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# Assessing the Vulnerability of Water Resources System Using VSD-SD Coupling Model: A Case of Pearl River Delta

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**Abstract:** Water plays an essential role in social and economic sustainable development, and the relationship between socio-economic development and water resources sustainable utilization has been an important issue in water resources management. We aim to propose a water resources vulnerability assessment index with the dimensions of exposure, sensitivity and adaptability, and establish a water resources system model over the Pearl River Delta network river region based on the Vulnerability Scoping Diagram (VSD) framework and System Dynamics (SD) model. The city of Zhongshan, which is located in the Pearl River Delta is used as a case study. The vulnerability of the water resources in Zhongshan from 2021 to 2050 is simulated in four different scenarios (normal, technical innovation, social economic improvement, and comprehensive development models). The results showed that the vulnerability in all four scenarios span three grades in 30 years, including moderately vulnerable, slightly vulnerable, and not vulnerable. Among them, similar trends were found between scenarios 1 and 3, and between scenarios 2 and 4. Furthermore, the vulnerability level in scenarios 2 and 4 was lower than that in scenarios 1 and 3. The vulnerability of both scenarios 2 and 4 decreased first and then increased, with the average values of 24.64 and 27.63, respectively. Scenario 2 experienced 7 years of not vulnerable (2034 to 2040) and 23 years of slightly vulnerable (2021–2033, 204–2050), scenario 4 experienced 5 years of not vulnerable (2032–2036), 21 years of slightly vulnerable (2021–2031, 2037–2046), and 4 years of moderately vulnerable (2047–2050). Although the vulnerability of scenario 4 was slightly worse than scenario 2, its adaptability to economic and social development, water resources, and water environment was much higher than scenario 2. Considering the extent of socio-economic development and the level of adaptability of the local water resources and water environment, the study concluded that the comprehensive development model is more suitable for cities in the network river area. In this scenario, sustainable water use and management can be made possible through policy regulation that encourages higher water efficiency, sewage reuse rate, and centralized sewage treatment rate.

**Keywords:** water resources system; vulnerability; system dynamics (SD); Vulnerability Scoping Diagram (VSD); network river region

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## 1. Introduction

Water resources play a critical role in maintaining human life and our ecosystem, and sustainable utilization of water resources is the key to sustainable development of society and economy [1,2]. With the continuous economic development and accelerated urbanization, the increase in industrial waste and urban sewage production may lead to more severe water pollution, which in turn, may further increase the vulnerability of the water resources system [3]. The degree of vulnerability of the water resources system, refers to the sensitivity and adaptability of a system [4]. Studies have shown that vulnerability assessment can explain the ability of water resources to meet the regional water demand under pressure [5–8].

Research on the vulnerability of water resources began in 1968, when Marget presented the term "underground water vulnerability" [9]. Since then, numerous scholars have presented different opinions on this concept. The water resources are vulnerable when external disturbance (e.g., climate change, human activities) makes it difficult for the system to recover to its original status [10]. Vladimir Živanović pointed out that the groundwater vulnerability assessment concept was used to describe how groundwater is vulnerable to contaminants released at the surface as a function of geological, hydrological, and hydrogeological environmental condition [11]. Albinet et al. believed that underground water vulnerability refers to the possibility of pollution sources infiltrating or spreading from the surface into the underground water [12]. Foster et al. highlighted that the vulnerability of the aquifer and the pollution load produced by human activities are the main causes of underground water pollution and proposed the concept of "aquifer vulnerability" [13]. Early research mostly focused on underground water and water quality. In recent years, under the demands of continued socio-economic development, the increasing industrial water consumption and sewage production are responsible for further deterioration of the surface water quality. Meanwhile, such conditions have also spurred an increase in research on water resources vulnerability, especially surface water vulnerability. Kulshreshtha considered that water resource vulnerability is the nature of the water resource being vulnerable to damage [14]. Perveen et al. believed that this concept involved regional vulnerability because of the limitation of water availability and concentrated water utilization [15]. Afterwards, the concept and connotation of water resources vulnerability have been improved and developed continuously and experienced a process from single groundwater or surface water vulnerability to comprehensive water resources vulnerability, from single water quality to water quality and water quantity combination [16]. Existing studies have shown that water resources vulnerability represents a characteristic and status in which the quantity and quality of groundwater and surface water are affected by internal and external factors and lead to system imbalance, and includes the adaptability and sensitivity of water resources system to external driving factors. The DRASTIC, Legrand, EPIK, and SEPPAGE vulnerability index models have been widely used for the vulnerability analysis [17,18]. Combining the above models with new technologies, such as global information systems is a research hotspot. Rahman applied the GIS-based DRASTIC model, to evaluate the vulnerability of the table water aquifer in Aligarh in India [19]. Pathak et al. analyzed the vulnerability in Kathmandu using the same method and highlighted that vulnerability is important to underground water management [20]. In addition, the study of water resource vulnerability under climate change is also a current research hotspot with the global warming. Strzepek et al. analyzed the water resource vulnerability in the Nile River in Egypt under the conditions of the changing climate [21]. Vörösmarty et al. studied water resource vulnerability through population growth and climate change from 1985 to 2025 [22]. Fowler et al. studied the vulnerability of the water resource system in Yorkshire in England in relation to climate change [23]. Gui et al. analyzed the vulnerability of the Lancang River Basin water resources system due to climate change and mapped the spatiotemporal characteristics of the water resource vulnerability in the LRB [24]. Existing research mainly focusses on vulnerability comparisons among different areas and rarely refers to the evolution law of the vulnerability of the water resource system under different development models.

In this study, Zhongshan City, an archetypal city in the Peral River Delta network river region in Guangdong Province, China is selected as case study. With its advantages in geography and rapid economic development, the Pearl River Delta river network region brings about a sharp rising in water utilization, as well as industrial waste and urban wastewater emissions, which easily leads to more severe water pollution. Considering the characteristics of the network river region, the water resource system model is constructed using the system dynamics method based on the VSD evaluation index system. The vulnerability of the water resource system from 2021 to 2050 is then evaluated using the synthetic index method. The changes in the water resources systems vulnerability are modeled under four different modes of development. The results can enable policy makers to choose the most appropriate policy interventions for the socio-economic development and sustainable water use in the network-river regions.

## 2. Study Area

Zhongshan City is located in the middle of the Pearl River Delta in China at 22°11′ to 22°47′ N and 113°09′ to 113°46′ E, in the subtropical monsoon climate. The city covers a total urban area of 1783 square kilometers with a population of 4.4181 million and the GDP of RMB 315.159 billion in 2020, including RMB 140.417 billion of the industrial added value [25]. Zhongshan City is located downstream of the river network area of the Pearl River Delta, going through Modaomen, Hengmen, and Hongqili waterways and flowing to the ocean. The Hongqili waterway is in the north of the Beijiang River. The lower branches of the Donghai waterway in the north, Jiya and Xiaolan waterways, join to form the Hengmen waterway. There are Xihai and Modaomen waterways in the west and Guizhou, Huangpu, and Huangshali waterways run across Zhongshan City to create the crisscross river network zone (Figure 1). Zhongshan is rich in water resources, but the majority is originated or channeled from elsewhere. The multi-year average total water storage volume is 1.738 billion $m^3$, in which the average surface water storage is 1.686 billion $m^3$, and the average groundwater storage is 258 million $m^3$ [26].

