water

MDPI

Article

The DPSIR Model-Based Sustainability Assessment of Urban Water Resources: A Comparative Study of Zhuhai and Macao

Yang Bai [1], Jiaman Qin [2], Wenjing Liu [2], Linhan Li [2], Yang Wu [2,]* and Peng Zhang [3,]*

[1] Key Laboratory of Poyang Lake Environment and Resource Utilization, Ministry of Education, School of Resources & Environment, Nanchang University, Nanchang 330031, China; baiyang@craes.org.cn
[2] National Observation and Research Station of Coastal Ecological Environments in Macao, Macao Environmental Research Institute, Faculty of Innovation Engineering, Macao University of Science and Technology, Macao SAR 999078, China; 2109853gem20002@student.must.edu.mo (J.Q.); 2230006014@student.must.edu.mo (W.L.); 2220024902@student.must.edu.mo (L.L.)
[3] China National Environmental Monitoring Centre, Beijing 100012, China
* Correspondence: yawu@must.edu.mo (Y.W.); zhangpeng@cnemc.cn (P.Z.)

Abstract: Based on the driving force-pressure-state-impact-response (DPSIR) model, 19 indicators were selected to construct a comparison between Zhuhai and Macao, two adjacent cities at the estuary of the Pearl River in China, which have different development models and water resource sustainable development strategies. Factors that may affect the sustainability of water resources were screened and placed according to the relationships of the five subsystems in the DPSIR model, establishing a sustainable evaluation model for water resources in the two cities. The results analyzed by Principal Component Analysis and Entropy methods showed that (1) Zhuhai City was greatly affected by the driving force, while Macao was greatly affected by the state system from 2012 to 2021. (2) From the trend changes, it can be seen that, in recent years, the water resources of the two cities have been moving towards sustainable development, and the management and protection of water resources have achieved remarkable results. From the evaluation results, it can be seen that implementing urban water-saving activities, strengthening the proportion of environmental water conservancy, public measures in public investment, upgrading sewage treatment machinery to improve sewage treatment rates, and other measures can effectively improve the current situation of water resources in both regions. In the future, the Zhuhai and Macao cities may continue to face a series of water resource pressures brought on by socio-economic developments. Therefore, an active adjustment of the development of the measurement of controlling wastewater discharge and saving water resources was proposed, adhering to the direction of sustainable development, and ensuring the benign development of socio-economic conditions and the ecological environment. This study can provide data to support regional water resource security and policy formulation with different political systems.

Keywords: DPSIR model; urban water resources; Zhuhai; Macao Special Administrative Region; socio-economic

check for updates

Citation: Bai, Y.; Qin, J.; Liu, W.; Li, L.; Wu, Y.; Zhang, P. The DPSIR Model-Based Sustainability Assessment of Urban Water Resources: A Comparative Study of Zhuhai and Macao. *Water* **2024**, *16*, 1413. https://doi.org/10.3390/w16101413

Academic Editors: Steve W. Lyon and Brindusa Sluser

Received: 4 March 2024
Revised: 28 April 2024
Accepted: 14 May 2024
Published: 16 May 2024

1. Introduction

Water resource security has become a challenge of global dimensions, being the comprehensive effect of water resources, water environment, water pollution, and water ecological disasters, and an important factor in promoting urbanization and sustainable social development [1]. To effectively address the potential crises ahead, it is essential to forecast the challenges that water resources might encounter in the future. Evidence suggests that by 2050, nearly half of the global population, around 5 billion people, is expected to reside in water-scarce regions [2]. Moreover, in the current context of global climate change, urbanization, industrialization, and population have witnessed a significant surge over the past four to five decades [3]. This rapid growth in human activities has intensified their impact on the ecological environment, leading to a wide array of ecological and environmental issues. Such problems include ecosystem disruption and degradation [4], land degradation [3], and soil pollution in specific regions [5,6], exacerbating the threat to water resource security. Thus, how to scientifically manage water resources will become an important issue. Additionally, sustainable water resources are usually aligned with the integration of social, economic, and environmental issues into water resource management [7]. Hence, it is necessary to propose an appropriate water management strategy to mitigate the issue of urban water scarcity in these areas [8]. A thorough assessment of these influential factors will enable city managers to comprehend regional water resource situations, and detect and adapt measures to counteract current issues, simultaneously offering valuable insights for future guidance across other regions.

Before evaluating the sustainability of a city's water resources, it is crucial to have a general understanding of the current water resource situation and socio-economic development status of the city. This is particularly important when the assessment and comparison involve two or more cities within a common framework, thereby laying a solid groundwork for subsequent models to extract suitable indicators. Currently, the 'driving force-pressure-state-impact-responses' (DPSIR) framework, first proposed by OECD in 1993 [9], can help unravel the multifaceted causality of environmental problems, streamlining researchers in understanding and elucidating the causes and consequences of related environmental issues [10]. The DPSIR model described the interconnections of the various societal and economic activities acting as environmental driving forces, exerting pressure on the environment. These pressures directly affected the system, leading to environmental changes influencing various processes therein, thereby compelling managers to address environmental problems and implement suitable measures. These measures were often reflected in legal, policy, and other instruments and could have reciprocal effects on the initial four subsystems. At present, the causal chain of this model has had a high adoption rate in some environmental topic reports, especially in environmental assessment work [11,12]. The DPSIR model enabled a comprehensive examination of the relationship between the economy, society, and environment. Moreover, this framework has been applied and developed in areas such as environmental change in coastal areas and marine ecosystems, urban water resource management, soil resource utilization, and agricultural management protection [13,14]. The application of the DPSIR framework in evaluating the water resources within a watershed has demonstrated promising prospects. The eco-environmental vulnerability of the Pearl River Delta was conducted based on RS and GIS techniques [15]. A study highlighted the efficacy of the DPSIR framework in assessing water resources within a watershed, emphasizing its ability to enhance the understanding of the complex interactions between human activities and environmental factors [16]. Despite offering a valuable framework for comprehending complicated interrelationships in water resource management, the DPSIR model faces the limitation of having insufficient quantitative and indicator tools to enhance its usability in real-world application scenarios.

In terms of model development, the DPSIR model introduced the driving force that led to stress while considering the impact of environmental conditions on humans, thus surpassing the previous framework that solely relied on analyzing environmental pollution indicators. This breakthrough empowered decision-makers to focus not only on the impact of human activities on the environment but also on the economic and social operations that they entail. The model enabled the unveiling of the causal relationships between the environment and economic and social operations, effectively integrating resources, development, the environment, and human health issues [9,17,18]. From the perspective of water resources, there was a shift in research focus from 2003 to 2007, with applications of the DPSIR model emerging, such as assessing the impact of urban expansion on the freshwater environment to achieve a balance in urban water use [19]. Another study explored the pressure of urban agglomeration on existing groundwater infrastructure and the environment [20]. The DPSIR has gained wide acceptance as an analytical tool, coupled with its high applicability in driving forces, pressures, and policy responses in water resource systems, greatly increasing the adoption rate of this model. As the development of models expands across various fields, limitations are also being identified, creating a pressing need for improvements. One notable improvement has been the use of e-DPSIR, which utilizes causal networks instead of traditional one-way causal chains to better illustrate the complexity of the processes underlying environmental indicators [21]. Another proposed enhancement is the differential DPSIR framework, which can analyze the network of connections between ecological and economic information within a certain time range [22]. These indicators are also classified based on their importance and generally accepted standards. The foundation for assessing water resource sustainability lies in establishing a new indicator system that aligns with local conditions, and applying it in practice. The DPSIR model is continuously being refined and enhanced. However, it is evident that the development of most frameworks and indicators was driven by the researchers themselves, necessitating the adoption of multiple approaches to validate indicators and minimize result biases. Classifying large volumes of mixed data into indicators remains a challenge, and clear causal relationships during analysis can help mitigate the multidimensional and uncertain nature of complex environmental and socio-economic systems.

This study was conducted on the sustainability of water resources in Zhuhai and Macao, two adjacent cities at the estuary of the Pearl River. Zhuhai is an open city in the Chinese Mainland, while Macao is a special administrative region of China, which has different development models and water resource sustainable development strategies. The DPSIR model was utilized to assess their water resources and establish an indicator system. This evaluation took into account the social, economic, environmental, and water resource factors of the cities. Therefore, this study was based on the data that were made available to the public (the data were obtained from Statistics and Census Service of Macau DSEC, Environmental Protection Bureau of Macau DSPA, Marine and Water Bureau of Macau DSAMA, Statistics of Bureau of Zhuhai, and Ecology and Environment of Bureau of Zhuhai [23–27]), as well as the DPSIR model, to construct a water resource security evaluation index system, and quantitatively evaluate the sustainability of the water resource security status between Zhuhai and Macao Cities. The main goal of this work was to provide insights into the current state of water resource sustainability in Zhuhai and Macao and identify the key factors contributing to this sustainability. These findings can be employed to develop effective measures to tackle water resource challenges in these regions.

2. Data Sources and Research Methods

2.1. Study Area

2.1.1. Location

Zhuhai and Macao, situated at the southwest bank of the Pearl River estuary facing the South China Sea, possess distinct geographical characteristics (Figure 1). Among the cities in the Pearl River Delta, Zhuhai City (21°48′–22°27′ N, 113°03′–114°19′ E) boasts the largest sea area, the largest number of islands, and the longest coastline. With a total area of 7836 km^2, Zhuhai encompasses 1711 km^2 of land surface, while the remaining four-fifths constitute the sea surface [28]. The climate of Zhuhai experiences a dry season from October to March of the following year and a wet season from April to September [28]. As urbanization progressed, cultivated lands and green areas in Zhuhai City were gradually acquired and converted for industrial or commercial purposes. According to the Zhuhai Yearbook, the local GDP has reached 388.175 billion CNY as of 2021, reflecting a year-on-year growth rate of 6.9%. The per capita GDP stands at 157,900 CNY. The primary industry contributes an added value of 5.502 billion CNY, with an economic contribution rate of 1.49%. The secondary industry records an added value of 162.747 billion CNY, contributing to the economy at a rate of 38.86% [29].

