

Article

Comprehensive Evaluation Model for Urban Water Security: A Case Study in Dongguan, China

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Abstract: Water security plays a critical role in the development and stability of a region. Constructing an objective and reasonable evaluation indicator system is beneficial to quantitatively evaluating the regional water security status and improving water resource management. In this paper, an urban water security indicator system was established based on the Driving–Pressure–State–Impact–Response (DPSIR) framework with Dongguan City as a case study. By introducing the projection pursuit (PP) algorithm, a DPSIR–PP model was developed to quantitatively evaluate urban water security. The evaluation results show that Dongguan City’s water security index had an overall upward trend during the 13th Five-Year Plan period, with the evaluation grade rising from IV to III. The indicators with the top five weights are: river water quality condition, ecological index, the leakage rate of water supply network, the value added by industry, and the Dongjiang water resources development and utilization rate. The evaluation results are essentially in line with the reality of Dongguan City. On this basis, the internal links of water security and future trends were further analyzed. Through the evaluation results and policy analysis, it is shown that the water security-related measures implemented during the 13th Five-Year Plan period have been effective. Overall, the methodology proposed in this study is beneficial for gaining an in-depth understanding of urban water security impact factors and provides some theoretical basis and reference for future water resources management.

Keywords: water security; indicator system; DPSIR; projection pursuit model



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1. Introduction

With water as a core component of global life support systems [1], water security is critical to the development and stability of a region [2]. Water is one of the most important security issues in the world, and water security is necessary for social and economic development [3]. Relevant studies [4] have shown that nearly 80% of the world’s population is facing threats to their water security. Water security has become more complex under the combined influences of human activities and natural factors. In addition to water scarcity, water security issues include, for example, deteriorating water quality, low water utilization, climate change, ecological damage, and inadequate sewage treatment rates [5–7]. While abundant water resources are conducive to socio-economic development and population growth, rapid urbanization can also lead to an increased risk of water environment degradation. In areas where water resources are scarce, water security can become a constraint to urban development if appropriate management measures are not taken [8,9]. Especially in China, rapid urbanization and industrialization pose a great threat to urban water security [10]. Enhancing water security also became a major undertaking during the Chinese 13th (2016–2020) and 14th (2021–2025) Five-Year Plans [11]. Therefore, an accurate and effective evaluation of urban water security and the analysis of its influencing factors are of great importance for water resources management and policymaking.

In view of the importance of water security, discussions and studies addressing water security have been focused on by numerous scholars and policy makers. Since the concept of water security was introduced, researchers have studied different aspects of water security. For example, Su et al. considered water resources, water environment, and water disasters as the three pillars of urban water security [12]. Han et al. explored the impact of climate change and socio-economic development on water security in the context of the water–energy–food nexus [13]. Liu and Yang analyzed the need for water management in China to be designed, implemented, and evaluated from the perspective of water sustainability in conjunction with policies on other issues across various sectors [14]. Du et al. evaluated water resources security in terms of water resource quantity, water resources pressure, and water use efficiency [15]. Although there is no single definition of water security, there are some widely cited definitions by relevant agencies, as shown in Table 1. As previous studies have shown, water security is a broad concept that can be approached from different perspectives. Reviewing previous studies, there are many that focus on the macro-scale [10,16,17], such as national, provincial, and basin, but often tend to ignore the actual local water conditions. In this paper, we focus on the urban dimension of water security. Urban water security is equally complex and variable, and the quantitative measures of urban water security are more valuable and meaningful [18]. The quantification makes the concept more concrete, facilitates evaluation and tracking, and provides valid information for decision making [19]. Therefore, it is necessary to establish a framework suitable for quantitative studies to comprehensively evaluate urban water security.

Table 1. Definition of water security by relevant institutions.

Reference	Definition
Global Water Partnership (2000) [20]	Water security, at any level from the household to the global, means that every person has access to enough safe water at affordable cost to lead a clean, healthy and productive life, while ensuring that the natural environment is protected and enhanced.
Grey and Sadoff (2007) [21]	Water security is the availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environments and economies.
UN-Water (2013) [22]	Water security is the capacity of a population to safeguard sustainable access to adequate quantities of and acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability.
UNESCO (2016) [23]	Freshwater is the most important resource for humankind, cross-cutting all social, economic and environmental activities. It is a condition for all life on our planet, an enabling or limiting factor for any social and technological development, a possible source of welfare or misery, cooperation or conflict.

Water security usually refers to the quantity and quality of water resources needed for the survival and development of a country or region [24]. The evaluation of water security cannot, of course, be separated from the evaluation methods of water quantity and quality, such as the Nemerow pollution index method, water quality index methods, fuzzy evaluation methods, and principal component analysis [25–29]. Moreover, the evaluation of only water quantity or quality ignores the effects of social and economic development, human activities, and environmental protection measures on water security; without evaluations of such topics, urban water security cannot be comprehensively evaluated [5,30]. Related studies have also found that ecological security cannot be revealed by simply analyzing the indicators of a particular aspect [31]. Urban water security is a result of a combination of natural, social, and economic factors [32]. Therefore, The Driving–Pressure–State–Impact–Response (DPSIR) based model is introduced in order to construct

an urban water security system in this paper. The DPSIR model was first proposed by the Organisation for Economic Co-operation and Development in 1993 on the basis of the PSR (Pressures–States–Responses) and the DSR (Driving–States–Responses) models, and was later adopted and improved upon by the European Environment Agency [33]. The DPSIR model and its extensions are widely applied in various fields and effectively describe socio-economic and environmental causality [34,35]. Hu et al. developed an urban adaptive capacity evaluation index system based on the DPSIR model and analyzed the level of adaptive capacity in Changsha City, Hunan Province [36]. Cao et al. proposed an evaluation model based on the DPSIR-improved matter-element extension cloud model to quantitatively evaluate ecological performance and make recommendations for carbon neutrality [37]. Mosaffaie et al. analyzed the main environmental issues affecting the health of the Gorganroud watershed through the DPSIR framework, which, despite limited data, provided a robust framework to elucidate causal relationships [17]. Establishing an indicator system for water security based on the city level provides a tool for water security policymaking and management. Therefore, in this paper, urban water security elements, such as pressure on water security from industry, agriculture, residential life, and local water quality indicators, are introduced into the DPSIR framework to reconstruct the urban water security indicator system.

Determining the indicator weights is the second key to the evaluation. The methods commonly used to determine the indicator weights are the expert consultation method, analytic hierarchy process (AHP), analytic network process (ANP), DEMATEL method, entropy weight method, and combined weighting method [17,38–42]. The subjective weighting method is able to use the knowledge and experience of experts to make judgments and does not rely on large amounts of data to make decisions [43]. With the complexity and variability of water resources conditions and rapid urban development, the dimensions of urban water security have become more varied. The objective weighting method can avoid the bias of subjective judgment due to its multidimensionality and the difficulty of determining weights due to multiple variables. In objective weighting, the entropy method determines weights based on the degree of information dispersion [44]. However, in some cases, the entropy method may not take full advantage of the data, focusing only on the more variable data [45,46]. Therefore, an algorithm suitable for analyzing high-dimensional data is introduced in this paper. The projection pursuit (PP) model is a data-driven data analysis method. The statistical method is used to establish the evaluation model, which eliminates the need to artificially set indicator weights and makes the evaluation results more objective [47]. The introduction of the PP model can provide a reliable method for the indicator system by mining the high-dimensional data structure and avoiding subjective bias.

In summary, the aims of this paper are (1) to introduce the DPSIR model to establish a comprehensive indicator system for water security at the city level and to identify the key elements of urban water security; (2) to establish the DPSIR–PP model for the quantitative evaluation of the urban water security index (WSI); (3) to analyze the internal links through an improved decoupling model and to forecast the development trend through a gray prediction model; and (4) to evaluate and analyze the water security situation and policy factors in Dongguan City during the 13th Five-Year Plan period.