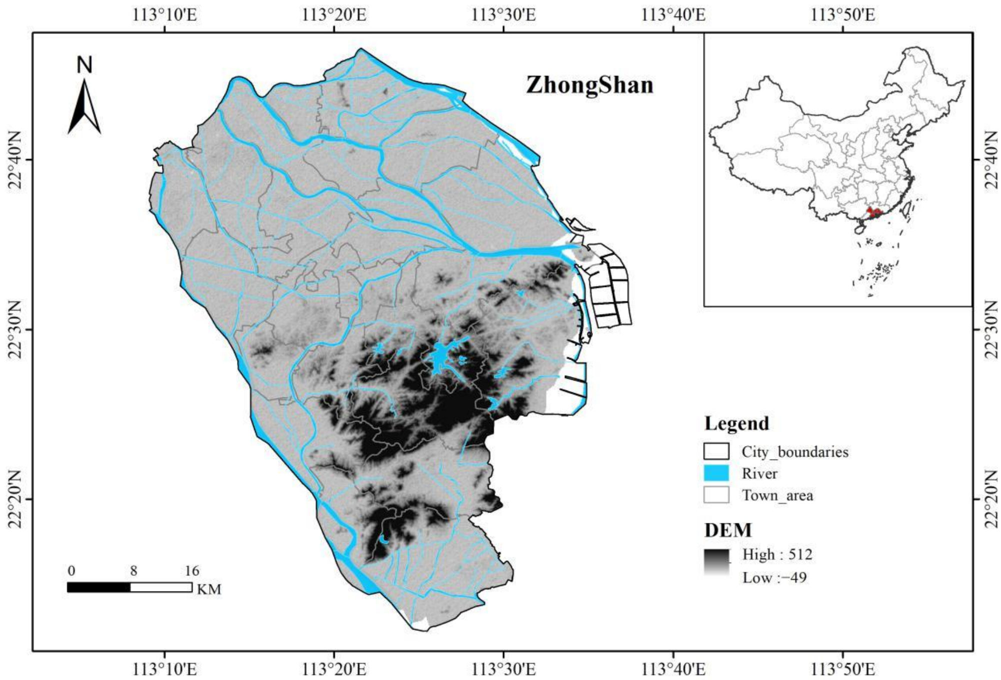


**Figure 1.** Location of Zhongshan city.

In recent years, along with the rapid economic and industrial development, the demand for water resources increased drastically as well. From 2001 to 2020, the total consumption of water in the city increased about 167% from 0.88 billion to 1.469 billion $m^3$. Agricultural water consumption increased from 0.474 billion to 0.493 billion $m^3$, essentially unchanged. Industrial water consumption rose 0.89 times from 0.249 billion to 0.471 billion $m^3$. Domestic water consumption increased 2.24 times from 0.156 billion to 0.505 billion $m^3$, indicating that the shortage of water resources and the contradiction between water supply and demand have intensified. The main water resource problems in Zhongshan include: (1) the growing population and urbanization increases domestic water demand; (2) the industrial production (including the thermal power industry) consumes a large amount of water with a low reclamation rate; (3) the quantity of COD discharged into the river increases, leading to serious pollution caused by water shortage which has an adverse impact on economic growth.

## 3. Methodology

### *3.1. System Dynamics (SD) Method*

Presented by Forrester in 1956, SD combines the relevant theories and methods of the application control, information, and decision theories and integrates structure and function, material and information, science, and experience [27]. SD integrates natural science and social science horizontally and is suitable for dealing with the high-order, nonlinear, multi-feedback, and complex time-varying system problems. Hence, SD is an ideal method to explore the motion law of the complex system [28]. SD is used to study the system problems through combination of quantitative and qualitative, overall thinking and analysis, reasoning, and synthesis. As an effective tool of modern scientific decision-making and prediction and known as the lab of strategies, it is widely used in regional macro development strategies' decision making [29]. SD utilizes the first-order differential equation to describe how the rate of change of the system state variables relates to other state variables or specific inputs. The state of change is then decomposed into several flow rates according to the target system and research needs. This way, the system can be more clearly defined, which is conducive to modeling and finding the control points of the system.

The essence of SD is a set of first-order differential equations with time-delay, which describes the dependence of the rate of change of each state variable or specific input according to the actual condition of the system and the requirement of the research to make the concept of the system clear and conducive for modeling and identifying the control points of the system. In the SD model, the flow rate equation describes the change regularity of the state variables (flow level) and is expressed using Euler's numerical integration. The general form of the equation is:

$$L.K = L.J + (IR.JK - OR.JK) \times DT \tag{1}$$

where $L.K$ and $L.J$ are the flow bit vectors at times $K$ and $J$, respectively; $IR.JK$ and $OR.JK$ are the inflow rate vector and the outflow rate vector, respectively;$DT$ is the time period from the past $J$ time to the present $K$ time.

By modifying the Formula (1), we obtain Equation (2), which is the derivative of the flow position that is equal to the algebraic sum of the inflow rate and the outflow rate. Obviously, the system dynamics model is a first-order differential equation set determined by the above-mentioned vector equations.

$$\frac{L.K - L.J}{DT} = \frac{DL}{DT} = IR.JK - OR.JK \tag{2}$$

where $DL$ is the difference of the stream bit vector at the time of $K$ and $J$.

SD can be divided into seven steps [30,31]: a. determination of the simulation target; b. determination of the system boundary; c. design of the system feedback mechanism; d. construction of the system flow diagram; e. establishment of the equation; f. model calibration and verification; and g. model implementation.

The water resource system is mainly composed of subsystems such as water supply, water demand, economy, population, and water environment. Each subsystem is the result of interaction of many factors, and the multiple feedback relations of the water resource system are formed through the mutual influence and restriction relations of variables among subsystems. The SD model has four main variables: level (L), rate (R), auxiliary (A), and constant variables (C). According to the present situation and development trend of the research area, we use the observed yearly data from 2015 to 2020 to validate the model and then simulate from 2021 to 2050. The water resource system model of Zhongshan City is established based on the Vensim-PLE platform, which is industrial-strength simulation software for improving the performance of real systems. The basic framework of the model is shown in Figure 2, and the flow graph of the water resource system is shown in Figure 3. The full names of the variables are presented in Table A1.

