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Water Sustainability and High-Quality Economic Development

Edited by
Yang Kong, Liang Yuan, Li Xu and Dagmawi Mulugeta Degefu

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Contents

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Editorial

Water Sustainability and High-Quality Economic Development

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1. Introduction

Water resources are a fundamental pillar of both socioeconomic development [1–3] and environmental sustainability [4]. However, due to their limited availability and uneven distribution, coupled with the continuous expansion of the intensity and scope of human activities and the impacts of climate change [5–7], approximately 1.5 billion people worldwide are facing severe water scarcity [8,9]. Since the beginning of the Anthropocene, human activities have disrupted the dynamic balance of the natural water cycle, restricting its normal functioning. Balancing water sustainability and high-quality economic development within the carrying capacity of the water environment to achieve mutually reinforcing and synergistic development has become a top priority. This requires a global, systematic, and interdisciplinary vision to address the many challenges facing water resources [10,11], to ensure the continuous prosperity of the social economy, and to safeguard the sound development of the environment.

Accordingly, this Special Issue serves as a key platform, presenting cutting-edge research that merges theoretical innovation with practical solutions. The editorial team has carefully selected diverse contributions that reflect the multifaceted nature of modern water resource management. These include in-depth analyses of conflict resolution in transboundary water management, advanced efficiency evaluation models using data analytics and machine learning, ecological optimization studies on balancing human water use with ecosystem health, and technological innovations in smart water monitoring and AI-driven flood and drought prediction. Together, these interdisciplinary studies offer a comprehensive view of sustainable water governance, bridging academia, policy-making, and practical implementation. The following overview highlights the key findings and methodologies of these studies, emphasizing their potential to transform real-world water challenges into opportunities for resilient development.

2. An Overview of the Contributions to this Special Issue

To address cross-basin water pollution conflicts involving heterogeneous sanctions, Contribution 1 employs an improved Graph Model for Conflict Resolution (GMCR), integrating case studies and evolutionary analysis to conduct a systematic modeling and strategic analysis of the cross-border water pollution dispute in Hongze Lake, China, in 2018. The study finds that the heterogeneity of sanctioning opponents affects the equilibrium outcomes of conflicts and even alters the evolution of conflict situations. Moreover, the newly developed method can accurately predict conflict equilibria, providing strategic insights for the governance of cross-basin water pollution.

To balance the interest-based conflicts over flood control and drainage between upstream and downstream regions and to achieve collaborative management, Contribution 2 conducts a comparative analysis of interest relationships in the Yangtze River Delta Ecological and Green Integration Development Demonstration Zone by applying evolutionary game theory and introducing external driving factors as well as internal balancing mechanisms. The study finds that the selection of a collaborative strategy is closely related to factors such as conflict costs and compensation amounts. A reasonable reward–punishment mechanism can drive the model to evolve toward stable strategies, and internal/external mechanisms, respectively, facilitate regional cooperation by compensating for economic losses and coordinating contradictions.

To improve the efficiency of water resources in China, Contribution 3 employs the Super-Efficiency Slacks-Based Measure (SE-SBM) model and a Tobit regression model to measure water resource use efficiency (WRUE) and analyzes its driving factors in China from 2005 to 2021. The study finds that Jilin has the highest agricultural WRUE (1.185) and Ningxia the lowest (0.687); in the industrial sector, Beijing has the highest WRUE (1.399) and Jiangxi the lowest (0.212). Factors such as economic structure and water resource endowment significantly influence WRUE, necessitating precautions against inefficiencies caused by the declining proportion of the industrial sector in the economic structure.

To explore the impact of the water resources tax reform on enterprises' green innovation and total factor productivity, Contribution 4 takes the high water-consuming A-share listed companies in China's Shanghai and Shenzhen stock markets from 2007 to 2021 as samples and conducts an empirical study by using the Difference-in-Differences (DID) method. The study finds that replacing water resources fees with taxes significantly improves enterprises' green innovation level and total factor productivity. Green innovation plays a partial mediating role in this process; that is, water resources tax reform promotes total factor productivity by driving enterprises' green innovation. From the perspective of enterprise property rights, the economic effect of the reform is more obvious in non-state-owned enterprises than in state-owned enterprises, providing empirical evidence for expanding the pilot scope of the water resources tax reform.

To address the issue of neglecting ecological benefits in reservoir water resource allocation and achieve coordination between ecology and water supply, Contribution 5 constructs an integrated multi-objective model based on the assessment of ecosystem service value-based supply and demand. By combining a forecasting model to set different scenarios, it conducts a case study on water allocation plans for Datun Reservoir, a key hub of the East Route of China's South-to-North Water Diversion Project. The study finds that optimizing water supply for domestic/industrial use and reservoir storage can enhance the overall ecosystem service value of Datun Reservoir by 5.15% to 11.36%. In scenarios of high economic growth, there is potential for synergy between water supply and ecosystem service value, while during economic downturns, a trade-off between ecological services and water supply capacity may emerge and could be maintained at a lower level.

To reveal the relationship between water resources and economic development from the perspective of ecosystem services, Contribution 6 selects the river ecosystem service values and comprehensive economic indices of the Yellow River Basin from 2007 to 2018, and uses a coupling coordination model to carry out a synergy assessment. The study finds that the overall ecosystem service values in the Yellow River Basin show an upward trend, with the highest values in the lower reaches and a gradual decrease from the middle to upper reaches. The synergy is mainly reflected in the supply and regulation functions, while the synergy of cultural functions needs to be improved. The overall degree of coupling coordination has increased, but the long-standing problem of lagging ecological development remains.

To achieve the decoupling of agricultural economic growth from water pollution, Contribution 7 combines the water footprint theory, Logarithmic Mean Divisia Index

(LMDI) model, and Tapio Decoupling Model (TDM) to conduct a decoupling analysis of the agricultural gray water footprint (AGWF) and economic growth of the Yellow River Basin (YRB) from 2016 to 2021. The study finds that the overall AGWF in the YRB first decreases and then slowly increases, dropping by 5.39% in 2021 compared with 2016. The decoupling status of AGWF and agricultural GDP evolves from "strong decoupling" to "weak decoupling", and the decoupling status of population and agricultural GDP remains in the "strong decoupling" category continuously.

To deeply explore the socioeconomic impacts of water-sensitive urban design (WSUD) and promote sustainable urban planning, Contribution 8 employs a review analysis method, focusing on the impacts of WSUD on community well-being, property values, infrastructure costs, and public participation, while discussing the roles of citizen perception, equity, and financing mechanisms. The study finds that WSUD requires the integration of socioeconomic factors, and that long-term sustainability can be ensured through interdisciplinary approaches and policy reforms to build resilient and equitable urban communities.

To address the challenges of water scarcity and desalination technologies in the Middle East and North Africa (MENA) region, Contribution 9 focuses on Gulf Cooperation Council (GCC) countries and employs a bibliometric approach to conduct a correlational study on water scarcity, energy, and desalination technologies, integrating solar photovoltaic/thermal technologies with traditional desalination processes, such as the multi-effect distillation (MED) and multi-stage flash (MSF) approaches. The study finds that solar powered desalination technologies can mitigate high energy consumption issues. Despite challenges like high investment costs and technical complexities, the integration of renewable energy and desalination presents opportunities for GCC countries, necessitating interdisciplinary collaboration to achieve water security and economic development.

To reveal the direct impact of water resources on corporate finance and analyze the water risks from the perspective of capital cost, Contribution 10 takes Chinese A-share listed companies from 2019 to 2023 as samples and uses regression model to examine the relationship between water vulnerability and capital cost, as well as the moderating effects of water regulation and water investment. The study finds that water vulnerability positively affects capital cost by exacerbating financing constraints. Water regulation has a positive moderating effect, while water investment has a negative moderating effect. Additionally, the positive relationship between water vulnerability and capital cost exhibits heterogeneity at both industry and firm levels, whereas the moderating effect of government water governance only shows industry-level heterogeneity.

3. Conclusions

This Special Issue focuses on interdisciplinary research at the intersection of water sustainability and high-quality economic development. By integrating methodologies such as game theory, ecological value quantification, and techno-economic assessment, it presents multi-disciplinary findings in conflict resolution for transboundary water management, water resource efficiency evaluation, and ecological optimization model construction, providing theoretical and practical solutions for balancing the feedback relationship between water and economic systems.

The team of Guest Editors expects that the outcomes of this Special Issue will serve as reference for researchers, policymakers, and practitioners, facilitating the identification of cutting-edge research directions. The proposed conflict analysis models, ecological service quantification methods, and technological innovation pathways hold significant value for analyzing the synergistic mechanisms of water–economy systems and optimizing regional water management policies.

Based on existing research, future studies may focus on three key research fields: constructing resilience in water–economy systems under climate change, innovating smart water management driven by digital technologies, and designing collaborative mechanisms for global water governance, so as to promote the deep integration of sustainable water use and economic prosperity.

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Article

The Coordination of Water Resources and Economic Development in a Water-Scarce Area: An Ecosystem Service Perspective

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Abstract: In water-scarce areas, there is a complex interrelationship between water resources and economic development. This paper studies the relationship between water resources and economic development from an ecosystem services perspective. This paper selected the value of river ecosystem service functions and the comprehensive index of economic development in the Yellow River Basin (YRB) from 2007 to 2018 as the research object, tested the synergy of ecosystem service functions in the basin, and introduced a coupling coordination model to evaluate the synergy of developmental factors. The research results showed that (1) the overall river ecosystem service value in YRB was on the rise, and its distribution was characterized by a high value in the lower reaches and a gradual decrease from the middle reaches to the upper reaches; (2) the synergy of river ecosystem service functions in YRB was mainly reflected in the supply and regulation functions, and the synergy of cultural functions should be improved; (3) the overall coupling and coordination degree showed an upward trend. However, judging from the characteristics of coupled and coordinated degrees, backward ecological development is a long-term problem. This article will help to put forward countermeasures and suggestions for the coordinated development of the river ecosystem service value and regional economy in YRB.

Keywords: river ecosystem service; economic development; the coupling coordination degree; sustainable development; water resources

1. Introduction

Ecosystem service function refers to the natural environmental conditions and utility formed by ecosystems and ecological processes on which human beings depend for survival and is an important basis for regional sustainable development [1]. Since the concept of ecosystem services was introduced, there has been a growing awareness that ecosystem services were much more important to human well-being than conventional economic thinking had given them credit for [2]. The evaluation of the value of ecosystem services has become an important part of ecosystem sustainability research. Many researchers, for example [3–5], used different methods to measure the value of different ecosystem services, including the material quantity and economic value methods. The economic value measurement method is a method of quantifying various services and their values provided by the ecosystem in the form of currency [6]; that is, ecosystem services with economic value are regarded as "natural capital" for accounting [7]. In terms of value assessment of ecosystem services, Costanza et al. [8] first proposed the scope of ecosystems, their service functions, and accounting methods in Nature, which pushed the research on ecosystem services to a new level centered on value accounting.

Among researchers focused on this area of study, water-related ecosystem services have received much attention. Xu [9] considered that the river ecosystem service system provides basic conditions such as water resources which are necessary for social and economic development, convenient transportation and shipping, and a suitable climate environment. Wilson [10] used travel cost methods, hedonic pricing methods, and conditional valuation methods to account for the economic value of non-market goods and services provided by US surface freshwater systems. Ouyang [11] divided the service functions of China's water ecosystem into four categories, and constructed a water ecosystem indirect value evaluation index system consisting of eight functions, including flood regulation and storage, water storage, and soil conservation. Thiele et al. [12] and Young et al. [13] assessed river ecosystem services to study their importance in providing different functions. In some water-scarce areas, water-related ecosystems play a dramatic role in sustaining local economic development and human welfare. At the same time, socio-economic activities can have an impact on local water ecosystems. Costanza et al. [8] proposed that the linkages between ecosystem processes and functions and human well-being are complex and the various pathways are still not well understood. Pluralistic and preventive approaches should be taken to assess these linkages and assess their benefits.

The relationship between ecosystem and economic development and water resources and economic development has been extensively studied. Wang [14] used the coupled coordination model to study the temporal and spatial evolution of the coordination degree between the quality of ecological protection and the level of economic development in the Yangtze River Economic Belt. In discussing the synergistic relationship between single ecological resource such as water resources, land resources, and regional economic development, Yang [15] used the system-coordinated development model to conduct dynamic coupling and spatial pattern analysis on the economic development and water environment system of the Songhua River Basin. Cao [16] calculated the ecosystem service value of Chongqing based on different land use types and conducted spatial autocorrelation analysis with economic development indicators. Based on the water footprint theory and water resources balance table, a quantity–quality–benefit model was constructed to evaluate the sustainability of water resources, and a coupling coordination degree model was introduced to evaluate the sustainability of water resources in the Yangtze River [17]. Some scholars have also researched the coupling coordination relationships among complex systems, such as ecology–economy–energy [18], and energy–economy–environment–society [18].

Existing studies have provided rich research results and theoretical references related to the evaluation of ecosystem service value and the relationship between regional ecological protection and economic growth. However, it is insufficient to study the relationship between different functions of water and economic development from the perspective of ecosystem services alone, especially in water-scarce areas. There is a complex interrelationship between water resources and economic development in these locations, so it is necessary to expand new research perspectives to interpret the complex relationship between them. This paper took nine provinces in Yellow River Basin (hereinafter referred to as YRB) as the research object, calculated the value of ecosystem services in YRB from 2007 to 2018 and deeply analyzed the correlation of various ecological service values, the synergy between ecological protection and economic development, and the regular pattern of temporal and spatial evolution. The coupling coordination degree of economic development and ecosystem service value was measured and the contributing factors were analyzed.

2. Study Area

2.1. River Ecosystem Service System in YRB

The Yellow River Basin (YRB) is not only an important ecological security barrier in China but also an important area for regional social and economic development. The Yellow River Basin ecological protection and high-quality development planning outline proposes to further improve the human–water relationship in the basin by 2030, with the goal of achieving a healthy and stable YRB ecosystem by 2035. The realization of the above planning objectives requires the YRB to correctly acknowledge the relationship between ecological protection and economic development from a dialectical perspective.

The YRB is located in northern and central China, with a length of about 5464 km, flowing through the Qinghai–Tibet Plateau, the Inner Mongolia Plateau, the Loess Plateau and the North China Plain. The basin plays an important role in water, soil and biodiversity conservation. At the same time, the YRB is also an important economic region in China, covering several provinces and regions, including Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shaanxi, Shanxi, Henan and Shandong, which are sites of national grain production and act as energy bases. However, the region also faces environmental problems such as water shortages, soil erosion and pollution. The ecosystem service system of the YRB includes six categories: forest, grassland, farmland, wetland, river and desert [19]. Based on the theory of sustainable development, referring to the "three-circle model" proposed by Zhang et al. [20], the structure of the river ecosystem service system in the YRB is shown in Figure 1.

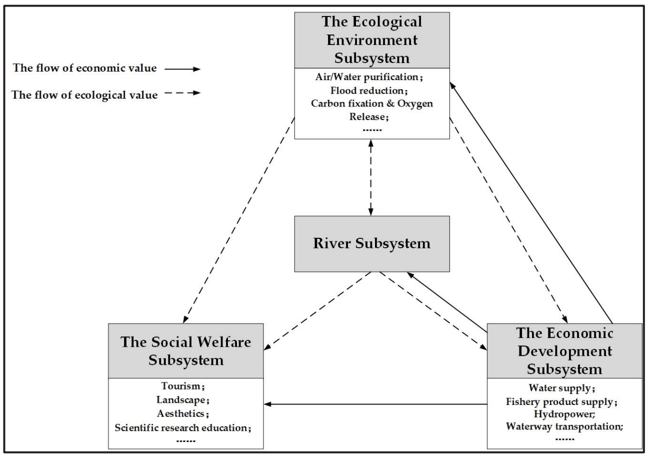

Figure 1. Structure of river ecosystem service system in the YRB.

It can be seen from Figure 1 that the river ecosystem service system in the YRB is composed of the ecological environment subsystem, the economic development subsystem, the social welfare subsystem, and the river subsystem. There is a flow of ecological value and economic value among the subsystems. Among them, the ecological environment subsystem mainly focuses on regulating functions, including functions such as water purification, air purification, carbon fixation and oxygen release, and flood regulation. The economic development subsystem mainly focuses on the supply functions, including water resource supply, fishery product supply, hydropower generation, and inland shipping. The social welfare subsystem mainly focuses on cultural functions, including functions such as tourism, cultural inheritance, ecological esthetics, scientific research, and education. From the perspective of value flow, the river subsystem provides direct ecological value to the other subsystems. At the same time, the ecological environment subsystem provides ecosystem services value for the river subsystem, economic development service subsystem, and social welfare subsystem through various functions. The economic development service subsystem utilizes the ecosystem functions provided by the river subsystem and the ecological environment subsystem, transforms them into economic value, and then flows to the remaining subsystems. The social welfare subsystem provides a large amount of indirect ecological service value for human society by making full use of the economic value and ecological value. Only when the four subsystems are coupled and coordinated within the basin can the high-quality development of YRB as a whole be promoted.

2.2. River Ecosystem Services in Nine Provinces of YRB

According to the analysis of the YRB ecosystem service system, following the principles of data availability and operability, and based on the classification of river ecosystem service functions in existing literature, this paper divided the river ecosystem service functions of the YRB into supply, regulation and cultural functions. Among them, the river subsystem and economic development subsystem provide the supply function, the ecological environment service subsystem provides the adjustment function, and the social welfare service subsystem provides the cultural function. The secondary functions are shown in Table 1. Due to the limitations of multiple factors, such as geographical location and climatic conditions, the ecosystem service functions of rivers in different provinces in YRB are different.

Table 1. River ecosystem services in nine provinces of YRB.

Functional Classification	Specific Function	Shanxi	Inner Mongolia	Shandong	Henan	Sichuan	Shaanxi	Gansu	Qinghai	Ningxia
Supply Function	Fishery product supply	√	√	√	√	√	√	√	√	√
	Water supply	√	√	√	√	√	√	√	√	√
	Hydropower	√	√		√		√	√	√	√
	Waterway Transportation	√				√	√			
Regulatory Function	Water purification	√	√	√	√	√	√	√	√	√
	Air purification	√	√	√	√	√	√	√	√	√
	Carbon fixation and oxygen release	√	√	√	√	√	√	√	√	√
	Flood regulation	√	√	√	√	√	√	√	√	√
Cultural Function	Tourism	√	√	√	√	√	√	√	√	√

3. Materials and Methods

3.1. Methods

The first step was to calculate the value of river ecosystem services. Commonly used ecosystem service value assessment methods include market value, shadow engineering, and afforestation cost. The calculation formulas of river ecosystem service value (hereinafter referred to as ESV) and area-average river ecosystem service value (hereinafter referred to as AESV) and their change rates in the YRB were developed using these methods (Table 2).

Table 2. Index system and method of river ecosystem service value accounting in YRB.

Functions	Indicators	Methods	Formulas
Supply function	Fishery product supply	Market value method	$V_a = \sum V_n$ V_n: Production value of different types of aquatic products in rivers
	Water supply		$V_b = \sum(Q_i \times P_i)$ Q_i: Water consumption by different types of use P_i: Water prices for different types of use
	Hydropower		$V_c = \sum(Y_i \times W_j)$ Y_i: The annual power generation of each hydropower station W_j: unit electricity price
	Waterway Transportation		$V_d = T_i \times P_i + T_j \times P_j$ T_i: Annual turnover of goods T_j: Annual Passenger Turnover P_i: Shipping price P_j: Passenger price

Table 2. *Cont.*

Functions	Indicators	Methods	Formulas
Regulatory function	Water purification	Shadow engineering method	$V_e = \sum(Q_i \times P_i)$ Q_i: The weight of different kinds of pollutants P_i: Treatment costs for different types of pollutants
	Air purification		$V_f = Q_i \times S_i \times P_i$ S_i: Surface area of river water in different provinces P: Industrial dust treatment costs Q_i: The weight of dust absorbed on the surface of river water in different provinces
	Carbon fixation and oxygen release	Forestation cost method; shadow engineering method	$V_g = V_{g1} + V_{g2}; V_{g_1} = Q_{g_1} \times P_{g_1}; V_{g_2} = Q_{g_2} \times P_{g_2}$ Q_{g_1}: Amount of fixed carbon dioxide P_{g_1}: Cost price of urban afforestation Q_{g_2}: Amount of oxygen released P_{g_2}: Industrial oxygen production cost V_{g1}: The value of carbon sequestration in river ecosystems V_{g2}: Value of oxygen release function in river ecosystem
	Flood reduction	Shadow engineering method	$V_h = Q_h \times P_h$: Q_h Q_h: Reservoir annual storage capacity P_h: The construction cost per unit of reservoir storage capacity
Cultural function	Tourism	Travel expense method	$V_k = T_e + T_t + T_s; T_t = W_s \div 3; T_s = T_e \times 40\%$ T_e: Comprehensive income of local tourism industry T_t: Traveler time cost T_s : Consumer surplus for tourists W_s: The average wage of urban workers divided by the annual working hours
Total ecosystem service value	River ecosystem service value (ESV)		$ESV = \sum(V_a + V_b + V_c + V_d + V_e + V_f + V_g + V_h + V_k)$
Average land value of ecosystem services	Average river ecosystem service value (AESV) and its change rate		$AESV = \frac{ESV}{S}$ $F = \frac{AESV_{t2} - AESV_{t1}}{AESV_{t1}} \times 100\% AESV_{t1}$ $AESV_{t1}$ & $AESV_{t2}$: Average river ecosystem service value at t_1 and t_2 time F : Average ecosystem service value change rate S: Area of each province

The second step was to design an index system for evaluating economic development and to calculate the index weight. To reflect the level of regional economic development, this paper drew on the existing literature [21–23] and adopted the comprehensive index method. According to current economic development in the YRB, and following the principles of scientificity, availability, and comparability, an index system including economic development scale, structure and quality was constructed. The weight of the index was calculated using the entropy method, as shown in Table 3.

Coupling coordination degree evaluation between ecology and economy adopted the coupling coordination degree model. The TOPSIS method was used to calculate the comprehensive index of river ecosystem service value (ESV) and economic development. TOPSIS is a multi-attribute decision-making evaluation method commonly used in system engineering, which can ensure the scientific rationality of data. The coupling coordination degree model is widely used in research on coupling coordination relationships among multiple systems, which can reflect the coupling strength between ESV and economic development. Referring to the work of Han et al. [24], who studied the coupling synergistic effect between complex systems, this paper constructed the following "ESV–economic development" coupling coordination model.

$$D = \sqrt{C \times T} \quad (1)$$

$$C = 2 \times \sqrt{(U_1 \times U_2) \div (U_1 + U_2)^2} \quad (2)$$

$$T = a \times U_1 + b \times U_2 \quad (3)$$

Table 3. Economic development evaluation index system and weight.

Division Criteria	Indicators	Unit	Weights
Economic scale	Gross regional product	100 million CNY	0.094
	Total retail sales of consumer goods		0.076
	Local fiscal revenue		0.066
	Total social investment in fixed assets		0.083
Economic structure	Contribution rate of the secondary industry	Percentage	0.091
	Contribution rate of the tertiary industry		0.093
	Proportion of employed population in the secondary industry		0.064
	Proportion of employed population in the tertiary industry		0.071
Economic quality	Energy consumption per ten thousand CNY GDP	Ton of standard coal/ten thousand CNY	0.117
	Urban residents' per capita disposable income	CNY	0.078
	Rural residents' per capita disposable income	CNY	0.079
	Income ratio of urban to rural residents	Percentage	0.088

In Formula (1), D is the coupling degree of coordination, and the value range is from 0 to 1. The larger the value, the more coordinated the development of the two systems, and vice versa; the lower the value, the lower the degree of coordination between the two systems. In Formula (2), C is the degree of coupling, and the value range is from 0 to 1. The larger the value, the better the coupling state between the two systems; otherwise, the two systems will tend to develop in a disorderly manner. U_1 and U_2 are the composite indexes of ESV and economic development, respectively. In Formula (3), T is the composite coordination index of the two systems; a and b are hypothetical coefficients. This paper believes that the growth of ecosystem service value and economic growth need to be given equal attention, so a = b = 0.5 was taken.

At the same time, to reflect the gap between ESV and economic development, this paper drew on Sun et al.'s [25] research results and introduced a relative development model to judge whether the ESV and economic development in the basin are in a lagging or leading state. The judgment criteria are detailed in Table 4.

$$Z = \frac{U_1}{U_2} \quad (4)$$

In the Formula (4), Z is the relative degree of development. U_1, U_2 are the composite index of ESV and economic development, respectively.

Table 4. Coupling coordinated development type and dividing standard.

Coupling Degree of Coordination	Relative Degree of Development	Coupling Coordination Type	Developmental Characteristics
$0 < D \leq 0.2$	$0 < Z \leq 2$	Severe disorder	Severe disorder—ecological lag
	$2 < Z \leq 4$		Severe disorder
	$Z > 4$		Severe disorder—economic lag
$0.2 < D \leq 0.4$	$0 < Z \leq 2$	Moderate disorder	Moderate disorder—ecological lag
	$2 < Z \leq 4$		Moderate disorder
	$Z > 4$		Moderate disorder—economic lag
$0.4 < D \leq 0.6$	$0 < Z \leq 2$	Basic coordination	Basic coordination—ecological lag
	$2 < Z \leq 4$		Basic coordination
	$Z > 4$		Basic coordination—economic lag
$0.6 < D \leq 0.8$	$0 < Z \leq 2$	Moderate coordination	Moderate coordination—ecological lag
	$2 < Z \leq 4$		Moderate coordination
	$Z > 4$		Moderate coordination—economic lag
$0.8 < D \leq 1$	$0 < Z \leq 2$	High coordination	High coordination—ecological lag
	$2 < Z \leq 4$		High coordination
	$Z > 4$		High coordination—economic lag

3.2. Data Sources

Since the concept of China's ecological compensation policy was gradually clarified and solidified in 2006, relevant policies have been subsequently put into practice one after another. Comprehensively considering the availability of data, the research period was selected as 2007–2018. The agricultural, economic, and water conservancy data used in the study come from the statistical yearbooks of various provinces, the annual fishery data of the Ministry of Agriculture and Rural Affairs of the People's Republic of China, the Water Resources Bulletin, the *Water Conservancy Statistical Yearbook*, the Yellow River Water Resources Bulletin, data published by local price bureaus, and provincial tourism industry annual statistical reports. A small amount of missing data were filled by interpolation.

4. Results

4.1. Research Results of Ecosystem Service Value in YRB

Figure 2 shows that as of 2018, the order of river ecosystem service value in the nine provinces of YRB from high to low is as follows: Shanxi (CNY 671.192 billion), Shaanxi (CNY 648.308 billion), Henan (CNY 345.885 billion), Shandong (CNY 186.182 billion), Gansu (CNY 160.452 billion), Qinghai (CNY 140.092 billion), Inner Mongolia (CNY 116.852 billion), Sichuan (CNY 69.987 billion) and Ningxia (CNY 50.6 billion). Basin-wide, the river ecosystem service value of the middle reaches was greater downstream than that of the upstream reaches. In terms of changing trends, Shanxi Province had the largest increase (+592%), followed by Shaanxi (+503%), Sichuan (+415%), Henan (+195%), Qinghai (+205%), Inner Mongolia (+203%) %), Ningxia (+180%), Gansu (+157%) and Shandong (+150%). The areas with larger increases in river ecosystem service value were mainly distributed in the middle and lower reaches, especially the middle reaches, while the upper reaches had the smallest growth rate.

To study the regional differences in ecosystem service value more intuitively, this paper introduced the AESV and its change rate (the calculation formula, as presented in Table 2). The number of provinces with an average ecosystem service value of more than CNY 7000 per hectare rose from only one in 2007 to five in 2018, and the value of river ecosystem services also gradually improved (Figure 3). This change could possibly be attributed to greening projects such as watershed ecological restoration which have been implemented in recent years. From the perspective of space, AESV was characterized as low upstream and high in the middle and downstream. Specifically, high-value areas have been concentrated in Shaanxi, Shanxi, Henan, and Shandong provinces in recent years. Compared with the upstream areas, these areas are relatively scarce in natural resources, denser in population and have greater levels of urbanization and more developed economies. By 2018, Ningxia also became a high-value area of ecosystem service value per land. On the one hand, this is because Ningxia is located in the upper reaches of the Yellow River, which is rich in ecological resources, and has a relatively large amount of ecological capital. On the other hand, this development is also related to Ningxia's vigorous implementation of the ecological zone strategy and the integration of ecological civilization construction into the track of legalization and institutionalization.

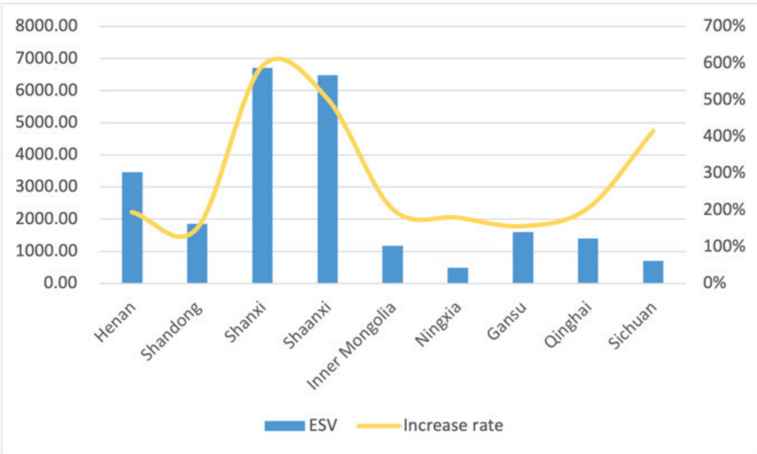

Figure 2. River ecosystem service value and change rate in 2018.

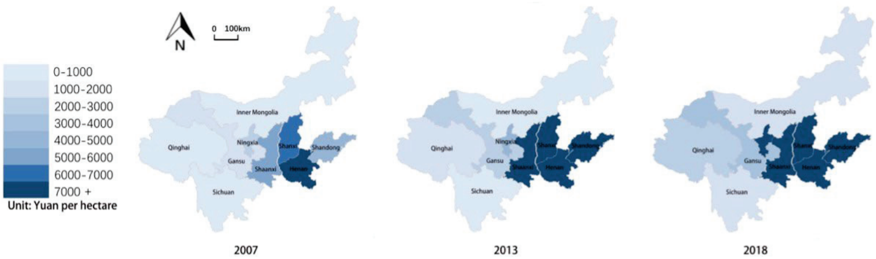

Figure 3. Spatial distribution of land average ecosystem service value of YRB from 2007 to 2018.

Judging from the temporal change in the land-average ecosystem service value change rate, the basin showed that the change rate of AESV in the whole region was greater than 0. The change rate was larger in the upper reaches and stable in the middle and lower reaches (Figure 4). The range of AESV change in the upper reaches can be divided into three types: "decrease first and then increase", "first increase and then decrease", and "continuous increase". The area of "decrease first and then increase" was typified by Qinghai Province. The growth rate slowed down significantly from 2011 to 2015, and picked up slightly from 2015 to 2018. Typical regions of the "increase first and then decrease" type were Sichuan Province and Inner Mongolia Province. Typical regions of the "continuous increase" type were Gansu Province and Ningxia Province, which maintained a stable growth rate from 2007 to 2018. Shanxi and Shaanxi provinces, in the middle reaches, have maintained a stable, high growth rate for twelve years. In the downstream reaches, there was a decline in the increase rate of the AESV in Shandong from 2011 to 2015, but the rest of the area increased year by year.

To explore the synergistic relationship between various service functions in the river ecosystem of the YRB, this study used panel data based on the economic value of each river ecosystem service function in the provinces in 2007, 2011, 2015, and 2018. SPSS 19.0 software was used to calculate the correlation coefficients among the ecosystem service functions. The results are shown in Table 5.

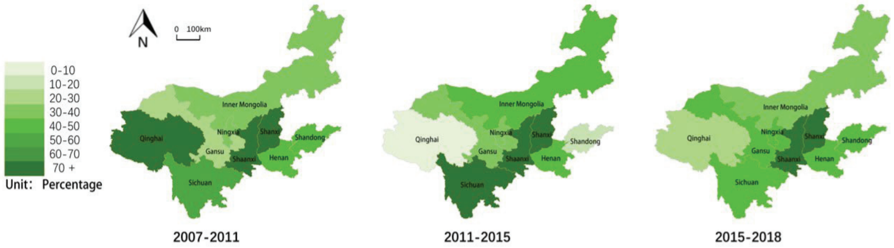

Figure 4. Spatial distribution of average land ecosystem service value in the nine YRB provinces from 2007 to 2018.

Table 5. Correlation of river ecological service functions in the YRB.

Functions	Fishery Product Supply	Water Supply	Hydropower	Waterway Transportation	Water Purification	Air Purification	Carbon Fixation and Oxygen Release	Flood Reduction	Tourism
Fishery product supply	1.000								
Water supply	0.671 **	1.000							
Hydropower	−0.245	−0.253	1.000						
Waterway transportation	0.244	0.234	−0.272	1.000					
Water purification	0.198	0.251	−0.074	−0.043	1.000				
Air purification	−0.224	0.008	0.473 **	−0.436 **	−0.112	1.000			
Carbon fixation and Oxygen release	−0.229	0.014	0.479 **	−0.433 **	−0.111	0.995 **	1.000		
Flood reduction	−0.255	−0.381 *	0.770 **	−0.203	0.107	0.383 *	0.400 *	1.000	
Tourism	0.039	0.048	−0.069	0.017	0.523 **	0.080	0.078	0.069	1.000

Notes: ** At the 0.01 level (two-tailed), the correlation is significant. * At the 0.05 level (two-tailed), the correlation is significant.

From the perspective of the synergistic relationship of the nine river ecosystem service functions, the comparative combinations with positive and significant correlations included "water supply–fishery product supply", "hydropower–air purification/carbon fixation and oxygen release/flood regulation", "water purification–tourism", "air purification– carbon fixation and oxygen release". The contrasting combinations with negative and significant correlations were "water supply–flood regulation", and "waterway transportation–air purification/carbon fixation and oxygen release". The results listed above show that although the YRB has a variety of river ecosystem service functions, the coordinated development of various river ecosystem services during the study period was not ideal. In particular, it is necessary to pay more attention to the joint development of cultural and the other two major functions.

4.2. Research Results of the Comprehensive Index of Economic Development in YRB

Changes in the comprehensive index of economic development can effectively reflect the economic development status in the region. The results are shown in Figure 5. From the perspective of the overall time change, the comprehensive economic development index of the nine provinces in YRB has been significantly improved after twelve years of development. From the perspective of the overall spatial change, the characteristics of the change can be summarized as "low in the west and high in the east". As far as specific provinces are concerned, Shandong and Henan, in the middle and lower reaches, have long been recognized as provinces with good economic development in the YRB. The economic development of Gansu, Ningxia, Shaanxi, Shanxi and Inner Mongolia in the middle and upper reaches continue to improve, but their overall development level is relatively mediocre in the YRB. The economic development level of Qinghai Province, in the upper reaches, has improved significantly, from relatively slow economic development in 2007–2013 to the top four in the YRB in 2018, which was particularly outstanding compared with the other upstream provinces.

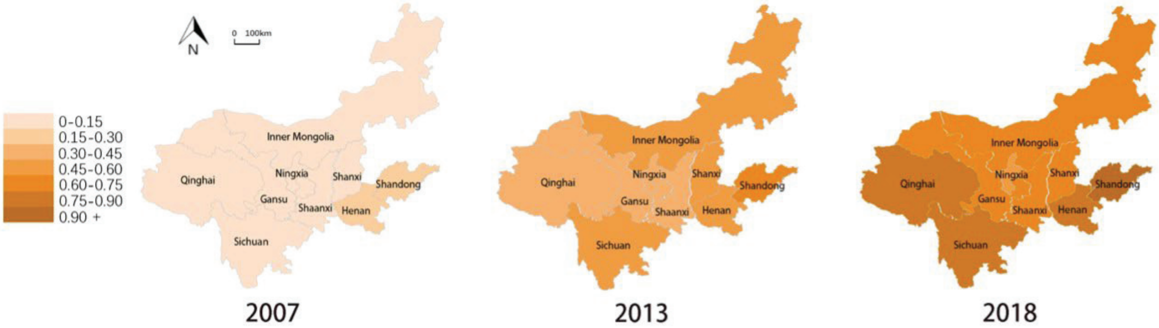

Figure 5. Spatial change in the economic development index of YRB from 2007 to 2018.

The changes in the comprehensive index of economic development in the YRB are largely related to the "contribution rate of the tertiary industry" and "energy consumption per ten thousand CNY of GDP" indicators with relatively high weights. From a more macroscopic perspective, it is related to the industrial structure and energy efficiency. The impacts of different industries on river ecology are dissimilar. The impact of the primary industry mainly includes positive impacts such as carbon sequestration of crops and ecological barriers of forestry, and negative impacts such as the use of pesticides and fertilizers that increase harmful inorganic substances in water bodies. But, generally speaking, the depth and breadth of the ecological impact of primary production on rivers is limited. The impact of the secondary industry on river ecology mainly includes the massive consumption of water resources and the discharge of high pollutants into the water. The stress effect on the river ecology is obvious. The impact of the tertiary industry on river ecology is smaller than that of the primary and secondary industries, and there is less direct consumption of river ecological resources. However, the development of tourism and transportation still has a direct impact on it. If not managed properly, extensive development may lead to the disappearance of some river landscapes located in ecologically sensitive areas. Energy efficiency refers to whether the use of less traditional energy can provide more economic benefits. The consumption of fossil energy has a huge impact on the ecology of rivers. On the one hand, the acquisition or purification of traditional energy requires a large amount of water resources. On the other hand, the consumption of fossil energy is accompanied by a large amount of carbon emissions and sewage discharge, which greatly increases the burden on rivers to fix carbon and purify water.

Combined with the above analysis of the spatial distribution characteristics of ESV, it was found that the spatial distribution characteristics of the comprehensive index of economic development and ecosystem service value were basically consistent; both were high in the middle and lower reaches and low in the upper reaches. However, judging from the resource endowment of the YRB, its abundance should have been higher in the upper and middle reaches and lower in the lower reaches. This is contrary to the distribution characteristics of the comprehensive index of economic development and the river ecosystem service value. That is to say, the economic development of the upper reaches, where ecological resources are rich, is relatively backward.

4.3. Coordinated Evaluation of Ecosystem Service Value and Economic Development in the YRB

According to Formulas (1)–(3), the coupling coordination degree and relative development degree of ESV and economic development comprehensive index of nine provinces in the YRB were calculated. Combined with the evaluation criteria in Table 4, the characteristics of coupled and coordinated development of each province are shown in Figure 6.

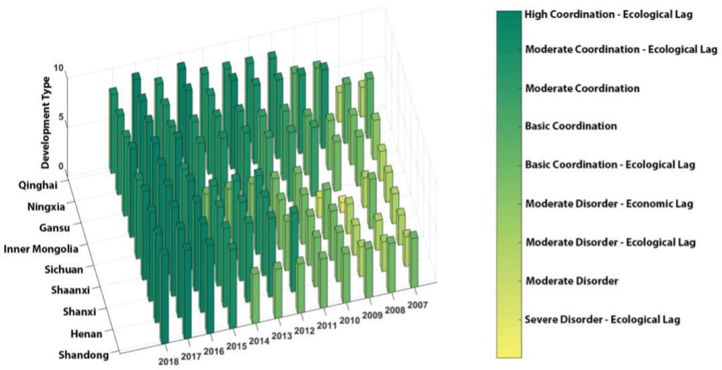

Figure 6. Characteristics of coupled and coordinated development in the YRB from 2007 to 2018.

From Figure 6, it can be seen that the overall coupling and coordination pattern of the YRB gradually improved during the study period, and gradually realized the transition from severe/moderate imbalance to medium/high coordination. At present, a basic pattern of medium/high coordinated development in the whole region has formed, and the differences between provinces are gradually narrowing. The characteristics of the coordinated development of the middle and lower reaches of the provinces have changed greatly, and the overall pattern from 2016 to 2018 has become balanced by degrees, indicating that the ecology and economy of the YRB are progressively realizing positive interaction and development. However, considering the development characteristics, the ecological development of nine provinces has lagged for long periods of time within the past twelve years. This showed that although the value of ecosystem services in the YRB continues to increase, its growth rate was far lower than the growth rate of the comprehensive index of economic development. They failed to form a high-quality development pattern, and a contradiction between ecological protection and economic development began to emerge.

The changes in the YRB's ecosystem service value matched the changes in the industrial structure of nine provinces and the level of energy use efficiency. The industrial structure of the YRB has long been dominated by secondary industries such as primary processing and energy mining, while the proportion of tertiary industries is lower than the national average, and the problem of "low-end industries" is more prominent. Energy consumption mainly consumes non-renewable resources such as coal resources, and the efficiency of energy use is relatively low. According to the above analysis of the interaction between industry, energy efficiency and ecological environment, the reason for the long-term ecological lag in the coordinated development of economy and ecological protection in the YRB can be explained as rapid economic development based on the excessive consumption of ecological resources. Basically, the efficiency of energy use has not been significantly improved during the development process. In addition, the ecological background of the YRB itself is extremely fragile. The negative effects of economic development on the ecology were far greater than the highest threshold of the ecological self-recovery ability, which required the consumption of excessive ecological service value. This kind of industrial development pattern led to ecological development lagging.

5. Conclusions

The links between ecosystems and human well-being are complex and multi-dimensional. In order to better assess these links and their impact on human well-being, this paper combines ecological, economic, and social factors to conduct interdisciplinary research. In this way, ecosystem services can be more fully understood and managed to ensure they provide sustainable benefits to human society. In the context of the high-quality development of the YRB, this paper used the economic value measurement method to calculate the river ecosystem service value of the nine provinces in the YRB from 2007 to 2018. An in-depth study was conducted on the correlation between the ecosystem service functions of rivers in the YRB and the coordination degree between the ecosystem service value and economic development of the provinces in the basin. The main research conclusions were as follows:

(1) From the perspective of the time dimension, the ecosystem service value of rivers in the YRB showed an overall upward trend. From the perspective of space, the ecosystem service value was highest downstream and gradually decreased from the middle reaches to the upper reaches. From the perspective of ecosystem service functions, different regions in the upper, middle and lower reaches had different functions that can truly provide a large number of efficient ecosystem service values. The functions providing ecosystem service value in the upper reaches were mainly water supply, hydropower, and tourism. The middle reaches' functions were mainly tourism, water purification, and hydropower. The downstream regions' functions were mainly tourism, water supply and fishery product supply.
(2) From the research on the correlation of river ecosystem service functions, it can be seen that river ecosystem service functions of the provinces in the YRB were not completely synergistic. Only the supply function and the regulation function had synergy between sub-functions, but there was no synergy between sub-functions in the cultural function. Judging from the positive/negative significance of the synergy relationship, the synergy between cultural, supply regulatory functions needed to be improved.
(3) During the study period, the provinces in the YRB developed rapidly, the river ecosystem was stable and the overall coupling and coordination degree showed an upward trend, gradually shifting from an imbalanced state to a coordinated state. However, the characteristics of coupling and coordinated development indicate that the growth rate of the ecosystem service value was far below the growth rate of economic development. Ecological protection has long lagged behind economic development, and the uncoordinated pattern of ecological lag has not been fundamentally changed.

This paper analyzed the ecological and economic development of the YRB from the perspective of ecosystem service value and its synergy with economic development, which has important practical significance for enriching the application system of ecosystem service value and promoting high-quality development. In particular, the study results found that economic development based on a large amount of resource consumption will cause problems post-ecological development, which should be paid attention to in other water-scarce areas worldwide. Through comprehensive management, policy support, scientific and technological innovation, community participation, regional cooperation, green transformation and other efforts, it can realize the sustainable use of water resources and the green development of the economy. These experiences have important implications for other countries and regions to address similar water resources and economic development challenges. In addition, building an ecosystem service value-economic development dual-accounting target system and adhering to an economic development route that matches the regional ecological pattern are important directions for achieving high-quality development in the new era.

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Data Availability Statement: The agricultural, economic, and water conservancy data used in the study come from the statistical yearbooks of various provinces, the annual fishery data of the Ministry of Agriculture and Rural Affairs of the People's Republic of China, the Water Resources Bulletin, the *Water Conservancy Statistical Yearbook*, the Yellow River Water Resources Bulletin, data published by

local price bureaus, and the provincial tourism industry annual statistical report. A small amount of missing data were filled by interpolation.

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water

Article

The Economic Impact of Water Vulnerability on Corporate Sustainability: A Perspective of Corporate Capital Cost

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Abstract: Studies have argued that water risk affects corporate sustainability, but few of them have fully explored whether or not and how water resources have a direct impact on corporate finance and strategy. This study takes the listed companies in the Chinese A-share market from 2019 to 2023 as a sample to understand the threat of water vulnerability to corporate sustainability from the perspective of capital cost. This study argues that water vulnerability positively relates to corporate capital cost by increasing corporate financing constraints. Meanwhile, this study also examines the role of water regulation and water investment in the relationship between water vulnerability and corporate capital cost. Water regulation brings legitimate pressure to corporations and increases the transformation risks faced by them, so it has a positive moderating effect. Water investment can alleviate the vulnerability of local water resources and reduce the physical water risk faced by corporations, so it has a negative moderating effect. The study finds that the two measures mainly play a significant moderating effect on the cost of debt. In addition, the study finds that the positive relationship between water vulnerability and capital cost has industrial and firm-level heterogeneity, while the moderating effect of government water governance has only industrial heterogeneity.

Keywords: water vulnerability; water governance; capital cost; water regulation; water investment; water risk; cost of debts; cost of equity; SOEs; water-intensive industry

1. Introduction

Water sustainability is central to several of the United Nations' sustainable development objectives. The World Meteorological Organization's report reveals that, currently, 3.6 billion individuals experience insufficient water supply for a minimum of one month per year. This number is projected to exceed 5 billion by 2050, primarily due to the combined effects of climate change and population growth (World Meteorological Organization, 2022) [1]. The water crisis has risen to become the third-greatest worldwide concern, making it one of the top risks that businesses must address (World Economic Forum, 2017) [2].

Research has demonstrated that businesses are confronted with multiple water-related risks, including physical, reputational, and regulatory risks, simultaneously (Jones et al., 2015; Tello, 2013) [3,4]. These risks have substantial consequences for business growth when companies acknowledge and address them (Zhu et al., 2024; Afrin et al., 2022; Liu et al., 2024) [5–7]. However, many academics primarily concentrate on transformational water risks. They examine the influence of social factors using institutional theory or stakeholder theory. Unfortunately, they overlook the straightforward consequences of water conditions on corporate sustainability, which are highlighted in studies by Dias et al. (2022), George et al. (2015), Tashman (2021), and Tashman & Rivera (2016) [8–11]. Water vulnerability refers to the condition of a water resource system that is susceptible to disturbances caused by both human activities and natural changes and indicates the level of difficulty in restoring the system to its original state after a disturbance occurs

(Xia J. et al., 2012) [12]. This concept is also employed as a measure of physical water risk (Zheng et al., 2022; Gui et al., 2021) [13,14]. Therefore, what is the precise influence of water vulnerability on businesses? What is the cause-and-effect relationship of this impact? How can businesses respond to these risks? These concerns are now being examined at the theoretical level, but there is limited empirical study being conducted at the practical level (Burritt et al., 2016; Ortas et al., 2019; Sojamo & Rudebeck, 2024) [15–17].

Government-led water governance is considered essential for addressing water-related challenges and preventing the Tragedy of the Commons. However, the bulk of research conducted so far has focused on regulatory tools, neglecting the diverse impacts of other governance mechanisms (Li & Yuan, 2021; Ban & Liu, 2021; Ma & Hou, 2020) [18–20]. Excessive emphasis on environmental regulation in research leads governments to impose more stringent regulations and fails to take into account the full range of environmental governance tools used by governments. Although stringent environmental rules are helpful in attaining regulatory goals, they have the potential to generate unanticipated negative consequences on the production and operation of enterprises if the burden becomes severe. Because of this, businesses may have a more difficult time successfully adapting to the external institutional environment in terms of sustainable growth. Consequently, there may be a dearth of effective methods at the micro-level to guarantee the long-term sustainability of water resources. (Cui & Jiang, 2019) [21].

By investigating the relationship between water vulnerability and corporate capital costs and testing the roles of the two kinds of water governance tools in the relationships, this study attempt to find evidence that water conditions and related government-led water governance are of vital importance to corporate sustainability because they could bring harmful influence on corporate financing activities. Based on the research above, it is possible to divide the contributions made by this research into two factors. The first thing to note is that water condition is proven to be one of the most important factors influencing corporate sustainability, which not only compensates for the neglect of natural environmental variability in current corporate management research but also expands the study of micro consequences of water vulnerability. Secondly, this study provides evidence that the various approaches used by the government for the purpose of environmental governance have distinct effects, therefore adding to the existing knowledge of environmental governance, concentrating only on regulatory measures.

2. Literature Review

2.1. The Socio-Economic Impact of Water Vulnerability

Current research on water vulnerability mainly focuses on the evaluation and the causes of water vulnerability, but some studies have expanded to areas such as adaptive management of water resources, water resource policy evaluation, and the socio-economic impact of water vulnerability (Yuan & Zheng, 2022) [22].

In the study of the socio-economic impact of water vulnerability, Jenkins et al. (2021) calculated that water vulnerability could bring a GBP 1.4 billion direct economic loss to the United Kingdom [23]. This economic loss comes not only from the direct impact of insufficient input of water resources as a production factor but also from the ripple effect generated by the linkage between water resources and other fields. Kim and Kaluarachchi (2016) found that, as the main representations of water vulnerability, water scarcity and salinization can result in smaller variable profits for land and thus reduce water productivity [24]. Wang et al. suggest that water resource issues in a region may inhibit the development of a low-carbon economy, as there is a strong correlation between water resource availability and low-carbon economic growth [25]. Furthermore, research has shown that trade is also an important pathway for water scarcity to spread from local to global levels. Yi et al. verified through data that local water scarcity can not only lead to economic losses in local or neighboring areas but also have remote effects on geographically distant regions through national supply chains [26]. Zhao et al. also found that, through trade, the chemical industry in Zhejiang, Jiangsu, and Shandong; the communication equipment, computer, and other electronic equipment industry in Jiangsu and Guangdong; and the food processing and tobacco industry in Shandong are easily affected by water scarcity in other provinces [27]. Other related economic loss calculated by researchers includes the loss of human life and medical costs caused by water pollution. Ugochukwu et al. (2022) reported that water pollution in Enyimagalagu and Mkpuma Akpatakpa communities in Ebonyi State, Nigeria, caused economic losses ranging from USD 20.7 million to USD 543.3 million in estimated lifespan, and medical expenses ranging from USD 1.41 million to USD 3.72 million [28]. Temkin et al. (2019) also calculated that nitrite pollution in water causes an economic cost equivalent to USD 250 million to USD 1.5 billion annually in cancer healthcare burden in the United States, as well as a potential impact of USD 1.3 to USD 6.5 billion due to productivity losses [29]. Furthermore, Gleick (2014) discovered that water vulnerability affected economic development and then brought social instability in Syria [30]. Schilling et al. (2020) also confirmed that social conflicts arose with the deterioration of water conditions because public's water needs cannot be met under water vulnerability [31].

Economic development and social stability are an important basis for corporate sustainability, and the harmful impacts of water vulnerability on economic growth and social stability mean that it is also a major hidden danger for corporate development. Some scholars have thus further presented that water vulnerability becomes a physical risk that affects business sustainability (e.g., Bonnafous et al., 2017; Muthulingam et al., 2022; Northey et al., 2019) [32–34]. Zheng. et al. (2022) proved that water vulnerability has a significantly direct negative influence on the ROA of enterprises [13]. Liu et al. (2024) opined that water risk affects operational and financial uncertainty and corporate legitimacy [7].

2.2. Environmental Factors Affecting Corporate Capital Costs

The factors affecting corporate capital costs can be categorized into technological factors, organizational factors, and environmental factors. Technological factors refer to the methods and assumptions used to estimate corporate capital costs (Jagannathan et al., 2017) [35] and to the new technologies used to alleviate corporate financial constrains, such as fintech (Lyu et al., 2023) [36]. Organizational factors refer to accounting factors such as profitability and capital structure (Jagannathan et al., 2017) [35], as well as factors such as corporate governance and strategy (Benlemlih, 2017) [37]. Environmental factors contain market-related, institutional-related and biophysical-related factors (e.g., Sassi et al., 2019; Li et al., 2024; Daouk et al., 2006) [38–40]. Among these three types of factor, although organizational factors are the ones most concerned by scholars, environmental factors have also received relatively high attention.

In the studies of environmental factors, Sassi et al. (2019) found that intensified product market competition results in lower equity financing costs [38], and Amairi et al. (2022) investigated the relationship between market competition and equity financing and found it to be a U-shape [41]. Apart from market competition, Hillier & Loncan (2019) and Li et al. (2024) respectively verified that stock market integration and stock market liberalization could reduce financing costs [39,42], and Vega-Gutierrez et al. (2021) found that labor market conditions are also another important factor [43]. Among institutional-related factors, economic policy uncertainty (Xie & Lin, 2023) [44]; government macroeconomic management tools such as monetary policy, tax, and security laws (Sheng et al., 2017; Lendvai et al., 2013; Daouk et al., 2006) [40,45,46]; and customer satisfaction (Truong et al., 2021) [47] have also been found to be influencing factors.

With the increasing attention from accounting and management academia on the deterioration of the natural environment, the relationship between biophysical environment and corporate capital costs also begins to grow, but it is still at the initial stage. At present, scholars mainly explore the impact of climate change on capital costs. Kling et al.

(2021), Huang et al. (2018), and Yildiz & Temiz (2024) verified that climate change does harm corporate financing [48–50], while the study from Du et al. (2023) denied there was a significant relationship between climate change and the cost of equity [51]. Other biophysical environments receive scattered attention. Liu (2016) and Tan et al. (2022) found that the cost of debts increases with the increase of air pollution [52,53]. As far as we know, only Nguyen et al. (2022) found that drought has negative effects on both leverage and the speed of leverage adjustment to enterprises [54], offering undirected evidence regarding the relationships between water conditions and the cost of capital.

2.3. Government Water Governance

In Section 2.1, we briefly review the negative socio-economic impacts of water vulnerability. To mitigate these negative impacts, researchers have proposed adaptive water resource management strategies, although some public management studies do not encourage top-down authoritative water regulation as they believe that mandatory and centralized water management policies may lead to conflicts between private actors (Heikkila, 2017; Harley et al., 2014) [55,56]. However, many countries, such as China and Israel, still believe that the government is the most important governing body in addressing water resource issues.

The government usually adopts various policy tools for water resource adaptive management. Firstly, the government adopts commend-and-control measures to strongly constrain the behavior of various subjects to improve water conditions. For example, the government directly allocates the amount of available water resources through administrative means, such as water intake permits (Li, et al., 2019) [57], and implements the Water Pollution Prevention and Control Action Plan to directly constrain industrial pollution discharge (Lu et al., 2022) [58]. In addition, the government also adopts market-incentive mechanisms such as water rights and discharge right, water pricing and water tax, ecological compensation, and so on, which can induce the economic interests of water users to achieve the goals of alleviating water scarcity and restoring the water ecological environment from a micro perspective. These regulation tools have been widely proven to alleviate water resource scarcity and degradation, promote industrial structure adjustment and economic development, and enhance the green transformation of enterprises (Li et al., 2019; Lin, X.C., et al., 2022; Luckmann et al., 2016; Zhou et al., 2021) [57,59–61].

Apart from regulation, the government will adopt various infrastructure investments to alleviate the scarcity problem of the uneven spatial and temporal distribution of water resources, repair damaged water ecological environments, and increase the region's ability to respond to water and drought disasters (Li, et al., 2020; Adeniran et al., 2021) [62,63]. For example, the Chinese government's investment in the construction of the South to North Water Diversion Project has alleviated the water resource problems in the Beijing Tianjin Hebei region (Long, et al., 2020) [64]. Meehan (2014) also showed that the advantages of these investments in water infrastructure will not only restore water conditions but could also help in maintaining social stability and consolidate political power in return [65].

2.4. Review

The literature review above shows that extensive research on water vulnerability, corporate capital costs, and government water governance has produced valuable results. However, research gaps and opportunities remain. Firstly, although the socio-economic impact of water vulnerability has received some attention, it focuses mainly on the macro impacts and lacks micro verifications such as the impact on organizations (Baudoin & Arenas, 2020; Zhu et al., 2024) [5,66], especially the impact on the cost of capital. For the study of the cost of capital, the biophysical impact is one of the cutting-edge topics in the current combined research of financial management and natural science. Kling et al. (2021) and Huang et al. (2018) have made relevant explorations [48,49], but there is still an urgent need for more empirical research to further clarify the specific relationship between the two, especially under different natural environments including water issues. Secondly, government water governance is regarded as the main means of water resources adaptive management, and both social scientists and natural scientists have studied it. Among them, natural scientists start from the perspective of water infrastructure investment and construction to verify its macro impact to ecology, society, and economic growth (Yang et al., 2024) [67] and overlook the impact of such measures on micro-entities such as enterprises (Li & Yuan, 2021; Ban & Liu, 2021; Ma & Hou, 2020) [18–20]. Social scientists typically focus on the direct constraints of institutions on social actors, seldom paying attention to how their interaction with the natural environment will affect social actors such as businesses (Tashman, 2016) [11]. Thus, the impact of water vulnerability and its interaction with government water governance measures on corporate capital costs requires further study.

3. Hypothesis

3.1. The Impact of Water Vulnerability on Corporate Capital Cost

Water vulnerability could be caused by water scarcity, water pollution, and variations across time and place because of climate change-related changes in precipitation patterns under extreme weather events (Xia et al., 2012; Gui et al., 2021; Sun & Kato, 2021) [12,14,68]. For water scarcity, it means the interruptions in the daily operations of enterprises located at the area of water scarcity or enterprises that heavily rely on goods from the area of water scarcity (Appiah & Abass, 2014; Hazelton, 2013; Vos & Hinojosa, 2016) [69–71]. For water pollution, it means the restrictions in the ability for enterprises to obtain investment and attract skilled individuals because water vulnerability would squeeze out populations and hinder economic development (Wang et al., 2023) [72]. Both water scarcity and water pollution bring rising operational costs. On one hand, enterprises encounter escalated water expenses as a result of higher water prices, water rights fees, water taxes, and other related charges in water diminishing areas (Martinez, 2015; Fogel & Elizabeth, 2014) [73,74]. On the another hand, the worsening water quality leads to increased expenses for businesses to maintain their legitimacy because the decline in water quality increases the likelihood of the local government and community questioning the legitimacy of firms (Northey et al., 2019; Christ, 2014) [34,75]. Additionally, droughts, floods, and other natural disasters rising from the variability of water resources are instances of the capricious physical risks that might jeopardize company operations (Bonnafous et al., 2017; Jiao et al., 2022) [32,76]. For enterprises, droughts can exacerbate water shortages, while floods can disrupt operations and result in equipment loss (Song et al., 2019) [77].

