. (2019b) developed a SD model and proposed recommendations for water resource management. While their research provided a good model, there are shortcomings. Existing research on the water supply side in Shenzhen mainly focus on reclaimed water and rainwater, with insufficient discussion on seawater. As a crucial water source for the future of Shenzhen, previous studies have not taken the Xijiang River into consideration. Additionally, existing studies on reclaimed water often setting an upper limit on the available quantity but lacking restrictions on the demand limit for reclaimed water. Therefore, there is a need to establish a system dynamics model that is more tailored to the actual water resources situation in Shenzhen.

In this study, we aim at utilizing a SD model to identify the sensitive factors within the integrated social-economic-ecological system of Shenzhen city, with the ultimate goal to propose an efficient water resource management strategy based on multiple accessible and potential water sources. Firstly, the key interactions within the integrated system were analyzed, and a SD model was developed. Subsequently, water supply and demand in Shenzhen from 2006 to 2035 were simulated to identify the sensitive factors within the integrated system. Various scenarios and novel strategies were then examined to accelerate water resource management and address water scarcity. Through the adjustment of sensitive factors and the scale of seawater utilization facilities, simulations were conducted to assess the impacts of different strategies on WSDR, GDP, and population size. Then, measures to enhance WSDR were identified, and which of these measures are more effective and deserving of emphasis were elucidated. Based on this, we proposed methods for combining these measures and future strategies for water resource utilization. Thus, an integrated strategy for water resource management was proposed, aiming to achieve a balance between water supply and demand in the future and ensure the sustainable development of Shenzhen city. It is anticipated that this study would provide valuable insights for policymakers, enabling them to take necessary actions and implement cost-effective and intelligent system dynamics models for improved and timely management of water resources in Shenzhen city.

Study area

As illustrated in Fig. 1, Shenzhen city is situated on the eastern coast of the Pearl River estuary in the southeast of Guangdong province, China. It is bordered by Huizhou city to the north and Dongguan city to the east. To the south, it is separated from Hong Kong's Kowloon and New Territories by the Shenzhen River, and to the west, it faces the Lingdingyang and Zhuhai city. The land area of Shenzhen ranges from approximately 114°37′21″ E to 113°45′44″ E in longitude and 22°51′49″ N to 22°26′59″ N in latitude. According to the "Shenzhen Statistical Yearbook 2022," the total land area of the city is 1997.47 km^2. Shenzhen experiences a subtropical maritime monsoon climate, which leads to uneven distribution of rainfall at both spatial and temporal scales. The period from April to September contributes to more than 85% of the annual rainfall (Zhang et al. 2020). Being one of the most developed cities in China, Shenzhen has a substantial water demand with a population of 17.7 million and a GDP exceeding 3.2 trillion RMB in 2022 (Liu 2023). By contrast, the per capita water resources in the city are only 1/12 of the national average and 1/48 of the global average, which leads to a more severe water shortage (Zhang et al. 2020; Yi and Ma 2008).

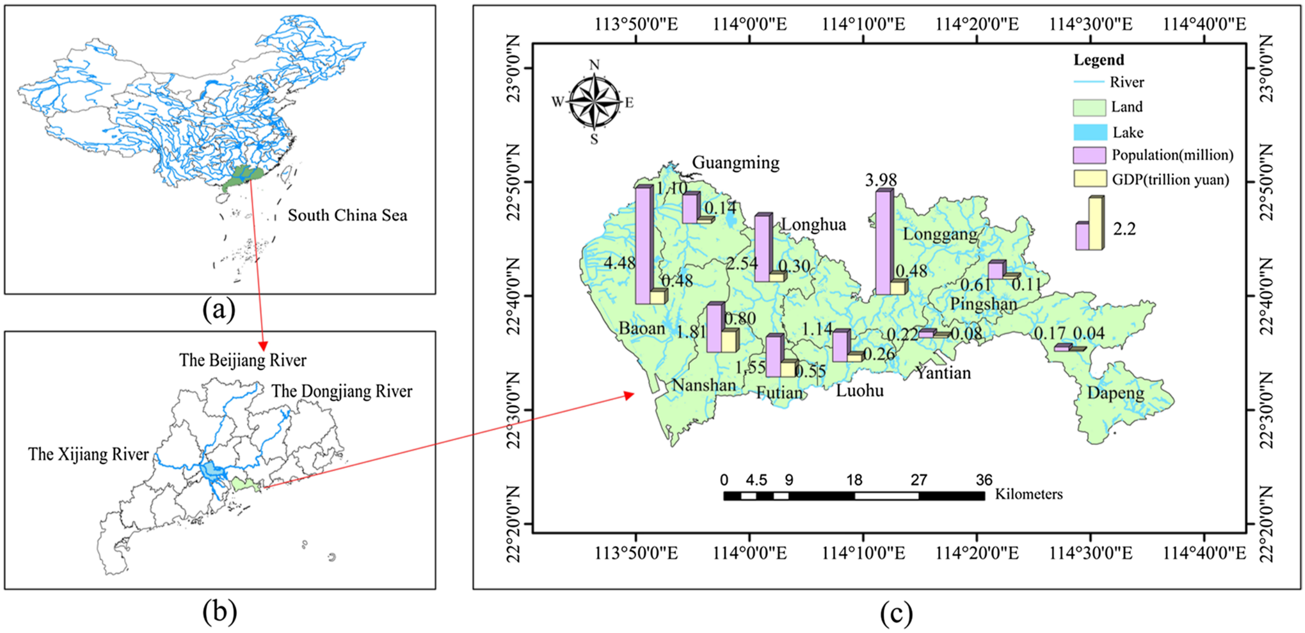


Fig. 1 The location of Shenzhen city. **a** China administrative map. **b** Guangdong province. **c** Water systems in Shenzhen