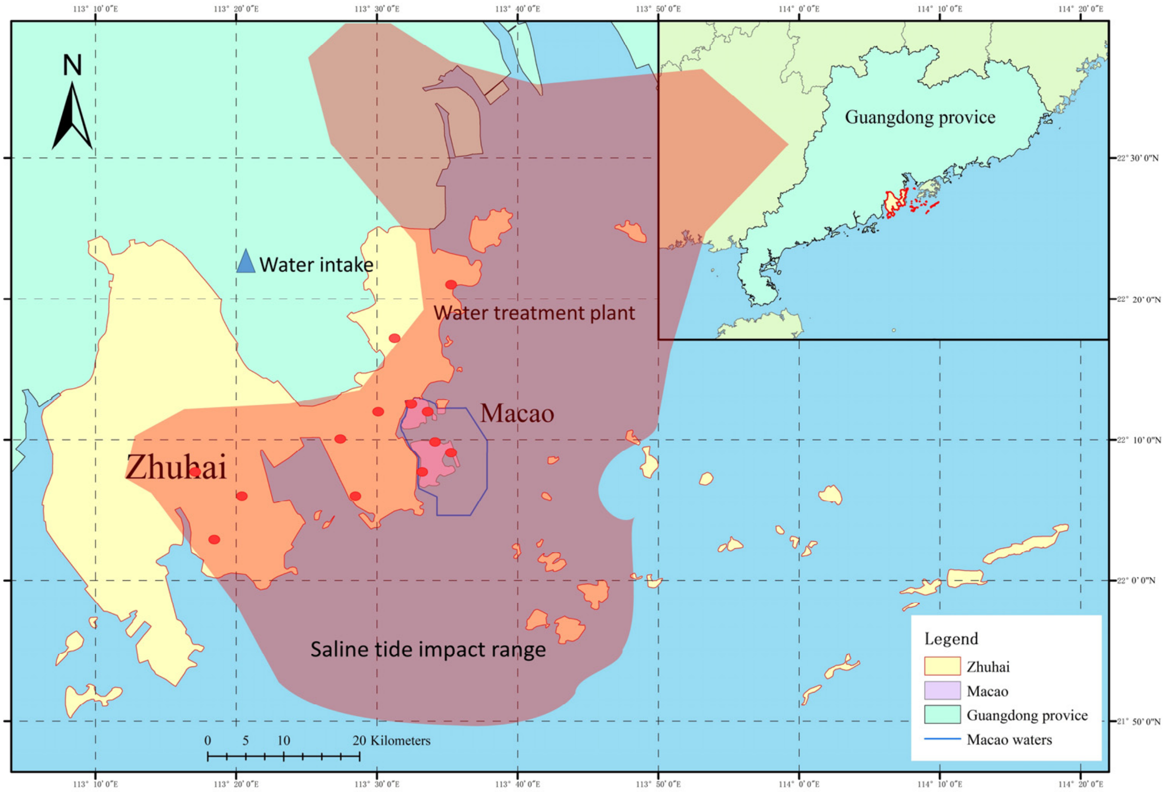

Figure 1. Overview of the study area between Macao and Zhuhai Cities.

The Macao Special Administrative Region (22°06′–22°13′ N, 113°31′–113°35′ E), despite its limited land area, is densely populated. As of 2021, the population density of Macao has reached 207,000 people per square kilometer, with an area of approximately 33 square kilometers. The region is comprised of two main areas, the Macau Peninsula and the Taipa Road Ring. Macao enjoys a pleasant subtropical oceanic monsoon climate, characterized by humid and rainy seasons in spring and summer, and drier conditions in autumn and winter, as well as Zhuhai City. The industrial structure of Macao sets it apart from other cities. According to the 2020 Macau Yearbook data, the secondary industry only contributed 8.7% to the city's total economy, while the tertiary industry accounted for a significant 91.3%. This discrepancy can be attributed to the city's thriving tourism and gambling sectors. On the other hand, due to its limited land area, Macao faced challenges in developing the primary industry [30]. As a result, water consumption in this sector need not be considered when selecting future indicators.

2.1.2. The Interconnection between Zhuhai and Macao

Although Macau was equipped with two storage reservoirs, namely the Macau Main Storage Reservoir (MSR) and the Seac Pai Van Reservoir (SPVR), it did not possess significant conventional water resources. As a result, a staggering 96% of its raw water supply heavily relied on mainland China; Macau's wastewater reuse policy was still in its initial stages and the rainwater use rate was only 3.4% in 2012 [31–33]. Currently, the water supply systems in Macao are divided into the West East Water Diversion System, the North System, and the South System. Specifically, the South System serves as the main water supply system for daily raw water supply to Macao during the flood season (April to September). During the dry season each year, the West to East Water Diversion System in Zhuhai serves as the main water supply facility for daily raw water supply to Macao. The fourth water supply pipeline to Macao, which opened in 2019, entered the Shipaiwan Reservoir from the direction of Hengqin in Zhuhai, forming a north–south bidirectional structure for the raw water supply pipeline to Macao. Compared to the current situation of a single water supply in Macao, Zhuhai is located near the South China Sea area, with a large number of rivers and abundant water resources within the city. However, due to the special geographical location of the Pearl River estuary, Zhuhai faces challenges such as decreased rainfall and Xi-Jiang River runoff in winter, as well as the impact of salt tides on waterways like Modaomen. As a result, Macao has had to rely on Zhuhai for raw water supply, creating pressure on its water supply system.

In Zhuhai, rapid urban population growth and socio-economic development have led to increased water consumption and pollution discharge. In 2021, the total water consumption for the year increased by 4.5% compared to the previous year, with industrial and domestic water consumption increasing by 11% and 9.5%, respectively. In terms of sewage treatment, measures and process adjustments in Macao have significantly improved the city's treatment capacity. The average daily sewage treatment volume in Macao in 2021 decreased by 2.5% compared to the previous year. Efforts will continue to rectify coastal sewage discharge, promote the construction of sewage treatment plants at the Hong Kong–Zhuhai–Macao Bridge Macao Port, upgrade existing facilities, and promote the reuse of reclaimed water. In Zhuhai, 19 urban domestic sewage plants will be built in 2021 with a designed daily average treatment capacity of 1.08 million tons, achieving a sewage treatment rate of 98.1% in urban areas.

2.1.3. Climate Parameters of Zhuhai and Macao

The average annual temperature in Zhuhai and Macao ranges from 19 °C (66 °F) to 25 °C (77 °F). The hottest months are typically July and August, with average temperatures around 28 °C (82 °F), while the coolest month is usually January, with temperatures averaging around 14 °C (57 °F). Zhuhai and Macao receive ample precipitation throughout the year, with the wettest months occurring from May to September. Annual rainfall amounts typically range from 1500 mm (59 inches) to 2000 mm (79 inches). The rainy season is influenced by monsoons and typhoons. Both regions have high humidity levels, especially during the summer months. Relative humidity often exceeds 70–80%, on average. Zhuhai and Macao receive a moderate amount of sunshine throughout the year. The annual average sunshine hours range from 1700 to 2200 h, with the sunniest months being November to February [34].

2.2. Data Collection

The main data for Macao in this study come from the "Yearbook of Statistics" published by the Macao Bureau of Statistics and Census from 2012 to 2021 [23] (https://www.dsec.gov.mo/zh-MO/Home/Publication/YearbookOfStatistics (accessed on 1 May 2024)). Some of the data come from the "Macao Environmental Status Report" published by the Macao Environmental Protection Bureau [24] (https://www.dspa.gov.mo/richtext_report2022_en.aspx (accessed on 1 May 2024)) and the "Macao Water Resources Status Report 2022" published by the Macao Marine and Water Bureau [25] (https://www.marine.gov.mo/subpage.aspx (accessed on 1 May 2024)). The relevant data of Zhuhai City can be found in the Zhuhai Yearbook published by the Zhuhai Municipal Bureau of Statistics from 2012 to 2021 [26] (https://tjj.zhuhai.gov.cn/tjsj/tjnj/ (accessed on 1 May 2024)) or in the environmental report published by the Zhuhai Municipal Environmental Protection Bureau [27] (https://ssthjj.zhuhai.gov.cn/xxgkml/tjsj/szhjxx/ (accessed on 1 May 2024)). It is worth noting that the units carried by the queried Macao data will involve exchange rate conversion. Therefore, this study will refer to the average exchange rate in the Macao Yearbook for subsequent unit conversions to avoid errors, of which the specific data are shown in Table 1. The compiled statistical data are shown in Appendix A.

Table 1. Pataca de Macau (MOP) to Renminbi (CNY) exchange rate.

Year	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Average exchange rate/%	78.98	76.88	77.11	78.89	83.19	84.11	81.83	85.67	86.39	80.59

2.3. Research Methods

2.3.1. The Framework of DPSIR Model

The Driving Force–State–Impact–Response (DSR) and Pressure–State–Impact–Response (PSR) models served as the foundation for the creation of the DPSIR model, an innovative framework capable of efficiently gathering information on resources, the environment, socio-economics, and human activities, as well as examining interrelationships among various variables for a comprehensive assessment of regional ecology and the environment (Figure 2) [35]. In addition, the DPSIR model categorized the assessment system of a regional system into five categories of indicators, which can be further divided into numerous sub-indicators within each category, rendering it a powerful tool for environmental decision-making and management.