In summary, water vulnerability destabilizes the supply and production of businesses and raises operational expenses, this presenting a risk to corporate sustainability. Zheng et al. (2022) also confirm that a company's financial performance is adversely affected by its vulnerability to water scarcity [13]. The risk compensation hypothesis posits that the cost of capital for a company represents the additional return that investors demand to compensate for assuming a certain level of uncertainty. The overall cost of capital for a corporate can be divided into two components: the cost of debt and the cost of equity. The cost of debt is calculated by adding the nominal risk-free rate to the risk premium. On the other hand, the cost of equity capital is determined by the level of risk according to the asset pricing model. Water vulnerability directly amplifies the business risk of a company as explained above, thereby exposing investors to elevated credit risk. The basis of this paper relies on the following hypothesis:

Hypothesis 1a: *The higher the water vulnerability, the higher the cost of debt.*

Hypothesis 1b: *The higher the water vulnerability, the higher the cost of equity.*

3.2. The Moderating Effect of Government Water Governance

Adaptive water resource management solutions are essential for dealing with the effects of climate change and human activities on water vulnerability (Xia, Qiu & Li 2012) [12], among which government intervention, as a way to adaptive water resource management, is widely recognized as being useful to prevent the Tragedy of the Commons and is necessary to ensure the efficient allocation of public goods for the benefit of society (Qin, Harrieon & Chen, 2019) [78]. Regulatory tools, such as law and enforcement, as well as investments in ecological engineering and environmental restoration, are the primary techniques that governments use to deal with environment challenges (Li, 2017) [79].

Environmental regulations exert pressure on businesses by requiring licenses to operate and by imposing substantial fines and fees. As the demand for stronger environmental regulations becomes more prominent, companies are facing greater pressure to maintain their environmental credibility. Meanwhile, environmental regulations reallocate resources from the production sector to the pollution sector, resulting in an increase in enterprises' marginal costs (Greenstone et al., 2012) [80], and the performance of businesses will see a decline in the near term (Zheng et al., 2022, Long & Wan, 2017) [13,81]. Research on corporate environmental responsibility has shown that enterprises that practice responsible water management could offset the harmful impact from water vulnerability and its related regulation pressures (e.g., Jones et al., 2015; Egan, 2015; Lambooy, 2011) [3,82,83]. However, the path of transformation is also one full of risks because green technologies entail a certain level of unpredictability and risk, and technological progress does not necessarily guarantee immediate safety for enterprises (Yan et al., 2021) [84]. Therefore, water regulation increases the uncertainty faced by businesses, resulting in investor demand for a higher risk premium. We predict the following:

Hypothesis 2a: *Water regulation positively moderates the relationship between water vulnerability and the cost of debts.*

Hypothesis 2b: *Water regulation positively moderates the relationship between water vulnerability and the cost of equity.*

Water infrastructure improvements and ecosystem restoration initiatives are the ways the government intends to alter water vulnerability (Petts & Gurnell, 2022) [85]. Investment in infrastructure projects could increase the availability of water and the resistance of an area to floods and droughts. In addition, improvements to the water quality caused by investment in restoration projects may result in a reduction in the costs of labor and bring about an increase in the total productivity of the corporation (Li et al., 2020; Zhu et al., 2023) [86,87]. Even businesses may experience greater expenses for water because these investments would be recovered through market mechanisms; it is believed that the operating burden from these water expenses could be in a reasonable and acceptable range, owing to the fact that water prices generally remain low under the acknowledgment of water resources as a human right (Egan, 2015; Martinez, 2015) [73,82]. Therefore, water investment mitigates the negative impact of water vulnerability on enterprises, leading investors to potentially request a reduced risk premium. We predict the following:

Hypothesis 3a: *Water investment negatively moderates the relationship between water vulnerability and the cost of debt.*

Hypothesis 3b: *Water investment negatively moderates the relationship between water vulnerability and the cost of equity.*

Based on the hypothesis above, the conceptual model of the study is shown as Figure 1.

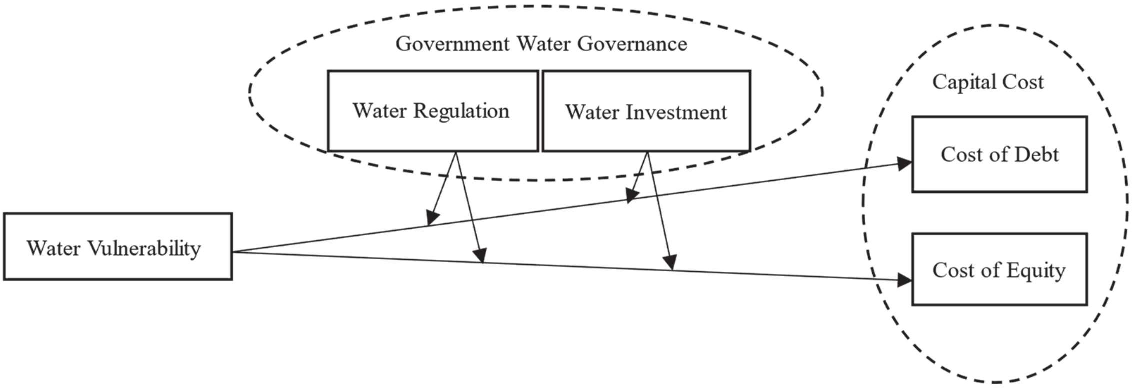

Figure 1. Conceptual model of the impact of water vulnerability on corporate capital costs considering government water governance moderating effects.

4. Study Design and Data Description

4.1. Sampling

This study utilizes data from 30 Chinese provinces and municipalities, excluding Tibet, Hong Kong, Macao, and Taiwan, for a period of five years (2019–2023). The rationale for excluding Hong Kong, Macao, and Taiwan is their significant level of autonomy, which clearly distinguishes their political systems from that of mainland China. The omission of Tibet is due to the absence of data.

This analysis also excludes companies in the financial sector due to their significantly different investment and financing patterns compared to the rest of the economy. Due to the distinct risk characteristics of organizations on delisting alert compared to non-delisting alert firms, the cost of capital for the former is also not considered in the sample. After excluding individuals with incomplete data, the article has a total of 12,361 samples.

Following is a list of the data sources that were employed in this paper: The databases maintained by CSMAR are the source of the financial information. Both the statistics on water vulnerability and the data on government water investment are gathered from a variety of sources, such as the China Statistical Yearbook, the China Water Resources Statistical Yearbook, the China Water Resources Bulletin, and the China Urban and Rural Construction Statistical Yearbook. The data represent water regulations acquired from work reports produced by the provincial government. Stata 17.0 was used to carry out the data processing duties.

4.2. Construction of Variables

4.2.1. Water Vulnerability

Water vulnerability refers to the state of a water resource system that is vulnerable to disturbances produced by human activities and natural fluctuations, as well as the degree to which it is difficult to restore the system to its original form when such disturbances have occurred (Xia J. et al., 2012) [12]. Gui, Chen, and He (2021) propose that water vulnerability can be categorized into four dimensions: sensitivity, exposure, hazard, and adaptivity [14]. Sensitivity indicates the extent of fluctuation in water resources. The concept of exposure highlights the extent to which economic and social progress relies on the availability and sustainability of water resources. Hazard denotes the magnitude of the economic and social consequences resulting from the temporal and spatial fluctuations of water resources. Adaptability refers to the degree to which water resources have been effectively managed in relation to social and economic growth. The relevant aspects were assessed using indicators from studies conducted by Gui, Chen & He (2021), Liu & Chen (2016), and Su et al. (2018) [14,88,89]. A complete assessment was conducted using the entropy approach. The precise indicators are displayed in Table 1.

Table 1. The assessment of water vulnerability.

Dimensions	Items	Data Sources
Sensitivity	Absolute value of annual precipitation variation	China Water Resources Statistical Yearbook
	Absolute value of annual total water resources variation	China Water Resources Statistical Yearbook
Exposure	GDP per capita	China Statistical Yearbook
	Share of GDP in primary production	China Statistical Yearbook
	Water resources per capita	China Statistical Yearbook
	Total water resources/total area of the region	China Water Resources Statistical Yearbook, China Urban and Rural Construction Statistical Yearbook
	Total water resources/total annual rainfall	China Water Resources Statistical Yearbook
	Proportion of high-quality surface water	China Water Resources Statistical Yearbook, China Environmental Statistical Yearbook
	Ratio of water resources supply to demand	China Urban and Rural Construction Statistical Yearbook
	Proportion of groundwater supply	China Water Resources Statistical Yearbook
	Water consumption of CNY 10,000 of GDP	China Water Resources Bulletin
	Water consumption of CNY 10,000 of industrial value added	China Water Resources Bulletin
	Water consumption by urban residents for domestic use	China Water Resources Bulletin
	Water consumption for agricultural irrigation	China Water Resources Bulletin
Hazard	Regional population affected/National population affected in the year	Bulletin of flood and drought disasters in China
	Regional direct economic losses/National losses in the year	Bulletin of flood and drought disasters in China
	Area of crops affected in the region/National damage in the year	Bulletin of flood and drought disasters in China
	Population with drinking water difficulties in the region/National population affected in the year	Bulletin of flood and drought disasters in China
Adaptivity	Wastewater treatment rate	China Urban and Rural Construction Statistical Yearbook
	Water reuse rate	China Urban and Rural Construction Statistical Yearbook
	Ratio of protected arable land	China Water Resources Statistical Yearbook
	Protection of population ratio	China Water Resources Statistical Yearbook
	Effective utilization rate of irrigation water	China Water Resources Bulletin

4.2.2. Capital Cost

The capital cost is primarily categorized into the debt cost and the equity cost. Currently, there are two primary methods for measuring the cost of debt. The first method involves using the interest rate on bank borrowings as a proxy variable. The second method involves using the current year's interest as a proportion of the firm's current year liabilities as a proxy variable. This study contends that bank borrowing is merely one avenue for obtaining debt financing. Bank funds offer a lesser interest rate compared to other funds, although banks establish a higher barrier for borrowers. This article asserts that bank borrowing rates inadequately capture the complete cost of debt. Referring to Zou et al. (2003) [90], the formula for calculating the cost of debt is as follows: divide the sum of interest expense and capitalized interest by the average amount of interest-bearing debt for the year.

There are multiple methods to determine the cost of equity, mostly categorized into ex-ante and ex-post models. The ex-ante approach, such as the PEG model, is regarded as more advantageous than the ex-post model, such as the CAMP model (Mao et al., 2012) [91]. However, because intermediate services like analyst forecasting in China started late, there is only a limited amount of analyst forecasting data available for a small number of enterprises. And the CAMP model's ability to determine the cost of equity for enterprises is restricted in developing countries (Kling et al., 2021) [48]. Thus, this work adopts the approach of Lin, Zheng & Bo (2015), Zhou et al. (2018a; 2018b) [92–94], etc., by utilizing the reciprocal of the P/E ratio as an indicator of the cost of equity.

4.2.3. Water Governance

This study aims to distinguish between the regulatory and investment aspects of government water governance. Currently, there are two methods to measure water regulation. The first method involves analyzing industrial emissions that are connected to water resources as a substitute variable. The second method involves analyzing the occurrence and significance of terms related to water resources in government work reports, which indicates the level of regulatory pressure exerted by the government (Chen & Chen, 2018; Chen et al., 2018) [95,96]. This article asserts that the government's work report is a strategic document that functions as a blueprint for the execution and enforcement of the authority's decisions and resolutions in compliance with the law. Because of this, the frequency and percentage of water-related phrases in the government work report serve as a more complete measure of water regulation.

The particular techniques that were followed in order to produce the indicators that represent water regulation are outlined in this research as follows: The first stage consisted of manually collecting work reports written by the government from thirty different provinces during the course of the years 2019 to 2023. As a further step, the terminology that represents water regulation was established. We followed the research done by Zheng et al. (2022) to choose the following terms: water environment, water resources, water pollution, water safety, water ecology, river and lake, river (lake) chiefs, water price, water use, and water quality [13]. The final step was to compute the frequency of these terms and the percentage of them to the total number of words that were found in the government work reports.

The China Water Statistics Yearbook states that government investment in water resources mostly focuses on flood control, irrigation, drainage, water supply, hydropower, soil conservation, ecological restoration, institutional capacity building, early-stage projects, and other related areas. The preliminary measurement of water investment is determined by calculating the sum of investments made during the current year after omitting the investments in hydropower and institutional capacity development. This approach is adopted since investments in hydropower primarily serve the purpose of addressing energy issues, while strengthening institutions is aimed at keeping the operation of the government. In the meantime, this study makes use of the ratio of total water investment to local GDP as the indicator of water investment to reduce the influence of regional economic inequalities on water investment and to improve the capability of comparing water investment across provinces.

4.2.4. Control Variables

A number of factors at the firm level, including financial performance (ROA), market-to-net ratio (BM), firm size (SIZE), asset-liability ratio (LEV), stock liquidity ratio (Turnover), and equity concentration (SHR), have been selected to be the control variables. This decision was made after taking into consideration previous research (for example, Kling et al., 2021; Huang et al., 2018; Zhou et al., 2018a,b) [48,49,87,88]. The total regional gross domestic product (GDP) and the growth rate of regional GDP (GGROWTH) are the representative variables at the regional level that are under consideration to be controlled.

4.3. Model and Estimate Method

In accordance with recent research results (Zheng et al., 2022; Kling et al., 2021) [13,48], we used the following equation to study and test the hypotheses:

$$Capital = \beta_0 + \beta_1\ Water_{Vul} + \sum_i \beta_i Controls_i + \sum_j \beta_j Industrial fixed_j + \sum_l \beta_l Year fixed_l + \varepsilon_{it} \quad (1)$$

To further test the moderating effect of water governance, the interaction term between water governance and water vulnerability is introduced in Equation (1). The equation is as follows:

$$\begin{aligned} Capital = \beta_0 + \beta_1\ Water_{Vul} + \beta_2\ Water_{Gov} + \beta_3\ Water_{Vul} * Water_{Gov} + \sum_i \beta_i Controls_i \\ + \sum_j \beta_j Industrial fixed_j + \sum_l \beta_l Year fixed_l + \varepsilon_{it} \end{aligned} \quad (2)$$

In the above equations, *Capital* respectively represents the cost of debt (r_debt) and the cost of equity(r_equity), $Water_{Vul}$ represents water vulnerability, $Water_{Gov}$ respectively represents water investment (Water_Inv) and water regulation (Water_Ins). In addition, the Hausman test indicates that the fixed effects model should be adopted in this paper.

5. Empirical Analysis

5.1. Descriptive Analysis

This report provides a comprehensive examination of water vulnerability in China, examining it at both a regional and a provincial level. The regional vulnerability of water resources is displayed in Table 2, whereas the provincial vulnerability is depicted in Figure 2. The descriptive statistics of water vulnerability are consistent with the geographical distribution of water resources in China, demonstrating that the assessment of water vulnerability in this study has reliability and could be used to investigate the true relationship with capital costs. According to our assessment, there are significant differences in the degree to which various areas in China are vulnerable to water crises. The vulnerable state of water resources is much more severe in the northern area compared to the southern region. Water vulnerability is most pronounced in north China. This is primarily due to the limited availability of water resources in the region, as well as the high demand for water by society. Meanwhile, there are problems with water resources and the water environment, such as the excessive extraction of groundwater and a decline in water quality (Sun & Kato, 2021) [68]. The area of southwest China has the lowest degree of water vulnerability and functions as the principal source of water for the rest of China. This may be ascribed to the abundant water resources located there as well as the comparatively low human density.

Table 2. Descriptive statistics of the yearly average of water vulnerability in seven regions of China.

Region	2019	2020	2021	2022	2023	Mean
North China	0.343	0.338	0.293	0.331	0.278	0.317
Northeast China	0.319	0.320	0.312	0.275	0.273	0.300
Northwest China	0.332	0.312	0.310	0.295	0.274	0.305
Eastern China	0.232	0.195	0.189	0.186	0.179	0.196
South-Central-China	0.192	0.183	0.177	0.162	0.159	0.175
Southwest China	0.143	0.140	0.131	0.130	0.119	0.133

Note: All values are calculated by entropy weight method based on the water vulnerability assessment system shown in Table 1.

When compared to the other provinces, Ningxia is the most susceptible to water vulnerability. Ningxia is the province that has the greatest degree of vulnerability among all of the provinces. According to Han et al. (2020) [97], the high concentration of human activity in the area, along with drought and frequent natural disasters, has led to severe water shortages in Ningxia. These elements have had a role in the present difficulties faced by the province. After Ningxia, Heilongjiang Province is the second-most vulnerable due to its high water sensitivity. The reasons for this include the considerable seasonal fluctuations in water resources, the limited capacity for generating water, and the abrupt growth in water demand brought on by socioeconomic development (Qiu et al., 2008) [98]. In addition to a water supply-and-demand mismatch, the three provinces of Beijing, Tianjin, and Shanghai are also battling water contamination issues (Cao et al., 2019) [99]. Consequently, these provinces have a greater susceptibility to water-related issues. Due to their exceptional water environment quality and abundance of water resources, provinces like Guangdong, Guangxi, Zhejiang, and Jiangxi are less susceptible to water scarcity than other provinces in China.

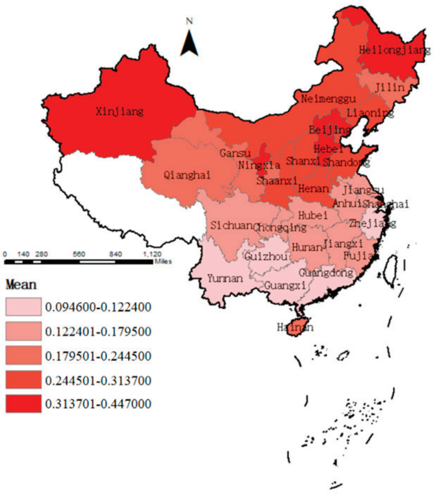

Figure 2. Diagram of the total average of water vulnerability in each province in China. Note: All values are calculated by entropy weight method based on the water vulnerability assessment system shown in Table 1.

The major factors are studied in a descriptive fashion, as shown in Table 3, in order to provide a more thorough assessment of the influence that water vulnerability has on the cost of capital. This is done in order to provide a more comprehensive study. When it comes to the cost of capital, the average cost is not very high; nonetheless, there is a substantial gap between the highest and lowest values within the value range. The fact that this is the case suggests that some groups continue to struggle with acquiring finance, which leads to significant expenditures associated with financing. The likelihood of development over the long run is negatively impacted by this circumstance. Water vulnerability in China varies geographically, with a mean value of 0.193, ranging from a low value of 0.047 to a high value of 0.392. Based on this, it can be concluded that China's overall water vulnerability is rather low; however, there are significant variations throughout the country's many areas. Despite the fact that the Chinese government has been able to accomplish exceptional achievement in water control, this finding also suggests that businesses may be unaware of the dangers associated with water or may underestimate the potential effect of water vulnerability. A number of additional control variables are also taken into consideration in this work. The values of these control factors are quite similar to those discovered in prior research.

Both the Pearson correlation test (highlighted in the bottom triangle) and the Spearman correlation test (highlighted in the top triangle) were employed in order to identify instances of multicollinearity within the model. In Table 4, the correlation coefficients are presented. The results of the study suggest that there is a significant connection between the cost of debt and the vulnerable state to water. Consequently, this provides a partial validity for hypothesis H1a, which shows that businesses are susceptible to the dangers associated with physical water risk. It is necessary to do more research since the current negligible negative association between water vulnerability and the cost of equity suggests the existence of a more complex connection between the two variables. Such a connection would need further examination. Some evidence in support of Hypotheses 2 and 3 may be found in the link between the instruments used by the government for water governance, the cost of capital, and water vulnerability. The correlation coefficients among all of the variables are substantially lower than 0.6, which indicates that there is not a serious collinear concern.

Table 3. Descriptive statistical results of each variable.

Variables	Mean	S.D.	Min	Max
r_debt	0.009	0.025	−0.097	0.063
r_equity	0.038	0.035	0.001	0.207
Water_Vul	0.193	0.091	0.065	0.392
Water_Ins	0.002	0.001	0.000	0.005
Water_Inv	0.006	0.004	0.001	0.026
ROA	0.056	0.045	0.002	0.228
BM	0.629	0.247	0.122	1.189
SIZE	22.343	1.246	20.114	26.140
LEV	0.401	0.183	0.064	0.837
TOVER	5.666	0.738	3.674	7.196
SHR	0.155	0.107	0.017	0.521
LGDP	10.718	0.679	8.499	11.615
GGROWTH	5.986	2.017	0.500	9.300

Table 4. Correlations of each variable.

	Water_Vul	r_equity	r_debt	Water_Ins	Water_Inv	ROA	BM	SIZE	LEV	TOVER	SHR	LGDP	GGROWTH
Water_Vul		0.045	0.043 ***	−0.164 **	−0.1034 ***	−0.124 ***	0.055 ***	0.099 ***	0.049 ***	−0.032 ***	0.027 ***	−0.472 ***	−0.079 ***
r_equity	0.013		0.020 **	−0.022 **	0.0083	0.561 ***	0.437 ***	0.425 ***	0.113 ***	−0.308 ***	0.157 ***	0.028 ***	−0.069 ***
r_debt	0.038 ***	0.049 ***		−0.004	0.0048	−0.054 ***	0.062 ***	0.082 ***	0.050 ***	−0.032 ***	−0.014	−0.039 ***	0.001
Water_Ins	−0.205 ***	−0.024 **	−0.003		0.1284 ***	0.024 **	−0.047 ***	−0.055 ***	−0.021 **	0.075 ***	−0.021 **	0.228 ***	0.060 ***
Water_Inv	0.055 ***	0.001	0.018 *	0.171 ***		0.000	−0.004	0.036 ***	0.012	0.039 ***	0.013	−0.468 ***	0.129 ***
ROA	−0.108 ***	0.368 ***	−0.044 ***	0.016	−0.028 ***		−0.338 ***	−0.091 ***	−0.382 ***	−0.105 ***	0.130 ***	0.123 ***	0.015
BM	0.078 ***	0.434 ***	0.072 ***	−0.052 ***	0.017 ***	−0.372 ***		0.518 ***	0.396 ***	−0.273 ***	0.087 ***	−0.067 ***	−0.079 ***
SIZE	0.133 ***	0.455 ***	0.083 ***	−0.052 ***	0.040 ***	−0.077 ***	0.532 ***		0.525 ***	−0.352 ***	0.124 ***	−0.132 ***	−0.037 ***
LEV	0.057 ***	0.167 **	0.046 ***	−0.015	0.035 ***	−0.366 ***	0.394 ***	0.532 ***		−0.051 ***	0.026 ***	−0.070 ***	−0.027 ***
TOVER	−0.046 ***	−0.254 ***	−0.043 ***	0.073 ***	0.041 ***	−0.010 ***	−0.281 ***	−0.386 ***	−0.060 ***		−0.310 ***	0.076 ***	−0.151 ***
SHR	0.048 ***	0.164 ***	−0.005	−0.028 ***	0.010	0.105 ***	0.115 ***	0.207 ***	0.052 ***	−0.357 ***		−0.032 ***	0.004
LGDP	−0.450 ***	0.005 ***	−0.033 ***	0.130 ***	−0.544 ***	0.108 ***	−0.073 ***	−0.128 ***	−0.077 ***	0.053 ***	−0.040 ***		−0.109 ***
GGROWTH	−0.042 ***	−0.037 ***	−0.008	0.089 ***	0.081 ***	0.009	−0.032 ***	−0.052 ***	−0.024 **	−0.180 ***	0.005	−0.017 *	

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively.

5.2. Results of Main Regression

The results of evaluating the correlation between water vulnerability and corporate capital cost are presented in Table 5. In the full-sample regression, we observe a statistically significant positive relationship between water vulnerability and company capital costs. An increase in water vulnerability of 1% could result in a 1.8% increase in the cost of debt and a 1.5% increase in the cost of equity. This discovery validates our prior hypothesis that water vulnerability has emerged as a significant risk for businesses, and financial markets have started to acknowledge the presence of this risk. H1a and H1b have been proven.

Table 5. Regression results of water vulnerability to corporate capital costs (2019–2023).

	Cost of Debt	Cost of Equity
Water_Vul	0.018 ***	0.015 ***
	(3.12)	(2.92)
ROA	−0.017 **	0.459 ***
	(−1.88)	(3.56)
BM	0.003 *	0.065 ***
	(1.74)	(3.07)
SIZE	0.001 ***	0.005 ***
	(4.41)	(2.83)
LEV	−0.002	0.011 **
	(−0.35)	(2.49)
TOVER	−0.001 *	0.002 ***
	(−1.98)	(3.42)
SHR	−0.007 ***	−0.006 **
	(−2.97)	(−2.12)
LGDP	0.001	0.001 ***
	(1.03)	(2.79)
GGROWTH	0.001	0.001 **
	(0.01)	(2.23)
Constant	−0.013	−0.185 ***
	(−0.35)	(−3.04)
Fixed Effects	Yes	Yes
Obs	12,363	12,363

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent the t-value after robust standard error adjustment.

5.3. Robustness

We performed two rigorous tests to assess the reliability and stability of our main regression findings. Initially, we modified a different time period of the sample in order to evaluate the resilience of the main regression. We utilized data from 30 Chinese provinces and municipalities, specifically excluding Tibet, Hong Kong, Macao, and Taiwan, for the time frame spanning 2014 to 2018. The data presented in Table 6 indicate a positive correlation between water vulnerability and both the cost of debt and the cost of equity.

Table 6. Robustness results of water vulnerability to corporate capital Costs.

	Sample Change		PSM	
	Cost of Debt	Cost of Equity	Cost of Debt	Cost of Equity
Water_Vul	0.021 ***	0.011 **	0.032 **	0.021 *
	(2.56)	(2.49)	(2.48)	(1.78)
Controls	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes
Constant	2.413 *	1.460 **	0.090 ***	0.011
	(1.75)	(2.41)	(2.81)	(1.34)
Obs	8736	8736	11,476	11,476

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent the t-value after robust standard error adjustment.

Furthermore, propensity score matching (PSM) is employed to conduct a more in-depth analysis of the reliability of the main regression findings. The principle of propensity matching involves comparing organizations that share similar traits but exhibit inconsistent behaviors in order to form a matching group. Given that firms have the freedom to choose their geographical location, we have chosen enterprises situated in regions with above-average water vulnerability as the treatment group, and enterprises located in regions with below-average water vulnerability as the control group. This article utilizes return on assets (ROA), price to book ratio (BM), total asset (SIZE), financial leverage (LEV), turnover of stocks (TOVER), and share concentration (SHR) as matching variables. The samples are paired one-on-one. The regression coefficients for water vulnerability are positively and significantly associated, confirming the reliability of the findings, as presented in Table 6.

5.4. Endogeneity Tests

As a result of our initial premise that water vulnerability comprises specific characteristics that are impacted by social and economic development, we conducted an analysis of the endogeneity of water vulnerability and capital costs. It is possible that the variable of water vulnerability does not fulfill the criterion of exogeneity owing to the existence of unaccounted variables or measurement mistakes. This is despite the fact that we have control over some factors that reflect the economic growth of the area. Thus, we follow the approach proposed by Wooldridge (2010) to test whether or not water vulnerability meets strict exogeneity requirements [100]. The result of endogeneity tests is shown in Table 7.

$$\mathrm{Capital}_{it} = \alpha_1 + \beta_1 \mathrm{Water\_Vul}_{jt} + \sum \mathrm{Controls}_{it} + \mu_i + \varepsilon_{it} \tag{3}$$

$$\mathrm{Water\_Vul}_{jt} = \alpha_2 + \delta_1 \mathrm{SUN}_{jt} + \beta\delta_2 \sum \mathrm{Controls}_{it} + \omega_{it} \tag{4}$$

Table 7. Endogeneity results of water vulnerability to corporate capital costs using two-stage regression method.

	Water_Vul	**r_equity**	**r_debt**
Water_Vul		0.010 ** (2.68)	0.013 ** (1.88)
VUL_hat		−0.006 (−0.37)	−0.012 (−0.17)
SUN	0.213 *** (4.59)		
Controls	Yes	Yes	Yes
Constant	−1.175 *** (−3.46)	−0.179 *** (−5.68)	−0.016 * (−1.73)
Obs	12,361	12,361	12,361

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent the t-value after robust standard error adjustment.

First, we start with a random-effects model, as Equation (3). The next step is to incorporate the variable of the yearly hour of sunlight (SUN) in order to determine whether or not the condition of endogeneity is satisfied by water vulnerability. In this study, it is considered that the amount of economic development in an area may have an effect on water vulnerability; nevertheless, the average annual hour of sunlight is less impacted by the level of social and economic development than water vulnerability is. We calculated the residuals by using Equation (4), and then we included those residuals into the initial Equation (3). The cost of equity, also known as r_equity, has a coefficient of the residual, which is written by the symbol VUL_hat, which is −0.006, and its *t*-value is −0.37. The cost of debt, also known as r_debt, has a coefficient of the residual, which is indicated by the symbol VUL_hat, which is −0.012, and its t-value is −0.17.

VUL_hat is the difference between the real Water_Vul and the Water_Vul fitted by Equation (4), representing the endogenous impact of the independent variable on the biased estimation of the dependent variable. If the regression coefficient of vul_hat in Equation (3) has no significance, it means that the endogenous influence of the real water_vul will not cause the regression result to produce a significantly biased estimation. In this study, the regression coefficients of VUL_hat for r_debt and r_equity are both not significant. That is to say, water_vul meets the assumption that the independent variable is exogenous to obtain a consistent estimator. Therefore, the multiple regression, applied by this study to test the relationship between water vulnerability and corporate capital costs, will not produce significant biased estimates due to the possible endogeneity of water_vul, indicating the robustness of the main regression results.

5.5. Channel Analysis

Hypothetically, we suggest that water vulnerability exposes investors to higher credit risks that increase corporate capital costs. Credit risk would result in financing constraints, so we apply financial constraints to measure credit risk. For the measurement of financing constraint, we draw on the research of Kaplan and Zingales (1997) [101]. The higher the value of the KZ, the greater the degree of financing constraints. The data of KZ are from CSMAR. We also draw on the method of Wen and Ye (2014) to construct models (5)–(7) to examine whether or not the mediating effect of financing constraint (KZ) exists [102]. Equation (5) is the main test model, and the coefficient α_1 measures the total effect of the independent variable on the dependent variable. Equation (6) is used to examine the impact of water vulnerability on financing constraints, and the coefficient β_1 is the focus. Equation (7) mainly examines the impact of water vulnerability and financing constraints on the corporate capital costs, and the coefficients γ_1 and γ_2 are the focus. If γ_1 is insignificant but γ_2 is significant, it indicates that financial constraints play a complete mediating effect. If γ_1 and γ_2 are both significant, it indicates that financial constraints play a partial mediating effect.

$$\mathrm{Capital}_{it} = \alpha_0 + \alpha_1 \mathrm{Water\_Vul}_{jt} + \sum \mathrm{Controls}_{it} + \sum_j \alpha_j \mathrm{Industrialfixed}_j + \sum_l \alpha_l \mathrm{Yearfixed}_l + \varepsilon_{it} \quad (5)$$

$$\mathrm{KZ}_{it} = \beta_0 + \beta_1 \mathrm{Water\_Vul}_{jt} + \sum \mathrm{Controls}_{it} + \sum_j \beta_j \mathrm{Industrialfixed}_j + \sum_l \beta_l \mathrm{Yearfixed}_l + \varepsilon_{it} \quad (6)$$

$$\mathrm{Capital}_{it} = \gamma_0 + \gamma_1 \mathrm{Water\_Vul}_{jt} + \gamma_2 \mathrm{KZ}_{it} + \sum \mathrm{Controls}_{it} + \sum_j \gamma_j \mathrm{Industrialfixed}_j + \sum_l \gamma_l \mathrm{Yearfixed}_l + \varepsilon_{it} \quad (7)$$

Table 8 displays the results of the channel analysis. The first step of the mediation effect test is presented in R1 and R4, which is also the outcome of the main regression in Equation (1). The regression coefficient for water vulnerability on corporate capital costs is positively and significantly related with the significance of α_1. The results of step 2 are shown in R2 and R5. The regression coefficient of water vulnerability on financing constraints is positive and significant at the $p < 5\%$ level, indicating that water vulnerability significantly promotes financing constraints. R3 and R6 present the outcomes of the third step, with the coefficients for water vulnerability and financing constraints both below significance at the $p < 5\%$ levels. This suggests that the increase in financing constraints, spurred by water vulnerability, contributes to the higher corporate capital costs, with financing constraints serving as a partial mediator.

Table 8. Channel analysis of water vulnerability to corporate capital costs.

	r_debt			r_equity		
	R1	**R2**	**R3**	**R4**	**R5**	**R6**
	r_debt	**KZ**	**r_debt**	**r_equity**	**KZ**	**r_equity**
Water_Vul	0.018 *** (3.12)	0.035 ** (2.17)	0.018 *** (3.35)	0.015 *** (2.92)	0.001 ** (2.03)	0.011 *** (3.06)
KZ			0.030 ** (2.84)			0.332 *** (2.98)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Fixed Effects	Yes	Yes	Yes	Yes	Yes	Yes

Table 8. *Cont.*

	r_debt			r_equity		
	R1	**R2**	**R3**	**R4**	**R5**	**R6**
	r_debt	**KZ**	**r_debt**	**r_equity**	**KZ**	**r_equity**
Constant	−0.013 (−0.35)	−0.043 (−0.68)	−0.012 (−0.93)	−0.185 *** (−3.04)	−0.614 (−0.54)	−0.172 ** (−2.16)
Obs	12,361	12,361	12,361	12,361	12,361	12,361

Note: ***, ** indicate significant at the 1%, 5% levels, respectively; the values in parentheses represent the t-value after robust standard error adjustment.

5.6. Moderating Effect

The findings displayed in Table 9 indicate that government water regulation generally has a positive influence on the connection between water vulnerability and the cost of debt. However, it has an insignificantly negative impact on the link between the cost of equity and the vulnerability of water. H2a has been proven, but H2b has not. The results on the cost of debt lend credence to the notion that government water regulation exacerbates the impact of water vulnerability on the financial performance of firms (Zheng et al., 2022) [13], hence encouraging creditors to demand higher premiums for water risks. The results of the equity cost analysis may indicate that government regulation of water resources has the potential to facilitate the transition of businesses towards environmentally friendly practices. This, in turn, would mitigate the risks associated with water scarcity and contribute to the long-term sustainability of enterprises.

Table 9. Moderating effects of water institutions and water investment on the relationship between water vulnerability to corporate capital costs.

	r_debt	**r_equity**
Water_Vul	0.019 *** (2.61)	0.065 *** (3.88)
Water_Ins	0.097 (1.03)	0.179 (1.24)
Water_Vul × Water_Ins	3.268 * (1.68)	−1.854 (−0.98)
Water_Vul	0.018 *** (2.75)	0.015 *** (2.94)
Water_Inv	0.232 * (1.71)	0.087 (1.08)
Water_Vul × Water_Inv	−1.397 * (−1.67)	−0.166 (−0.83)
Controls	Yes	Yes
Fix Effects	Yes	Yes
Obs	12,363	12,363

Note: ***, * indicate significant at the 1%, and 10% levels, respectively; the values in parentheses represent the t-value after robust standard error adjustment.

The findings displayed in Table 9 indicate that government water investment has a minor adverse moderating influence on the relationship between water vulnerability and the cost of debt. However, it does not have any meaningful moderating effects on mitigating the impact of water vulnerability on the cost of equity. H3a has been validated; however, H3b does not pass the hypothesis testing. The results on the cost of debt support the idea that government investment in water infrastructure mitigates the negative effects of water vulnerability on business financial performance (Zheng et al., 2022) [13], hence reducing the demand for higher water risk premiums from creditors. The findings of the cost of equity analysis may suggest that government investment in water infrastructure has the potential to enhance local water conditions and mitigate the disadvantageous effects of water vulnerability, albeit to a limited extent.

5.7. Heterogeneity

This paper further investigates the two heterogeneities in the relationship between water vulnerability and corporate capital costs. This is due to the fact that there are significant differences in water risk perception between water-intensive industries and non-water intensive industries, as well as between state-owned and non-state-owned corporations (Zheng et al., 2022) [13].

5.7.1. Industrial Heterogeneity

Currently, there is a lack of cohesion in the allocation of water-intensive businesses. The National Bureau of Statistics of China regulates the water consumption data of ten industries that are considered to be water-intensive. These industries include coal mining and washing, ferrous metal smelting and rolling processing, non-metallic mining and selection, electric power and heat production and supply, textiles, paper products industry, nonferrous metal smelting and rolling processing, chemical raw materials and chemical products manufacturing, non-metallic mineral products industry, petroleum processing and coking, and nuclear fuel processing.

Table 10 exhibits the industrial heterogeneity in main regression. The coefficient of water vulnerability, as seen in R1 and R5, suggests that it does not have a substantial impact on the capital cost of water-intensive enterprises. This outcome appears anomalous and contradicts conventional wisdom. Nevertheless, we contend that the impact of water vulnerability on the capital cost of water-intensive enterprises is minimal due to their implementation of adaptive water resource management strategies. These enterprises have taken measures to protect themselves from water vulnerability, as evidenced by studies conducted by Bulcke et al. (2020), Burritt et al. (2016), and Northey et al. (2019) [15,34,103]. This is primarily due to the greater institutional pressure faced by water-intensive enterprises compared to non-water intensive counterparts. Callaghan et al. (2020) discovered that companies that consume large amounts of water have improved their ability to cope with water vulnerability by using technology innovation and embracing environmentally friendly practices [104].

Table 10. Heterogeneity in regression results of water vulnerability to corporate capital costs.

	r_debt				**r_equity**			
	Industrial Heterogeneity		**Firm Heterogeneity**		**Industrial Heterogeneity**		**Firm Heterogeneity**	
	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**
Water_Vul	0.004	0.022 ***	0.020 **	0.016 **	0.010	0.013 **	0.002	0.024 ***
	(0.36)	(2.67)	(2.45)	(2.02)	(1.10)	(1.88)	(0.19)	(2.86)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fix Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	3246	9015	4001	8360	3246	9015	4001	8360
Chow Test	3.01 **		2.75 *		3.72 **		4.72 ***	

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent the *t*-value after robust standard error adjustment.

Table 11 exhibits the industrial heterogeneity regarding moderating effects. Panel A illustrates the diversity in the moderating impact of water regulation. R1 and R2 demonstrate that the positive moderating effect is significant in industries that are not highly dependent on water, but not in the water-intensive sector. Water-intensive firms have implemented adaptive management practices and have been subject to government monitoring and regulation for a significant period of time (Bulcke et al., 2020; Burritt et al., 2016; Northey et al., 2019) [15,34,103]. As a result, the risk associated with water-related regulations is minimal and decreasing. Thus, water regulation has a negligible effect on water-intensive firms but a slightly noticeable effect on non-water-intensive industries.

Table 11. Heterogeneity in moderating effects of water institutions and water investment on the relationship between water vulnerability and corporate capital costs.

Panel A—Water Regulation								
	r_debt				r_equity			
	Industrial Heterogeneity		Firm Heterogeneity		Industrial Heterogeneity		Firm Heterogeneity	
	R1	R2	R3	R4	R5	R6	R7	R8
Water_Vul	0.004	0.023 ***	0.024 **	0.017 **	0.014	0.013 **	0.002	0.026 ***
	(0.34)	(3.57)	(1.98)	(2.21)	(0.17)	(2.11)	(1.09)	(2.67)
Water_Ins	0.174	0.076	0.341	0.036	0.321	0.055	−0.041	0.220
	(0.39)	(0.73)	(0.12)	(0.24)	(0.81)	(0.52)	(0.18)	(1.25)
Water_Vul ×	1.752	4.018 *	3.675	3.481 *	−2.404	−2.410	−4.966	3.147
Water_Ins	(1.08)	(1.82)	(1.59)	(1.92)	(−1.69)	(−1.42)	(−1.59)	(1.44)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fix Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	3246	9015	4001	8360	3246	9015	4001	8360
Chow Test	4.44 **		4.15 **		3.96 **		4.88 ***	
Panel B—Water Investment								
	r_debt				r_equity			
	Industrial Heterogeneity		Firm Heterogeneity		Industrial Heterogeneity		Firm Heterogeneity	
	R1	R2	R3	R4	R5	R6	R7	R8
Water_Vul	0.004	0.022 ***	0.0210**	0.016 **	0.112	0.012 **	0.001	0.024 ***
	(0.34)	(3.56)	(1.88)	(2.08)	(0.16)	(2.09)	(1.03)	(2.64)
Water_Inv	0.090	0.276 *	0.111	0.302 *	0.346	−0.069	−0.1131	0.220*
	(0.22)	(1.85)	(0.37)	(1.94)	(0.84)	(−1.06)	(−0.17)	(1.77)
Water_Vul ×	−0.184 *	1.733 *	−0.404	−2.652 **	−2.868 **	1.780 **	0.256	0.160
Water_Inv	(−1.69)	(1.79)	(−1.15)	(−2.24)	(−2.53)	(1.98)	(0.86)	(0.44)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fix Effects	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Obs	3246	9015	4001	8360	3246	9015	4001	8360
Chow Test	4.72 **		3.98 **		4.01 **		4.90 ***	

Note: ***, **, * indicate significant at the 1%, 5%, and 10% levels, respectively; the values in parentheses represent the *t*-value after robust standard error adjustment.

Panel B demonstrates the heterogeneity in the moderating effect of water investment. The analysis reveals that government water investment has a notable negative impact on water-intensive enterprises, but it has a considerable beneficial impact on non-water-intensive firms, as indicated by the results in R1 and R2 and R5 and R6, respectively. As previously stated, government investment in water can enhance local hydrological conditions, and water-intensive companies already employ adaptive management strategies. Consequently, companies that use significant amounts of water experience substantially reduced water-related risks, which suggests a decrease in the additional return on investment required by investors. Government expenditures in water infrastructure would be paid off through marketing incentive tools such as water prices. However, enterprises that do not heavily rely on water resources may have limited understanding of the importance of implementing adaptive water management practices. Therefore, it is possible that non-water intensive companies would see more pressure on their profitability, indicating that investors are still taking into account the possibility of a water risk premium.

5.7.2. Firm Heterogeneity

We further categorize the sample into two groups: state-owned and non-state-owned firms. This division allows us to determine whether enterprise ownership mitigates or exacerbates the impact of water risk. Certain researchers hold the belief that state-owned firms have the potential to enhance their profitability by utilizing natural resources rent (Lim & Morris, 2022) [105]. Contrarily, other researchers argue that state-owned firms serve as a means to implement government policies, although they may not achieve satisfactory financial results in order to fulfill non-commercial objectives (Huang et al., 2020) [106]. The issue of water is closely intertwined with human rights (Hazelton, 2013) [70], and it is imperative for state-owned corporations to assume more duties in safeguarding civil rights. As an illustration, Huang et al. (2020) discovered that state-owned firms incur higher costs in terms of pollutant discharge fees [106].

Table 10 demonstrates that the effect of water vulnerability varies between the cost of debts and the cost of equity. Regarding state-owned enterprises (SOEs), it appears that creditors are more inclined to request a water risk premium (R3), whilst equity investors show less concern about water risk to SOEs (R7). The water risk premium of debt of SOEs is attributed to their financial underperformance, as corporate solvency and corporate financial risk are significant determinants of the cost of debt. SOEs are more susceptible to experiencing greater financial losses and typically exhibit larger levels of debt ratios, as highlighted by Ferrarini and Hinojales (2019) [107]. The lack of concern from equity investors towards water risk can be understood as SOEs demonstrating a greater commitment to social responsibility in order to uphold their social and environmental credibility. Extensive research has consistently shown that companies with better corporate social responsibility performance tend to have lower costs of equity. Additionally, a company's previous responsible performance can provide significant insurance effects to protect their equity (Afrin et al., 2021) [6].

Furthermore, SOEs possess inherent political benefits when it comes to obtaining natural resources (Chen et al., 2011; Zhou et al., 2018a, b) [87,88,108]. SOEs, when compared to non-SOEs, are more favorable for engaging in rent-seeking activities and less inclined to suffer the associated costs (Zhou et al., 2018a, b) [87,88]. Consequently, investors are less inclined to want greater compensation for the uncertainty associated with the cost of equity of SOEs due to water risks. This implies that non-SOEs will face increased demands for compensation from equity investors for their water-related risks. The findings indicate that if water risk were to increase by 1%, equity investors would increase the cost of equity for non-SOEs by 2.4% (R8).

Table 11 demonstrates that firm heterogeneity mostly influences the moderating impact on debt costs. Panel A illustrates the diversity in the moderating impact of water regulation. R3 indicates that government water regulation does not appear to have a substantial influence on SOEs. As previously understood, SOEs may have a greater obligation to pursue non-commercial objectives, making them more inclined to comply with government directives for adaptive water management. The market would provide greater value to SOEs due to their governmental characteristics (Xiao & Yang, 2021) [109], which might counterbalance the adverse effects of underperformance. Meanwhile, SOEs are able to engage in power rent-seeking more effortlessly in order to mitigate the negative consequences of policies, without incurring the expenses associated with rent-seeking activities (Chen et al., 2011; Zhou et al., 2018a, b) [87,88,108]. Panel B illustrates the diversity in the moderating impact of water investment. R3 illustrates that government investment in water infrastructure does not replace the ongoing social responsibility of SOEs in addressing water-related matters.

6. Discussion and Conclusions

Examples of academics emphasizing the importance of recognizing and valuing natural resources and the significant impacts on the sustainability of businesses are limited. Our findings illustrate that the negative impact of deteriorating nature on corporate sustainability also rise from access to financial resources. Companies located in areas with high susceptibility to water vulnerability experience more financial expenses. Aligning with works done by Zheng et al. (2022) and Huang et al. (2018), who have confirmed that ecological issues themselves do negatively impact corporate financial sustainability [13,49], our findings with the research conducted by Kling et al. (2021) demonstrate that the detrimental consequences of ecological degradation rise from the availability of financial resources [48]. Along with the research done by Chen & Chen (2018) [95], Liu et al. (2022) [110], etc., this discovery also confirms the crowding out effect of natural environmental degradation on corporate resource acquisition, providing reasons for the necessity of green transformation for enterprises. Meanwhile, our findings also provide incremental information that the water issue has the same effect as climate change, rather than the highly heterogeneous impact of different environmental issues on businesses, as Bowen et al. (2018) believed [111].

However, we should also be cautious of the finding because the negative impact of current water vulnerability does have a limited impact on the increase in capital costs for enterprises. There may be two important reasons for this, one of which is that the current capital market has not yet attached great importance to the water risks faced by enterprises. But this does not mean that water risk is not important. In fact, some investors have started to examine the impact of water risks faced by companies on their operations. S&P has compiled the Global Water Resources Index to reflect investment opportunities in the current water crisis. Robeco, a portfolio investment bank in Hong Kong, stated that it has begun to consider the impact of water scarcity on semiconductor companies and has made corresponding adjustments in asset valuation for related companies. Some financial news has also reported that the world's largest climate fund managed by Nordea Asset Management will liquidate all its holdings of TSMC stocks by the end of July 2023, as the water usage for TSMC wafer mask layers did not meet expected targets. These business cases indicate that incorporating water risk into investment decisions may be an emerging trend. Secondly, water vulnerability has a potential long-term negative impact on business operations; thus, the significant short-term impacts of water vulnerability on business operations is hard to perceive (except for natural disasters such as sudden floods, which are often considered force majeure and excluded from corporate financing decisions). Therefore, if investors evaluate the availability of financing through the operational status of enterprises, the part that can reflect the impact of water vulnerability is also very limited.

Furthermore, we also investigate the moderating impact of two types of water governance tools, specifically water regulation and water investment. Our research indicates that water regulation is a risk factor that is linked to water vulnerability, because it has a positive moderating effect on the impact of water vulnerability on corporate capital cost. This discovery aligns with the research conducted by Tan et al. (2022), which suggests that external regulatory pressure intensifies the influence of environmental issues on the capital cost of corporations [49]. Meanwhile, the finding also indicates that government regulation, which is generally considered to contribute to the sustainable development of water resources, has benefits with potentially huge costs. In other words, we provide additional evidence supporting the notion that environmental regulations impose economic costs on businesses (Greenstone et al., 2012; Long & Wan, 2017) [78,79]. We believe that environmental regulation would lose its micro realization path and fail if it does not consider its impacts on social subjects such as enterprises, because social subjects cannot recognize and consciously abide by environmental regulation out of their own interests. Therefore, governments should pay attention to the social and economic costs brought by regulation and provide diversified ways to help enterprises and other social subjects adapt to and comply with environmental regulation. For example, our findings endorse the government's decision to expand green credit programs for enterprises, which helps address the capital costs associated with their transition to environmentally friendly practices.

It is self-evident that investment in water conservancy projects, etc., is important for the sustainable development of water resources; our research shows that investing in water resources overall is serendipity to corporations because it has a minor negative moderating effect on the relationship between water vulnerability and the cost of debt, providing empirical evidence that such investment to mitigate water risk brings economic benefits, especially in the context of corporate financing activities. At present, some voices question the necessity of investment in water conservancy, etc., but this study proves the value of this kind of tool from a commercial perspective; that is, improving natural conditions can stimulate economic growth by reducing the financing cost of enterprises, so as to enhance economic vitality and promote regional development (Kling et al., 2021; Huang et al., 2018) [48,49].

Moreover, we thoroughly analyze the aforementioned relationships using various sub-samplings and discover intriguing findings. Companies that use a significant amount of water could have put water adaptive management strategies in place, making them immune to water vulnerability. They seem to be less affected by water regulatory pressure, and investments in water infrastructure may generate short-term harms that prevent them from accessing financing. Industries that do not need significant amounts of water are vulnerable to water conditions and are influenced by government policies and investment for water resources. Their carelessness in managing water resources might be the cause of this. The findings align with the principles of the Natural Resource Dependence Theory, which posits that the deterioration of ecosystems diminishes the dependability of natural resource provisions, thereby heightening the environmental unpredictability encountered by businesses. (Tashman, 2021; Tashman & Rivera, 2016) [10,11]. There is a paucity of choices for enterprises to deal with natural resource scarcity since neither external organizations nor themselves can control the supply of natural resources, and they cannot internalize this supply via partnerships, mergers, or acquisitions. To successfully manage the negative implications of ecological uncertainty, enterprises must reduce their dependency on resources (Tashman & Rivera, 2016) [11]. When it comes to dealing with ecological uncertainty, our study shows that symbolic change initiatives, like trying to modify company identity, do not work. But by adopting eco-friendly practices, such as improving water resource management, businesses may increase their ability to deal with ecological uncertainty.

For businesses, water vulnerability is a major concern. Businesses should work together to ensure a steady supply of water. Businesses that do not use significant amounts of water should make it a top priority to collaborate with other social actors, such as residents in the local communities and business partners, about water risk and use water adaptive management strategies. Private companies should pitch in to solve water issues and divide up the load when it comes to water management. Furthermore, the current lack of stringent government water regulations has not significantly affected enterprises, and it has also failed to increase businesses' awareness of water-related issues. Enhancing the regulatory framework for water management is necessary, but it is also crucial to take into account the adverse consequences for enterprises when intensifying water regulation in the future. Additionally, water investments often have a positive effect in reducing regional water vulnerability, but there can be some adverse consequences for enterprises as a result of the internalization of such expenditures. Companies that implement water adaptive management practices have the potential to mitigate this cost problem, thereby gaining a competitive advantage.

7. Limitation and Future Research

This study is constrained by certain restrictions. Initially, we made an effort to include as many widely used indicators for assessing water vulnerability as feasible, but there is a lack of consensus on what these indicators should be. At present, there are many methods to evaluate water vulnerability. One is the single index evaluation method, such as the amount of water resources per capita. The defect of this method is that it can only reflect one aspect of water vulnerability. For example, the amount of water resources per capita can only reflect water scarcity to a certain extent. Thus, comprehensive evaluation methods become mainstream. The comprehensive assessment method requires the assessment framework to be set in advance, but the current assessment framework of water vulnerability is diverse, including the DPSIR framework for environmental assessment and the VSD framework proposed by the IPCC. The VSD framework only included three dimensions—sensitivity, exposure, and adaptability—while some scholars have further proposed the disaster dimension to be the fourth, which was also the water vulnerability assessment framework used in this study. At the same time, in order to improve the accuracy of the assessment, scholars have shifted from using statistical data to using remote sensing data, making water vulnerability assessment increasingly complex. However, the reason why the more advanced remote sensing measurement methods are not used in this study is that the main purpose of this study is not to propose a new method to evaluate water vulnerability but to strengthen the dialogue and connection between water resource management research and business research. Of course, we are still aware of the shortcomings of this paper in the assessment of water vulnerability. Thus, we mentioned that this study is only an attempt to perform interdisciplinary research. It is hoped that, in the future, more accurate data of water vulnerability data assessed by hydro-scientists can be used to study its impact on enterprise behavior decision-making and its economic consequences.

Furthermore, despite our efforts to utilize a comprehensive dataset encompassing all publicly listed companies in the Chinese A-share market, there is still a possibility of a selection bias due to the fact that listed firms represent only a small portion of all companies in China. Hence, it is advisable to use caution when interpreting our findings in relation to Chinese companies in general.

Additionally, our analysis reveals that water investment only negatively moderates the relationships between water vulnerability and the cost of debt at a slight significance and have no significantly moderating effect on the relationships between water vulnerability and the cost of equity. However, we have read the current literature and failed to find a better explanation. Thus, future research could perform further investigations to obtain a more robust and reasonable explanation.

Finally, this report represents a preliminary investigation into the microeconomic effects of water vulnerability. Given the aforementioned constraints, it is imperative that further investigations are conducted to substantiate the conclusions presented in this work. Hence, it is advisable to take caution when relying on the findings presented in this paper.

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Developing Collaborative Management Strategies for Flood Control and Drainage across Administrative Regions Using Game Theory

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Abstract: There exist conflicts of interest between upstream and downstream regions in flood control and drainage; how to balance these conflicts and achieve collaborative flood management remains an important scientific problem. To explore a balanced governance strategy, this study took the Demonstration Zone of Green and Integrated Ecological Development of the Yangtze River Delta, which consists of three separate administrative regions, as the research domain. Using evolutionary game theory, the study conducts a comparative analysis of the interests between upstream and downstream areas. It introduces external drivers, such as the intervention of higher-level administrative bodies and incentive-constraining policies, along with internal balancing mechanisms like bidirectional compensation. The goal is to explore collaborative strategies and cooperation mechanisms that can balance the conflicts of interest between upstream and downstream areas. Results indicate that: (1) The final collaborative strategy was closely related to factors such as the cost of conflict, the amount of two-way compensation, additional benefits of flood control and drainage, and the intensity of incentive constraints. (2) Incorporating a reasonable two-way compensation and reward and punishment mechanism into the evolutionary game theory model can promote the model to a stable strategy. (3) The external driving mechanisms aim to coordinate the conflicts between upstream and downstream regions through incentive or constraint policies, which help motivate and encourage proactive collaboration in flood control and drainage management. The internal balancing mechanism is responsible for compensating for economic losses caused by imbalances, thereby creating pressure that fosters regional cooperation in flood control and drainage governance. In a word, the collaborated management mechanism helps provide a more balanced strategy across different administrative regions.

Keywords: the demonstration zone of green and integrated ecological development of the Yangtze River delta; flood control and drainage; evolutionary game; cross administrative region; collaboration mechanism

1. Introduction

A large basin is a complex system with both integrity and correlation [1,2]. In the basin, cities and towns are usually distributed along the river from upstream to downstream; these cities or towns are referred to as administrative regions. The location of these administrative regions determines the order of access to water conservancy project resources; for example, cities in the upstream area usually have priority in storm drainage or pollution discharge, while the cities in the downstream area have to bear the flood pressure or pollution pressure from upstream areas [3,4]. To give a simple example, the carrying capacity of the regional water environment is fixed. Consequently, upstream discharges inevitably impact the downstream water environment, thereby affecting the downstream discharge capabilities [5]. This has led to the development of the concept of pollution discharge rights [6]. However, when the available resources within a watershed are limited and each region strives to maximize its interests, conflicts between administrative regions become inevitable. How to balance the interests and minimize the conflicts is essentially a game question, which remains a challenge for water-related management in a basin [7–9].

As a long-term and complex game process, water security management in the basin involves multiple administrative regions. Within a basin, resources such as water, water environment carrying capacity, and hydraulic engineering facilities are limited [10,11]. These resources fall into the category of common-pool resources, characterized by scarcity, non-excludability, and rivalry [12,13]. Under such resource constraints, administrative entities within the basin may engage in continuous competition for resources, which can easily trigger conflicts of interest and lead to the "Tragedy of the Commons". Scholars have studied this problem based on multi-objective optimization, game theory, and other methods [14,15]. Game theory is a modeling approach that focuses on decision-making subject behavior and decision equilibrium problems from a mathematical perspective; it can better simulate conflicts of interest among different stakeholders and eventually obtain feasible solutions. Therefore, it has been widely used in water pollution control, water resource management, and water rights allocation. Rogers [16] was the first to use non-cooperative game theory to study water resource allocation problems in different regions of the Ganges River Basin. Kucukmehmetoglu [17] proposed a cross-border water resource allocation method based on non-cooperative game theory and Pareto frontier theory to solve the cross-border water resource allocation problem in the Euphrates and Tigris River basins. This method primarily involves using a non-cooperative game theory approach with rational constraints to search for feasible solutions located on the Pareto frontier. The goal is to find the optimal allocation of water resources among different countries within a basin. Wang et al. [18] constructed a cooperative game model for watershed water resource allocation under the premise of reasonable initial water rights allocation for water users and the existence of a water rights trading market and proposed an effective algorithm for an equilibrium solution based on the principle of fairness. Shi et al. [19] applied the concept of cooperative game theory to address transboundary basin water pollution issues. They analyzed the distribution of benefits among the game participants from the perspective of game theory and discussed the stability of cooperative games. Their findings suggest that differences in the marginal cost of pollutant reduction across regions are crucial in determining whether regions can collaborate effectively to prevent transboundary watershed pollution. Lin [20] established an optimization model for cross-border water pollution with upstream and downstream relationships based on Stackelberg's dynamic game theory. This model considered the reduction and transfer of pollutants in various regions to minimize environmental costs and maximize governance benefits. Roy and Bhaumik [21] constructed a matrix game model in a fuzzy environment where the payoff functions of the participants were represented by triangular Type-II intuitionistic fuzzy numbers. They then proposed a ranking function method to effectively solve this model. Finally, using this model, they focused on exploring management mechanisms for fair and equitable access to limited water resources. Both domestic and foreign scholars have studied the issues of initial water rights allocation, water pricing, and water rights trading markets from various perspectives based on game theory. These studies have yielded significant findings. However, due to the limitations of analytical methods, many of these results—particularly those derived from non-cooperative game models—are based on models with highly restrictive assumptions, followed by analyses of the equilibrium outcomes of these game models.