Model formulation and configurations

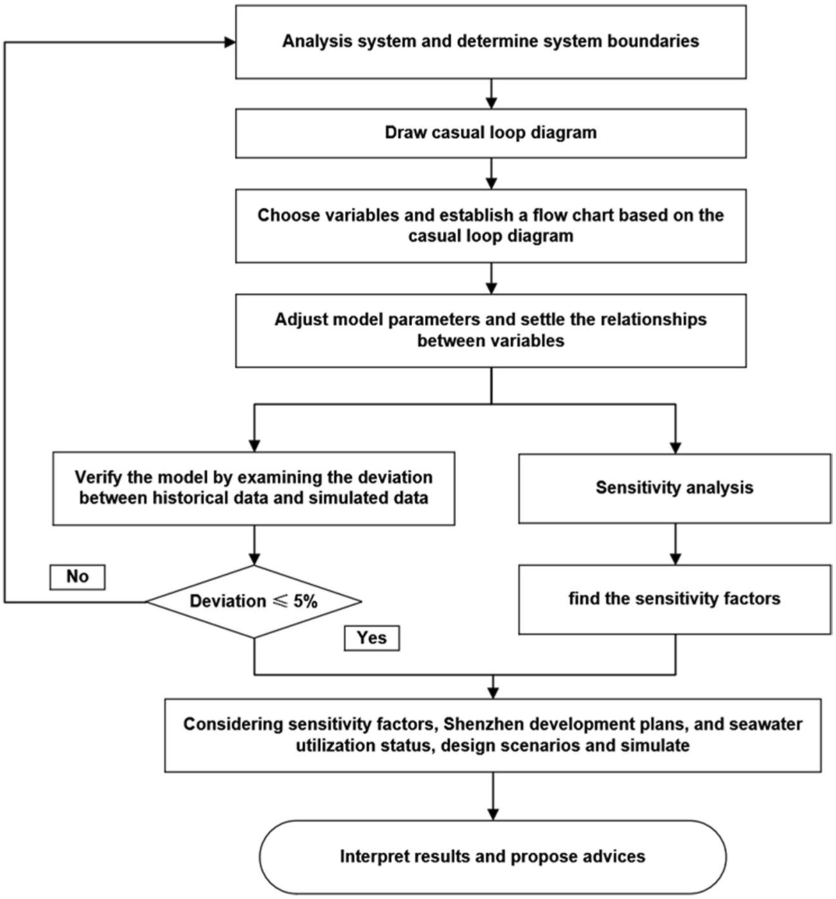
To develop effective methods for water resource management, it is essential to establish a system dynamics model to analyze various water resource management strategies. The modeling processes are outlined as follows. Firstly, the temporal and spatial boundaries of the water resource system under study were determined. Then, a causal loop diagram was constructed, which served as the basis for enriching variables, determining the relationships between variables, and building the system dynamics model. Finally, the established model was iteratively adjusted until it successfully passed the validation using historical data. With the validated model, simulations were conducted to analyze the water supply and demand in Shenzhen. Key sensitivity factors that have a significant impact on the system were identified. Using these sensitivity factors as main control variables, multiple scenarios reflecting the execution status of the water management strategies were formulated and simulated. The modeling formulation and analysis framework are presented in Fig. 2.

The Vensim (Ventana 2022) package was utilized for accurate simulation of the system dynamics. This modeling tool is known for its robust capabilities in building system dynamics models, and it has been widely employed in various research studies (Abraham et al. 2022). For a practical model demonstration, the simulation period was selected from 2006 to 2035. The historical data from 2006 to 2020 was considered as the simulation period for training the model, spanning 15 years. By incorporating this extensive dataset, the model's reliability would be enhanced. Predictions were then performed for the period from 2021 to 2035. Note that a time-step of 1 year was set for the simulations.

Feedback loop diagram

The causal loop diagram, which provides a visual representation of key variables and their interconnections, is presented in Fig. 3. The diagram illustrates that the integrated system can be divided into two components: the supply and the demand sides. These components interact with each other through the supply–demand gap to achieve dynamic balance in the water system. In situations where the water supply is abundant, the growth in water demand will not be limited until it approaches the capacity of the water supply system. Conversely, when the water supply is insufficient,

Fig. 2 Modeling formulation and analysis framework



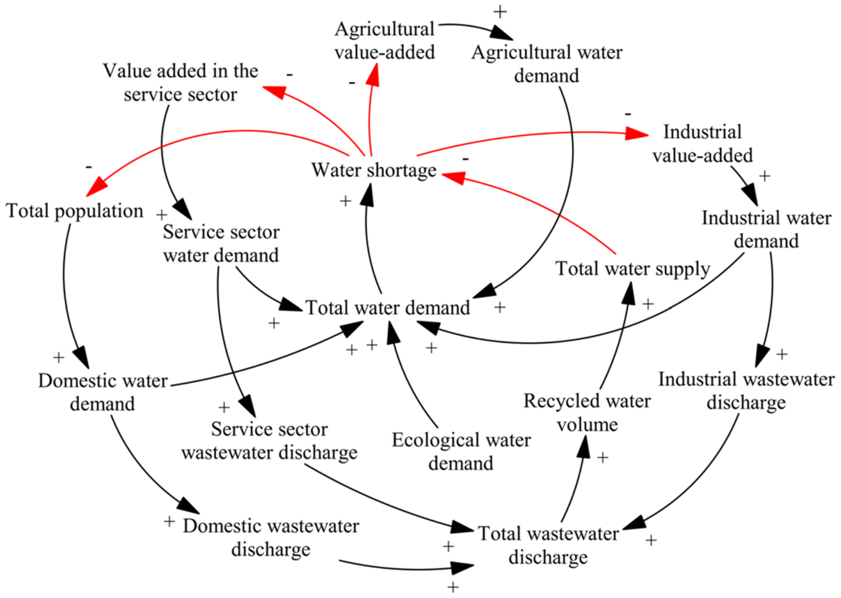


Fig. 3 Causal loop diagram: The red arrows indicate the negative feedback, and the black arrows indicate the positive feedback

the development of production, daily life, and ecological activities will be constrained, resulting in a decrease or slower growth in water demand, aligning with the available supply. Through this mechanism, the supply and demand within the system gradually attain a state of balance.

Water supply side

Currently, Shenzhen relies on five main sources of its water supply: surface water, groundwater, rainwater, reclaimed water, and the Dongjiang River. However, considering the development plans of the Shenzhen government, it is anticipated that the available water sources will potentially increase in the near future. For instance, the Pearl River Delta Water Resources Allocation Project, which extracts source water from the Xijiang River, is currently under construction and is expected to be operational in 2024 (Jiang 2022). Additionally, as a coastal city, Shenzhen has abundant seawater resources. Therefore, future scenarios should take the construction of seawater desalination plants and facilities for seawater toilet flushing into account. Thus, the water sources included in the model comprise surface water within the city, groundwater, rainwater, reclaimed water, Dongjiang River, Xijiang River, and seawater.

Water demand side

On the water demand side, there are three key components: water demand from the economic sector, social sector, and ecological sector. In the economic sector, water demand is primarily influenced by water use efficiency and the scale of value-added activities. For the social sector, domestic water demand is a major factor, and it mainly depends on the population size and the per capita domestic water consumption rate. The ecological water demand encompasses water requirements for various ecological elements such as rivers, parks, greenways, and ecological belts (EBs). Among them, greenway refers to an ecological corridor for pedestrians and cyclists, while EBs incorporates additional functions such as sightseeing, recreation, and other ecological aspects. The water demand in this sector is closely linked to the size of these ecological features, such as their area or length, as well as the water consumption per unit area or length.