2. Materials and Methods

2.1. Study Area

Dongguan (113°31′–114°15′ E, 22°39′–23°09′ N) is located in the south-central part of Guangdong Province, downstream of the East River in the Pearl River Delta (Figure 1). Dongguan is one of the central cities of the Pearl River Delta and the Guangdong–Hong Kong–Macao Greater Bay Area. Dongguan is an emerging city with a dense population and has undergone rapid urbanization. It is also known as the “world’s factory” [48,49]. The resident population of Dongguan City reached 10.48 million in 2020, with a population density of up to 4262 people per square kilometer. According to the results of the Seventh

National Census, Dongguan City is the second most densely populated city in China (not including Hong Kong, Macao, and Taiwan). Its gross domestic product reached CNY 965.019 billion in 2020. Dongguan has a subtropical monsoon climate with an average annual temperature of about 22 °C and an average annual rainfall of 1693 mm. Dongguan is rich in water resources but per capita water resources are scarce. The rivers in Dongguan mainly belong to the Dongjiang River Basin. Of the city's water supply, surface water sources account for 97.79%, groundwater sources account for 0.01%, and other water sources (such as sewage reuse, rainwater use, desalination, etc.) account for 2.20%. The water system map of Dongguan City is shown in Figure 1, which was obtained from the National Geomatics Center of China (www.ngcc.cn/ngcc/, accessed on 1 October 2022).

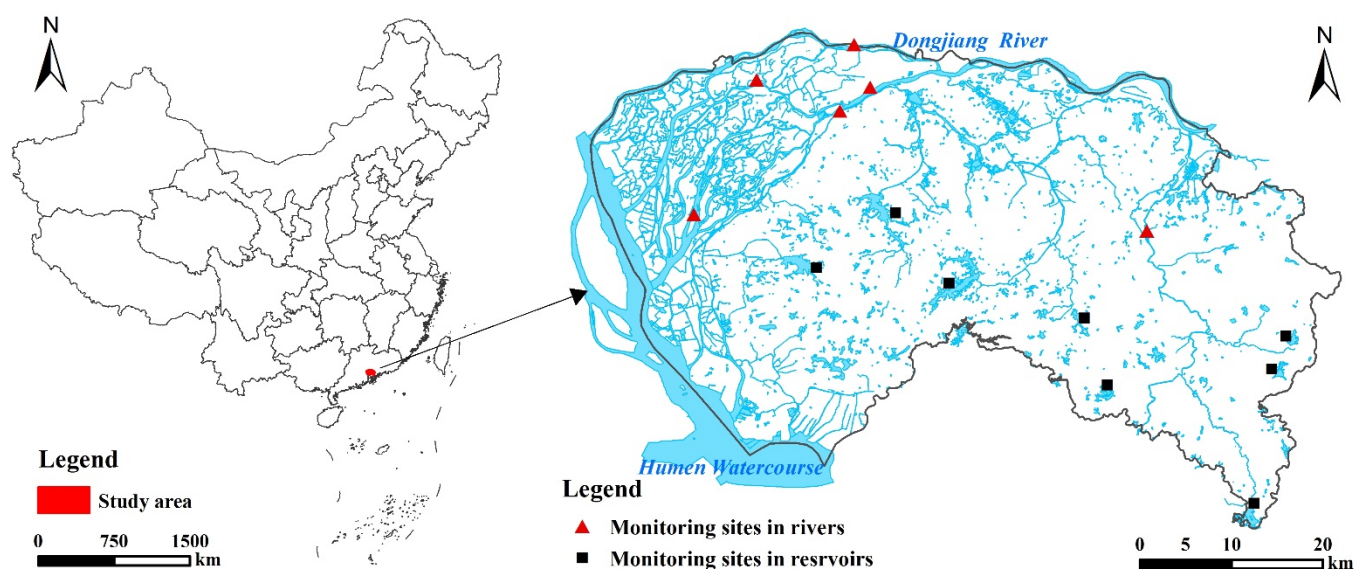


Figure 1. The Water System Map of Dongguan City.

2.2. DPSIR Model

In the DPSIR model, the driving force (D) is the social and economic development status of the region. Pressure (P) refers to the consumption of regional water resources by human activities and the pollution of the water environment. In this case, this includes industrial, agricultural, and domestic sources. State (S) is the amount and state of regional water resources. Impact (I) refers to the interaction between ecosystems and socio-economics. Response (R) refers to the effective measures taken by management in response to water security as well as countermeasures. The interrelationships [50] are shown in Figure 2.

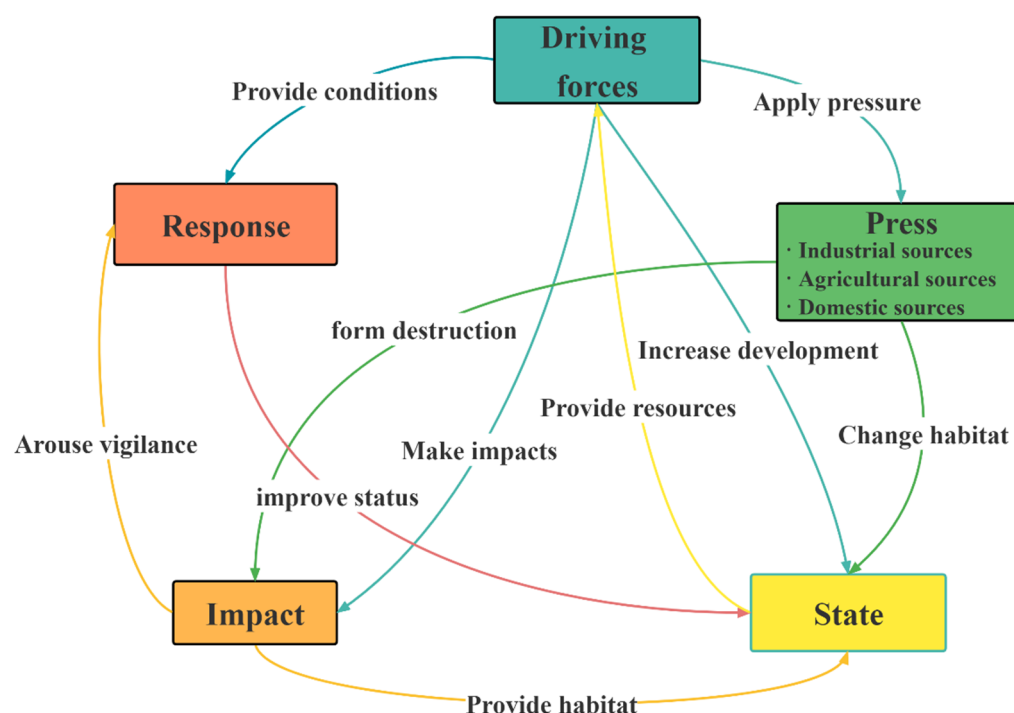


Figure 2. The structure of the DPSIR model.

2.2.1. Indicator Selection

Considering the availability of data and after conducting a literature review, 23 representative indicators were selected to construct the water security evaluation system of Dongguan City. Indicators were divided into two categories: (1) positive indicators (+), where the value of the indicator is positively correlated with the evaluation result, i.e., the larger the value of the indicator, the better; (2) negative indicators (−), where the value of the indicator is negatively correlated with the evaluation result, i.e., the smaller the value of the indicator, the better. The indicator system is shown in Table 2.

Table 2. Dongguan City water security evaluation indicator system.