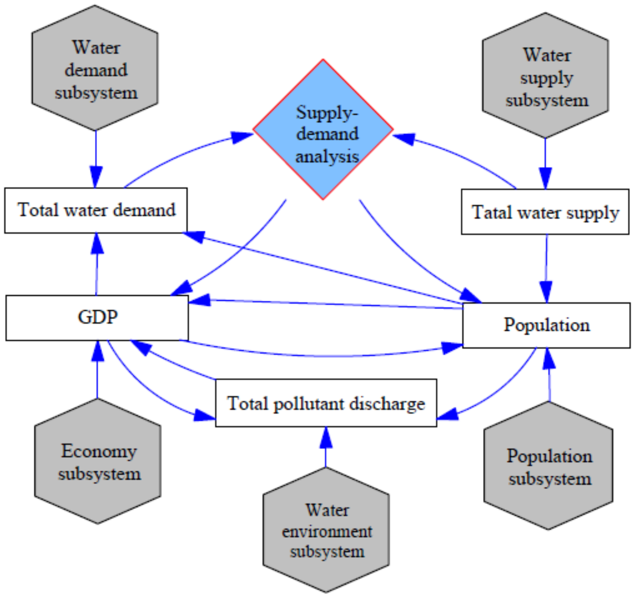


**Figure 2.** The framework of the water resource system.

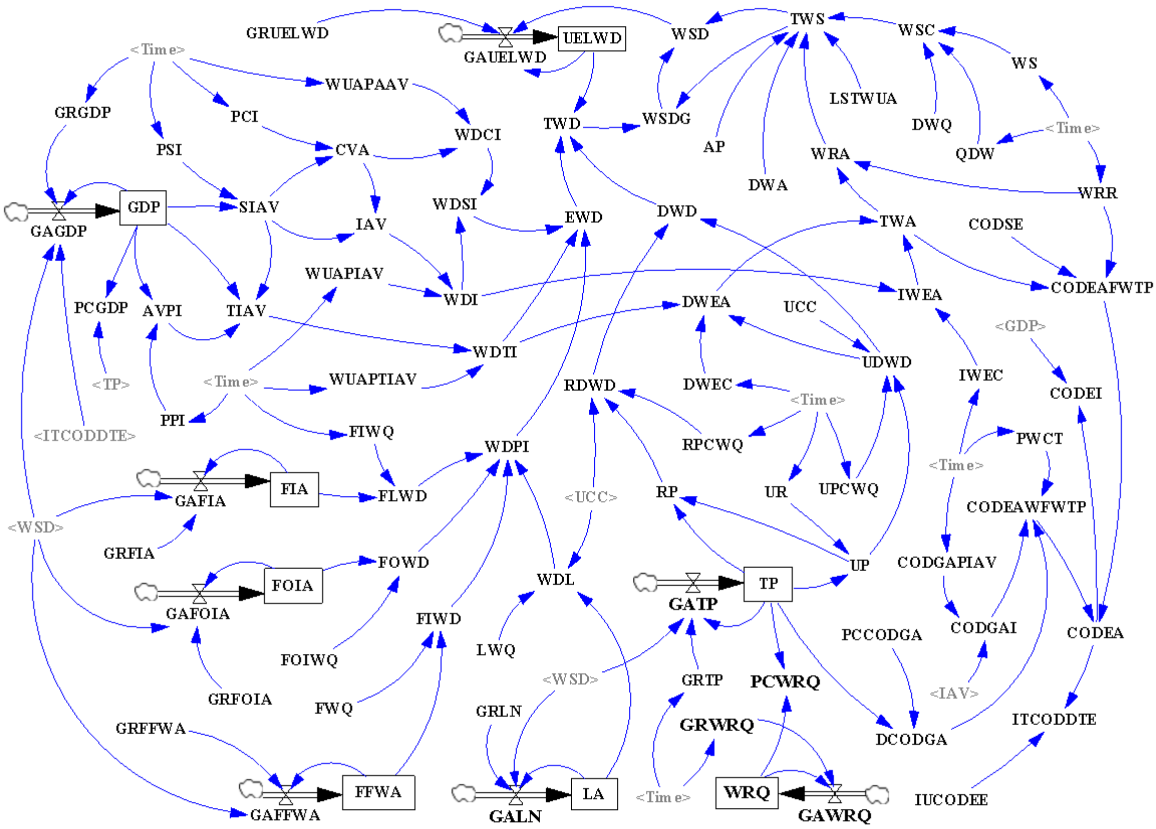


**Figure 3.** The flow graph of the water resource system.

### 3.2. Construction of Water Resources Vulnerability Index System

#### 3.2.1. Evaluation Index System Construction

The Vulnerability Scoping Diagram (VSD) conceptual framework was first proposed by Polsky in 2007 [32] which has been widely used in the analysis of the vulnerability of coupled systems. The construction of the vulnerability evaluation index system of the water resource system is designed to seek a series of representative characteristic variables that can directly reflect the degree of vulnerability of the system. According to the principles of opposition, relative stability, comparability, and operability for index selection and referring to the research results related to the water resource evaluation index system [33,34], this study focuses on three subsystems of water resource, water environment, and social economy to establish the vulnerability evaluation index system of the water resource system. The three dimensions of analysis are exposure, sensitivity, and adaptability. We adopt the "criteria layer–element layer–indicator layer" to establish a water resource system vulnerability assessment index system with three sub-systems of water resources, water environment, and social economy. As each level involves a lot of content, this article selects more important indicators that can reflect the characteristics of the research area for research.

The water resource subsystem selects per capita water resources (PCWRQ), water consumption per RMB 10,000 of industrial added value (WUAPIAV), and annual water supply guarantee rate (YWSGR) as the evaluation indices of the vulnerability of the system [35]. PCWRQ is a recognized standard index for measuring the renewable freshwater resource condition of a country or a region and reflecting the water condition of the regional development. WUAPIAV reflects the industrial production level and water consumption level of a region, where a larger value indicates greater industrial water demand and industrial water pressure. YWSGR is an important index used to evaluate the annual regional water supply and demand capability.

Zhongshan City is a textbook example of the river network area. Existing research has emphasized that sewage discharge is the main source of damage to the water environment [36]. In this study, RWCT and CODEI, which reflects the intensity of sewage treatment and the emission situation of COD, respectively, are used to evaluate the water environment sub-system. PCGDP, UR, and GRGDP are critical indexes for the vulnerability of the system [37]. PCGDP is an important index used to measure the economic power of a country or a region. UR measures the degree of urbanization. GRGDP reflects the sustainability of the regional economic development. The exposure indicators include the rate of centralized sewage treatment, sensitivity indicators include per capita water resources, GDP annual growth rate and water consumption of RMB 10,000 of industrial added value, and adaptability indicators include per capita GDP, urbanization rate, and water supply guarantee rate.

#### 3.2.2. Weight Determination of the Index System and the Scoring Criterion

The weight of each evaluation index determines the contribution of each factor to the vulnerability of the water resource system. Here, we use the analytic hierarchy process (AHP) to confirm the weight of each evaluation index. Firstly, a judgment matrix is constructed by pairwise comparison of the level indicators through expert scoring. Then, the level single sorting and total level sorting and their consistency test are carried out. More detailed calculations can be retrieved from [38].

The index system adopts a scoring range from 0 to 100 with five levels. The scores are determined by comparing the actual and predicted indices to the scoring criteria. The limit theory is adopted for the indexes in the open interval. The scoring criterion of the index systems is based on existing research results [39,40], as shown in Table 1.

**Table 1.** Evaluation index scoring criterion and weight.

| Criteria Layer | Element Layer | Index Layer | Unit | Weight | The Vulnerability Grade of Water Resource System | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | Extremely Vulnerable | Very Vulnerable | Moderately Vulnerable | Slightly Vulnerable | Not Vulnerable |
| Exposure | Water environment | RWCT (−) | % | 0.1038 | [0, 20] | (20, 40] | (40, 60] | (60, 80] | (80, 100) |
| | | CODEI (+) | kg | 0.3130 | (6, +∞) | (3, 6] | (2.25, 3] | (1.5, 2.25] | [0, 1.5] |
| Sensitivity | Load on population and economy | PCWRQ (−) | $m^3$/people | 0.1528 | [0, 1000] | (1000, 1500] | (1500, 2000] | (2000, 3000] | [3000, +∞) |
| | | GRGDP (−) | % | 0.0221 | [0, 8] | (8, 11] | (11, 14] | (14, 20] | (20, +∞) |
| | | WUAPIAV (+) | $m^3/10^4$ RMB | 0.0447 | (200, +∞) | (90, 200] | (30, 90] | (10, 30] | [0, 10] |
| Adaptability | Economic, social and water supply | PCGDP (−) | $10^4$ RMB | 0.0802 | [0, 1] | (1, 2.5] | (2.5, 5] | (5, 10] | (10, +∞) |
| | | UR (−) | % | 0.0221 | (80, 100) | (50, 80] | (35, 50] | (20, 35] | [0, 20] |
| | | YWSGR (−) | % | 0.2613 | [0, 75] | (75, 82] | (82, 90] | (90, 95] | (95, 100) |
| Scoring Criterion | | | | | 100~80 | 80~60 | 60~40 | 40~20 | 20~0 |

Note: (+) indicates a positive indicator, the larger the indicator, the more fragile the system is; (−) indicates a negative indicator, the larger the indicator is, the better it is to reduce the fragility of the system.

### 3.2.3. Vulnerability Calculation

The synthetic index shows the degree of comprehensive influence of the factors on the system. This index establishes the mathematical induction and statistics with the contribution indexes of these factors and calculates the value representing the condition of the system through the mathematical relationship based on the single index. As a common evaluation method, the synthetic index has the advantages of strong comprehensiveness and comparability [41]. This method is applied in this paper to evaluate the vulnerability of the water resource system.

Firstly, the raw data is made dimensionless and homogenized. The larger the value, the greater the exposure, sensitivity, and adaptability, as shown in Equation (3). The smaller the value, the larger the exposure, sensitivity and adaptability larger, as shown in Equation (4).

$$Z_i{}^* = \frac{Z_i - Z_n}{Z_m - Z_n} \tag{3}$$

$$Z_i{}^* = 1 - \frac{Z_i - Z_n}{Z_m - Z_n} \tag{4}$$

where $i$ is the number of indexes, $i = 1, 2, \ldots 8$; $Z_i{}^*$ is the standardized index value; $Z_i$ is the original index value; $Z_m$ is the maximum value; $Z_n$ is the minimum value.