Variables and equations

According to historical data, the parameters for the SD model were determined. The model includes 10 state variables, 10 rate variables, 58 auxiliary variables, 15 constants, and 24 table functions. The values and equations for these parameters were established through regression analysis method and the application of the grey prediction algorithm, and hence the model would be performed for both historical simulation period and prediction period (Wang et al. 2014; Wu et al. 2013). The historical data primarily originated from the Shenzhen Statistical Yearbook and the Shenzhen Water Resources Bulletin. The main variables and equations used in the SD model are provided in Appendix. We further determined the relationships between various variables using methods such as linear fitting, forming the corresponding equations. With the information described above, a general stock-flow diagram was developed as depicted in Fig. 4.

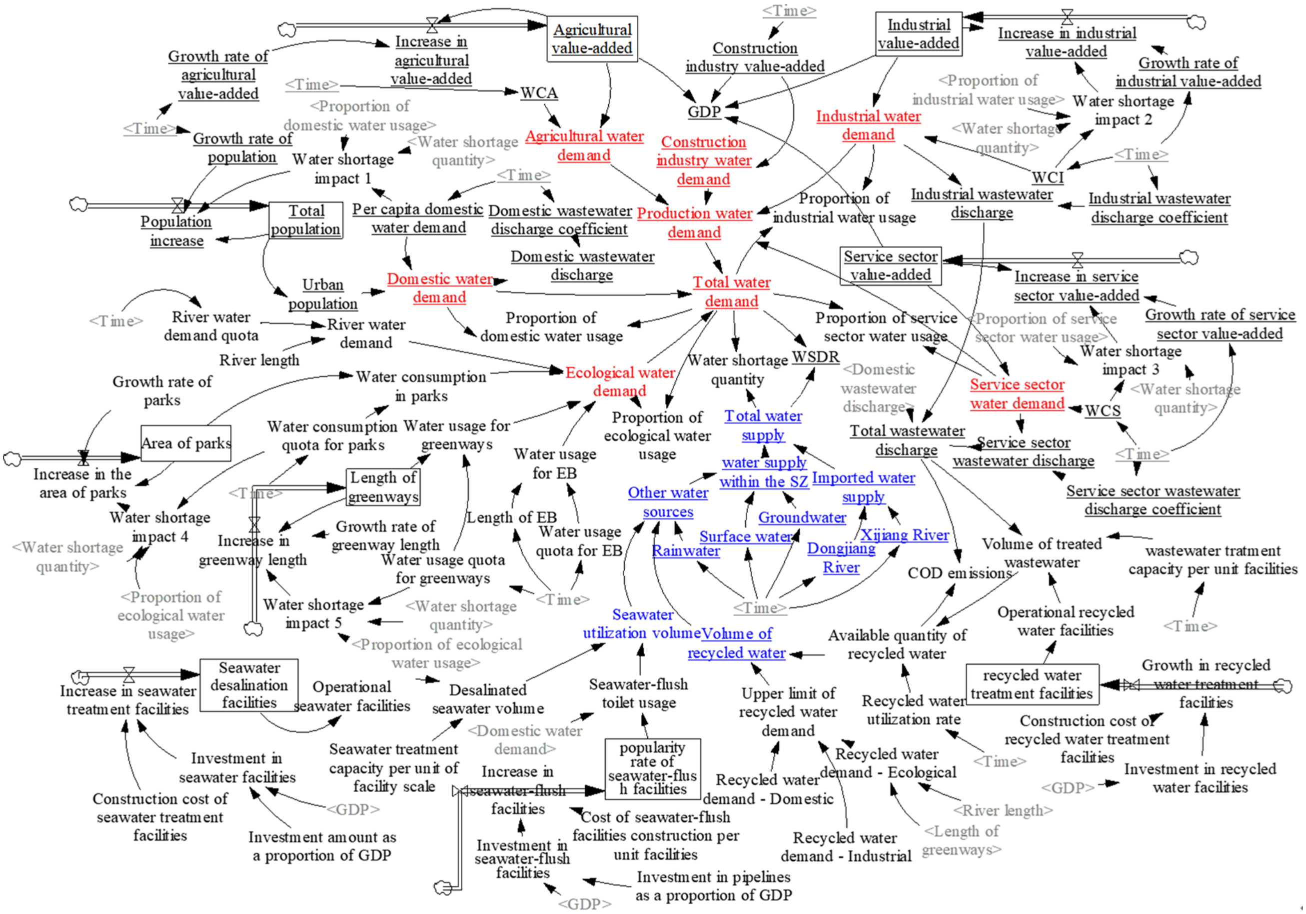


Fig. 4 The stock-flow diagram of SD model. Red fonts indicate the main variables of water demand sector, blue fonts indicate the main variables of water supply sector, and black fonts indicate variables related to further disaggregation of the main variables. WCI is water consumption per 10^4 yuan of industrial value-added; WCS is water consumption per 10^4 yuan of service sector value-added; WCA is water consumption per 10,000 yuan of agricultural value-added

Model validation and sensitivity analysis

Before utilizing the SD model, it is essential to assess its credibility using appropriate methods (Bala et al. 2017). In this study, we employed the relative error as a measure of the discrepancy between simulated data and historical data, aiming to validate the effectiveness of the model. In addition, sensitivity analysis was conducted to evaluate the relationship between changes in specific parameters and their impact on the output results. This analysis involves examining the ratio between the magnitude of changes in output results and the magnitude of changes in a particular parameter, while keeping other parameters constant (Eq. 1). A higher ratio indicates that the parameter has a greater sensitivity and influence on the system. This sensitivity analysis provided valuable insights and served as a guide for setting different scenarios (Susnik et al. 2012).

$$S(t) = \left| \frac{\Delta Y(t) / Y(t)}{\Delta X(t) / X(t)} \right| \tag{1}$$

Results

Model validation

The population, GDP, ecological water demand, domestic water demand, industrial water demand, service sector water demand, agricultural water demand, and wastewater discharge for the period from 2006 to 2020 were validated through compared the simulation results with historical statistics, and the relative errors are shown in Table 1. It can be observed that the errors for each variable during the

Table 1 Relative errors between the results and historical data

Year	Total population	GDP	Ecological water demand	Domestic water demand	Industrial water demand	Service sector water demand	Agricultural water demand	Total wastewater discharge
2006	0%	0%	0%	0%	0.07%	0.02%	0.07%	0.02%
2007	0%	0%	0%	0%	0.04%	0.03%	0.04%	1.01%
2008	0%	0%	0%	0%	0.05%	0.09%	0.05%	1.52%
2009	0%	0%	1.02%	0%	0.19%	0.10%	0.19%	1.14%
2010	0%	0%	2.01%	0%	0.04%	0.11%	0.04%	0.02%
2011	0%	0%	0.67%	0.02%	0.90%	0.04%	0.90%	1.03%
2012	0%	0%	2.09%	0.01%	0.12%	0.08%	0.01%	1.52%
2013	0%	0%	3.78%	0.03%	0.08%	0.05%	0%	3.12%
2014	0%	0%	2.12%	0.06%	0.05%	0.02%	0%	1.67%
2015	0%	0%	1.60%	0.02%	0.57%	0.17%	0%	2.21%
2016	0%	0%	0.56%	0.01%	1.98%	0.22%	0.03%	2.70%
2017	0%	0%	4.13%	0%	2.32%	0.14%	0.01%	1.44%
2018	0%	0.01%	1.83%	0%	1.22%	0.06%	0.07%	0.02%
2019	0%	0.03%	2.58%	0.04%	0.07%	0.16%	0.18%	0.98%
2020	0%	0.11%	2.46%	0.03%	0.05%	0.44%	0.09%	3.03%

simulation period are all below 5%, indicating that the model would effectively capture and simulate the system behavior of Shenzhen's water resource system.