The evolutionary game model is an application of the game model to the evolution of organisms, which combines game analysis with a dynamic evolutionary process [22]. It can reflect the evolution of group size and strategy without requiring participants to have complete information and rationality; such advantages make the evolutionary game model more convenient and effective than the traditional models. As participants in a game can continuously adjust their strategies through learning and imitation, evolutionary game theory focuses on the exploration of equilibrium stability. The concept of an evolutionarily stable strategy (ESS) has thus become foundational. An ESS yields higher payoffs than any other non-stable strategy and is considered the dominant strategy for individuals [23]. In recent years, scholars have applied evolutionary game theory to water resources and ecology. Lu et al. [24] constructed a three-party evolutionary game model of water demand in the upper, middle, and lower reaches of a river basin and systematically explored the game equilibrium state and evolution trend between different regions. Mirzaei-Nodoushan et al. [25] proposed an evolutionary game method to analyze the long-term water resource-sharing strategy of riparian countries in a transboundary river basin over time. Numerical examples were used to illustrate the strategy change process generated by the evolutionary game process, and the impact of factors such as water use, economy, political gains, and socio-economic losses on strategy choices among riparian countries was elaborated in detail. Biancardi et al. [26] explored the evolutionary stability strategy of compliance and non-compliance of enterprises in groundwater exploitation based on the evolutionary game model and emphasized the importance of the government's active crackdown on illegal groundwater exploitation. Guo et al. [27] took the Aral Sea Basin as the research object, studied the multi-objective evolutionary game process and evolutionary stability strategy of water, energy, and food in the upstream and downstream countries, and analyzed the evolutionary stability strategy under the intervention of the basin committee. Shen et al. [28] took the local government and polluting enterprises in the Taihu Basin as the research object, established an evolutionary game model between local governments and polluting enterprises, and simulated the decision-making behavior and influencing factors of basin ecological compensation. Yuan et al. [29] established a dynamic differential game model of cross-basin pollution control composed of upstream and downstream governments and polluting enterprises and analyzed the changes in strategic choices of different stakeholders under cost sharing and non-cost sharing. The results showed that multiple stakeholders had interactive effects on the choice of governance strategies, and the proportion of cost-sharing and incentives affected the changes in the cooperation utility of upstream governments, downstream governments, and polluting enterprises. Satar Mahdevari et al. [30] took the Shahid gravel mine near the Kodan River in Alborz Province, Iran, as the research object and introduced regulatory factors such as government incentives and penalties into the evolutionary game model between the mining party and the government. Finally, a green mining principle implementation model for river sand and gravel resources was proposed.

Existing research has utilized stakeholder analysis and evolutionary game theory models to reveal the conflicts and negotiation processes between upstream and downstream entities in the use of public resources. These studies have contributed valuable insights into the development of negotiation mechanisms and improved oversight systems. However, there are notable limitations. First, stakeholder analysis is often insufficiently systematic. The upstream–downstream game involves various aspects, including economic, social, ecological factors, and higher-level administrative management. Current research typically presents these issues in terms of overall utility, lacking attention to regional collaborative mechanisms that influence environmental governance strategies. This approach somewhat detaches from the reality of regional integration and collaboration. Second, evolutionary game models are frequently constructed simplistically and statically, assuming fixed and conflicting interests between upstream and downstream entities. This approach overlooks the deeper connections between administrative regions within a basin. Third, current research mainly focuses on collaborative water environment management, water resource allocation, and water rights integration, with an emphasis on defining stakeholders and constructing governance models. Despite the significance of flood control and drainage issues in a basin, there has been limited in-depth research on the integrated collaborative governance of flood control and drainage involving multiple stakeholders.

Therefore, this study selected the Demonstration Zone of Green and Integrated Ecological Development of the Yangtze River Delta (DZGIED) as the research domain. The DZGIED is composed of three separate administrative regions with complicated flooding conflicts. By analyzing the conflicts of interest among the administrative regions of the DZGIED from economic, social, and management perspectives and considering the dynamic and in-depth connections between upstream and downstream entities, this study develops a watershed strategy evolutionary game model to explore collaborative governance between upstream and downstream areas. This study aims to provide a theoretical basis and decision-making support for achieving balanced governance of flood control and drainage.

2. Study Domain and Conflicts of Interest

2.1. Study Domain

DZGIED is located in the plain river network area of the Yangtze River Delta, in the lower reaches of the Taihu Basin and the upper reaches of the Huangpu River (Figure 1). DZGIED encompasses the Qingpu District of Shanghai City, Wujiang District of Suzhou City, and Jiashan County of Jiaxing City, covering an area of 2413 km^2. The overall terrain of DZGIED is low, with ground elevation generally ranging from 2.5 to 4.0 m. DZGIED has numerous rivers and lakes, a rich water system, and strong hydraulic connections. The Wusong River in the northern part of the region and the Taipu River that runs through DZGIED are important flood discharge channels for Taihu. As a testing ground for China's institutional innovation and a region for sharing public services and infrastructure, DZGIED mainly focuses on planning management, ecological protection, land management, etc., explores effective integrated institutional arrangements, and strives to build a water ecological environment protection and restoration system of joint protection and governance and a comprehensive water management system for joint consultation and management.

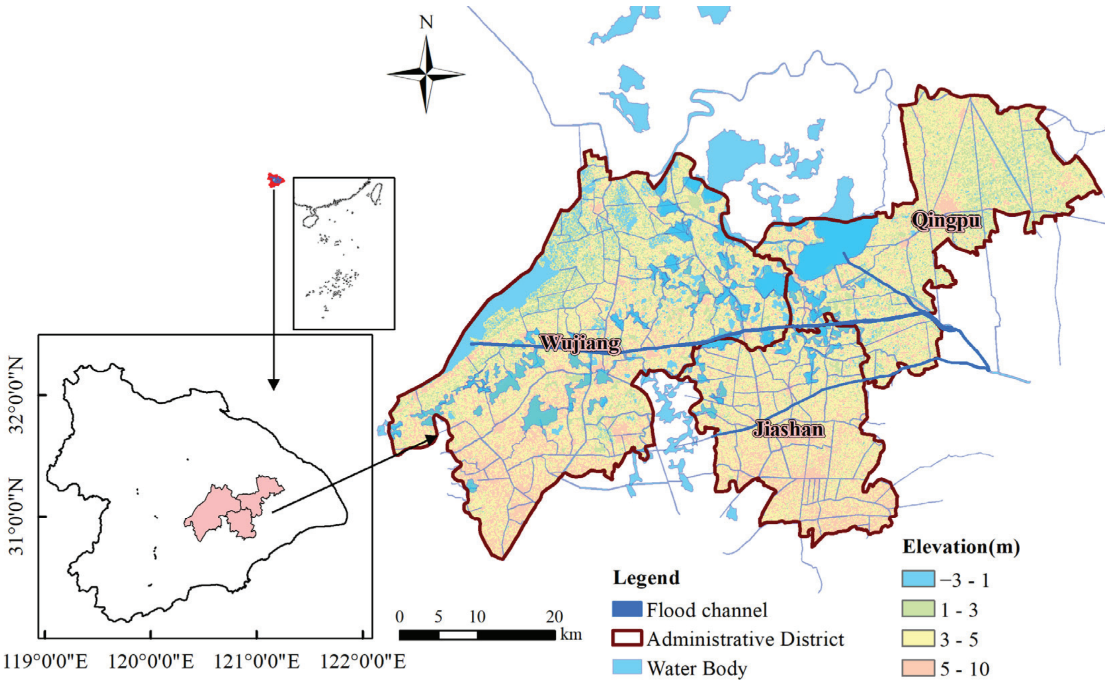

Figure 1. Geographical location, main flood channels, and administrative regions involved in DZGIED.

DZGIED is a plain tidal river network area. The rivers in the area are affected by downstream tides, upstream water, and surface runoff, making DZGIED one of the areas with the greatest flood pressure in the Taihu Basin. The floods in Taihu, as well as waterlogging in the Hangjiahu area and the Dianmao area, must be discharged into the

Huangpu River via the Taihu River, Hongqitang, and Lanlugang. Under the current conditions, the flood control standard in DZGIED is set for a 50-year return period. When cities enhance their drainage standards, this leads to an increase in water levels in the regional backbone rivers, thereby raising flood risks. Significant differences exist between upstream Wujiang District and downstream Jiashan County and Qingpu District in terms of socio-economic development and flood control and drainage standards. Specifically, Wujiang has a drainage standard set for a 20-year return period, Qingpu for 15 years, and Jiashan for approximately 10 years [31]. The overall drainage capacity in the downstream cities is inadequate, resulting in severe waterlogging [32]. As the drainage capacity in the downstream areas increases, it will inevitably heighten flood control pressure across the region, thereby reducing the drainage capacity available to Wujiang [33]. There are urgent conflicts and demands between the upstream and downstream areas due to flood control and drainage, as well as the utilization of water conservancy engineering resources, to alleviate urban flood pressure.

2.2. Conflicts of Interest for Flood Control and Drainage

Most of the flood control and drainage systems in the basin are built with state funding. Therefore, water conservancy projects, such as rivers and reservoirs, are owned by the state. From the perspective of the integrity of water conservancy project resources, water conservancy project resources are the common property of all regional entities in the basin and belong to the category of public pool resources. They are characterized by scarcity, non-exclusivity, and competitiveness [34]. Regional entities (provinces, cities, counties, etc.) upstream and downstream and on the left and right banks of the river can discharge water into the river. Currently, China has a territorial management system, which is manifested in the division of local administration. Local governments at all levels are responsible for local flood management matters [35]. In the basin, various areas are distributed along the river and have a certain geographical order, that is, upstream and downstream areas. The upstream, middle, and downstream areas and tributaries have similar geographical environments and hydraulic characteristics. Different geographical locations mean that the order of water discharge in each area is different. Due to its geographical advantage, the upstream area can discharge its water into the river before the downstream area. Once heavy rainfall is concentrated and the drainage demand of each area is large, each area upstream and downstream, on the left and right banks, and the main and tributary rivers will drain as much water as possible into the main river channels of the basin to reduce its flood pressure out of consideration for its interests. This may lead to the plundering and uncontrolled use of water conservancy project facilities such as rivers, resulting in a competitive drainage situation, causing “Overconsumption” and “Crowding effect”. This will generate negative externalities, which have a negative impact on drainage in other areas. At the same time, due to the large differences in the design methods of flood control and drainage standards between cities, there are also large differences in flood control and drainage capabilities between cities, which further increases the contradiction of drainage between cities.

Conflicts between upstream and downstream areas. The conflicts of interest between upstream Wujiang and downstream Qingpu and Jiashan of DZGIED can be divided into two situations. Firstly, when the flood control and drainage capabilities of Wujiang, Qingpu, and Jiashan are not coordinated, that is, the flood control and drainage capabilities of the more socio-economically developed areas are higher, while those of the less developed areas are lower. At this point, the interests of the developed areas in terms of flood control and drainage are ensured, while the interests of the underdeveloped areas are undermined, which leads to dissatisfaction among the local governments of the underdeveloped areas whose interests have been compromised, thereby generating hostility towards the developed local governments that have benefited. It will result in conflicts of interest between the developed and underdeveloped governments. Secondly, when the flood control and drainage capabilities of the cities in DZGIED are uniformly planned, that is, when the flood control and drainage capacity of the upstream Wujiang and the downstream Qingpu and Jiashan are coordinated, the three cities will drain as much water as possible into the river to reduce their losses from flood disasters based on their interests. At this point, the upstream areas rely on their geographical advantages; they will discharge regional flood water into the river at will. However, the downstream governments cannot discharge regional flood water into the river due to their geographical disadvantages, thus suffering from flood disasters and greater economic losses. Therefore, conflicts will arise between the upstream and downstream areas.

Interest demands between upstream and downstream areas. As a subsystem of the overall basin system, the upstream and downstream areas of the basin are responsible for local economic development, social stability, and flood control and drainage safety. Governments should not only execute the administrative instructions of the competent authorities of DZGIED but also take into account the social and economic development and flood control and drainage requirements of their respective areas. During the flood season, the interests of the upstream and downstream areas mainly include the following two points. Firstly, for their interests, the upstream and downstream areas will employ every possible means to drain water to alleviate their own flood control and drainage pressure and ensure that regional development is not or is less affected by flood disasters. Simultaneously, governments should implement the unified flood control and drainage standards formulated by the basin's competent authorities to avoid conflicts between regions and penalties from the authorities. Secondly, under the premise of formulating a fair and reasonable drainage rights allocation plan, the upstream and downstream areas should have global strategic thinking, take the overall interests as the starting point, and regulate their drainage behavior. Actively implement the relevant flood control and drainage plans formulated in a coordinated manner and drain water following reasonable drainage capacity under the supervision of the competent authorities of DZGIED. To reduce drainage conflicts between upstream and downstream areas, ensure the balance of basin interests, and promote overall harmonious development.

3. Game Analysis

3.1. Game Model Scenario Assumptions

Flood control and drainage design in cross-regional urban areas involves multiple administrative entities and multi-level departments. To fully account for the interests and relationships among these various entities, this study can draw on the application of evolutionary game theory in areas such as transboundary water pollution, collaborative governance, and multi-administrative water resource allocation [25,27,36]. By introducing a bidirectional compensation mechanism and an administrative reward and penalty mechanism, the basic assumptions for this study are established.

Rule 1: In the basin, cities are ranked according to their geographical locations and can be divided into upstream areas and downstream areas. In this study, Wujiang is located in the upstream area of DZGIED, while Jiashan and Qingpu are located in the downstream area of DZGIED, which is easily affected by the drainage of Wujiang. Therefore, in the game process, Jiashan and Qingpu formed a unified alliance to jointly deal with Wujiang's drainage strategy.

Rule 2: This evolutionary game model includes two types of trading groups, the upstream area Wujiang and the downstream area Jiashan-Qingpu Alliance (JQA). Since the two groups are limited by information and knowledge, they are both limited rational groups. Both groups pursue their interests. Firstly, the drainage plan set by the DZGIED management agency is reasonable. The strategy set by the upstream government is to limit the drainage capacity by bearing the regional flood pressure and to improve the drainage capacity based on the maximization of its interests (Reducing drainage capacity, Increasing drainage capacity). The probability that Wujiang takes the initiative to bear the regional flood pressure and limit the drainage capacity is p ($0 < p < 1$), and the probability of improving the drainage capacity according to the maximization of its interests is $1 - p$.

As an area that undertakes the flooding in the upstream area, JQA has a strategy set of not requiring Wujiang to limit the drainage capacity and requiring Wujiang to limit the drainage capacity, that is, (Non-conflict, Conflict). The probability that JQA does not require the upstream area to limit the drainage capacity is q ($0 < q < 1$), and the probability of requiring the drainage capacity of Wujiang to be limited is $1 - q$.

Rule 3: The water capacity of the river is fixed, and the drainage capacity of each region is fair and reasonable. The different levels of socio-economic, environmental, and ecological development in different areas result in different marginal benefits per unit of drainage. Therefore, the marginal benefit per unit of drainage in Wujiang is x, and that in JQA is y.

Rule 4: When Wujiang chooses to reduce its drainage capacity while ensuring its safety, JQA chooses the "Conflict" strategy. To reduce the flood pressure within the region and improve the drainage capacity within JQA, JQA causes a conflict with Wujiang, resulting in a conflict cost. The conflict cost of JQA is F_1. Wujiang reduces its drainage capacity, resulting in a reduction in JQA flood control pressure, so the benefit JQA obtains is M. Assuming that Wujiang accepts the conflict, JQA can increase the drainage power of Q units, and the benefit obtained by JQA is $M + yQ$. Since JQA caused a conflict with Wujiang, it is necessary to compensate Wujiang, and the compensation amount is B. Wujiang suffered a certain loss Qx due to the conflict caused by JQA.

Rule 5: When Wujiang chooses to reduce its drainage capacity while ensuring its safety and JQA chooses the 'Non-conflict' strategy, JQA gains M, and Wujiang gains 0.

Rule 6: When Wujiang chooses to continue to improve its drainage capacity, and JQA chooses the "Non-conflict" strategy, Wujiang can obtain Q more drainage units, and the income obtained is Qx. Due to the increased flood control pressure of Wujiang, JQA has to limit its drainage capacity, and the loss it suffers is Qy. At the same time, Wujiang needs to pay a certain amount of compensation to JQA, which is C.

Rule 7: When Wujiang chooses to continue to improve its drainage capacity, and JQA chooses the "Conflict" strategy, both sides have a 50% chance of winning the conflict caused by Wujiang's increase in drainage capacity and increasing their respective drainage capacities. Therefore, the potential benefit of Wujiang is $\frac{1}{2}Qx$, and the cost of causing conflict with JQA is F_2. The potential benefit of JQA is $\frac{1}{2}Qy$, and the cost of causing conflict with Wujiang is F_1.

Rule 8: Based on the intervention of the DZGIED management agency, a corresponding reward and punishment mechanism is proposed. That is, if any city in DZGIED adopts a cooperative strategy (i.e., the corresponding "Reducing drainage capacity" and "Non-conflict"), the DZGIED management agency will reward it; otherwise, it will be punished, and the amounts of reward and punishment are G and T, respectively.

The specific parameter meanings are shown in Table 1.

Table 1. Description of relevant parameters of the game model.

Parameter	Illustrate
q	The probability that JQA does not require Wujiang to limit its drainage capacity is q ($0 < q < 1$).
p	The probability that Wujiang will take the initiative to bear the regional flood pressure and limit its drainage capacity is p ($0 < p < 1$).
F_1	Conflict costs incurred by JQA due to conflicts.
F_2	The conflict costs incurred by the conflict caused by increasing drainage capacity in Wujiang.
M	The flood control benefit obtained by JQA due to Wujiang's reduced drainage capacity is M.
x	Marginal benefits of unit drainage capacity change in Wujiang.
y	Marginal benefits of unit drainage capacity change in JQA.
Q	The drainage power of Wujiang to increase drainage capacity, and the drainage power obtained by JQA causing conflict.

Table 1. *Cont.*

Parameter	Illustrate
B	Compensation to Wujiang when conflicts arise between JQA.
C	Wujiang increases drainage capacity to compensate for JQA.
G	Rewards from management agencies when cities in DZGIED adopt cooperative strategies (i.e., "Reducing drainage capacity" and "Non-conflict").
T	Penalties from management agencies for non-cooperative strategies (i.e., "Increasing drainage capacity" and "Conflict").

According to the above rule design and parameter setting, different profit matrices of Wujiang and JQA under different behavior strategy selections can be obtained, as shown in Table 2.

Table 2. Game profit matrix of flood control and drainage between Wujiang and JQA in DZGIED.

	Wujiang Reduces Its Drainage Capacity (p)	**Wujiang Increases Drainage Capacity ($1-p$)**
JQA conflict ($1-q$)	JQA: $Qy+M-F_1-B-T$ Wujiang: $G+B-Qx$	JQA: $\frac{1}{2}Qy-F_1-T$ Wujiang: $\frac{1}{2}Qx-F_2-T$
JQA does not conflict (q)	JQA: $M+G$ Wujiang: G	JQA: $G+C-yQ$ Wujiang: $Qx-C-T$

3.2. Analysis of the Game Stability Strategy

The boundedly rational players will not make the best strategy choice at the beginning of the game, but in the continuous random game, the players will keep on learning the behavior strategies of the higher-yield players and constantly adjust their strategy choices to maximize their benefits. Therefore, the continuous learning and adjustment process is the process of the evolutionary game, and the final strategy choice is the equilibrium strategy of the evolutionary system.

3.2.1. Strategy Stability in JQA

The expected benefits of JQA when choosing the "Non-conflict" and "Conflict" strategies are U_{D1} and U_{D2}, respectively, and the overall average expected benefit is U_D, then:

$$U_{D1}=p(M+G)+(1-p)(G+C-Qy) \tag{1}$$

$$U_{D2}=p(Qy+M-F_1-B-T)+(1-p)(\frac{1}{2}Qy-F_1-T) \tag{2}$$

$$U_D=qU_{D1}+(1-q)U_{D2} \tag{3}$$

The replication dynamic equation of JQA is:

$$\begin{aligned} X(q)=\frac{dq}{dt} &= q(U_{D1}-U_D)=q(1-q)(U_{D1}-U_{D2}) \\ &= q(1-q)(p(\frac{1}{2}Qy+B-C)+G+C+F_1+T-\frac{3}{2}Qy) \end{aligned} \tag{4}$$

The first-order derivative of $X(q)$ can be obtained as:

$$X'(q)=(1-2q)(p(\frac{1}{2}Qy+B-C)+G+C+F_1+T-\frac{3}{2}Qy) \tag{5}$$

Let $X(q) = 0$, according to the replication dynamic equation, it can obtain $q^* = 0$ and $q^* = 1$ are two possible stable state points.

Firstly, when $p = p_0 = \frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, there exists $0 < \frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C} < 1$, at this time, for any $q \in [0, 1]$, there is always $X(q) = 0$. That is, any level of q in the range of $[0, 1]$ is a stable state. In this case, when Wujiang chooses the "Reducing drainage capacity" strategy with a probability of $p = p_0 = \frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, there is no difference in the benefits of JQA choosing the "Conflict" and "Non-conflict" strategies. At this time, all strategy choices are stable states for JQA.

When $p \neq p_0$, $q^* = 0$ and $q^* = 1$ are two possible system equilibrium points. According to the local stability analysis principle of differential equations, when $X(q) = 0$, $X'(q) < 0$, q is the local stable point of the system. There exists:

$$\begin{cases} X'(0) = (\frac{1}{2}p(Qy + B - C) + G + C + F_1 + T - \frac{3}{2}Qy) \\ X'(1) = -(\frac{1}{2}p(Qy + B - C) + G + C + F_1 + T - \frac{3}{2}Qy) \end{cases} \tag{6}$$

Secondly, when $p > p_0 = \frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, there exists $X'(0) > 0$, $X'(1) < 0$, so $q^* = 1$ is a system evolutionary stable strategy. When Wujiang chooses the strategy of "Reducing drainage capacity" at a level higher than $\frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, JQA gradually changes from the "Conflict" strategy to the "Non-conflict" strategy. The strategy of not having a drainage conflict with Wujiang is the evolutionarily stable strategy of JQA.

Thirdly, when $p < p_0 = \frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, there exists $X'(0) < 0$, $X'(1) > 0$, so $q^* = 0$ is the evolutionarily stable strategy of the system. When Wujiang chooses the strategy of "Reducing drainage capacity" at a level lower than $\frac{\frac{3}{2}Qy - C - F_1 - G - T}{\frac{1}{2}Qy + B - C}$, JQA gradually changes from the "Non-conflict" strategy to the "Conflict" strategy. The strategy that eventually conflicts with Wujiang in drainage is the evolutionarily stable strategy of JQA.

3.2.2. Strategy Stability in Wujiang

The expected returns of Wujiang when choosing the strategies of "Reducing drainage capacity" and "Increasing drainage capacity" are U_{U1} and U_{U2}, respectively, and the overall average expected return is U_U, then:

$$U_{U1} = q(G) + (1 - q)(G + B - Qx) \tag{7}$$

$$U_{U2} = q(Qx - C - T) + (1 - q)(\frac{1}{2}Qx - F_2 - T) \tag{8}$$

$$U_U = pU_{U1} + (1 - p)U_{U2} \tag{9}$$

The replication dynamic equation of Wujiang is:

$$\begin{aligned} Y(p) = \frac{dp}{dt} &= p(U_{U1} - U_U) = p(1-p)(U_{U1} - U_{U2}) \\ &= p(1-p)[q(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx] \end{aligned} \tag{10}$$

The first-order derivative of $Y(p)$ can be obtained as:

$$Y'(p) = (1-2p)[q(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx] \tag{11}$$

Let $Y(p) = 0$, according to the replication dynamic equation, we can obtain $p^* = 0$ and $p^* = 1$ are two possible stable state points.

Firstly, when $q = q_0 = \frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, there exists $0 < \frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2} < 1$, at this time, for any $p \in [0,1]$, there is always $Y(p) = 0$, that is, any level of p in the range of [0, 1] is a stable state. In this case, when JQA chooses the "Non-conflict" strategy with a probability of $q = q_0 = \frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, there is no difference in the benefits of Wujiang choosing the two strategies of "Reducing drainage capacity" and "Increasing drainage capacity". At this time, all strategy choices are stable for Wujiang.

When $q \neq q_0$, $p^* = 0$ and $p^* = 1$ are two possible system equilibrium points. According to the local stability analysis principle of differential equations, when $Y(p) = 0$, $Y'(P) < 0$, p is the local stable point of the system. There exists:

$$\begin{cases} Y'(0) = [q(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx] \\ Y'(1) = -[q(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx] \end{cases} \tag{12}$$

Secondly, when $q < q_0 = \frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, there exists $Y'(0) > 0$, $Y'(1) < 0$, so $p^* = 1$ is a stable strategy for the system evolution. When JQA chooses the "Non-conflict" strategy at a level higher than $\frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, Wujiang gradually shifts from the "Increase drainage capacity" strategy to the "Reducing drainage capacity" strategy. Finally, the "Reducing drainage capacity" strategy is the evolutionarily stable strategy of Wujiang.

Thirdly, when $q > q_0 = \frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, there exists $Y'(0) < 0$, $Y'(1) > 0$, so $p^* = 0$ is the evolutionarily stable strategy of the system. When JQA chooses the "Non-conflict" strategy at a level lower than $\frac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}$, Wujiang gradually shifts from the "Reducing drainage capacity" strategy to the "Increasing drainage capacity" strategy. Finally, the "Increasing drainage capacity" strategy is the evolutionarily stable strategy of Wujiang.

3.2.3. Strategy Stability in Wujiang and JQA

In the dynamic evolutionary game between Wujiang and JQA, $\left(\dfrac{\frac{3}{2}Qx - B - F_2 - G - T}{\frac{1}{2}Qx + C - B - F_2}, \dfrac{\frac{3}{2}Qy - B - F_1 - G - T}{\frac{1}{2}Qy + B - C}\right)$ is a threshold for the change of structural evolution characteristics. When the strategies of both parties in the game are close to this threshold, any slight change in the strategy of either party will cause the strategy of the other party to change.

Formula (1) and Formula (7) constitute a dynamic replication system of the evolutionary game between the JQA and Wujiang. The local equilibrium point stability of this system has five possible evolutionary stable equilibrium points: (0,0), (0,1), (1,0), (1,1), and (q_0, p_0). The Jacobian matrix of this system is:

$$J = \begin{pmatrix} \frac{\partial X(q)}{\partial q} & \frac{\partial X(q)}{\partial p} \\ \frac{\partial Y(p)}{\partial q} & \frac{\partial Y(p)}{\partial p} \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix}$$
$$= \begin{pmatrix} (1-2q)(p(\frac{1}{2}Qy + B - C) + G + C + F_1 + T - \frac{3}{2}Qy) & q(1-q)(\frac{1}{2}Qy + B - C) \\ p(1-p)(\frac{1}{2}Qx + C - B - F_2) & (1-2p)[q(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx] \end{pmatrix} \tag{13}$$

The determinant and trace of the matrix are:

$$\begin{cases} \det.J = a_{11}a_{22} - a_{12}a_{21} = \frac{\partial X(q)}{\partial q}\frac{\partial Y(p)}{\partial p} - \frac{\partial X(q)}{\partial p}\frac{\partial Y(p)}{\partial q} \\ \text{tr}.J = a_{11} + a_{22} = \frac{\partial X(q)}{\partial q} + \frac{\partial Y(p)}{\partial p} \end{cases} \tag{14}$$

Since the five possible local equilibrium points of the replicated dynamic equation are not necessarily the stable equilibrium points of the system, the local stability of the Jacobian matrix should be analyzed to determine whether the possible local equilibrium point is the stable equilibrium point of the system. When there is a game strategy combination that satisfies: $\det.J > 0$ and $\text{tr}.J < 0$, the game strategy combination is a stable strategy for the evolutionary game. Table 3 shows the values of $\det.J > 0$ and $\text{tr}.J < 0$ at possible equilibrium points in the game between the Wujiang and JQA. It can be seen from Table 3 that at point (q_0, p_0), $\text{tr}.J = 0$. So (q_0, p_0) did not meet the stable strategy conditions, so the possible local equilibrium point (q_0, p_0) is not the system's evolutionary stable strategy.

Table 3. The values of det.J and tr.J in the game between Wujiang and JQA at possible equilibrium points.

Balance Point	det.J	tr.J
O (0,0)	$(G + C + F_1 + T - \frac{3}{2}Qy)(G + B + F_2 + T - \frac{3}{2}Qx)$	$(G + C + F_1 + T - \frac{3}{2}Qy) + (G + B + F_2 + T - \frac{3}{2}Qx)$
A (1,0)	$\left[-(G + C + F_1 + T - \frac{3}{2}Qy)\right](G + C + T - Qx)$	$\left[-(G + C + F_1 + T - \frac{3}{2}Qy)\right] + (G + C + T - Qx)$
B (1,1)	$[-(G + B + F_1 + T - Qy)] \cdot [-(G + C + T - Qx)]$	$[-(G + B + F_1 + T - Qy)] + [-(G + C + T - Qx)]$
C (0,1)	$(G + B + F_1 + T - Qy) \cdot \left[-(G + B + F_2 + T - \frac{3}{2}Qx)\right]$	$(G + B + F_1 + T - Qy) + \left[-(G + B + F_2 + T - \frac{3}{2}Qx)\right]$
$D(q_0, p_0)$	$(1 - 2q_0)(p_0(\frac{1}{2}Qy + B - C) + G + C + F_1 + T - \frac{3}{2}Qy) \cdot (1 - 2p_0)[q_0(\frac{1}{2}Qx + C - B - F_2) + G + B + F_2 + T - \frac{3}{2}Qx]$	0

3.3. Simulation Analysis of the Strategy Evolution

The specific determination results of the system stability points of the evolutionary game are shown in Table 4. As can be seen from Table 4, there are merely four system stability points in the evolutionary game, indicating that there are four situations in which the flood control and drainage strategies of the Wujiang and JQA can be coordinated with each other. According to the stability analysis and judgment of the evolutionary game, the evolutionary simulation is carried out using Matlab R2019b software to explore the mutual changes between the strategy choices of the upstream and downstream areas based on the stability results. The results are shown in Figure 2.

Table 4. Analysis of system stability points in the game between Wujiang and JQA.

Balance Point	Scene	det.*J* Symbol	tr.*J* Symbol	In Conclusion
(0,0)	$G + C + F_1 + T - \frac{3}{2}Qy < 0$, $G + B + F_2 + T - \frac{3}{2}Qx < 0$	+	−	*ESS*
	$G + C + F_1 + T - \frac{3}{2}Qy > 0$, $G + B + F_2 + T - \frac{3}{2}Qx > 0$	+	+	Unstable
	$G + C + F_1 + T - \frac{3}{2}Qy > 0$, $G + B + F_2 + T - \frac{3}{2}Qx < 0$	−	±	Saddle Point
	$G + C + F_1 + T - \frac{3}{2}Qy < 0$, $G + B + F_2 + T - \frac{3}{2}Qx > 0$	−	±	Saddle Point
(0,1)	$G + B + F_1 + T - Qy < 0$, $-(G + B + F_2 + T - \frac{3}{2}Qx) < 0$	+	−	*ESS*
	$G + B + F_1 + T - Qy > 0$, $-(G + B + F_2 + T - \frac{3}{2}Qx) > 0$	+	+	Unstable
	$G + B + F_1 + T - Qy > 0$, $-(G + B + F_2 + T - \frac{3}{2}Qx) < 0$	−	±	Saddle Point
	$G + B + F_1 + T - Qy < 0$, $-(G + B + F_2 + T - \frac{3}{2}Qx) > 0$	−	±	Saddle Point
(1,0)	$-(G + C + F_1 + T - \frac{3}{2}Qy) < 0$, $G + C + T - Qx < 0$	+	−	*ESS*
	$-(G + C + F_1 + T - \frac{3}{2}Qy) > 0$, $G + C + T - Qx > 0$	+	+	Unstable
	$-(G + C + F_1 + T - \frac{3}{2}Qy) > 0$, $G + C + T - Qx < 0$	−	±	Saddle Point
	$-(G + C + F_1 + T - \frac{3}{2}Qy) < 0$, $G + C + T - Qx > 0$	−	±	Saddle Point
(1,1)	$-(G + B + F_1 + T - Qy) < 0$, $-(G + C + T - Qx) < 0$	+	−	*ESS*
	$-(G + B + F_1 + T - Qy) > 0$, $-(G + C + T - Qx) > 0$	+	+	Unstable
	$-(G + B + F_1 + T - Qy) > 0$, $-(G + C + T - Qx) < 0$	−	±	Saddle Point
	$-(G + B + F_1 + T - Qy) < 0$, $-(G + C + T - Qx) > 0$	−	±	Saddle Point
(q_0, p_0)	none	+	0	Center

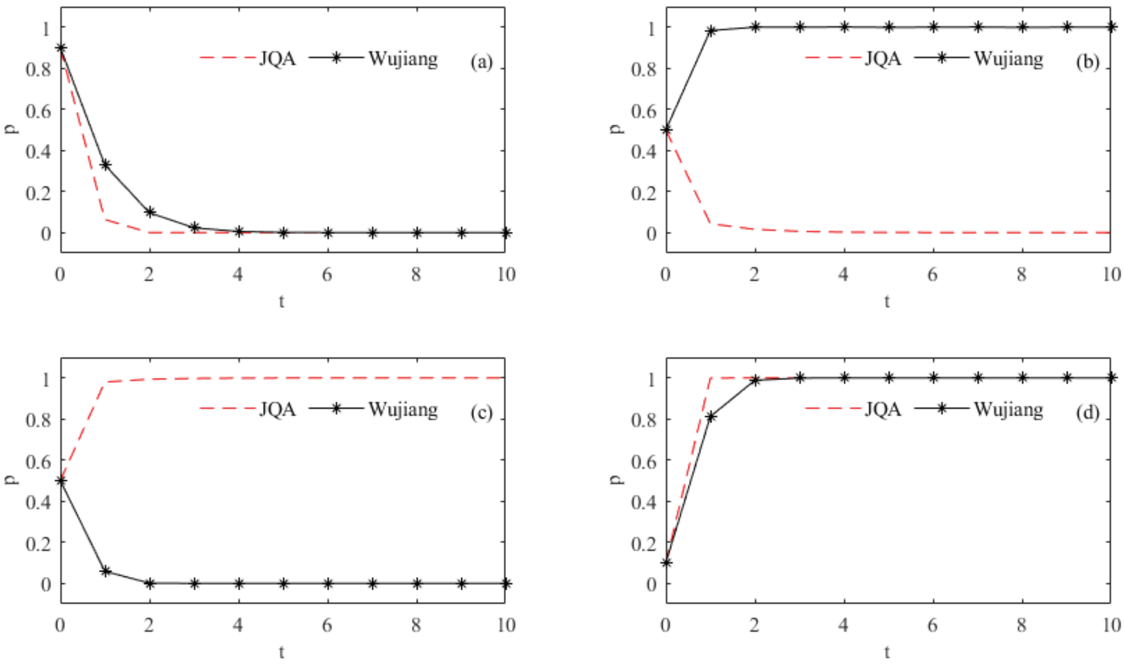

Figure 2. Evolution results of the four system stability strategies in Wujiang and JQA. (**a**). result of the equilibrium point *O* (0,0); (**b**). result of the equilibrium point *A* (0,1); (**c**). result of the equilibrium point *B* (1,0); (**d**). result of the equilibrium point *C* (1,1).

Case 1: At the equilibrium point *O* (0,0), when $G + C + F_1 + T - \frac{3}{2}Qy < 0$, $G + B + F_2 + T - \frac{3}{2}Qx < 0$, the system is in an evolving stable state. When Wujiang chooses the strategy of "Increasing drainage capacity", JQA's flood risk increases due to the increase in Wujiang's drainage capacity. Since the compensation from Wujiang to JQA, the cost of JQA's conflict choice, and the sum of rewards and penalties from the management agency are less than the benefits obtained by JQA for opposing Wujiang's increase in drainage capacity, JQA tends to choose the strategy of "Conflict" with Wujiang. However, when JQA chooses the "Conflict" strategy with Wujiang, the sum of the conflict compensation for Wujiang caused by JQA, the cost of the conflict caused by JQA due to the increase in its drainage capacity, and the rewards and penalties from the management agency are less than the benefits obtained by Wujiang from increasing its drainage capacity, so Wujiang tends to choose the "Increase drainage capacity" strategy.

In this state, to pursue its interests and to reduce its own flood control and drainage pressure, Wujiang continuously increased its drainage capacity, causing the water level of the backbone river to rise and the flood pressure of JQA to increase. To ensure its flood control safety, JQA had to restrict its drainage. JQA was unwilling to be outdone and launched a resistance and clashed with Wujiang, demanding that Wujiang assume regional flood control responsibilities and limit drainage. At this time, since the beneficiary's compensation to the injured party was very small, it was insufficient to make up for the economic and environmental losses in the disaster-stricken areas. Moreover, the cost of increasing drainage capacity and conflicts caused by JQA in Wujiang is very low. At the same time, the benefits of Wujiang increasing its drainage capacity and causing conflicts with JQA were significant. Under such conditions, both parties would choose extreme ways to obtain benefits. In this situation, the regional flood control and drainage effectiveness is the worst. For the entire basin, the drainage conflicts between cities are intensifying, affecting the coordinated management of flood control and drainage between cities across regions.

Scenario 2: At the equilibrium point A (0,1), when $G + B + F_1 + T - Qy < 0$, $-(G + B + F_2 + T - \frac{3}{2}Qx) < 0$, the system is in an evolving stable state. When Wujiang chooses the strategy of "Reducing drainage capacity", the flood risk of JQA decreases due to the reduction in Wujiang's drainage capacity. At this time, since the sum of the rewards and punishments of the management agency to JQA, the compensation of JQA to Wujiang, and the cost of choosing to conflict is less than the benefits obtained by JQA continuing to require Wujiang to reduce its drainage capacity, JQA tends to choose the "Conflict" strategy. When JQA chooses the "Conflict" strategy with Wujiang, the sum of the rewards and punishments obtained by Wujiang from the management agency, the compensation caused by the "Conflict" caused by JQA, and the cost of the conflict caused by the increase in its drainage capacity is greater than the benefits obtained by Wujiang to increase its drainage capacity, Wujiang tends to choose the "Reducing drainage capacity" strategy. At this time, the stable point of the system is (0,1)

In this state, after JQA triggers a conflict, the flood pressure on JQA is reduced, thereby obtaining huge flood control benefits and thus causing conflicts with Wujiang. At this time, the cost of the conflict caused by JQA and the compensation to the Wujiang area are both low, which further prompts JQA to continuously demand that Wujiang reduce its drainage capacity. After the conflict initiated by JQA, Wujiang has a high cost of confronting JQA and can obtain certain compensation from JQA, which is enough to make up for the flood losses caused by the reduction in drainage capacity. At the same time, Wujiang will gain little benefit by increasing its drainage capacity. Therefore, Wujiang will not confront JQA, and choose the strategy of "Reducing drainage capacity". However, in this state, JQA will unrestrictedly require Wujiang to reduce its drainage capacity. For the entire basin, it will cause a serious imbalance in drainage capacity between cities, affecting the integrated and coordinated development of regional flood control and drainage.

Scenario 3: At the equilibrium point B (1,0), when $-(G + C + F_1 + T - \frac{3}{2}Qy) < 0$, $G + C + T - Qx < 0$, the system is in an evolving stable state. When Wujiang chooses the strategy of "Increasing drainage capacity", JQA will face an increased flood risk due to the increase in Wujiang's drainage capacity. Since the sum of the management agency's rewards and punishments on JQA, Wujiang's compensation to JQA, and the cost of JQA's choice of conflict is greater than the benefits obtained by JQA from opposing Wujiang's increase in drainage capacity, JQA tends to choose the "Non-conflict" strategy. When JQA chooses the "Non-conflict" strategy with Wujiang, the sum of Wujiang's compensation to JQA due to its increase in drainage capacity and the management agency's rewards and punishments on Wujiang is less than the benefits obtained by Wujiang's increase in drainage capacity, so Wujiang tends to choose the "Increase drainage capacity" strategy. At this time, the stable point of the system is (1,0).

Under this state, to alleviate its own flood control and drainage pressure, Wujiang continuously increased its drainage capacity, causing the water level of the backbone river to rise, and obtained greater flood control and drainage benefits. The cost of JQA causing conflicts with Wujiang is high, which hinders the motivation of JQA to conflict with Wujiang. At the same time, after Wujiang increases its drainage capacity, considering the regional flood disaster losses, out of social responsibility, Wujiang will give JQA considerable economic compensation to make up for the economic and environmental losses suffered by JQA. Therefore, JQA tends not to fight back against Wujiang's behavior of increasing drainage capacity. At this time, the effect of regional flood control and drainage coordinated governance is poor. Because Wujiang unscrupulously increases its drainage capacity, it affects the flood safety of JQA while obtaining greater benefits, while JQA relies solely on the compensation of Wujiang to make up for the huge losses caused by flood disasters. For the entire basin, it will cause a serious imbalance in flood control and drainage capacity among cities, affecting the integrated and coordinated development of regional flood control and drainage.

Scenario 4: At the equilibrium point C (1,1), when $-(G + B + F_1 + T - Qy) < 0$, $-(G + C + T - Qx) < 0$, the system is in an evolving stable state. When Wujiang chooses the strategy of "Reducing drainage capacity", the flood risk of JQA decreases due to the reduction in Wujiang's drainage capacity. At this time, since the sum of the costs of the downstream alliance's compensation to Wujiang, the conflict caused by JQA's choice, and the management agency's rewards and punishments on JQA is greater than the benefits obtained by JQA continuing to require Wujiang to reduce its drainage capacity, JQA tends to choose a "Non-conflict" strategy. When JQA chooses the "Non-conflict" strategy, the sum of the cost of Wujiang's compensation to JQA due to increased drainage capacity and the cost of the management agency's reward and punishment of Wujiang is greater than the benefit obtained by Wujiang's increased drainage capacity, Wujiang tends to choose the "Reducing drainage capacity" strategy. At this time, the stable point of the system is (1,1).

In this state, the cost of causing conflict for JQA is huge, and causing conflict requires huge compensation to Wujiang, so JQA will not cause conflict with Wujiang. At this time, the compensation given to JQA by Wujiang for increasing drainage capacity is huge, and the benefits are also small, so Wujiang also tends to choose the strategy of "Reducing drainage capacity". In this state, the overall flood control and drainage effect of the region is the best because Wujiang actively assumes the responsibility of regional flood control and drainage. From the perspective of the whole region, Wujiang reduces its drainage capacity and reduces the flood pressure of JQA. At the same time, JQA also actively assumes the responsibility of regional flood control and drainage, which will not cause regional flood control and drainage conflicts. This strategy promotes integrated and coordinated management of regional flood control and drainage.

4. Collaborative Governance Strategy

The above analysis reveals that the marginal benefits of flood control and drainage for both parties, the costs of conflict (F_1 and F_2), the compensation (B and C) provided by the party causing the conflict, the additional flood control and drainage benefits gained by the conflicting parties, and the rewards (G) and penalties (T) imposed by DZGIED's management on the choices of both parties (such as "Reducing drainage capacity" versus "Non-conflict" or "Increasing drainage capacity" versus "Conflict") are the main factors influencing the strategic behavior of the upstream Wujiang and the downstream JQA. This is similar to the findings of Shi Guangming et al. [19,28,29], who identified that differences in marginal pollutant reduction costs and conflict compensation costs are key factors in determining whether regions can collaborate to prevent transboundary watershed pollution. Therefore, the collaborative governance of urban flood control and drainage in the Demonstration Zone can be approached from the following perspectives:

(1) Unified planning and management of DZGIED, along with the coordinated integration of urban flood control and drainage planning within DZGIED

Firstly, the intervention by the DZGIED management agency can facilitate overall management, coordination, and guidance. Additionally, it can provide a negotiation platform to foster coordinated cooperation between the upstream Wujiang and the downstream Jiashan and Qingpu. Secondly, the DZGIED management agency and the Taihu Basin Authority of Ministry of Water Resources should fully leverage their roles in basin flood control and drainage management. Establishing a consultation system and promoting equitable dialogue between upstream and downstream areas will facilitate effective communication and collaboration. Overall coordination of flood control and drainage planning between upstream and downstream can effectively coordinate the contradiction of inconsistent flood control and drainage needs in Wujiang, Jiashan, and Qingpu. At the same time, it is necessary to further rationally adjust the layout of flood control and drainage projects in Wujiang, Jiashan, and Qingpu, clarify the flood control and drainage capabilities and needs of each region under the current conditions, and make unified and coordinated planning for the layout and capabilities of flood control and drainage projects in upstream and downstream areas.

(2) Enhance the reward and punishment mechanism to incentivize the cities in DZGIED to cooperate.

As an external driving force, the incentive and constraint policy form a policy mechanism with well-defined rewards and punishments, which fully mobilizes the enthusiasm and initiative of Wujiang, Jiashan, and Qingpu to enhance cooperation and protection in flood control and drainage across the regions. Based on the results of the game analysis, the intensity of incentives and constraints can be adjusted to balance the flood disaster losses caused by the reduction in drainage capacity in Wujiang and reduce the pressure of compensation payment for the increase in drainage capacity in Jiashan and Qingpu to Wujiang. Therefore, the DZGIED management agency actively explores the implementation of the reward and punishment mechanisms of "Rewarding positive compensation" and "Punishing negative compensation". Under the reward mechanism, on the one hand, Wujiang is rewarded for actively assuming the regional flood control and drainage responsibilities and sharing the regional flood pressure. This can alleviate the losses caused by flood disasters in Wujiang due to bearing regional flood pressure and ensure the enthusiasm and stability of Wujiang to actively bear flood pressure. On the other hand, Jiashan and Qingpu are rewarded for actively participating in the work of regional flood control and drainage integrated management. This can reduce the flood pressure caused by the current insufficient drainage capacity in Jiashan and Qingpu. Under the penalty mechanism, if the upstream Wujiang fails to actively assume the responsibility of regional integrated flood control and drainage management and chooses to continue to increase its drainage capacity, thereby increasing the flood control pressure on JQA and even the entire DZGIED. Or if the downstream Jiashan and Qingpu fail to actively follow the DZGIED management department to reasonably set up the local flood control and drainage capabilities, resulting in unbalanced development of upstream and downstream flood control and drainage capabilities. The DZGIED management agency shall impose penalties on the upstream and downstream areas. The funds obtained shall be used for the construction of flood control and drainage projects in DZGIED.

(3) Introducing an internal equilibrium mechanism and a two-way compensation mechanism between cities.

As an internal coordination mechanism for upstream and downstream cooperation, the compensation mechanism can effectively make up for the economic losses caused by the reduction in drainage capacity in Wujiang and the flood losses caused by Wujiang drainage in JQA. It is beneficial for resolving the conflicts of interest between upstream and downstream areas. Therefore, the DZGIED management agency, based on the principle of "Who benefits, Who pays", determines a reasonable compensation subject through consultation among the cities in DZGIED. It determines the compensation basis based on the layout of flood control and drainage projects in DZGIED and the current socio-economic conditions. Taking into account the cost of flood losses in the upstream Wujiang and the downstream Jiashan and Qingpu to calculate scientifically reasonable compensation standards. In terms of compensation methods, provide diversified compensation methods such as technical compensation and physical compensation in addition to economic compensation.

5. Conclusions

By analyzing the interests of the upstream Wujiang and the downstream Jiashan and Qingpu, an evolutionary game model of flood control and drainage between upstream and downstream areas was constructed to explore the factors that affect the behavioral strategies of areas in the process of allocating flood control and drainage capacity. The main conclusions are as follows:

(1) Based on the game stability analysis, the strategy of the two parties in the game changes according to the strategy of the other. Five elements, namely the cost of conflict, the compensation of one party to the other, the additional benefits obtained

by the two parties, the reward for the choices, and the punishment for the choices, are the main factors affecting the behavioral strategy of Wujiang and JQA.

(2) The strategies of both parties will evolve towards those that are beneficial to themselves, thereby maximizing each party's interest. To promote the game model towards a stable strategy (Reducing drainage capacity, Non-conflict), a reasonable two-way compensation mechanism and reward and punishment mechanism should be established. It can share the losses caused by the assumption of flood pressure upstream and alleviate the compensation pressure downstream.

(3) The collaborative management strategy for flood control and drainage is proposed: for the external part, the agency of DZGIED is responsible for coordinating the conflicts; for the downstream and upstream, it should implement incentive and constraint policies with clear rewards and punishments; for the internal part, a two-way compensation mechanism should be established to compensate for the economic losses caused by the imbalanced capabilities of both parties.

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water

Article

Decoupling Agricultural Grey Water Footprint from Economic Growth in the Yellow River Basin

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Abstract: Decoupling agricultural economic growth from agricultural water pollution is of great importance to regional sustainable development. It is necessary to further explore the decoupling state and key driving factors connecting agricultural water pollution and agricultural economic growth on the basis of accurate measurement of agricultural water pollution. Accordingly, taking the Yellow River Basin (YRB) as the research object, this study combined the water footprint theory, the Logarithmic Mean Divisia Index (LMDI) model and the Tapio decoupling model (TDM) to conduct an in-depth decoupling analysis of the connection between the agricultural grey water footprint (AGWF) and agricultural economic growth in the YRB. Specifically, this study first calculated the AGWF of the YRB during 2016–2021 and objectively evaluated the water resource utilization in this region based on the AGWF. Then, the LMDI model was used to explore the driving factors of the AGWF in the YRB. Finally, the decoupling states between the AGWF and its driving factors with agricultural GDP (AGDP) were studied using the TDM. The main results are as follows: (1) The overall AGWF in the YRB showed a decreasing trend and a slow increase, decreasing by 5.39% in 2021 compared to 2016. (2) The primary promoting factor and inhibiting factor of AGWF reduction are the efficiency effect and agricultural economic effect, respectively. (3) The decoupling states of the AGWF and AGDP presented strong decoupling (SD) and then weak decoupling (WD) in the YRB during the research period. The decoupling states between the agricultural grey water footprint intensity (AGWFI) and AGDP changed from expansive negative decoupling (END) to SD. The decoupling state of population and AGDP remained SD. This study will contribute to alleviating agricultural water pollution in the YRB and help policymakers in water-stressed countries to formulate agricultural water management policies.

Keywords: agricultural water pollution; grey water footprint; economic growth; decoupling; Yellow River Basin

1. Introduction

Rapid economic growth, dramatic population expansion, and climate change have led to an exponential increase in water demand [1–3]. Globally, 1.5 billion people face severe and increasing water scarcity problems [4]. It is projected that this number will increase to 3.9 billion by 2050 [5]. Agricultural water occupies the highest proportion (70%) of freshwater resource utilization [6]. The leading cause of water pollution is agricultural non-point source pollution, which generates 75% of nitrogen-related global warming potential and 38% of phosphorus-related global warming potential [7–9]. More than 50% of nitrogen and phosphorus flows into water bodies due to inefficient use of fertilizers and pesticides [10]. The ineffective management of agricultural water pollution will result in a massive waste of resources and environmental damage. However, current studies have given little consideration to controlling pollutants produced by agricultural production [6,11]. With only 8% of the world's arable land and a quarter of the global average per capita water supply, China needs to feed about 20% of the world's population, which is also a considerable challenge [12]. Meanwhile, China's agriculture has not fully realized large-scale operation, with low production efficiency and slow progress in adopting agricultural technology [13]. In this context, China can only continue to overuse fertilizers and pesticides to provide more food, becoming the fastest-growing country in the world for agrochemicals [14]. At the same time, animal husbandry aggravates agricultural grey water in China [15].

To quantitatively analyze water pollution, scholars put forward the grey water footprint, defined as the amount of polluted water diluted and managed to standard water quality according to natural concentration and current environmental water quality standards [16]. Researchers have recognized the need to manage and evaluate water resources by measuring the grey water footprint [17,18]. Regarding the measurement of agricultural water pollution, scholars either set up macroscopic hydrological models to conduct overall measurement analysis of agricultural grey water [7,11] or select only a few indicators to analyze the changing trend of water pollution [10,19,20]. In most of the published studies, the grey water footprint has been ignored or only partially considered because of the complexity of its calculation and the difficulty of its estimation due to the lack of data [21]. Although some studies can grasp the changes in agricultural grey water footprint, few of them have made accurate measurements of agricultural grey water footprint. In terms of driving factors of the agricultural grey water footprint (AGWF), scholars generally use the formula in the Water Footprint Assessment Manual [16] to calculate the AGWF more accurately from the two aspects of planting and breeding [15,18,22]. Still, more in-depth analyses of the specific factors that significantly impact the AGWF are needed. Therefore, some researchers introduced the Logarithmic Mean Divisia Index (LMDI) model to conduct in-depth studies of agricultural GDP (AGDP) driving factors [23,24]. Using the LMDI model for factor decomposition can avoid the impact of residual and zero values on the results, and it is a universally adaptable research method [25]. The LMDI model has been widely used in water resources and the environment. Zhang et al. utilized the LMDI model to explore the factor of AGWF decomposition in the midstream of the Heihe River from 1991 to 2015 only from the perspective of the planting industry [26]. Through the LMDI model, it was discovered that agricultural economic effect became the most critical factor in enhancing the AGWF efficiency [27]. In addition, it was found that AGDP and the intensity of the AGWF exerted the most significant promoting and inhibiting effects upon AGWF change in China, respectively [6]. According to the Sustainable Development Goals (SDGs), decoupling resources and environmental pressures from economic growth is integral. Although the LMDI model can identify the driving factors affecting the change in water resources, it cannot quantitatively measure the decoupling state between economic growth and water consumption.

China's rapid agricultural modernization has been accompanied by continued growth in economic output, water resource use and environmental pressures, and water resources and economic growth are quite related [28]. There are some existing studies that applied the Gini coefficient method, the imbalance index method, and other methods to research the relationship between water resources and the economy [28]. For example, Peng et al. applied the water footprint calculation model VAR and co-integration models in their study to find the correlation between water resources and economic growth [29]. Since water pollution and scarcity significantly impact agricultural economic growth, which can cause environmental damage, it is critical to decouple the agricultural grey water footprint from economic growth [30]. Decoupling theory is a related theory applied to physics to illustrate that the mutual correlation between two or more physical quantities decreases or no longer exists. In 2005, Tapio analyzed the relationship between the transportation sector and GDP from 1970 to 2001, and decoupling elasticity was proposed [31]. The Organization for Economic Co-operation and Development (OECD) first used the decoupling theory to discuss the correlation between environmental quality and economic development [32]. It defined "decoupling" as the rupture of the coupling relationship between ecological quality change and economic progress. It believed that decoupling broke the connection between environmental pressure and financial performance and put forward the conceptions of relative and absolute decoupling. Gradually, scholars began to use Tapio decoupling analysis to discuss the decoupling relationships between water resources, ecological environment and economic progress [1,33,34]. Tao adopted the decoupling theory to study the relationship between water resource utilization and economic development in Beijing [35]. Wang et al. also conducted the decoupling theory to study a decomposition analysis of decoupling from water use and economic growth in 31 regions of China [36]. In addition, the Tapio decoupling model (TDM) was adopted to detect the correlation between carbon emissions and agricultural economic progress [37]. Subsequently, the LMDI method was combined with the TDM to study the relationships between resource reserves, energy and carbon emissions [38–41]. Few scholars have combined the LMDI and the TDM to conduct in-depth research on the AGWF in the YRB. Kong et al. employed LMDI and TDM to review changes in the water footprint within three provinces of China (Beijing, Tianjin and Hebei) [1]. However, a vast area is covered by the Yellow River Basin (YRB), and the basin faces additional intricate influencing factors.

To fill in the research gaps mentioned above, this paper takes the YRB as the research objective and combines the LMDI and TDM to conduct AGWF research in seven provinces and two regions in the YRB. The key contributions of our research include the following points: (1) The AGWF in the YRB during 2016–2021 was accurately estimated via crop farming and animal husbandry, and the trend of the AGWF was evaluated as a whole. (2) The LMDI model was adopted to quantitatively decompose and analyze the driving factors of the AGWF. (3) The TDM was introduced to dissect the decoupling state between the AGWF and AGDP in the YRB, and the decoupling relationship between AGWF driving factors and AGDP was discussed. The rest of this paper is organized as follows: Section 2 introduces the research areas, research approaches and data origins. Section 3 depicts the fundamental discoveries. A deep analysis and discussion regarding essential results are offered in Section 4. Conclusions are shown in Section 5, including main discoveries, suggestions and limitations.

2. Materials and Methods

The overall technical route flowchart of this paper is shown in Figure 1.

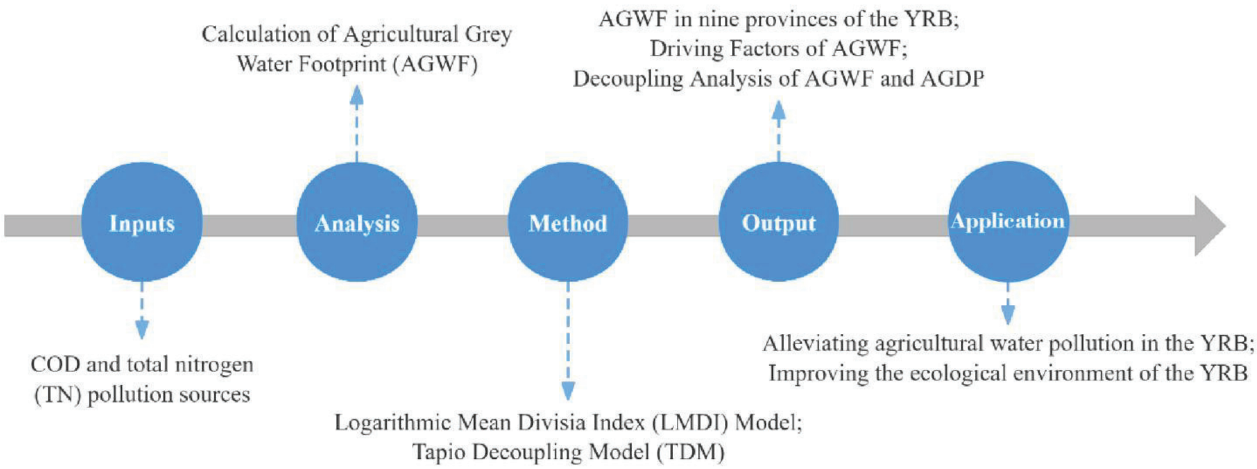

Figure 1. Technical route flowchart.

2.1. Study Area

The Yellow River is China's second longest river. It has a length of 5646 km and a drainage area of 79.5 billion m^3, occupying roughly 8% of China's total drainage regions. The YRB spans several provinces, most of which are arid regions and semi-arid regions. The mean annual precipitation of YRB ranges from 123 mm to 1021 mm with an increase from the northwest to the southeast [42]. The Yellow River flows through the following seven provinces and two regions: Qinghai, Sichuan, Gansu, Ningxia Hui Autonomous Region (referred to as Ningxia in the later text), Inner Mongolia Autonomous Region (Referred to as Inner Mongolia in the later text), Shaanxi, Shanxi, Henan and Shandong. The YRB has developed agriculture and flows through several grain production bases, crucial to ensuring China's food security. In 2021, the agricultural output value reached 2584.8 billion Chinese Yuan (CNY), contributing 33% of China's AGDP. However, the severe drought problem in the YRB is serious, and water resources have become scarce. Total water resources in the YRB account for roughly 2% of China's total water resources, and per capita water resources merely obtain 25% of the average. With limited water resources, the YRB irrigates 15% of Chinese cultivated land and feeds 8% of China's population [43]. Accordingly, agricultural progress in the YRB is over-reliant upon water resources. Additionally, agricultural water use efficiency is low [20]. In 2021, the total quantity of agricultural water within the YRB reached 11,588.4 m^3, occupying 66.26% of the total water, and 90% of the agricultural water was utilized to irrigate farmland. Still, only 39% of the farmland was effectively irrigated. At the same time, livestock production and the overuse of fertilizers and pesticides have caused the destruction of water resources in the research area, and low agricultural water use efficiency becomes the norm. In 2022, the productivity coefficients of farmland irrigation water in Shanxi, Sichuan, Qinghai, Inner Mongolia, and Ningxia were 0.543, 0.473, 0.499, 0.543 and 0.535, respectively. Additionally, the coefficients for these provinces and regions were lower than the national average amount of 0.554 [18]. There is a sense of urgency to enhance agricultural water use efficiency and decrease the agricultural grey water footprint of the YRB [44]. A map of the YRB is displayed in Figure 2.