Exposure ($f(E_j)$), sensitivity ($f(S_k)$), and adaptability ($f(A_l)$) are, respectively, composed of the indicator variables in Table 1, and the three indexes are calculated by weighting and summing, respectively, see Formulas (5)–(7). For calculation of the vulnerability of a water resources system, see Formula (8).

$$f(E_j) = \sum_{j=1}^{2} w_j E_j \tag{5}$$

$$f(S_k) = \sum_{k=1}^{3} w_k S_k \tag{6}$$

$$f(A_l) = \sum_{l=1}^{3} w_l A_l \tag{7}$$

$$WRSVD = f(E, S, A) \tag{8}$$

where $j, k, l$ are the number of indicators; $w$ is the weight; $E_j$ is the exposure index value; $S_k$ is the sensitivity index value; $A_l$ is the adaptability index value; $WRSVD$ represents the vulnerability of the water resources system; $E$ is the exposure; $S$ is the sensitivity; $A$ is the adaptability. A larger $WRSVD$ indicates higher vulnerability and instability of the system. Conversely, a lower vulnerability indicates higher stability of the system. The index values are between 0 and 100.

## 4. Results and Discussion

### *4.1. Model Validation*

After constructing the SD water resources model, four methods (i.e., visual test, running test, historical test, and sensitivity) are generally used to calibrate the SD model in order to ensure the consistency between the simulation results and the actual system. Given that the first two methods have been implemented in the modeling process, here we mainly verified the last two.

#### 4.1.1. Historical Test

The parameters of the model are based on population, economy, resources, environment, and other data in the Statistical Yearbook and Water Resources Bulletin of Zhongshan City from 2005 and 2010. The state equation, constant equation, and the table function are used to establish the quantitative relationship among all variables. By intuitively and operationally testing the model, it was found that the causality and units of the model were in line with reality. The simulated total population (TP), GDP, and total water demand (TWD) were compared with the real values from 2015 and 2020 for the historical test. The result shows that the errors between the simulation values and the historical values are less than 10% (Table 2), which is the standard basis to judge whether a model is credible [42]; thus indicating a high reliability of the model.

**Table 2.** The error statistics of model simulation results.

| Year | TP ($10^4$ People) | | | GDP ($10^4$ RMB) | | | TWD ($10^4$ $m^3$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Simulation Value | Historical Value | Error (%) | Simulation Value | Historical Value | Error (%) | Simulation Value | Historical Value | Error (%) |
| 2015 | $3.21 \times 10^2$ | $3.21 \times 10^2$ | 0.00 | $2.71 \times 10^7$ | $2.71 \times 10^7$ | 0.00 | $1.57 \times 10^5$ | $1.58 \times 10^5$ | −1.01 |
| 2016 | $3.23 \times 10^2$ | $3.23 \times 10^2$ | −0.04 | $2.71 \times 10^7$ | $2.83 \times 10^7$ | −4.22 | $1.54 \times 10^5$ | $1.50 \times 10^5$ | 2.11 |
| 2017 | $3.26 \times 10^2$ | $3.26 \times 10^2$ | −0.06 | $2.83 \times 10^7$ | $2.94 \times 10^7$ | −3.73 | $1.52 \times 10^5$ | $1.44 \times 10^5$ | 5.56 |
| 2018 | $3.31 \times 10^2$ | $3.31 \times 10^2$ | −0.10 | $2.94 \times 10^7$ | $3.05 \times 10^7$ | −3.77 | $1.51 \times 10^5$ | $1.42 \times 10^5$ | 6.59 |
| 2019 | $3.38 \times 10^2$ | $3.38 \times 10^2$ | −0.11 | $3.05 \times 10^7$ | $3.10 \times 10^7$ | −1.57 | $1.52 \times 10^5$ | $1.48 \times 10^5$ | 2.28 |
| 2020 | $4.41 \times 10^2$ | $4.42 \times 10^2$ | −0.12 | $3.10 \times 10^7$ | $3.15 \times 10^7$ | −1.56 | $1.57 \times 10^5$ | $1.47 \times 10^5$ | −1.48 |

#### 4.1.2. Sensitivity Analysis

Sensitivity analysis is an important method to validate model effectiveness. An effective model with good robustness should have low sensitivity [40]. Sensitivity analysis examines the influence of parameter changes on the variable output results of the model by adjusting the parameters in the model [43]. This paper uses the sensitivity model to undertake the sensitivity analysis of the system. The formula is as follows [44]:

$$S_Q = \left| \frac{\Delta Q_{(t)}}{Q_{(t)}} \frac{X_{(t)}}{\Delta X_{(t)}} \right| \tag{9}$$

where $t$ refers to the time; $S_Q$ refers to the sensitivity of the level variable $Q$ to the parameter $X$; $Q_{(t)}$ and $X_{(t)}$ refer to the values of $Q$ and $X$ at Time $t$, respectively; and $\Delta Q_{(t)}$ and $\Delta X_{(t)}$ refer to the increments of $Q$ and $X$ at Time $t$, respectively.

For $n$ level variables $(Q_1, Q_2, \ldots, Q_n)$, the average sensitivity of any parameter at Time $t$ is

$$S = \frac{1}{n} \sum_{i=1}^{n} S_{Q_i} \tag{10}$$

where $n$ refers to the number of level variables, $S_{Q_i}$ refers to the sensitivity of $Q_i$, and $S$ refers to the average sensitivity of parameter $X$ to $n$ level variables.

The simulation and modeling of the water resource system involves numerous parameters and variables. Thus, five key parameters and six variables in the system were selected to analyze the data between 2005 and 2010. By changing one parameter at a time (increasing by 10%), we were able to analyze its influence on the other six variables. The sensitivity of the parameter to each variable can be calculated according to Formula (9). The average sensitivity of each variable to a parameter, that is, the sensitivity of this parameter to the system model, can be calculated according to Formula (10). The sensitivity analysis results (see Table 3) show that the sensitivity of parameters is less than 10%, indicating the low sensitivity of the system to the parameters and strong system stability [40,44]. Combining the historical test results, this model is suitable for simulating the actual system of Zhongshan City.

**Table 3.** Results of sensitivity analysis.

| *X* / *Q* | GRTP | GRGDP | GRFOIA | GRLN | WRR |
|---|---|---|---|---|---|
| TP | 0.03347 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| GDP | 0.00000 | 0.04645 | 0.00000 | 0.00000 | 0.00000 |
| WDPI | 0.00000 | 0.00000 | 0.00440 | 0.00017 | 0.00000 |
| DWD | 0.03287 | 0.00000 | 0.00000 | 0.00000 | 0.00000 |
| CODEA | 0.01483 | 0.02895 | 0.00000 | 0.00000 | 0.04386 |
| WRA | 0.00960 | 0.03576 | 0.00000 | 0.00000 | 0.49590 |
| *S* | 0.01513 | 0.01853 | 0.00073 | 0.00003 | 0.08996 |

### *4.2. Water Resource System Vulnerability in Different Scenarios*

The vulnerability of the water resource system was simulated under four different scenarios. The Normal development model describes the business-as-usual scenario, where all the indicators are steadily increasing. Based on this scenario, three other scenarios are developed. The technical innovation development model is a scenario where parameters affecting water usage efficiency are modified; the social-economic improvement mode is a scenario where parameters related to social development are modified; and the comprehensive development mode is a combination of the previous two scenarios. By comparing the variations in the vulnerability of the water system under different developmental scenarios, it is then possible to demonstrate how policy regulations can be a useful approach for improving the reliability of the water resource system.