Water supply estimation

Table 2 presents the projected water supply capacity for the near future in Shenzhen. At a reliability rate of 50%, the available supply of surface water was estimated to be 232 million m^3, whereas at a higher reliability rate of 97%, the estimated supply was 83 million m^3. The long-term average supply of surface water was approximately 239 million m^3. The estimated amount of available groundwater resources was 5 million m^3. Regarding the Dongjiang River, under a water supply frequency of 50% and 97%, the estimated water diversion from the main stream was 1.608 billion m^3 and 1.593 billion m^3, respectively. The average water supply from the Xijiang River was projected to be 847 million m^3 annually, and the annual availability of unconventional water sources, including reclaimed water and rainwater, was estimated to be 120 million m^3.

Water demand simulation

Water demand simulation under sufficient water supply

In situations where there is a water supply deficit, the development of the economic, social, and ecological sectors is hindered. To assess the development potential of Shenzhen city, we conducted simulations using the SD model under the assumption of sufficient water supply (Fig. 5a). For the industrial sector, we assumed that water consumption per 10^4 yuan of industrial value-added (WCI) would decrease from 4.8 m^3 in 2020 to 3.0 m^3 in 2035. Similarly, the water consumption per 10^4 yuan of service sector value-added (WCS) was projected to decrease from 2.76 m^3 in 2020 to 2.0 m^3 in 2035. Based on these assumptions, the industrial and service sector water demand was estimated to reach 944 million m^3 and 828 million m^3 in 2035, respectively. Domestic water demand is mainly influenced by population size, and assuming a daily per capita domestic water demand of 55 m^3, the domestic water consumption was projected to gradually increase, reaching 921 million m^3 between 2021

Table 2 Capacity of water supply in the future

Annual reliability	Water supply within the Shenzhen (10^8 m^3)	Dongjiang River (10^8 m^3)	Xijiang River (10^8 m^3)	Other water sources (10^8 m^3)	Total (10^8 m^3)
50%	2.37	16.08	8.47	1.2	27.12
97%	0.88	15.93	8.47	1.2	26.48
Average	2.44	15.93	8.47	1.2	27.54

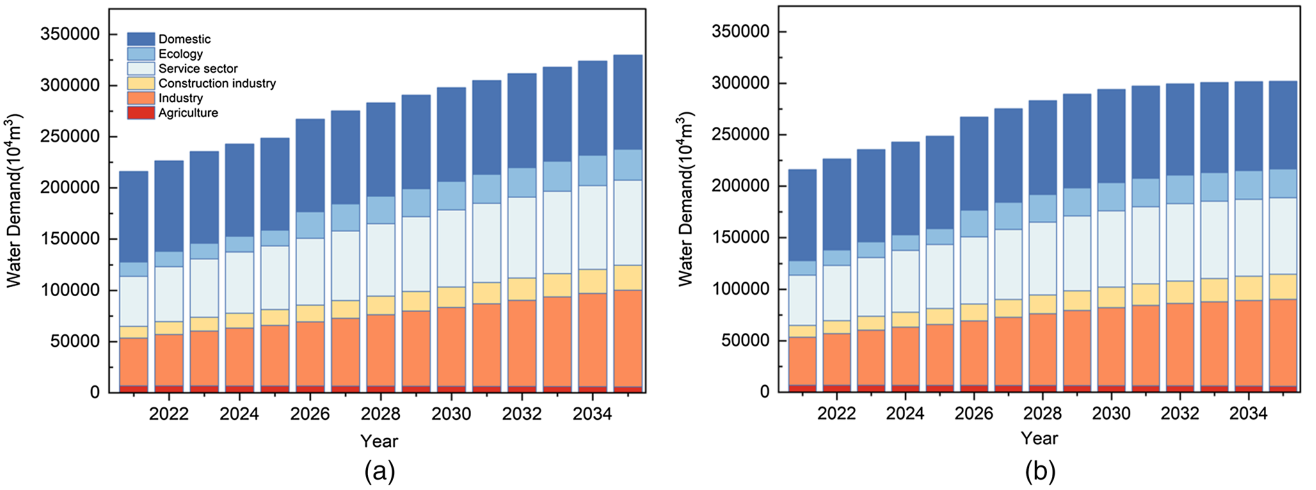


Fig. 5 Water demand of Shenzhen city from 2021 to 2035. **a** Water demand under sufficient water supply. **b** Water demand under limited water supply

and 2030. Ecological water demand is closely related to the area of green space. Before 2030, the construction of ecological areas was expected to experience rapid growth, leading to an increase in ecological water demand to 278 million m^3 by 2030. After 2030, as ecological construction becomes relatively well-established, there would be a relatively smaller increase in water consumption. Taking all the projections into account, the total water demand was estimated to reach 3.29 billion m^3 in 2035.

Water demand simulation under water supply constraints

By incorporating the actual capacity of water supply within model simulations, the obtained results of water demand in Shenzhen from 2021 to 2035 are illustrated in Fig. 5b. In 2035, the total water demand decreased to 3.01 billion m^3, including 845 million for the industrial sector, 740 million for the service sector and 852 million for the population. Comparing these results with those in the "Water demand simulation under sufficient water supply" section, it is evident that the water demand has decreased. This decrease can be attributed to the impact of water scarcity, resulting in a decline of water demand across various sectors.

Sensitivity analysis

Based on the simulation results from the "Water demand simulation" section and previous research (Li et al. 2019b, Liu and Cheng 2010, Zhou et al. 2021), we selected nine parameters for analysis, i.e., WCS, WCI, WCA (water consumption per 10,000 yuan of agricultural value-added), GRAV (growth rate of agricultural value-added), GRIV (growth rate of industrial value-added), GRSV (growth rate of service sector value-added), GRP (growth rate of population), DWDPC (domestic water demand per capita), and WCQFP (water consumption quota for parks). The sensitivity values of these nine parameters are depicted in Fig. 6, illustrating their respective impacts on the system dynamics.