Rule Layer		Index Layer	Unit	Identifier (Type)	Statistical Methods
Driving force (D)		GDP per capita	Chinese Yuan	D1 (+)	Gross regional product/Resident population
		Total agricultural output	hundred million Chinese Yuan	D2 (+)	Gross output value of farming, forestry, animal husbandry and fishery
		Value added by industry	hundred million Chinese Yuan	D3 (+)	-
		Population density	person/km ²	D4 (−)	Number of resident population/Area
Pressure (P)	Industrial sources	Water consumption of ten thousand Yuan industrial value added	m ³	P1 (−)	Industrial water consumption/Industrial value added
		Industrial wastewater emissions of ten thousand Chinese Yuan GDP	m ³ /ten thousand Chinese Yuan	P2 (−)	Industrial wastewater discharge/Secondary industry output

Table 2. Cont.

Rule Layer	Index Layer	Unit	Identifier (Type)	Statistical Methods
Agricultural sources	Water consumption for agricultural irrigation	m ³ /ha	P3 (−)	Agricultural water consumption/Farmland area
	Fertilizer application per unit sown area	kg/ha	P4 (−)	Annual fertilizer use/Sown area
Domestic sources	Per capita water consumption for residential use	L/d	P5 (−)	Daily domestic water consumption/Resident population
	Annual per capita domestic sewage discharge	m ³ /person	P6 (−)	Annual domestic sewage discharge/Resident population
State (S)	Water resources per capita	m ³ /person	S1 (+)	Total water resources/Resident population
	Dongjiang water resources development and utilization rate	%	S2 (−)	-
	River water quality conditions	-	S3 (−)	Comprehensive pollution index method
	Reservoir water quality conditions	-	S4 (−)	Comprehensive trophic level index method
	Annual precipitation	mm	S5 (+)	-
Impact (I)	Greenery coverage rate	%	I1 (+)	-
	Industrial waste gas emissions	one hundred million m ³	I2 (−)	-
	Industrial solid waste generation	ten thousand tons	I3 (−)	-
	Ecological index	-	I4 (+)	Eco-environmental status evaluation method
Response (R)	Centralized treatment rate of sewage plants	%	R1 (+)	-
	Ecological water use ratio	%	R2 (+)	Ecological water consumption/Total water consumption
	Comprehensive utilization rate of industrial solid waste	%	R3 (+)	-
	Leakage rate of water supply network	%	R4 (+)	-

2.2.2. Data Source

The indicators selected in this paper are taken from the Dongguan Statistical Yearbook, the Dongguan Water Resources Bulletin, Report on the State of Dongguan's Ecological Environment, and the Guangdong Water Resources Bulletin. The ecological index (I4) is derived from the Report on the State of Dongguan's Ecological Environment and calculated in accordance with the Technical Criterion Ecosystem Status Evaluation (HJ/T 192-2015), which mainly reflects the ecological environment status such as biodiversity and vegetation quantity. Dongguan water resources mainly come from rivers and reservoirs, so the water quality evaluation takes the water quality condition of rivers and reservoirs as indicators. The data for river water quality condition (S3) and reservoir water quality condition (S4)

were obtained from the annual statistics of the routine testing by the Dongguan Water Affairs Bureau, listed in Tables S1 and S2. The time frame of the study is the 13th Five-Year Plan period (from 2016 to 2020).

The indicator S3 used the annual average water quality statistics of six major river cross-sections in Dongguan City from 2016 to 2020 (See Table S1). Dissolved oxygen (DO), permanganate index (COD_{Mn}), chemical oxygen demand (COD_{Cr}), five-day biochemical oxygen demand (BOD_5), ammonia nitrogen ($\text{NH}_3\text{-N}$), and total phosphorus (TP) were selected for water quality evaluation. The indicator was calculated using the comprehensive pollution index (CPI) method. The CPI is calculated by the following equations [51–53]:

$$\text{CPI} = \frac{1}{n} \sum_{i=1}^n P_i \quad (1)$$

where n is the number of water quality indicators and P_i is a single factor pollution index; the larger the value—the higher the degree of pollution.

$$P_i = \frac{C_i}{S_i} \quad (2)$$

where C_i is the monitoring value of the index, S_i is the limit value in the corresponding standard; this paper adopts the standard of Class III water in the Environmental quality standard for surface water (GB 3838-2002) in China as the reference value.

The indicator S4 used the annual average water quality statistics of eight medium-sized reservoirs in Dongguan City from 2016 to 2020 (See Table S2). The indicator was calculated using the trophic level index (TLI) method. The TLI is calculated using the following equation [54,55]:

$$\text{TLI}(\Sigma) = \sum_{j=1}^m W_j \cdot \text{TLI}(j) \quad (3)$$

where $\text{TLI}(\Sigma)$ is the comprehensive trophic level index; W_j is the correlation weight of TLI for parameter j ; and $\text{TLI}(j)$ is the TLI for parameter j . The correlation weights were calculated according to the following equation:

$$W_j = \frac{r_{ij}^2}{\sum_{j=1}^m r_{ij}^2} \quad (4)$$

where m is the number of parameters involved in the evaluation, the indicators involved in the evaluation are chlorophyll a (chl a), total phosphorus (TP), total nitrogen (TN), transparency (SD), and the permanganate index (COD_{Mn}) and r_{ij} is the correlation coefficient between chl a and the other parameters. The correlation coefficient r_{ij} and the formula for $\text{TLI}(j)$ are derived from the Technical guidelines of prevention and treatment of eutrophication for important lake and reservoir water sources in the Guangdong–Hong Kong–Macao Greater Bay Area (T/CWEC 25-2021, T/CAQI 178-2021), as shown in Table S3. The results of the sensitivity analysis of the weights are shown in Figure S1.

Since there is no uniform classification standard for the grades of each evaluation index [56], this paper set five grades by reviewing literature, national standards, national averages, and relevant reports. The grading standards and sources are detailed in Table S4.

2.3. Projection Pursuit Model

The projection pursuit (PP) model can be used to optimize the projection objective function to obtain the best projection vector reflecting the multidimensional data structure or features [57]. The basic principle is to find the projection direction that reflects the characteristics of the comprehensive index of the problem to be evaluated, make linear projections of multiple influencing factors, obtain the projected eigenvalues, and then establish the mapping relationship between the eigenvalues and the dependent variables;

thus, transforming the multidimensional problem into a one-dimensional problem for research [58]. The specific calculation steps are as follows:

Step 1: The normalization of evaluation indicators.

Each indicator has a different outline quantity and range. In order to eliminate the effect of outline magnitude and range, the extreme value normalization method was used.

For positive indicators:

$$X_{ij} = \frac{x_{ij}^0}{x_{jmax}} \quad (5)$$

For negative indicators:

$$X_{ij} = \frac{x_{jmin}}{x_{ij}^0} \quad (6)$$

where X_{ij} is the normalized value of the j th indicator of sample i ; x_{ij}^0 is the value of the j th indicator of sample i ; and x_{jmin} and x_{jmax} are the minimum and maximum values of the j th indicator in the sample, respectively.

Step 2: Construct the projected eigenvalues.

The projection eigenvalues Z_i are:

$$Z_i = \sum_{j=1}^m a_j \cdot x_{ij} \quad (7)$$

where m is the number of indicators; $a = (a_1, a_2, \dots, a_m)$ is the projection vector; and a_j is the projection coefficient of the j th indicator, also known as the weight of the indicator.

The key to determining the Z_i is to find the optimal projection direction a that reflects the characteristic structure of the multidimensional data, so it is necessary to construct the projection indicator function $Q(a)$.

Step 3: Construct the projection indicator function.