The schematics of the four scenarios are presented in Table 4. By using the simulation results of the four scenarios, in combination with the scoring and weights of the evaluation indexes, the vulnerability of the water resource system of Zhongshan City between 2021 and 2050 was calculated using the synthetic index weighted sum method introduced in Section 3.2.3. The results are shown in Table 5 and the specific parameters are shown in Table A2.

**Table 4.** Parameter setting schematics of the four different scenarios.

| No. | Scenario Name | Parameter Setting |
|---|---|---|
| 1 | Normal Development mode | Automatically feedback the analogue simulation in the normal development according to the development situation of the research area. |
| 2 | Technical Innovation Development mode | Strengthen water saving according to the development situation of the research area; adjusting WUAPIAV, WUAPAAV, WUAPTIAV, UPCWQ, RPCWQ, FIWQ, FOIWQ, FWQ, LWQ, and other parameters to be 80% of those of the normal development model and increase WRR and RWCT to be 1.2 times of those of the normal development. |
| 3 | Social Economic Improvement Development mode | Adjust the industrial structure proportions according to the development situation of the research area. Adjust PPI to be 95%, PSI to be 97%, and GRGDP, GRTP, and UR to be 1.2 times of those of the normal development model. |
| 4 | Comprehensive Development mode | Integrate scenarios 2 and 3 based on the normal development model. |

**Table 5.** The WRSVD of Zhongshan City in the four scenarios.

| Scenario Year | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 25.45 | 25.05 | 24.67 | 24.32 | 23.98 | 23.54 | 23.10 | 22.66 | 22.36 | 23.00 | 24.86 | 26.78 | 28.74 | 30.76 | 32.34 |
| 2 | 25.02 | 24.24 | 23.47 | 22.73 | 22.03 | 21.66 | 21.28 | 20.90 | 20.63 | 20.42 | 20.30 | 20.17 | 20.05 | 19.92 | 19.80 |
| 3 | 25.42 | 24.98 | 24.57 | 24.17 | 23.81 | 23.30 | 22.80 | 22.64 | 24.75 | 26.94 | 29.51 | 32.05 | 33.71 | 35.42 | 37.31 |
| 4 | 24.99 | 24.17 | 23.36 | 22.59 | 21.87 | 21.44 | 21.01 | 20.64 | 20.41 | 20.18 | 20.05 | 19.92 | 19.79 | 19.66 | 19.53 |
| **Scenario Year** | **2036** | **2037** | **2038** | **2039** | **2040** | **2041** | **2042** | **2043** | **2044** | **2045** | **2046** | **2047** | **2048** | **2049** | **2050** |
| 1 | 33.89 | 35.48 | 37.23 | 39.18 | 41.17 | 41.44 | 41.53 | 41.62 | 41.72 | 41.82 | 41.92 | 42.03 | 42.14 | 42.25 | 42.37 |
| 2 | 19.71 | 19.63 | 19.55 | 19.46 | 19.95 | 22.36 | 24.82 | 27.34 | 29.76 | 31.37 | 33.01 | 34.71 | 36.66 | 38.64 | 39.53 |
| 3 | 39.84 | 41.50 | 41.64 | 41.78 | 41.94 | 42.09 | 42.26 | 42.43 | 42.61 | 42.79 | 42.98 | 43.17 | 43.36 | 43.55 | 43.74 |
| 4 | 19.44 | 21.29 | 24.46 | 27.73 | 30.52 | 32.65 | 34.89 | 37.49 | 39.64 | 39.80 | 39.96 | 40.13 | 40.30 | 40.46 | 40.63 |

### *4.3. Discussion*

The vulnerability of a city's surface water resource system is generally divided into five grades: not vulnerable (<40 points), slightly vulnerable (40–50 points), moderately vulnerable (50–60 points), very vulnerable (60–70 points), and extremely vulnerable (> 70 points) [45]. The annual vulnerability in each scenario is calculated by considering the vulnerability score results of the four scenarios and the water resources system vulnerability scoring criteria, and results are exhibited in Figure 4a–d.

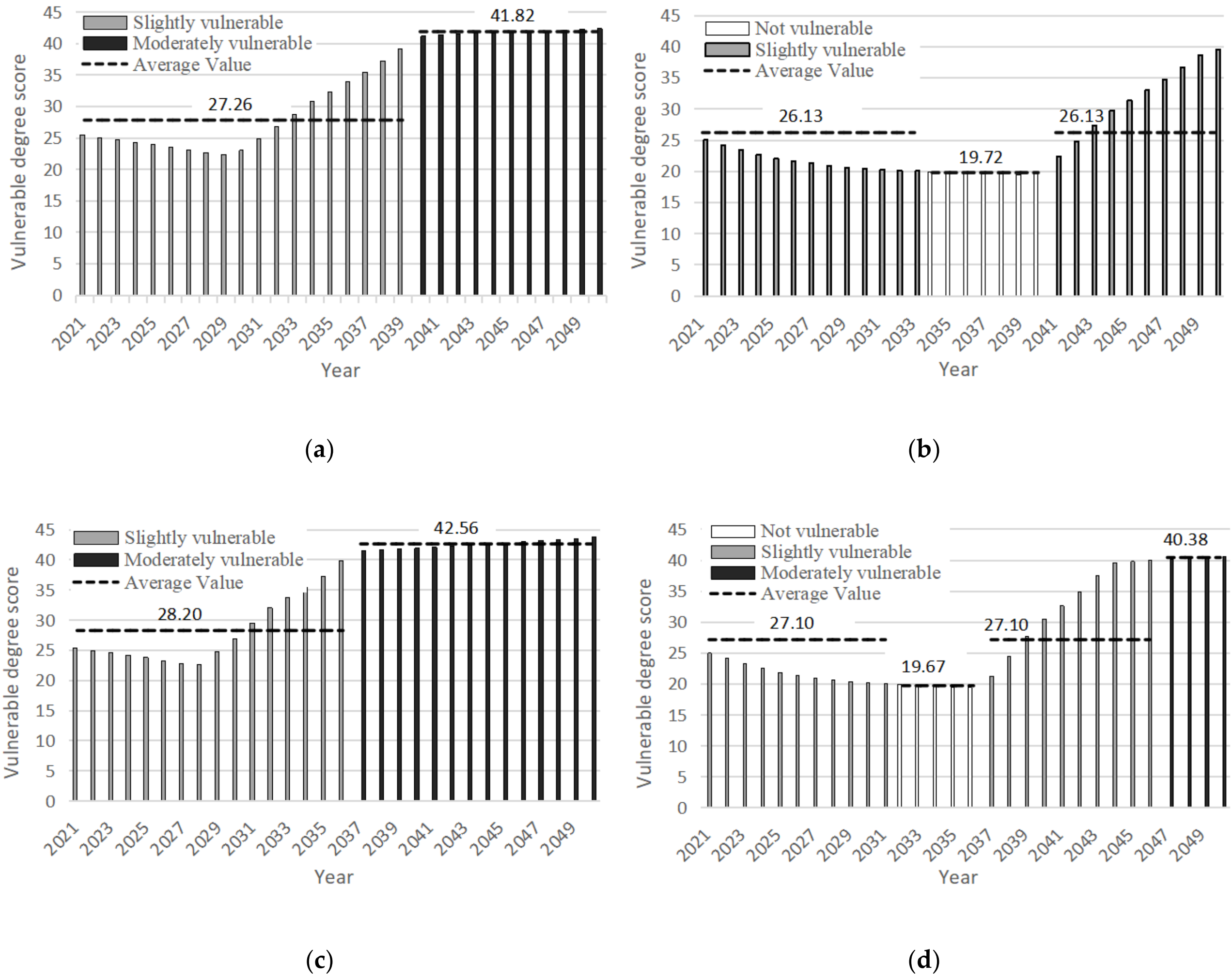


**Figure 4.** Vulnerability score and grading in different scenarios. (**a**) Scenario 1; (**b**) scenario 2; (**c**) scenario 3; (**d**) scenario 4.