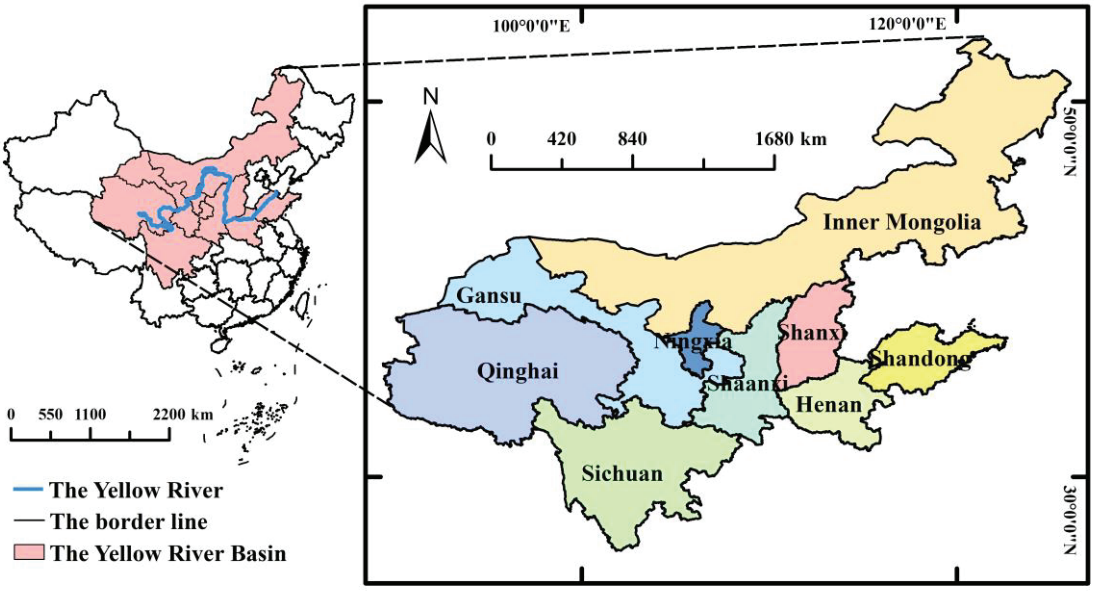

Figure 2. Map of the Yellow River Basin (YRB).

2.2. Methods

2.2.1. Agricultural Grey Water Footprint (AGWF)

To calculate the AGWF, the AGWF generated by farming and breeding should be considered [16,45]. Nitrogen fertilizer used in agriculture is the most critical factor of water pollution. Chemical Oxygen Demand (COD) is a major water pollutant in industrial discharges monitored by the Chinese government, according to publicly available discharge data [46]. The urine and feces produced by sheep, pigs, cattle and poultry include significant quantities of COD and total nitrogen (TN), constituting the primary origin of water pollution from breeding. This paper only considered the TN and COD produced by farming and breeding in the calculation of the AGWF to simplify the calculation process.

Likewise, it was assumed that the rearing cycle for pigs and poultry is less than one year and the rearing cycle for cattle and sheep was greater than one year; hence, the year-end slaughter quantity was adopted for pigs and poultry, and the year-end stock quantity was adopted for cattle and sheep. The river flow, utilization patterns, precipitation levels, and climate change in the YRB were variable between the years 2016 and 2021; however, these variables were not employed in the model of the paper and were, therefore, not considered. In this paper, the calculation formulas of the AGWF are referred to as defined in Kong et al. [6].

The specific formulas are listed below:

$$AGWF_{pla} = \frac{\partial \times Appl}{C_{TN,max} - C_{TN,nat}} \tag{1}$$

$$AGWF_{bre} = max(AGWF_{bre(COD)}, AGWF_{bre(TN)}) \tag{2}$$

$$AGWF_{bre(i)} = \frac{EM_{bre(i)}}{C_{i,max} - C_{i,nat}} \tag{3}$$

$$EM_{bre(i)} = \sum_{a=1}^{4} N_a \times D_a \times (f_a \times p_{af} \times \beta_{af} + u_a \times p_{au} \times \beta_{au}) \tag{4}$$

$$AGWF = max[(AGWF_{pla} + AGWF_{bre(TN)}), AGWF_{bre(COD)}] \tag{5}$$

In Formulas (1)–(5), $AGWF_{pla}$ represents the grey water footprint of planting based on TN. ∂ represents the leaching rate of nitrogen fertilizer. $Appl$ represents the application amount of nitrogen fertilizer. $C_{i,max}$ represents the water quality standard concentration of Class i pollutants, and $C_{i,nat}$ represents the natural background concentration of Class i pollutants, which is assumed to be zero. $C_{i,nat}$ for water pollutants is extremely small and non-significant compared to $C_{i,\max}$ [47]. $AGWF_{bre}$ represents the grey water footprint of the livestock industry. $AGWF_{bre(i)}$ represents the grey water footprint of Class i pollutants (COD, TN). $EM_{bre(i)}$ represents the emission of Class i pollutants; a represents pigs, poultry, cattle and sheep; and N_a represents the number of species a. D_a represents the feeding period of a. f_a and u_a represent the daily excretion and urine volume of a. p_{af} represents the content of fecal pollutants per unit of a. p_{au} represents the pollutant content in urine per unit of a. β_{af} represents the rate of pollutant loss per unit of feces of a. β_{au} represents the rate of pollutant loss per unit of urine of a. $AGWF$ represents the agricultural grey water footprint. Please refer to Appendix A for the specific values of each parameter.

2.2.2. Logarithmic Mean Divisia Index (LMDI) Model

To explore the driving factors of the AGWF, the LMDI model was employed to divide the AGWF into three parts: the AGWF intensity (AGWFI), the agricultural economic development and the population [1]. The formulas of LMDI model are referred to as defined as Kong et al. [1], and they are listed below:

$$AGWF_t = \sum_j AGWF_{j,t} = \sum_j \frac{AGWF_{j,t}}{AGDP_{j,t}} \cdot \frac{AGDP_{j,t}}{P_{j,t}} \cdot P_{j,t} = \sum_j AGWFI_{j,t} \cdot AED_{j,t} \cdot P_{j,t} \tag{6}$$

In Equation (6), $AGWF_t$ means the AGWF of the YRB during the year t. $AGWF_{j,t}$ means the AGWF of j province during the year t. $P_{j,t}$ means the permanent population of j province during the year of t. $AGWFI_{j,t}$ means the AGWF intensity of j province during the year t, indicating the AGWF produced by a unit of AGDP. The agricultural water resource efficiency will be higher if the index is smaller. $AED_{j,t}$ means the per capita AGDP of j province during the year t, which denotes the developmental level of the agricultural economy. If the index becomes greater, the influence of agricultural economic development level upon the AGWF will be more significant. $P_{j,t}$ means the population size of j province during the year t. According to Equations (7)–(10), the total effect (ΔA) of the AGWF is decomposed into three effects, namely the efficiency effect ($\Delta AGWFI$), agricultural economic effect (ΔAED) and population effect (ΔP).

$$\Delta A = \Delta AGWFI + \Delta AED + \Delta P \tag{7}$$

$$\Delta AGWFI = \sum_j \frac{AGWF_{j,t} - AGWF_{j,0}}{\ln AGWF_{j,t} - \ln AGWF_{j,0}} \ln \frac{AGWFI_{j,t}}{AGWFI_{j,0}} \tag{8}$$

$$\Delta AED = \sum_j \frac{AGWF_{j,t} - AGWF_{j,0}}{\ln AGWF_{j,t} - \ln AGWF_{j,0}} \ln \frac{AED_{j,t}}{AED_{j,0}} \tag{9}$$

$$\Delta P = \sum_j \frac{AGWF_{j,t} - AGWF_{j,0}}{\ln AGWF_{j,t} - \ln AGWF_{j,0}} \ln \frac{P_{j,t}}{P_{j,0}} \tag{10}$$

2.2.3. Tapio Decoupling Model (TDM)

The TDM was adopted to measure the degree of decoupling between two variables [31]. The specific formula of TDM is referred to as defined in He et al. [15]:

$$\varphi = \frac{G_{t_1} - G_{t_0}}{G_{t_0}} / \frac{E_{t_1} - E_{t_0}}{E_{t_0}} \tag{11}$$

In Equation (11), φ represents the decoupling elastic coefficient, G_t represents the AGWF and its driving factors and E_t represents AGDP. The decoupling state can be decomposed into eight categories in Table 1 in light of the calculated value [48]. Notably, the strong decoupling (SD) is a perfect state, and this indicates that when the AGDP increases, the AGWF decreases. Meanwhile, the strong negative decoupling (SND) is the worst state; additionally, this shows that the agricultural grey water footprint still rises when an economic recession occurs.

Table 1. Decoupling status classification.

Decoupling State	φ	ΔG	ΔE
Strong decoupling (SD)	$(-\infty, 0)$	<0	>0
Weak decoupling (WD)	(0, 0.8)	>0	>0
Recessive decoupling (RD)	$(1.2, +\infty)$	<0	<0
Expansive coupling (EC)	(0.8, 1.2)	>0	>0
Recessive coupling (RC)	(0.8, 1.2)	<0	<0
Expansive negative decoupling (END)	$(1.2, +\infty)$	>0	>0
Weak negative decoupling (WND)	(0, 0.8)	<0	<0
Strong negative decoupling (SND)	$(-\infty, 0)$	>0	<0

2.3. Data Sources

The relevant AGDP information, resident population, fertilizer, pesticide application, livestock, poultry feeding, etc., involved in this research were supplied by the "Statistical Yearbook of China", the "China Rural Statistical Yearbook", and the "Water Resources Bulletin". All of the AGDP data used in this paper were converted, with 2016 taken as the base period. With data from the livestock rearing cycle, pollutant content in defecation and the fecal loss rates of livestock and poultry were supplied by the Technical Report on Pollution Survey and Countermeasures of Large-Scale Livestock and Poultry Farming in China [49]. COD, nitrogen, ammonia emission standards, nitrogen leaching rate, natural background concentration, and other parameters were taken from He et al. [15].

3. Results

3.1. Spatial–Temporal Characteristics of the AGWF in the YRB

The AGWF of the YRB and its seven provinces and two regions for the period 2016–2021 was calculated, as shown in Figures 3–5 and Tables 2 and 3 (below). The AGWF in the YRB first decreased and then slowly increased during 2016–2021 (Figure 3). In 2016–2019, the AGWF in YRB reduced yearly, reaching its lowest level in 2019, when it decreased by 9.45%. During 2019–2021, the AGWF in the YRB showed a gradual increase of 4.48% compared with 2019. Overall, the AGWF in the YRB cumulatively decreased by 5.649 billion m^3 in six years, with a reduction of 5.39%. From the perspective of the changing trend of the AGWF in the planting and breeding sectors during 2016–2021, the AGWF of the planting industry decreased by 9.093 billion m^3, which represented a decrease of 23.96%. The AGWF of the breeding industry cumulatively increased by 3.444 billion m^3, an increase of 5.15%. Furthermore, the AGWF of plantation was lower than the AGWF of breeding. In 2016, the AGWF in the breeding sector grew to 1.76 times that of the planting sector. By 2021, the ratio between the two rose to 2.44 times. The gap is gradually widening, as can be seen by comparing these two results.

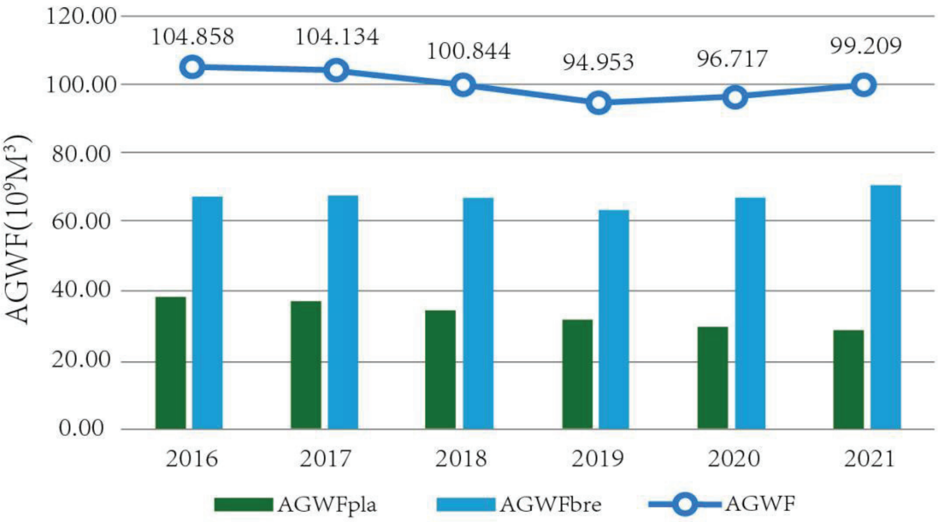

Figure 3. AGWF, AGWF of planting and AGWF of breeding in YRB.

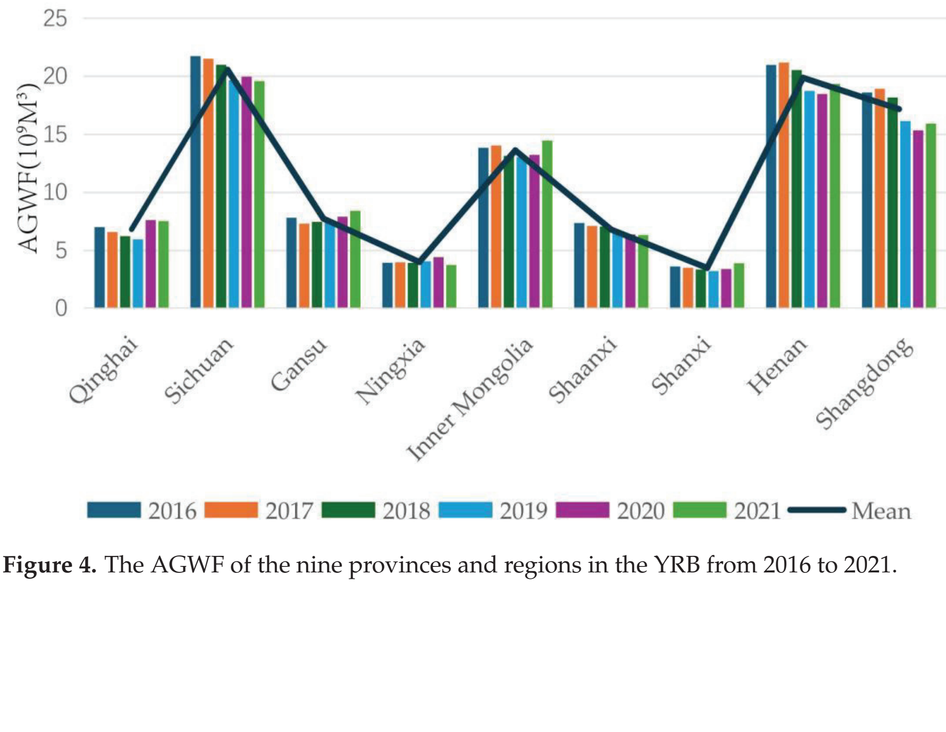

Figure 4. The AGWF of the nine provinces and regions in the YRB from 2016 to 2021.

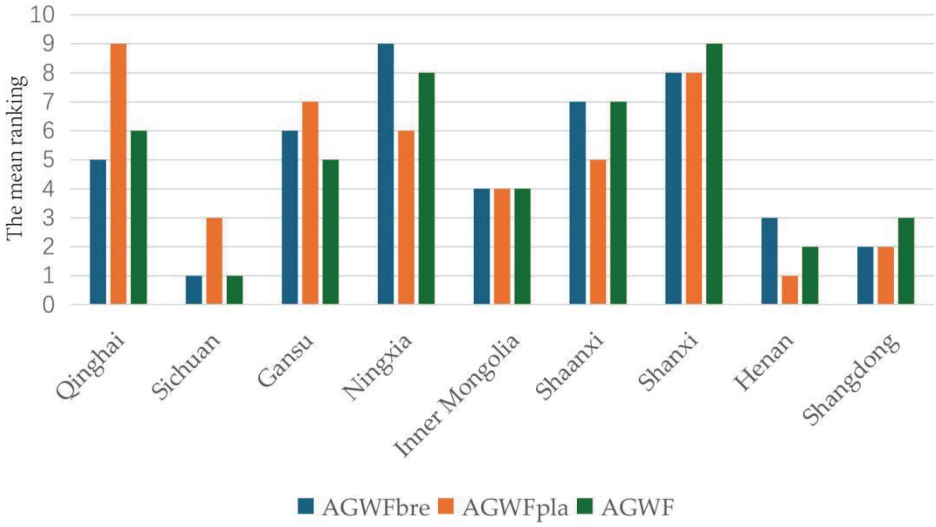

Figure 5. The mean rankings of the AGWF of breeding, AGWF of planting and AGWF.

Table 2. The AGWF in the YRB and nine provincial regions from 2016 to 2021 (Unit: 10^9 m^3).

Region	2016	2017	2018	2019	2020	2021	Mean
Qinghai	7.006	6.591	6.226	5.955	7.612	7.528	6.820
Sichuan	21.732	21.507	20.989	19.654	19.967	19.571	20.570
Gansu	7.817	7.303	7.456	7.580	7.900	8.416	7.745
Ningxia	3.931	3.982	3.918	4.066	4.425	3.745	4.011
Inner Mongolia	13.831	14.042	13.147	13.023	13.225	14.463	13.622
Shaanxi	7.359	7.111	7.059	6.570	6.383	6.319	6.800
Shanxi	3.622	3.510	3.358	3.222	3.399	3.897	3.501
Henan	20.969	21.179	20.525	18.742	18.467	19.348	19.872
Shangdong	18.592	18.908	18.166	16.141	15.340	15.923	17.178
YRB	104.858	104.134	100.844	94.953	96.717	99.209	100.119

Table 3. The mean ranking of the AGWF of breeding, AGWF of planting and AGWF.

Region	AGWFbre	AGWFpla	AGWF
Qinghai	5	9	6
Sichuan	1	3	1
Gansu	6	7	5
Ningxia	9	6	8
Inner Mongolia	4	4	4
Shaanxi	7	5	7
Shanxi	8	8	9
Henan	3	1	2
Shangdong	2	2	3

From Table 2 and Figure 4, it can be seen that the AGWFs in five of the seven provinces and two regions in the YRB showed a downward trend during 2016–2021. Among them, Shandong experienced the largest decrease, with a decrease of 14.36% to 2.669 billion m^3, and Ningxia experienced the smallest decrease, with a decrease of 4.73% to 0.186 billion m^3. The AGWFs of the other four provinces showed an upward trend, among which Gansu had the largest increase of 7.67% and Inner Mongolia had the smallest increase of 4.57%. The difference may be due to the fact that these four provinces are located in the central and western regions of China, where ecological and economic development is slow, agricultural technology is relatively backward, and a high-resource-consuming agricultural development model is preferred.

According to the average AGWF ranking, the top three provinces are Sichuan, Henan and Shandong (Table 3 and Figure 5). The last three on the list are Shaanxi, Shanxi and Ningxia. Combined with the rankings of the breeding AGWF and planting AGWF, Sichuan's total AGWF and breeding AGWF both ranked first, and its planting AGWF ranked third. Henan's planting AGWF ranked first. The total amount of AGWF in Shanxi ranked ninth, and the breeding and planting of AGWF ranked eighth. This shows that the AGWF of the breeding industry significantly impacts the total AGWF ranking.

3.2. Analysis of Driving Factors of AGWF

In this study, the LMDI approach was adopted to decompose the AGWF in the YRB into three parts: efficiency effect, agricultural economic effect and population effect. According to Equations (6)–(10), the results are as exhibited in Figures 6 and 7 and Tables 4–7. According to Table 4, during 2016–2021, the total effect of the AGWF first showed a sharp decline and, subsequently, a slow rise, cumulatively decreasing by 5.647 billion m^3 during the six years. The total effect of the AGWF declined yearly from 2016 to 2019, and the maximum reduction was 5.891 billion m^3 from 2018 to 2019. The total effect of the AGWF rose slowly year by year in 2019–2021. Additionally, the maximum increase was 2.492 billion m^3 during 2020–2021.

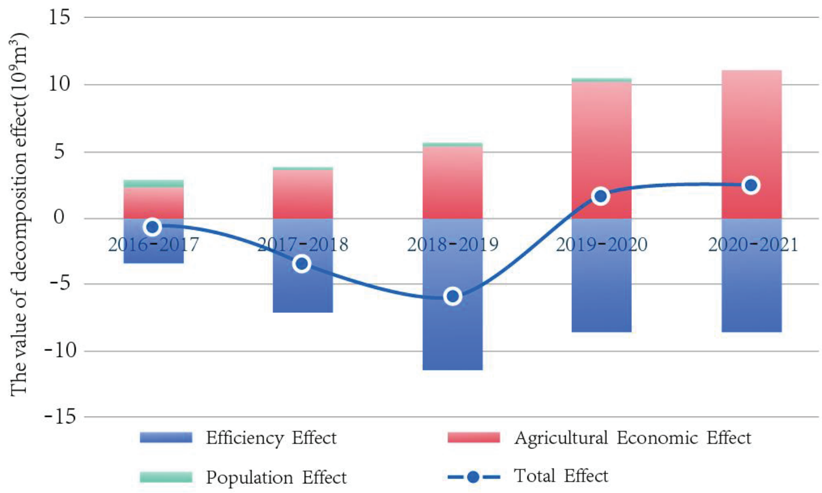

Figure 6. The changing trend of the AGWF of the YRB LMDI decomposition effect.

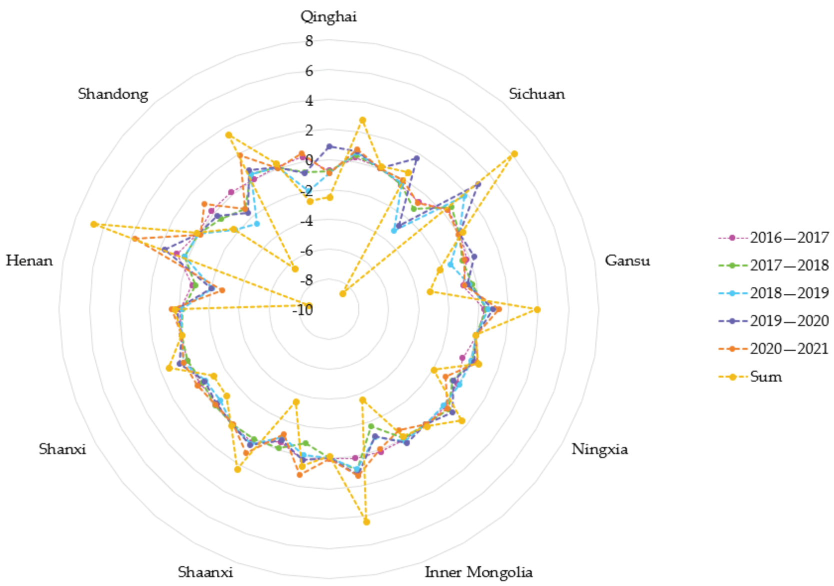

Figure 7. The LMDI analysis of AGWF change in seven provinces and two regions in the YRB.

Table 4. The LMDI analysis of AGWF change in the YRB (Unit: 10^9 m^3).

Year	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect
2016–2017	−3.486	2.371	0.465	−0.650
2017–2018	−7.184	3.587	0.235	−3.362
2018–2019	−11.514	5.395	0.228	−5.891
2019–2020	−8.635	10.206	0.193	1.764
2020–2021	−8.570	11.192	−0.131	2.492
Sum	−39.389	32.752	0.990	−5.646

From the decomposition effect of the AGWF (Figure 6), the efficiency effect was always negative, and its absolute value first increased and then decreased. This showed that agricultural water use efficiency became the main factor when the AGWF was reduced. A maximum of 11.514 billion m^3 reduced the efficiency effect in 2018–2019. The agricultural economic effect was always positive, and the effect increased year by year. The population effect was positive in most years and decreased year by year. The AGWF increase results from a mixture of the agricultural economic effect and the population effect. As the agricultural economic level gradually improves and the population continues to grow, the problem of rural water pollution will continue to rise. However, the cumulative impact of the agricultural economic effect on AGWF growth over the six years 2016–2021 was about 30 times greater than the cumulative impact of the population effect, indicating that the progress of the agricultural economy dominated the AGWF increase.

From the related provinces (Tables 5–7 and Figure 7), during the time period of 2016 to 2021, the total effects of the AGWF in Sichuan, Ningxia, Henan and Shandong all decreased, while the full effects of the AGWF in Qinghai, Gansu, Inner Mongolia and Shanxi increased. Among them, the total reduction effects for the AGWF in Shandong, Sichuan and Henan ranked among the top three, with 2.669 billion m^3, 2.161 billion m^3 and 1.621 billion m^3, respectively, contributing significantly to the decrease in the AGWF from 2016 to 2021. The total AGWF effect of Inner Mongolia increased the most, and it was 0.632 billion m^3. Via the decomposition effect, the cumulative contribution of the efficiency effect in the seven provinces and two regions was negative, and the incremental contribution from the agricultural economic effect was positive, while the cumulative contribution of the population effect was negative only in Shanxi, Inner Mongolia and Gansu, and the other provinces were positive. The increase or decrease in the AGWF in the seven provinces and two regions was mainly caused by agricultural economic effects or efficiency effects, which were similar to the results in Table 4. It is noteworthy that the cumulative contribution from agricultural economic effects to the AGWF increase in Shandong, Sichuan and Henan ranked fifth, second, and first, respectively. However, the cumulative reduction in the AGWF caused by efficiency effects ranked third, first, and second, respectively, much higher than the cumulative reductions in the AGWF caused by efficiency effects in other provinces. It shows that the agricultural water-saving technology and irrigation technology within three provinces have been prominently enhanced compared to the other six provinces, thus strengthening the agricultural water use efficiency and alleviating the problem of agricultural water pollution.

Table 5. The LMDI analysis of AGWF change in Qinghai, Sichuan and Gansu (Unit: 10^9 m^3).

Period	Qinghai				Sichuan				Gansu			
	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect
2016–2017	−0.736	0.275	0.047	−0.414	−0.660	0.336	0.099	−0.225	−0.899	0.379	0.006	−0.514
2017–2018	−0.809	0.433	0.011	−0.365	−1.239	0.639	0.082	−0.518	−0.311	0.485	−0.021	0.153
2018–2019	−0.939	0.637	0.031	−0.271	−3.205	1.797	0.073	−1.336	−0.496	0.638	−0.018	0.124
2019–2020	0.895	0.728	0.034	1.657	−2.766	3.033	0.047	0.314	−0.633	0.978	−0.025	0.320
2020–2021	−0.902	0.805	0.013	−0.084	−0.751	0.352	0.002	−0.396	−0.823	1.375	−0.036	0.517
Sum	−2.491	2.878	0.136	0.522	−8.622	6.157	0.304	−2.161	−3.163	3.855	−0.093	0.600

Table 6. The LMDI analysis of AGWF change in Ningxia, Inner Mongolia and Shaanxi (Unit: 10^9 m^3).

Period	Ningxia				Inner Mongolia				Shaanxi			
	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect
2016–2017	−0.114	0.109	0.057	0.052	0.116	0.113	−0.017	0.212	−0.573	0.270	0.056	−0.248
2017–2018	−0.486	0.394	0.028	−0.064	−1.701	0.867	−0.062	−0.895	−0.157	0.056	0.049	−0.053
2018–2019	0.085	0.023	0.039	0.148	−0.936	0.849	−0.038	−0.124	−0.904	0.393	0.022	−0.489
2019–2020	−0.422	0.758	0.024	0.359	−0.968	1.235	−0.065	0.202	−0.705	0.500	0.018	−0.188
2020–2021	−0.996	0.294	0.023	−0.679	−0.064	1.319	−0.017	1.238	−1.122	1.060	−0.002	−0.064
Sum	−1.932	1.577	0.170	−0.185	−3.553	4.384	−0.199	0.632	−3.463	2.278	0.144	−1.041

Table 7. The LMDI analysis of AGWF change in Shanxi, Henan and Shandong (Unit: 10^9 m^3).

Period	Shanxi				Henan				Shandong			
	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect	Efficiency Effect	Agriculture Economic Effect	Population Effect	Total Effect
2016–2017	−0.084	0.051	−0.004	−0.038	−0.717	0.818	0.110	0.210	0.183	0.021	0.112	0.316
2017–2018	−0.252	0.037	−0.008	−0.223	−0.971	0.244	0.074	−0.654	−1.256	0.433	0.081	−0.742
2018–2019	−0.489	0.358	−0.005	−0.136	−2.113	0.256	0.073	−1.783	−2.518	0.444	0.049	−2.025
2019–2020	−0.399	0.583	−0.007	0.177	−2.011	1.661	0.075	−0.275	−1.624	0.731	0.092	−0.802
2020–2021	0.142	0.365	−0.010	0.497	−2.792	3.783	−0.111	0.881	−1.262	1.838	0.008	0.583
Sum	−1.083	1.394	−0.034	0.277	−8.605	6.762	0.222	−1.621	−6.478	3.466	0.342	−2.669

3.3. Decoupling Analysis of AGWF and AGDP

The changing trend of AGDP and the AGWF in the YRB during 2016–2021 is exhibited in Figure 8. The decoupling state of the AGWF and its decomposition factors from AGDP are displayed in Table 8. The AGDP showed a stable growing trend, while the AGWF showed a changing trend of, firstly, a sharp decline and then a slow rise (Figure 8). According to the data in Table 8, the decoupling states of the AGWF and AGDP were manifested as SD in 2017–2019 and WD in 2019–2021, which conforms to the changing trend in Figure 8. In light of the decoupling relationship between the decomposition factors of the AGWF and AGDP, the decoupling between them was not considered since AGDP and agricultural economic development belong to the economic category. In addition, the AGWFI and AGDP showed END in 2017–2019, followed by SD in 2019–2021. Furthermore, the decoupling state always presented SD between the population effect and AGDP.

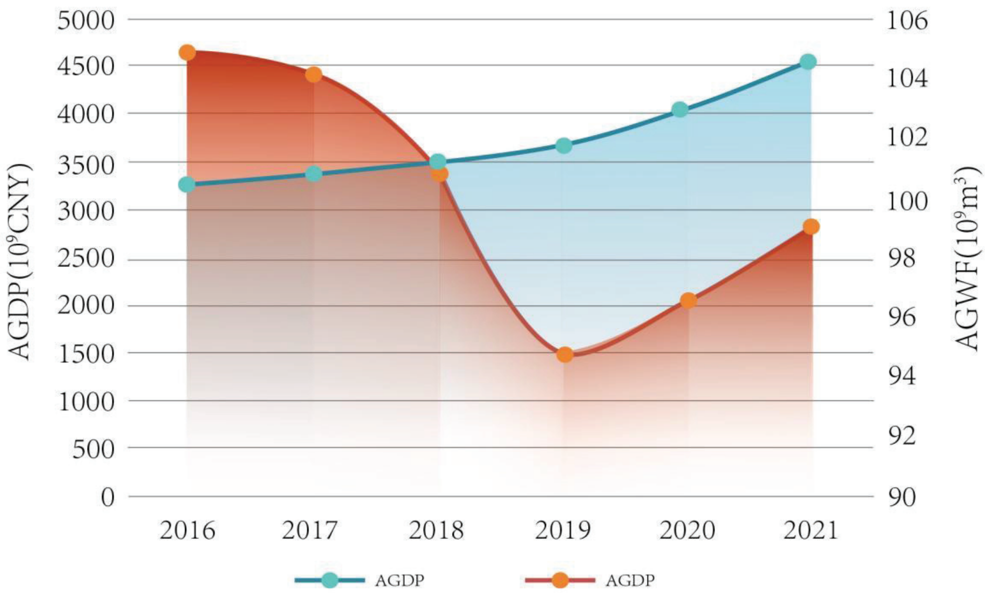

Figure 8. The changing trend of the AGWF and AGDP in the YRB (2016–2021).

Table 8. Decoupling status of AGWF and its driving factors and AGDP.

Year	Decoupling Elasticity of AGWF and AGDP	Decoupling Status	Decoupling Elasticity of AGWFI and AGDP	Decoupling Status	Decoupling Elasticity of P and AGDP	Decoupling Status
2017–2018	−1.002195098	SD	33.6473	END	−0.495061127	SD
2018–2019	−1.094079494	SD	11.29061	END	−0.029251404	SD
2019–2020	0.173306378	WD	−2.33237	SD	−0.152678292	SD
2020–2021	0.208439086	WD	−0.06081	SD	−1.675894151	SD

Notes: Green represents strong decoupling; light green indicates weak decoupling; and red indicates expansion negative decoupling.

Separately, (1) although the decoupling state between the AGWF and AGDP was SD in 2017–2019, from a numerical point of view, the decoupling state of 2018–2019 was higher than that of 2017–2018, while the decoupling state was WD after 2019. The decoupling state gradually became weaker over time, indicating that from 2017 to 2019, with the continuous increase in AGDP, continuous decrease in the AGWF, and the reduction speed becoming faster and faster, the agricultural water pollution problem in the YRB was effectively controlled. From 2019 to 2021, with the continuous increase in AGDP, the AGWF increased. Still, the growth rate of the AGWF was significantly slower than that of AGDP, indicating that the control of agricultural grey water footprint in the YRB was relaxed. (2) The decoupling state between the AGWFI and AGDP showed END in 2017–2019, but the value of 2018–2019 was much lower than that of 2017–2018, indicating that although both were in the END state, the END state gradually decreased with the increase in time. Although the AGWFI increased with the increase in AGDP, and the growth rate of the AGWFI was much higher than that of AGDP, the growth rate of the AGWFI slowed down, indicating that the agricultural water use efficiency in the YRB was not greatly improved, but decision-makers have paid the issue of improving agricultural water use efficiency attention. Although the decoupling state between the AGWFI and AGDP was in SD from 2019 to 2021, the value of 2019–2020 is lower than that of 2020–2021, indicating that the SD state was unstable. This indicates that although the AGWFI decreased with the growth of AGDP during 2019–2021, the rate of AGWFI decline slowed down, that is, agricultural water use efficiency was yet to be steadily improved. (3) The decoupling state between P and AGDP showed SD during 2017–2021, illustrating that with the AGDP increase, the population in the YRB decreased to some degree, that is, the AGDP increase did not depend on population growth. However, the decoupling strength of different stages was different, as the SD state was strongest during 2018–2019 and weakest during 2020–2021.

4. Discussion

4.1. Discussion of AGWF

This paper first calculated and evaluated the 2016–2019 AGWF in the YRB. Subsequently, the LMDI approach was adopted to decompose the AGWF drivers. Next, the decoupling relations were detected among the AGWF, its driving factors, and AGDP growth through the Tapio decoupling model.

This study confirms that the overall AGWF decreased in the YRB, with a downward trend in 2016–2019 and an upward trend in 2019–2021 (Figure 3). Kong et al. also found that China's AGWF showed a downward trend from 2015 to 2019 [6]. Xu et al. further found that the AGWF of prefecture-level cities in the YRB continued to decline from 2015 to 2019 [50]. The research conclusions of this paper are consistent with those of Kong et al. and Xu et al. [6,50]. The reason why the AGWF in the YRB decreased at first and then rose slowly during 2016–2021 may be that the implementation of the high-quality development strategy in the YRB had a strong promotion effect on reducing the agricultural grey water footprint and improving agricultural water use efficiency in the region in 2016 and for the following three years. However, there was an increase in the AGWF in the YRB between 2019 and 2021, which COVID-19 may have influenced. The impact of COVID-19 may have led to a loosening of controls on agricultural pollutants. This result is consistent with that of Kuttippurath et al., who found that agricultural activities and the use of nitrogen fertilizer increased during the COVID-19 period due to lack of restrictions [51]. To ensure national agricultural security, China's National Development and Reform Commission put agricultural output in first place in 2020 and temporarily weakened agricultural pollution controls.

This paper found that the AGWF in Qinghai, Shanxi, Gansu and Inner Mongolia increased from 2016 to 2021, mainly due to the severe shortage of water resources in the above four provinces. Wei et al. pointed out that water resource endowment plays a decisive role in alleviating the problem of the agricultural grey water footprint [52]. To promote the rapid development of the agricultural economy, the four provinces mentioned above often used sewage for agricultural irrigation while applying fertilizer in large quantities for a long time. Although sewage irrigation can provide land with a stable water source and bring phosphorus, nitrogen and other chemical elements needed for crops, it inevitably aggravates the problem of agricultural non-point source pollution. In addition, Qinghai, Gansu and Inner Mongolia are major provinces of animal husbandry, and the rapid development of animal husbandry has increased the loads of resources and the environment. This finding is supported by the study of Wen et al., who suggest that the high concentrations of pollutants in the soil have led to the worsening of agricultural water pollution in northern China [53].

The AGWF in the YRB reached its lowest level in 2019, a significant decrease compared with 2016. The reasons may be as follows: On the one hand, the research data in this paper show that the AGWF was greatly affected by $AGWF_{bre}$, and the $AGWF_{bre}$ in the YRB reached its lowest level in 2019, reaching 63.112 billion m^3, while $AGWF_{pla}$ decreased year by year. On the other hand, implementing the new development concept in the YRB continued to promote the green transformation of agricultural development. China promulgated the National Water Saving Action Plan and subsequently brought forward a nationwide strategy for the ecological protection and high-quality progress of the YRB in 2019. During the same year, the related provinces responded to the nation's call and actively launched water-saving action implementation plans aligned with other provinces. With the promotion of various policies, the problem of agricultural water pollution in the YRB has been controlled.

4.2. Discussion of Driving Factors of AGWF

In our study, the driving factors of the AGWF are split into the efficiency effect, agricultural economic effect and population effect by the LMDI model, and the contribution degree of the three decomposition effects to the AGWF are discussed. From 2016 to 2021, the agricultural economic effect was the primary factor driving AGWF increase in the YRB, while the population effect contributed little to the rise in the AGWF, and the efficiency effect was an essential reason for the decrease in the AGWF. The same conclusion can be reached from the relevant provinces. Similarly, it was concluded that the increase or decrease in the grey water footprint was mainly caused by economic or technological effects through the LMDI approach [27]. Moreover, the Generalized Divisia Index Method (GDIM) was adopted to dissect the driving factors of the AGWF in China and Hubei Province, respectively. It was found that agricultural economic growth inhibited the decline of the AGWF, while the AGWFI promoted the AGWF's decrease [6,15]. Chen et al. analyzed the water resource carrying capacity (WRCC) in the YRB during 2009–2018 through LMDI decomposition and concluded that wastewater treatment technology promoted the WRCC. However, the WRCC was inhibited by the economic effect [54]. The above studies demonstrate that the reduction in the AGWF is mainly promoted by the efficiency effect and inhibited by the agricultural economic effect. The efficiency effect in our research area on AGWF reduction in 2021 increased by 1.5 times compared with that in 2016, suggesting that the planting technology was enhanced, as well as agricultural sewage treatment technology; animal husbandry was transformed into a green development model; and the AGWF was, thus, reduced. This finding is supported by the study of He et al., who suggest that agricultural science and technology improvement could lead to AGWF reduction [15]. The degree of agricultural development in southern China is higher than that in northern China; therefore, it can be inferred that the AGWF in southern China is higher than that in northern China. This is consistent with the research conclusion of Kong et al. [6]. However, Wen et al. found that the upward trend of the AGWF in southern China was significantly lower than that in northern China, possibly due to the higher total water resources and better water quality in southern China, as well as higher agricultural resource utilization efficiency compared with northern China [53].

4.3. Discussion of Decoupling States of AGWF with AGDP

In addition, the TDM was adopted in this study to explore the decoupling relationships between the AGWF, its driving factors, and AGDP during 2016–2021. It is shown that the decoupling states of the AGWF and AGDP presented SD in 2017–2019 and WD in 2019–2021. These two decoupling states indicate that in the AGDP growth process, the AGWF first decreased and then rose slowly, thus achieving sustainable agricultural development to a certain extent [6]. Simultaneously, the AGWFI and AGDP showed END during 2017–2019 and SD during 2019–2021. It is highlighted that agricultural water use efficiency was dramatically improved as agricultural irrigation technology and water-saving technology developed, and the ideal state of the AGWFI decreasing with the AGDP increasing was finally realized. Therefore, when dealing with agricultural grey water, it is imperative to properly handle the correlations between the economy, ecology, and resources based upon the water environment carrying capability, focus upon the influences of AGDP and AGWF intensity upon agricultural water use, and improve agricultural water use efficiency through continuously improving agrarian technology [44,54].

5. Conclusions

With the sustained and rapid growth of the agricultural economy, the massive application of chemical fertilizers and pesticides and the arbitrary discharge of livestock and poultry manure have aggravated the water pollution of China's agriculture, seriously restricting the green development of China's agricultural economy. As an important agricultural region in China, the YRB has a broad plain and fertile soil, which provides unique conditions for China's agricultural development. This paper provides a method to accurately calculate the AGWF in the YRB during 2016–2021, which can be applied in similar cases in further studies. The LMDI approach was employed to decompose the driving factors that impacted the AGWF. Next, the TDM was adopted to explore the decoupling relationships between the AGWF, its driving factors, and AGDP. The following conclusions were reached:

(1) In 2016–2021, the AGWF in the YRB decreased by 5.39%. The AGWF in the research area varied greatly.

(2) The primary promoting and inhibiting factors of AGWF reduction were the efficiency effect and agricultural economic effect; however, the population effect had a weak inhibiting effect upon AGWF reduction.

(3) Regarding the decoupling states between the AGWF and AGDP, SD and WD were presented first. Moreover, the decoupling state between the AGWFI and AGDP shifted from END to SD. The decoupling between the population and AGDP was in SD. This indicates that agriculture in the research area realized the sustainable development pattern step by step.

Based on the above research conclusions, this paper puts forward the following policy recommendations: (1) Agricultural grey water in different provinces varies greatly; therefore, agricultural water management policies should be formulated according to local conditions, rational allocation of resources and coordinated regional development. (2) It is also vital to constantly improve various infrastructure, accelerate the diversified development of the agricultural economy, cultivate and expand characteristic industries and achieve sustained progress in the agricultural economy. (3) Finally, policymakers should strengthen the protection and scientific and rational use of water resources, further promote the application of water-saving technologies, accelerate the development of green agricultural technologies, consolidate and improve coordination between the agricultural economy and agricultural water use, and achieve the high-quality development of green agriculture.

Although the AGWF in the YRB was measured and analyzed, as were its driving factors, some areas are still worth improving. The generalization of these results is subject to certain limitations. For instance, (1) on account of the challenges of attaining some information related to agricultural grey water, only COD and TN pollution sources were considered in the calculation of the AGWF in this paper, and there may be specific differences between the calculation results of the AGWF and the actual situation of agricultural water pollution. (2) The dynamic evolutionary path between the AGWF and its drivers and AGDP is worth further exploration. (3) Due to time constraints, this paper did not study how the COVID-19 pandemic influenced agricultural pollutants, and this could be further explored.

Author Contributions: This section specifies individual contributions: Conceptualization, Y.X. and X.Z.; methodology, Y.X. and X.Z.; software, Y.X.; validation, Y.X. and X.Z. and T.S.R., Q.P. and S.L.; formal analysis, Q.P.; investigation, Q.P.; resources, Q.P.; data curation, S.L.; writing—original draft preparation, S.L.; writing—review and editing, Q.P. and T.S.R.; visualization, Q.P.; supervision, S.L.;

project administration, S.L.; funding acquisition, S.L. and X.Z. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: Due to the team's privacy policy, data are not publicly available, but the corresponding author can be contacted if you need to obtain data.

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

Appendix A

Table A1. The parameters mentioned in this paper and their values.

Parameters	Values
∂	7% for ∂
$C_{i,max}$	60 mg/L for $C_{COD,max}$; 15 mg/L for $C_{TN,max}$
$C_{i,nat}$	Assumed to be zero.
D_a	365 days for D_{cattle} and D_{sheep}; 199 days for D_{pigs}; 210 days for $D_{poultry}$
f_a	0.02 t/day for f_{cattle}; 0.002 t/day for f_{pigs}; 0.0026 t/day for f_{sheep}; 0.000125 t/day for $f_{poultry}$
u_a	0 t/day for u_{sheep} and $u_{poultry}$; 0.01 t/day for u_{cattle}; 0.0033 t/day for u_{pigs}
p_{af} (for COD)	31 kg/t for $p_{cattlef}$; 52 kg/t for p_{pigsf} ; 4.63 kg/t for p_{sheepf} ; 45.65 kg/t for $p_{poultryf}$
p_{af} (for TN)	4.37 kg/t for $p_{cattlef}$; 5.88 kg/t for p_{pigsf}; 7.50 kg/t for p_{sheepf}; 10.42 kg/t for $p_{poultryf}$
p_{au} (for COD)	0 kg/t for p_{sheepu}; $p_{poultryu}$, 6 kg/t for $p_{cattleu}$; 9 kg/t for p_{pigsu}
p_{au} (for TN)	0 kg/t for p_{sheepu} and $p_{poultryu}$; 8 kg/t for $p_{cattleu}$; 3.3 kg/t for p_{pigsu}
β_{af} (for COD)	6.16% for $\beta_{cattlef}$; 5.58% for β_{pigsf}; 5.50% for β_{sheepf}; 8.59% for $\beta_{poultryf}$
β_{af} (for TN)	5.68% for $\beta_{cattlef}$; 5.34% for β_{pigsf}; 5.30% for β_{sheepf}; 8.47% for $\beta_{poultryf}$
β_{au}	50% for β_{au}

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Does the Water Resource Tax Reform Bring Positive Effects to Green Innovation and Productivity in High Water-Consuming Enterprises?

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Abstract: Water resources are a fundamental natural and strategic economic resource and are closely related to high-quality economic and societal development. This paper uses the pilot implementation of the water resource tax reform to explore the impact of that reform on the green innovation and total factor productivity of enterprises. The study sample includes data for high water-consuming A-share listed enterprises in Shenzhen and Shanghai, China, from 2007 to 2021; the double-difference method was used for the analysis. Study findings indicate that replacing water resource fees with taxes significantly improves the green innovation level and total factor productivity of enterprises. Green innovation has a significant partial mediating effect between the water resource tax reform and total factor productivity. The water resource tax reform promotes green innovation in enterprises, enhancing total factor productivity. When considering different types of enterprise property rights, the economic effect of the water resource tax reform is more pronounced in non-state-owned enterprises, compared to state-owned enterprises. This paper provides empirical evidence for expanding the pilot scope of the water resource tax reform.

Keywords: water resource tax; green innovation; total factor productivity

1. Introduction

Developing countries have long relied on large-scale and low-cost resource investments to gain product cost advantages, encouraging industrial competitiveness and rapid economic growth. However, the undervaluation of water resource factor prices and insufficient collection and management of water resources have led to extensive use of water resources by enterprises, leading to significant pressure on water resources and constraining industrial transformation and upgrades (Yao and Li, 2023) [1]. On 26 August 2021, the Food and Agriculture Organization of the United Nations released the *Progress on Level of Water Stress* report, stating that about one-third of the world's population (2.3 billion people) live in countries experiencing water scarcity. One-tenth of the population (733 million people) live in countries facing high or severe water shortages. By 2050, major cities are likely to face water crises, including Beijing, London, Mumbai, and Tokyo. The high interdependence among urban, agricultural, and industrial water use highlights the need to promote sustainable, inclusive, and comprehensive governance approaches.

There are many disadvantages in the design and implementation of a water resource fee system, including low collection standards, the arbitrary selection of collection subjects, a low actual collection rate, and ineffective income use. This results in water prices not effectively reflecting the scarcity of water resources, decreasing the potentially protective role of a fee system. This makes it difficult for governments and enterprises to adapt to the needs of green development in the new era. This has led to calls to implement rigid constraints on water resources, promote the water resource tax reform, improve the water resource tax system, comprehensively improve water resource utilization efficiency, and expand development space by saving water (Lv et al., 2022) [2].

The theory of resource depletion posits that, as human society continuously develops, resources are continuously developed and consumed, decreasing reserves. This increases resource prices and decreases resource demands (Huang, 2018) [3]. The theory of resource depletion highlights that resource exhaustibility can affect demand and prices. This highlights the need for the government to regulate resource prices to protect resources, reduce resource usage, and improve resource utilization efficiency. Ing (2020) proposed that the government should design relevant tax policies to generate resource rents and alleviate resource depletion problems [4]. Welsch (2008) studied mineral resource externalities, positing that the presence of negative externalities indicates that the government should impose corresponding taxes and fees on miners to effectively address the associated problems [5]. Doing so should promote the rational development of mineral resources and alleviate excessive mining. Liu and Ruebeck (2020) noted that the negative externality problem associated with water bodies should be addressed in accordance with local conditions, and an effective charging mechanism should be developed based on the actual local environmental situation [6].

Many developed countries have used taxation to regulate water resources (Thomas and Zaporozhets, 2017) [7]. For example, Sweden's introduction of a water resource tax has achieved results with respect to residential water use. The approach has increased government tax revenue, driving other government activities, such as water resource protection, and has improved the efficiency of residential water resource utilization (Höglund, 1999) [8]. The practice of levying a water resource tax in the Netherlands has shown that, in the short term, a water resource tax increases water-use costs for enterprises. The tax encourages enterprises to actively change their water-use methods, enhance their technological competitiveness, and improve their water resource utilization efficiency (Clinch et al., 2001) [9]. Berbel et al. (2019) studied the water resource tax systems of some European Union countries; the study found that introducing water resource taxes in these countries achieved significant water-saving effects and internalized the environmental and resource costs of agricultural irrigation water [10].

In contrast, while the introduction of a water resource tax in South Africa increased tax revenue and saved water consumption in the short term, the tax also reduced agricultural household income and lowered national consumption levels in the long run (van Heerden et al., 2008) [11]. Porcher (2017) studied the relationship between a French water tax and consumer behavior. The study found that the water consumption saved by levying a water tax was essentially the same as the reduction in water consumption achieved by directly increasing water prices [12]. There remains controversy about the economic consequences of introducing a water resource tax.

Porter's hypothesis states that the design and effective operation of environmental controls can force enterprises to actively engage in green innovation activities (Porter and Linde, 1995) [13]. Fan (2021) analyzed the functional position of taxation and the specific purpose of individual resource taxes to determine the functional position of China's taxes [14]. That paper argues that the resource tax, as a specific-purpose tax, plays a unique role in saving resources and protecting the environment. Jia and Lin (2022) simulated that analysis by constructing a general equilibrium model; the study found that the resource tax supports the protection of economic aggregates [15]. Legitimacy is an important prerequisite for enterprise survival; paying taxes in accordance with the law is a basic obligation. Given the cost of tax violations, enterprises will choose to reduce water resource consumption and waste. Enterprises cultivate a green competitive advantage and receive the benefits of innovation by reforming traditional production methods, improving existing processes and technologies, strengthening wastewater recycling through innovative governance at the end of production, and developing a circular economy (Chen et al., 2018) [16]. Porter and Linde (1995) [13] and Ambec et al. (2013) [17] also argued that environmental regulations may promote enterprise R&D investment and technological innovation and realize joint improvements in environmental performance and productivity through the innovation compensation effect. However, research is still needed to determine if a water tax reform also promotes the green innovation of enterprises and enhances their total factor productivity.

This paper provides the following innovations to this research field: First, some scholars have posited that a water resource tax improves water resource utilization efficiency and enhances the technological competitiveness of enterprises (Clinch et al., 2001; Berbel et al., 2019) [9,10]. In contrast, other scholars have posited that a water resource tax reduces the level of national consumption (van Heerden et al., 2008) [11]. Further, other scholars have posited that water resource tax reforms produce insignificant water savings (Porcher, 2017) [12]. Therefore, this study explores the economic consequences of a water tax reform from a micro-firm innovation and productivity perspective, providing empirical evidence to inform the water tax reform debate.

Second, the study considers the intrinsic mechanism of a water resource tax reform and its effect on enterprise total factor productivity. By applying an enterprise perspective, the research reveals the innovation incentive effect of a water resource tax reform. This helps to deepen the understanding of how a water resource tax reform affects enterprise behavior and provides an empirical reference to promote efficiency improvements and green innovation development among high water-consuming enterprises.

2. Literature Review

2.1. Water Resource Tax

In contrast to a traditional business model, green economic development requires that enterprises both pursue profits and reduce negative externalities. Levying a resource tax plays an important role in promoting green economic development (Mikhno et al., 2021) [18]. Illustrating this, Ing (2020) called for government policies to regulate the extraction of non-renewable water resources by imposing resource taxes and limiting the time frame for companies to extract those resources [4].

Most studies have found that implementing a water resource tax policy produces positive economic effects. Munguía-López et al. (2019) used a theoretical analysis to conclude that water taxes and tax credits contribute to higher profits and environmental benefits, such as reduced water extraction and increases in aquifer recharge [19]. Berbel et al. (2019) studied the water tax system in selected countries of the European Union, finding that implementing a water tax is effective in saving water, which optimizes environmental quality and internalizes the cost of resources for irrigated agriculture [10]. Thomas and Zaporozhets (2017) [7] examined the economic effects of water taxes in the United States, the Netherlands, and several other European countries. The study found a “win-win” situation, with increased water-use efficiency and reduced total water use. Ouyang (2022) also found that a water resource taxation policy improved water-use efficiency and optimized water-use structures [20]. Biancardi et al. (2021) used a differential game approach to analyze user and public authority behavior. They found that, in a non-cooperative case, imposing a water tax has a significant positive effect on protecting public groundwater resources [21]. Guo et al. (2022) examined the relationship between a water resource tax, sewage tax, and corporate green innovation decision making [22]. The study found that a water resource tax is significantly better than a sewage tax in terms of economic effects on water saving and emission reduction; this approach supports external ecological compensation. A few scholars have also explored water resource tax implementation. For example, Chen et al. (2020) argued that implementing a water resource tax motivates residents and businesses to look for lower cost alternatives [23].

2.2. Corporate Green Innovation

Green innovation refers to the development and design of new technologies and products that support energy savings, pollution prevention, and recycling to achieve ecological sustainability (Oltra and Saint, 2009) [24]. The goal of green innovation is to reduce ecological risks and enhance environmental governance effects (Vasileiou et al., 2022) [25]. Previous papers have explored the factors that influence green innovation with respect to the external system and environment, as well as at the corporate and managerial levels.

Applying an external regime and environment perspective, Frondel et al. (2008) noted that environmental regulations are an instrument of government environmental policy and are an important driver of green innovation [26]. Horbach (2008) also argued that government regulations are a major determinant of a firm's green innovation [27]. Borsatto and Bazani (2021) found that environmental regulatory pressure from the government has a positive impact on green innovation [28]. This is because enterprises avoid penalties for violating environmental laws by actively investing resources in green technological innovations that lower the cost of violating the law. However, coercive pressure that pushes enterprises to follow environmental policies and regulations also dampens green innovation practices (Stucki, 2019) [29]. Other scholars have found that consumer preferences and demands (Fernando et al., 2021) [30] and institutional investors (Zhang et al., 2021) [31] significantly impact on enterprise green innovation.

Some researchers have applied an enterprise perspective, arguing that basic enterprise characteristics and the resources and capabilities an enterprise holds have a greater impact on the enterprise's green innovation in each context. Segarra-Ona et al. (2012) argued that enterprise size generally indicates if an enterprise has the many resources needed for innovation [32]. As such, size is often considered important for enterprises to engage in green innovation. In contrast, Sáez-Martínez et al. (2016) argued that enterprise size does not impact an enterprise's implementation of environmentally friendly products or process innovations [33]. Keskin et al. (2013) argued that newly established enterprises and those established for a relatively shorter time have an advantage in green innovation [34]. Other important success factors encouraging green innovation include qualified human resources (Ogbeibu et al., 2020) [35], adequate cash flow (Scarpellini et al., 2018) [36], and abundant and high-quality administrative resources (Bezerra et al., 2020) [37]. An enterprise's absorptive (Shahzad et al., 2020) [38], technological (Triguero et al., 2013) [39], dynamic (Wang and Ahmed, 2007) [40], and organizational (Lončar et al., 2019) [41] capabilities are also important factors affecting the ability to undertake green innovation.

From a managerial perspective, managers' environmental awareness and personal characteristics significantly impact their decisions to implement green innovation. Environmentally cost-effective managers focus more on improving existing product lines and producing green products with shorter payback cycles and greater visibility (Sumrin et al., 2021) [42]. Arena et al. (2018) found that chief executive officers (CEOs) with arrogant personalities are more likely to invest in projects with uncertain outcomes, given their high self-concept and tendency to like challenges [43]. This allows them to take high risks with respect to green innovation, and they may earn high returns from them. Zhang et al. (2023) used data from Chinese listed enterprises to demonstrate that CEOs' overseas experience improves the green innovation level in corporate firms [44]. In addition to this, manager attention is also an important influence on green innovation in enterprises (Papagiannakis et al., 2019) [45].

2.3. Total Factor Productivity of Enterprises

Total factor productivity (TFP) covers many factors, such as technological progress, management efficiency, and scale effect, and comprehensively reflects resource allocation efficiency and the market competitiveness of enterprises. Overall, the key factors affecting enterprise TFP include government behavior, market behavior, and enterprise behavior.

Applying a government behavior perspective, Bernard et al. (2019) found that improving transportation infrastructure construction can optimize enterprise production chains, creating economies of scale, and ultimately promote enterprise TFP [46]. Aghion et al. (2015) found that government resource allocations to competitive enterprises increases enterprise TFP—total factor productivity [47]. This countered Kiyota and Okazaki (2010) [48], who argued that government subsidies allow a large number of enterprises without economies of scale to consume significant resources, preventing the transfer of government resources to enterprises with economies of scale and thus preventing an overall increase in TFP.

Applying a market behavior perspective, financial market development can provide financial support for enterprise technological upgrades, promote continuous upgrading, and ultimately promote enterprise TFP (Arizala et al., 2013) [49]. Research has also found that financial development has a non-linear effect on TFP (Méon and Weill, 2010) [50]. Financing constraints in an enterprise's broader industry may also inhibit the enterprise's TFP (Caggese, 2019) [51]. Human capital, intellectual property rights, and research and development (R&D) expenditures appear to be statistically significant and are strong factors in determining changes in TFP (Habib et al., 2019) [52]. An increase in information regarding share prices in the capital market can improve corporate governance and reduce factor costs, this improves enterprise performance and contributes to the enterprise TFP (Bennett et al., 2020) [53].