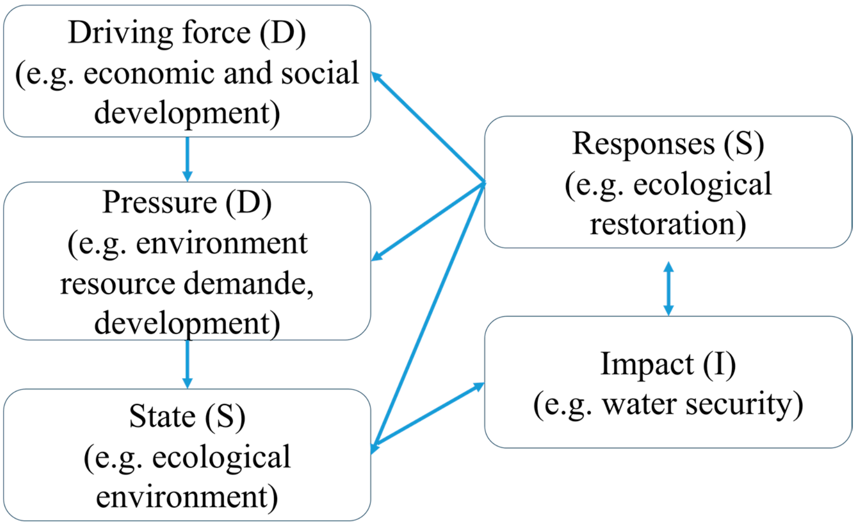

Figure 2. DPSIR model structure and logical relationships.

Regarding the indicators used to evaluate the sustainability of urban water resources, the selected indicators were summarized (Table 2). The driving force factor is a significant element that instigates changes in different factors within the study area [36]. Although the driving force factors may vary across different study areas, the literature review reveals that they are generally similar [35]. These driving forces primarily encompass the economic development status within the study area, the level of industrial development in each city, the population, and resident income [37]. For instance, when examining a water resource system, it is crucial to consider annual precipitation as a vital natural factor since its magnitude indirectly influences the sustainability of a region's water resources [7,20]. Social factors, on the other hand, consist of population density, gross domestic product (GDP), and annual GDP growth rate, among others. By assessing the number of individuals, we can comprehend the extent of people's utilization of water resources. Additionally, the GDP value and annual GDP growth rate serve as indicators of the level of socio-economic development, which in turn impacts the consumption of water resources by the public. Through a comprehensive review of the literature, it becomes evident that the driving force indicators in various studies often exhibit overlapping meanings. To address this redundancy, it is necessary to categorize and consolidate similar indicators for further statistical analysis. After conducting a thorough literature analysis, per capita GDP growth rate (%), the proportion of the tertiary industry in GDP (%), per capita annual income of residents (CNY), per capita total industrial output value (CNY $\times$ 10^4), and population density (person/km^2) emerged as the most representative driving force indicators.

Table 2. The Zhuhai and Macao ecological environment safety assessment index system.

Criterion Stage	Indicator Stage	Safety Trends
Driving force (D)	Per capita GDP growth rate (%)	+
	The proportion of the tertiary industry in GDP (%)	+
	Per capita annual income of residents (CNY)	+
	Per capita total industrial output value (CNY × 10^4)	+
	Population density (person/km^2)	−
Pressure (P)	Water consumption per CNY 10,000 of GDP	−
	The daily average total inflow of each sewage treatment plant/station	−
	Commercial fee collection water volume	−
	Living expenses and water volume	−
	Public fee collection water quantity	−
State (S)	Annual rainfall	+
	GDP output per cubic meter of water	+
	Per capita annual water supply	+
	Per capita water resources	+
	Sewage treatment rate	+
Impact (I)	Water resource development and utilization rate	
	Per capita green space area	
	Environmental expenses	
Responses I	Efficiency/rating of integrated water resource management	

The second significant factor influencing water resource sustainability is pressure, which originates from external forces and has a direct impact. Previous studies in the scientific literature have primarily focused on water demand, consequently encompassing factors such as water consumption, sewage plant inflow, and water infrastructure. Water consumption spans beyond daily domestic usage to also include industrial, agricultural, and ecological activities [37]. To further refine the indicators related to water consumption, various aspects can be considered. It is evident that several indicators can be selected to assess pressure on water resources. These indicators include water consumption per 10,000 yuan of GDP, agricultural water consumption, urban household water consumption, per capita arable land area, water consumption per 10,000 yuan of industrial added value, wastewater discharge rate, the proportion of water consumption for the ecological environment, and groundwater extraction.

Next is the state indicator, which is the state that the water resource system exhibits under pressure. Most of the references are related to the supply of water resources, and the main factors include the degree of water resource development and utilization, water supply capacity, per capita water resources, drought severity, biodiversity, etc. [12–14]. Among them, there will also be some subdivisions of the state indicators in terms of granularity. This includes the development and utilization rate of water resources, which can be subdivided into the availability index, development and utilization degree, and available amount. In addition, urban water resources are divided into surface and groundwater for discussion. In terms of water quality, it is divided into the water quality compliance rate, nearshore functional area water quality compliance rate, and the proportion of river sections with water quality standards below Class III. It can be seen that the water resource development and utilization rate, per capita water resources, annual precipitation, per capita annual water supply, effective irrigation area of farmland, surface water resources, groundwater resources, industrial water reuse rate, and drought index are more commonly used as selection objects.

Then, come the impact indicators, which demonstrate that changes in water resource status have indirect effects on the water environment system, specifically leading to water quality pollution. Several influencing factors can be considered, such as investments in sewage treatment facilities, the comprehensive utilization rate of industrial waste, and the proportion of investment in water conservancy and public infrastructure. These factors serve as indicators that reflect the continuous improvement of the scientific approach to water resource management by the government and the relevant organizations in most research cities. Consequently, the impact of these indicators primarily manifests in the green coverage, sewage treatment rate, and environmental investment ratio of the water resource system.

Finally, the response indicator refers to the policy measures implemented to mitigate the effects of the first four subsystems on the overall system, with the aim of achieving a well-balanced state. Hence, indicators such as public satisfaction with government actions, the actual state of urban water resource management, and the number of legal documents pertaining to water resources can all serve as the city's responses within the entire water resource system.

2.3.2. Principal Component Analysis

Principal component analysis (PCA) is a statistical technique introduced by Pearson with the aim of simplifying high-dimensional data by objectively assigning weights, all while preserving its variance [38]. This study employed PCA to analyze the indicator test in the analysis, and the contribution values were used to calculate the score of each principal component, which was then used to obtain the weighted average of each criterion layer. Then, five driving force indicators (per capita GDP growth rate, the proportion of the tertiary industry in GDP, per capita annual income of residents, per capita total industrial output value, population density), five pressure indicators (water consumption per CNY $\times$ 10^4 of GDP, the daily average total inflow of each sewage treatment plant/station, commercial fee collection water volume, living expenses and water volume, public fee collection water quantity), five status indicators (annual rainfall, GDP output per cubic meter of water, per capita annual water supply, per capita water resources, sewage treatment rate), and three impact indicators (water resource development and utilization rate, per capita green space area, environmental expenses) were performed by PCA, respectively, with the modifying feature values greater than 0.5. Since the evaluation of water resources in the cities of Zhuhai and Macau involves multiple levels, numerous indicators, and variations across different dimensions, it is also necessary to pre-standardize the data using a Z-score

$$F_k = a_{1\mathrm{i}} * Z_{X_1} + a_{2\mathrm{i}} * Z_{X_2} + \cdots + a_{\mathrm{ni}} * Z_{X_n} \tag{1}$$

where F_k denotes the score of the k-th component, a_{ni} signifies the eigenvector value of the indicator, X_n represents the original data value, and Z_{X_n} serves as the normalized value of the original data. The computed score coefficients and variance contribution rates for each principal component serve as the basis for calculating the weighted average for each component, which will ultimately be utilized in the determination of the final score. By aggregating these computed values, a composite measure that accurately reflects the overall performance or strength of each principal component can be created, thereby enabling a comprehensive evaluation of the underlying factors influencing the variable of interest.

2.3.3. Entropy Method

Prior to utilizing the entropy method for calculation, it is essential to standardize the indicators to compare them uniformly [12]. It is worth noting that during standardization, it is necessary to ensure that the final processing result is between 0 and 1. Therefore, in order to eliminate the possible impact of the 0 value on subsequent calculations, the original result was shifted 0.1 units to the right in the formula. The calculation formula of the original matrix normalization processing is as follows:

Positive indicators:

$$\mathrm{A_{ij}} = \frac{\mathrm{x_{ij}} - \min(\mathrm{x_{ij}})}{\max(\mathrm{x_{ij}}) - \min(\mathrm{x_{ij}})} + 0.1 \tag{2}$$

Negative indicators:

$$A_{ij} = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} + 0.1 \tag{3}$$

where A_{ij} is the raw data of the i-th evaluation object for the j-th evaluation indicator; (x_{ij}) is the original indicator; $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum and minimum values value of (x_{ij}), respectively.

Next, perform the entropy method calculation and first determine the index ratio

$$R_{ij} = \frac{A_{ij}}{\sum_{j=1}^{n} A_{ij}} \tag{4}$$

where R_{ij} is index ratio.

Calculate the entropy of the j-th index

$$E_j = -\frac{1}{\ln n}\sum_{i=1}^{n} R_{ij}\ln R_{ij} \tag{5}$$

Calculate the difference system for the j-th index

$$G_j = 1 - E_j \tag{6}$$

Calculate the weight of the jth index

$$W_j = \frac{G_j}{\sum_{j=1}^{n} G_j} \tag{7}$$

Finally, calculate the weight values of each criterion layer based on the weights of each indicator.