(a) Scenario 1—the normal development model: In this scenario, the indicators (e.g., social economy) are steadily increasing. The vulnerability scores of the water resource system of Zhongshan City under the normal development model and the grading results are shown in Table 5 and Figure 4a, respectively. The results indicate that the vulnerability score of the water resources system decreased year by year from 2021 to 2029, but it began to increase annually thereafter. The vulnerability score was the lowest in 2029, with a score of 22.36 (slightly vulnerable) and the highest in 2050, which is 42.37 (moderately vulnerable). From 2021 to 2050, the vulnerability score of the water resource system of Zhongshan City spans two grades, including slightly vulnerable for 19 years (2021–2039) with an average vulnerability score of 27.26, and moderately vulnerable for 11 years (2040–2050) with an average vulnerability score of 41.82. Thus, with the development of the economy and society, the water resources system has gradually stabilized, but gradually deteriorated with the passage of time.

(b) Scenario 2—the technical innovation development model: This scenario is a water-saving development model that aims at increasing the water usage efficiency through the technical innovation. In this scenario, the quota of agricultural, production, and domestic water consumption is reduced to 80% of the normal development mode, and the sewage reuse rate and sewage centralized treatment rate are increased to 120% of the conventional development mode after the renovation of the sewage treatment plant and the improvement of technology. Table 5 and Figure 4b show the vulnerability scores of the water resource system in this scenario and the grading results, respectively. The results show that the vulnerability score of the water resources system first showed a rapid downward trend, and then reached to relative stability status in 2034, and then shows a rapid upward trend in 2041. The vulnerability score is the highest in 2050 at 39.53 (slightly vulnerable) and the lowest in 2039 at 19.46 (not vulnerable). In the span to 30 years between 2021 and 2050, the vulnerability score of the water resources system of Zhongshan city has changed two grades; there is a period of 7 years that is not vulnerable (2034–2040) with an average vulnerability score of 19.72, and a period of 23 years of slightly vulnerable (2021–2033, 2041–2050), with an average vulnerability score of 26.13. Therefore, we can see that although technological innovation plays a significant role in the stability of a water resources system, as the economic and social development reach a certain level, the stability of the water resources system starts to gradually deteriorate.

(c) Scenario 3—improving the social and economic development mode: This scenario is a development mode that promotes social development by adjusting the proportion of industrial structure, GDP growth rate, population growth rate, and urbanization rate through the current development status. In this scenario, PPI and PSI are adjusted to 95% and 97% of the normal development model, respectively. GRGDP, GRTP, and UR are increased to 120% of the normal development mode, as shown in Table 5 and Figure 4c, respectively. The results showed that the vulnerability of water resources system decreased first and then increased until it gradually stabilized. The vulnerability score was the lowest in 2028, with a score of 22.64 (slightly vulnerable) while the highest is in 2050 with a score of 43.74 (moderately vulnerable). In the 30 years between 2021 and 2050, the vulnerability of the water resources system in Zhongshan city spans two levels, and the average vulnerability of slightly vulnerable is 28.20 in between 2021 and 2036, and moderately vulnerable for between 2037 and 2050 with an average vulnerability of 42.56. Compared with the normal development model, the social economic improvement development model can obviously contribute to an increased vulnerability of the water resource system.

(d) Scenario 4—the comprehensive development model: This scenario is a water-saving development model that is based on the first model and satisfies the second and third models. The parameters of this scenario are adjusted according to scenarios 2 and 3. The vulnerability scores of the water resource system in this scenario and the grading results are shown in Table 5 and Figure 4d, respectively. The results show that the vulnerability of the water resource system first showed a downward trend, then stabilized, followed by a rapid upward trend, before finally stabilizing. The vulnerability score value is the highest in 2050 at 40.63 (moderately vulnerable) and the lowest in 2036 at 19.44 (not vulnerable). In the 30 years between 2021 and 2050, the vulnerability score of the water resource system of Zhongshan City spans three grades, including not vulnerable for 5 years (2032–2036) with an average vulnerability score of 19.67, slightly vulnerable for 21 years (2021–2031, 2037–2046) with an average vulnerability score of 27.10, and moderately vulnerable for 4 years (2047–2050) with an average vulnerability score of 40.38. Thus, we can see that the comprehensive development model is greatly influenced by the technological innovation model, and that they follow similar trends.

Figure 4a–d shows the vulnerability scores and grading predictions of the water resource system of Zhongshan City in the next 30 years in four development models. The vulnerabilities of scenarios 1 and 3 span two grades, namely, slightly vulnerable and moderately vulnerable. Scenario 2 spans two levels of not vulnerable and slightly vulnerable, and scenario 4 spans three levels of not vulnerable, slightly vulnerable, and moderately vulnerable. As shown in Table 6, among the not vulnerable levels, scenario 2 has the highest number of years, 7 years, and the average vulnerability is 19.72, accounting for 0.23; scenario 4 is the second, with 5 years, and the average vulnerability is 19.67, accounting for 0.17; scenarios 1 and 3 have no non-vulnerable years. Among the slightly vulnerable levels, four scenarios are involved, scenario 2 has the highest number of years, 23 years, and average vulnerability of 26.13, accounting for 0.77; scenario 3 has the lowest number of years, 16 years, and average vulnerability is 28.2, the proportion is 0.53. In the middle level of vulnerability, except for scenario 2, all other scenarios are involved. Among them, scenario 3 has the highest number of years, 14 years, the average vulnerability is 42.56, and the proportion is 0.47; scenario 4 has the lowest number of years, 4 years, and average vulnerability is 40.38, the proportion is 0.13.

**Table 6.** Vulnerability grade comparison of different scenarios.

| Scenario | Moderately Vulnerable | | | Slightly Vulnerable | | | Not Vulnerable | | | Total Average Value |
|---|---|---|---|---|---|---|---|---|---|---|
| | Years | Average Value | Proportion | Years | Average Value | Proportion | Years | Average Value | Proportion | |
| 1 | 11 | 41.82 | 0.37 | 19 | 27.76 | 0.63 | 0 | 0 | 0.00 | 32.91 |
| 2 | 0 | 0 | 0.00 | 23 | 26.13 | 0.77 | 7 | 19.72 | 0.23 | 24.64 |
| 3 | 14 | 42.56 | 0.47 | 16 | 28.2 | 0.53 | 0 | 0 | 0.00 | 34.90 |
| 4 | 4 | 40.38 | 0.13 | 21 | 27.1 | 0.70 | 5 | 19.67 | 0.17 | 27.63 |

The average vulnerability score of the four scenarios, in descending order: scenario 3 (34.90), scenario 1 (32.91), scenario 4 (27.63), and scenario 2 (24.64). Scenarios 1 and 3 are relatively similar, and scenario 2 is more similar to scenario 4. All four scenarios entered the slightly vulnerable level at the same time, in 2021, but ended at different times. In scenarios 1 and 3, it switches to moderately vulnerable after the end of 2039 and 2036, respectively. In scenarios 2 and 4 it switches to invulnerability mode after the end of 2033 and 2031, respectively, but then switches to slightly vulnerable again. Compared to scenario 3, although scenario 4 is slightly weaker, its economic and social development is far greater than in scenario 3. This shows that both technological innovation and a certain level of economic and social development have a more obvious effect on the stability of the water resources system.