Applying a behavioral perspective, Hsieh and Klenow (2009) argued that talent acquisition and rising labor costs can increase enterprise TFP [54]. Tian and Twite (2011) noted that measures to improve corporate governance, such as improving the efficiency of the board of directors and executive compensation, exerts an effect similar to competition in the product market and effectively raises the TFP level [55]. Import-intensive firms are less productive; however, the productivity of firms with greater board connectivity generates a positive industry-level spillover effect (Ahamed et al., 2023) [56].

This literature review indicates there have been extensive studies on water resource tax reform, green innovation, and TFP, and that research has yielded valuable research results. However, research gaps and opportunities remain. First, the economic effects of a water resource tax reform have been mainly analyzed from the perspective of water-saving effects and ecological protection. Few studies have focused on green innovation and productivity. Further, many studies have considered the factors that influence enterprise green innovation from the perspectives of external institutions and environments, basic enterprise characteristics, resource capabilities, and manager characteristics. However, researchers have not yet fully explored the relationship between a water resource tax reform and enterprise green innovation. In particular, the economic effects of a water resource tax reform on enterprise green innovation deserve further study.

3. Theoretical Analysis and Research Hypothesis

No consensus has been reached on whether and how environmental regulations affects enterprise TFP. The various arguments can be broadly categorized into the following three views: The first is the "Porter's hypothesis", which states that environmental regulations promote firm TFP. Based on Porter's hypothesis, reasonable and moderate environmental regulations will not only reduce the net cost of meeting regulatory requirements but will also fully stimulate enterprise innovation vitality, resulting in an "innovation compensation effect" that can promote the technological progress of enterprises and the efficiency of resource allocation (Porter and Linde, 1995) [13]. The second view is the "disincentive hypothesis" of neoclassical economics, which suggests that environmental regulations inhibit firm TFP. The "compliance cost effect" of environmental taxes increases the burden on enterprises and has a crowding-out effect on R&D investment and technological innovation, and, thus, enterprise TFP declines (Wang et al., 2023) [57]. Hancevic (2016) also argued that, under strict environmental regulations, enterprises tend to spend more money on unproductive activities, such as the purchase of environmental protection equipment [58]. In addition, their additional wastage, combined with the decline in the matching of the means of production with the original production equipment, ultimately results in productivity losses. The third view is the "uncertainty theory", which states that a non-linear relationship exists between the impact of environmental regulations on enterprise TFP. Gray et al. (1995) argued that environmental regulations do not have a significant uplifting effect on either technological progress or efficiency improvement in enterprise TFP [59].

Medeiros et al. (2018) argued that a non-linear relationship exists between environmental regulations and enterprise productivity [60].

At the beginning of the implementation of water resource fees and taxes, there was the "disincentive hypothesis" of neoclassical economics. However, there is seldom an abrupt end to the phenomenon of changing water resource fees and taxes, but rather a tendency to implement them over the long term. In addition, the lure of compensatory returns from innovation will help entrepreneurs see the potential profitability of green production methods, products, and services. Water consumption by enterprises is inextricably linked to their production and business activities, and the water resource tax levied by China's government is directly linked to the amount of water consumed by enterprises. The policy design of "more consumption, more tax" will greatly increase the cost to enterprises for environmental violations. Enterprise behavioral decisions are mainly oriented toward economic interests. In order to reduce the cost of environmental violations and production costs, high water-consuming enterprises have an incentive to eliminate outdated production capacity, to purchase environmentally friendly and energy-saving special equipment, and to improve production technology. They also have an incentive to engage in the research and development of green products and to optimize the allocation of resources, so as to better cope with the impact of the water resource tax reform on their own enterprise. Water resource fees or taxes can force enterprises to carry out green technological innovation and engage in the research and development of environmentally clean production technology and products. These fees will also make enterprises more inclined to purchase energy-saving and environmentally friendly equipment, thus eliminating a backward production capacity. This in turn promotes the technological optimization and upgrading of enterprises and improves their TFP. Based on the above, the following hypothesis is proposed:

Hypothesis 1: *Water tax reform increases the total factor productivity (TFP) of high water-consuming firms.*

Environmental taxes are levied to achieve environmental improvements. This is ultimately realized by driving enterprises toward green technological innovation. As such, promoting green technological innovation has become an important objective in environmental tax implementation (Magat, 1979) [61]. Porter's hypothesis posits that appropriate environmental regulations incentivize technological innovation, offsetting the increased costs of environmental protection and improving firm productivity and profitability (Porter and Linde, 1995) [13]. Earlier still, Weitzman (1978) theorized that using tax instruments more effectively encourages technological innovation more than command-and-control instruments alone [62]. The "double dividend" theory states that environmental taxes force enterprises to save energy and reduce emissions; this also improves production technology, increases production, and increases revenue. Montero (2002) found that taxes provide the best positive incentives for green technology innovation under perfectly competitive markets [63]. By purchasing special water-saving equipment, improving production technology, and optimizing resource allocations, high water-consuming enterprises can flexibly choose countermeasures that improve production efficiency. This may reduce the cost of production water and ultimately slow or offset the pressure on operating costs created by the shift in water resource policy from a fee to a tax (Wang et al., 2023) [57].

Water taxes are an important component of water-use constraints, and they internalize enterprise external costs through price transmission (Larson et al., 1996) [64]. In the new era of water resource fees, high water-consuming enterprises will no longer be able to form a low-cost competitive advantage by seizing water resources at low prices. In addition, the newly designed water resource tax system will form a forcing mechanism by restraining the behavior of economic participants. The steep increase in the cost of water use by high water-consuming enterprises has forced them to change their rough water use and restrain their improper water-use behavior (Marriott et al., 2021) [65]. At the same time, these enterprises have had to increase their investment in green innovation and enhance their green technological innovation level. Ambec and Barla (2002) found that the implementation of a sewage charge policy, although it will increase enterprise costs, will lead enterprises to actively reflect on their own problems in green development [66]; they will also have to formulate corresponding green development strategies and promote the innovation of governance mechanisms (Wang and Wu, 2023) [67]. In addition, the water tax reform makes enterprise costs stickier and gives those enterprises the ability to allocate more idle resources on their own, especially when business volumes are declining (Cannon, 2014) [68]. This forces enterprises to allocate idle resources to green transformation activities. For this reason, China's water resource tax reform will motivate enterprises to engage in green innovation and also bring the pressure of green innovation to enterprises. On this basis, this paper puts forward the following hypothesis:

Hypothesis 2: *Water tax reform increases green innovation in high water-consuming enterprises.*

Green technology innovation is the recombination of green production factors and production and manufacturing conditions, mainly including the innovation and application of energy savings and emission reduction, pollution control and management, recycling, and timely utilization in the field of manufacturing (Cai and Li, 2018) [69]. If an enterprise engages in technological innovation with an environmental bias, this not only can stimulate the enterprise to improve environmental quality but also can promote healthy and sustainable economic development (Song et al., 2020) [70]. Compared to traditional technological innovation, the manifestation of green technological innovation is more intense (Gilli et al., 2014) [71]. Replacing high-polluting production technologies with green production technologies reduces raw material inputs, energy consumption, and pollution emissions; lowers pollution control costs; and improves business performance (Porter and Linde, 1995) [13]. According to the theory of endogenous economic growth, an increase in the level of technological innovation can improve the relevant enterprise production process and methods; optimize the combination of labor, capital, and other production factors; and increase the levels of input and output, thus enhancing enterprise TFP (Klette and Griliches, 2000) [72].

Enterprise green technology innovation is conducive to reducing the consumption of raw materials, improving the efficiency of natural resource utilization, reducing enterprise production costs, and improving the input–output ratio (Carrión-Flores and Innes, 2010) [73]. High water-consuming enterprises that want to maximize profits can reduce water costs by actively developing or adopting new water-saving technologies, accelerating the elimination of outdated water-using processes, equipment, and appliances; increasing the sustainability of water resource use; and improving the reuse rate of water resources. All of these steps will help the enterprise to obtain additional revenues. At the same time, high water-consuming enterprises improve their production efficiency by improving production processes and methods and by optimizing the way they combine production factors. This in turn improves the TFP of high water-consuming enterprises. On this basis, the following hypothesis is proposed:

Hypothesis 3: *Green innovation in high water-consuming enterprises is positively correlated with TFP. That is, green innovation in high water-consuming enterprises helps to improve TFP.*

Based on the above theoretical analysis, the theoretical framework of this article is constructed, as shown in Figure 1.

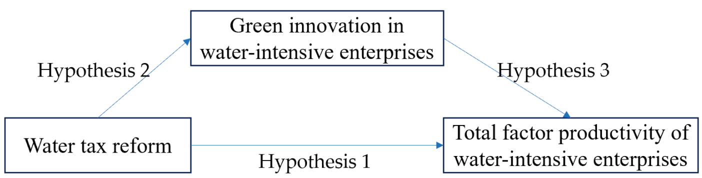

Figure 1. Theoretical framework diagram.

4. Research Design

4.1. Sample Selection

To accurately identify the impact of a water resource tax reform on the green innovation of high water-consuming enterprises, the study sample includes all high water-consuming enterprises in Chinese A-share listed enterprises, from 2007 to 2021. Excluded enterprises include ST and *ST enterprises, as well as enterprises that had unsound financial data and extreme values during the observation period. Finally, financial enterprises and enterprises with gearing ratios greater than 1 were also excluded. Sample data are from the China Stock Market and Accounting Research (CSMAR) database and include a total of 8949 sample observations from 1081 listed enterprises.

According to the Guidelines for the Industry Classification of Listed Companies (revised in 2012), this study selected 21 industries as high water-consuming industries and used industry codes to screen high water-consuming enterprises. These 21 industries include coal mining and washing; oil and gas mining; ferrous metal mining; non-ferrous metal mining; mining auxiliary activities; agro-food processing; food manufacturing; wine, beverage and refined tea manufacturing; textile, textile garments and apparel; leather, fur, feathers, and their products and footwear; paper and paper products; printing and recording media reproduction; petroleum processing; coking and nuclear fuel processing; chemical raw material and chemical products manufacturing; ferrous metal smelting and rolling; non-ferrous metal smelting; rolling and processing; metal products; power and heat production and supply; and gas production and supply. The statistical software used in this article is Stata16.0.

4.2. Variable Measurement

The water tax reform is a dummy variable (denoted by *TT*), where $TT_{it} = Treated_i \times Time_t$. The term $Treated_i$ is a policy group dummy variable and has a value of 1 if the province where the firm is located has implemented the water tax reform, and 0 if it has not. The term Timet is a time dummy variable. Based on timing and sequential differences in the water resource tax reform, this variable has a value of 1 in the year of the reform pilot and later; otherwise, it is 0. Hebei Province was the first to start the water resource tax reform pilot on 1 July 2016. In 2017, the pilot scope of the reform was expanded to nine provinces: Beijing, Tianjin, Shanxi, Inner Mongolia, Shandong, Henan, Sichuan, Shaanxi, and Ningxia.

An enterprise's green innovation level (denoted by *GI*) is represented by the number of its patent applications. Patents, as a standard for measuring a company's technological innovation capability, have been widely recognized by the academic community. They reflect an enterprise's innovation capability in terms of new materials, processes, and technologies (Fleming and Sorenson, 2004) [74]. Green patents can intuitively reflect the output capacity of green innovation, and patent authorization is related to various factors, such as approval time. This makes measuring the impact of institutional shocks on corporate green innovation behavior quite difficult. Patent applications are more stable, reliable, and timely than patent authorizations (Wurlod and Noailly, 2018) [75]. The data on green invention patents come from the CNRDS (Chinese National Research Data Services) platform database. The data calculation steps are as follows: Firstly, this study downloaded and organized the list of listed enterprises and their subsidiaries through the annual reports of the Shenzhen and Shanghai Stock Exchanges in China, and data were collected based on the summary list. Secondly, enterprise patent information was obtained through the official website of the China National Intellectual Property Administration, mainly involving patent applicants, application time, and IPC classification number. Finally, based on the IPC codes listed in the International Patent Classification green list, the number of green invention patent applications of the sample companies were manually identified. Based on Wurlod and Noailly (2018) [75] and Liu et al. (2023) [76], this study used the natural logarithm of the number of green invention patents filed by enterprises plus 1 to measure the green innovation level of enterprises.

The TFP of enterprises (denoted by TFP_LP) was determined using the LP method (Levinsohn and Petrin, 2003) [77]. The specific processing was as follows: Based on the Cobb–Douglas production function, the intermediate input variables were added to estimate TFP. The specific Model (1-1) was as follows: $y_{it} = \beta_k k_{it} + \beta_l l_{it} + \beta_m m_{it} + \omega_{it} + \varepsilon_{it}$ $(1-1)$. In this expression, y_{it} is the total output, with the operating income of the sample firms used as the proxy variable; k_{it} denotes capital inputs, with the net fixed assets serving as the proxy variable; l_{it} denotes labor inputs, with the number of firm employees used as the proxy variable; m_{it} denotes intermediate inputs, with the sum of operating costs, selling expenses, administrative expenses, and financial expenses, minus the balance of depreciation and amortization versus cash payments made to and for employees as the proxy variable, and ω_{it} denotes the TFP (*TFP_LP*). The LP method makes three basic assumptions. Firstly, assuming that the TFP of an enterprise follows an exogenous first-order Markov process, Model (1-2) can be obtained: $\omega_{it} = E(\omega_{it}|\omega_{it-1} + \theta_{it})$ (1-2). Secondly, the influencing factors of intermediate input variables are limited to capital and technology, i.e., $m_{it} = m_{it}(\omega_{it}, k_{it})$ (1-3). Thirdly, the assumption was made that, when capital investment remains constant, the intermediate input variable increases in line with the increase in TFP, and the two are monotonically increasing functions, i.e., $\omega_{it} = \omega_{it}(m_{it}, k_{it})$ (1-4). Substituting Models (1-2), (1-3), and (1-4) into Model (1-1) yields Model (1-5), which is $y_{it} = \beta_l l_{it} + \beta_k (k_{it} + m_{it}) + \varepsilon_{it}$ (1-5). Once Model (1-5) is estimated, all coefficients in the production function will be successfully estimated. Using this result, one can fit Equation (1-5) to obtain the logarithmic value of the residuals, which is also the logarithmic value of TFP.

Green innovation requires a large amount of capital investment (Gramkow and Anger-Kraavi, 2018) [78], and enterprises with strong profitability can provide sufficient financial flow for green innovation. The higher the growth potential of an enterprise is, the more funds and resources that enterprise will allocate to expanding production scale and marketing, which squeezes out investment in innovation (Filson and Lewis, 2000) [79]. The higher the financial leverage of an enterprise is, the more that enterprise will increase the availability of funds and have a positive impact on technological innovation (Amore et al., 2013) [80]. Independent directors can better fulfill their regulatory functions through their professional competence and have an impact on the innovation output of the enterprise (Francis and Smith, 1995) [81]. Expanding the size of the board of directors can promote corporate innovation, as increasing the number of directors can enrich the decision-making level of the enterprise. This enables the enterprise to make more comprehensive and thoughtful innovation decisions, thereby improving the innovation performance of the enterprise (Cleyn and Braet, 2012) [82]. Unlike the free-riding behavior of small and medium-sized shareholders, major shareholders often actively participate in corporate governance, due to their high shareholding ratio and large market value. Belloc (2013) confirmed that major shareholders can influence corporate innovation through “hand voting” and “foot voting” [83]. A general manager concurrently serving as the chairman will expand the power of the management, which will lead to the weakening of the supervisory function of the board of directors. Zahra et al. (2000) argued that job separation contributes to rational decision making in enterprises and is significantly positively correlated with research and development expenditures [84]. Raising the annual salary of executives can enhance their risk-taking ability and further stimulate their willingness to innovate (Coles et al., 2006) [85]. Implementing equity and salary incentives for executives can encourage them to view business development from a long-term perspective, thereby further enhancing their willingness to innovate (Miller et al., 2007) [86]. The deep evolution of digital technology has had a great impact on the productivity growth of enterprises (Yoo et al., 2010) [87]. Driven by digital transformation, enterprises have achieved “cost reduction” and “strong innovation” by constructing different data management systems, improving production efficiency (Mikalef and Pateli, 2017) [88]. Financial subsidies and tax incentives have a positive impact on corporate innovation, a finding which has been extensively validated (Bronzini et al., 2016; Lokshin and Mohnen, 2012) [89,90].

Based on the above considerations, green innovation in enterprises is not only influenced by the water resource tax reform but also by profitability, growth, financial leverage, board governance, major shareholder governance, manager incentives, market competition, technology spillover, and fiscal policies. Therefore, these variables were used as control variables.

See Table 1 for specific variable definitions and descriptions.

Table 1. Specific variable definitions and descriptions.

Variable Type	Variable Name	Variable Symbol	Definition
Explained variable	Total factor productivity	*TFP_LP*	Total factor productivity calculated using the LP method
Mediator variable	Enterprise green innovation	*GI*	Add 1 to the number of invention patents applied for by the enterprise in the current year, taking the natural logarithm.
Explanatory variable	Water resource tax reform	*TT*	Whether to carry out pilot water resource tax reform, represented by the dummy variable *TT*, $TT_{it} = Treated_i \times Time_t$
Control variable	Company profitability	*ROA*	Net profit margin on total assets
	Company growth	*Growth*	Total assets growth rate
	Financial leverage	*Lev*	Asset–liability ratio
	Independent director governance	*Id*	The proportion of independent directors to the size of the board of directors
	Director board size	*Bs*	Total number of directors in the board of directors
	Governance of major shareholders	*Msg*	Shareholding ratio of the largest shareholder
	CEO duality	*Pt*	The value of the general manager concurrently serving as the chairman is 1; otherwise, the value is 0.
	Managerial ownership	*MS*	Proportion of shares held by company executives
	Executive compensation	*MC*	The total monetary compensation of company executives is calculated as the natural logarithm.
	Product market competition	*HHI*	$HHI = \sum_{i=1}^{n}(x_i/X)^2$, x_i represents the size of the *i*-th enterprise, and *X* represents the total market size.
	Digital transformation	*DT*	Data calculation of text mining based on digital lexicon
	Financial subsidy	*FS*	(Government subsidies—returns of various taxes and fees received)/total assets
	Tax incentives	*TI*	Returns of various taxes and fees received/total assets
	Industry	*Industry*	Industry dummy variable
	Year	*Year*	Year dummy variable

4.3. Model Setup

Model (1) was constructed to test Hypothesis 1. The explained variable is enterprise TFP, and the explanatory variable is the water resource tax reform. Based on Hypothesis 1, it is expected that the regression coefficient α_1 of the water resource tax reform is significantly positive; such a result indicates that the water resource tax reform effectively enhances enterprise TFP.

$$TFP\_LP_{i,t} = \alpha_0 + \alpha_1 TT_{i,t} + \alpha_i Control_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (1)$$

$$GI_{i,t} = \beta_0 + \beta_1 TT_{i,t} + \beta_i Control_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (2)$$

$$TFP\_LP_{i,t} = \gamma_0 + \gamma_1 GI_{i,t} + \gamma_i Control_{i,t} + \sum Industry + \sum Year + \varepsilon_{i,t} \quad (3)$$

Model (2) was constructed to test Hypothesis 2. The explanatory variable is corporate green innovation, and the explained variable is the water tax reform. According to Hypothesis 2, the regression coefficient of β_1 in Equation (2) is expected to be significantly positive, which indicates that the water tax reform will significantly promote corporate green innovation.

Model (3) was constructed to test Hypothesis 3. The explanatory variable is enterprise TFP, and the explained variable is enterprise green innovation. According to Hypothesis 3, it is expected that the regression coefficient of γ_1 in Equation (3) is significantly positive, which indicates that enterprise green innovation will significantly enhance total factor productivity.

5. Empirical Results and Analysis

5.1. Descriptive Statistics and Pearson Correlation Analysis

Table 2 shows the descriptive statistics of the main variables. In Table 2, the mean of *TFP_LP* is 10.9894; the median is 10.8418, and the standard deviation is 1.2855. This indicates that there are relatively small individual differences in the TFP of high water-consuming enterprises. The mean of *GI* is 0.2082; the median is 0, and the standard deviation is 0.5843. This indicates that there are large individual differences in the green innovation of high water-consuming enterprises, and most sampled enterprises do not have patents for green inventions. The mean value of *TT* is 0.1406, indicating that about 14.06% of the sample data were from the year of the water resource tax implementation and the year after.

Table 2. Descriptive statistics of the main variables.

Variable	Mean	Median	Max	Min	SD	Obs
TFP_LP	10.9894	10.8418	14.7543	4.4336	1.2855	8949
GI	0.2082	0	6.6983	0	0.5843	8949
TT	0.1406	0	1	0	0.3476	8949
ROA	0.0410	0.0363	0.6271	−0.6449	0.0709	8949
Growth	0.1326	0.0780	19.0954	−0.8490	0.4286	8949
Lev	0.4453	0.4448	0.9970	0.0080	0.2014	8949
Id	0.3724	0.3333	0.8	0.1429	0.0555	8949
Msg	0.3661	0.3468	0.8999	0.0029	0.1559	8949
Pt	0.2206	0	1	0	0.4146	8949
Bs	8.9136	9	18	0	1.9163	8949
MS	0.0507	0.0001	0.7259	0	0.1216	8949
MC	14.7365	14.7958	18.5844	0	1.1287	8949
HHI	0.1248	0.1049	1	0.0144	0.1138	8949
DT	0.7037	0	5.0689	0	0.9758	8949
FS	0.0048	0.0023	0.4212	0	0.0166	8949
TI	0.0006	0	0.1132	0	0.0029	8949

Table 3 shows the Pearson correlation analysis. In Table 3, the correlation coefficient between *GI* and *TFP_LP* is 0.3779, which is significant at a 1% level. This indicates that green innovation significantly improves enterprise TFP. The correlation coefficient between *TT* and *TFP_LP* is 0.1292, which is significant at a 1% level. This indicates that the water resource tax reform improves enterprise TFP. The correlation coefficient between *TT* and *GI* is 0.1051, which is significant at a 1% level. This indicates that the water resource tax reform increases the relevant enterprise green innovation level. The Pearson correlation coefficients of all variables are less than 0.8, indicating that the possibility of covariance is small when later analyzing linear regression.

Table 3. Pearson correlation analysis.

Variable	TFP_LP	GI	TT	ROA	Growth	Lev	Id
TFP_LP	1						
GI	0.3779 ***	1					
TT	0.1292 ***	0.1051 ***	1				
ROA	0.1375 ***	−0.0017	0.0267 **	1			
Growth	−0.0140	−0.0230 **	−0.0273 ***	0.1735 ***	1		
Lev	0.3670 ***	0.1195 ***	−0.0223 **	−0.3497 ***	−0.0057	1	
Id	0.0271 **	0.0287 ***	0.0157	0.0080	0.0020	−0.0521 ***	1
Msg	0.3281 ***	0.1503 ***	−0.0397 ***	0.1236 ***	−0.0196 *	0.0588 ***	0.0551 ***
Pt	−0.1547 ***	-0.0693 ***	−0.0547 ***	0.0394 ***	0.0297 ***	−0.1432 ***	0.1180 ***
Bs	0.2549 ***	0.1430 ***	−0.0026	0.0115	−0.0265 **	0.2334 ***	−0.6101 ***
MS	−0.1822 ***	−0.0633 ***	−0.0630 ***	0.1026 ***	0.0461 ***	−0.2433 ***	0.1246 ***
MC	0.3162 ***	0.1719 ***	0.1081 ***	0.1823 ***	0.0099	−0.0474 ***	−0.0033
HHI	−0.0911 ***	−0.0116	−0.0868 ***	−0.0891 ***	−0.0326 **	0.0177	0.0093
DT	0.0149	−0.0194	−0.0187	0.0144	−0.0061	0.0153	0.0114
FS	−0.0365 **	−0.0599 ***	0.0175	0.0504 ***	−0.0037	−0.0074	0.0189
TI	0.1645 ***	0.0590 ***	0.0335 **	−0.0261 *	0.0237	−0.0068	0.0956 ***
Variable	Msg	Pt	Bs	MS	MC	HHI	DT
Msg	1						
Pt	0.0518 ***	1					
Bs	0.0806 ***	−0.0755 ***	1				
MS	−0.3995 ***	0.0803 ***	−0.1653 ***	1			
MC	0.1003 ***	−0.0647 ***	0.4409 ***	−0.1910 ***	1		
HHI	0.0408 ***	−0.0296 ***	0.0534 ***	0.0688 ***	0.0514 ***	1	
DT	−0.0002	−0.0015	−0.0218	0.0446 ***	−0.0390 ***	0.0148	1
FS	0.0458 ***	0.0380 ***	−0.0441 ***	0.0432 ***	0.0369 **	−0.0513 ***	−0.0015
TI	0.0331 **	0.0629 ***	−0.0717 ***	0.0654 ***	0.2166 ***	0.0732 ***	−0.0077
Variable	FS	TI					
FS	1						
TI	0.0358 **	1					

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

5.2. Benchmark Regression Analysis

Table 4 shows the baseline regression analysis. First, Model (1) was used to assess the impact of the water resource tax reform on enterprise TFP. The regression coefficient of the water resource tax reform is 0.1147, with a *t*-value of 4.49, which is significant at a 1% level. This indicates that the water resource tax reform significantly increases enterprise TFP. That is, Hypothesis 1 was tested.

Table 4. Benchmark regression analysis.

Variable	Model (1)	Model (2)	Model (3)
TT	0.1147 *** (4.49)	0.1029 *** (5.73)	
GI			0.3547 *** (24.29)
ROA	3.4274 *** (27.16)	−0.0214 (−0.24)	3.4413 *** (28.14)
Growth	−0.0775 *** (−4.15)	−0.0189 (−1.44)	−0.0716 *** (−3.96)
Lev	1.6378 *** (35.40)	0.1726 *** (5.31)	1.5783 *** (35.14)
Id	0.9539 *** (6.07)	0.6019 *** (5.45)	0.7413 *** (4.85)
Msg	1.3241 *** (24.11)	0.4250 *** (11.02)	1.1692 *** (21.83)
Pt	−0.1292 *** (−6.06)	−0.0361 ** (−2.41)	−0.1197 *** (−5.80)
Bs	0.0644 *** (12.99)	0.0365 *** (10.47)	0.0522 *** (10.80)
MS	−0.3707 *** (−4.95)	−0.0710(−1.35)	−0.3620 *** (−5.00)
MC	0.2051 *** (26.57)	0.0594 *** (10.95)	0.1834 *** (24.36)
HHI	0.1317 (0.83)	0.1510 (1.36)	0.0730 (0.48)
DT	3.7172 (1.36)	2.1639 (1.13)	2.9031 (1.09)
FS	−3.6460 *** (−7.71)	−0.4637 (−1.40)	−3.4948 *** (−7.62)
TI	0.1054 *** (11.16)	0.0069 (1.04)	0.1019 *** (11.14)
Constant	2.8642 *** (19.23)	−1.7303 *** (−16.54)	3.4882 *** (23.80)
Year/industry	Yes	Yes	Yes
Adjust_R^2	0.4800	0.2191	0.5113
Obs	8949	8949	8949

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

Second, Model (2) was used to assess the impact of the water resource tax reform on enterprise green innovation. The regression coefficient of the water resource tax reform is 0.1029, with a *t*-value of 5.73, which is significant at a 1% level. This indicates that China's water resource tax reform significantly improves the level of enterprise green innovation. That is, Hypothesis 2 was tested.

Finally, Model (3) was used to assess the impact of green innovation on enterprise TFP. The results show that the regression coefficient of enterprise green innovation is 0.3547, with a *t*-value of 24.29. That is, Hypothesis 3 was tested.

5.3. Robustness Tests

Robustness tests were performed to assess the robustness of the study results.

5.3.1. Fixed Effects Model

Given possible endogeneity problems, this paper applied a panel fixed effects model to empirically test the relationship among the water resource tax reform, green innovation, and enterprise TFP. Table 5 shows the results of the test using the fixed effects model. This is consistent with the results of the benchmark regression.

Table 5. Results of the test using the fixed effects model.

Variable	Model (1)	Model (2)	Model (3)
TT	0.1147 *** (4.49)	0.1029 *** (5.73)	
GI			0.3547 *** (24.29)
$Control_{i,t}$	Yes	Yes	Yes
Constant	3.1830 *** (21.53)	−1.6088 *** (−15.49)	3.7774 *** (26.05)
Year/industry	Yes	Yes	Yes
Adjust_R^2	0.4639	0.2048	0.4966
Obs	8949	8949	8949

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

5.3.2. Substitution of Key Variables

Table 6 shows the test results when replacing the key variables. Based on Liu et al. (2023) [76], the natural logarithm of the total number of an enterprise's green patent applications plus 1 was used to measure the enterprise's green innovation level, denoted by GI'. Green patents include green utility model patents and green invention patents. When using the LP method (Levinsohn and Petrin, 2003) [77], the GMM model was used to calculate the enterprise's TFP during the linearization of the Cobb–Douglas production function. The regression results in Table 6, including the tests replacing the explained variables or the explanatory variables, and re-testing Models (1), (2), and (3), indicate that the water tax reform has a positive contribution to green innovation and the enterprise's TFP, while green innovation of enterprises has a positive contribution to the enterprise's TFP.

Table 6. Test results when replacing the key variables.

Variable	Replacing the Explanatory Variables		Replacing the Explained Variables	
	Model (2)	**Model (3)**	**Model (1)**	**Model (3)**
TT	0.3387 *** (13.49)		0.0732 *** (3.83)	
GI'		0.3135 *** (34.20)		
GI				0.1303 *** (10.57)
$Control_{i,t}$	Yes	Yes	Yes	Yes
Constant	−2.7356 *** (−17.19)	3.7379 *** (26.46)	0.9412 *** (7.77)	1.1697 *** (9.56)
Year/industry	Yes	Yes	Yes	Yes
$Adjust\_R^2$	0.2442	0.5264	0.2499	0.2580
Obs	8949	8949	8949	8949

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

5.3.3. PSM-DID Model

To mitigate the systematic differences in the trend of changes in the water resource tax reform and other tax reforms and to reduce the estimation bias of the double-difference method, this study further applied the PSM-DID method to conduct a robustness test. In the specific estimation, this study used the kernel matching method for estimation to test the robustness of the role of the water tax reform in promoting green innovation and enhancing enterprise-level TFP. Figure 2 shows the density function plot of the propensity score value. Before estimation, the study also assessed the match between the experimental group and the control group. This was performed by drawing the density function plot of the propensity score value. The resulting matching is relatively close, indicating that the matching effect of this paper is very good. Thus, the feasibility and rationalization of the PSM-DID approach is further demonstrated, based on the common support assumptions.

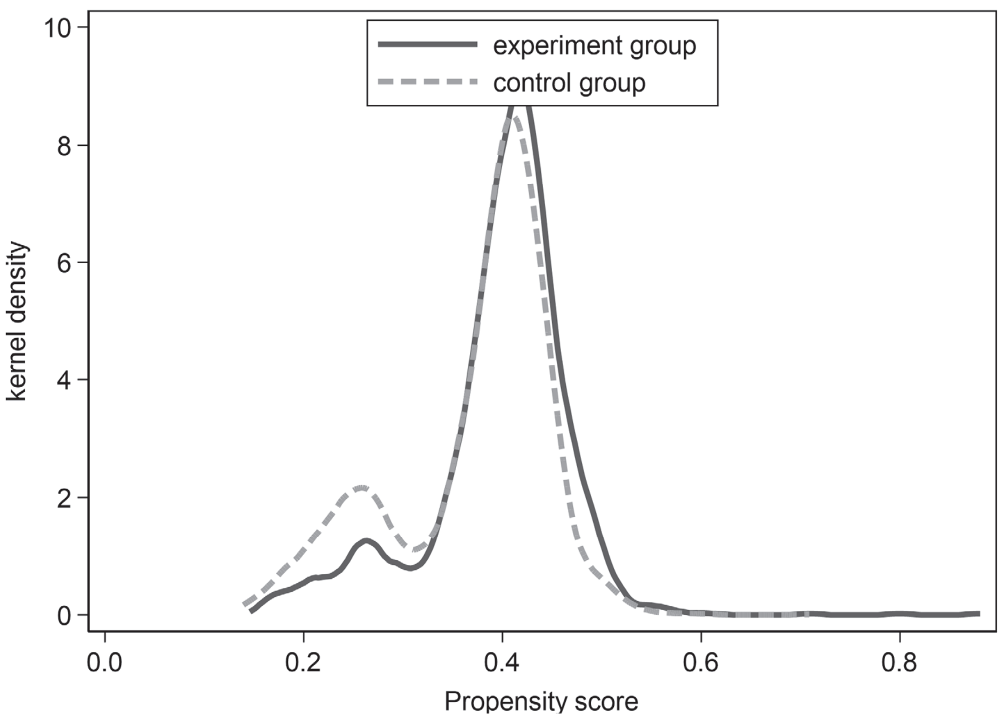

Figure 2. Density function plot of the propensity score value.

Table 7 shows the PSM-DID model test results and indicates that, after applying the PSM-DID method, China's water tax reform still significantly increased the number of green invention patents of enterprises (by 9.1%) and improved enterprise TFP (by 18.2%). The results of the PSM-DID estimation do not significantly differ from the double-difference results in the previous section.

Table 7. PSM-DID model.

Column 1: *TT* → *TFP_LP*					
Weighted variable(s)	Mean control	Mean treated	Diff.	∣t∣	Pr (∣T∣ > ∣t∣)
TFP_OLS	8.275	8.458	0.182	5.63	0.0000 ***
ROA	0.037	0.039	0.002	0.88	0.3773
Growth	0.145	0.150	0.005	0.32	0.7504
Lev	0.493	0.491	−0.002	0.33	0.7419
Id	0.364	0.364	0.000	0.13	0.8999
Msg	0.384	0.390	0.006	1.12	0.2642
Pt	0.117	0.112	−0.004	0.45	0.6532
Bs	9.415	9.429	0.013	0.20	0.8416
MS	0.023	0.024	0.001	0.38	0.7046
MC	14.402	14.427	0.025	0.56	0.5783
HHI	0.134	0.139	0.005	1.02	0.3087
TI	0.001	0.001	0.000	0.18	0.8593
FS	0.004	0.004	0.000	0.35	0.7250
DT	0.311	0.310	-0.001	0.06	0.9529
Column 2: *TT* → *GI*					
Weighted variable(s)	Mean control	Mean treated	Diff.	∣t∣	Pr (∣T∣ > ∣t∣)
GI	0.128	0.219	0.091	5.18	0.0000 ***
ROA	0.037	0.039	0.002	0.88	0.3773
Growth	0.145	0.150	0.005	0.32	0.7504
Lev	0.493	0.491	−0.002	0.33	0.7419
Id	0.364	0.364	0.000	0.13	0.8999
Msg	0.384	0.390	0.006	1.12	0.2642
Pt	0.117	0.112	−0.004	0.45	0.6532
Bs	9.415	9.429	0.013	0.20	0.8416
MS	0.023	0.024	0.001	0.38	0.7046
MC	14.402	14.427	0.025	0.56	0.5783
HHI	0.134	0.139	0.005	1.02	0.3087
TI	0.001	0.001	0.000	0.18	0.8593
FS	0.004	0.004	0.000	0.35	0.7250
DT	0.311	0.310	−0.001	0.06	0.9529

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

5.4. Intrinsic Mechanism of Action Test

According to the above theoretical analysis and empirical test, the water resource tax reform significantly promotes enterprise green innovation and enhances TFP, while enterprise green innovation significantly enhances TFP. Based on the principle underlying the mediation effect test (Baron and Kenny, 1986) [91], the relationship between the water tax reform, corporate green innovation, and TFP was tested using the Sobel method. Table 8 shows the results of the Sobel test. Among them, *Path c* is the regression result of China's water resource tax reform on enterprise TFP; *Path a* is the regression result of the water resource tax reform on enterprise green innovation, and *paths b* and *c′* are the regression results of the water resource tax reform and enterprise green innovation, respectively, on enterprise TFP. In Table 8, the path test value shows that enterprise green innovation has a significant partial mediating effect between the water resource tax reform and enterprise TFP.

Table 8. Results of the Sobel test.

Variable	***Path c*** **(Model with dv Regressed on iv)**	***Path a*** **(Model with Mediator Regressed on iv)**	***Paths b and c′*** **(Model with dv Regressed on Mediator and iv)**
TT	0.2412 *** (9.64)	0.1550 *** (9.02)	0.1847 *** (7.59)
GI			0.3646 *** (24.44)
$Control_{i,t}$	Yes	Yes	Yes
Constant	2.4059 *** (17.11)	−1.9716 *** (-20.42)	3.1247 *** (22.43)
Year/industry	Yes	Yes	Yes
$Adjust\_R^2$	0.3682	0.0903	0.4077
Obs	8949	8949	8949

Table 8. *Cont.*

Variable	***Path c*** **(Model with dv Regressed on iv)**		***Path a*** **(Model with Mediator Regressed on iv)**	***Paths b and c′*** **(Model with dv Regressed on Mediator and iv)**
Column 1: Sobel–Goodman Mediation Tests				
	Est	Std_err	z	P > ∣z∣
Sobel	0.057	0.007	8.463	0.000
Aroian	0.057	0.007	8.457	0.000
Goodman	0.057	0.007	8.469	0.000
Column 2: Indirect, Direct, and Total Effects				
	Est	Std_err	z	P > ∣z∣
a_coefficient	0.155	0.017	9.021	0.000
b_coefficient	0.365	0.015	24.441	0.000
Indirect_effect_aXb	0.057	0.007	8.463	0.000
Direct_effect_c′	0.185	0.024	7.586	0.000
Total_effect_c	0.241	0.025	9.637	0.000
Proportion of total effect that is mediated:		0.234		
Ratio of indirect to direct effect:		0.306		
Ratio of total to direct effect:		1.306		

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

5.5. Heterogeneity Analysis

Considering the special nature of enterprise property rights in China, enterprises are divided into two groups: state-owned enterprises (SOEs) and non-state-owned enterprises (non-SOEs), based on the ultimate economic controller of the enterprise. Table 9 shows the regression results when comparing the two sets of enterprises. For the SOE sample, the Model (1) test results indicate that the regression coefficient of *TT* is not significantly positive. The Model (2) test results also show the regression coefficient of *TT* is significantly positive. The test results for Model (3) indicate that the regression coefficient of *GI* is significantly positive. In the non-SOE sample, the test results of Models (1) and (2) indicate that the regression coefficients of *TT* are significantly positive. The test results of Model (3) indicate that the regression coefficients of *GI* are significantly positive. Whether in SOEs or non-SOEs, the water tax reform plays a significant role in promoting green innovation in enterprises, and green innovation in enterprises also plays a significant role in promoting TFP. However, the contribution of the water tax reform to TFP is significant only in non-SOEs, compared to SOEs.

Table 9. Distinguishing the property nature of enterprises.

Variable	SOEs			Non-SOEs		
	Model (1)	**Model (2)**	**Model (3)**	**Model (1)**	**Model (2)**	**Model (3)**
TT	0.0484(1.17)	0.0615 * (1.88)		0.1149 *** (3.79)	0.0640 *** (3.73)	
GI			0.3704 *** (19.84)			0.1708 *** (6.63)
$Control_{i,t}$	Yes	Yes	Yes	Yes	Yes	Yes
Constant	3.0283 *** (15.46)	−2.0909 *** (−13.49)	3.8029 *** (19.88)	3.4272 *** (13.03)	−0.6637 *** (−4.46)	3.5634 *** (13.57)
Year/industry	Yes	Yes	Yes	Yes	Yes	Yes
Adjust_R^2	0.5202	0.3210	0.5613	0.4537	0.0834	0.4571
Obs	4237	4237	4237	4712	4712	4712

Note: *, **, and *** denote the significance levels at 10%, 5%, and 1%, respectively.

The contribution of the water tax reform to enterprise TFP is not significant in SOEs, probably because SOEs are less sensitive to the water tax. SOEs naturally have good government-enterprise relations, have easier access to policy information, and are able to withstand a higher water tax levy.

6. Conclusions

Strengthening the constraints on water resources is important for modernizing a harmonious coexistence between human beings and nature. This paper analyzes the opportunities offered by the pilot implementation of a policy shift from a water resource fee to a tax. This study focuses on the role of the water resource tax reform in strengthening the constraints of a water resource tax, forcing enterprises to move toward green innovation and enhancing the intrinsic mechanisms involved in productivity. The double-difference method was used to explore the relationship among the water resource tax reform, enterprise green innovation, and total factor productivity (TFP). The study finds that shifting water resource reforms from a fee to a tax significantly increases the green innovation level and TFP of enterprises. Green innovation has a significant partial mediating role between the water tax reform and TFP. Green innovation also enhances enterprise TFP. Further differentiating the sample with respect to firm property rights shows that the economic effects of the water tax reform are larger for non-state-owned firms than state-owned firms. This study provides empirical evidence for expanding the scope of the pilot water resource tax reform.

This study's findings lead to the following recommendations. On the one hand, it is important to accelerate the reform of the water resource tax and optimize the system of paid water resource use. There is currently a significant contradiction between the supply and demand of water resources, highlighting the need for an intervention strategy that is market-oriented and government-supplemented. It is also important to maximize the decisive role of the market price mechanism and to rely on the water resource tax reform to promote water resource intensification and water resource conservation. It is also vitally important to maximize the information advantage of local governments and to rationalize the formulation of the water resource tax rate. The goal should be to effectively constrain enterprise water-use behavior, while avoiding an excessive crowding effect on the focal production and business activities of the enterprise. These actions should promote industrial transformation and upgrading.

On the other hand, enterprises are encouraged to engage in green technological innovation and to continuously improve their green innovation level. Green transformation and development have become consensus approaches in the international community. This represents a shared global response to the climate change crisis, environmental pollution, and ecological damage and creates major opportunities for future economic and societal development. The key to enterprise green transformation is to rely on technological innovation to improve efficiency. Enterprises can use technological innovation to improve resource utilization rates, drive development toward the two ends of the "smile curve", and transform technology-intensive and high-value-added industries. These actions promote green enterprise development and optimize industrial structures.

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Optimizing Multi-Scenario Water Resource Allocation in Reservoirs Considering Trade-Offs between Water Demand and Ecosystem Services

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Abstract: Reservoir engineering plays a critical role in achieving rational water resource allocation, providing ecological services, and promoting regional development. However, in the formulation of water allocation plans, there is often a tendency to prioritize meeting regional water demand while overlooking ecological benefits. This study develops a multi-objective water allocation model based on evaluating ecosystem services value supply and demand, integrating indicators such as ecosystem service fulfillment ability, water resources fulfillment ability, and equilibrium operation degree. Different development scenarios are also established using a forecasting model to formulate water allocation plans and apply a case study of the Datun Reservoir, a key hub on the eastern route of the South-to-North Water Diversion Project in China. This study demonstrates that (1) by optimizing the allocation of domestic and industrial water supply and reservoir storage, the overall ecosystem service value of the Datun Reservoir can be enhanced by 5.15% to 11.36% and (2) in scenarios of high economic growth, there is potential to achieve coordination between water supply and ecosystem service value. (3) However, lower-than-expected economic growth may lead to a trade-off between ecosystem services and water supply capacity in the reservoir, which could be maintained at a lower level. The methods proposed in this paper are of significant practical importance for guiding rational reservoir water allocation and achieving coordination between ecological services and water supply capacity.

Keywords: ecosystem services; water allocation; reservoir management; demand forecasting; multi-scenario setting

1. Introduction

Water resources are an integral part of natural ecology and essential resources for the sustainable development of human society. Humans need an adequate supply of water to meet basic needs such as drinking, sanitation, and washing [1,2]. Agricultural irrigation is crucial for ensuring food production and the supply of agricultural products [3]. Water resources are also part of the material supply of natural ecosystem services, thus influencing human well-being [4]. Ecosystem services (ESs) encompass a range of resources and environmental processes that nature offers to human society, such as water supply, solid recycling, etc. [5–7]. Water resources (WRs) comprise an essential component supporting ecosystem services. For instance, the creation and preservation of wetlands and the propagation and stability of aquatic organisms are linked to water resources [8]. Wetlands have important functions such as water purification, flood prevention, and maintaining hydrological balance [9]. Aquatic ecosystems, such as lakes and rivers, provide numerous species and resources, maintaining the ecological balance of food chains. At the same time, aquatic species directly or indirectly provide ecosystem services such as food, medicine, and raw materials to humans. Furthermore, the development of many tourism industries is closely related to water resources and ecosystem services as the attractiveness of water resource attractions such as lakes, beaches, and hot springs impacts the development and economic benefits of the tourism industry [10]. Water resources and ecosystem services exert substantial influence on socioeconomic development and human welfare [11]. The abundance or scarcity of water resources affects the development and expansion of economic activities. Adequate water resources can meet human domestic and agricultural irrigation needs while providing a sustainable and stable source of funding for ecosystems, maintaining ecological balance, and ensuring the health of ecosystem services [12,13]. To achieve sustainable economic and social development for humanity, the preservation and judicious utilization of water resources serve as effective facilitators.

Reservoirs, as a type of water engineering, are essential means for achieving rational water allocation and the spatial optimization of water resources [6]. They bear the important mission of ensuring the safe use of water in regions. Moreover, reservoirs are typical artificial ecosystems, possessing functions such as maintaining wetland ecological stability and protecting biodiversity [14]. Therefore, achieving scientifically optimized reservoir management facilitates the efficient use of water resources and enhances their ability to provide ecosystem services to specific regions [15]. Water resources management and optimization involve the scientific and reasonable management and distribution of reservoir storage and discharge to meet human needs and ensure sustainable socioeconomic development. For water resource management in reservoirs, incorporating the improvement and optimization of ecosystem service effects into the measurement framework not only contributes to the sustainable use of water resources but also takes into account the maintenance of regional ecological homeostasis [16]. The processes of reservoir storage and discharge can affect riverine ecosystems, affecting ecosystem services such as aquatic biodiversity, wetland protection, and water quality improvement [17]. Thus, in reservoir water resources management, the ecological needs of riverine ecosystems should be considered under the premise of ensuring human water resource needs. Rational reservoir storage and discharge plans should be developed to minimize adverse effects on ecosystems [18]. Secondly, there is also an inherent need for reservoir management agencies to realize the ecological service potential of each project as much as possible with the help of the scientific allocation of water resources [19]. Configuration options should maximize ecosystem service provisioning while meeting the needs of different regions and stakeholders, thereby contributing to sustainable socioeconomic development [20]. Furthermore, it is imperative to implement long-term water resource planning and comprehensive management to make scientifically sound predictions and adjustments to reservoir water quantity, thereby addressing future challenges related to water resources.

To ensure that reservoir water allocation schemes meet regional water demand while also considering the effect of ecosystem services, this study conducted the following research from the standpoint of balancing supply and demand: (1) referring to the ecosystem services theory framework, a model for assessing the service value of plain reservoirs was proposed, integrating various methods such as shadow engineering and willingness to pay; (2) a water resources multi-objective optimization model was constructed, including indicators such as the index of ES meeting (ESI) and the index of WR meeting (WSI) and their coordination degree (WED); (3) the ARIMA time series forecasting model was applied to set multiple external scenarios for reservoir water quantity management, exploring water allocation schemes under changing economic growth rates and scenarios of improved societal water use efficiency; and (4) finally, using the Datun Reservoir, a key hub of the water transfer project along the northern part of Shandong Province, part of the South-to-North Water Diversion East Route Project in China, as an actual case, the model was applied.

2. Materials and Methods

2.1. Ecosystem Service Supply and Demand Relationship

2.1.1. Calculation of Ecosystem Service Functions and Values of Reservoirs

Reservoirs in water transfer projects provide WRs to the regions along their routes to support economic production and residential life. They are also crucial to maintaining the water abundance of water systems along their routes and purifying water quality [21,22]. Some reservoirs also have the function of providing ecological replenishment to regional ecosystems, such as wetlands and swamps [23]. The development of scenic water areas also provides recreational facilities for residents, and some large reservoirs have been transformed into tourist attractions, bringing significant tourism benefits to the region [15,16]. This study categorizes ecosystem services following the classification framework of Pahl-Wostl et al. [24] and Zhao et al. [25] into regulation, provision, support, and cultural services. Based on the engineering characteristics of reservoirs and referring to the research of Safaei et al. [26] and Sun et al. [27], this study summarizes a total of five sub-services that reservoirs may provide.

Drawing from existing research on various ecosystem service valuation methods, this study combines various accounting methods, including the market value method [28], shadow engineering method [29], and the willingness-to-pay method [30], to determine reservoirs' ecosystem service values (ESVs). The calculation methods for each service function are presented in Table 1.

2.1.2. The Index of Ecosystem Service Meeting

The index of ES meeting (*ESI*) is used as an indicator to quantify the relationship between regional demand and a reservoir's contribution. In the following calculation process, the *ESS* represents the value of ecosystem services provided by the reservoir, which is the sum of the values of various service functions. The *ESD* represents the region's ES demand.

$$ESI = \frac{ESS}{ESD} \quad (1)$$

The ecosystem service supply (*ESS*) of a reservoir comprises the service values provided by various service functions, and the calculation process is as shown in Formula (2).

$$ESS = V_{RS} + V_{SS} + V_{PS} + V_{CS} \quad (2)$$

In the above formula, $V_{RS}, V_{SS}, V_{PS},$ and V_{CS} refer to the values of regulation, supporting, provisioning, and cultural services. These values are calculated by summing the results of the corresponding sub-service functions.

The *ESD* refers to human preferences for the services provided by ecosystems and is often described using broader socioeconomic characteristics to express the demand for ESs. Drawing on the research results of Wang et al. [31], the *ESD* is calculated using economic density (E_j, in billions of CNY/km^2), population density (H_j, in people/km^2), and land development level (D_j). The formula for calculating ecosystem service demand is as follows:

$$ESD = D_j \times ln(E_j) \times ln(H_j) \quad (3)$$

2.2. Water Resource Supply and Demand Relationship

Similarly, by creating an index of water resource meeting (*WSI*), the WR supply and demand relationship between the reservoir and the region can be reflected.

$$WSI = \frac{WSS}{WSD} WSS = \sum_{i=1}^{n} Q_{W_i} WSD = \sum_{j=1}^{m} W_{U_j} \times N_j \quad (4)$$

In Formula (4), the *WSS* represents the amount of water resources provided by the reservoir to the region, while the *WSD* represents the region's water demand. Q_{W_i} represents the water provided by the reservoir, W_{U_j} is the annual per capita water use in a region j (m^3/person), and N_j is the total population of region j for the current year.

Table 1. Methods of calculating reservoirs' ESVs.

ES Types		Methods	Accounting Models
Regulation services	Flood regulation	Shadow project	$V_{FR} = (Q_M - Q_C) \times C_{FR}$ Q_M: the reservoir's ultimate storage capacity (m3); Q_C: the reservoir's actual storage capacity (m3); C_{FR}: the cost of average flood storage (CNY/m3), the value is 0.67 in this paper concerning Qi et al. [32].
Supporting services	Carbon sequestration and oxygen release	Industrial generation	$V_{CR} = V_{CS} + V_{OR}$ V_{CS}: the service value of sequestering carbon; V_{OR}: the service value of releasing oxygen. $V_{CS} = Q_{CS} \times P_{CO_2}$ P_{CO_2}: the unit market value of CO_2 (CNY/t), 1242; Q_{CS}: the total CO_2 sequestered in plain reservoir(t). $V_{OR} = Q_{OR} \times P_{O_2}$ P_{O_2}: the unit industrial O_2 cost (CNY/t), 400; Q_{OR}: the amount of oxygen released from the reservoir(t). $Q_{CS} = (M_{CO_2}/M_C) \times S \times Q_C$ S: the rate of water absorbing CO_2 $(t \bullet CO_2 \bullet m^2/m^3)$; M_{CO_2}/M_C: the conversion ratio of C to CO_2, 44/12. $Q_{OR} = (M_{O_2}/M_{CO_2}) \times Q_{CS}$ M_{O_2}/M_{CO_2}: the conversion ratio of CO_2 to O_2, 32/12.
	Water storage	Market value	$V_{WT} = P_{WT} \times Q_C$ P_{WT}: the unit water storage value, 0.611(CNY/m3), referring to Jia et al. [33].
Provision services	Water supply	Shadow project	$V_{WS} = \sum P_{W_i} \bullet Q_{W_i}$ P_{W_i}: the shadow price of various types of water supply; Q_{W_i}: the amount of each type of water supply (m3); i = 1,2,3, and 4 indicate the types of water supply, divided into industrial, agricultural, domestic, and ecological water.
Cultural services	Social education and scientific research	Willingness to pay	$V_{ED} = N \times R \times \delta$ N: the population of the service area; R: the per capita disposable income of the service area (CNY); δ: the proportion of disposable income that residents are willing to pay (%).

2.3. Synergy between ES and WR Supply and Demand

The primary function of a reservoir is to ensure the water security of a region while also providing substantial ecosystem services for the well-being of the local community. Achieving a coordinated and harmonious relationship between these two aspects is important for realizing sustainable management [34]. So, to reflect the coordination relationship between WR and ES supply and demand for reservoirs, a coupling coordination model was used as follows:

$$WED = \sqrt{M \times N} M = 2 \times \left[\frac{WSI \bullet ESI}{(WSI + ESI)^2} \right]^{\frac{1}{2}} N = \alpha WSI + \beta ESI \quad (5)$$

The WED represents the coordination degree between the WSI and ESI. M refers to the coupling degree, for which N reflects the comprehensive coordination; α and β are both 0.5.

2.4. Water Optimization Allocation Model

2.4.1. Objective Function

The objective of the water optimization allocation model in this study is to maximize the *ESI*, *WSI*, and the level of synergy between the ES supply and WR supply for a reservoir serving an area. So, the model's objective function contains three parts and is constructed as follows:

$$F = \max\ (ESI, WSI, WED) \tag{6}$$

2.4.2. Constraints

A reservoirs' supply of WRs and ESs to a region is influenced by its design parameters. Constraints in the planning model are set based on aspects related to the accounting of ES and WR supply and demand, such as storage capacity, water diversion, and water supply capacity.

(1) Constraint on storage capacity:

$$C_{min} \leq Q_C \leq C_{max} \tag{7}$$

In the above formula, C_{min} and C_{max} represent the dead storage capacity and maximum storage capacity of the reservoir, respectively. Q_C stands for the actual storage capacity based on the annual records of the reservoir management authorities.

(2) Constraint on water supply capacity:

$$\begin{cases} \sum\limits_{i=1}^{n} Q_{W_i} \leq WS_{max} \\ \sum\limits_{i=1}^{n} Q_{W_i}/WSD \geq \gamma_{min} \\ \sum\limits_{i=1}^{n} Q_{W_i} \leq Q_D \end{cases} \tag{8}$$

In the above equation, WS_{max} represents the maximum annual water supply designed for the reservoir, the minimum water supply reliability designed for the reservoir, and Q_D stands for the water diversion.

(3) Realistic constraint:

All variables in this study are non-negative constants.

2.4.3. Model Solution

There are three maximization-form objectives (*ESI*, *WSI*, and *WSD*) that comprise the optimization aim of the multi-objective optimization model in this paper. To obtain the model's results, a mature multi-objective optimization (NSGA-II) was used after setting the variables. The NSGA-II can accelerate the optimization speed and achieve good results by using a crowding distance comparison as the criterion for comparing individuals in a population [35,36]. This algorithm is commonly applied in studies addressing the allocation of multi-type water consumption in a region.

2.5. Data Prediction and Scenario Setting

Optimally configuring the ecosystem services and water resources of a reservoir requires a thorough consideration of the development status of the region's economic and social systems. In this study, by constructing a multi-scenario prediction model, various time series variables and reservoir evaporation in the service area of the reservoir project were predicted. Multiple development scenarios were set to further simulate reservoir water allocation plans for the future.

2.5.1. ARIMA Prediction Model

Population, GDP, and other economic statistical data in a region often exhibit characteristics of stable time series data. Therefore, when conducting long-term studies on such issues, time series forecasting methods are commonly used to predict future changes. The Autoregressive Integrated Moving Average Model (ARIMA) is a mature method in time series forecasting [37]. This study utilized the ARIMA model to forecast changes in social and economic statistical data such as population, GDP, and industrial and agricultural water consumption, etc. The basic model is as follows:

$$\Delta^d Y_t = \mu + \sum_{i=1}^{m} \varphi_i \Delta^d Y_t + \sum_{j=1}^{n} \theta_j \varepsilon_{t-1} \tag{9}$$

In Equation (9), Y_t represents the original time series data, $\Delta^d Y_t$ is the time series obtained after differencing d times, μ represents the residual, m is the autoregressive order, n is the moving average order, $\varphi_i (i = 1, 2, \ldots, m)$ and $\theta_j (j = 1, 2, \ldots, n)$ represent the model parameters, and ε_{t-1} is the white noise error sequence.

The root mean square error (*RMSE*) was used as an indicator to measure the fit of the model and ensure the accuracy of the forecasted results. The following shows the calculation process:

$$\begin{gathered} R^2 = 1 - \sum\left(T - \hat{T}_t\right)^2 / \sum\left(T - \overline{T}_t\right)^2 \\ RMSE = \sqrt{\frac{\sum_{i=1}^{k} \left|T_t - \hat{T}_t\right|^2}{k}} \end{gathered} \tag{10}$$

In the equation, T_t represents the original data sequence, $\hat{T}_t$ represents the predicted data sequence, and $\overline{T}_t$ represents the mean value of the predicted data sequence. The closer R^2 is to 1, the better the prediction result, and the smaller the RMSE, the higher the prediction accuracy.

2.5.2. Scenario Setting

Various factors, including government policies and shifts in industrial structure, will impact the future economic development and utilization of water resources in a reservoir service area. Therefore, relying solely on predictive results for formulating water resource allocation plans is insufficient. In this study, based on the predictive results, various simulation scenarios were further set around economic development and societal water conservation awareness to ensure that water resource management plans by reservoir management agencies can adapt to the future development of the region.

Table 2 presents three regional development scenarios set in this study. Using the predictive results of the time series forecasting model as a baseline reference, scenarios were established for economic conditions higher or lower than predicted. Considering that regional water usage is influenced by water efficiency and technological progress, scenarios were also set for improved water efficiency. Referring to Ma et al. [38], in which 1% technological progress promotes a 0.73% improvement in water efficiency, in scenarios with improved water efficiency, the baseline prediction of total societal water usage was downwardly adjusted by 7%.

Table 2. Multi-scenario setting.

Scenarios	Instructions	Economic Indicators	Social Water Usage Indicators
1	Baseline scenario: based on the predictive model results.	Using predictive results	Using predictive results
2	High economic growth exceeding expectations with improved water efficiency.	Making upward adjustments to the predictive results, referring to the region's economic plans.	Make downward adjustments to the baseline predictive results.
3	Low economic growth below expectations with improved water efficiency.	Making downward adjustments to the predictive results, referring to the region's economic plans.	Make downward adjustments to the baseline predictive results.