The projection indicator function $Q(a)$ is as follows:

$$Q(a) = S(a) \cdot D(a) \quad (8)$$

where $S(a)$ is the inter-class scatter and $D(a)$ is the inner-class scatter, calculated as follows:

$$S(a) = \sqrt{\frac{1}{n} \sum_{i=1}^n (Z_i - \bar{Z})^2} \quad (9)$$

$$D(a) = \sum_{i=1}^n \sum_{j=1}^n (R - r_{ij}) \cdot f(R - r_{ij}) \quad (10)$$

where \bar{Z} is the mean value of Z_i ; $r_{ik} = |Z_i - Z_k|$ ($i, k = 1 \sim n$); R is the window width of the density, the usual range of values is $r_{max} + m/2 \leq R \leq 2m$, and $R = 0.1 S(a)$ is used in this paper [3,47,59]; and $f(R - r_{ij})$ is the unit step function, which is calculated as follows:

$$f(R - r_{ij}) = \begin{cases} 1, & R \geq r_{ij} \\ 0, & R < r_{ij} \end{cases} \quad (11)$$

Step 4: Optimize the projection indicator function.

The vector a is the optimal projection direction when $Q(a)$ reaches its maximum value. Thus, the problem can be transformed as follows:

$$\begin{cases} \max Q(a) \\ \text{s.t. } \sum_{j=1}^m a_j^2 = 1 \end{cases} \quad (12)$$

This is a complex nonlinear constrained optimization problem. In this paper, a genetic algorithm was used for the solution. The genetic algorithm (GA) is a method for solving global optimization problems and it can be suitable for avoiding the problem of falling into local optimal solutions [60]. The process of GA includes the following phases:

I—initialization, II—evaluation, III—selection, IV—crossover, and V—mutation. First, the initial generation population is randomly generated, the individuals with better adaptation are selected by evaluation, and crossover and mutation are performed to generate the next generation. The operations II to V are repeated until the optimal individual objective function reaches a set value or the algorithm runs a predetermined number of times. Finally, the best individual in the population is used as the result of the solution.

By substituting the obtained optimal projection direction a into Formula (7), the projection eigenvalue Z_i of each sample can be obtained. The sample can be analyzed by Z_i and indicator weights, where a larger value of Z_i indicates a better sample.

2.4. Gray Prediction Model

The gray system model utilizes uncertain systems as the research objects [61] and provides research methods for systems with “little data” and “poor information” [62]. It has been widely used in finance, economy, energy, environment, and other fields. GM (1,1) is one of the most commonly used gray prediction models able to help predict problems using less data [61,63]. In this study, the evaluation data from the 13th Five-Year Plan period can be used to predict future trends for the 14th Five-Year Plan. The calculation is as follows:

From the original sequence $X^{(0)} = \{x_1^{(0)}, x_2^{(0)}, \dots, x_n^{(0)}\}$, the 1-order accumulation sequence, $X^{(1)} = \{x_1^{(1)}, x_2^{(1)}, \dots, x_n^{(1)}\}$, can be obtained and a sequence of successive adjacent means, $Z^{(1)} = \{z_2^{(1)}, z_3^{(1)}, \dots, z_n^{(1)}\}$, can be generated.

$$x_k^{(1)} = \sum_{k=1}^k x_k^{(0)}, k = 1, 2, \dots, n \quad (13)$$

$$z_k^{(1)} = \frac{x_{k-1}^{(1)} + x_k^{(1)}}{2}, k = 2, 3, \dots, n \quad (14)$$

After establishing the differential equation for the above sequence, the following can be obtained:

$$\frac{dx^{(1)}}{dt} + ax_t^{(1)} = b \quad (15)$$

The data matrices B and Y can be constructed:

$$Y = [x_2^{(0)}, x_3^{(0)}, \dots, x_n^{(0)}]^T \quad (16)$$

$$B = \begin{bmatrix} -z_2^{(1)} & 1 \\ -z_3^{(1)} & 1 \\ \vdots & \vdots \\ -z_n^{(1)} & 1 \end{bmatrix} = \begin{bmatrix} -(x_1^{(1)} + x_2^{(1)})/2 & 1 \\ -(x_2^{(1)} + x_3^{(1)})/2 & 1 \\ \vdots & \vdots \\ -(x_{n-1}^{(1)} + x_n^{(1)})/2 & 1 \end{bmatrix} \quad (17)$$

The coefficients can be solved by the least squares method:

$$\hat{u} = (a, b)^T = (B^T B)^{-1} B^T Y \quad (18)$$

Finally, the prediction sequence can be obtained by solving the differential equation:

$$\hat{x}_{k+1}^{(1)} = \left(x_1^{(0)} - \frac{b}{a}\right)e^{-ak} + \frac{b}{a}, k = 1, 2, \dots, n-1 \quad (19)$$

After the construction of the GM (1,1) model, accuracy tests are required to determine the degree of model fit. When the accuracy of the model is in the acceptable range, the

model can be used to analyze the trend of the original series. The standards of the accuracy test [64] are shown in Table 3.

Table 3. The accuracy test standards of the GM (1,1) model.

Standard	Average Relative Percentage Error *	Variance Ratio *	Minor Probability *
Excellent	<0.01	<0.35	>0.95
Good	<0.05	<0.5	>0.8
Qualified	<0.10	<0.65	>0.7
Unqualified	≥0.20	≥0.65	≤0.7

* The accuracy calculation formula can be found in Supplementary Material Chapter S4.

2.5. Decoupling Method

Decoupling is usually the degree of divergence between two variables. The Organisation for Economic Cooperation and Development first introduced the decoupling model to environmental economics to measure the relationship between economic growth and resource consumption or environmental pollution [65,66]. In this paper, the Tapio decoupling model [67] is used and improved to describe the interrelationships between the subsystems of the DPSIR model. The decoupling states were classified into eight categories according to the variables, as shown in Table S5.

$$DI_t(P, D) = \frac{(P_t - P_{t-1})/P_{t-1}}{(D_t - D_{t-1})/D_{t-1}} = \frac{\Delta P/P}{\Delta D/D} \quad (20)$$

$$DI_t(SI, R) = \frac{(SI_t - SI_{t-1})/SI_{t-1}}{(R_t - R_{t-1})/R_{t-1}} = \frac{\Delta SI/SI}{\Delta R/R} \quad (21)$$

where Equation (20) is used for the decoupling index of water security pressures and socio-economic drivers; Equation (21) is used for the decoupling index of water and ecological status and response measures; and D , P , S , I , and R are the projected eigenvalues of each subsystem obtained by the DPSIR-PP model.

3. Results

3.1. Indicator System

The WSI indicator system is divided into five categories based on the DPSIR framework. The data of specific indicators and grading standards are shown in Table S4. Four socio-economic indicators (D1~D4) were selected in the driver layer to reflect the driving forces and trends that drive the development and changes in water security. Changes in the socio-economic development indicators cause changes in the pressure layer. The indicators for industrial sources (P1, P2), agricultural sources (P3, P4), and domestic sources (P5, P6) were selected to reflect the pressure on water security. Under the influence of human social activities as well as natural factors, five indicators (S1~S5) were selected to characterize the state layer of the water environment. The impact layer is mainly utilized to select relevant indicators to reflect the ecological impact of the region, revealing the socio-economic impact on the ecological environment (I1~I3) and the feedback situation (I4). The response layer is the situation of measures taken in the face of social development pressure on water security and changes in the state of the water environment (R1~R4).

3.2. The Weights of Each Indicator and Subsystem

The normalized data were substituted into the formula of the projection pursuit model and optimized by the genetic algorithm. The optimal projection direction vector was obtained as: $a = (0.2204, 0.0626, 0.3012, 0.1299, 0.2626, 0.1926, 0.0568, 0.2558, 0.2031, 0.1192, 0.1708, 0.2769, 0.3578, 0.1856, 0.0138, 0.0708, 0.0986, 0.0729, 0.3290, 0.1749, 0.2731, 0.1158, 0.3072)$.