The sensitivity values of WCA, WCI, and WCS consistently remained above 0.2, indicating their status as sensitive factors throughout the simulation period. On the other hand, the sensitivity values of GRSV, GRIV, and GRP showed an increasing trend over time. Initially, in the early years, their values were below 0.2, but all these parameters exceeded the threshold of 0.2 as time progressed, suggesting their importance as sensitivity factors in the long term. Besides, GRSV, GRIV, and GRP should be denoted as the sensitivity factors in the long term. In contrast, GRAV, WCA, and

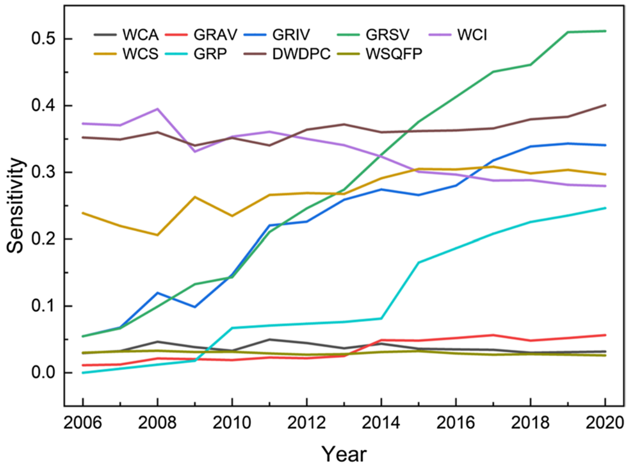


Fig. 6 Sensitivity values for the nine parameters over the period from 2006 to 2020

WSQFP were not considered as sensitive factors since their sensitivity values remained below 0.1. It should be noted that the simulation and prediction period in this study spans 15 years, which is why WCA, WCI, WCS, GRSV, GRIV, and GRP were identified as the key sensitivity factors for analysis.

Scenario simulation and evaluation

Considering the development plan of the Shenzhen city government, various scenarios can be devised by adjusting the six parameters to reduce water demand. Furthermore, increasing the available water sources should also be taken into account. Given the limited potential for utilizing surface water, groundwater, and rainwater resources (Qin et al. 2022), particular attention was given to seawater as a potential source for freshwater production and direct flushing. Additionally, with the significance of Eco-city construction in Shenzhen's urban planning, it is essential to explore how ecological construction and the recycled water utilization rate (RWUR) can influence the water demand of the system. Therefore, scenarios can be developed by adjusting the scale of seawater desalination facilities (SDF), the growth rate of ecological area (GREA) and RWUR. These adjustments would allow for simulations of WSDRs in different scenarios from 2021 to 2035. Table 3 shows the development goals of Shenzhen in various aspects.

Based on the results and discussions presented above, a range of scenarios were established to explore different aspects of water resource management in Shenzhen (Table 5). Scenario 1 served as the baseline scenario, aligning with the values outlined in the development plan of Shenzhen. Subsequent scenarios were derived from Scenario 1 with specific parameter adjustments. In Scenario 2, the GRP was reduced to examine the impact of population control on water demand. Scenario 3 explored the effects of economic incentive policies under water shortage conditions by increasing the values of GRIV and GRSV by 1.1 times. In Scenario 4, GRIV was adjusted to 0.9 times that of Scenario 1, while GRSV was increased to 1.1 times, investigating the influence of economic structure adjustment on the WSDR. Water-saving technologies and their impact on development were explored in Scenario 5 by reducing the three water consumption quotas to 0.8 times those in Scenario 1. Scenario 6 focused on improving the environment by increasing the growth rate of ecological area (GREA) and RWUR. Scenario 7 combined the advantages of Scenarios 1–6, while Scenario 8 emphasized the continuous construction of SDF and the widespread use of seawater-flush toilets. In Scenario 8, the seawater was included. There are two methods of seawater utilization: desalination and using seawater for toilet flushing. For desalination, it is necessary to build a centralized, and large-scale desalination project with a processing capacity of 400,000 tons/day. The construction period for the first desalination facility is set to be 5 years. Considering technological advancements, the construction periods for the second and third desalination facilities are shortened to 4 and 3 years, respectively. As for using seawater for toilet flushing, since Shenzhen lacks a water supply network suitable for seawater flushing, it is essential to gradually update and replace the network over the next few years. This process should be integrated into the construction of a new network and the replacement of the old network in Shenzhen, with the goal of completing a seawater-applicable water supply

Table 3 Shenzhen's development objectives for the year 2035

Elements	Values	Elements	Values
DWDPC	55 m^3/d	RWUR	99.9%
Population size	19 million	Length of greenway	5000 km
Industrial value-added	1.8 trillion yuan	WCI	3 $m^3/10^4$ yuan
Service sector value-added	3.8 trillion yuan	WCS	2 $m^3/10^4$ yuan

Table 4 Parameter settings for various development scenarios

	GRP	GRIV	GRSV	DWDPC	WCI	WCS	GREA	RWUR	SDF (2035)	PRSFT (2035)
Scenario 1	0.46%	5.4%	6.1%	55	3.90	2.38	2%	72%	0	0
Scenario 2	0.32%	4.9%	6.5%	55	3.90	2.38	2%	72%	0	0
Scenario 3	0.46%	5.94%	6.71%	55	3.90	2.38	2%	72%	0	0
Scenario 4	0.46%	4.9%	6.71%	55	3.90	2.38	2%	72%	0	0
Scenario 5	0.46%	5.4%	6.1%	49.5	3.51	2.14	2%	72%	0	0
Scenario 6	0.46%	5.4%	6.1%	55	3.90	2.38	4%	90%	0	0
Scenario 7	0.46%	5.94%	6.71%	49.5	3.51	2.14	4%	90%	0	0
Scenario 8	0.46%	5.4%	6.1%	55	3.90	2.38	2%	70%	3	100%