2.3.4. Comprehensive Evaluation Score

This article combines principal component analysis and the entropy method. To obtain the comprehensive evaluation score of Zhuhai City and Macao from 2012 to 2021, the specific formula is as follows:

$$S_{year} = W_D * F_{Dyear} + W_P * F_{Pyear} + W_S * F_{Syear} + W_I * F_{Iyear} \tag{8}$$

where S_{year} is the comprehensive evaluation score for each year; W_D, W_P, W_S, and W_I are the criteria layer weights of the driving force, pressure, state, and impact, respectively; and F_{Dyear}, F_{Pyear}, F_{Syear}, and F_{Iyear} are the weighted average of principal component scores of the driving force, pressure, state, and impact in each year, respectively.

3. Results and Discussion

3.1. Key Factors for the Sustainable Development of Water Resources

In order to ensure the feasibility of the selected indicators of the DPSIR model in the analysis of the contribution values by the PCA, it is necessary to verify the indicator data through the Kaiser–Meyer–Olkin (KMO) test. The KMO measure was a statistical tool applied to assess the partial correlations existing between variables [39]. On the other hand, sphericity tests were employed to determine the degree of independence among each variable. The closer the KMO statistic is to 1, the stronger the correlation between the variables is indicated to be. As shown in Table 3, the selected indicators can be subjected to principal component analysis.

Table 3. KMO and Bartlett's test for each criterion layer indicator in Zhuhai and Macao.

	Zhuhai				Macao			
	(D)	(P)	(S)	(I)	(D)	(P)	(S)	(I)
KMO of Sampling·Adequacy	0.611	0.813	0.527	0.517	0.523	0.532	0.546	0.721
Bartlett's·Test·of Sphericity	0.000	0.000	0.026	0.000	0.012	0.000	0.000	0.044

Taking into account the statistical data on the sustainable development of urban water resources in two cities from 2012 to 2021, a comparison and analysis were conducted by performing principal component analysis on indicator data (Table 4). The cumulative contribution rates of the principal components of the four subsystems in Zhuhai were 98.7%, 97.4%, 94.1%, and 97.7%, while in the Macao Special Administrative Region, they were 94.7%, 98.1%, 87.1%, and 88.6%, all of which were greater than 85%. It was suggested that all the components can explain most of the data well in the DPSIR model [40,41].

Table 4. Characteristic values and contribution rates of principal components in Zhuhai and Macao.

	Criterion Stage	Principal Component	Eigenvalue	Contribution Rate (%)	Accumulated Contribution Rate (%)
Zhuhai	(D)	$F1_Z$	3.095	61.897	61.897
		$F2_Z$	1.256	25.126	87.024
		$F3_Z$	0.585	11.691	98.715
	(P)	$F4_Z$	4.869	97.383	97.383
	(S)	$F5_Z$	2.632	52.644	52.644
		$F6_Z$	1.199	23.975	76.619
		$F7_Z$	0.872	17.442	94.061
	(I)	$F8_Z$	1.716	57.192	57.192
		$F9_Z$	1.216	40.520	97.712
Macao	(D)	$F1_M$	2.786	55.716	55.716
		$F2_M$	1.270	25.400	81.116
		$F3_M$	0.679	13.586	94.703
	(P)	$F4_M$	3.075	61.494	61.494
		$F5_M$	1.831	36.620	98.114
	(S)	$F6_M$	2.689	53.774	53.774
		$F7_M$	1.664	33.276	87.050
	(I)	$F8_M$	1.773	59.103	59.103
		$F9_M$	0.885	29.496	88.599

The single-factor scores of principal components for each criterion layer were calculated concurrently. The weighted average of principal component scores was then determined based on the contribution rate of these single-factor scores and their respective eigen values. For instance, in the case of the driving force in Zhuhai, the weighted average of the principal component scores was computed (Equation (9)).

$$\begin{aligned} F_D = & \frac{\text{Accumulated contribution rate 1}}{\text{Contribution rate}(1+2+3)} * F_1 + \frac{\text{Accumulated contribution rate 2}}{\text{Contribution rate}(1+2+3)} \\ & * F_2 + \frac{\text{Accumulated contribution rate 3}}{\text{Contribution rate}(1+2+3)} * F_3 \end{aligned} \tag{9}$$

As shown in Tables 5 and 6, it was found that, among the five subsystems of DPSIR in Zhuhai, the driving force system had the highest weight, which reflected that in Zhuhai, as a member of the Guangdong–Hong Kong–Macao Greater Bay Area, the impact of different industries on GDP in economic and social development, as well as the strong influence of population and other factors, contributes to the the evaluation of the sustainable development of urban water resources, and has a significant promoting effect on improving the sustainable development status of urban water resources. Similarly, among the five subsystems of the DPSIR model in the Macao SAR, the weight of the state system accounted for the largest proportion, reflecting Macao's strong support for the city in terms of annual precipitation, water supply, and sewage treatment in recent years. In the Zhuhai evaluation system, there are 19 evaluation indicators. The top 25% weighted indicators are annual precipitation, per capita annual income of residents, population density, water revenue from living expenses, and the proportion of the tertiary industry in GDP. This ranking result reflects the growing importance Zhuhai City has placed on household income, population, and the tertiary industry from 2012 to 2021. Similarly, among the 19 evaluation indicators, the top 25% weighted indicators included per capita green space area, water resource development and utilization rate, population density, per capita total industrial output value, and commercial revenue water volume. This ranking result demonstrated Macao's increasing focus on urban greening, resource development, population issues, industrial development, and water use in the tertiary industry in recent years. After further analysis, it has been determined that per capita annual income, living expenses, annual precipitation, and environmental protection expenses have a significant influence on the various subsystems of Zhuhai City. These factors are vital in optimizing the sustainable development of water resources in the city and require the attention of future managers to implement appropriate measures and policies. In particular, the indicator of "annual precipitation" is crucial in guiding the improvement of water resource utilization in Zhuhai. Similarly, in the Macao subsystem, population density, commercial revenue, annual precipitation, and per capita green space area carry greater weight and play a crucial role in the sustainability of water resources. The indicator of "per capita green space area" also provided guidance for future water resource management in the city.

Table 5. Principal component score, weighted average score, and comprehensive score in Zhuhai and Macao.

	Year		2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Zhuhai	(D)	$F1_Z$	−1.34	−0.93	−0.86	−0.73	−0.39	0.57	0.22	0.62	1.22	1.63
		$F2_Z$	−0.66	0.29	0.43	0.06	0.08	2.19	−0.68	−0.95	−1.34	0.58
		$F3_Z$	−1.41	−0.49	0.02	0.72	1.92	−0.88	0.68	0.26	−1.10	0.28
		FD_Z	−1.13	−0.33	−0.05	0.12	0.70	0.56	0.09	−0.08	−0.60	0.72
	(P)	$F4_Z$	−1.44	−1.18	−0.81	−0.50	−0.17	0.11	0.59	0.84	0.88	1.67
		FP_Z	−1.44	−1.18	−0.81	−0.50	−0.17	0.11	0.59	0.84	0.88	1.67
	(S)	$F5_Z$	−1.60	−1.45	−0.92	−0.05	0.30	0.45	0.65	0.43	0.80	1.39
		$F6_Z$	−0.99	1.95	−0.85	−1.06	1.14	−0.17	0.25	0.12	−0.87	0.47
		$F7_Z$	0.68	−1.02	−0.56	0.24	0.87	1.21	0.84	0.27	−1.94	−0.59
		FS_Z	−0.43	−0.10	−0.74	−0.27	0.83	0.56	0.59	0.26	−0.93	0.24
	(I)	$F8_Z$	−2.06	−1.27	0.26	0.66	0.05	0.18	−0.02	−0.04	0.88	1.35
		$F9_Z$	−0.21	0.46	−1.38	−1.62	−0.56	0.53	−0.25	1.54	0.90	0.59
		FI_Z	−0.89	−0.18	−0.77	−0.78	−0.34	0.40	−0.16	0.96	0.90	0.87
Macao	(D)	$F1_M$	−0.40	0.04	0.51	−0.29	0.00	0.94	0.81	1.45	−1.22	−1.84
		$F2_M$	−1.47	−1.68	−0.13	0.72	1.18	1.17	−0.62	0.19	0.13	0.52
		$F3_M$	0.37	0.26	−0.23	−0.89	0.24	0.72	0.15	−0.20	−2.12	1.68
		FD_M	−0.46	−0.47	−0.02	−0.18	0.51	0.93	0.04	0.33	−1.11	0.43
	(P)	$F4_M$	−1.87	−1.31	−0.28	−0.08	0.23	0.63	1.06	1.44	0.00	0.19
		$F5_M$	−0.47	−0.51	−0.48	−0.18	−0.25	−0.52	−0.65	−0.62	2.27	1.40
		FP_M	−1.01	−0.82	−0.40	−0.14	−0.06	−0.08	0.01	0.18	1.40	0.93
	(S)	$F6_M$	−0.07	−0.30	0.40	0.22	0.73	0.70	1.07	0.71	−1.61	−1.85
		$F7_M$	−0.76	2.07	0.14	−1.53	1.09	−0.51	−0.30	0.19	−0.40	0.02
		FS_M	−0.50	1.17	0.24	−0.86	0.95	−0.05	0.22	0.39	−0.86	−0.69
	(I)	$F8_M$	0.68	2.06	0.75	0.63	−0.90	−0.81	−0.39	−0.16	−0.87	−0.97
		$F9_M$	2.64	−0.64	−0.62	−0.63	−0.66	−0.13	−0.38	−0.08	−0.02	0.51
		FI_M	1.85	0.44	−0.07	−0.13	−0.76	−0.40	−0.39	−0.11	−0.36	−0.08

Table 6. Index system and weights for the sustainable utilization of water resources in Zhuhai and Macao.