In the projection pursuit model, each component of the optimal projection direction vector represents the degree of influence of each indicator on the WSI. The larger value represents the greater influence weight of the indicator, as shown in Figure 3. The top five indicators affecting the WSI are: the river water quality condition (S3), ecological index (I4), leakage rate of water supply network (R4), value added by industry (D3), and the Dongjiang water resources development and utilization rate (S2). As shown in Figure 4, the weight proportions of the Driving, Pressure, State, Impact, and Response layers are: 16.79%, 25.64%, 23.64%, 13.44%, and 20.49%, respectively. The Pressure and State layers account for a high percentage, while industrial sources have the greatest impact on the Pressure layer.

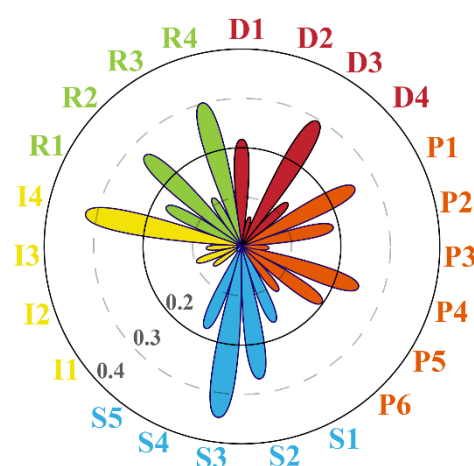


Figure 3. The projection weights of each indicator.

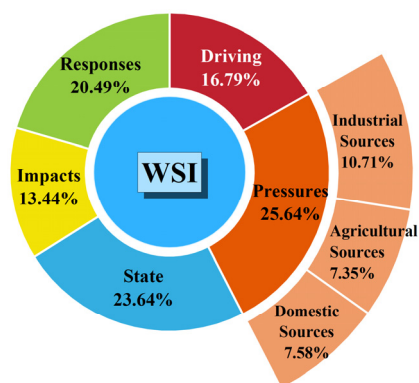


Figure 4. The weight proportion of each subsystem.

3.3. WSI Comprehensive Evaluation Results

The value of the WSI is the projection characteristic value obtained by the DPSIR–PP model as the evaluation result. The weights of indicators and data and the critical values of grading standards are used to calculate the WSI (Z-value) for each year and the evaluation grade by substituting Formula (7), as shown in Figure 5. The predicted values are calculated by the gray prediction model based on the evaluation results.

The evaluation grade is divided into I–V, and its critical values are 8.44, 5.14, 3.63, 2.51, and 1.87, respectively. The WSI decreased slightly during 2016–2017 and increased significantly in the subsequent four years. The evaluation grade was changed from IV to III in 2019. The evaluation results and predicted trend results show that the water security situation in Dongguan is improving. As can be seen from Table 4, the fitting accuracy of the prediction model is within an acceptable range for predicting development trends.

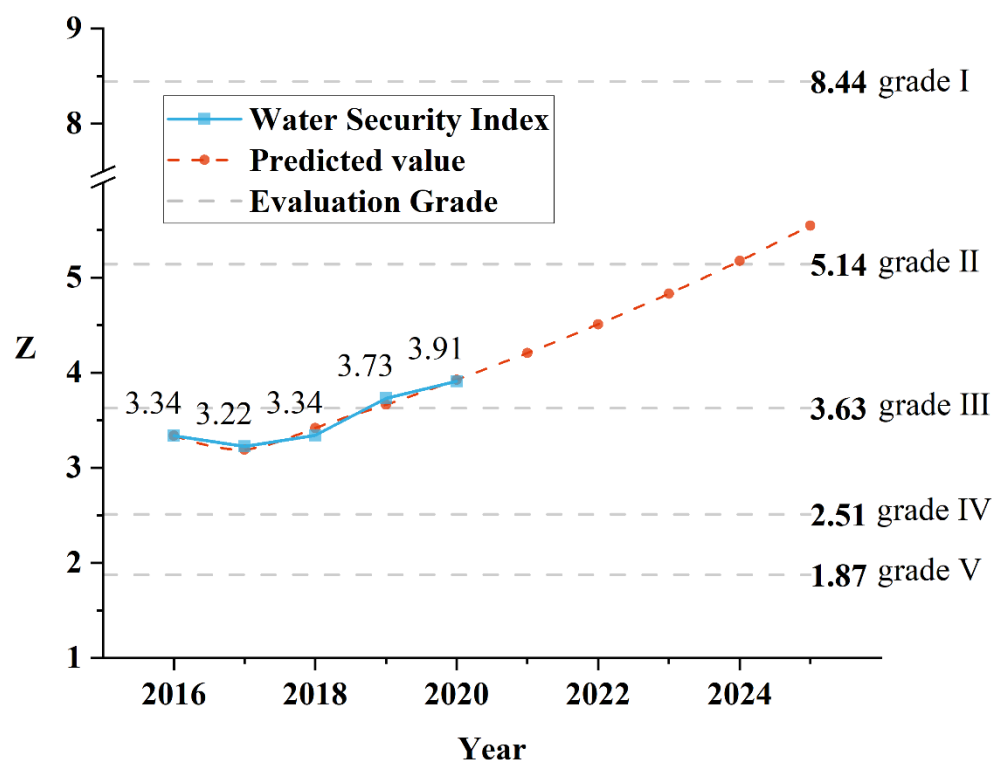


Figure 5. The WSI evaluation results and predicted trends.

Table 4. The accuracy test of the GM (1,1) model.

Standard	Average Relative Percentage Error Φ	Variance Ratio C	Minor Probability p
Predicted value error	0.0110 (Good)	0.1825 (Excellent)	1 (Excellent)

4. Discussion

4.1. Analysis of Changes in WSI System Indicators

The trend of each indicator during the study period is shown in Figure 6. In terms of subsystem D, indicator D1 grew rapidly. As a famous manufacturing city known throughout China and even throughout the world, Dongguan is known as the “world’s factory” [49,68], and its GDP rose from CNY 726.092 billion in 2016 to CNY 965.019 billion in 2020, with an average annual growth rate of 7.37%. Both total agricultural output and the value added by industry (D2, D3) maintained a stable growth. This indicates that the economy of Dongguan City was on a continuous rise during the study period. At the same time, the population of Dongguan City also grew rapidly. According to the Seventh National Census, Dongguan’s resident population exceeded 10 million. In 2020, Dongguan’s resident population reached 10.48 million, with an urbanization rate of 92.15% of the population. The population density (D2) rose from 4132 to 4262 persons/km². In general, excessive population density leads to reduced residential comfort [69], restricted water use, and increased polluting emissions. On the other hand, densely populated cities with a high level of urbanization usually see a better level of economic development. Therefore, they also have relatively good pollution control facilities and operational capabilities, which improve the efficiency of pollution control [70].