2.6. Case and Data Source

2.6.1. Case of Datun Reservoir

The Datun Reservoir is a key hub for water delivery projects in northern Shandong Province and is part of the eastern route of the South-to-North Water Diversion project in China (As shown in Figure 1). It is located on the east side of Wucheng County, Dezhou City, Shandong Prnovince. The main areas supplied are Decheng District and Wucheng County in Dezhou City. The designed reservoir water level of the Datun Reservoir is 29.80 m with a 52.09 million m^3 total storage capacity; it covers a total area of 9553.04 acres and has a water surface area of up to 61 square kilometers. The total investment in the project is CNY 1,014,224.3 million. After the completion of the Datun Reservoir in 2014, it undertook the important mission of supplying industrial and domestic water for Dezhou City, relieving the local water resource load pressure significantly and playing a positive role in improving the quality of life for local people.

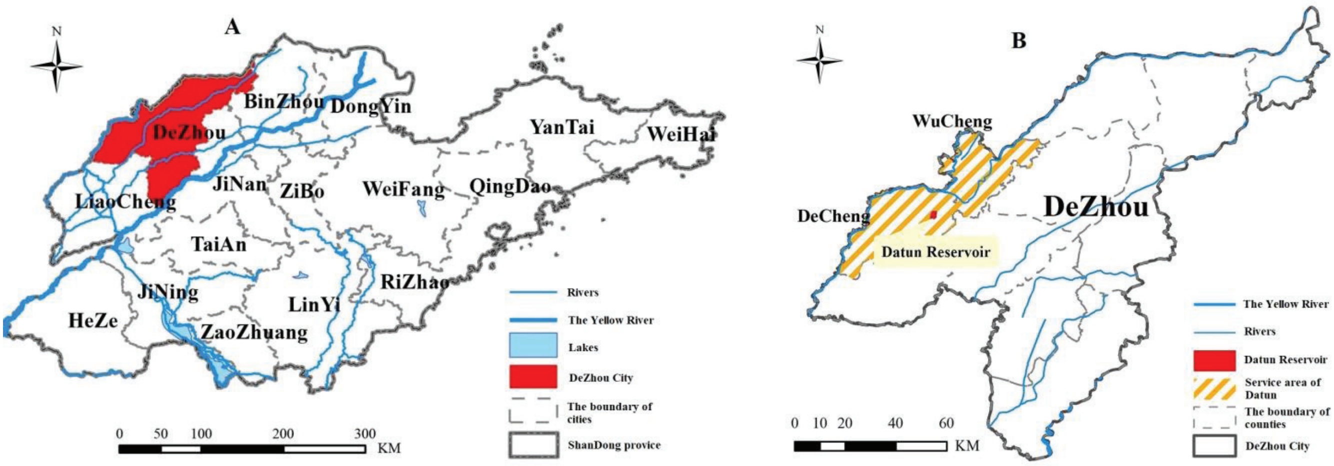

Figure 1. The service area of the Datun Reservoir. (**A**) Shandong Province. (**B**) Dezhou City.

2.6.2. Data Resource

This study primarily utilized data encompassing economic, social, and ecological aspects relevant to the service area of the reservoir as well as engineering parameters and daily water management scheduling data for the reservoir. Statistical data comprising social, economic, and ecological data were mainly sourced from the Shandong Statistical Yearbook, Dezhou Statistical Yearbook, and Dezhou Water Resources Bulletin. The specific data for the Datun Reservoir in the actual case calculation were provided by the Datun Reservoir Management Office. These data included reservoir parameters, expansion plans, water quality monitoring data, and historical water supply volumes.

3. Results

3.1. The Ecological System Service Value of the Datun Reservoir

The Datun Reservoir supplies industrial water to the Decheng District of Dezhou City and domestic water to Wucheng County. The water delivery process uses a pipe–culvert direct delivery form. Therefore, water losses such as evaporation during the water delivery process are not considered in the calculation of ESVs. Only water evaporation during the daily storage process of the reservoir is considered for calculating the value of its climate regulation service. Through field investigations and an analysis of the Datun Reservoir, it was found that the Datun Reservoir employs “fish farming for water quality” ecological aquaculture. In addition, since the Datun Reservoir is an artificially constructed plain reservoir, the main body of the project was built based on saline–alkali land restoration, mainly using a concrete construction. This paper continues the research viewpoint of Guo, Boeing, Borgomeo, Xu, and Weng [15] and argues that the reservoir does not possess the ecological functions, such as biodiversity and habitat, that natural water bodies like lakes have.

Figure 2 presents the accounting results for various ESVs for the Datun Reservoir from 2015 to 2021. The overall ecosystem service value of the reservoir was CNY 83.68 million in 2015, increasing to CNY 128.01 million by 2021. The composition of the reservoir's regulatory, supporting, provisioning, and cultural services shows that provisioning services, particularly water supply services, dominate. In 2021, the water resource provisioning service value accounted for 46.97% of the total ESVs. This is primarily due to the main mission of such reservoir projects, which is to provide sufficient water for production and daily life in the serviced area. Water supply service value had the highest proportion in the annual ESVs, reaching CNY 70.23 million in 2020.

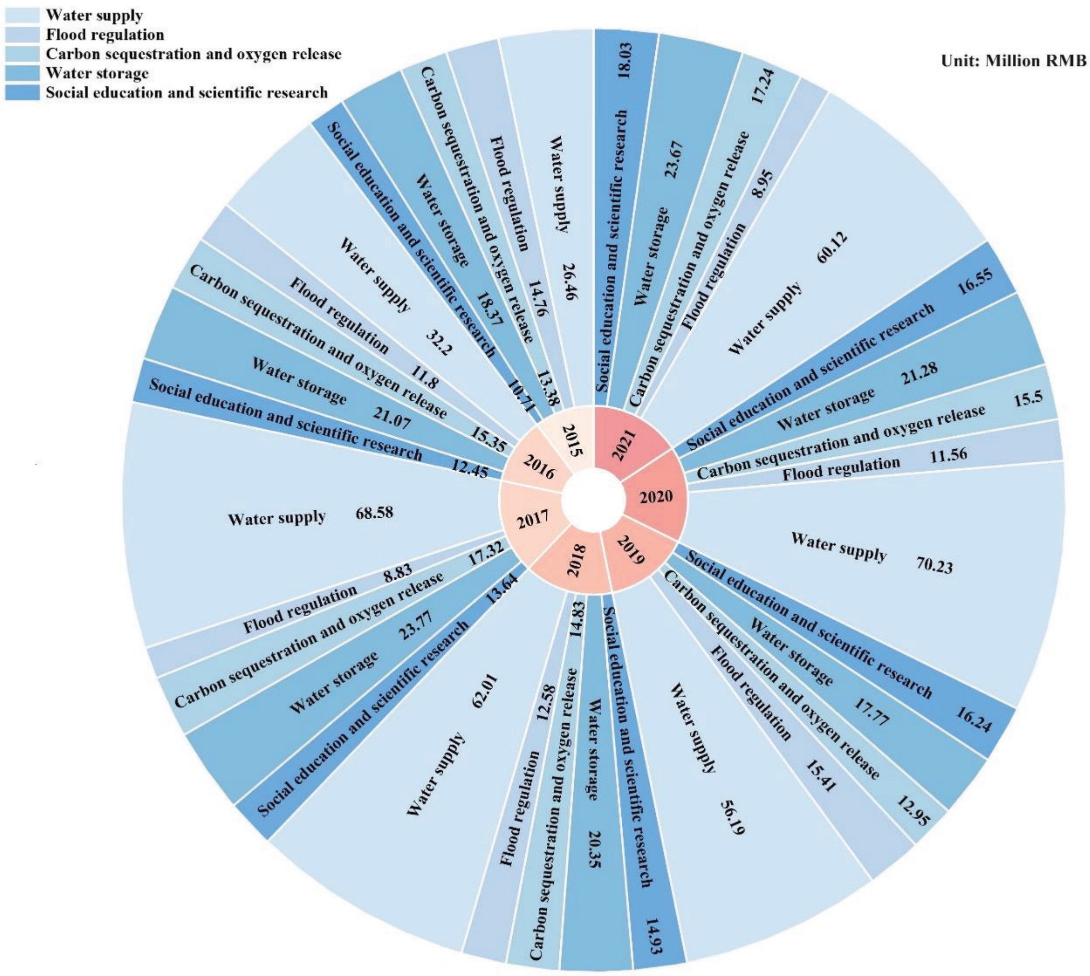

Figure 2. Ecosystem service value of the Datun Reservoir in 2015–2021.

Additionally, water storage value is another significant component of the ecosystem service value of the project, second only to water supply service value in quantity. In 2017, the water storage service value reached its highest at CNY 23.77 million. The reservoir's support for the regional ecosystem also includes carbon sequestration and oxygen release functions, with up to an CNY 17.24 million service value in 2021. On the cultural service front, the Datun Reservoir maintains a close collaboration with educational and research institutions in the serviced area, fulfilling social missions such as safety education and water science projects. It also serves as the base for water ecology and safety education in Dezhou City, providing a cultural service value of CNY 18.03 million in 2021.

The ESV assessment results from 2015 to 2021 highlight the importance of water supply and water storage services, which are closely related to water scheduling and management, as significant sources of the reservoir's ecosystem service provision. So, adopting more scientific water resource scheduling and allocation schemes to achieve balance between improvements in service value and regional water supply is deemed necessary.

3.2. Results of ARIMA Model Prediction

This study applied the time-series-forecasting ARIMA model to predict social and economic statistical data, including population growth, GDP, and social water demand, for the Datun Reservoir service area. Additionally, historical data were used to forecast the water storage of the Datun Reservoir. These predictions served as a basis for subsequent optimization model calculations and the development of multiple scenario plans. Figure 3 presents a fitting situation between the predicted data curves and historical data for these indicators.

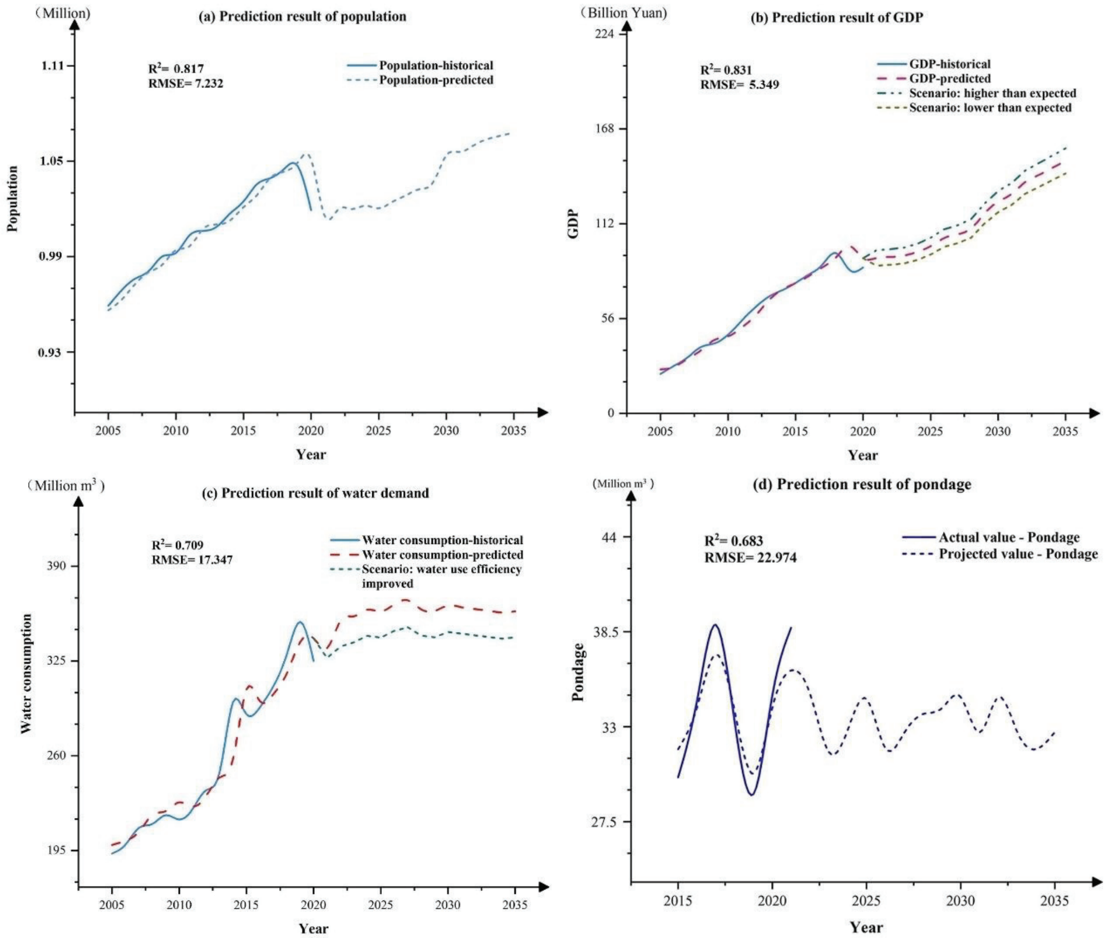

Figure 3. Results of the projections regarding the (**a**) population, (**b**) GDP, (**c**) water demand of the service area, and (**d**) pondage of the Datun Reservoir.

In Figure 3a, regarding population changes, the predicted curve maintains a good fit with historical values before 2020. The evaluation indicators R^2 and $RMSE$ are 0.817 and 7.232, respectively, indicating reasonably accurate predictions. The historical data show that population growth in the service area was relatively stable before 2020, with an annual increase of around 17,000 people. Due to a decline in population numbers in 2020, the model's predicted curve maintains a growth trend but with a deceleration in growth rate.

In Figure 3b, the GDP forecast includes scenarios in which economic growth exceeds or falls below expectations, with adjustments of +5% and −5% applied to the predicted results. The predicted curve exhibits a good fit with historical values, and both the R^2 and $RMSE$ performance indicators are satisfactory, indicating reliable predictions. In Figure 3c, the forecast of water demand in the service area considers a scenario of improved societal water efficiency due to technological advancements. Based on conclusions about technological progress and closure efficiency from Ma, Huang, Zhang, and Tian [38], the predicted results were adjusted downwards by 7%. The overall fit between the predicted curve and historical values remains effective.

Similarly, in Figure 3d, the forecast of water storage data for the Datun Reservoir ensures the validity of the results.

3.3. Results of Water Optional Allocation

The water-resource-related scheduling of the Datun Reservoir was optimized using the *ESI*, *WSI*, and *WED* as optimization objectives. As the reservoir is not responsible for agricultural irrigation tasks in the service area and does not provide direct ecological replenishment, the use of the water supply mainly includes domestic and industrial water use. Additionally, water scheduling involves reservoir storage. Table 3 presents the numerical results of the optimized water allocation for the reservoir. Comparing these results with the actual water allocation records for the reservoir from 2015 to 2021 reveals significant optimization potential within the effective design parameters of the reservoir. The existing water resource allocation scheme has not fully realized the reservoir's potential.

Table 3. The optimized results of water allocation (unit: million m^3).

Year	Domestic Water Supply		Industrial Water Supply		Pondage	
	Initial	**Optimal**	**Initial**	**Optimal**	**Initial**	**Optimal**
2015	2.949	3.096	7.075	7.166	30.060	34.077
2016	3.352	3.519	8.847	9.085	34.484	40.829
2017	5.033	5.284	20.946	21.878	38.908	42.580
2018	6.607	6.837	16.881	17.245	33.311	38.304
2019	7.141	7.598	14.144	15.124	29.090	30.817
2020	9.516	9.891	17.085	18.477	34.830	35.279
2021	7.811	8.102	14.961	16.056	38.738	40.359
2025	8.473	8.597	16.114	18.374	34.603	36.984
2030	8.731	8.968	20.272	21.116	34.714	40.129
2035	10.781	11.420	17.838	19.334	32.689	33.496

Note: the initial values after 2021 refer to the results of the forecast model under the base scenario.

In terms of domestic water supply, the optimized supply is higher than the recorded values. For the service area, the domestic water supply is primarily sourced from groundwater extraction, and the use of transfer reservoirs for the domestic water supply is still at a relatively low level, far from meeting the actual domestic water demand. Increasing the use of external pumped water is beneficial for ensuring local groundwater security and water ecosystem stability. In terms of the industrial water supply, the optimized results are also higher than the original data, indicating that the reservoir's potential for providing industrial water for Dezhou City has not been fully exploited.

Table 4 shows the results after comparing the difference in the total ESVs provided by the reservoir before and after optimization. It can be seen that since the completion of the reservoir's construction in 2014 and its initial operational stages in 2015 and 2016, the biggest improvements in overall ESVs after optimization were 10.05% and 11.36%, respectively. In other years, after optimization through the water allocation model, the overall service value can be improved by 5.15% to 8.57%. This indicates that the optimization model constructed in this study has practical application value for enhancing the ecological service value of reservoir projects.

The ESVs of the Datun Reservoir's various segmented services were reassigned through the process of optimizing water resource allocation. Figure 4 displays changes in flood regulation, carbon sequestration and oxygen release, water storage, and water supply services before and after optimization.

Table 4. The optimized results for total ESVs (unit: million CNY).

Year	2015	2016	2017	2018	2019	2020	2021
Initial value	83.68	92.87	132.14	124.70	118.57	135.12	128.01
Value after optimization	92.09	103.42	141.28	134.92	126.23	143.69	133.98
Increased percentage	10.05%	11.36%	6.91%	8.20%	6.46%	6.34%	4.67%
Year	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**
Initial value	134.47	129.23	130.36	134.54	136.84	135.40	142.35
Value after optimization	145.99	137.64	139.22	145.68	145.36	143.41	152.44
Increased percentage	8.57%	6.50%	6.80%	8.27%	6.22%	5.91%	7.09%
Year	**2029**	**2030**	**2031**	**2032**	**2033**	**2034**	**2035**
Initial value	147.21	150.98	158.72	155.87	159.95	154.61	154.42
Value after optimization	158.52	160.21	166.89	166.63	169.88	164.63	163.89
Increased percentage	7.68%	6.11%	5.15%	6.91%	6.21%	6.48%	6.13%

Note: the initial values after 2021 refer to the results of the forecast model under the base scenario.

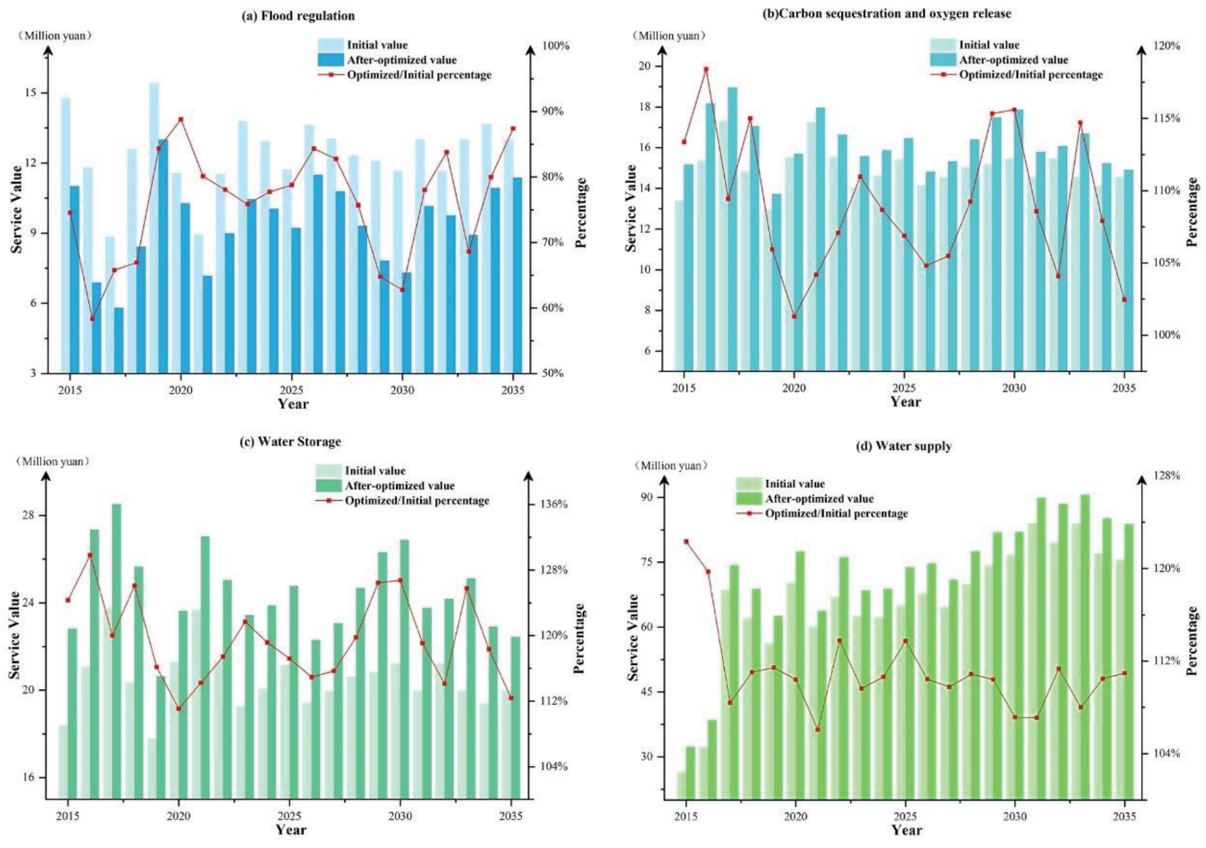

Figure 4. The results of the Datun Reservoir's flood regulation (**a**), carbon sequestration and oxygen release (**b**), water storage (**c**), and water supply (**d**) service values after optimization.

Figure 4a shows the flood regulation service value, which experienced a significant decrease after water allocation optimization. In 2016, the value dropped to only 60% of the pre-optimization level. Figure 4b indicates that the carbon sequestration and oxygen release service value increased by 2% to 18% after optimization, with a noTable 18% growth in 2016 from CNY 15.349 million to CNY 18.173 million. Figure 4c demonstrates a substantial improvement in the water storage service value after water allocation optimization, consistently exceeding 110% of the original values. In 2016, the value increased by CNY 6.286 million. Figure 4d reflects the differences in the water supply service value before and after optimization. In 2015 and 2016, during the initial operational stages of the Datun Reservoir, domestic and industrial water supply levels were relatively low, leading to a significant gap between the actual demand in the service area and the allocated water. After optimization, the water supply service value increased to 124% and 120% of the pre-optimization levels in 2015 and 2016, respectively. The subsequent improvement in water allocation optimization remained at around 9%.

Figure 5 illustrates changes in optimization objectives, namely the *ESI*, *WSI*, and *WED*, before and after water allocation optimization. From the information in the graph, it can be observed that through the reallocation of water for domestic, industrial, and reservoir storage purposes, the ecological service, water supply, and water–ecology harmony provided by the Datun Reservoir to its service area have all been enhanced. Specifically, in 2016, the *ESI* experienced the highest improvement, increasing by 11.36% from 0.047 to 0.052. The *ESI* achieved its most significant increase in 2015, rising by 22.33% from 0.0347 to 0.042. Similarly, the *WED* saw its most substantial increase in 2015, reaching 7.715% from 0.196 to 0.222 after optimization.

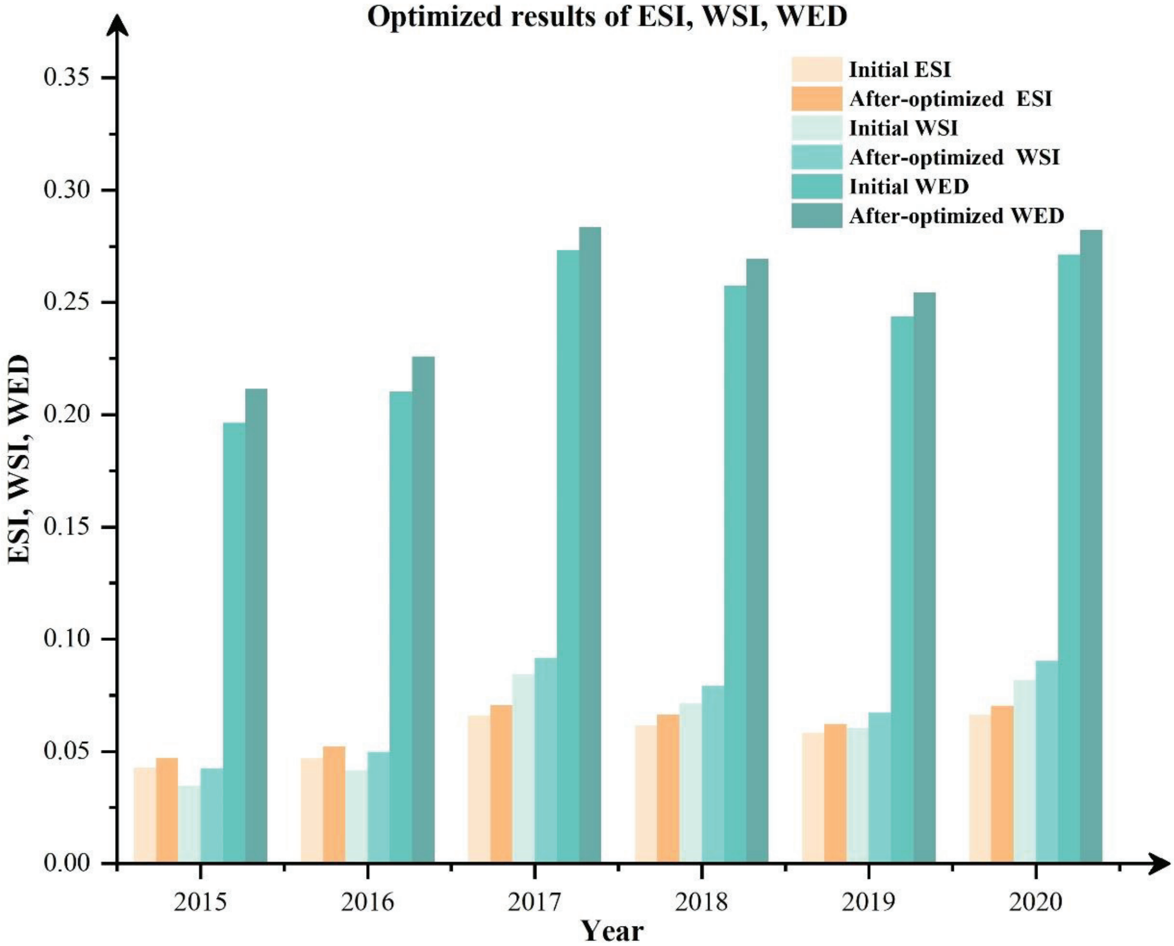

Figure 5. Optimized results for the ESI, WSI, and WED.

3.4. Water Allocation under Different Scenarios

In three different scenarios considering variations in economic growth and social water use efficiency, water allocation for the Datun Reservoir was optimized, and the results are presented in Table 5.

Under Scenario 1 conditions, in which the economic growth level and social water use efficiency in the service area remain at the current level, the baseline predicted results were used for the calculation. In this scenario, after optimization, the allocated volumes for the domestic water supply are projected to reach 8.60, 8.97, and 11.42 million m^3 in 2025, 2030, and 2035, respectively. Industrial water supply volumes are estimated to be 18.37, 21.12, and 19.33 million m^3 for the same years, while reservoir storage volumes are expected to be 36.98, 40.13, and 33.50 million m^3.

Table 5. Water allocation in different scenarios (unit: million m^3).

Year	Scenario 1			Scenario 2			Scenario 3		
	Domestic	Industrial	Pondage	Domestic	Industrial	Pondage	Domestic	Industrial	Pondage
2022	8.91	17.94	37.39	9.17	22.45	39.3	8.26	21.18	38.43
2023	8.28	17.66	34.99	8.65	21.19	38.45	7.79	19.99	37.77
2024	7.88	18.12	35.66	8.29	20.16	40.13	7.46	19.02	38.9
2025	8.6	18.37	36.98	8.88	19.74	39.73	7.99	18.62	38.51
2026	8.1	19.22	33.29	8.92	21.96	34.7	8.03	20.71	32.97
2027	8.28	17.62	34.44	9.14	19.76	35.17	8.22	18.64	33.41
2028	8.37	19.01	36.85	9.25	20.91	37.59	8.32	19.72	36.71
2029	9.14	20.8	39.29	9.44	24.46	42.33	8.49	23.07	41.43
2030	8.97	21.12	40.13	9.08	25.81	44.14	8.17	24.35	43.94
2031	10.08	22.99	35.48	10.25	27.56	38.2	9.23	25.99	37.29
2032	9.29	22.26	36.12	9.5	24.78	40.22	8.55	23.38	38.21
2033	10.52	23.8	37.49	10.81	26.18	40.16	9.73	24.7	38.15
2034	9.44	22.82	34.21	9.55	25.36	39.42	8.6	23.92	38.45
2035	11.42	19.33	33.5	11.71	20.84	38.78	10.54	19.66	37.84

Under Scenario 2 conditions, in which the economic growth level in the service area exceeds expectations and social water use efficiency improves, the allocated volumes for various water resources are generally higher than those in Scenario 1. Domestic water supply volumes are projected to reach 8.88, 19.74, and 39.73 million m^3 in 2025, 2030, and 2035, respectively. Industrial water supply volumes are estimated to be 9.08, 25.81, and 44.14 million m^3, while reservoir storage volumes are expected to be 11.71, 20.84, and 38.78 million m^3 for the same years.

Under Scenario 3 conditions, in which the economic growth level in the service area is lower than expected but social water use efficiency improves, the domestic water supply volumes are generally lower than those in Scenario 1. In 2025, 2030, and 2035, they are projected to reach 7.99, 18.62, and 38.51 million m^3, respectively. Industrial water supply volumes are higher than in Scenario 1 but lower than in Scenario 2, estimated to be 8.17, 24.35, and 43.94 million m^3. Reservoir storage volumes are expected to be 10.54, 19.66, and 37.84 million m^3 for the same years.

Figure 6 illustrates the various ESVs provided by the Datun Reservoir after optimization in different scenarios. Figure 6a reflects changes in the water supply service value. In Scenario 2, the configuration provides the highest water resource supply, resulting in a higher water supply service value compared to the other two scenarios. In terms of flood regulation service value, in Figure 6b, Scenario 2 performs better than the other two scenarios, with the highest flood regulation service value reaching CNY 13 million in 2027. Figure 6c shows the carbon sequestration and oxygen release service value; Scenarios 2 and 3 maintain consistency, and both surpass Scenario 1. As for the water storage service value of Figure 6d, the differences in the water source conservation service value among the three scenarios are relatively small and remain at a similar level. Figure 6e shows that the total ESV in Scenario 2 outperforms the other two scenarios.

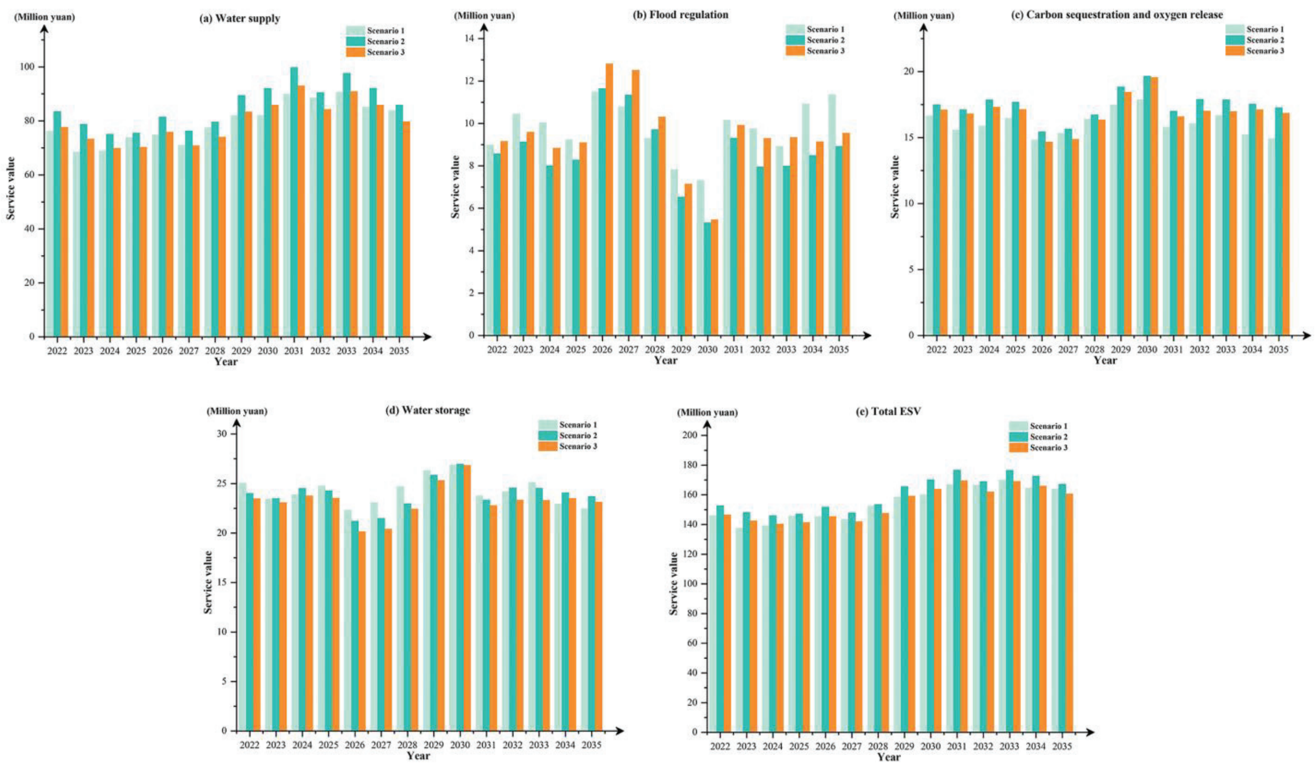

Figure 6. (**a**) water supply, (**b**) flood regulation, (**c**) carbon sequestration and oxygen release, (**d**) water storage and (**e**) total ESVs in different scenarios.

Figure 7 illustrates the water allocation schemes and corresponding changes in the *ESI*, *WSI*, and *WED* for the three scenarios. Figure 7a shows that Scenario 2 consistently outperforms the other two scenarios for the *ESI* except in 2028, when it is comparable to Scenario 1. The *ESI* values for Scenario 1 and Scenario 3 exhibit significant fluctuations. In terms of the *WSI* in Figure 7b, due to the higher-than-expected economic growth in Scenario 2, the water demand is significantly higher. Consequently, the water resource supply for the Datun Reservoir is enhanced, resulting in a significantly better *WSI* compared to Scenario 1 and Scenario 3. In Scenario 3, the improvement in the *WSI* is facilitated by the combined effect of increased water use efficiency and slowed economic growth, reducing societal water demand. Figure 7c reflects that the water allocation scheme in Scenario 2 exhibits a significantly better *WED* than the other two scenarios. Over time, the gap between the *WEDs* of Scenario 3 and Scenario 1 widens, indicating that under the conditions of Scenario 3, when economic growth slows down, reservoir management should prioritize balancing the water supply with ecological service achievement, gradually achieving a more coordinated development between the two.

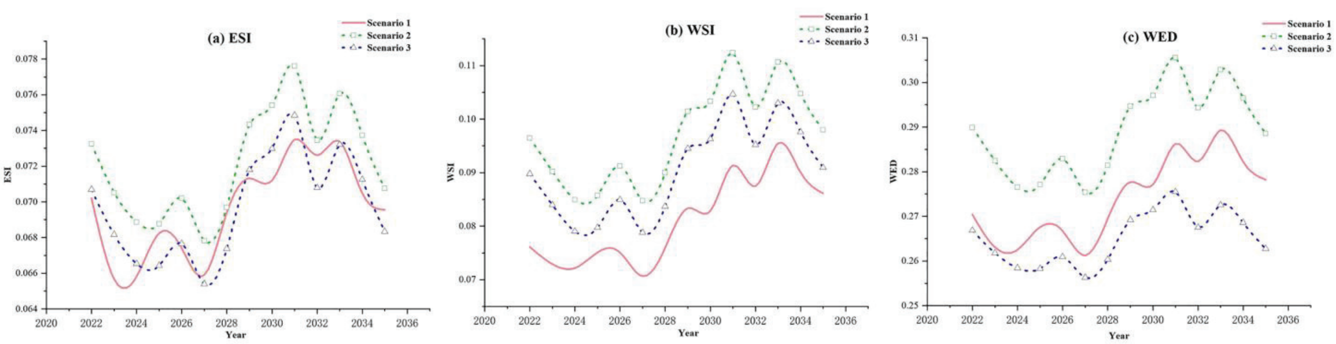

Figure 7. Different scenarios: results for (**a**) ESI, (**b**) WSI, and (**c**) WED.

4. Discussion

4.1. The Basic Functions and Ecosystem Service Roles of Reservoirs

In this paper, following the framework of the ecosystem services theory, the reservoir is identified to have five types of ecosystem service functions. These functions provide regulation, supply, support, and cultural services to the reservoir's service area. Reservoirs, as typical hydraulic engineering projects, bear the important responsibility of achieving interregional water transfer and ensuring the water demand for local production activities is met, which is significant for human well-being in the region (Figure 8). The transport, storage, supply, and purification of water are the core tasks of reservoir engineering. Thus, water supply and water purification, a reservoir's core functions which are closely related to water flow, bring ESVs to the region. Reservoirs can also provide clean electrical energy to a region through the construction of hydroelectric power stations. This helps reduce dependence on traditional energy sources, lower greenhouse gas emissions, and promote sustainable development in the region. In water-deficient areas, reservoirs can play a supporting role in restoring natural ecosystems through ecological water replenishment. Large valley-type reservoirs, in addition to the main engineering structure, also include surrounding natural ecosystems such as wetlands, shoreline vegetation, and water bodies, providing important ecological functions at a large-scale regional level and, for example, preserving wetlands and riverbank zones, planting suitable vegetation, providing habitat and food sources, and sustaining various types of wildlife. Some reservoirs with abundant natural resources are gradually developed into water scenic areas, making full use of natural landscapes and historical cultural scenery, attracting tourists, and generating economic income and cultural services for the region. In addition, reservoirs can also explore social education functions such as hydroculture and historical heritage, serving as research bases for ecological conservation and artificial ecosystem-related studies.

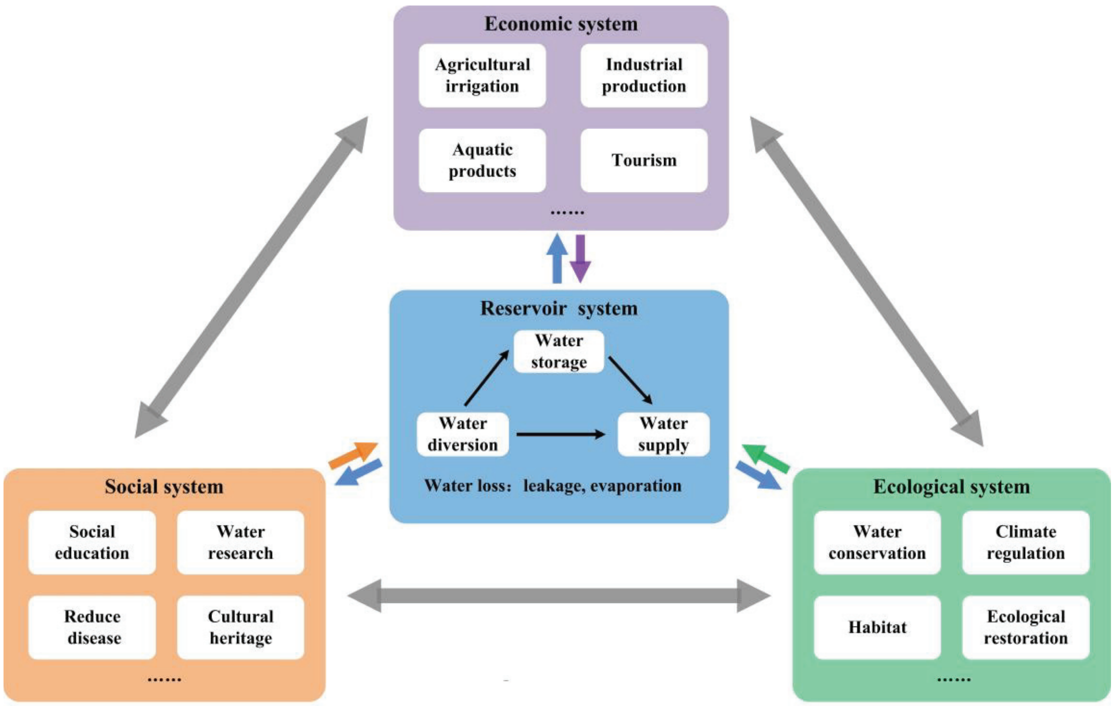

Figure 8. The interaction between reservoir functions and regional economic, social, and ecological systems.

4.2. Optimization Management of Reservoir Water Allocation and ESVs

This study focuses on the indexes of WR meeting (*WSI*) and ES meeting (*ESI*) of reservoirs and further establishes the coordinated degree index (*WED*) to measure their coordination. A water allocation model for reservoirs is collectively constructed. In the case application of the Datun Reservoir, it is found that due to its late completion date, the potential of the reservoir in terms of water supply and ecosystem services has not been fully explored. Furthermore, the findings indicate that optimizing the distribution of reservoir storage, domestic water, and industrial water supply can lead to improvements in the *ESI*, *WSI*, and *WED* to varying degrees while still meeting regional water demand, as compared to the actual water allocation scheme implemented from 2015 to 2021. Among them, the optimized ESI shows the most significant improvement, with an increase of 22.33% compared to the actual ESI in 2015. There exists considerable potential for enhancing the current water management program of the Datun Reservoir. The reservoir can moderately increase the water supply for agricultural production and residents in the service areas and replace the use of groundwater with water transfer in different places, thus easing the load on the local water resources ecosystem. The management authorities also did not pay enough attention to the project's role in providing ecosystem services. Merely satisfying the regional water resource demand while neglecting ecological effects is not conducive to the sustainable management of hydraulic engineering. There is a close connection between reservoirs and the socioeconomic and ecological systems of the service area, and water flow plays a crucial role. Water supply, purification, hydropower generation, etc., are not only the core functions of reservoirs but also the main sources of ESVs. According to the case, the calculated water supply service value reached CNY 60.12 million in 2021, accounting for 46.97% of the overall service value of the reservoir. Therefore, by constructing a water allocation model that considers both water resource supply and ESVs, reservoirs can help provide optimized ESVs to the surrounding areas while fulfilling their basic functions.

To address different economic and social development trends, this study, using a predictive model, sets water allocation scenarios for reservoirs under different economic growth rates and social water use efficiency scenarios. In the case application, the *WSI* maintains a similar trend in all three scenarios, while the ESI shows significant differences: when the economy maintains high growth (Scenario 2), the reservoir can achieve high levels for both the *ESI* and *WSI*, and the water supply and ecosystem service supply show good coordination. However, when economic growth slows down (Scenario 3), the reservoir's *ESI* will change dramatically due to factors such as a decrease in regional water demand, and the *WED* will also remain at a lower level. Changes in population, economic growth, and water use efficiency in the development situation will cause salient changes in the demand for industrial, agricultural, and domestic water supply from the areas surrounding the reservoir. This directly affects changes in the water supply service value, thereby altering the overall service value. For reservoir management organizations facing different trends in economic and social development, it is imperative to develop real-time water allocation strategies that effectively harmonize water and ecosystem service supply coordination. In particular, when economic growth slows down, as the demand for water resources in economic production activities decreases, reservoir management agencies should optimize the scheme of allocating ecological, domestic, and agricultural water in real time by strengthening the water replenishment function of the reservoir to wetland, river, and other ecological systems. The ecological service benefits of the project can be improved so as to achieve the maximum value of ecological services as much as possible while meeting water demand, and maintaining a balance between the two.

4.3. Research Shortcomings and Outlook

In this paper, the ESVs of reservoirs are assessed, and ecosystem services are incorporated into the institutional standards of reservoir water optimization management policies. A case study was conducted on the Datun Reservoir, demonstrating that through water optimization allocation while considering the demand satisfaction for ecosystem services and water resources, comprehensive improvements can be achieved in the *ESI*, *WSI*, and *WED*. However, in setting constraints for this study, only constraints at the parameter level of the reservoir's engineering itself were considered. Constraints were constructed based on storage capacity, water intake, and water supply capabilities to establish constraints for the water optimization model. This study emphasizes that reservoir management should not only ensure basic water supply but also emphasize additional ESVs. However, the operational and maintenance costs resulting from different reservoir operation scenarios were not within the scope of this study, mainly due to the study's primary objectives and limitations in relevant data. Additionally, under different scenario settings, in the water optimization results of the Datun Reservoir, when the economy exhibits low growth, the coordination degree (*WED*) between the water supply and ecosystem services remains at a lower level and even shows a declining trend. External economic downturn pressures will likely further influence reservoir management organizations' consideration of cost factors.

In future research, when constructing water allocation models that consider ecological effects, the study will further incorporate operating costs, social factors, and other internal and external factors into the research scope. This approach aims to make the model more realistic and applicable to guide the work of reservoir and other hydraulic engineering management organizations. Additionally, considering the societal demand for sustainable development and clean production, analyzing the ecological support functions of artificial structures such as reservoirs and exploring the role of artificial ecosystems in promoting regional sustainability will be a focus of future work.

5. Conclusions

To achieve the optimization of reservoirs, balancing regional water resource supply and considering the value of ecosystem services, this paper sequentially constructs an assessment model for the ESVs of reservoirs, including a multi-objective water allocation model that incorporates the *ESI*, *WSI,* and *WED*. Additionally, the ARIMA model is applied to predict trends in regional economic and social development, considering three different scenarios to adapt water allocation to different future situations, accounting for the effects of improved social water use efficiency due to technological advancements. Finally, the study model is applied to the Datun Reservoir as a practical case.

The research findings indicate that integrating ESVs into the reservoir water allocation scheme can promote an overall increase in ESVs. Through a case analysis considering the actual conditions of the Datun Reservoir, optimizations are made for the domestic water supply, industrial water supply, and storage capacity. The actual water allocation scheme of the reservoir in 2021 resulted in an overall service value of CNY 128.01 million, which increased to CNY 133.98 million after optimization, achieving a growth of 4.67%. The most significant improvement occurred in 2016, reaching 11.36%. Furthermore, since the reservoir was completed in 2014, allocations of domestic water supply and industrial water supply have increased, indicating significant optimization potential in the water allocation of the reservoir within the effective design parameter range. The existing water resource allocation scheme has not fully realized the configuration potential of the reservoir.

In formulating water allocation schemes for different future development scenarios, when the economy maintains high-speed growth and social water use efficiency improves (Scenario 2), the Datun Reservoir can ensure regional water supply needs are met (a high *WSI*) while maximizing the satisfaction of regional ecosystem service demands (a high *ESI*). The two factors exhibit good coordination (a *WED* maintaining a high level). However, with a slowdown in economic growth, even with an improved social water use efficiency, the reservoir faces a sharp decline in regional water demand. After ensuring the regional water supply (the *WSI* is high), its role in satisfying the demands of regional ecosystem services is weakened (the *ESI* is at a low level), and the *WED* is also at a low level. Therefore, facing a slowdown in economic growth, the decline in water consumption will cause the water supply function of the reservoir to weaken. At this time, the management organization should expand an ecological restoration function of the project, promote the value of ecological services, and promote coordination between the water supply and ecological benefits.

This study integrates ecosystem service value into the development of reservoir water allocation schemes and daily management, establishing a multi-objective allocation model that addresses both regional water resources and ecosystem service requirements. This model can assist engineering management organizations, such as reservoirs, in formulating more reasonable management plans. It ensures the completion of the reservoir's basic functions while optimizing the provision of ESVs to the region. It is of great significance to promote the scientific management and sustainable development of such projects.

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A Comparative Study of the Driving Factors of Water Resources Use Efficiency in China's Agricultural and Industrial Sectors

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Abstract: The efficient use of water resources has become an important topic in China. Research on measurement and driving factors is the foundation for improving water resources use efficiency (WRUE). In this paper, the super-efficiency slacks-based measure (SE-SBM) model is used to measure the WRUE of China from 2005 to 2021. The agricultural carbon emissions and chemical oxygen demand (COD) in industrial wastes are taken as undesirable by-products. The driving factors of WRUE are discussed with use of the Tobit regression model. The results show that China's agricultural WRUE ranges from 1.185 in Jilin to 0.687 in Ningxia. In the industrial sector, the WRUE ranges from 1.399 in Beijing to Jiangxi 0.212. The economic structure and development level, water resources endowment, government influence and environmental regulation, agricultural planting scale and urbanization rate have impacts on WRUE. Precautionary measures need to be applied to prevent inefficient WRUE caused by the declining share of the industrial sector in the economic structure. More financial support should be focused on water-saving irrigation in agriculture and energy and resource efficiency in industry. The organizational structure and technological advantages of urbanization should also be emphasized in efforts to improve water efficiency.

Keywords: water resources use efficiency; driving factors; SE-SBM; agricultural water; industrial water

1. Introduction

Water resources are important natural and strategic economic resources that underpin the survival and development of human societies [1,2]. Under the challenge of climate change, water scarcity has become a growing problem [3,4]. By 2025, approximately two-thirds of the population will have to live under water-stressed conditions. Water resources use efficiency (WRUE) is a crucial indicator of the sustainability of an economy [5,6]. Therefore, comprehensively improving WRUE is an urgent priority to address the prominent imbalance between water supply and demand [7]. Governments are encouraging efficiency measures to conserve water resources [8]. So, the sustainable development of water resources and green and high-quality economic development are promoted [9].

The total water resources of China in 2022 were 2708.81 billion m^3, ranking fourth in the world [10]. However, the per capita water resources possession is only one quarter of the world level, making China one of the 13 countries with the poorest water resources in the world [7,11]. China is currently in a critical stage of industrialization and modernization. However, the rough economic development of the past decades has led to low WRUE in China. Water scarcity is particularly pronounced [12,13]. Research on the measurement and driving factors of WRUE is the foundation for improving [14], which would provide the support for alleviating water scarcity.

There are various methods to measure WRUE. The parametric approach represented by stochastic frontier analysis (SFA) [15,16] and the non-parametric approach typified by data envelopment analysis (DEA) are the dominant methods. There is a complex interaction between the environment and the production process during the use and treatment of water resources. It is difficult to apply an explicit functional form to evaluate the WRUE by parametric methods. Therefore, non-parametric methods were introduced to measure WRUE. The super-efficiency DEA model [17], three-stage DEA model [18], slacks-based measure (SBM) model [19], undesirable output super efficiency slacks-based measure (SE-SBM) model [20], network DEA model [21], and other various DEA improvement methods have been developed. In the spatial dimension, WRUE has been measured at the urban [22], provincial [23,24], basin [19,25], and national [21,26] levels. Scholars have evaluated WRUE in different water use sectors of agriculture, industry, the domestic sphere, and ecology. Huang et al. [27] evaluated the efficiency of the plantation, forestry, animal husbandry, and fishery industries, concluding that China's overall agricultural WRUE has shown a fluctuating downward trend. Shi et al. [28] and Qi and Song [29] evaluated the WRUE of the Yangtze River Economic Belt for agriculture and industry, respectively.

The literature has also explored the drivers of WRUE changes from natural, economic, and social perspectives. Yu and Liu [30] concluded that WRUE is negatively correlated with investment in wastewater treatment projects and industrial water use structure, and positively correlated with the total amount of water supplied and the level of science and technology. Ma et al. [31] concluded that the technological progress has a positive impact on WRUE, whereas water costs and environmental pollution reduced the efficiency. For the factors affecting agricultural WRUE, researchers have focused on resource endowment [32], industrial structure [33], soil type [34], water conservancy facilities [35], and the agricultural planting structure [36]. The driving factors of industrial WRUE have been studied. Cheng and Zhang [37] argued that the water price is an important factor influencing industrial WRUE. He et al. [38] explored the impact of variables such as per capita gross domestic product (GDP), per capita water consumption, the proportion of secondary and tertiary industry water use, foreign direct investment, and research & development (R&D) intensity. Furthermore, scholars have also looked at the influence of environmental regulation [39], population density [22], and government policy [29].

These studies have provided evidence on the measurement and driving factors of WRUE. However, there are still some gaps in the research. On the one hand, the measurements of WRUE have focused on desirable outputs. The attention paid to undesirable outputs such as pollution emissions from industrial and agricultural production has been limited. As environmental issues are gradually being paid attention to, adding appropriate environmental indicators as undesirable outputs will undoubtedly make the measurement results reasonable. On the other hand, most studies have analyzed WRUE in society as a whole, or have focused on only one of the industrial or agricultural sectors in isolation. This makes comparative analysis between the agricultural and industrial sectors difficult. Neglecting undesirable outputs makes the study results invalid for supporting cleaner production and sustainability. The lack of comparative analysis will also make policy implications incompatible with both the agricultural and industrial sectors.

Therefore, this paper adopts the SE-SBM model with the undesirable outputs to measure WRUE in agriculture and industry in 31 provinces or cities in China. Then, Tobit regression is applied to investigate the driving factors in different water use sectors. For the first time, a comparative discussion is conducted on the driving factors of agricultural and industrial WRUE. The foundation for water management policy development from a comprehensive agriculture–industry perspective is provided.

The rest of the paper is organized as follows. Section 2 introduces the research methods and materials. Section 3 presents the results. Section 4 discusses the empirical results. Finally, Section 5 summarizes the main conclusions and proposes policy implications.

2. Methods and Materials

2.1. Research Methods

2.1.1. SE-SBM Model

The SBM model was originally proposed by Tone [40]. It is a non-radial and non-angular data envelopment analysis method. However, when multiple decision-making units (DMUs) are evaluated as effective in the SBM, the efficiency level of effective DMUs cannot be further distinguished. Andersen and Petersen proposed the super-efficiency model to resolve this [41]. Besides the outputs defined as "good" such as GDP, there are also "bad" or "undesirable" outputs such as wastewater, exhaust, and solid waste. Based on this, Tone [42] further proposed the SE-SBM model of undesirable outputs, which could comprehensively consider the relationship between inputs, outputs, and pollution. Therefore, an undesirable output-oriented SE-SBM model was selected to measure the WRUE.

The undesirable output SE-SBM model of water resources uses efficiency as follows [42]: In Equation (1), the objective function W is the efficiency value of the decision unit, i.e., the WRUE of each region in this paper; x_{ij} is the input i of the DMU j; y_{rj} is the output r of the DMUs j; s_i^-, s_r^{g+}, s_t^{b-} are the slack variables of the inputs, desirable outputs, and undesirable outputs, respectively; λ is the vector of weights. For a decision-making unit, it is valid if and only if its value is 1, i.e., it satisfies the equality of s^-, s^g, and s^b. Otherwise, the decision-making unit is invalid or has efficiency losses.

$$MinW = \frac{1 + \frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{ik}}}{1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^{g+}}{y_{rk}^g} + \sum_{t=1}^{q_2}\frac{s_t^{b-}}{y_{tk}^b}\right)} \tag{1}$$

$$s.t.\begin{cases} \sum_{j=1,j\neq k}^{n} x_{ij}\lambda_j - s_i^- \leq x_{ik} \\ \sum_{j=1,j\neq k}^{n} y_{rj}^g\lambda_j + s_r^{g+} \geq y_{rk}^g \\ \sum_{j=1,j\neq k}^{n} y_{tj}^b\lambda_j - s_t^{b-} \leq y_{tk}^b \\ 1 - \frac{1}{q_1+q_2}\left(\sum_{r=1}^{q_1}\frac{s_r^{g+}}{y_{rk}^g} + \sum_{t=1}^{q_2}\frac{s_t^{b-}}{y_{tk}^b}\right) > 0 \\ s^- > 0, s^g > 0, s^b > 0, \lambda > 0 \\ i = 1,2,\cdots,m; r = 1,2,\cdots,q; j = 1,2,\cdots,n(j \neq k) \end{cases}$$

2.1.2. Tobit Regression Model

The Tobit model is a standard censored model. Tobit differs from discrete variable models or continuous variable models in that the dependent variable is restricted and consists of two types of equations. The efficiency obtained by the DEA model is affected by the input and output indicators and other environmental factors such as the regional economic level, labour market, and financial support [43]. The estimation of linear regression in the presence of censoring includes additional computational complications. The ordinary least squares regression produces inconsistent parameter estimates because the censored samples are not representative of the total. The values of the SE-SBM model measured in this paper are truncated data greater than 0. Therefore, the Tobit model is appropriate for exploring the drivers of WRUE.

The general form of the Tobit model is Equation (2) [44]. The negative values of the explanatory variable y_i are replaced by 0. The bias brought by the regression reduced.

$$y_i = \beta x_i + u_i \tag{2}$$

The model (2) can be transformed to:

$$WRUE_{it} = c + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_i X_i + \cdots + \beta_9 X_9 + \varepsilon_{it}(i = 1,2,\cdots,9) \tag{3}$$

where $WRUE_{it}$ is the WRUE considering undesirable outputs, i, t denote the values for different regions in different time periods, $X_i(i = 1, 2, \cdots, 9)$ are independent variables, which will be explained in detail below; $\beta_i(i = 1, 2, \cdots, 9)$ denote the coefficients to be estimated for the variables of interest; ε is the random error.

2.2. Variable Selection and Data

2.2.1. WRUE Measurement Variables

Measurement variables should be able to effectively reflect the economic, social and environmental impacts of water use. Regarding the input–output relationship of water resources use in the process of economic growth, Jorgenson and Stiroh [45] proposed the KLEM (capital, labor, energy, and materials) model. The KLEM model decomposes inputs into capital, labor, energy, and intermediate inputs, and outputs refer to desirable outputs of economic significance. While obtaining agricultural and industrial products, some undesirable by-outputs cannot be avoided. Referring to literature, the input–output index system is constructed.

(1) Agricultural sector

In agricultural production, inputs such as land, labor, and capital are indispensable. However, the carbon emissions that come with receiving crops are undesirable but objective. The rural population, amount of agricultural fertilizer (in tons), total power of agricultural machinery (in kilowatts), agricultural water consumption (m^3), and the effective irrigated area (hectares) are selected as the input indicators. The real GDP of agricultural output (in CNY) and the grain yield (tons) are the desirable output indicators. The undesirable output is agricultural carbon emissions (tons) [20,31,46] (Table 1).

Table 1. Input–output index system in agricultural WRUE.

Indicator	Name	Index	Units
Input indicators	Labor	Rural population	10,000 people
	Capital	Amount of agricultural fertilizers	10,000 tons
	Technology	Agricultural machinery power	10,000 kilowatts
	Natural resources	Agricultural water consumption	100 million m^3
		Effective irrigated area	1000 hectares
Output indicators	Desirable output	Agricultural GDP	CNY 100 million
		Grain yield	10,000 tons
	Undesirable output	Agricultural carbon emissions	10,000 tons

(2) Industrial sector

Similarly, the number of employees, capital stock (CNY), and industrial water consumption (m^3) are selected as input variables. The real GDP (CNY) and chemical oxygen demand (COD) emissions (ton) from wastewater are selected as desirable outputs and undesirable outputs, respectively (Table 2).

Table 2. Input–output index system in industrial WRUE.