Criterion Stage	Indicator Stage	Zhuhai Indicator Weight	Zhuhai Criteria Layer Weights	Macao Indicator Weight	Macao Criteria Layer Weights
Driving force (D)	Per capita GDP growth rate (%)	0.0428	0.3097	0.0292	0.2516
	The proportion of the tertiary industry in GDP (%)	0.0601		0.0524	
	Per capita annual income of residents (CNY)	0.0498		0.0613	
	Per capita total industrial output value (CNY $\times$ 10^4)	0.0911		0.0449	
	Population density (person/km^2)	0.0659		0.0638	
Pressure (P)	Water consumption per CNY 10,000 of GDP	0.0483	0.2530	0.0379	0.2469
	The daily average total inflow of each sewage treatment plant/station	0.0504		0.0545	
	Commercial fee collection water volume	0.0382		0.0590	
	Living expenses and water volume	0.0645		0.0395	
	Public fee collection water quantity	0.0516		0.0561	
State (S)	Annual rainfall	0.0928	0.3001	0.0561	0.2546
	GDP output per cubic meter of water	0.0569		0.0465	
	Per capita annual water supply	0.0395		0.0473	
	Per capita water resources	0.0523		0.0499	
	Sewage treatment rate	0.0586		0.0548	
Impact (I)	Water resource development and utilization rate	0.0431	0.1371	0.0914	0.2469
	Per capita green space area	0.0404		0.1222	
	Environmental expenses	0.0536		0.0332	

Although Zhuhai and Macau are adjacent cities, their differences in water resources, sewage treatment, development models, and other factors result in certain differences in the driving force, pressure, state, and impact. Therefore, different response modes are required. The relationship between ecology and socioeconomic parameters can be interpreted as the former constraining the latter and the latter acting on the former [42]. The results highlighted the significance of the driving force system in Zhuhai and the state system in Macao SAR within the DPSIR model. This indicated the importance of the industries, population, and factors influencing sustainable development in urban water resources. These findings aligned with previous research that emphasized the impact of economic and social factors on water resource management, which presented a significant difference compared to mainland cities [43,44]. Additionally, the top-weighted indicators reflected the growing importance of household income, population, and the tertiary industry in Zhuhai. This is in line with studies highlighting the relationship between economic factors and sustainable water resource management [45]. Similarly, the focus on indicators such as per capita green space area, resource development, population density, industrial output value, and commercial revenue water volume in Macao SAR aligned with the increasing recognition of urban greening, resource management, and population issues in achieving sustainable water resource management [46]. To optimize sustainable development, future managers in both Zhuhai and Macao SAR should consider factors such as income, living expenses, annual precipitation, and environmental protection. These factors are vital for enhancing water resource utilization and require the implementation of appropriate measures and policies.

3.2. Evaluation Results of the DPSIR Index

The changes in the sustainable comprehensive evaluation of water resources in Zhuhai City from 2012 to 2021 are shown in Figure 3a (scored by Equation (8)). The comprehensive value of the sustainable utilization and development index of water resources in Zhuhai showed a fluctuating trend, but the overall score increased, indicating an overall trend of improvement in the sustainable development level of water resources in the city. The major decrease in the comprehensive index in 2014 can be attributed to the rapid economic and social development of the city, which negatively impacted the sustainability of water resources, such as a reduction in urban green coverage and environmental investment. However, the index rebounded due to the concerted efforts in Zhuhai to promote economic and environmental development, with the goal of becoming a "National Ecological Civilization Demonstration City" by 2016. The second significant decline occurred in 2020, primarily due to the outbreak of COVID-19 and the resulting increase in emissions and water consumption from various industries in Zhuhai. As a result, per capita water resources notably declined, leading to a significant decrease in the sustainable development index of water resources.

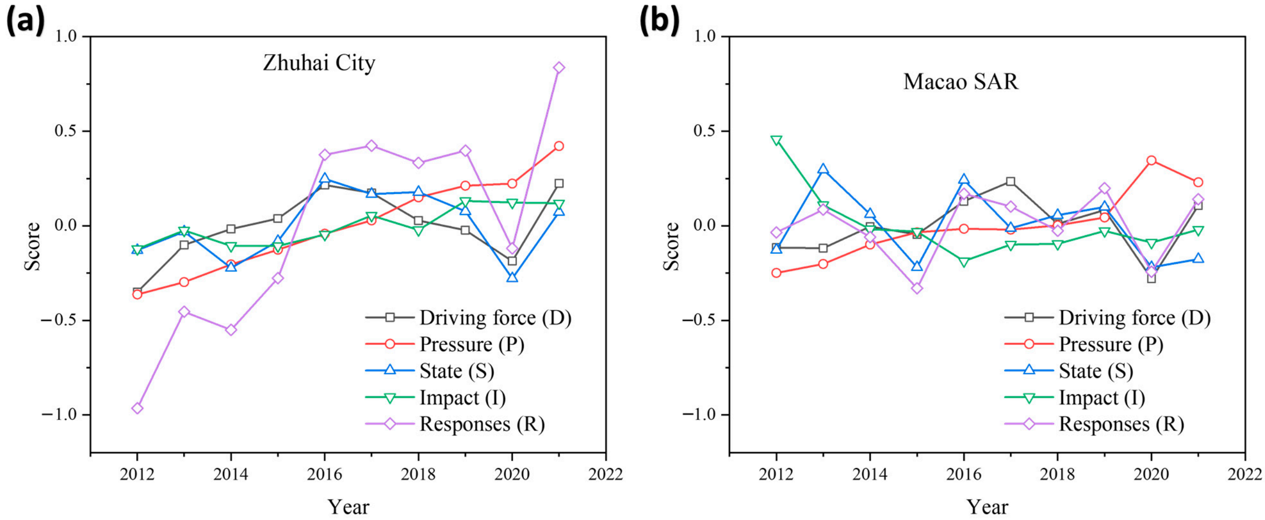

Figure 3. The comprehensive evaluation score. (**a**) Zhuhai City. (**b**) Macao SAR.

The changes in the sustainable comprehensive evaluation of water resources in Macao from 2012 to 2021 are shown in Figure 3b (scored by Equation (8)). The fluctuation of the city's sustainable comprehensive index was severe, and the upward trend was not obvious, resulting in a relatively slow development of the city's water resource sustainable development level overall. It can be seen from the figure that the precipitation decreased significantly in 2015. The data collected showed that the precipitation in that year was less than that in previous years. At the same time, it decreased significantly in 2020 but then rebounded. This is because the total water consumption in Macao kept rising during this period. The outbreak of COVID-19 has greatly impacted the economy and livelihood of the people in Macao. While water consumption in various industries has declined, residents spending more time at home has led to increased water consumption. The opening of the fourth water supply pipeline in 2019, connecting the Shipaiwan Reservoir from Hengqin in Zhuhai, has enhanced local water supply capacity. However, environmental governance is an ongoing process, and special policies implemented during specific periods cannot have a long-term effect on the city's sustainable development. Therefore, the comprehensive index has remained in a fluctuating state. In 2021, the construction of the Shipai Bay Water Plant increased the total production capacity to 520,000 cubic meters per day, effectively meeting the city's long-term water demand. Government measures, such as increased environmental investment, have yielded positive results, with a significant increase in the sustainable development index, indicating ample room for further sustainability in the city. It is crucial to implement long-term governance measures that align with practical situations to ensure steady progress in the city's sustainable development.

The changes in the evaluation index of sustainable water resources in various subsystems of Zhuhai and Macao from 2012 to 2021 are shown in Figure 3. In terms of the driving force system, Zhuhai has experienced significant growth. Despite a decline in 2017, its overall performance remains good. On the other hand, Macao has shown fluctuating patterns, reaching a new historical high in 2020, likely due to the impact of COVID-19 on its economy and society. At the same time, it was noted that the pressure subsystem in Zhuhai had been steadily increasing from 2012 to 2021, indicating that the economic development of Zhuhai has increased urban water consumption and emissions, but the overall speed of water resource consumption has slowed down, without causing any negative impact on urban resources and environment. Similarly, there is a relationship between the pressure subsystem and the driving force system in Macao. Generally, a city's development is achieved by bearing significant environmental pressure [47]. While this development model is not sustainable, both subsystems in Macao showed an upward trend, suggesting that the city aims to achieve coordinated development between economic growth and ecological environment protection. Regarding the state subsystem index, Zhuhai generally showed an upward trend, with slow growth due to fluctuations in the middle value, reflecting the city's good water supply and per capita water resources. Macao generally showed a downward trend and reached its minimum value in 2021. This indicated that, in recent years, the annual rainfall and water supply capacity has been unstable, affecting the sustainability of urban water resources, and the state of resources and the environment has not been well maintained. Considering the impact subsystem index, it is susceptible to various factors such as international and domestic economic and social development. While the index for both Zhuhai and Macao fluctuate, Zhuhai generally demonstrates an upward trend, indicating the effectiveness of the city's measures. However, the overall downward trend of Zhuhai suggests that environmental governance in the city has some effect, but it may also lead to new problems in the governance process. Waiting for problems to occur before solving them limits the establishment of a warning and pre-control mechanism, which could effectively prevent water resource pollution and damage in the future. Overall, both cities made progress in urban development between 2012 and 2021. Although the COVID-19 pandemic has greatly affected some cities, it is crucial to adjust economic growth promptly after the epidemic, which may otherwise result in poor water resource management. Continuous efforts should be made towards the sustainable development and utilization of urban water resources.