The vulnerability of the water resources system is influenced by a combination of several factors. Even if the vulnerability level of the water resource systems is similar or even the same, the contributing factors and, therefore, the reflected water resource problems can be very different [46]. With unique geographical advantages and rich natural resources, the river network area enjoys rapid economic development. However, the inharmonious relationship between the water environment, the development, and the utilization of the water resources has become a major factor that restricts social and economic development. The common water resource problems include water-quality-induced water shortage, low-water resource utilization rate, imperfect water conservancy facilities, and unsound water resources management system [47]. To solve these problems, we analyzed four scenarios to identify the optimal solution to ensure the safety of the system. Xiong et al. used the SD method to establish a model in research on the water resource supply and demand system of the Changsha–Zhuzhou–Xiangtan City Group, which has a developed water system. After setting four scenarios, namely, the traditional development, economic development, water-saving, and coordinated models, the results show that the coordinated model is the optimal one for the water resource development and utilization in the Changsha–Zhuzhou–Xiangtan City Group [48]. Li et al. adopted similar methods and drew the conclusion that the coordinated model is the optimal one for the water resource development and utilization around the Dongting Lake area with the same method [49]. The research results of this paper highlight that by increasing the water utilization efficiency, WRR, and RWCT can ensure the sound development of the social economy in the river network area and maintain the stable water resource system. This is confirmed by a recent study on the control measures of water security of Zhongshan, where it showed that the percentage of wastewater reuse and wastewater centralized treatment are among the main contributing factors towards the alleviation of water scarcity, and that policy regulation is an effective approach for improving the city's water security [50]. Therefore, we believe this is currently the most rigorous and accurate model for the sustainable development of the network-river regions.

## 5. Conclusions

With the acceleration of urbanization and the rapid increase in population as well as economic development, the water environment problems become more prominent, further threatening the water resources security of the Pearl River Delta's river network region. In the key period of social development, it is critical to maintain the stability of the water resource system. Using the VSD-based evaluation index system, this study used the SD method to establish a water resource system model and evaluated it in four scenarios (normal, technical innovation, social economic improvement, and comprehensive development models). According to the simulation results of the model, the comprehensive index method was adopted to evaluate the vulnerability of the water resources system of Zhongshan City from 2021 to 2050. The main findings are illustrated as follows:

(1) In all four scenarios, the annual vulnerability score first shows degrees of decline and then degrees of growth. Scenarios 1 and 3 show similar trends, while scenarios 2 and 4 are similar. The results indicate that a certain degree of government regulations and control measures, technical innovation, and industrial structure adjustment serve a positive function in the stability of the water resource systems.

(2) In the 30 years between 2021 and 2050, the vulnerabilities of all four scenarios are classified into three grades, namely, not vulnerable, slightly vulnerable, and moderately vulnerable. Scenario 2 has the lowest average score of vulnerability with an average value score of 24.64, while scenario 3 has the highest vulnerability with an average value of 34.90. Scenario 3 focuses on economic and social development and fails to effectively balance water resources. Scenario 4, although slightly weaker than scenario 2, in terms of vulnerability, has achieved greater economic and social development.

(3) Compared to scenario 1, scenario 3 shows higher vulnerability, while both scenarios 2 and 4 have lower vulnerability scores. Scenario 4 is a combination of scenarios 2 and 3, that is, pursuing rapid economic development while increasing water use efficiency. While pursuing economic and social development to ensure water resources security, scenario 4 is more suitable for the development needs of cities in the network-river area, but we also need to consider whether the limited resources can support the healthy development of society when the economic and social development reaches a certain level. Particularly, in the Pearl River Delta, an economically developed are, what we should focus on is how to make sure that the limited resources can be used to maximize the benefits of future water resources management through timely and effective policy adjustments.

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**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix A

**Table A1.** Abbreviations for variables in the water resources system model.

| No. | Abbreviation | Variables | Unit |
|---|---|---|---|
| 1 | TP | Total Population | $10^4$ persons |
| 2 | GDP | Gross Domestic Product | $10^4$ RMB |
| 3 | LA | Livestock Amount | $10^4$ heads |
| 4 | FFWA | Fishpond Filling Water Area | $10^4$ mu |
| 5 | FOIA | Forestland and Orchard Irrigation Area | $10^4$ mu |
| 6 | FIA | Farmland Irrigation Area | $10^4$ mu |
| 7 | UELWD | Urban Ecological Landscaping Water Demand | $10^4$ $m^3$ |
| 8 | WRQ | Water Resources Quantity | $10^4$ $m^3$ |
| 9 | GATP | Growth Amount of Total Population | $10^4$ persons/year |
| 10 | GAGDP | Growth Amount of GDP | $10^4$ RMB/year |
| 11 | GALN | Growth Amount of Livestock Number | $10^4$ heads/year |
| 12 | GAFFWA | Growth Amount of Fishpond Filling Water Area | $10^4$ mu/year |
| 13 | GAFOIA | Growth Amount of Forestland and Orchard Irrigation Area | $10^4$ mu/year |
| 14 | GAFIA | Growth Amount of Farmland Irrigation Area | $10^4$ mu/year |
| 15 | GAUELWD | Growth Amount of Urban Ecological Landscaping Water Demand | $10^4$ $m^3$/year |
| 16 | GAWRQ | Growth Amount of Water Resources Quantity | $10^4$ $m^3$/year |
| 17 | CODEI | COD Emissions Intensity | kg/($10^4$ RMB) |
| 18 | CODEA | COD Emission Amount | kg |
| 19 | GRGDP | Growth Rate of GDP | 1/year |
| 20 | AVPI | Added Value of Primary Industry | $10^4$ RMB |
| 21 | PPI | Proportion of Primary Industry | Dmnl |
| 22 | WDPI | Water Demand of Primary Industry | $10^4$ $m^3$ |
| 23 | WUAPTIAV | Water Used Amount Per $10^4$ RMB Tertiary Industry Added Value | $m^3$/($10^4$ RMB) |
| 24 | CODGAPIAV | COD Generated Amount of Per $10^4$ RMB Industry Added Value | kg/($10^4$ RMB) |
| 25 | WUAPIAV | Water Used Amount Per $10^4$ RMB Industry Added Value | $m^3$/($10^4$ RMB) |
| 26 | WUAPAAV | Water Used Amount Per $10^4$ RMB Architectural Added Value | $m^3$/($10^4$ RMB) |
| 27 | TIAV | Tertiary Industry Added Value | $10^4$ RMB |
| 28 | WDTI | Water Demand of Tertiary Industry | $10^4$ $m^3$ |
| 29 | SIAV | Secondary Industry Added Value | $10^4$ RMB |
| 30 | PSI | Proportion of Secondary Industry | Dmnl |
| 31 | WDSI | Water Demand of Secondary Industry | $10^4$ $m^3$ |
| 32 | GRTP | Growth Rate of Total Population | 1/year |
| 33 | PCGDP | Per Capita GDP | RMB/person |
| 34 | PCWRQ | Per Capita Water Resources Quantity | $m^3$/person |
| 35 | TWS | Total Water Supply | $10^4$ $m^3$ |
| 36 | WSC | Water Supply Capacity | $10^4$ $m^3$ |