Indicator	Name	Index	Units
Input indicators	Labor	Number of employees	10,000 people
	Capital	Capital stock	CNY 100 million
	Water resources	Industrial water consumption	100 million m^3
Output indicators	Desirable output	Industrial GDP	CNY 100 million
	Undesirable output	Industrial COD emissions	tons

2.2.2. Tobit Regression Variables

Based on previous research and referring to the literature [20,31,46], the driving factors of WRUE are considered from the following aspects: (1) industrial structure: primary industrial proportion (%) and secondary industrial proportion (%); (2) economic level: per capita GDP (CNY); (3) water resources: water resources endowment (m^3), groundwater proportion (%), utilization rate of water (%), and industrial water proportion (%); (4) influence of the government: financial support (proportion of regional financial expenditure on science and technology, %) and R&D intensity (proportion of R&D expenditure to GDP, %); (5) environmental protection: environmental regulation (proportion of completed investment in pollution control to GDP, %); (6) in the agricultural sector: the agricultural planting area (hectares) are added; (7) in the industrial sector: the urbanization rate (%) is added. The definitions and descriptions of variables are shown in Tables 3–5. Given the existence of ratio-type variables and numerical variables in factors, to make the data comparable, the numerical data are firstly logarithmically processed.

Table 3. Definition and description of variables in China.

X	Variable Name	Variable Definition	Units
X_1	Tertiary industrial proportion	Tertiary industrial GDP/total GDP	%
X_2	Level of opening up	Total import and export volume	1000 dollars
X_3	Economic level	Per capita GDP	CNY
X_4	Water resources endowment	Per capita water resources	m^3
X_5	Agricultural water proportion	Agricultural water consumption/total water consumption	%
X_6	Population	Total population at the end of the year	people
X_7	Urbanization rate	Proportion of urban population	%
X_8	Financial support	Proportion of regional financial expenditure on science and technology	%

Table 4. Definition and description of variables in agricultural sector.

X	Variable Name	Variable Definition	Units
X_1	Primary industrial proportion	Agricultural GDP/total GDP	%
X_2	Secondary industrial proportion	Industrial GDP/total GDP	%
X_3	Economic level	Per capita GDP	CNY
X_4	Water resources endowment	Per capita water resources	m^3/
X_5	Groundwater proportion	Groundwater supply/total water supply	%
X_6	Effective irrigated area	Effective irrigated area	1000 hectares
X_7	Agricultural planting area	Sown area of grain crops	1000 hectares
X_8	Financial support	Proportion of national financial expenditure on agriculture, forestry and water affairs	%
X_9	Environmental regulation	Proportion of completed investment in pollution control to GDP	%

Table 5. Definition and description of variables in industrial sector.

X	Variable Name	Variable Definition	Units
X_1	Primary industrial proportion	Agricultural GDP/total GDP	%
X_2	Secondary industrial proportion	Industrial GDP/total GDP	%
X_3	Economic level	Per capita GDP	CNY
X_4	Water resources endowment	Per capita water resources	m^3
X_5	Utilization rate of water	Total water consumption/total water resources	%
X_6	Industrial water proportion	Industrial water consumption/total water consumption	%
X_7	Urbanization rate	Proportion of urban population	%
X_8	R&D intensity	Proportion of R&D expenditure to GDP	%
X_9	Environmental regulation	Proportion of completed investment in pollution control to GDP	%

2.2.3. Data

The data are obtained from the China Statistical Yearbook and the statistical yearbooks published by the official of the regional statistical bureaus. The economic-related data are all processed with 2005 as the base period.

The data on agricultural carbon emissions are calculated by combining the methodology in the recommended guidelines of the Intergovernmental Panel on Climate Change (IPCC) and the study of Hu et al. [47]. The capital stock data of the secondary industry are calculated by the "perpetual inventory method" mentioned by Zhang et al. [48].

3. Results

Inter-provincial WRUE from 2005 to 2021 in China was measured with the SE-SBM model. The WRUE of the agricultural and industrial sectors was also measured separately. The WRUE results for the industrial sector are up to 2020.

3.1. WRUE Measurement Results

3.1.1. Overall Results of WRUE in China

The WRUE results are shown in Table 6. Given the space limitation, not all results up to 2015 have been listed. The average inter-provincial WRUE in China ranges from 1.156 in Beijing, the highest, to 0.501 in Ningxia, the lowest. In Beijing, Tianjin, Shanghai, and Guangdong, some WRUE values are greater than 1. This is a further distinction of the efficiency level of effective DMUs when they are evaluated as effective in the SBM. This is the advantage of "super-efficiency" in the SE-SBM.

Table 6. WRUE of China.

Province	Year									Mean
	2005	2010	2015	2016	2017	2018	2019	2020	2021	
Beijing	1.212	1.198	1.154	1.061	1.211	1.065	1.062	1.142	1.168	1.156
Tianjin	1.023	1.028	1.081	1.183	1.068	1.104	1.097	1.116	1.108	1.055
Hebei	0.714	0.659	0.604	0.632	0.553	0.599	0.600	0.526	0.515	0.625
Shanxi	0.701	0.623	0.593	0.584	0.555	0.590	0.588	0.528	0.536	0.613
Inner Mongolia	0.658	0.632	0.623	0.675	0.658	0.757	0.769	0.573	0.567	0.648
Liaoning	0.658	0.633	0.610	0.652	0.601	0.659	0.677	0.555	0.562	0.626
Jilin	0.656	0.611	0.578	0.662	0.598	0.640	0.645	0.545	0.535	0.612
Heilongjiang	0.698	0.650	0.595	0.631	0.598	0.622	0.607	0.537	0.552	0.630
Shanghai	1.059	1.069	1.094	1.101	1.107	1.111	1.111	1.107	1.100	1.084
Jiangsu	0.808	0.734	0.725	0.663	0.628	0.663	0.660	0.604	0.610	0.715
Zhejiang	0.713	0.747	0.711	0.685	0.637	0.714	0.713	0.601	0.597	0.700
Anhui	0.664	0.613	0.552	0.557	0.509	0.508	0.494	0.452	0.452	0.568
Fujian	0.731	0.693	0.642	0.625	0.568	0.600	0.603	0.566	0.570	0.655
Jiangxi	0.655	0.604	0.541	0.530	0.489	0.474	0.469	0.458	0.458	0.559
Shandong	0.799	0.740	0.665	0.700	0.636	0.715	0.712	0.591	0.588	0.698
Henan	0.740	0.654	0.611	0.636	0.571	0.616	0.613	0.507	0.502	0.631
Hubei	0.672	0.638	0.594	0.596	0.546	0.563	0.561	0.470	0.477	0.601
Hunan	0.659	0.632	0.574	0.593	0.558	0.547	0.532	0.481	0.481	0.593
Guangdong	1.063	1.058	0.714	0.729	0.658	0.669	0.661	0.580	0.585	0.856
Guangxi	0.631	0.602	0.553	0.544	0.490	0.464	0.445	0.422	0.423	0.555
Hainan	0.642	0.630	0.534	0.558	0.503	0.493	0.490	0.441	0.449	0.564
Chongqing	0.656	0.642	0.637	0.716	0.667	0.760	0.756	0.558	0.552	0.654
Sichuan	0.647	0.624	0.588	0.598	0.556	0.555	0.540	0.479	0.479	0.593
Guizhou	0.633	0.610	0.549	0.530	0.474	0.456	0.438	0.400	0.388	0.548
Yunnan	0.670	0.636	0.582	0.583	0.544	0.568	0.538	0.430	0.426	0.589
Xizang	0.663	0.582	0.578	0.493	0.444	0.427	0.409	0.401	0.403	0.552
Shaanxi	0.663	0.629	0.599	0.632	0.556	0.612	0.609	0.505	0.497	0.610
Gansu	0.639	0.607	0.522	0.563	0.516	0.553	0.556	0.448	0.449	0.568
Qinghai	0.594	0.570	0.516	0.511	0.494	0.497	0.501	0.462	0.460	0.542
Ningxia	0.557	0.537	0.470	0.459	0.448	0.448	0.449	0.443	0.444	0.501
Xinjiang	0.630	0.603	0.535	0.504	0.484	0.479	0.478	0.443	0.440	0.552
Mean	0.726	0.693	0.643	0.651	0.610	0.630	0.625	0.560	0.560	0.660

3.1.2. Agricultural WRUE

The agricultural WRUE results are shown in Table 7 and Figure 1.

Table 7. Agricultural WRUE.

Province	Year									Mean
	2005	2010	2015	2016	2017	2018	2019	2020	2021	
Beijing	1.119	1.124	1.102	1.084	1.071	1.034	1.028	1.052	1.083	1.077
Tianjin	0.666	0.757	0.809	0.921	1.035	1.086	1.093	1.115	1.125	0.956
Hebei	0.688	0.825	0.865	0.899	0.911	0.920	0.920	0.977	0.973	0.886
Shanxi	0.766	0.766	0.788	0.790	0.842	0.863	0.811	0.858	0.827	0.812
Inner Mongolia	0.873	0.775	0.799	0.788	0.779	0.814	0.793	0.787	0.762	0.797
Liaoning	1.043	0.941	1.083	1.071	1.085	1.097	1.120	1.093	1.108	1.071
Jilin	1.188	1.151	1.174	1.219	1.227	1.209	1.227	1.129	1.142	1.185
Heilongjiang	1.054	1.163	1.173	1.161	1.157	1.191	1.214	1.197	1.179	1.165
Shanghai	1.135	1.261	1.166	1.034	1.019	1.199	1.093	1.062	1.035	1.112
Jiangsu	0.874	0.988	1.058	1.063	1.073	1.069	1.062	0.947	0.949	1.009
Zhejiang	0.864	0.774	0.775	0.838	1.023	1.067	1.073	1.075	1.070	0.951
Anhui	0.701	0.765	0.830	0.825	0.833	0.801	0.781	0.791	0.768	0.788
Fujian	0.770	0.779	0.731	0.778	0.885	0.866	0.880	1.007	1.016	0.857
Jiangxi	0.867	0.883	0.939	0.953	0.964	0.979	0.975	0.990	0.977	0.947
Shandong	0.855	0.847	1.000	1.005	1.020	1.037	1.027	1.058	1.086	0.993
Henan	1.049	1.023	1.099	1.091	1.109	1.137	1.123	1.198	1.138	1.107
Hubei	0.788	0.733	0.750	0.748	0.760	0.810	0.786	0.799	0.783	0.773
Hunan	0.862	0.892	0.879	0.876	0.864	0.864	0.852	0.863	0.851	0.867
Guangdong	1.017	1.009	0.937	0.961	1.012	1.007	1.016	1.038	1.037	1.004
Guangxi	0.738	0.738	0.698	0.681	0.674	0.710	0.689	0.701	0.686	0.702
Hainan	1.128	1.170	1.160	1.143	1.146	1.146	1.139	1.142	1.143	1.146
Chongqing	1.279	1.272	1.118	1.105	1.102	1.108	1.099	1.091	1.086	1.140
Sichuan	1.011	0.962	0.969	1.001	1.010	1.021	1.008	1.024	1.013	1.002
Guizhou	1.050	1.005	0.992	1.008	1.026	1.016	1.043	1.044	1.065	1.028
Yunnan	0.804	0.781	0.741	0.731	0.738	0.866	0.851	0.895	0.907	0.813
Xizang	1.267	1.140	1.025	0.875	0.946	1.035	1.031	1.040	1.046	1.045
Shaanxi	0.716	0.777	0.761	0.785	0.768	0.793	0.798	0.825	0.812	0.782
Gansu	0.801	0.776	0.763	0.786	0.859	0.921	0.898	0.867	0.869	0.838
Qinghai	0.802	0.723	0.664	0.767	0.780	0.812	1.012	1.050	1.096	0.856
Ningxia	0.682	0.684	0.660	0.691	0.681	0.711	0.680	0.710	0.682	0.687
Xinjiang	0.855	0.790	0.805	0.734	0.743	0.742	0.763	0.748	0.760	0.771
Mean	0.913	0.912	0.913	0.916	0.940	0.966	0.964	0.973	0.970	0.941

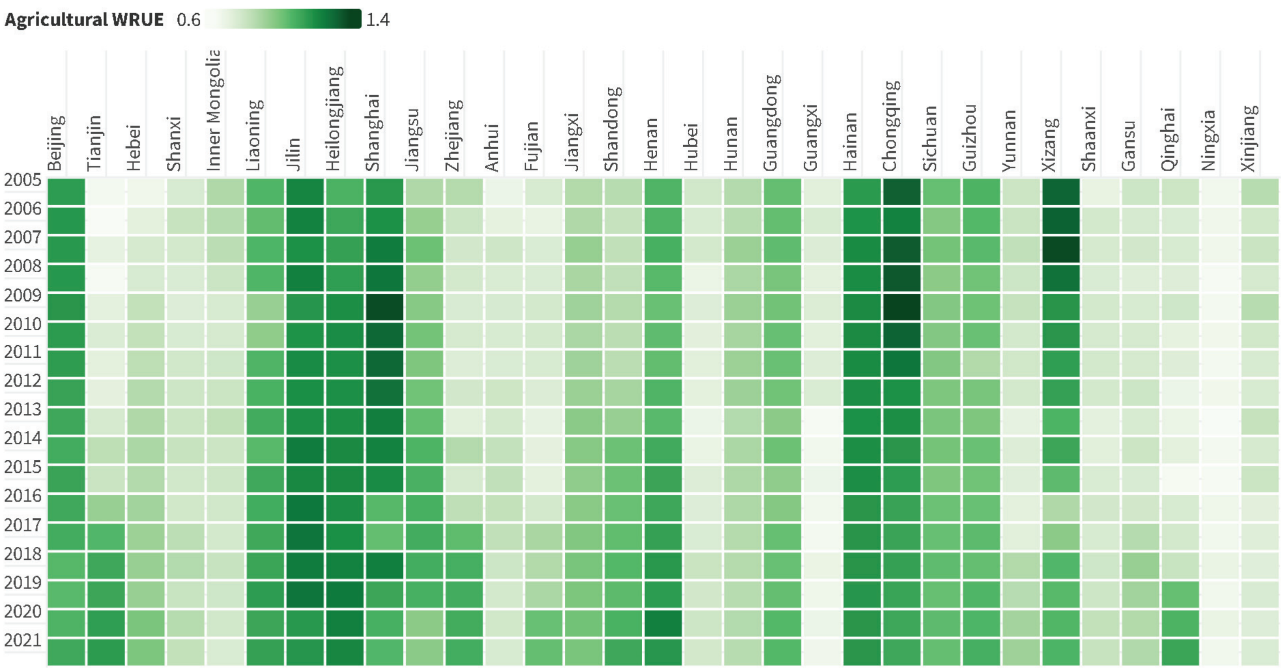

Figure 1. Agricultural WRUE.

The mean value of agricultural WRUE in China was above 0.9 from 2005 to 2021. The highest value was Jilin (1.185), indicating that Jilin was better matched in terms of fertilizers, machinery, labor, and water resources. The lowest mean value was Ningxia (0.687), which is in the arid inland areas of Northwestern China. The inefficiency indicates the mismatch between agricultural activities in economic layout and water use [49].

3.1.3. Industrial WRUE

The industrial WRUE results are shown in Table 8 and Figure 2.

Table 8. Industrial WRUE.

Province	Year								Mean
	2005	2010	2015	2016	2017	2018	2019	2020	
Beijing	1.459	1.468	1.480	1.237	1.251	1.277	1.302	1.305	1.399
Tianjin	1.112	1.162	1.155	1.150	1.116	1.082	1.070	1.200	1.152
Hebei	0.453	0.365	0.318	0.311	0.314	0.311	0.298	0.315	0.362
Shanxi	0.435	0.356	0.291	0.280	0.286	0.290	0.306	0.348	0.352
Inner Mongolia	1.048	1.157	1.083	1.086	1.082	1.087	1.112	1.023	1.101
Liaoning	0.466	0.409	0.408	0.365	0.382	0.395	0.398	0.464	0.429
Jilin	0.369	0.315	0.298	0.296	0.309	0.299	0.300	0.421	0.334
Heilongjiang	0.465	0.387	0.360	0.357	0.356	0.335	0.330	0.363	0.393
Shanghai	1.075	0.692	1.037	1.046	1.086	1.072	1.047	1.040	0.998
Jiangsu	0.387	0.310	0.306	0.282	0.284	0.270	0.260	0.294	0.323
Zhejiang	0.380	0.318	0.327	0.320	0.326	0.320	0.314	0.333	0.339
Anhui	0.268	0.186	0.181	0.171	0.171	0.161	0.153	0.188	0.197
Fujian	0.391	0.317	0.299	0.280	0.286	0.275	0.282	0.350	0.326
Jiangxi	0.306	0.196	0.187	0.176	0.175	0.168	0.161	0.190	0.212
Shandong	1.025	0.568	0.510	0.457	0.472	0.434	0.423	0.459	0.607
Henan	0.422	0.282	0.257	0.255	0.256	0.252	0.266	0.326	0.304
Hubei	0.262	0.274	0.264	0.257	0.260	0.247	0.237	0.225	0.269
Hunan	0.298	0.249	0.234	0.223	0.228	0.218	0.209	0.233	0.252
Guangdong	1.008	0.399	0.394	0.375	0.372	0.360	0.345	0.367	0.515
Guangxi	0.306	0.220	0.227	0.227	0.224	0.207	0.194	0.180	0.236
Hainan	0.324	0.334	0.296	0.288	0.287	0.276	0.267	0.310	0.314
Chongqing	0.294	0.258	0.278	0.273	0.280	0.262	0.254	0.310	0.277
Sichuan	0.266	0.246	0.280	0.264	0.266	0.264	0.263	0.338	0.277
Guizhou	0.284	0.211	0.213	0.207	0.210	0.205	0.199	0.191	0.219
Yunnan	0.373	0.262	0.289	0.286	0.292	0.293	0.280	0.279	0.298
Xizang	0.401	0.263	0.272	0.223	0.218	0.215	0.200	0.395	0.287
Shaanxi	0.412	0.333	0.414	0.410	0.407	0.418	0.400	0.387	0.403
Gansu	0.278	0.222	0.211	0.206	0.201	0.201	0.203	0.251	0.233
Qinghai	0.246	0.249	0.261	0.270	0.275	0.275	0.260	0.276	0.261
Ningxia	0.257	0.257	0.242	0.237	0.235	0.242	0.239	0.210	0.247
Xinjiang	0.557	0.371	0.317	0.304	0.301	0.301	0.281	0.308	0.389
Mean	0.504	0.408	0.409	0.391	0.394	0.387	0.382	0.415	0.429

In the industrial sector, WRUE ranges from the highest of 1.399 in Beijing to the lowest of 0.212 in Jiangxi. The average WRUE is 0.429 during 2005–2020 in the industrial sector, with a declining trend. This suggests that China's rapid economic growth over the period was based on low industrial WRUE. There was an average annual decrease of 4.16% from 2005 to 2010 and 1.84% after 2011. The slowdown in efficiency reduction is indicative of China's sustainable development efforts.

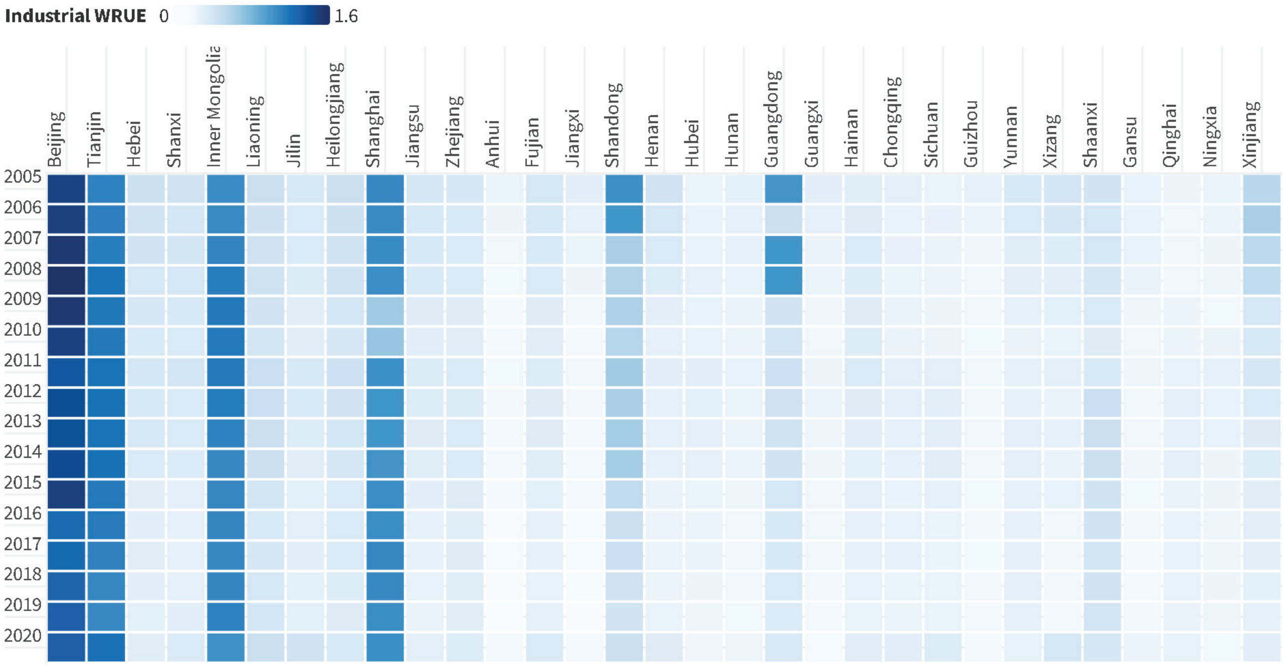

Figure 2. Industrial WRUE.

3.2. Driving Factors

The results of Tobit regression are shown in Tables 9–11.

The overall driving factors result of WRUE in China (Table 9).

Table 9. Tobit regression result of driving factors in China.

X	Variable Name	Regression Coefficient	Standard Deviation
X_1	Tertiary industrial proportion	−0.00085	0.0039398
X_2	Level of opening up	−0.0173821	0.0477747
X_3	Economic level	0.3056228 ***	0.0984446
X_4	Water resources endowment	−0.034023	0.0338003
X_5	Agricultural water proportion	−0.0141513 ***	0.0032433
X_6	Population	−0.1791625 **	0.083117
X_7	Urbanization rate	−0.017255 **	0.0070058
X_8	Financial support	0.0650491 **	0.0294161
C	Constant term	1.271306 *	0.7247596

Note: *, **, *** indicate significant at the 10%, 5% and 1% levels, respectively.

The WRUE driving factors result in agricultural sector (Table 10).

Table 10. Tobit regression result of driving factors in agricultural sector.

X	Variable Name	Regression Coefficient	Standard Deviation
X_1	Primary industrial proportion	−0.0007142	0.0019784
X_2	Secondary industrial proportion	−0.0050987 ***	0.0006222
X_3	Economic level	0.0175212	0.0113597
X_4	Water resources endowment	−0.0049376	0.0091182
X_5	Groundwater proportion	−0.1183793 *	0.0671602
X_6	Effective irrigated area	−0.1469869 ***	0.0260604
X_7	Agricultural planting area	0.1446299 ***	0.0202212
X_8	Financial support	−0.0040641 **	0.0017402
X_9	Environmental regulation	−0.0270033 ***	0.0098143
C	Constant term	1.041346 ***	0.1827509

Note: *, **, *** indicate significant at the 10%, 5% and 1% levels, respectively.

The WRUE driving factors result in industrial sector (Table 11).

Table 11. Tobit regression result of driving factors in industrial sector.

X	Variable Name	Regression Coefficient	Standard Deviation
X_1	Primary industrial proportion	−0.0013346	0.0025046
X_2	Secondary industrial proportion	0.0036085 ***	0.0009079
X_3	Economic level	−0.0724771 ***	0.0198431
X_4	Water resources endowment	−0.0152294	0.014615
X_5	Utilization rate of water	−0.0002677 ***	0.000101
X_6	Industrial water proportion	−0.0040386 ***	0.0011027
X_7	Urbanization rate	0.003648 **	0.0016135
X_8	R&D intensity	−0.0415154 ***	0.0146881
X_9	Environmental regulation	−0.0086181	0.0113406
C	Constant term	1.124456 ***	0.2088492

Note: **, *** indicate significant at the 5% and 1% levels, respectively.

4. Discussion

In the agricultural sector, the average WRUE reached over 1.0 in Beijing, Shanghai, Hainan, Heilongjiang, Jilin and Liaoning. As in the industrial sector, developed provinces and cities pay more attention to urban pollution and resource intensification issues. Therefore, the industrial WRUE of such provinces as Beijing, Tianjin, and Shanghai is basically above 1.0. In the less developed regions, there is still a need for water-intensive enterprises to promote economic growth. The industrial WRUE in these regions has been made to be inefficient, with all of them below 0.3.

Based on the Tobit regression results, the driving factors of WRUE change are discussed as follows.

4.1. Economic Structure and Level

The share of the industrial sector is significantly negatively correlated with water efficiency in agriculture, and positively correlated with industrial water efficiency. The regression coefficients are −0.0050987 and 0.0036085, respectively. An increase in the share of the industrial sector usually means a lower share of agriculture in GDP and better economic development. This confirms that the scale effect also exists in the efficient use of industrial water. Whereas, as a whole, the level of economic development positively drives WRUE. The agglomeration effect of industry, higher levels of management and technology, better water protection policies, and infrastructure investments in wastewater treatment all contribute to efficiency.

The negative relationship with the coefficient of −0.0724771 between the economic level and industrial WRUE deserves attention. This may be attributed to the fact that with the economy developing, the share of the tertiary sector increases and the weight of industry decreases. The reduction in the size of industry makes the sector less efficient in water use, which is also in line with the previous scale effect. There is no doubt that economic development is conducive to the efficient use of water. However, in the economic growth driven by the tertiary sector, the problem of declining industrial water efficiency cannot be ignored.

4.2. Water Resources Endowment

Water resources endowment is negatively correlated with WRUE in both agriculture (−0.0049376) and industry (−0.0152294) with P not being significant at 10% (0.31 in the whole, 0.58 in agriculture, 0.29 in industry). This suggests an underlying tendency for water scarcity areas to use water more efficiently than water-abundant areas. The proportion of groundwater in total water consumption is significantly negatively correlated (−0.1183793) with agricultural WRUE.

A high share of groundwater use in agricultural production usually implies a poor water endowment. It means that results, after taking into account for agricultural carbon emissions, provide evidence to the contrary. In other words, after accounting for agricultural carbon emissions, agricultural water efficiency in water-scarce areas will be lower than in water-abundant areas.

Similarly, in industry, the higher the proportion of water resources exploited is, the poorer will be the water endowment. At this point, the industrial WRUE after considering the industrial COD emissions is lower in water-scarce areas.

This is a result that diverges from common sense and previous research. This result indicates that the relationship between water resources endowment and WRUE needs to be further studied, given that climate change and environmental protection are increasingly concerned [50].

4.3. Government Influence and Environmental Regulations

Government financial support positively (0.0650491) promotes the overall WRUE. However, the negative (−0.0040641) impact of government investment in agriculture, forestry and water affairs on agricultural WRUE is of great concern. The maintenance and construction of new water conservancy facilities are believed to improve the efficiency of irrigation water use [51]. This view is challenged by the negative impact of government financial support for agriculture on WRUE. This becomes reasonable when the focus of financial support is on ensuring the total water supply and output in agriculture, rather than on water-saving facilities. Government financial support for agriculture should raise the concern for agricultural water conservancy in order to avoid excessive waste of precious water resources and improve water efficiency. A similar situation also occurs in the industrial sector. The increase in R&D intensity reduces industrial WRUE. It shows that the focus of R&D is not on energy conservation and resource efficiency, but on other aspects. This coincides with the fact that China's industry has not yet reached the stage of high-quality development. Whether it is agriculture or industry, on the path of green and sustainable development, financial support should encourage more efficient use of resources.

Unsurprisingly, environmental regulations have had a negative impact (−0.0270033 in agriculture, −0.0086181 in industry) on water efficiency [52]. The reason is clear: environmental protection has increased the cost of production. However, this is not a reason to relax environmental regulations. On the contrary, it confirms that government financial support should increase investment in the green ecological development of agriculture and industry.

4.4. Non-Shared Factors between Agriculture & Industry

In the agricultural sector, the effective irrigation area and the sown area of grain crops have a negative (−0.1469869) and positive (0.1446299) impact on agricultural water resources, respectively. It is clear that more sown area of grain crops will increase agricultural water use. However, the scale effect of agricultural cultivation has improved WRUE. The effective irrigation area is also closely related to agricultural water consumption. More agricultural water use leads to a decrease in efficiency, confirming low irrigation efficiency in China. This is consistent with China's low level of water-saving irrigation construction. Promoting water-saving irrigation is an important way to improve the WRUE in the agricultural sector.

The urbanization rate and industrial WRUE are significantly positively correlated, with a coefficient of 0.00364. China's urbanization rate rose from 43.0% to 64.7% between 2005 and 2021. The high urbanization rate has led to a rapid increase in the total amount of domestic and industrial water use, accompanied by increasing industrial WRUE [53]. The positive relationship indicates that high urbanization rates have been able to eliminate negative impacts through organizational coordination and technological progress. It shows that China's urbanization construction is in the stage of high-quality. Organizational advantages and scientific and technological means have been utilized to achieve ecological and green development of efficient use of resources.

5. Conclusions

This paper firstly measures the WRUE of agriculture and industry in China with the SE-SBM model, considering agricultural carbon emissions and industrial pollution as undesirable outputs. Then, the Tobit regression is applied to discuss the driving factors of WRUE in the agricultural and industrial sectors.

The main conclusions are as follows: (1) Economic development is conducive to the improvement of overall WRUE. The higher the proportion of industry there is in the economy, the higher will be the industrial WRUE. There is a scale effect in industrial WRUE. When the proportion of the tertiary industry in the economic structure increases and the industrial proportion decreases, the WRUE will be negatively affected. (2) The agricultural WRUE of the areas with poor water endowment is lower than that of the areas with abundant water resources. Similarly, industrial WRUE in water-scarce areas is lower than that in water-rich areas. Today, ecological development has received great attention and the relationship between water resources endowment and WRUE needs to be further studied. (3) Government financial support positively promotes the WRUE. However, the failure of agricultural financial support to improve agricultural WRUE indicates that investment in water-saving irrigation construction is still insufficient. R&D investment in industry has not improved industrial WRUE. (4) The scale of agricultural planting has a positive driving effect on agricultural WRUE. Agricultural production also has scale effects on the WRUE. However, the agricultural WRUE will decline as the effective irrigated area increases. Irrigation in China is inefficient. The urbanization rate plays a positive role in industrial WRUE. China's urbanization needs to continue to be focused on quality.

The policy implications are as follows: (1) High-quality economic development needs to be upheld. Precautionary measures need to be taken to prevent the inefficient use of resources from being neglected as the industrial sector declines in economic development. (2) From the perspective of green ecology, the relationship between water endowment and WRUE needs to be further studied. (3) Financial support for agricultural and industrial ecological development needs to be increased. In agriculture, more support should be given to water-saving irrigation construction. In industry, energy conservation and efficient use of resources should be the focus. (4) Urbanization should pay attention to high-quality development. We should be making use of organizational advantages and scientific and technological means to achieve ecological and green development of efficient use of resources.

This paper has limitations. The study depends on inter-provincial and annual data. With the rise in big data applications, the exploration of WRUE-driving factors at scales such as the city or county requires future research.

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Strategic Analyses for a Cross-Basin Water Pollution Conflict Involving Heterogeneous Sanctions in Hongze Lake, China, within the GMCR Paradigm

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Abstract: The graph model for conflict resolution (GMCR) methodology was enhanced in this research for addressing cross-basin water pollution conflicts involving heterogeneous sanctions, as a more intuitive and straightforward definition for mixed unilateral improvements was proposed, followed by an integrated procedure for performing mixed stability analyses. Furthermore, the cross-border water pollution dispute that occurred in 2018 in Hongze Lake, China, is systematically modeled and strategically analyzed for the first time, using the improved GMCR method. In addition, an evolution analysis was carried out within the framework of GMCR for verifying the applicability of the eco-compensation mechanism in addressing cross-basin water pollution disputes. This case study demonstrates that the heterogeneity of sanctioning opponents could influence equilibrium outcomes and even change the evolution of conflict situations. Moreover, the developed novel approach is able to accurately predict the equilibrium outcomes of the conflict and provide more strategic insights and valuable findings in making effective conflict resolutions for solving cross-basin water pollution conflicts.

Keywords: cross-basin water pollution; conflict analysis; ecological compensation; graph model for conflict resolution; Hongze Lake; mixed stability analysis

1. Introduction

Cross-basin water pollution refers to the environmental contamination across administrative regions within the same river basin caused by the fluidity of water pollution [1], meaning that the water pollution that originated in one area could be transported to another region in the same watershed. In China, cross-basin water pollution is increasingly pervasive in many river basins, such as the Yellow, Yangtze, and Songhua River Basins, causing severe water security issues and economic losses and even posing great threats to human and ecosystem health [2–4]. Meanwhile, mass environmental disputes across administrative regions have occurred frequently in China in recent years due to cross-basin water pollution [5,6]. For example, the cross-basin water pollution disputes took place in Huai River in 2013 (Anhui Province), Huangpu River in 2013 (Shanghai City), Tuo River in 2015 (Anhui Province), Hongze Lake in 2018 (Jiangsu Province), Shu River in 2020 (Jiangsu Province), etc. In inter-basin water pollution conflicts, the upstream and downstream belong to different political regions and do things in their own way, and they often argue back and forth regarding the source and responsibility of cross-regional pollution because of the lack of a unified joint pollution control mechanism. Inevitably, more and more cross-basin water pollution conflicts happen. Cross-border water pollution disputes have always been a tough and complex system problem that is difficult to deal with because a series of conflicts of interest and dynamic interactions in terms of moves and countermoves exist in multiple stakeholders or decision makers (DMs) involved, including the upstream and downstream governments, industrial enterprises and local residents situated in river basins, environmental non-governmental organizations, and so on.

Due to the behavioral diversity of DMs involved in cross-basin water pollution disputes, stakeholders are sometimes heterogeneous when sanctioning a focal DM's unilateral improvements, which may dramatically influence the equilibrium outcomes and resolutions for addressing the conflict. Specifically, when a focal DM moves to a more preferred state, some non-credible players may block the unilateral improvement (UI) of the focal DM by going to any reachable state regardless of preference, whereas credible players will utilize only their UIs as sanctions. For instance, there exist three main DMs in a water contamination dispute: the local government (LG), chemical plants (CP), and local residents (LR). To save on sewage treatment costs, CP may secretly discharge industrial wastewater into the surroundings, which may severely damage the local ecosystem and even endanger human health. From the perspective of CP, their opponents are LG and LR, in which the sanction by LG is credible if LG is economically oriented and pursues local economic growth instead of environmental protection, while the countermove from LR is non-credible and will take all possible actions at any cost to fight against CP when their health is threatened by the discharge of sewage by CP. Therefore, from the viewpoint of CP, the sanctioning behavior of LG and LR is heterogeneous instead of homogeneous. The sanctioning moves by heterogeneous and homogeneous opponents may be different and the heterogeneity of opponents could affect the outcomes and resolutions of cross-basin water pollution conflicts. Hence, an effective decision-making methodology is urgently needed for modeling and analyzing cross-border water pollution conflicts with heterogeneous sanction behaviors.

The graph model for conflict resolution (GMCR) is a very powerful and systematic methodology developed on the basis of the Metagame Theory [7] and F-H conflict analysis technique [8] for strategically modeling and analyzing real-world disputes arising from social, economic, and environmental areas, among others [9–11]. Compared with classical game theory, the GMCR methodology needs only relative preference information instead of cardinal utilities, and it has a richer set of solution concepts for portraying complex decision-making behaviors. GMCR has been applied to many water resource disputes, such as the Devils Lake outlet diversion conflict in United States [12], the cross-basin groundwater allocation dispute in Snake Valley, USA [13] and a water rights conflict in Iran [14]. The GMCR method is also employed for addressing cross-basin water pollution disputes [15,16]. However, the impact of heterogeneous sanctions on equilibrium outcomes and conflict resolutions were not taken into account in the aforesaid literature.

In this research, an intuitive definition for mixed unilateral improvements (MUIs), as well as a detailed procedure for performing mixed stability analyses, is put forward within the framework of GMCR to portray heterogeneous sanctioning behaviors in disputes, as it is more straightforward and easier to understand than that developed by Zhao et al. [17,18]. Subsequently, the cross-basin water pollution conflict regarding Hongze Lake that occurred on 25 August 2018 in China was systematically modeled any analyzed by using the general and mixed stability analysis approaches by which the equilibrium outcomes of the dispute can be predicted. One of the reasons for taking the Hongze Lake pollution incident as a case study is that the cross-basin water contamination issue took place in Hongze Lake for many years (1974, 2004, 2007, and 2018) but has not been well addressed until now. Another reason is that the decision-making behaviors of stakeholders involved in the dispute and their strategic interactions are diverse and complex, where both rational and irrational sanctions exist. Furthermore, we investigated the impact of cross-basin eco-compensation on the equilibrium outcomes and possible solutions for addressing this kind of cross-border water contamination dispute based on the evolution analysis approach of GMCR.

The rest of the paper is organized as follows. To begin with, the literature review is present in Section 2. Then, the basic concepts of GMCR methodology, logical definitions for MUIs and mixed stabilities, as well as a procedure for mixed stability analyses, are introduced in Section 3. In Section 4, the cross-basin water pollution conflict in Hongze Lake is systematically modeled by using the GMCR methodology, including the extraction of DMs, options, feasible conflict states, and preferences over states, as well as the drawing of a graph model for describing state transitions of DMs. Subsequently, the Hongze Lake conflict model is analyzed in Section 5 by using the general and mixed stability analysis techniques, respectively, followed by a brief discussion. Finally, conclusions, limitations, and future work are presented.

2. Literature Review

2.1. Research on Cross-Basin Water Pollution Disputes

The existing studies regarding cross-basin water pollution disputes mainly focus on the cause–effect analysis, compensation mechanism design, and conflict evolution and resolutions. In regard to the cause–effect analysis of cross-basin water pollution, many scholars investigated the source and effects of pollution, as well as the impact of means and public policies on cross-border pollution control. The key factors that could reduce beggar-thy-neighbor behavior in transboundary pollution disputes were studied by Bernauer and Kuhn [19], and it was found that the observed effects of the variables vary considerably across forms of pollution. Using the empirical analysis method, Wang et al. [20] discussed the reasons that cause water pollution at political borders in China from the perspective of promotion incentives. Based on the evidence data of river-water-quality data in China, Lu [21] adopted the triple-difference method to evaluate the impact of central environmental protection inspection on cross-basin water pollution. To analyze the cost effectiveness of reducing water pollutant emissions in the Jialu River Basin in China, a game theoretic simulation model was established by Shi et al. [3] by taking into account the stability and fairness of cost allocation schemes. The environmental monitoring and impact assessment of Prut River cross-border pollution were discussed by Neamtu et al. [22]; they evaluated the water pollution level and impacts on the Prut River cross-border area from 2015 to 2019. Moreover, a cross-basin eco-compensation mechanism was designed for promoting cross-border joint prevention and control of water pollution. More specifically, two econometric models were developed by Li et al. [23] based on theoretical and empirical analyses for investigating a cross-basin eco-compensation mechanism of Songhua River Basin, and the polluter pays principle was verified in this research. Furthermore, Chen and Qi [24] studied the international dispute settlement mechanisms for the cross-basin water pollution dispute due to the Fukushima contaminated water discharge, using the qualitative analysis method. Considering the power and varying intensities of conflict, Zeitoun and Warner [25] constructed a conceptual framework of Hydro-Hegemony for an analysis of trans-boundary water conflicts. In addition to the aforementioned quantitative and empirical analyses, there are also some studies in relation to evolution analysis and conflict resolutions for cross-basin water pollution disputes, using game-theoretical techniques. The evolutionary game theory was utilized by Wang et al. [26] for exploring the interaction mechanism between upstream and downstream countries in transboundary river basins under the Belt and Road, and then the optimal ecological compensation mechanism was designed. Within the GMCR paradigm, Akbari et al. [15] strategically investigated a tripartite environmental conflict in the Tigris River Basin and claimed that the option for water diplomacy would generate new equilibria for addressing this dispute. Yang et al. [14] employed the improved GMCR method to analyze the dynamic evolution of cross-basin water conflicts in the Yangtze River Delta in China and then proposed some useful insights for resolving the cross-basin water conflict. Considering the fuzziness of stakeholders in ecological compensation conflicts, Wang et al. [27] developed a graph model with intuitionistic preferences and then employed the proposed method for modeling and analyzing the ecological compensation conflicts in the Taihu Lake basin, China. Furthermore, a new grey inverse GMCR was constructed by Li et al. [28] to effectively mediate the water resources conflicts in the Poyang Lake Basin, China.

To summarize, the causes and effects of cross-basin water pollution disputes, the eco-compensation mechanism design, and the conflict evolution and solutions have been systematically discussed in current research. Most studies on cross-basin water pollution disputes are based on qualitative methods and empirical analyses. However, limited research has been conducted on strategic analyses established on game-theoretical approaches such as game theory and the GMCR methodology. Moreover, all of sanctioning behaviors of stakeholders involved in a cross-basin water pollution conflict are assumed to be rational of irrational (homogeneous) in the literature [15,16,27,28], and the impacts of heterogeneous sanctions on equilibrium outcomes and conflict mediation strategies are not discussed. Last but not the least, the effects of eco-compensation mechanisms are not investigated from the perspective of an evolution analysis within the framework of GMCR.

2.2. Research on the Solution Concepts in GMCR

To reflect different kinds of interactive behavior of DMs involved in a conflict, four basic solution concepts or stability definitions, namely Nash stability [29], general metarationality (GMR) [7], symmetric metarationality (SMR) [7], and sequential stability (SEQ) [8,30], have been developed to determine whether a state is stable for a DM under a specific solution concept within the GMCR paradigm. Subsequently, the four classical stabilities mentioned above were expanded to diverse solution concepts for handling conflicts with strength preference [31,32], unknown preference [33,34], hybrid preference [35–37], fuzzy preference [38–41], and DMs' attitudes [42–44]. In SMR, the sanctioning opponents are assumed to be irrational who move to any reachable states. In SEQ and in symmetric sequential stability (SSEQ) [45], however, the sanctions are rational, and the opponents can move only to more preferred states.

In the definitions of GMR and SMR, the focal DM who believes that all of the sanctions by its opponents are non-credible can be regarded as being conservative. Alternatively, the sanctioning opponents could be deemed to be irrational when their preferences are unknown to a conservative DM. The focal DM in SEQ and SSEQ, however, is adventurous since it believes that all of the sanctions are rational and that its opponents move only to more preferred states. In brief, all of the sanctioning opponents in the aforementioned stabilities are assumed to be homogeneous. In a real-world conflict, each decision maker (DM) has its own perception and behavior. When a focal DM unilaterally moves to a more preferred state, the sanctioning moves by opponents may be heterogeneous, in which non-credible rivals move to any reachable states to block the DM at any cost whereas credible opponents levy only unilateral improvements as sanctions. To handle a conflict with heterogeneous opponents, Zhao et al. [17,18] proposed a novel mixed stability analysis method based on the GMCR paradigm, in which an inductive method for obtaining MUIs and two types of mixed stabilities are formally defined. However, the definition of MUIs is not in an intuitive form and difficult to understand. Moreover, the detailed process for implementing the mixed stability analyses and applications on cross-basin water pollution disputes are not discussed by Zhao et al. [17,18].

2.3. Summary

The novelties of this research work in comparison with existing methods are summarized in Table 1.

As shown in Table 1, most of the research [20,22–25] in cross-border water pollution disputes is based on qualitative and empirical analysis methods, in which the preference of stakeholders and the complex strategic interactions among DMs are not taken into account. The dynamic interactions among stakeholders were investigated in some other studies [3,26], using game theory. However, the preference of DMs in the aforementioned research is represented by numerical utilities, which are difficult to obtain in real-world situations, and the sanctions by opponents are not considered. Within the framework of GMCR, cross-border water pollution disputes are modeled and analyzed in the literature [15,16,28], where only relative preferences are required, and the sanctioning moves by opponents are considered. Furthermore, the GMCR methodology provides various kinds of solution concepts for portraying the complex decision-making behaviors, such as GMR, SMR, SEQ, and so on, except for Nash. However, the sanctioning opponents are assumed to be homogenous (either irrational or rational) in the above studies. In many actual conflicts, the sanctions are heterogeneous. In other words, irrational and rational sanctioning moves could coexist. Therefore, the main novelty of this study is that the heterogeneous sanctioning behavior among stakeholders was taken into account when modeling and analyzing the cross-border pollution dispute in Hongze Lake, China, as compared to existing the literature.

Table 1. The novelties of this research work in comparison with existing methods.

Reference	Method	Preference	Stability	Sanctions by Opponents
Wang et al. [20]; Chen and Qi [24]; Zeitoun and Warner [25]	Qualitative analysis	Not consider	Not consider	Not consider
Neamtu et al. [22]; Li et al. [23]	Empirical analysis	Not consider	Not consider	Not consider
Shi et al. [3]; Wang et al. [26]	Game theory	Quantitative utility (difficult to obtain)	Nash	Not consider
Akbari et al. [15]; Yang et al. [16]; Li et al. [28]	GMCR	Relative preference (easy to obtain)	Nash, GMR, SMR, SEQ	Homogeneous (either rational or irrational DMs)
Wang et al. [27]	GMCR	Relative preference (easy to obtain)	IR, IGMR, ISMR, ISEQ	Homogeneous (either rational or irrational sanctions)
This research work	GMCR	Relative preference (easy to obtain)	MTS, MSMR (more general than traditional stabilities)	Heterogeneous (rational and irrational sanctions could coexist)

The main contributions of this research include the following: (1) a more intuitive and straightforward definition for MUIs and a specific procedure for mixed stability analyses are proposed in this paper within the GMCR paradigm for handing cross-basin water pollution disputes with heterogeneous sanctioning moves; (2) the cross-border pollution dispute in Hongze Lake is systematically modeled and strategically analyzed for the first time, using the improved GMCR methodology, in which the impact of heterogeneous sanctions of opponents on the equilibrium outcomes is discussed; (3) an evolution analysis based on GMCR is carried out in this research for verifying the applicability of the eco-compensation mechanism in addressing cross-basin water pollution disputes.

3. Methodology

3.1. Basic Concepts in GMCR

A real-world conflict can be modeled as $G = \langle N, S, \{A_i, \succsim_i: i \in N\}\rangle$ within the GMCR paradigm, containing four key elements [7–9]:

(1) $N = \{1, 2, \ldots, i, \ldots, n\}$, the set of DMs involved in the conflict, in which "n" is the total number of DMs;
(2) $S = \{s_1, s_2, \ldots, s_l, \ldots, s_m\}$, the set of feasible states, in which "m" is the total number of feasible states;
(3) A_i, the set of oriented arcs of DM $i \in N$, which records all the unilateral moves (UMs) in one step by DM i;

(4) $\succsim_i$, the preference relations of DM i, in which $q \succ_i s$ means that state q is more preferred to state s by DM i, and $q \sim_i s$ indicates that q is equally preferred to s by DM i. Furthermore, $q \succsim_i s$ means that $q \succ_i s$ or $q \sim_i s$.

If DM i can unilaterally move to a state which is more preferred to the initial state, then this kind of move is called a unilateral improvement (UI). The set of UMs and unilateral improvements (UIs) for DM i can be defined as follows, respectively [10,11].

Definition 1. *Let $s,\ q \in S$ and DM $i \in N$. The set of UMs of DM i at state s can be denoted by*

$$R_i(s) = \{q \in S : (s,\ q) \in A_i\}. \tag{1}$$

Definition 2. *Let $s,\ q \in S$ and DM $i \in N$. The set of UIs of DM I at state s can be expressed by*

$$R_i^+(s) = \{q \in S :\ q \in R_i(s) \text{ and } q \succ_i s\}. \tag{2}$$

Let a coalition be $H \subseteq N$ and $H \neq \varnothing$. The reachable list of H at state $s \in S$ can be denoted by $R_H(s)$, including all the states that can be reached by any legal sequences of UMs by the DMs in H [8,9]. Note that no DM can move twice consecutively in $R_H(s)$.

Definition 3. *Let $s,\ q \in S$. State q can be reached by H from state s, as denoted by $q \in R_H(s)$, if and only if there exists a legal sequence $\{s_0,\ i_1,\ s_1,\ i_2,\ s_2, \ldots,\ s_{l-1},\ i_l,\ s_l, \ldots,\ s_{k-1},\ i_k,\ s_k\}$ in which $s_0,\ s_1, \ldots,\ s_k \in S$ and $i_1,\ i_2, \ldots,\ i_k \in H$, such that $s_0 = s$, $s_k = q$, and $s_l \in R_{i_l}(s_{l-1})$ for $l = 1,\ 2, \ldots,\ k$, with the constraint that $i_l \neq i_{l-1}$ for $l = 2,\ 3, \ldots,\ k$.*

Definition 4. *Let $s,\ q \in S$. State q is a UI from state s for H denoted by $q \in R_H^+(s)$ if and only if there exists a legal sequence $\{s_0,\ i_1,\ s_1,\ i_2,\ s_2, \ldots,\ s_{l-1},\ i_l,\ s_l, \ldots,\ s_{k-1},\ i_k,\ s_k\}$ in which $s_0,\ s_1,\ \ldots,\ s_k \in S$ and $i_1,\ i_2, \ldots,\ i_k \in H$, such that $s_0 = s$, $s_k = q$, and $s_l \in R_{i_l}^+(s_{l-1})$ for $l = 1,\ 2, \ldots,\ k$ with the constraint that $i_l \neq i_{l-1}$ for $l = 2,\ 3, \ldots,\ k$.*

Note that in Definition 4, each DM in H is credible and moves to only more preferred states, and this is different from that in Definition 3.

Let a focal DM $i \in N$, the set of other DMs except i, be $H = N \backslash \{i\}$, and the initial state $s \in S$. Then, the four classical solution concepts, i.e., Nash, GMR, SMR, and SEQ, can be formally defined as follows [10,11].

Definition 5. *State s is Nash stable for DM i, denoted by $s \in S_i^{Nash}$, if $R_i^+(s) = \varnothing$.*

In Nash stability, the focal DM i only takes into account its unilateral improvements from the initial state s but does not consider the counterattacks or sanctions from its opponents (one-step game).

Definition 6. *State s is GMR stable for DM i, denoted by $s \in S_i^{GMR}$, iff for any state $s_1 \in R_i^+(s)$, there exists at least one reachable state $s_2 \in R_H(s_1)$ by H such that $s \succsim_i s_2$.*

In GMR stability, DM i considers all possible sanctions by its opponents, H, after its unilateral improvements from state s (two-step game).

Definition 7. *State s is SMR stable for DM i, denoted by $s \in S_i^{SMR}$, if for any state $s_1 \in R_i^+(s)$, there exists at least one reachable state $s_2 \in R_H(s_1)$ by H, such that $s \succsim_i s_2$, and $s \succsim_i s_3$ holds for each state $s_3 \in R_i(s_2)$.*

In comparison to GMR, SMR stability further considers the re-movement by DM I (three-step game).

Definition 8. *State s is SEQ stable for DM i, denoted by* $s \in S_i^{SEQ}$*, if for any state* $s_1 \in R_i^+(s)$*, there exists at least one reachable state* $s_2 \in R_H^+(s_1)$ *by H such that* $s \succsim_i s_2$.

Compared to GMR, all of the counterattack actions by the opponents, *H*, are assumed to be rational in SEQ stability (two-step game).

The aforementioned four classical stabilities dynamically characterize the complex interactions and decision-making behaviors and can predict the equilibrium outcomes of conflict games with rational or irrational counterattacks and attitudes to risk (conservative or adventure) taken into account.

However, the counterattacks or sanctions of DM *i*'s opponents are assumed to be homogeneous in GMR, SMR, and SEQ stabilities, either rational or irrational. In many conflicts, in fact, the sanctions could be hybrid or heterogeneous with both rational and irrational counterattacks, in which non-credible opponents take any countermoves regardless of preference when sanctioning, whereas credible players levy only unilateral improvements as sanctions. In order to describe this kind of heterogeneous sanctioning behaviors of stakeholders involved in a given conflict, the MUIs and two mixed stabilities are formally defined below, followed by a detailed procedure for carrying out the mixed stability analyses to systematically forecast the equilibrium outcomes or possible solutions for cross-basin water pollution disputes with heterogeneous sanctions.

3.2. Mixed Stabilities with Heterogeneous Opponents

Let a focal DM $i \in N$ and the set of its heterogeneous opponents be $O = N \backslash \{i\}$, and *O* consists of two subsets: the set of rational opponents, O_C; and the set of irrational opponents, O_{NC}. A mixed unilateral improvement (MUI) by heterogeneous opponents should satisfy the following three requirements:

(1) If DM $j \in O_C$, then the sanctioning DM *j* can shift only to more preferred states;
(2) If DM $j \in O_{NC}$, then sanctioning DM *j* can move to any reachable states regardless of preference;
(3) Each DM $j \in O$ cannot move twice consecutively.

Let $R_O^{\oplus}(s)$ be the set of MUIs for the heterogeneous opponents *O* from state *s*. The set of MUIs, $R_O^{\oplus}(s)$, can be defined similar to Definitions 3 and 4.

Definition 9. *Let* $s,\ q \in S$*. State q can be reached by the heterogeneous opponent O from state s, denoted by* $q \in R_O^{\oplus}(s)$*, if and only if there exists a legal sequence* $\{s_0, i_1, s_1, i_2, s_2, \ldots, s_{l-1},\ i_l, s_l, \ldots, s_{k-1}, i_k, s_k\}$ *in which* $s_0,\ s_1,\ \ldots,\ s_k \in S$ *and* $i_1,\ i_2, \ldots,\ i_k \in H$*, such that* $s_0 = s$*,* $s_k = q$*,* $s_l \in R_{i_l}(s_{l-1})$ *if* $i_l \in O_{NC}$ *and* $s_l \in R_{i_l}^+(s_{l-1})$ *if* $i_l \in O_C$ *with the constraint that* $i_l \neq i_{l-1}$ *for* $l = 2,\ 3, \ldots,\ k$.

In Definition 9, if DM *i*'s opponent is credible, then it levies only UIs against DM *i*; if DM *i*'s opponent is non-credible, then it can shift to any reachable states to block DM *i*.

According to Definitions 3, 4, and 9, one can determine that $R_O^+(s) \subseteq R_O^{\oplus}(s) \subseteq R_O(s)$. In particular, $R_O^{\oplus}(s) = R_O(s)$ holds if $O = O_{NC}$, and $R_O^{\oplus}(s) = R_O^+(s)$ holds when $O = O_C$. This indicates that Definition 9 is the same as Definitions 3 and 4 if all of the opponents are irrational and rational, respectively. The interrelationships among $R_O(s)$, $R_O^+(s)$, and $R_O^{\oplus}(s)$ are illustrated in Figure 1.

Mixed stabilities were developed by Zhao et al. [17,18] to systematically portray the different sanctioning behavior of heterogeneous opponents. Let DM $i \in N$ and the set of its heterogeneous opponents be $O = N \backslash \{i\}$. Then, two kinds of mixed stabilities can be defined as follows.

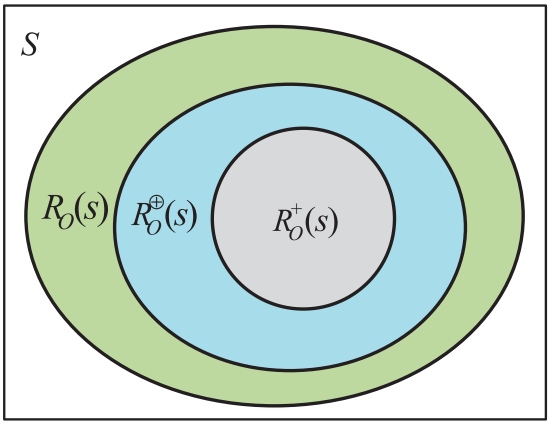

Figure 1. Logical interrelationships among $R_O(s)$, $R_O^+(s)$, and $R_O^{\oplus}(s)$.

Definition 10. *State $s \in S$ is mixed two-step stability (MTS) stable for DM i, as denoted by $s \in S_i^{MTS}$, if for every $s_1 \in R_i^+(s)$, there exists at least one state, $s_2 \in R_O^{\oplus}(s_1)$, such that $s \succsim_i s_2$.*

In MTS stability, DM i believes that its sanctioning opponents are heterogeneous, in which case some credible opponents levy only UIs to block DM i's UIs, while some non-credible opponents go to any reachable states when sanctioning. Note that MTS in Definition 10 will be identical to GMR and SEQ if all of DM i's opponents are non-credible and credible, respectively.

Definition 11. *State $s \in S$ is mixed SMR (MSMR) stable for DM i, as denoted by $s \in S_i^{MSMR}$, if for every $s_1 \in R_i^+(s)$, there exists at least one state, $s_2 \in R_O^{\oplus}(s_1)$, such that $s \succsim_i s_2$ and $s \succsim_i s_3$ for every $s_3 \in R_i(s_2)$.*

In comparison with Definition 10, DM i in Definition 11 considers not only the sanctions by its heterogeneous opponents but also its further reaction to escape from the deterrent by its opponents. Furthermore, MSMR stability will be the same as SMR and SSEQ if all of DM i's opponents are non-credible and credible, respectively. The mixed stabilities and four classical stabilities are compared in Table 2.

Table 2. The comparisons of mixed stabilities and four classical stabilities.

Types	Stabilities	A Focal DM's Opponents	Steps
Classical Stabilities	Nash	The opponents are not taken into account.	One
	GMR	All of the opponents are homogeneous and non-credible.	Two
	SMR	All of the opponents are homogeneous and non-credible.	Three
	SEQ	All of the opponents are homogeneous and credible.	Two
Mixed Stabilities	MTS	The opponents are heterogeneous, including both non-credible and credible players.	Two
	MSMR	The opponents are heterogeneous, including both non-credible and credible players.	Three

A detailed procedure for implementing mixed stability analyses was purposefully designed, as shown in Figure 2, for addressing a conflict with heterogeneous sanctions.

As illustrated in Figure 2, the mixed stability analyses are divided into two stages: the modeling and analysis stages. In the modeling stage, the key DMs involved in the conflict, their options, feasible states, and each DM's preference should be identified. Furthermore, from the perspective of a particular DM, its credible and non-credible opponents should be determined. In the analysis stage, the outcomes of individual mixed stability analyses can be determined according to Definitions 10 and 11. Subsequently, the equilibria of the conflict can be obtained. A state is called an equilibrium if it is stable for all of the DMs under a particular solution concept in a conflict. Furthermore, one can conduct sensitivity analyses to determine how the changes of the elements in the modeling stage, such as DMs' preferences and opponents' different sanctioning behavior, can affect the results of the analysis. Consequently, valuable strategic insights can be attained to make more informed decisions for addressing the dispute.