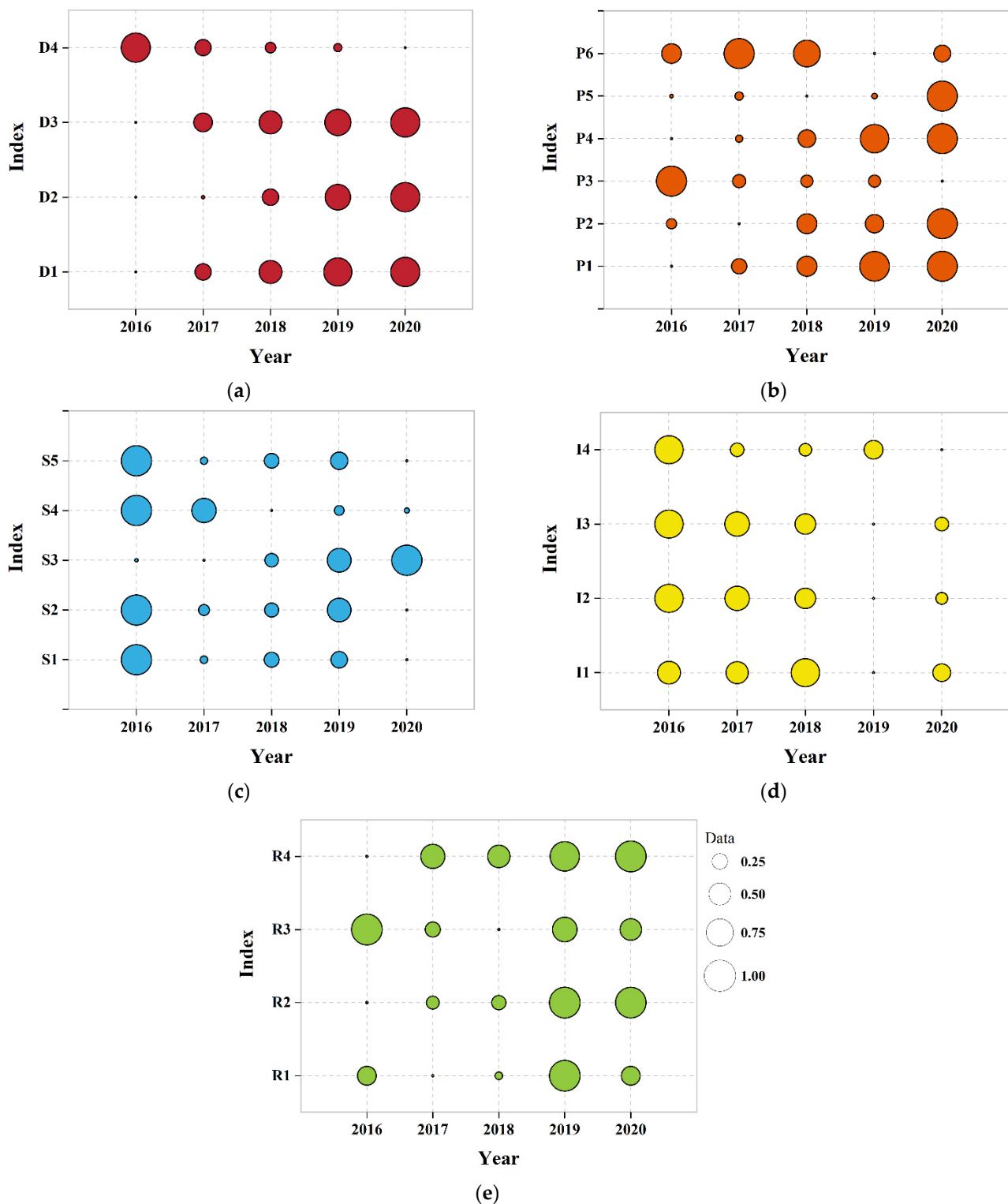


Figure 6. (a–e) Trends in normalized indicators for each subsystem.

In terms of subsystem P, it is divided into industrial sources, agricultural sources, and domestic sources. Regarding industrial sources, there is a clear trend toward improvement in both the utilization of water resources (P1) and the rate of pollution discharge (P2). It shows that Dongguan City is reducing the pressure of industry on water security while achieving sustained economic growth. Related studies have shown that Dongguan City had a similar situation regarding its the atmospheric environment [49]. In terms of agricultural

sources, agricultural water use (P3) increased and was mainly influenced by variations in the levels of water resources in different years, such as changes in precipitation. Fertilizer use (P4) decreased year by year, indicating a decrease in surface source pollution from agriculture. According to the Statistical Yearbook, the agricultural output value grew steadily, indicating the effectiveness of the high-quality development of agriculture during the study period. Regarding domestic sources, per capita domestic water consumption (P5) decreased, which was attributed to the construction of water-saving cities. In addition, Dongguan City was elected as the “tenth (2020) national water-saving cities”. Due to the rapid growth of the population, the discharge of domestic wastewater increased, while the discharge of domestic wastewater per capita (P6) fluctuated slightly with little overall change. The city’s total water consumption increased year by year from 1.854 billion m³ in 2016 to 1.975 billion m³ in 2019, with a small decrease to 1.96 billion m³ in 2020 due to the impact of the COVID-19 pandemic. This indicates that the demand for water resources is still increasing with economic growth.

In terms of subsystem S, the amount of water resources (S5) varied considerably. According to the hydrological year classification, 2016 was a wet year and the rest were normal years. According to the water resources bulletin, the total amount of water resources in 2020 was 2.002 billion m³ (98.80% and 1.20% for surface water and groundwater, respectively). Although Dongguan is located in the Pearl River Delta region and has relatively abundant water resources, the amount of water resources per capita (S1) is scarce due to the dense population and rapid economic growth. According to the Falkenmark index [8], less than 500 m³ of water per person per year means absolute water scarcity. The per capita amount of water resources in 2020 was only 190.96 m³/person. Currently, most of Dongguan City’s water intake comes directly or indirectly from the Dongjiang River, yet the development utilization rate (S2) of the Dongjiang River Basin reached 30% in 2020. A related study [71] concluded that a region is water scarce if the annual water withdrawals are between 20% and 40% of the annual supply and the region is severely water scarce if this figure exceeds 40%. Therefore, both the per capita water resources and the development and utilization rate of the Dongjiang River Basin indicate that Dongguan City’s water resources are relatively scarce. Dongguan’s surface water resources are mainly rivers and reservoirs. During the study period, the water quality condition (S3) of the major river crossings in Dongguan City improved significantly. According to the Report on the State of Dongguan’s Ecological Environment, the national surface water examination section in 2020 eliminated the poor results of all five categories of water quality. Relevant government reports also show that black odorous water bodies in built-up areas have largely been eliminated. This was made possible by the implementation of measures such as the River Chief System policy and the treatment of black odorous water bodies implemented during the 13th Five-Year Plan. At the same time, the water quality condition of major reservoirs (S4) has not changed significantly, and the water quality of some reservoirs still shows a deteriorating trend. This suggests that endogenous pollution is probably a key factor in eutrophication and that it is difficult to improve water quality by reducing external pollution alone [72].

The water environment is an important part of the ecosystem, so water security and the stability of the ecosystem are closely related [73]. In terms of subsystem I, indicator I1 changed inconsistently due to rapid urbanization and increased land area in built-up areas. During the 13th Five-Year Plan, Dongguan City created three forest parks and eleven wetland parks. This shows that, despite the economic development, ecological environment construction nevertheless received some attention. Indicators I2 and I3 showed an increasing trend, which is basically consistent with the trend of economic development. According to the Technical Criterion for Ecosystem Status Evaluation, the ecological index (EI) is a reflection of the state of the ecological environment, such as biodiversity, the amount of vegetation, etc. The overall change of EI (I4) in Dongguan was not significant, only decreasing slightly, which still represents good ecological condition.