Climate change has significantly affected the sustainability of water resources [48]. Climate change is believed to have significant negative impacts on the management of water resources [49]. It is expected to accelerate the frequency of extreme events such as floods and droughts, as well as increase the demand for water in irrigation [50]. These negative effects are projected to worsen over time. By 2030, it is estimated that 5.55% to 20.37% of the total urban area will be potentially affected by climate change [51]. Studies have shown that rainfall has a limited influence on water demand, while temperature has a significant correlation with water demand [52]. According to global climate change projections for the 2050s, temperatures are expected to increase by 1.5 to 3.6 °C, and precipitation is expected to decrease by 10% to 20% in most areas, depending on the season [50]. For coastal cities such as Zhuhai and Macau, rising global temperatures have led to increased evaporation rates, causing a reduction in freshwater availability. This has a direct impact on both surface water and groundwater sources, threatening the availability of potable water for human consumption and agricultural needs. Furthermore, climate change has disrupted the water cycle, resulting in more frequent and severe droughts and floods. These extreme weather events can lead to water scarcity in some regions while causing devastating deluges in others. These fluctuations in water availability make planning and managing water resources more challenging and less predictable. In addition, the melting of glaciers and polar ice caps, triggered by global warming, has contributed to rising sea levels. As a consequence, coastal freshwater aquifers are becoming contaminated with saltwater intrusion, endangering the availability of freshwater for coastal communities and ecosystems. Moreover, climate change exacerbates water pollution through the increased runoff of pollutants from agricultural and urban areas. Higher temperatures also enhance the growth of harmful algal blooms in water bodies, affecting the quality of water resources and posing health risks to humans and aquatic life. Overall, climate change poses significant threats to the sustainable development of water resources. Mitigating its impacts requires a comprehensive approach that combines adaptive measures to address current challenges and efforts to reduce greenhouse gas emissions for long-term sustainability.

3.3. Prediction of Sustainable Utilization Level of Water Resources in Zhuhai and Macao

Studying the trend of sustainable changes in urban water resources in the future can help managers take scientific and effective measures to enhance the sustainability of water resources, which also indirectly affects the economy and society of cities. The sustainability of water resources in Zhuhai and Macao from 2012 to 2021 was predicted by the grey prediction model method using GM (1, 1). This method effectively establishes a correlation between indicator factors' development trends and analyzes them [53,54]. By organizing factor data and expressing the observed patterns through data sequences, future development changes can be predicted through the establishment of differential equation models. However, it is important to note that this method is not suitable for limited data samples and long-term prediction research. From Table 7, it can be seen that the original values in Zhuhai need to be combined with translation values to ensure that the data level comparison test values are within the standard range of [0.834, 1.199]; hence, the translation transformation shift value was 5 in Zhuhai indicators, and the final translated data were suitable for model construction. Meanwhile, the translation transformation shift value was 3 in Macao indicators with a range of [0.834, 1.199]. From Table 8, it can be seen that the C value of 0.283 < 0.35 in Zhuhai represents a very good level of model accuracy. A *p*-value of 0.800 < 0.95 also means that the model accuracy is qualified. Meanwhile, the C value of 0.978 > 0.65 in Macao showed that the model accuracy level was unqualified. Therefore, as shown in Table 9, the three-year water resource sustainability prediction from 2022 to 2024 shows that the sustainable utilization level of water resources in both Zhuhai and Macao was on the rise (Figure 4). Compared with the sustainable evaluation values in 2021, Zhuhai had the largest increase, indicating that more attention needs to be paid to Macao in the future sustainable management of water resources in these two cities to avoid a decline in the future. However, due to the unsatisfactory fitting effect of the two cities and the inability to meet higher requirements, this prediction result can only be used as a reference opinion.

Table 7. Zhuhai and Macao GM (1,1) model level ratio.

	Year	Original Value	Grade Ratio λ	Original Value + Shift Value for Translation Conversion (Shift = 5)	Converted Level Ratio λ
Zhuhai	2012	−0.965	-	4.035	-
	2013	−0.455	2.121	4.545	0.888
	2014	−0.551	0.826	4.449	1.022
	2015	−0.277	1.990	4.723	0.942
	2016	0.376	−0.737	5.376	0.879
	2017	0.424	0.886	5.424	0.991
	2018	0.333	1.273	5.333	1.017
	2019	0.397	0.838	5.397	0.988
	2020	−0.119	−3.329	4.881	1.106
	2021	0.837	−0.143	5.837	0.836
Macao	2012	−0.035	-	2.965	-
	2013	0.086	−0.411	3.085	0.961
	2014	−0.060	−1.432	2.940	1.049
	2015	−0.331	0.180	2.669	1.102
	2016	0.169	−1.956	3.169	0.842
	2017	0.102	1.661	3.102	1.022
	2018	−0.027	−3.816	2.973	1.043
	2019	0.199	−0.134	3.199	0.930
	2020	−0.243	−0.818	2.757	1.160
	2021	0.140	−1.733	3.140	0.878

Table 8. Model construction predicted the score results of Zhuhai and Macao.

City	Development Coefficient a	Grey Action Amount b	Posteriori Difference Ratio C Value	*p*-Value
Zhuhai	−0.0249	4.4558	0.2832	0.800
Macao	−0.0030	2.9553	0.9782	0.500

Table 9. The predicted score of Zhuhai and Macao.

Year	Zhuhai		Macao	
	Original Value	Predict Value	Original Value	Predict Value
2012	−0.965	−0.965	−0.035	−0.035
2013	−0.455	−0.387	0.086	−0.032
2014	−0.551	−0.270	−0.060	−0.023
2015	−0.277	−0.151	−0.331	−0.014
2016	0.376	−0.029	0.169	−0.005
2017	0.424	0.097	0.102	0.004
2018	0.333	0.225	−0.027	0.013
2019	0.397	0.357	0.199	0.022
2020	−0.119	0.492	−0.243	0.031
2021	0.837	0.631	0.140	0.040
2022	–	0.773	–	0.049
2023	–	0.918	–	0.058
2024	–	1.068	–	0.067

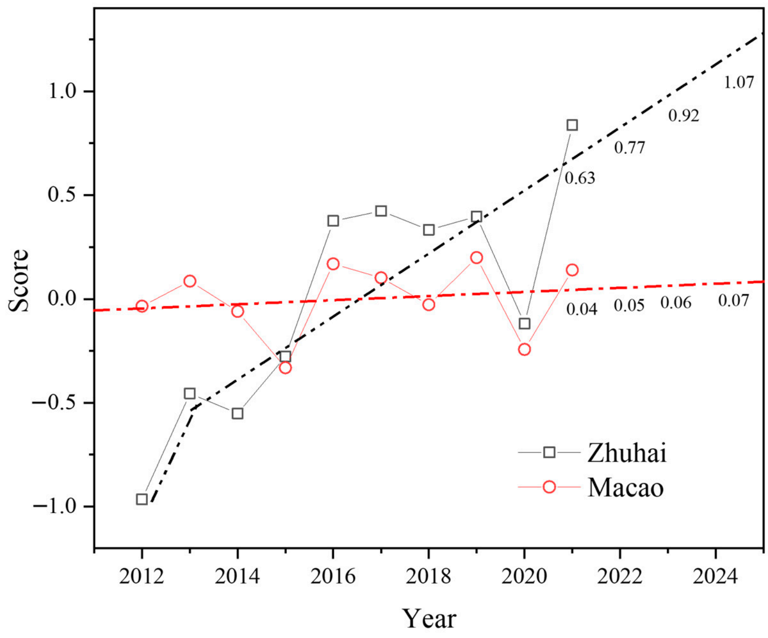

Figure 4. Comprehensive evaluation score of Zhuhai and Macao.

3.4. *Proposal*

Research analysis indicates that in order to enhance the capacity for the sustainable development of water resources in the Zhuhai and Macao Special Administrative Region, it is essential for the government to take the lead while citizens cooperate and respond effectively. The following adjustments should made to address the various aspects mentioned.

There should be an increase in investment for research and development aimed at controlling wastewater discharge and conserving water resources. Additionally, it is crucial to establish appropriate laws and regulations that will contribute to the reduction of wastewater discharge and enhance the efficiency of water resource utilization.

Measures should be taken to minimize water consumption across different industries. Relevant documentation should be proposed to enterprises and factories, accompanied by reward and punishment systems. Furthermore, efforts should be made to establish water resource input channels between the two regions, optimize the industrial structure, and provide support to industries involved in environmental protection and clean production.

Emphasis should be placed on strengthening education and public awareness regarding the sustainable development of water resources. It is vital to cultivate a shared consciousness of water conservation within society as a whole. Moreover, communication between the two regions needs to be intensified in order to protect water resources. This includes learning from each other's experiences in water management development and drawing inspiration from other cities. Additionally, local conditions should be considered to optimize the sustainable development of water resources in the Zhuhai and Macao Special Administrative Region.

4. Conclusions

In this study, using the framework of the DPSIR model, and considering the socio-economic connotation between Zhuhai and Macao Cities, the sustainability of the current state of urban water resources in Zhuhai and Macao was analyzed with the key factors for sustainable development from 2012 to 2021. The results showed that both cities are moving towards sustainable development. Factors that potentially influence the sustainability of water resources in both cities were carefully evaluated and integrated within the five subsystems of the DPSIR model, resulting in the establishment of a robust and sustainable evaluation framework specific to each location. Findings revealed that Zhuhai City experienced significant impacts from driving forces, whereas Macao was predominantly affected by the state system between 2012 and 2021. Furthermore, recent trends indicate progressing water resource sustainability in both cities, with notable achievements in water resource management and protection. The evaluation results highlight the effectiveness of implementing urban water-saving initiatives, increasing investment in environmental and water conservation measures, and upgrading sewage treatment infrastructure to optimize treatment rates, improving the current water resource situation in both regions. Looking ahead, Zhuhai and Macao may continue to encounter water resource pressures driven by socio-economic developments. Consequently, we strongly recommend actively adjusting wastewater discharge regulations and promoting water resource conservation, while steadfastly adhering to the principles of sustainable development to ensure the harmonious advancement of socio-economic conditions and the preservation of the ecological environment. This study provides valuable insight and data to support regional water resource security and policy formulation, considering the diverse political systems in place.