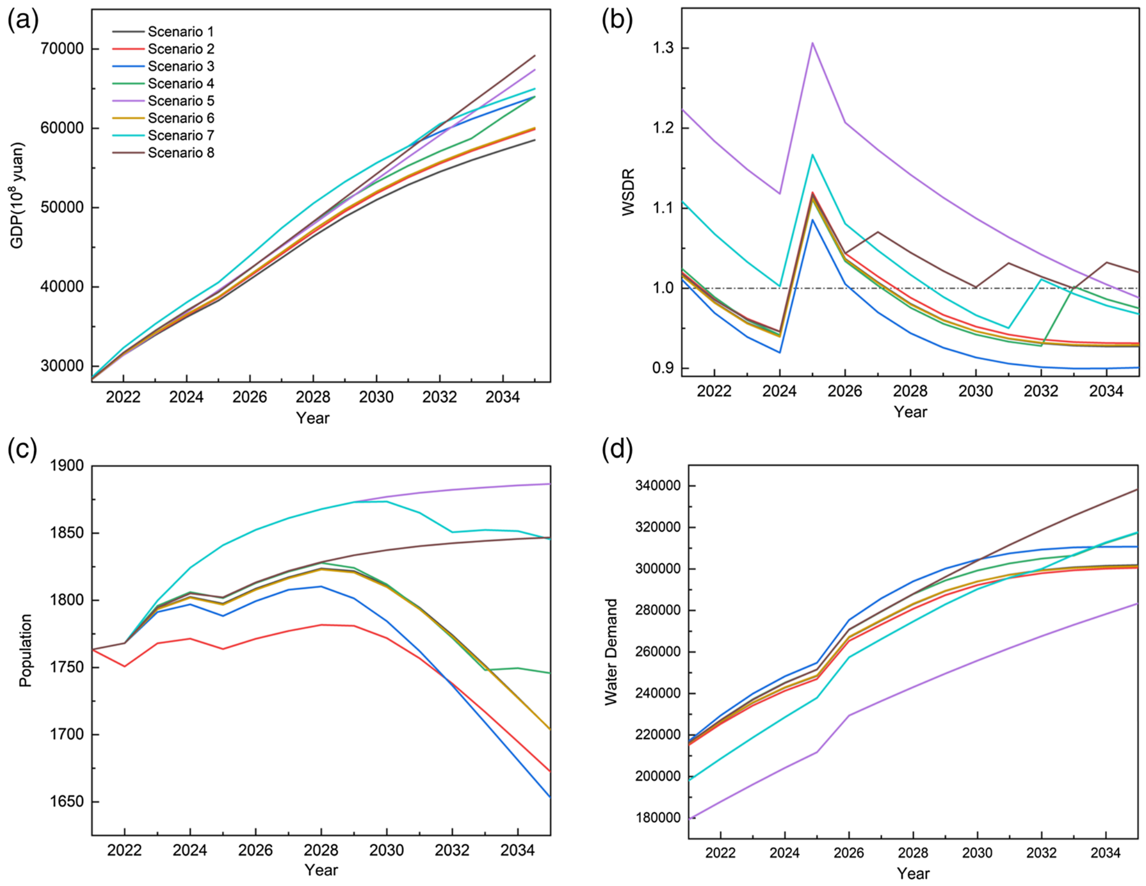


Fig. 7 Simulation results of the scenarios. **a** GDP. **b** WSDR. **c** Population size. **d** Water demand

Table 5 Adjusted parameters and the WSDRs

Year	Unit water consumption			WSDR	Desalinated seawater volume	WSDR	Seawater volume used for toilet flushing	WSDR
	WCI	WCS	DWDPC					
2021	4.71	2.66	53.98	0.99	0.00	1.02	0.00	1.02
2022	4.38	2.49	51.52	0.99	0.00	0.98	0.00	0.98
2023	4.08	2.34	49.34	0.99	0.00	0.96	0.00	0.96
2024	3.81	2.20	47.41	0.99	0.00	0.94	0.00	0.94
2025	4.45	2.60	57.15	1.06	0.00	1.11	0.00	1.11
2026	3.99	2.36	52.75	1.03	0.00	1.04	0.00	1.04
2027	3.75	2.24	51.19	1.02	199.00	1.01	199.00	1.00
2028	3.53	2.13	49.78	1.02	8057.00	1.00	8057.00	1.00
2029	3.32	2.03	48.48	1.01	15,643.00	1.00	15,643.00	1.00
2030	3.13	1.94	47.29	1.01	22,938.00	1.00	22,938.00	1.01
2031	2.95	1.85	46.21	1.00	29,935.00	1.00	29,935.00	1.00
2032	2.78	1.77	45.21	1.00	36,613.00	1.00	32,161.89	0.99
2033	2.62	1.69	44.31	1.00	42,955.00	1.00	32,190.41	0.97
2034	2.47	1.62	43.48	1.00	48,955.00	1.00	32,215.72	0.95
2035	2.33	1.55	42.70	1.00	54,798.00	1.00	32,234.62	0.93

network by 2035. Additionally, the upper limit of seawater utilization for toilet flushing is set at approximately 35% of domestic water use. Table 4 provides an overview of the parameter settings for each scenario, with the average values of them derived from 2021 to 2035.

Figure 7 illustrates the simulation results of WSDR, water demand, GDP, and population size for various scenarios. Among the simulated scenarios, Scenario 5, 7, and 8 demonstrated favorable performance. These three scenarios consistently maintained a WSDR greater than 1 for the majority of the simulation period, indicating a sufficient water supply and higher GDP growth rates compared to other scenarios. In terms of population dynamics, Scenario 5 did not experience population decline but instead showed a gradual increase, approaching the population capacity limit of 19 million. Scenarios 7 and 8 had a slightly negative impact on population growth, while the remaining scenarios led to rapid population outflow due to water shortages. Scenario 5 exhibited a low water demand, indicating its superiority in water management. Conversely, all scenarios except for Scenarios 5, 7, and 8 experienced water shortages, resulting in poor GDP growth rates. These results suggest that while the West River Water Diversion can provide temporary relief for Shenzhen's water issues, prioritizing water-saving technologies and accelerating the utilization of seawater resources would be more effective strategies for addressing long-term water scarcity challenges.

The WSDRs in Scenarios 5, 7, and 8 were consistently above 1 in most years, suggesting that there was unused water available during those periods. To assess the water-saving capacity, the scale of SDF and PRSFT that can maintain the WSDR at 1 in every single year, simulations were conducted, in which it was assumed that the DWDPC, WCI, and WCS change in the same proportion.

Table 5 provides the specific values for the unit water consumption, seawater processing capacity, and the amount of seawater used for flushing toilets that would maintain a WSDR of 1. It should be noted that the implementation of seawater utilization facilities, such as SDF and seawater-flush toilets in the model was assumed to begin in 2026. Analyzing the unit water consumption, it can be observed that WSDR will gradually decrease after the water diversion from the Xijiang River. To maintain WSDR at 1, a 2% reduction in the initial values of WCI, WCS, and DWDPC is required each year. If only seawater desalination is considered, the seawater treatment capacity needs to reach 1.5 million ton/day by 2035. On the other hand, constructing seawater flush toilet facilities alone can save a significant amount of freshwater. However, after 2032, the amount of seawater used for flushing toilets reaches its limit of 35% of domestic water demand, causing the WSDR to fall below 1. Based on the data from 2027 to 2031, using seawater for flushing toilets can save an equivalent amount of tap water or desalinated water. This means that if the seawater treatment capacity only needs to be 600,000 ton/day by 2035 if PRSFT reaches 100%. According to Table 5, Eq. 2 approximately holds between 2026 and 2035.

$$\mathrm{WD_I} + 363563X = 611100 + \mathrm{RSW} \tag{2}$$

where $\mathrm{WD_I}$ is the water demand for the year I under the situation that unit water consumption takes the value in 2021 and water supply is sufficient, I ranges from 2026 to 2035, X is the ratio of unit water consumption in a future year to unit water consumption in year 2021, and RSW is the required amount of seawater utilization when unit water consumption is X times unit water consumption in year 2021. $\mathrm{WD_I}$ can be easily calculated using SD model. Then, with Eq. (2), we can clearly know the relationship between X and RSW and their values in year I can be planned.