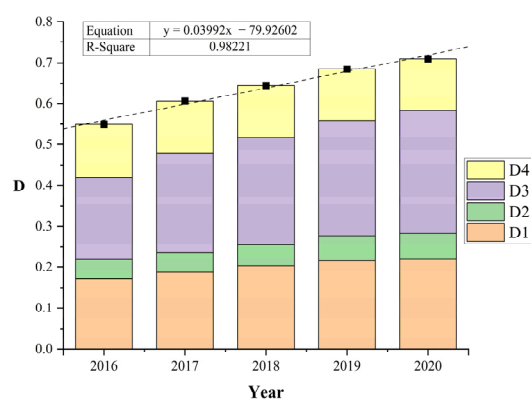
In terms of subsystem R, the centralized treatment rate of wastewater plants (R1) fluctuated slightly and was generally at a high level. According to the Report on the

State of Dongguan's Ecological Environment, the annual new interceptor network grew from 260 km in 2016 to 5700 km in 2020. By 2021, a cumulative total of around 14,000 km of interceptor network had been completed, essentially achieving full sewage collection coverage. The city's wastewater treatment capacity reached 4.31 million tons per day. Indicator R2 maintained a consistent increase over the study period, suggesting that economic development was accompanied by an increased focus on ecology. The indicator R3 has large variations, with the lowest value being in 2018 at only 66.3%. In the 14th Five-Year Plan of Dongguan Ecological Environmental Protection, the "Zero-waste City" city will be built. There is still room for improvement regarding solid waste treatment in the future as a way to reduce the threat to the environment and to water security. From indicator R4, it can be seen that Dongguan City has achieved a certain level of success in terms of water conservation measures.

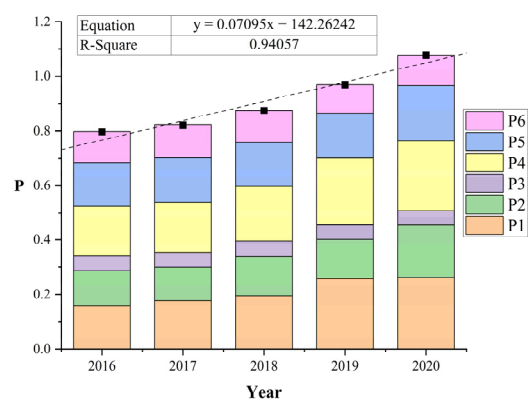
4.2. Analysis of the WSI System

By substituting the weights of the subsystems in the optimal projection vector a and the normalized data into Equation (7), the WSI of each subsystem can be obtained. The trend of each subsystem during the study period and the percentage of each indicator are shown in Figure 7. Except for subsystem I, all the subsystems showed an increasing trend. The largest upward trend is for subsystem P, which has a trend slope of 0.07. The contribution of subsystem P is also seen to be larger in Figure 7f. This indicates that improvements are being made in terms of pressure on water security, which has been made possible by the increasing efficiency of water use in Dongguan and the control of the water environment discharge situation. Subsystem D maintained a slow increase, indicating that Dongguan City's socio-economic development is relatively stable. Subsystem S showed a faster decrease from 2016 to 2017, mainly due to the fact that 2016 was a wet year with 64.07% more total water resources (3406 million m^3) than the multi-year average (2076 million m^3). The years 2017–2020 saw a return to normal resource levels. Subsystem I slowly declined, indicating that there is still some potential for improvement in Dongguan's ecological environment. Subsystem R showed an overall upward trend, with the latter two years significantly better than the previous three years, indicating an increase in the importance given to water security response measures. As shown in Figure 5, the WSI has maintained a steady increase since 2017, and water security in Dongguan City is improving. It shows that in Dongguan City socio-economic growth has occurred alongside the improvement of the situation of water security to a certain extent and that management measures have been effective. The gray prediction model shows that it will continue to improve during the 14th Five-Year Plan. However, the projected value may be overestimated due to the economic slowdown caused by the COVID-19 pandemic, population growth, and water constraints.

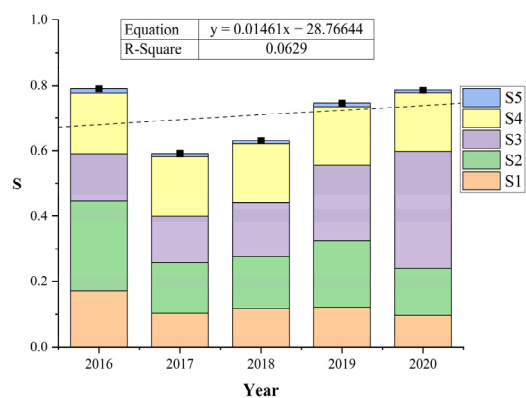
Figure 8 shows the decoupling status of P & D and SI & R. During the 13th Five-Year Plan period, the decoupling state of water security pressure and socio-economic drivers gradually changed from weak decoupling to expansive negative decoupling. The pressure on water security improved faster than economic development, which means that the pressure on water security from economic development was offset to some extent. However, the rate of improvement in water and ecosystem status has not been consistent with the response measures. On the one hand, there might be a certain delay in the effect of the previous response measures. On the other hand, the increase in response measures was lower than the improvement in water security status. Therefore, while economic growth was accompanied by some improvement in water utilization and pollution emissions, there is still some room for improvement regarding the government's response measures.



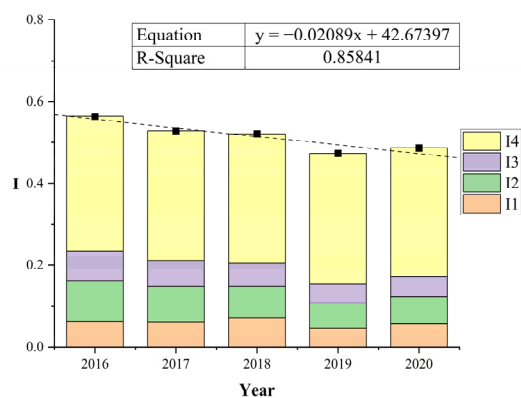
(a)



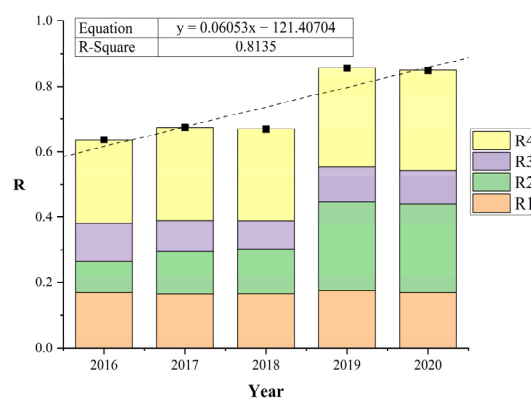
(b)



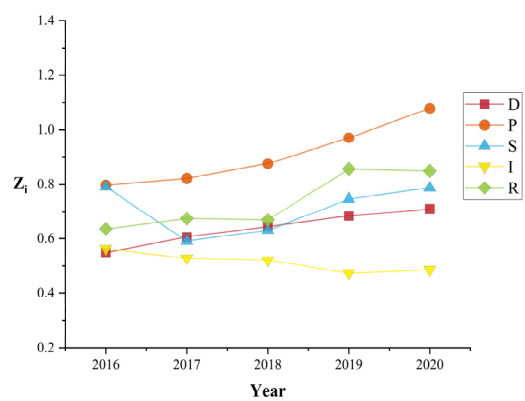
(c)



(d)



(e)



(f)

Figure 7. (a–e) Trends in the projection eigenvalues of each subsystem and the proportion of indicators; (f) trends of change in each subsystem.