Author Contributions: Conceptualization, Y.B., J.Q. and Y.W.; methodology, Y.B. and J.Q.; software, Y.B. and J.Q.; formal analysis, Y.B. and J.Q.; investigation, L.L. and W.L.; data curation, J.Q. and W.L.; writing—original draft preparation, Y.B. and Y.W.; writing—review and editing, P.Z. and Y.W.; supervision, P.Z.; funding acquisition, Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by The Science and Technology Development Fund, Macao SAR [0034/2022/ITP, 001/2022/NIF].

Data Availability Statement: Data available in a publicly accessible repository The data presented in this study are openly available in the Government of Macao Special Administrative Region Statistics and Census Service https://www.dsec.gov.mo/zh-MO (accessed on 1 May 2024), DSPA https://www.dspa.gov.mo/index.aspx (accessed on 1 May 2024), and Zhuhai Yearbook http://tjj.zhuhai.gov.cn/tjsj/tjnj/ (accessed on 1 May 2024).

Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A. The Public Data of Indicators of the DPSIR Model in Zhuhai and Macao Cities

Criterion Stage	Indicator Stage	City	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Driving force (D)	Per capita GDP growth rate (%)	Zhuhai	2.93	7.85	8.82	7.31	7.88	14.89	2.91	0.90	−2.99	7.30
		Macao	6.10	7.40	−5.20	−23.90	−1.50	9.40	4.70	−4.50	−54.80	19.00
	The proportion of the tertiary industry in GDP (%)	Zhuhai	47.70	48.80	49.70	50.70	52.50	54.10	53.20	54.20	57.00	56.70
		Macao	93.80	96.30	94.90	92.20	93.30	94.90	95.80	95.70	91.30	92.30
	Per capita annual income of residents (CNY)	Zhuhai	32,978	36,375	33,235	36,158	40,154	44,043	48,107	52,495	55,936	61,390
		Macao	412,211	449,245	469,022	410,035	427,413	466,569	490,617	503,450	304,211	283,660
	Per capita total industrial output value (CNY × 10^4)	Zhuhai	18.99	20.42	21.10	21.94	23.53	20.42	21.87	21.33	19.55	21.77
		Macao	1.27	1.20	1.31	1.26	1.32	1.46	1.34	1.46	1.16	1.21
	Population density (person/km^2)	Zhuhai	1006	1041	1081	1095	1131	1192	1272	1343	1411	1430
		Macao	19,000	19,500	20,500	21,100	21,400	21,100	20,000	20,400	20,800	20,700
Pressure (P)	Water consumption per CNY × 10^4 of GDP	Zhuhai	32.01	29.00	27.00	25.00	22.90	20.97	19.42	18.77	18.41	14.96
		Macao	3.11	2.77	2.73	3.30	3.23	2.87	2.76	2.70	5.28	4.73
	The daily average total inflow of each sewage treatment plant/station (×10^4 t)	Zhuhai	61.86	65.99	73.67	76.70	86.60	86.65	96.99	96.77	96.22	110.09
		Macao	20.31	21.50	22.90	23.30	23.70	24.20	24.90	25.40	23.40	23.60
	Commercial fee collection water volume (×10^4 m^3)	Zhuhai	12,569	12,929	13,486	14,069	14,153	14,810	15,004	15,443	15,602	17,349
		Macao	3398	3408	3630	3796	3920	4058	4236	4303	3251	3499
	Living expenses and water volume (×10^4 m^3)	Zhuhai	10,058	10,016	10,524	11,189	11,610	12,201	12,877	13,428	13,930	14,343
		Macao	3219	3351	3527	3632	3698	3739	3828	3915	4282	3992
	Public fee collection water quantity (×10^4 m^3)	Zhuhai	5530	5892	6277	6475	6970	7250	8686	9439	9038	10,424
		Macao	492	511	552	547	555	569	576	592	558	570
State (S)	Annual rainfall (mm)	Zhuhai	1760	2885	1891	1720	2538	1949	2183	1984	1799	2393
		Macao	1556	2565	1584	1341	2336	1783	1796	2248	1713	2206
	GDP output per cubic meter of water (CNY × 10^4/m^3)	Zhuhai	31,929	37,413	40,338	43,892	48,090	54,718	56,834	59,796	65,033	66,812
		Macao	3.21	4.05	4.10	3.42	3.48	3.84	4.00	4.01	2.07	2.26
	Per capita annual water supply (m^3)	Zhuhai	203	191	196	199	201	204	202	197	185	194
		Macao	147.19	142.58	145.98	147.53	150.45	149.54	151.64	149.68	140.90	138.98
	Per capita water resources (m^3)	Zhuhai	1142	1331	941	893	1049	1010	929	1100	718	667
		Macao	150	149	152	153	157	155	157	155	143	142
	Sewage treatment rate (%)	Zhuhai	87.78	88.50	90.13	95.70	96.30	96.36	96.40	96.62	97.18	98.10
		Macao	87.90	99.00	94.76	82.83	97.05	87.19	89.56	87.80	89.32	86.02
Impact (I)	Water resource development and utilization rate (%)	Zhuhai	19.03	22.50	33.02	34.59	29.03	30.62	28.05	26.04	31.51	35.30
		Macao	96.91	86.95	86.10	86.11	85.50	87.37	86.91	88.14	87.76	89.21
	Per capita green space area (m^2/person)	Zhuhai	16.12	17.77	18.75	19.50	19.70	19.80	19.90	21.00	22.04	22.18
		Macao	14.00	14.50	14.00	13.50	10.90	10.80	10.60	10.50	10.50	11.40
	Environmental expenses (CNY × 10^4)	Zhuhai	12.61	16.19	7.34	5.62	10.13	17.26	11.57	20.84	17.67	16.82
		Macao	11.91	7.81	13.52	13.35	16.87	15.93	13.68	12.15	15.66	17.30

References

1. Larsen, T.A.; Hoffmann, S.; Lüthi, C.; Truffer, B.; Maurer, M. Emerging solutions to the water challenges of an urbanizing world. *Science* **2016**, *352*, 928–933. [CrossRef] [PubMed]
2. Boretti, A.; Rosa, L. Reassessing the projections of the World Water Development Report. *Npj Clean Water* **2019**, *2*, 15. [CrossRef]
3. Tauqeer, H.M.; Basharat, Z.; Adnan Ramzani, P.M.; Farhad, M.; Lewinska, K.; Turan, V.; Karczewska, A.; Khan, S.A.; Faran, G.-E.; Iqbal, M. Aspergillus niger-mediated release of phosphates from fish bone char reduces Pb phytoavailability in Pb-acid batteries polluted soil, and accumulation in fenugreek. *Environ. Pollut.* **2022**, *313*, 120064. [CrossRef] [PubMed]
4. Yu, G.R.; Wang, Y.S.; Yang, M. Discussion on the ecological theory and assessment methods of ecosystem quality and its evolution. *Chin. J. Appl. Ecol.* **2022**, *33*, 865–877.
5. Turan, V. Arbuscular mycorrhizal fungi and pistachio husk biochar combination reduces Ni distribution in mungbean plant and improves plant antioxidants and soil enzymes. *Physiol. Plant.* **2021**, *173*, 418–429. [CrossRef]
6. Rasool, B.; Mahmood-ur-Rahman Zubair, M.; Khan, M.A.; Ramzani, P.M.A.; Dradrach, A.; Turan, V.; Iqbal, M.; Khan, S.A.; Tauqeer, H.M.; Farhad, M.; et al. Synergetic Efficacy of Amending Pb-Polluted Soil with P-Loaded Jujube (Ziziphus mauritiana) Twigs Biochar and Foliar Chitosan Application for Reducing Pb Distribution in Moringa Leaf Extract and Improving Its Anti-cancer Potential. *Water Air Soil. Pollut.* **2022**, *233*, 344. [CrossRef]
7. Sun, S.; Wang, Y.; Liu, J.; Cai, H.; Wu, P.; Geng, Q.; Xu, L. Sustainability assessment of regional water resources under the DPSIR framework. *J. Hydrol.* **2016**, *532*, 140–148. [CrossRef]
8. Morote, Á.-F.; Eslamian, S. Urban Water Scarcity in Semi-arid Regions: Water Management in Southern Spain. In *Clean Water and Sanitation. Encyclopedia of the UN Sustainable Development Goals*; Leal Filho, W., Azul, A.M., Brandli, L., Lange Salvia, A., Wall, T., Eds.; Springer: Berlin/Heidelberg, Germany, 2022.
9. Organization of Economic Cooperation and Development. OECD. *Core Set of Indicators for Environmental Performance Review*; Environmental Monograph No. 83; OECD: Paris, Italy, 1993.
10. Gari, S.R.; Newton, A.; Icely, J.D. A review of the application and evolution of the DPSIR framework with an emphasis on coastal social-ecological systems. *Ocean. Coast. Manag.* **2015**, *103*, 63–77. [CrossRef]