The poorly performing scenarios also provided valuable insights: (1) Implementing population control policies had limited benefits. Reducing the population growth only led to a minor decrease in population size, which had almost no effect in alleviating the water crisis. Ultimately, both water crisis and population outflow continued to occur. (2) When water usage was restricted, further stimulating economic development through policies only yielded minor economic benefits. Even if the expected GDP growth rate increased to 1.1 times the original rate, the economy was only marginally stimulated, while both population and ecological water sectors were suppressed. (3) Adjusting economic structure showed potential in promoting economic development, raising the upper limit of economic growth and alleviating water pressure. (4) Reusing reclaimed water had the potential to increase water supply capacity, but its impact was limited in Shenzhen. (5) Developing the ecological sector resulted in a slight increase in water shortage, implying that it may not be the most effective solution for addressing the water crisis in the city.

Strategy proposal and recommendations

Taking above considerations into account, the water resources management strategy can be outlined as follows: (1) Significantly enhance water-saving capacity and prioritize the construction of seawater utilization facilities to meet the requirements of Eq. 2. (2) The priority for construction should be given to seawater-flush toilet facilities over seawater desalination facilities until the maximum amount of seawater used for flushing toilets is reached. (3) Implement various measures to reduce water demand, including optimizing industrial structure, limiting population size, increasing water reuse rates, and continuing ecological construction. With respect to the strategy, desalinated seawater will be a crucial source of water for domestic water in Shenzhen and can also serve as a supplementary source for other industrial water needs. And seawater that used for toilet flushing can reduce the demand for freshwater from other sources, with lower water treatment costs, making it a viable alternative for freshwater in toilet flushing, and it will be a crucial source of water for domestic water, too.

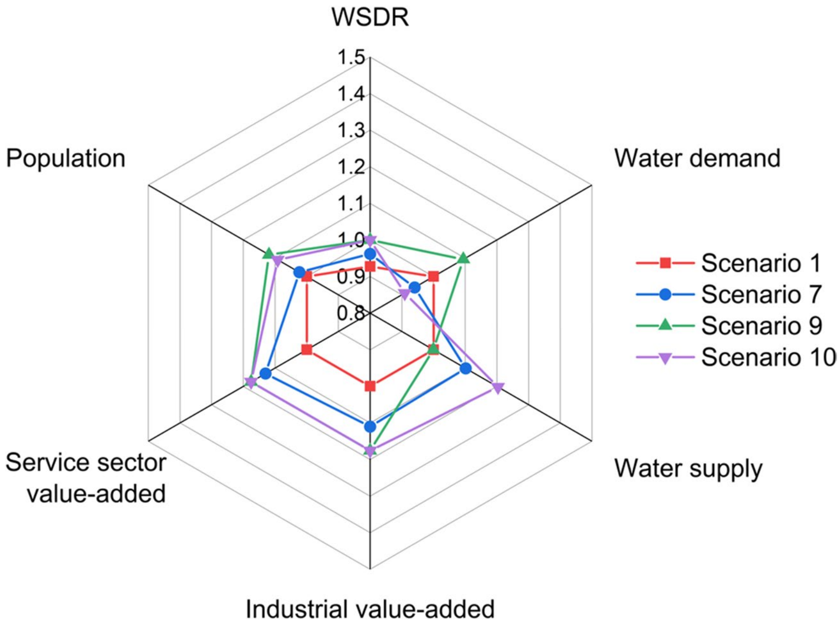
To explore the effectiveness of the proposed strategy, two extreme scenarios were designed as follows: (1) Scenario 9: Focus on improving water conservation capability. In this scenario, the values of WCI, WCS, and DWDPC are set to the specified values in Table 5, while keeping all other parameters unchanged. (2) Scenario 10: Focus on constructing SDF. In this scenario, the volume of desalinated seawater to the values in Table 5, while keeping other parameters unchanged. Scenarios 1, 7, 9, and 10 were simulated, and the simulation results were processed using following methods: (1) No processing was applied to WSDR; (2) Divide the water demand values by the water demand value in scenario 1, and the reciprocal of the results was taken. (3) Divide other values by the corresponding values in scenario 1. The processed values are presented in Fig. 8. It can be observed that all scenarios outperformed Scenario 1 in terms of water resource management. Scenario 7 showed significant improvement, but it still fell short in overcoming the water shortage issue, resulting in a WSDR below 1 and lower performance in other aspects compared to Scenarios 9 and 10. Scenarios 9 and 10 exhibited deficiencies in water supply capacity and water conservation capability respectively, but their overall performance was greatly enhanced, indicating the effectiveness of the proposed strategy.

Discussion

As presented in the “Water demand simulation” section, rapid development of Shenzhen would result in a substantial increase in water demand from the economic sectors. However, the available water resources in Shenzhen are not sufficient to satisfy the growing demand, thereby leading to water scarcity issues. To address this impending risk, it is imperative to implement appropriate water resources management strategies. Given limited availability of local water resources, Shenzhen relies heavily on external water sources. Therefore, it is crucial to prioritize the utilization of seawater in future water resources management efforts.

Based on further simulations conducted in the “Scenario simulation and evaluation” section, we proposed a comprehensive strategy to address the imbalance between supply and demand. The core of this strategy was to ensure that water conservation capabilities and the amount of seawater utilization to satisfy the relation in Eq. 2. Additionally, the strategy would include supplementary measures including optimizing industrial structure, limiting population size and increasing water reuse rates that can contribute to alleviating the pressure of water shortage. By utilizing the established SD model and implementing the strategy, we transformed the methods for tackling the water scarcity problem into accessible indicators that can be readily used by policy makers. The strategy provided a high level of accuracy and flexibility, as policy makers can adjust their water resources management objectives in accordance with Eq. 2, while maintaining the effectiveness

Fig. 8 Simulation results for Scenarios 1, 7, 9, and 10



of the overall strategy. The simulation results demonstrate that Shenzhen has the capability to overcome its water shortage challenges by proactively increasing the utilization of seawater and enhancing water conservation capabilities. This study not only provides valuable references for enriching the planning content of Shenzhen but also opens up new directions for future research.