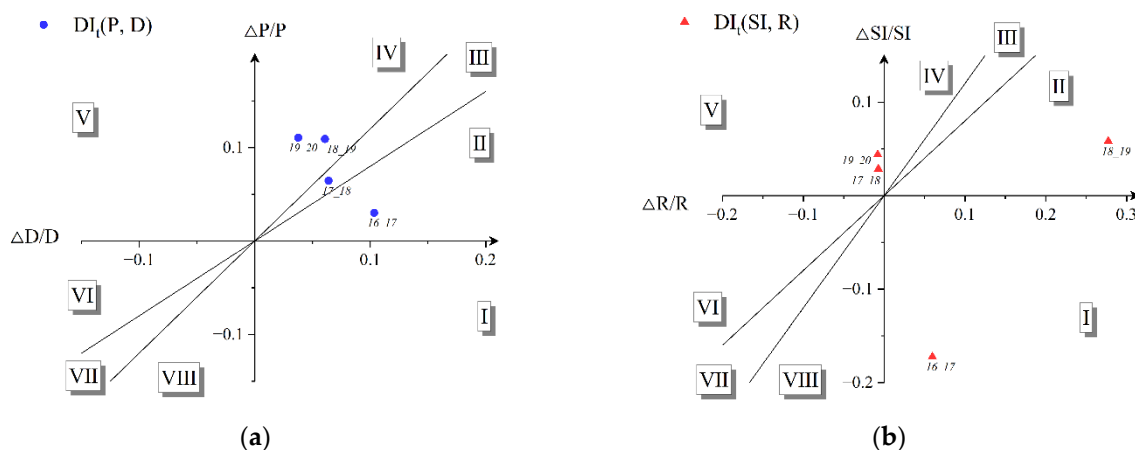


Figure 8. (a) The decoupling state of water security pressures and socio-economic drivers; (b) The decoupling state of water and ecological status and response measures; I–VIII are eight categories of decoupling states, see Table S5.

4.3. Policy Analysis

It is worth noting that the improvement of the WSI in Dongguan during the study period was closely related to some of the policies implemented during the 13th Five-Year Plan. The Five-Year Plan is an important part of China’s national economic planning, setting the goals and directions for the vision of national economic development. With the country’s focus on environmental protection, the five-year plan also incorporates measures to protect the environment rather than just aiming for economic growth [74]. For example, starting with the 10th Five-Year Plan, environmental policies were included for the first time, with targets set for the reduction of pollutants, such as sulfur dioxide and chemical oxygen demand [75]. In the 11th Five-Year Plan, moreover, environmental protection targets were linked to the performance of local governments [76]. During the 13th Five-Year Plan, the State Council issued the 13th Five-Year Plan for Ecological Environmental Protection. In terms of water security, the relevant state departments have also released relevant documents, such as the “13th Five-Year Plan” of Action for the Double Control of Total Water Consumption and Intensity and the “13th Five-Year Plan” for the Comprehensive Management of Water Environment in Key Watersheds. Water security is not a fixed goal but rather a dynamic process that is continuously updated to respond to constant change [5]. As an adaptive governance method [77], the upcoming 14th Five-Year Plan can also play an important role in water security governance. Sustainability is achieved through the governance, planning, implementation of decisions, and monitoring and evaluation of subsequent outcomes [78] with continuous adjustment and feedback.

In the specific local sector, Dongguan City also issued the “13th Five-Year Plan” for Environmental Protection and Ecological Construction in Dongguan, the “13th Five-Year Plan” for Water Development in Dongguan and other related plans. Some of the targets set in the above plan, such as the water consumption of CNY 10,000 industrial added value (P1), the river water quality conditions (S3), the greenery coverage rate (I1), the centralized treatment rate of sewage plants (R1), and other related indicators, have met planning expectations. The results of the WSI evaluation also show that the implementation of the policy has been effective. During the 13th Five-Year Plan period, for water environment management, Dongguan City developed the Work Plan for the Comprehensive Implementation of the River Chief System in Dongguan and the Implementation Plan for the Battle on Urban Black-Odor Water Bodies in Dongguan. The implementation of the river chief system and the treatment of black odorous water bodies have achieved certain results. By 2021, 22 black odorous water bodies in the built-up area of the city have been essentially eliminated. This has led to the task of preventing water bodies from returning to a black and odorous state and the continued task of eliminating rural black odorous

water bodies during the 14th Five-Year Plan. In addition, in order to address the lack of per capita water resources, as well as to reduce the pressure on the Dongjiang water source, the Zhujiang Delta Water Resources Allocation Engineering has been officially launched. The engineering project, which draws water from the Xijiang River, is expected to be opened in 2023 and will be able to provide water resources of 330 million m³ per year for Dongguan City.

By comparing the relative trends of the economy and river water quality, it is found that there may be a turning point for the Environmental Kuznets Curve [79] (EKC) hypothesis (i.e., that environmental pollution presents a variation of an inverted U shape in its relationship with socio-economic development). Although there are not enough data to prove the EKC hypothesis, what can be determined is that economic growth and the state of the water environment were in a state of decoupling [80] throughout the 13th Five-Year Plan period. By analyzing the indicator data and policies, the improvement of water security in Dongguan City can be summarized in the following three aspects: (1) restructuring and optimizing the industrial structure to maintain economic growth while reducing pressure on water security; (2) implementing water body and ecological restoration to improve the condition of water bodies and ecological environments, such as the treatment of black odorous water bodies; and (3) the appointment of local officials as river chiefs to ensure the effective implementation of relevant measures.

5. Conclusions and Recommendations

This paper established a water security evaluation system under the DPSIR–PP model, quantitatively evaluated the WSI of Dongguan City during the 13th Five-Year Plan and predicted the change trends in the 14th Five-Year Plan. The results show that the WSI of Dongguan City has been improving and increasing since 2017. The evaluation grade changed from IV to III during the 13th Five-Year Plan. The prediction model results also show an upward trend in the coming 14th Five-Year Plan period. In terms of subsystems, all subsystems show an increasing trend, except for subsystem I, which decreases slightly. The subsystems P and S have a higher weight of influence. In addition, the pressure on water security has improved in the context of increased socio-economic conditions. However, the decoupling of response measures from the state of the water and ecological environment shows that more attention still needs to be paid to measures in ecological restoration.

Through evaluation results and policy analysis, it can be concluded that the water resources management measures in Dongguan City have been effective to a certain extent. In keeping with the original policy implementation, the following aspects can be further considered: (1) Although the current water resources meet the present requirements, the existing water resources of Dongguan City are primarily from a single source and the amount per capita is scarce. Considering the rapid development of the city and the influence of the climate, corresponding measures should be accelerated to ensure the safety of the water supply. For example, the corresponding water transfer project and reservoir storage project should be improved. (2) Regarding the analysis of water quality conditions, the river water quality has been greatly improved, but reservoir water quality and ecological environment conditions remain unimproved. Therefore, more attention needs to be paid to ecological restoration measures to improve the regulation capacity of the water environment and water security. (3) Since sudden water security incidents are difficult to quantify, they cannot be applied to model calculations, such as flood drainage and rapid water pollution. Therefore, the government should take measures to ensure water security, such as increasing monitoring, improving municipal facilities, and designating emergency plans.

This paper constructed a water security indicators system through urban water security elements and proposed the DPSIR–PP model to quantitatively evaluate the water security index. In addition, an improved Tapio decoupling model was used to analyze the internal links of water security in the DPSIR framework and a gray prediction model was used to predict future trends. This model provides a feasible approach for the comprehensive

evaluation of urban water security and water resources management. However, there are certain limitations. Future studies may need to consider the following points: (1) Due to the availability of data, some of the indicators can still be further improved. For example, more specific indicators such as biodiversity could be added to the ecological impact assessment. (2) This study focused on the 13th Five-Year Plan period, and further research could be conducted in the future on large scale changes, such as changes between multiple five-year plans. (3) The prediction model was mainly based on existing data and did not take into account the macro-regulation of policies. In future studies, trends in water security could be predicted based on the assumptions of different policy developments.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w14233957/s1>, Table S1: The annual average water quality statistics of six major river cross-sections in Dongguan City; Table S2: The annual average water quality statistics of eight medium-sized reservoirs in Dongguan City; Table S3: The correlation r_{ij} between parameters and $chl\ a$ and the value of r_{ij}^2 ; Table S4: Dongguan WSI evaluation indicators and grading standards; Table S5: The classification criteria for the decoupling states; Figure S1. The sensitivity analysis of TLI weights. Refs. [81–86] are cited in the Supplementary Materials.

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