11. Tesfaldet, Y.T.; Ndeh, N.T. Assessing face masks in the environment by means of the DPSIR framework. *Sci. Total Environ.* **2022**, *814*, 152859. [CrossRef]
12. Xi, H.; Chen, Y.; Zhao, X.; Sindikubwabo, C.; Cheng, W. Safety assessment of fragile environment in Badain Jaran Desert and its surrounding areas based on the DPSIR model. *Ecol. Indic.* **2023**, *146*, 109874. [CrossRef]
13. Borja, A.; Galparsoro, I.; Solaun, O.; Muxika, I.; Tello, E.M.; Uriarte, A.; Valencia, V. The European Water Framework Directive and the DPSIR, a methodological approach to assess the risk of failing to achieve good ecological status. *Estuar. Coast. Shelf Sci.* **2006**, *66*, 84–96. [CrossRef]
14. Malmir, M.; Javadi, S.; Moridi, A.; Neshat, A.; Razdar, B. A new combined framework for sustainable development using the DPSIR approach and numerical modeling. *Geosci. Front.* **2021**, *12*, 264–277. [CrossRef]
15. Xu, Q.Y.; Huang, M.; Liu, H.S.; Yan, H.M. Integrated assessment of ecoenvironmental vulnerability in Pearl River Delta based on RS and GIS. *Chin. J. Appl. Ecol.* **2011**, *22*, 2987–2995. (In Chinese)
16. Kagalou, I.; Leonardos, I.; Anastasiadou, C.; Neofytou, C. The DPSIR Approach for an Integrated River Management Framework. A Preliminary Application on a Mediterranean Site (Kalamas River -NW Greece). *Water Resour. Manag.* **2012**, *26*, 1677–1692. [CrossRef]
17. Svarstad, H.; Petersen, L.K.; Rothman, D.; Siepel, H.; Wätzold, F. Discursive biases of the environmental research framework DPSIR. *Land Use Policy* **2008**, *25*, 116–125. [CrossRef]
18. Atkins, J.P.; Burdon, D.; Elliott, M.; Gregory, A.J. Management of the marine environment: Integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Mar. Pollut. Bull.* **2011**, *62*, 215–226. [CrossRef]
19. Haase, D.; Nuissl, H. Does urban sprawl drive changes in the water balance and policy? The case of Leipzig (Germany) 1870–2003. *Landsc. Urban. Plan.* **2007**, *80*, 1–13. [CrossRef]
20. Kaur, M.; Hewage, K.; Sadiq, R. Investigating the impacts of urban densification on buried water infrastructure through DPSIR framework. *J. Clean. Product.* **2020**, *259*, 120897. [CrossRef]
21. Wang, Y.L.; Zhao, C.Y.; Ma, Q.L.; Li, Y.K.; Jing, H.J.; Sun, T.; Milne, E.; Easter, M.; Paustian, K.; Yong, H.W.A.; et al. Carbon benefits of wolfberry plantation on secondary saline land in Jingtai oasis, Ga–su—A case study on application of the CBP model. *J. Environ. Manag.* **2015**, *157*, 303–310. [CrossRef]
22. Nobre, A.M. An Ecological and Economic Assessment Methodology for Coastal Ecosystem Management. *Environ. Manag.* **2009**, *44*, 185–204. [CrossRef]
23. Statistics and Census Service of Macau (DSEC). *Yearbook of Statistics 2012 to 2021*; Statistics and Census Service of Macau: Macau, China, 2022.
24. Environmental Protection Bureau of Macau (DSPA). *Report on the state of the Environment of Macao 2012 to 2021*; Environmental Protection Bureau: Macau, China, 2022.
25. Marine and Water Bureau of Macau (DSAMA). *Macao Water Resources Status Report 2022*; Marine and Water Bureau: Macau, China, 2022.
26. Statistics of Bureau of Zhuhai. *Zhuhai Yearbook 2012 to 2021*; Statistics of Bureau of Zhuhai: Zhuai, China, 2022.
27. Ecology and Environment of Bureau of Zhuhai. *Environmental Quality Status of Zhuhai City 2012 to 2021*; Ecology and Environment of Bureau of Zhuhai: Zhuai, China, 2022.
28. Sheng, N.; Tang, U.W. Zhuhai. *Cities* **2013**, *32*, 70–79. [CrossRef]
29. Hong, G. Locating Zhuhai between land and sea: A relational production of Zhuhai, China, as an island city. *Isl. Stud. J.* **2017**, *12*, 7–24. [CrossRef]
30. Tang, U.W.; Sheng, N. Macao. *Cities* **2009**, *26*, 220–231. [CrossRef]
31. Huang, J.Y.; Lou, I.C.; Li, Y.X. Integrated water resources management for emergency situations: A case study of Macau. *J. Environ. Sci.* **2016**, *50*, 72–78. [CrossRef]
32. Wei, T.; Lou, I.C.; Yang, Z.F.; Li, Y.X. A system dynamics urban water management model for Macau, China. *J. Environ. Sci.* **2016**, *50*, 117–126. [CrossRef]
33. Huang, J.L.; Ho, M.H.; Du, P.F. Assessment of temporal and spatial variation of coastal water quality and source identification along Macau peninsula. *Stoch. Environ. Res. Risk Assess.* **2011**, *25*, 353–361. [CrossRef]
34. DSEC. *Macau Yearbook of Statistic*; Driving Start Engine Consulting: Macau, Chian, 2022.
35. Carr, E.R.; Wingard, P.M.; Yorty, S.C.; Thompson, M.C.; Jensen, N.K.; Roberson, J. Applying DPSIR to sustainable development. *Int. J. Sustain. Dev. World* **2007**, *14*, 543–555. [CrossRef]
36. Hou, X.R.; Lv, T.; Xu, J.; Deng, X.; Liu, F.; Lam JS, L.; Zhang, Z.Z.; Han, X.S. Evaluation of urban public transport sustainability in China based on the Driving Force-Pressure-State-Impact-Response (DPSIR) framework—A case study of 36 major cities. *Environ. Impact Assess. Rev.* **2023**, *103*, 107263. [CrossRef]
37. Skoulikidis, N.T. The environmental state of rivers in the Balkans—A review within the DPSIR framework. *Sci. Total Environ.* **2009**, *407*, 2501–2516. [CrossRef]
38. Asante-Okyere, S.; Shen, C.B.; Ziggah, Y.Y.; Rulegeya, M.M.; Zhu, X.F. Principal component analysis (PCA) based hybrid models for the accurate estimation of reservoir water saturation. *Comput. Geosci.* **2020**, *145*, 104555. [CrossRef]
39. Li, S.; Li, J.; Zhang, Q. Water quality assessment in the rivers along the water conveyance system of the Middle Route of the South to North Water Transfer Project (China) using multivariate statistical techniques and receptor modeling. *J. Hazard. Mater.* **2011**, *195*, 306–317. [CrossRef]

40. Hu, W.M.; Zhang, S.B.; Fu, Y.S.; Jia, G.Y.; Yang, R.H.; Shen, S.Y.; Li, Y.; Li, G. Objective diagnosis of machine learning method applicability to land comprehensive carrying capacity evaluation: A case study based on integrated RF and DPSIR models. *Ecol. Indic.* **2023**, *151*, 110338. [CrossRef]
41. Xu, Y.Y.; Wang, H.; Zhang, K.J.; Han, Y. Ecological security assessment of urban park landscape using the DPSIR model and EW-PCA method. *Environ. Dev. Sustain.* **2024**. [CrossRef]
42. Gong, L.L.; Yu, Y.C.; Xu, Q.Y.; Wang, C.Y.; Han, J.W. Research on the coupling relationship between ecological environment and socio-economic development in Baoji City from 2010 to 2019. *J. Baoji Univ. Arts Sci. (Nat. Sci. Ed.)* **2021**, *41*, 69–75.
43. Yan, B.; Xu, Y. Evaluation and prediction of water resources carrying capacity in Jiangsu Province, China. *Water Policy* **2022**, *24*, 324–344. [CrossRef]
44. Zhao, M.D.; Wei, J.H.; Han, Y.P.; Shi, J.H.; Wang, S.B. Water resource security evaluation and barrier analysis in Henan Province utilizing the DPSIR framework. *Front. Env. Sci.* **2024**, *12*, 1354175. [CrossRef]
45. Peng, L.C.; Ma, X.W.; Ma, W.W.; Zhou, Y.X. Evaluation of Economic Security of Water Resources and Analysis of Influencing Factors. *J. Glob. Inf. Manag.* **2022**, *30*, 19. [CrossRef]
46. Xu, M.; Li, C.H.; Wang, X.; Cai, Y.P.; Yue, W.C. Optimal water utilization and allocation in industrial sectors based on water footprint accounting in Dalian City, China. *J. Clean. Product.* **2018**, *176*, 1283–1291. [CrossRef]
47. Santos, E.; Fonseca, F.; Santiago, A.; Rodrigues, D. Sustainability Indicators Model Applied to Waste Management in Brazil Using the DPSIR Framework. *Sustainability* **2024**, *16*, 2192. [CrossRef]
48. Kundzewicz, Z.W.; Krysanova, V.; Benestad, R.E.; Hov, O.; Piniewski, M.; Otto, I.M. Uncertainty in climate change impacts on water resources. *Environ. Sci. Policy* **2018**, *79*, 1–8. [CrossRef]
49. Dawadi, S.; Ahmad, S. Evaluating the impact of demand-side management on water resources under changing climatic conditions and increasing population. *J. Environ. Manag.* **2012**, *114*, 261–275. [CrossRef] [PubMed]
50. Iglesias, A.; Quiroga, S.; Moneo, M.; Garrote, L. From climate change impacts to the development of adaptation strategies: Challenges for agriculture in Europe. *Clim. Chang.* **2011**, *112*, 143–168. [CrossRef]
51. Humpenoder, F.; Popp, A.; Stevanovic, M.; Muller, C.; Bodirsky, B.L.; Bonsch, M.; Dietrich, J.P.; Lotze-Campen, H.; Weindl, I.; Biewald, A.; et al. Land-use and carbon cycle responses to moderate climate change: Implications for land-based mitigation. *Environ. Sci. Technol.* **2015**, *49*, 6731–6739. [CrossRef] [PubMed]
52. Haque, M.M.; Egodawatta, P.; Rahman, A.; Goonetilleke, A. Assessing the significance of climate and community factors on urban water demand. *Int. J. Sustain. Built Environ.* **2015**, *4*, 222–230. [CrossRef]
53. Wang, Y.H.; Lu, J. Improvement and application of GM(1,1) model based on multivariable dynamic optimization. *J. Syst. Eng. Electron.* **2020**, *31*, 593–601.
54. Deng, J.L. Control problems of grey systems. *Syst. Control Lett.* **1982**, *1*, 288–294.