Compared to previous studies, this study developed a more comprehensive SD model for water resources management. In addition to considering the Dongjiang River, local water resources, reclaimed water and rain water, this study also incorporates seawater and the Xijiang River as important water sources. Hence, this study provided a more accurate representation of the water supply side. Moreover, this study identified seawater utilization and water conservation capacity as the primary factors influencing the WSDR in Shenzhen, highlighting the significance of these factors, and thereby offering a clearer focus of water resources management in Shenzhen.

However, this study still has many limitations. Factors influencing the WSDR encompass a range of complex subsystems such as hydrological, economic, environmental, political, and social aspects. Hence, building comprehensive water resources SD models requires a rich interdisciplinary knowledge and experience, posing significant challenges for researchers. Consequently, current water resources SD models usually consider only two to three subsystems, necessitating further expansion of the scope of SD models. In the future, the influence of water prices and political factors can be incorporated into the model proposed in this study to enhance its accuracy, and the model's representation of seawater utilization facilities and reclaimed water reuse facilities can also be further enriched. Additionally, modeling often requires the omission of many details, which leads to misleading results. This deficiency can be compensated for by employing abundant statistical data and causality tests. The output of SD methods depends on input variables, and SD models themselves lack analytical capabilities, resulting in suboptimal planning decisions. However, SD methods have a strong capability to be combined with other approaches, allowing for the integration of other tools such as game theory, ANN, and MOP with SD models to enhance decision-making capabilities. Another problem with SD is that spatially distributed data cannot be modeled easily. The model proposed in this study does not further refine the spatial scope to various districts, which fails to capture the uneven distribution of water supply and demand in space in Shenzhen. Besides, uncertainties in both the data and model structure as well as simplified representations of complex system dynamics would lead to varying strategies, which should be further investigated in the future research works.

Conclusion

A system dynamics model was developed to analyze the water resource system in Shenzhen city. The simulation results revealed a potential water supply–demand imbalance in the future, which could significantly impede the city's development. Through a sensitivity analysis of the water resource system in Shenzhen, six key factors that have a significant impact on water demand were identified. By considering these factors and the abundant seawater resources as control variables, simulations were conducted to evaluate the WSDR, GDP, and population size. The findings emphasized that the importance of integrating seawater utilization and developing water-saving technologies to achieve sustainable development goals. Additionally, optimizing industrial structure, increasing wastewater reuse, and controlling population growth were identified as essential measures, and it is crucial for Shenzhen to maintain the utility relationship among various factors to ensure a balanced and efficient water resources management systems. We believe that these research findings will provide policymakers with valuable insights to address existing water allocation issues, mitigate system risks associated with excessive economic development, resolve water shortages in water consumption sectors, and reduce uncertainties and potential risks in decision-making related to water resource allocation.

Appendix

Table 6 Main variables and equations in the SD model

Variables	Equations	Units
GDP	GDP = agricultural value-added + industrial value-added + service sector value-added + construction industry value-added	10^4 yuan
Volume of recycled water	Volume of recycled water = IF THEN ELSE (upper limit of water demand > available recycled water volume, available recycled water volume, upper limit of water demand)	10^4 m^3
Total water supply	Total water supply = domestic water supply + imported water supply	10^4 m^3
WSDR	WSDR = total water supply/total water demand	Dmnl
Area of parks	Area of parks = INTEG (increase in the area of park, 21,559)	Hectare
Increase in the area of parks	Increase in the area of parks = IF THEN ELSE (water shortage impact 4 ≤ 0, area of parks × growth rate of parks, area of parks × growth rate of parks – water shortage impact 4)	Hectare
GRIV	GRIV = table < time >	Dmnl
GRAV	GRAV = table < time >	Dmnl
GRSV	GRSV = table < time >	Dmnl
Industrial value-added	"Industrial value-added" = INTEG ("increase in industrial value-added," 9528)	10^4 yuan
Increase in industrial value-added	"Increase in industrial value-added" = IF THEN ELSE (water shortage impact 2 ≤ 0, "industrial value-added" × GRIV, "industrial value-added" × GRIV – water shortage impact 2)	10^4 yuan
Industrial wastewater discharge	Industrial wastewater discharge = industrial wastewater discharge coefficient × industrial water demand	10^4 m^3
Industrial water demand	Industrial water demand = WCI × "industrial value-added"	10^4 m^3
Population increase	Population increase = IF THEN ELSE (water shortage impact 1 ≤ 0, total population × growth rate of population (GRP), total population × population growth rate – water shortage impact 1)	10^4 people
Domestic wastewater discharge	Domestic wastewater discharge = domestic wastewater discharge coefficient × domestic water demand	10^4 m^3
Increase in greenway length	Increase in greenway length = IF THEN ELSE (water shortage impact 5 ≤ 0, Length of greenways × growth rate of greenway length, length of greenways × growth rate of greenway length-water shortage impact 5)	Kilometer
Water shortage impact 1	Water shortage impact 1 = water shortage quantity/per capita domestic water demand × proportion of domestic water usage × 0.2	10^4 people
Water shortage impact 2	Water shortage impact 2 = water shortage quantity × proportion of industrial water usage × 0.3/WCI	10^4 yuan
Water shortage impact 3	Water shortage impact 3 = water shortage quantity × proportion of service sector water usage × 0.3/WCS	10^4 yuan

Acknowledgements We thank the editor and two anonymous reviewers for their insightful comments to help us improve this manuscript. Also, we would express our thanks to the following agencies for funding this work: Ministry of Science and Technology of the People's Republic of China, National Natural Science Foundation of China, Qinghai Science and Technology Bureau, Shenzhen Science and Technology Innovation Committee and Shenzhen University.

Author contribution Guangzhi Zheng: data curation, writing—original draft preparation, software and simulation. Jing-Cheng Han: idea and conceptualization, methodology, writing—reviewing and editing. Ping Li: data curation, visualization. Bing Li: conceptualization, writing—reviewing and editing. Xiaofeng Wu: project administration, supervision. Muhammad Ahmad: writing—reviewing and editing. Yuefei Huang: project administration, writing—reviewing and editing.

Funding This research was financially supported by the China National Key R&D Program (No. 2022YFC3201803), Major Basic Research Development Program of the Science and Technology, Qinghai Province (2021-SF-A6), National Natural Science Foundation of China (No. 51809007), and Fundamental Research Funds for the Shenzhen Science and Technology Innovation Committee (No. 20220807162217001).

Data availability Applicable.

Declarations

Ethics approval This paper has not been published or is being considered for publication elsewhere.

Consent to participate Not applicable.

Consent for publication The authors are giving consent to publish the article in the submitted journal.

Competing interests The authors declare no competing interests.

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