**Table A1.** *Cont.*

| No. | Abbreviation | Variables | Unit |
|---|---|---|---|
| 37 | RP | Rural Population | $10^4$ persons |
| 38 | RPCWQ | Rural Per Capita Water Quota | L/(person·day) |
| 39 | RDWD | Rural Domestic Water Demand | $10^4$ $m^3$ |
| 40 | FIWQ | Farmland Irrigation Water Quota | $m^3$/mu |
| 41 | GRFIA | Growth Rate of Farmland Irrigation Area | 1/year |
| 42 | FLWD | Farmland Water Demand | $10^4$ $m^3$ |
| 43 | UP | Urban Population | $10^4$ persons |
| 44 | UPCWQ | Urban Per Capita Water Quota | L/(person·day) |
| 45 | UR | Urbanization Rate | Dmnl |
| 46 | GRUELWD | Growth Rate of Urban Ecological Landscape Water Demand | 1/year |
| 47 | UDWD | Urban Domestic Water Demand | $10^4$ $m^3$ |
| 48 | CODGAI | COD Generated Amount of Industrial | kg |
| 49 | IAV | Industrial Added Value | $10^4$ RMB |
| 50 | IWEC | Industrial Wastewater Emission Coefficient | Dmnl |
| 51 | IWEA | Industrial Wastewater Emission Amount | $10^4$ $m^3$ |
| 52 | WDI | Water Demand of Industry | $10^4$ $m^3$ |
| 53 | CVA | construction value added | $10^4$ RMB |
| 54 | PCI | Proportion of Construction industry | Dmnl |
| 55 | WDCI | Water Demand of construction industry | $10^4$ $m^3$ |
| 56 | ITCODDTE | Influence of Total COD Dischargment To Economic | $10^4$ RMB/year |
| 57 | TWA | Total Wastewater Amount | $10^4$ $m^3$ |
| 58 | QDW | Quantity of Delivery Water | $10^4$ $m^3$ |
| 59 | CODEAWFWTP | COD Emission Amount Without From Wastewater Treatment Plant | kg |
| 60 | GRFOIA | Growth Rate of Forestland and Orchard Irrigation Area | 1/year |
| 61 | FOWD | Forestland and Orchard Water Demand | $10^4$ $m^3$ |
| 62 | WSDG | Water Supply and Demand Gap | $10^4$ $m^3$ |
| 63 | GRWRQ | Growth Rate of Water Resources Quantity | 1/year |
| 64 | WRR | Wastewater Reuse Rate | Dmnl |
| 65 | WRA | Wastewater Reuse Amount | $10^4$ $m^3$ |
| 66 | CODEAFWTP | COD Emission Amount From Wastewater Treatment Plant | kg |
| 67 | RWCT | The rate of Wastewater Concentrated Treatment | Dmnl |
| 68 | FIWD | Fishery Water Demand | $10^4$ $m^3$ |
| 69 | GRLN | Growth Rate of Livestock Number | 1/year |
| 70 | WDL | Water Demand of Livestock | $10^4$ $m^3$ |
| 71 | DCODGA | Domestic COD Generated Amount | kg |
| 72 | DWEC | Domestic Wastewater Emission Coefficient | Dmnl |
| 73 | DWEA | Domestic Wastewater Emission Amount | $10^4$ $m^3$ |
| 74 | DWD | Domestic Water Demand | $10^4$ $m^3$ |
| 75 | EWD | Economic Water Demand | $10^4$ $m^3$ |
| 76 | WSD | Water Shortage Degree | Dmnl |

**Table A1.** *Cont.*

| No. | Abbreviation | Variables | Unit |
|---|---|---|---|
| 77 | WS | Water Storage | $10^4$ $m^3$ |
| 78 | TWD | Total Water Demand | $10^4$ $m^3$ |
| 79 | PCCODGA | Per Capita COD Generated Amount | kg/($10^4$ persons) |
| 80 | CODSE | COD Standard of Effluent | kg/($10^4$ $m^3$) |
| 81 | IUCODEE | Influence of Unit COD Emission to Economic | $10^4$ RMB /(kg·year) |
| 82 | UCC | Unit Conversion Coefficient | $m^3$/L |
| 83 | AP | Availability Proportion | Dmnl |
| 84 | DWQ | Diversion Water quantity | $10^4$ $m^3$ |
| 85 | FOIWQ | Forestland and Orchard Irrigation Water Quota | $m^3$/mu |
| 86 | LWQ | Livestock Water Quota | L/(d·head) |
| 87 | LSTWUA | Limitation Standard of Total Water Used Amount | $10^4$ $m^3$ |
| 88 | DWA | Diversion Water Amount | $10^4$ $m^3$ |
| 89 | FWQ | Fishpond Water Quota | $m^3$/mu |
| 90 | GRFFWA | Growth Rate of Fishpond Filling Water Area | 1/year |
| 91 | YWSGR | Yearly Water Supply Guarantee Rate | Dmnl |

**Table A2.** Parameter setting of the four different scenarios.

| Parameters | | | Scenario 1 | Scenario 2 | Scenario 3 | Scenario 4 |
|---|---|---|---|---|---|---|
| **Variables** | **Year** | **Unit** | **Normal Development Mode** | **Technical Innovation Development Mode** | **Social Economic Improvement Development Mode** | **Comprehensive Development Mode** |
| WUAPIAV | 2020 | $m^3/(10^4$ RMB) | 28.000 | 22.400 | - | 22.400 |
| | 2030 | | 25.000 | 20.000 | - | 20.000 |
| WUAPAAV | 2025 | $m^3/(10^4$ RMB) | 31.000 | 24.800 | - | 24.800 |
| | 2035 | | 28.000 | 22.400 | - | 22.400 |
| | 2050 | | 22.000 | 17.600 | - | 17.600 |
| WUAPTIAV | 2025 | $m^3/(10^4$ RMB) | 7.800 | 6.240 | - | 6.240 |
| | 2035 | | 6.500 | 5.200 | - | 5.200 |
| | 2050 | | 4.500 | 3.600 | - | 3.600 |
| UPCWQ | 2025 | L/(person·day) | 205.000 | 164.000 | - | 164.000 |
| | 2030 | | 210.000 | 168.000 | - | 168.000 |
| | 2035 | | 215.000 | 172.000 | - | 172.000 |
| | 2050 | | 220.000 | 176.000 | - | 176.000 |
| RPCWQ | 2025 | L/(person·day) | 145.000 | 116.000 | - | 116.000 |
| | 2030 | | 150.000 | 120.000 | - | 120.000 |
| | 2035 | | 155.000 | 124.000 | - | 124.000 |
| | 2050 | | 160.000 | 128.000 | - | 128.000 |
| FIWQ | 2025 | $m^3$/mu | 640.000 | 512.000 | - | 512.000 |
| | 2030 | | 605.000 | 484.000 | - | 484.000 |
| | 2035 | | 569.000 | 455.200 | - | 455.200 |
| | 2050 | | 498.000 | 398.400 | - | 398.400 |
| FOIWQ | - | $m^3$/mu | 189.000 | 151.200 | - | 151.200 |
| FWQ | - | $m^3$/mu | 1000.000 | 800.000 | - | 800.000 |
| LWQ | - | L/(person·day) | 50.050 | 40.040 | - | 40.040 |
| WRR | 2025 | Dmnl | 0.150 | 0.180 | - | 0.180 |
| | 2035 | | 0.200 | 0.240 | - | 0.240 |
| | 2050 | | 0.300 | 0.360 | - | 0.360 |
| RWCT | 2025 | Dmnl | 0.950 | 1.000 | - | 1.000 |
| | 2035 | | 0.970 | 1.000 | - | 1.000 |
| | 2050 | | 0.980 | 1.000 | - | 1.000 |
| PPI | 2025 | Dmnl | 0.011 | - | 0.0105 | 0.0105 |
| | 2035 | | 0.009 | - | 0.0086 | 0.0086 |
| | 2050 | | 0.007 | - | 0.0062 | 0.0062 |
| PSI | 2025 | Dmnl | 0.413 | - | 0.4010 | 0.4010 |
| | 2035 | | 0.351 | - | 0.3409 | 0.3409 |
| | 2050 | | 0.300 | - | 0.2910 | 0.2910 |

**Table A2.** *Cont.*

| | | | | | | |
|---|---|---|---|---|---|---|
| GRGDP | 2024 | 1/year | 0.065 | - | 0.0780 | 0.0780 |
| | 2025 | | 0.065 | - | 0.0780 | 0.0780 |
| | 2034 | | 0.065 | - | 0.0780 | 0.0780 |
| | 2050 | | 0.070 | - | 0.0840 | 0.0840 |
| GRTP | 2024 | 1/year | 0.035 | - | 0.0420 | 0.0420 |
| | 2025 | | 0.002 | - | 0.0026 | 0.0026 |
| | 2034 | | 0.002 | - | 0.0026 | 0.0026 |
| | 2035 | | 0.015 | - | 0.0181 | 0.0181 |
| | 2050 | | 0.015 | - | 0.0181 | 0.0181 |
| UR | 2020 | Dmnl | 0.930 | - | 1.0000 | 1.0000 |
| | 2035 | | 0.950 | - | 1.0000 | 1.0000 |
| | 2050 | | 0.970 | - | 1.0000 | 1.0000 |

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