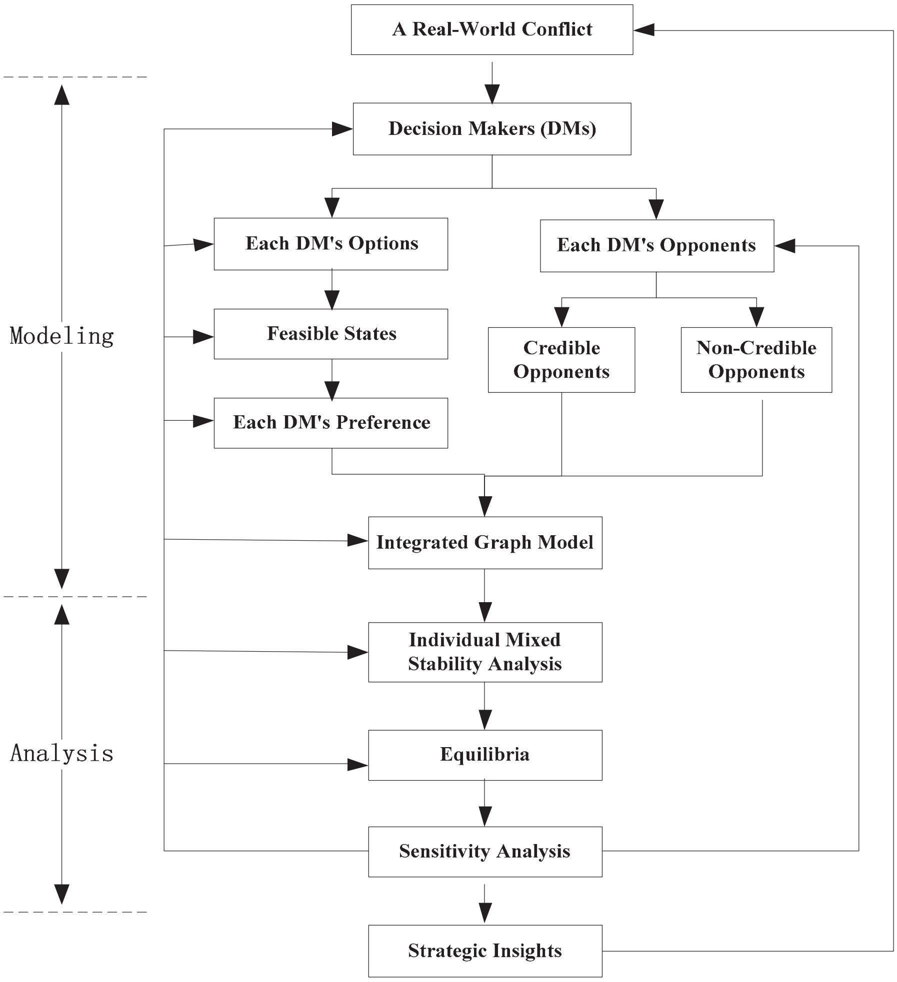

Figure 2. The procedure for mixed stability analyses.

Compared with existing research related to cross-border water pollution disputes, the improved GMCR methodology in this study incorporates the impact of heterogeneous sanctions that were not taken into account in the other literature on the optimal strategies of DMs and the equilibria of the transboundary pollution controversy and can provide useful strategic insights and meaningful information for addressing transboundary water pollution disputes with both rational and irrational sanctions.

4. Conflict Modeling

4.1. Background

Hongze Lake (118°10′ E–18°52′, 33°06′–33°40′ N) is the fourth largest freshwater lake in China and the important water passage of the eastern part of the famous South-to-North Water Diversion Project. It is located in the lower reaches of the Huai River in the west of Jiangsu Province and within the boundaries of Huai'an and Suqian cities in Jiangsu Province. The lake is 65 km long and has an average width of 24.4 km. Its basin area is 160,000 square kilometers, with a total storage capacity of 13 billion cubic meters. The whole lake is composed of three major lake bays: Chengzi Lake Bay, Li Lake Bay, and Huai Lake Bay. The main upstream rivers entering Hongze Lake include Xinbian River and Xinsui River in Suzhou City, Anhui Province, as shown in Figure 3.

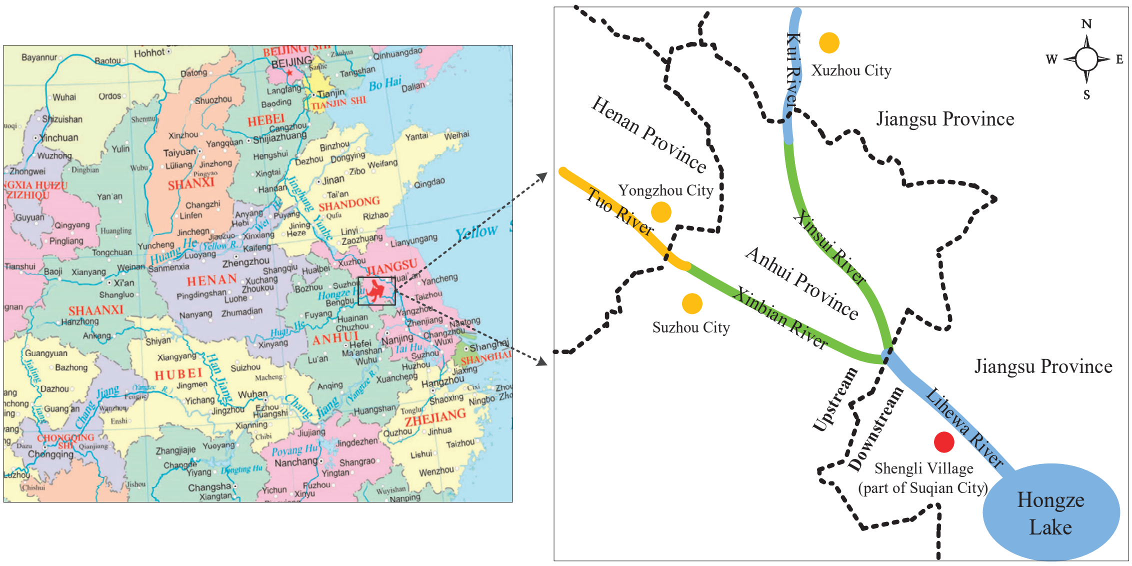

Figure 3. The watershed map of Hongze Lake, China.

On 25 August 2018, a large number of fish and crabs died in Shengli Village (the red area in Figure 3), Suqian City, Jiangsu Province, China, due to a sudden influx of upstream sewage from Suzhou City. The water pollution incident caused serious economic losses to local fishermen and severely damaged the ecosystem of Hongze Lake [46]. According to the preliminary investigation from the Environmental Protection Bureau (EPB) of Suqian City, the sewage came from the Xinbian River, which flows through Suzhou City, as shown in Figure 3. As shown in Figure 3, the upper reaches of Hongze Lake are the Lihe Wa, located in Sihong County, in Jiangsu Province, which is further divided into Xinsui River and Xinbian River, Suzhou City, Anhui Province. However, the upstream government of Suzhou City denied that this was the case and claimed that the dirty water originated in the Kui River, which flows through Xuzhou City, Jiangsu Province, as displayed at the top of Figure 3. Both of the environmental protection departments of Jiangsu Province and Anhui Province recognized that the sewage was discharged to Hongze Lake through Xinsui River and Xinbian River. However, the two sides disagreed on whether the source of sewage originated from Anhui Province or from Kui River, a tributary of Xinsui River in Jiangsu Province. Moreover, they differed in their presentations on the water-quality data of the Kui River. The Jiangsu side believed that the water quality of the Kuihe River was not bad when it entered Anhui from Jiangsu. However, the Anhui side claimed that when the Kui River reaches Anhui, the water quality is already very bad. Furthermore, the two sides did not reach an agreement on whether the upstream gates should be opened to release water in advance to inform the downstream in this pollution incident. There was also a dispute over the issue of compensation for fishermen.

In conclusion, there are three main controversies in the complex cross-basin water pollution conflict that occurred in Hongze Lake, China.

(1) Where does the sewage come from? It is still unknown whether the pollution is from the upstream rivers of Anhui Province or the Kui River in Xuzhou City located in Jiangsu Province.
(2) Does the sewage contain industrial wastewater? The downstream government of Suqian City in Jiangsu Province suspects that industrial wastewater from the upstream is the most likely cause of thousands of dead fish and crabs in Shengli Village. However, the upstream government of Suzhou City in Anhui Province claims that there were no polluting enterprises that discharged sewage into rivers.
(3) Who should take the responsibility for this cross-basin water pollution incident? The upstream and downstream governments have not yet reached an agreement about

the economic compensation for the local fishermen's losses and ecological pollution in Hongze Lake.

4.2. DMs, Options, and States

The stakeholders involved in the Hongze Lake cross-basin water pollution dispute include the upstream (Suzhou City, Anhui Province), the downstream (Suqian City, Jiangsu Province), environmental non-governmental organizations (ENGOs), the Ministry of Environmental Protection (MEP), and local fishermen. The MEP was not considered in this study since it is an indirect and external participant. Moreover, the local fishermen and the ENGOs are regarded as being one DM because they have common interest. Therefore, in this research, we mainly investigate the dynamic strategic interactions among three key decision makers (i.e., upstream, downstream, and ENGOs).

Since the upstream and downstream parties cannot reach an agreement on the aforementioned controversies, the cross-basin water pollution dispute in Hongze Lake is still ongoing and not well resolved up to now. This water pollution conflict concerning Hongze Lake can be formally investigated using the GMCR methodology. In the conflict model, the key DMs, their options, preferences, and transitions among states should be identified. According to the background, the main DMs involved in this dispute and their options are given as follows:

- The upstream government (upstream), Suzhou City, Anhui Province. The upstream failed to inform the downstream before it decided to open the floodgates, which caused cross-basin pollution and serious economic losses to the downstream. Since the source of sewage is still unknown, the Upstream has to decide whether or not to agree to negotiate regarding compensating the downstream's serious losses.
- The downstream government (downstream), Suqian City, Jiangsu Province. The downstream has two options: (1) whether or not to negotiate with the upstream regarding the compensation for the affected fishermen and the environmental ecological remediation in Hongze Lake; and (2) whether or not to appeal to the Ministry of Environmental Protection (MEP) of China for an intervention.
- Environmental non-governmental organizations (ENGOs) for environment protection, such as Friends of the Earth and the Environmental Investigation Agency. ENGOs have one option: whether or not to file a public interest litigation (PIL) in court against the environmental offenders involved in the severe cross-basin water pollution (lawsuit).

When each DM selects its options, a state comes into being. In this conflict, there are a total of four options, and, mathematically, the number of possible states is $2^4 = 16$. However, some states are infeasible, such as a state in which the upstream agrees to negotiate about the compensation for the downstream's losses, whereas the downstream does not intend to negotiate with the upstream. GMCR II is a very powerful and comprehensive decision support system for modeling and analyzing real-world conflicts [43,44]. The infeasible states in the cross-basin water pollution dispute can be removed in the GMCR II by using two logical option statements, "1&−2" and "−2&3", where the numbers represent the corresponding options. More specifically, the statement "1&−2" is used to eliminate states where the upstream agrees to negotiate with the downstream, but the latter one does not initiate to negotiate with the former one. Similarly, the statement "−2&3" is given for removing states where the downstream chooses not to negotiate with the upstream and meantime wants to call for the intervention of MEP.

After removing infeasible states, there are a total of 10 feasible states (s_1–s_{10}), as given in Table 3, where "Y" means that the corresponding option in the same row is selected, and "N" indicates that the option is not chosen. For instance, the fifth column in Table 3 is s_3 (Y Y N N), meaning that the upstream agrees to negotiate with the downstream about compensation for the cross-basin water pollution involving Hongze Lake (Y), the downstream wants to negotiate with the upstream and does not appeal for intervention by MEP (Y N), and the ENGOs does not file a PIL (N).

Table 3. Feasible states in the Hongze Lake dispute.

DMs	Options	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	s_9	s_{10}
Upstream	1. Agree	N	N	Y	N	Y	N	N	Y	N	Y
Downstream	2. Negotiate	N	Y	Y	Y	Y	N	Y	Y	Y	Y
	3. Appeal	N	N	N	Y	Y	N	N	N	Y	Y
ENGOs	4. Lawsuit	N	N	N	N	N	Y	Y	Y	Y	Y

4.3. Preferences and Graph Model

According to the background of the Hongze Lake cross-basin pollution conflict, each DM's preference over states can be determined by using the GMCR II software [47,48], as given in Table 4, in which the states are ranked from the most preferred on the left to the least preferred on the right.

Table 4. Preference ranking of DMs in the Hongze Lake dispute.

DMs	Preference Ranking from Most to Least Preferred
Upstream	$s_1 \succ s_2 \succ s_6 \succ s_7 \succ s_4 \succ s_9 \succ s_3 \succ s_8 \succ s_5 \succ s_{10}$
Downstream	$s_3 \succ s_8 \succ s_5 \succ s_{10} \succ s_9 \succ s_7 \succ s_1 \succ s_2 \succ s_4 \succ s_6$
ENGOs	$s_3 \succ s_{10} \succ s_5 \succ s_8 \succ s_9 \succ s_4 \succ s_7 \succ s_2 \succ s_6 \succ s_1$

The integrated graph for the cross-basin water pollution conflict involving Hongze Lake is displayed in Figure 4, in which the vertexes represent the feasible states, oriented arcs indicate the direction of state transitions, and labels on the arcs refer to the DM controlling the move. Note that an arc with double arrows means that the transition between two states is reversible.

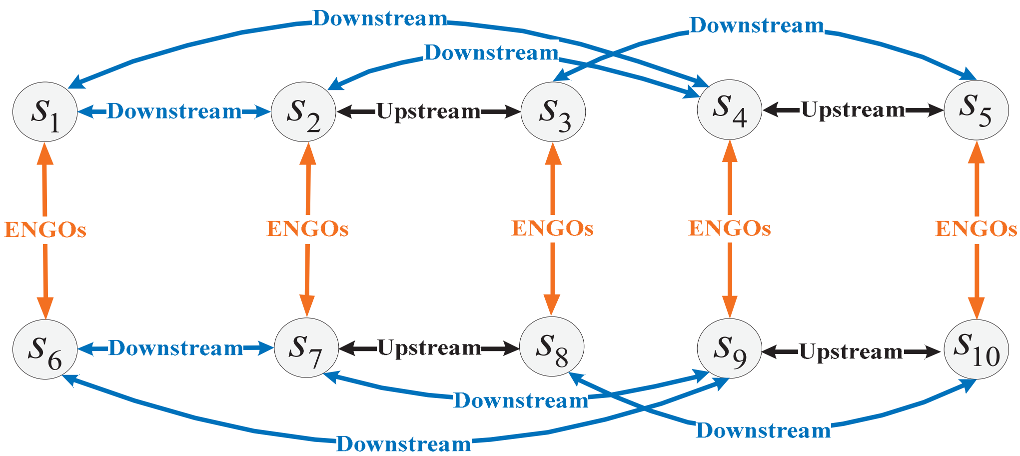

Figure 4. Integrated graph of the cross-basin water pollution conflict in Hongze Lake.

5. Results and Discussion

5.1. General Stability Analyses with Homogeneous Opponents

As mentioned earlier in Section 3, there are four classical stabilities within the GMCR paradigm, namely Nash, GMR, SMR, and SEQ, which can be utilized to conduct general stability analyses of the cross-basin water pollution conflict involving Hongze Lake. In the stabilities of GMR, SMR, and SEQ, all of the sanctioning opponents from each DM's viewpoint are assumed to be homogeneous, either non-credible or credible. Alternatively, the sanctioning behavior of each opponent in general stability analyses is the same or homogeneous from each DM's perspective as explained in Table 5.

Table 5. Homogeneous opponents from each DM's perspective in the Hongze Lake dispute.

Focal DM	Homogeneous Opponents	
	GMR/SMR	SEQ
Upstream	Both downstream and ENGOs are non-credible.	Both downstream and ENGOs are credible.
Downstream	Both upstream and ENGOs are non-credible.	Both upstream and ENGOs are credible.
ENGOs	Both downstream and upstream are non-credible.	Both downstream and upstream are credible.

Let $N = \{1, 2, 3\}$ be the set of DMs in the cross-basin water pollution dispute, in which the numbers 1, 2, and 3 represent upstream, downstream, and ENGOs, respectively. As explained earlier, $N\backslash\{i\}$ is the set of DM i's sanctioning opponents. If all of the opponents of a focal DM i are non-credible and credible, as shown in Table 5, then the set of their sanctioning movements at state s can be denoted by $R_{N\backslash\{i\}}(s)$ and $R^+_{N\backslash\{i\}}(s)$, respectively. Using Definition 3, the set of unilateral moves (UMs) by DM i's non-credible opponents at state s, $R_{N\backslash\{i\}}(s)$, is given in Table 6. Similarly, the set of unilateral improvements (UIs) by DM i's credible opponents at state s, $R^+_{N\backslash\{i\}}(s)$, is presented in Table 7, according to Definition 4.

Table 6. The set of UMs by non-credible opponents in the Hongze Lake dispute.

State	$R_{N\backslash\{1\}}(s)$	$R_{N\backslash\{2\}}(s)$	$R_{N\backslash\{3\}}(s)$
s_1	$\{s_2, s_4, s_6, s_7, s_9\}$	$\{s_6\}$	$\{s_2, s_3, s_4, s_5\}$
s_2	$\{s_1, s_4, s_6, s_7, s_9\}$	$\{s_3, s_7, s_8\}$	$\{s_1, s_3, s_4, s_5\}$
s_3	$\{s_5, s_8, s_{10}\}$	$\{s_2, s_7, s_8\}$	$\{s_1, s_2, s_4, s_5\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_5, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_5\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_1, s_2, s_4, s_7, s_9\}$	$\{s_1\}$	$\{s_7, s_8, s_9, s_{10}\}$
s_7	$\{s_1, s_2, s_4, s_6, s_9\}$	$\{s_2, s_3, s_8\}$	$\{s_6, s_8, s_9, s_{10}\}$
s_8	$\{s_3, s_5, s_{10}\}$	$\{s_2, s_3, s_7\}$	$\{s_6, s_7, s_9, s_{10}\}$
s_9	$\{s_1, s_2, s_4, s_6, s_7\}$	$\{s_4, s_5, s_{10}\}$	$\{s_6, s_7, s_8, s_{10}\}$
s_{10}	$\{s_3, s_5, s_8\}$	$\{s_4, s_5, s_9\}$	$\{s_6, s_7, s_8, s_9\}$

Table 7. The set of UIs by credible opponents in the Hongze Lake dispute.

State	$R^+_{N\backslash\{1\}}(s)$	$R^+_{N\backslash\{2\}}(s)$	$R^+_{N\backslash\{3\}}(s)$
s_1	$\{s_6, s_7, s_9\}$	$\{s_6\}$	$\emptyset$
s_2	$\{s_1, s_6, s_7, s_9\}$	$\{s_7\}$	$\{s_1\}$
s_3	$\emptyset$	$\{s_2, s_7\}$	$\{s_1, s_2\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_9\}$	$\{s_1, s_2\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_7, s_9\}$	$\emptyset$	$\{s_7, s_9\}$
s_7	$\{s_6, s_9\}$	$\emptyset$	$\{s_9\}$
s_8	$\{s_3\}$	$\{s_2, s_3, s_7\}$	$\{s_7, s_9\}$
s_9	$\emptyset$	$\emptyset$	$\emptyset$
s_{10}	$\{s_3, s_8\}$	$\{s_9\}$	$\{s_7, s_8, s_9\}$

Using the GMCR II; [47,48] software, the results of the general stability analyses for the cross-basin water pollution conflict can be determined, as summarized in Table 8, in which "E" is the abbreviated form of equilibrium. Moreover, under a particular stability, the check "√" means that the state in the same row is stable for the DM in the column, and an asterisk "*" indicates that the state in the same row is an equilibrium which is stable for each DM. As illustrated in Table 8, s_2 is an equilibrium state under GMR stability; s_7 is an equilibrium state under both GMR and SMR stabilities; and s_9 is a strong equilibrium state under all of the Nash, GMR, SMR, and SEQ stabilities.

Table 8. The equilibrium outcomes of general stability analyses for the Hongze Lake dispute.

State	Nash				GMR				SMR				SEQ			
	1	2	3	E	1	2	3	E	1	2	3	E	1	2	3	E
s_1	√	√			√	√			√	√			√	√		
s_2	√				√	√	√	*	√		√		√	√		
s_3		√	√			√	√			√	√			√	√	
s_4	√				√		√		√		√		√			
s_5						√	√			√	√			√	√	
s_6	√		√		√		√		√		√		√		√	
s_7	√		√		√	√	√	*	√	√	√	*	√		√	
s_8		√				√	√			√	√			√	√	
s_9	√	√	√	*	√	√	√	*	√	√	√	*	√	√	√	*
s_{10}			√			√	√			√	√			√	√	

5.2. Mixed Stability Analyses with Heterogeneous Opponents

As mentioned above, the opponents of each DM in general stability analyses are assumed to be homogeneous, meaning that every opponent's sanctioning behavior is the same. When determining the stability results under GMR and SMR, for example, both upstream and ENGOs are regarded as being non-credible from the perspective of the downstream. In this cross-basin water pollution dispute involving Hongze Lake, however, ENGOs should be considered credible when sanctioning since ENGOs and downstream share a common interest that upstream agrees to negotiate regarding compensating the economic losses of downstream. Therefore, from the downstream's viewpoint, upstream is non-credible, and ENGOs are credible when sanctioning, meaning that the downstream's opponents are heterogeneous instead of homogeneous. The heterogeneous opponents of each DM in the cross-basin water pollution dispute are presented in Table 9, which is different from that shown in Table 5.

Table 9. Heterogeneous opponents from each DM's perspective in the Hongze Lake dispute.

Focal DM	Heterogeneous Opponents (MTS/MSMR)	
Upstream	Downstream is non-credible.	ENGOs is credible.
Downstream	Upstream is non-credible.	ENGOs is credible.
ENGOs	Upstream is non-credible.	Downstream is credible.

When the opponents are hybrid or heterogeneous, their sanctioning movements could be different from those in Tables 6 and 7, which may further influence the results of the analysis. By employing Definition 9, the set of mixed unilateral improvements (MUIs) by heterogeneous opponents can be obtained as shown in Table 10. By comparing Table 10 with Tables 6 and 7, one can find that the sanctioning movements by heterogeneous opponents at some states differ from those made by homogeneous (either non-credible or credible) opponents in Table 5. For example, ENGOs can move to a more preferred state, s_7, from s_2. Then, it may consider the countermoves by its two opponents, upstream and downstream, at s_7. There are three possible cases with respect to the sanctioning opponents when they together sanction the UI by ENGOs:

(1) Both upstream and downstream are non-credible (the fourth row and second column in Table 5). The set of their UMs from s_7 is $R_{N\backslash\{3\}}(s_7) = \{s_6, s_8, s_9, s_{10}\}$, as shown in Table 6. The homogeneous movements by upstream and downstream are displayed step by step in Figure 5a.
(2) Both upstream and downstream are credible (the fourth row and third column in Table 5). The set of their UIs from s_7 is $R^{+}_{N\backslash\{3\}}(s_7) = \{s_9\}$, as shown in Table 7. The homogeneous movements by upstream and downstream are illustrated in detail in Figure 5b, in which "Downstream^{+}" means that the DM is credible.
(3) Upstream is non-credible, whereas downstream is credible (the fourth row in Table 9). The set of their MUIs from s_7 is $R^{\oplus}_{N\backslash\{3\}}(s_7) = \{s_8, s_9, s_{10}\}$, as shown in Table 10. The mixed sanctioning movements by the upstream and downstream are illustrated in Figure 5c.

Table 10. The set of MUIs by heterogeneous opponents in the Hongze Lake dispute.

State	$R^{\oplus}_{N\backslash\{1\}}(s)$	$R^{\oplus}_{N\backslash\{2\}}(s)$	$R^{\oplus}_{N\backslash\{3\}}(s)$
s_1	$\{s_2, s_4, s_6, s_7, s_9\}$	$\{s_6\}$	$\emptyset$
s_2	$\{s_1, s_4, s_6, s_7, s_9\}$	$\{s_3, s_7, s_8\}$	$\{s_1, s_3\}$
s_3	$\{s_5, s_8, s_{10}\}$	$\{s_2, s_7, s_8\}$	$\{s_1, s_2\}$
s_4	$\{s_1, s_2, s_6, s_7, s_9\}$	$\{s_5, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_5\}$
s_5	$\{s_3, s_8, s_{10}\}$	$\{s_4, s_9, s_{10}\}$	$\{s_1, s_2, s_3, s_4\}$
s_6	$\{s_7, s_9\}$	$\emptyset$	$\{s_7, s_8, s_9, s_{10}\}$
s_7	$\{s_6, s_9\}$	$\{s_2, s_3, s_8\}$	$\{s_8, s_9, s_{10}\}$
s_8	$\{s_3, s_5, s_{10}\}$	$\{s_2, s_3, s_7\}$	$\{s_7, s_9, s_{10}\}$
s_9	$\{s_6, s_7\}$	$\{s_{10}\}$	$\{s_7, s_8, s_{10}\}$
s_{10}	$\{s_3, s_5, s_8\}$	$\{s_9\}$	$\{s_7, s_8, s_9\}$

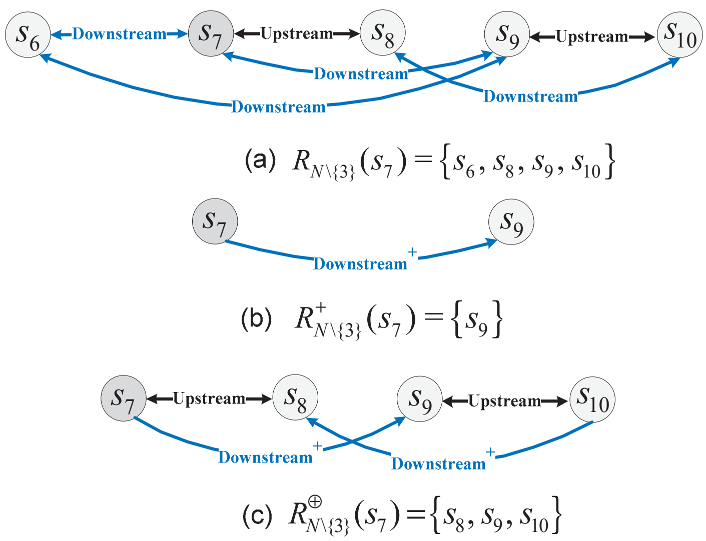

Figure 5. Graphs illustrating state transitions by (**a**) non-credible opponents, (**b**) credible opponents, and (**c**) heterogeneous opponents.

As indicated previously, the mixed sanctioning movements by heterogeneous opponents could affect the equilibria of the cross-basin water pollution dispute involving Hongze Lake. To reflect different sanctioning behavior of heterogeneous opponents in Table 11, the mixed stability analyses developed in the second part are utilized to obtain the stability results of the conflict, as given in Table 11. Note that, in Table 11, the notation

"×" indicates the different results in comparison with the results in Table 8. For instance, s_2 is not MTS and MSMR stable for ENGOs in Table 11, whereas it is GMR and SMR stable in Table 8. The reason is that downstream, who is regarded as being credible instead of non-credible, cannot move to a less preferred state, s_6, from s_7 when sanctioning if ENGOs moves to a more preferred state, s_7, from the initial state, s_2. Similarly, s_7 is not MTS and MSMR stable for downstream, since ENGOs is credible and cannot prevent downstream from moving to a more preferred state, s_9, starting at s_7. Moreover, s_4, which is unstable for ENGOs under SEQ stability in Table 8, becomes MTS stable in Table 11 because credible upstream and non-credible downstream can move together to s_7, which is less preferred to s_4 by ENGOs.

Table 11. The equilibrium outcomes of mixed stability analyses for the Hongze Lake dispute.

State	Nash				MTS				MSMR			
	1	2	3	E	1	2	3	E	1	2	3	E
s_1	√	√			√	√			√	√		
s_2	√				√	√	×	×	√		×	
s_3		√	√			√	√			√	√	
s_4	√				√		√		√		√	
s_5						√	√			√	√	
s_6	√		√		√		√		√		√	
s_7	√		√		√	×	√	×	√	×	√	×
s_8		√				√	√			√	√	
s_9	√	√	√	*	√	√	√	*	√	√	√	*
s_{10}			√			√	√			√	√	

5.3. Discussion

By comparing the equilibria of Tables 8 and 11, one can find that only s_9 is an equilibrium, while both s_2 and s_7 are no longer equilibria in the cross-basin water pollution conflict, as is consistent with the real situation. To calm down the strong protests from the local fishermen, the downstream government planned to negotiate with the upstream government to provide economic compensation. However, the upstream did not agree to negotiate with the downstream and delayed its decision since the source of the sewage flowing to the downstream was still unknown. On 30 October 2018, an environmental protection organization in China called SIP Lvse Jiangnan Public Environment Concerned Center filed public interest litigation against the environmental offenders involved in the severe cross-basin water pollution. Therefore, the mixed stability analysis approach provides more insightful and reasonable findings than general stability analyses for handling a conflict with heterogeneous sanctioning opponents.

To solve such cross-border water pollution issues, effective market-oriented means or public policies should be adopted as soon as possible for adjusting the complex interest relationship among stakeholders and exploring a new cooperative win-win solution in which the upstream actively strengthens ecological protection and the downstream supports the upstream. In the Hongze Lake pollution conflict, the key controversy is that the two sides disagreed on whether the source of sewage originated from Anhui Province or Jiangsu Province. To clearly figure out who should be in charge of the cross-basin water pollution issue, therefore, a cross-provincial horizontal ecological compensation mechanism could be systematically established based on regular water quality monitoring at inter-provincial borders. More specifically, if the water-quality-monitoring data become worse in the cross-border section of the two provinces, this means that the water pollution comes from the upstream, and Anhui Province should afford Jiangsu Province an ecological compensation fee. Otherwise, the water contamination is from the downstream, and Jiangsu Province should take the responsibility of the water pollution control of Hongze Lake. In addition, financial rewards could be assigned to the upstream for encouraging it to strengthen ecological governance and cooperation with downstream if the water quality at inter-provincial boundaries meets the standards. Furthermore, the cross-regional compensation funds can be used to compensate for water environmental protection, water pollution remediation, losses of local residents, etc.

The cross-basin eco-compensation mechanism makes the upstream more willing to negotiate with the downstream for possible solutions to resolve the Hongze Lake dispute. As a result, the conflict situation evolves from s_9 to s_{10} by the upstream, which prefers to agree to a negotiation with the downstream; it then moves from s_{10} to s_8 due to the withdrawal of the appeal by the downstream and eventually shifts to s_3 from s_8 by ENGOs, as illustrated in Table 12. Moreover, s_3 is the state in which both the upstream and downstream prefer to negotiate with each other regarding the compensation for the affected fishermen and the environmental ecological remediation in Hongze Lake without any appeal or lawsuit, making it a good solution for mediating cross-basin water pollution disputes. Last but not the least, effective measures could be taken for exploiting the role of participation supervision of ENGOs who increasingly become an important force in promoting ecological protection in the cross-basin water pollution control.

Table 12. Evolutionary path analysis from s_9 to s_3 in the Hongze Lake dispute.

DMs	Options	s_9		s_{10}		s_8		s_3
Upstream	Agree	N	→	Y		Y		Y
Downstream	Negotiate	Y		Y		Y		Y
	Appeal	Y		Y	→	N		N
ENGOs	Lawsuit	Y		Y		Y	→	N

6. Conclusions

Cross-basin water pollution conflicts pose great threats to water quality, human health, and ecosystems. The strategic interactions among stakeholders involved in those disputes are dynamic and complicated. Moreover, the sanctioning opponents are usually heterogeneous or hybrid, instead of homogeneous, in which case, some opponents move to any reachable states, whereas others levy only unilateral improvements when sanctioning. To illustrate the mixed unilateral improvements (MUIs) more intuitively and directly by heterogeneous sanctioning opponents, a direct and intuitive definition for MUIs is presented in this paper. Subsequently, a comprehensive procedure was purposefully designed in this research to conveniently execute mixed stability analyses and forecasting the possible resolutions of a conflict with heterogeneous opponents.

To demonstrate how the mixed stability approach can be applied to a real-world conflict, a cross-basin water pollution conflict that occurred in Hongze Lake, China, was systematically modeled and analyzed by using general and mixed stability analyses, respectively. The case study demonstrates that the heterogeneous sanctions could affect the outcomes of a conflict, and it is more reasonable and realistic to regard the sanctioning opponents as being heterogeneous in the cross-basin water pollution dispute. Furthermore, the mixed unilateral improvements by heterogeneous opponents from some states are different from unilateral movements and unilateral improvements by homogeneous opponents, thus greatly influencing the equilibria of the conflict. By comparing the results of the general and mixed stability analyses, one can find that mixed stabilities provide more meaningful and reasonable insights than classical stabilities can. The predicted results of stability analyses provide an important decision-making basis for mediating or resolving the Hongze Lake trans-border pollution disputes. Furthermore, the case study shows that an effective solution for addressing the cross-basin water pollution issue in Hongze Lake is the co-funded eco-compensation mechanism based on the results of regular water quality monitoring in cross-border areas. The ecological compensation strategy could boost the motivation of the upstream to participate in cross-basin water pollution control and enhance the cooperation of the upstream with downstream in ecological governance. This makes the conflict state evolve from the equilibrium state s_9 to a better state, s_3, where both the upstream and downstream choose to cooperate with each other for addressing the cross-border water contamination dispute.

The improved GMCR approach could be used to forecast the outcomes and evolutionary trend of environmental disputes with dynamically strategic interactions and heterogeneous sanctions. Moreover, this research provides a very general theoretical analysis framework with wide applicability, which could be employed for modeling and analyzing any strategic environmental disputes that occur in any countries or international regions. One can refer to the procedure in Figure 2 for more specific details about the application process. However, we considered only three main decision makers and their key options in the Hongze Lake conflict model. In the future, other stakeholders, such as the local fishermen and social media, as well as their possible choices, could be taken into account when modeling and analyzing the Hongze Lake cross-basin water pollution dispute. In fact, the journalists and lawyers also played an important role in the Hongze Lake water pollution dispute. In the future study, they could be regarded as being an independent decision maker if their standpoint is different from the ENGOs. Furthermore, an opponent in mixed stabilities could be non-credible at some states and credible at other states, thus indicating that the sanctioning behavior of an opponent may dynamically change in terms of the initial state. Hence, the mixed stability analysis approach could be extended by considering the dynamic sanctioning behavior of heterogeneous opponents in the future.

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Review

Social and Economic Impacts of Water Sensitive Urban Design: A Review

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Abstract: Water Sensitive Urban Design (WSUD) has emerged as a vital framework for integrating sustainable water management into urban planning, tackling the increasing challenges posed by urbanization and climate change. WSUD aims to align water systems with natural ecosystems by minimizing runoff, improving water quality, and promoting biodiversity while also offering recreational and aesthetic benefits for urban residents. While the environmental advantages of WSUD are well-established, its social and economic aspects warrant more in-depth exploration. This review analyses the social and economic impacts of WSUD, focusing on its effects on community well-being, property values, infrastructure costs, and public engagement. It also discusses the significance of citizen perceptions, socio-economic equity, and financing mechanisms in the adoption of WSUD. The findings highlight the necessity for interdisciplinary approaches and policy reforms that incorporate social and economic considerations into WSUD planning to ensure long-term success and sustainability. This analysis aims to enhance understanding of how WSUD can contribute to resilient, equitable, and sustainable urban communities.

Keywords: WSUD; stormwater; sustainable water management; urban planning; social impacts; economic impacts; cost–benefit analysis; resilience; climate adaptation

1. Introduction

Water Sensitive Urban Design (WSUD) is a holistic approach to urban water management that integrates ecological sustainability with urban planning needs, aiming to restore and enhance the natural water cycle within cities [1]. Key WSUD practices use Best Planning and Management Practices/Best Management Practices (BPMPs/BMPs) to protect natural water systems, improve water quality, reduce stormwater runoff, and limit reliance on costly drainage infrastructure [2]. This approach helps cities build resilience to changing climate and socio-economic conditions by sustainably managing water resources and services [3]. Core WSUD principles include protecting natural water bodies, reducing potable water demand through reuse and conservation, and employing green infrastructure like rain gardens, bio-retention systems, wetlands, and permeable pavements. These green infrastructures mitigate flooding risks, improve water quality, and foster urban biodiversity [4,5]. Beyond environmental benefits, WSUD enhances social and economic outcomes by creating attractive urban spaces, increasing property values, and reducing traditional stormwater infrastructure costs [6].

Urban water management is evolving from centralized infrastructure-heavy solutions to decentralized and multifunctional systems like WSUD. Initially, urban water systems in the early 20th century focused on supplying potable water and managing wastewater, with little regard for environmental sustainability or the broader impacts of urbanization [5]. As urban areas expanded and environmental consequences became apparent, traditional systems proved inadequate, especially under extreme weather conditions like floods and droughts [7].

This shift toward integrated, eco-conscious water management is reflected in WSUD and related practices like Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDS), Low-Impact Development, Green Infrastructure (GI), Nature-Based Solutions (NBS), and Stormwater Control Measures (SCM) [8]. For example, BMPs in North America focus primarily on water quality and pollution control, while SUDS and LID, more common in the UK and North America, prioritize reducing the effects of extreme rainfall events and restoring natural water cycles. Water Sensitive Urban Design (WSUD), originally developed in Australia in the early 1990s as a response to the growing need to address stormwater pollution and promote sustainable urban water management, is unique in its integration of the entire urban water cycle into city planning, aiming to mitigate the hydrological impacts of urbanization and improve resilience to climate change [9,10]. In contrast, GI and NBS emphasize the broader integration of green spaces to enhance environmental quality in urban areas. Despite differences in terminology and geographic application, these approaches collectively contribute to more sustainable, resilient, and liveable urban environments by reconnecting water management with natural systems [11,12].

The first formal WSUD guidelines in 1994 marked a turning point, focusing on reducing runoff, improving water quality, and promoting ecological health [10,13]. While the environmental aspects of WSUD (water quantity and quality aspects and hydraulics and hydrology components) have been extensively studied, its social and economic dimensions remain less explored, creating a significant research gap. These aspects are critical for fostering public acceptance, informing policy development, and ensuring the financial viability of water-sensitive infrastructure [14]. This review addresses this gap by examining how WSUD's social and economic aspects can support its wider implementation and long-term success.

The objectives of this study are threefold: first, to explore the socio-economic characteristics of WSUD, including its effects on community well-being, property values, and infrastructure costs; second, to assess citizen perceptions, socio-economic equity, and financing mechanisms in WSUD implementation; and third, to provide actionable policy recommendations for improving the adoption of WSUD practices. Through its novel focus on socio-economic dimensions, this study contributes to the global discourse on water-sensitive urban developments, supporting cities in becoming more resilient, inclusive, and sustainable.

2. Methodology

This review followed a systematic approach to comprehensively analyze the social and economic impacts of WSUD. The methodology was designed to ensure transparency, replicability, and adherence to best practices for conducting scientific reviews. The review considered studies conducted globally to capture the diverse socio-economic contexts in which WSUD has been implemented.

Publications from 2004 to 2024 were reviewed. While earlier studies contributed to understanding key principles, the primary focus was on publications from 2016 to 2024, which provided the most relevant insights into the social and economic impacts of WSUD. This ensured that the review balanced historical perspectives with contemporary evaluations.

The search process began with the identification of relevant literature using established academic databases, including Scopus, Web of Science, and Google Scholar. A set of predefined keywords was employed to capture a broad range of studies, including "Water

Sensitive Urban Design", "WSUD social impacts", "WSUD economic impacts", "stormwater management", "urban planning", "cost–benefit analysis", and "community well-being".

The selection of studies was guided by strict inclusion and exclusion criteria. To be included, studies focus on the social and economic dimensions of WSUD. Articles addressing technical, environmental, hydrological, or water quality aspects without any discussion of social or economic impacts were excluded.

The process of screening and selection involved an initial review of titles and abstracts, followed by a full-text review of potentially relevant studies. Data extraction was performed systematically, with key information from each study being coded into a structured framework. This included details such as study objectives, methodologies, findings, and implications. A thematic analysis was then conducted to identify common trends, gaps, and emerging themes in the literature. The identified themes were organized into key categories, including citizen perceptions, quality of life, property values, and financing mechanisms, providing a clear structure for presenting the findings.

Figure 1 shows the flow diagram of the methodology adopted for relevant literature search, exclusion and inclusion of literature, including the final selection of the most pertinent literature for review. N represents the number of publications identified at each stage. This critical review is based on 92 publications (N = 92).

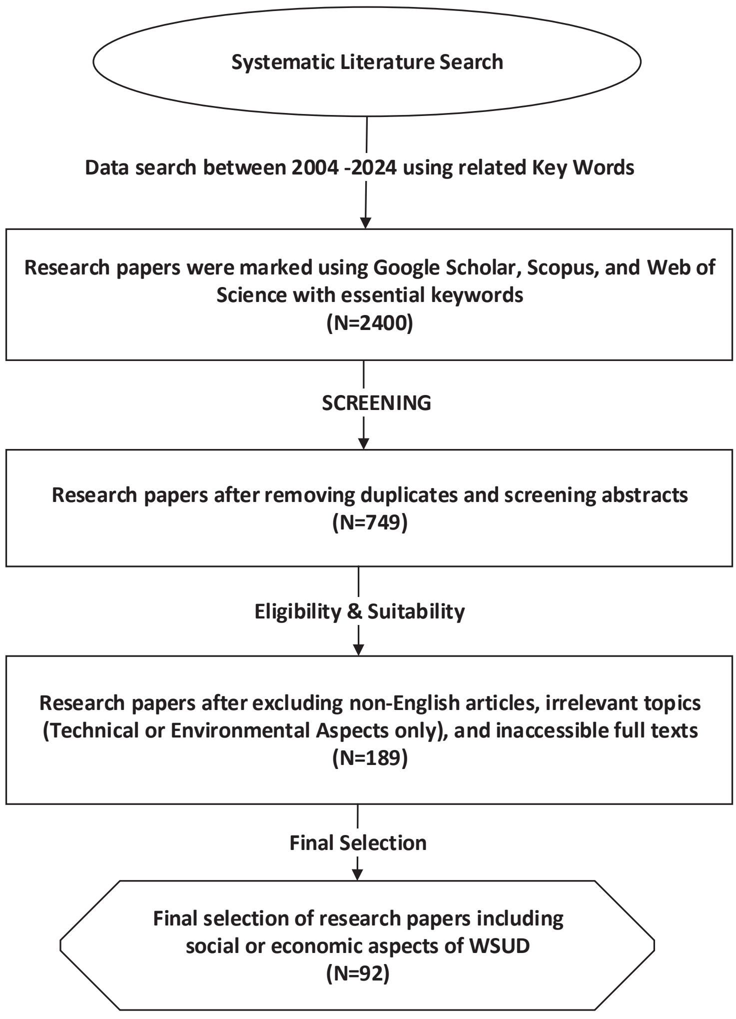

Figure 1. Flow chart of the review methodology.

3. Social and Economic Aspects of WSUD

The integration of social and economic dimensions into Water Sensitive Urban Design (WSUD) highlights the broader implications of sustainable urban water management beyond environmental impact. This section covers the social implications, such as community awareness, citizen concerns about water quality, and the potential improvements in quality of life. Economically, the section addresses the costs and benefits of WSUD, including investment mechanisms and the role of public/private partnerships in financing projects.

3.1. Social Implication of WSUD

This section covers the social aspects of WSUD, highlighting citizen concerns and perceptions, human satisfaction, and quality of life, including some case studies demonstrating positive social outcomes of developments with WSUD features.

3.1.1. Citizen Concerns and Perceptions

- Public awareness and understanding of WSUD

Public awareness and understanding of Water Sensitive Urban Design (WSUD) are crucial for its successful implementation. Although WSUD is often recognized for its environmental benefits, such as flood mitigation and water conservation, many people are unaware of its broader social, economic, and ecological impacts. For example, WSUD can play a significant role in addressing social inequities related to water access and quality. However, public understanding of these wider benefits remains limited, which often hinders the broader adoption of WSUD practices [4].

Sharma et al. [15] suggested that public attitudes toward WSUD systems, such as rainwater tanks, are influenced by how normalized and ubiquitous these systems become in daily life. The more widespread WSUD features like rainwater tanks are implemented, the more likely people are to view them as a standard part of urban infrastructure. Additionally, a heightened sense of vulnerability to water scarcity or drought can drive the decision to adopt WSUD technologies, particularly when individuals believe these systems can effectively mitigate such risks [16].

The slow transition toward widespread WSUD and Integrated Urban Water Management (IUWM) is not solely due to technical challenges but also social and institutional barriers. Organizational resistance, weak political support, outdated institutional structures, and a lack of necessary skills continue to slow progress [17–19]. These barriers are typical of large technical systems, like drainage and water supply, which are historically embedded in political and economic values. As a result, the shift to sustainable water management systems such as WSUD becomes challenging, highlighting the need for interdisciplinary approaches that address both the technical and social dimensions of this transition.

Addressing these barriers requires enhanced education and awareness programs. Research emphasizes the importance of improving public and governmental understanding of WSUD, with public engagement and community education being pivotal for its long-term success. Developing targeted education initiatives, increasing industry knowledge, and fostering government outreach can facilitate the effective implementation of WSUD systems [4]. These programs are particularly crucial in retrofitted systems, where community involvement is key to ongoing management and success.

In communities where WSUD systems have been implemented, knowledge levels vary widely, with some residents being well-informed while others have a limited understanding of WSUD's functions. For example, while many appreciate the aesthetic value of WSUD features such as rain gardens and landscaped swales, fewer are aware of their role in improving water quality and managing stormwater. This gap in knowledge can lead to mismanagement or underutilization of these systems [4,6]. Therefore, increasing public education on the technical benefits of WSUD, such as water filtration and flood control, is essential for fostering broader community support and proper usage.

To effectively overcome the barriers to WSUD adoption, both technical and social elements must be addressed as part of a unified "socio-technical system" [17]. The Multi-Level Perspective (MLP), a socio-technical model, explains how innovations like WSUD evolve within the broader societal framework, moving from niche innovations (micro level) to becoming mainstream practices (meso and macro levels). This interdisciplinary approach provides a foundation for understanding how WSUD can transition from isolated projects to widely accepted urban planning solutions, emphasizing the need for both societal and institutional support [20].

Public support for WSUD is also influenced by socio-economic factors. According to studies, willingness to invest in WSUD practices varies by income level, education, and environmental awareness. For example, residents in flood-prone areas are generally more willing to adopt WSUD technologies compared to those in areas with lower perceived risks [21–23]. Demonstration projects paired with effective media outreach have proven successful in overcoming public skepticism and increasing awareness of WSUD's benefits, showing that tangible examples of WSUD in action can encourage broader public engagement [14].

However, while many people recognize the environmental benefits of WSUD, they may still lack a deep understanding of the technical processes involved. For instance, the function of WSUD features like rain gardens in filtering water and reducing runoff is often underappreciated by the public [4]. As such, public education campaigns that explain the technical workings of these systems, combined with broader community involvement, are crucial to increasing public support.

Furthermore, WSUD offers not only environmental advantages but also contributes to urban biodiversity, public health, and social cohesion. However, these broader social benefits are often overlooked by communities and policymakers. For instance, while WSUD is typically valued for flood prevention, its ability to enhance urban biodiversity or improve public health may not be fully understood, which can act as a barrier to its widespread adoption [24]. To address this, capacity-building efforts should focus on framing WSUD in ways that resonate with local communities and align with broader environmental and social goals [25].

Community participation is essential in making WSUD more relatable and acceptable to residents. By involving communities in the decision-making process and tailoring WSUD solutions to meet their specific needs, urban planners can foster greater social acceptance of these sustainable water management systems. Participatory approaches not only improve the alignment of WSUD technologies with community values but also enhance social cohesion, demonstrating the potential for WSUD to address water management issues while simultaneously improving urban life [26].

Effective public engagement initiatives are critical to closing the knowledge gap regarding WSUD. Studies show that, despite some initial misconceptions or misunderstandings, people generally appreciate the aesthetic and ecological benefits of sustainable stormwater management once they are properly informed [27]. This highlights the importance of continued public education efforts, including media campaigns, school programs, and community initiatives, to sustain public interest and support for WSUD systems [2,28].

Finally, transitioning to decentralized and hybrid water systems, key components of WSUD, requires improved public understanding and stronger stakeholder engagement. Smart-meter water trials, for instance, have shown that real-time feedback on water use can significantly alter consumer behavior, illustrating how WSUD systems can benefit from technological integration and public cooperation [29]. Additionally, professionals in the water management sector emphasize the need for political support and public awareness to drive meaningful change. While water professionals are highly aware of the importance of stormwater management, there remains a gap between their expertise and the priorities of decision-makers, underscoring the need for stronger political advocacy for WSUD [30].

In conclusion, public awareness and understanding of WSUD are critical for its successful implementation. Education and outreach programs play an essential role in bridging the gap between technical knowledge and public perception, ensuring that WSUD systems are properly managed and appreciated for their broader social, environmental, and economic benefits. Engaging communities in the planning and management of WSUD not only enhances public understanding but also fosters a shared commitment to sustainability, ultimately driving the widespread adoption of WSUD in urban environments.

- Water quality, accessibility, and affordability concerns

A key social dimension of Water Sensitive Urban Design (WSUD) is addressing concerns about water quality, accessibility, and affordability. While WSUD seeks to improve water management, it can inadvertently deepen social inequalities if not carefully executed. Instances of WSUD projects leading to the displacement of marginalized communities or raising water service costs emphasize the need for socially inclusive approaches [31].

Retention basins, initially designed to reduce stormwater peak discharge, have evolved to also focus on improving water quality, driven by rising public environmental awareness [2]. Despite these efforts, concerns about water quality persist, particularly regarding the risks associated with non-potable water sources and the costs of maintaining WSUD infrastructure, which affect community acceptance [4].

Although WSUD systems like reed beds significantly improve water quality, the public often overlooks these benefits. Features like fountains or lakes can raise concerns about water wastage through evaporation, particularly in hot climates. Additionally, maintenance activities, such as draining wetlands, may cause public dissatisfaction due to unpleasant sights or odors [4,32].

Safety and affordability remain significant concerns. Although stormwater reuse is a valuable resource, some residents hesitate to use it for domestic purposes like laundry due to risks of contamination. The perceived high costs of maintaining WSUD systems also impact acceptance despite the value of having alternative water supplies [4]. Poor design or maintenance can lead to additional costs for residents, especially in smaller developments, reducing support for future projects [32,33].

Research shows that proximity to water bodies strongly influences perceptions of water quality, surpassing socio-economic factors. People living near creeks or lakes are more likely to engage in environmental concerns, whereas those farther away prioritize other services like road maintenance. Coastal and rural communities often have different priorities related to stormwater management and water quality, reflecting varying local contexts [25,34–36].

Addressing these concerns through inclusive design, effective communication, and ongoing public engagement is essential for ensuring the success and long-term sustainability of WSUD initiatives.

3.1.2. Human Satisfaction and Quality of Life

- Impact of WSUD on community well-being and satisfaction

WSUD has the potential to significantly enhance community well-being by providing green spaces, improving air and water quality, and reducing urban heat islands. These benefits contribute to higher levels of satisfaction among urban residents, particularly in densely populated areas. Research by Leonard et al. [4] demonstrates that WSUD enhances community well-being through aesthetic and recreational benefits, improved local habitats, and opportunities for social interaction, leading to increased resident satisfaction and a stronger sense of community attachment. Symons et al. [37] further supported this by indicating that the social benefits of WSUD encompass improvements in human health, cultural values, and visual aesthetics.

GI, as a crucial component of WSUD, plays a significant role in enhancing human health, especially for vulnerable populations like older adults and children. By promoting physical activity and mental relaxation, GI fosters social support and emotions. The aesthetic appeal of green spaces also encourages community interaction, offering areas for walking, cycling, and informal gatherings such as gardening and picnicking. Linear parks and community parks enhance physical activity and contribute to mental health benefits [38]. Notably, even small-scale WSUD implementations, such as street trees, help cool urban environments, making them more walkable and encouraging outdoor activities [39].

However, the effectiveness of WSUD is contingent upon proper maintenance. Dissatisfaction can arise when the appearance of WSUD areas declines due to neglect, littering, or weed infestations. While residents generally appreciate well-maintained public spaces, frustrations can emerge when maintenance actions, such as draining wetlands, negatively impact aesthetics and enjoyment [4]. This highlights the importance of effective upkeep and community involvement in managing WSUD systems, which can foster a sense of ownership and understanding among residents [32].

Moreover, the perception of risk, including concerns about potential health risks and system failures, can significantly impact community satisfaction. Residents, however, often value the effectiveness of WSUD features, such as rain gardens, in reducing flood risks—especially those who have experienced flooding in the past. Long-term residents frequently acknowledge the benefits of WSUD systems in managing rains and preventing floods, contributing positively to overall community satisfaction [32]. This discussion leads us to explore the two key health effects of Water Sensitive Urban Design.

1. Mental Health Benefits

The mental health benefits of WSUD are substantial, as access to green spaces is linked to reduced anxiety, depression, and other mental health issues, ultimately enhancing the quality of life for urban residents [24]. Research by Abraham et al. [40] and Ely and Pitman [41] highlight how landscapes and green infrastructure promote mental health through stress reduction and by fostering community engagement. Regular contact with green spaces fosters psychological attachment, enhances mental well-being, and supports community building [42]. Key findings indicate that time spent in green environments aids relaxation and concentration, with greenery near homes and schools proving particularly beneficial. Additionally, studies show that green play settings can reduce attention deficit hyperactivity disorder (ADHD) symptoms in children and contribute to lower crime rates in urban areas [43]. Organized sports and recreational activities in parks are crucial for community engagement and public health, especially among youth [44]. While Lee and Maheswaran [45] found only weak evidence for the links between green spaces and mental health, they emphasized the importance of green space quality, accessibility, and individual factors like age and safety perceptions.

2. Physical Health Benefits

In addition to its mental health benefits, WSUD significantly enhances physical health by promoting increased levels of physical activity through well-designed urban landscapes and green spaces. Research indicates that the design and accessibility of these areas can create opportunities for physical activity while reducing barriers. Studies by Frumkin et al. [46] and Humpel et al. [47] emphasize how the layout of urban landscapes affects walking, cycling, and recreational activities. Proximity to parks and the aesthetic quality of recreational areas are strongly linked to physical activity levels; findings show that perceived safety and appealing design encourage more frequent use of these spaces [48]. Furthermore, research distinguishes between recreational and transport walking, identifying residential density and access to safe pedestrian infrastructure as crucial factors. Attributes such as safety, well-maintained paths, and aesthetics promote both forms of walking [49]. As highlighted by Symons et al. [37] and Kent et al. [50], effective policies should prioritize the maintenance and enhancement of green spaces to foster physical activity, social connectivity, and overall well-being. Exposure to green spaces helps reduce the risk of lifestyle diseases by providing opportunities for physical activity, recreation, and social interaction, thereby improving community cohesion and health.

Finally, Symons et al. [37] underscore that community liveability encompasses a range of factors, including cultural, visual, and aesthetic values associated with green infrastructure. Effective design of urban spaces incorporating GI significantly enhances social integration by fostering incidental interactions among residents and improving access to green areas. Key attributes necessary for green spaces to promote community liveability include safety, aesthetic appeal, and multi-functionality. The integration of green spaces in cities fosters biophilic design, enhancing cognitive function, reducing stress, and improving overall well-being. Furthermore, WSUD promotes social cohesion through communal green spaces, which encourage cultural and social activities across diverse groups. Minimizing waste and resources supports the circular economy and influences societal norms around production and consumption, ultimately creating healthier and more attractive urban environments, which are essential for fostering social experiences, cultural values, and a sense of community [51].

3.1.3. Some Example Case Studies Demonstrating Positive Social Outcomes

Case studies from around the world demonstrate how WSUD projects can yield positive social outcomes by integrating sustainable stormwater management with community engagement and ecological restoration. For instance, the transformation of Bishan-Ang Mo Kio Park in Singapore, as detailed by Wang et al. [52], exemplifies how ecological landscape redesign can foster stronger connections between urban residents and natural water systems. By converting a traditional concrete drainage system into an expansive recreational area, the project restored the Kallang River and increased its water storage capacity by 40%. This redevelopment not only enhanced biodiversity by 30% but also expanded recreational space by 12%, reinforcing a harmonious interaction between infrastructure and nature for the community.

As highlighted by Dai [53], the Sponge City Construction (SCC) initiative in Wuhan, China, addresses critical issues like urban flooding, water shortages, and pollution, which have emerged from rapid urbanization. SCC, which integrates WSUD principles, revitalized a 3000-hectare former rubbish dump by incorporating green infrastructure such as pervious pavements and rainwater gardens. This transformation allowed 600 displaced residents to return to the area, creating a more vibrant community. Additionally, SCC projects have improved public health and safety by mitigating flood risks, especially during extreme events like the devastating 2016 flood that resulted in over 30 fatalities [53,54]. These efforts underscore the social benefits of WSUD in terms of community revitalization, safety, and enhanced living conditions.

The importance of community engagement in WSUD projects is also illustrated by the Lochiel Park development in Adelaide, Australia. Despite operational challenges, a resident-led group collaborates with local authorities to address issues, showcasing the social resilience and cohesion that such projects can foster [4]. Similarly, the EVA Lanxmeer development in Culemborg, Holland, demonstrates the power of community-driven management of public areas and environmental systems, with residents actively participating in the upkeep and management of WSUD elements, which strengthens social cohesion and collective responsibility [4].

In the United States, the Rain to Recreation program in Lenexa, Kansas, highlights the effectiveness of engaging communities in the management of urban water systems. With an 84% satisfaction rate among residents regarding the stormwater program, the initiative's success is largely due to transparent decision-making processes that actively involve the public at all levels. This approach has fostered a strong sense of ownership and trust among stakeholders, who feel their voices are heard. Additionally, the program has built solid relationships with developers, who are drawn to the demonstrated cost savings and community benefits associated with LID and GI standards [55].

Finally, in the San Francisco Bay Area, Darnthamrongkul and Mozingo [27] explored public perceptions of LID practices by analyzing responses from 502 participants across 16 sites. Most respondents appreciated LID landscapes over conventional designs, with key factors such as aesthetics, naturalness, and neatness influencing public satisfaction. The inclusion of interpretive signs further enhanced public understanding and appreciation, highlighting the potential for public education to foster support for sustainable stormwater management. Overall, these case studies collectively demonstrate how WSUD projects can improve community engagement, public health, safety, and environmental awareness while fostering stronger connections between urban residents and their natural surroundings.

3.2. Economic Aspects of WSUD

Urban water systems must balance social and economic considerations. Therefore, this section focuses on the economic aspects of water-sensitive urban design, which are just as important as the social aspects.

3.2.1. Cost–Benefit Analysis for Understanding WSUD Economics

Incorporating cost–benefit analysis (CBA) into WSUD planning is crucial for assessing the economic feasibility of these initiatives. By evaluating the trade-offs and financial advantages of WSUD investments, cost–benefit analysis offers a comprehensive perspective on the lasting value these projects can deliver to communities and urban ecosystems.

- Overview of economic benefits and costs associated with WSUD

WSUD presents numerous economic benefits, such as reduced infrastructure costs, lower flood damage, and increased property values. However, these advantages must be considered against the initial investment and ongoing maintenance expenses. WSUD minimizes the environmental impact of urban development by managing stormwater sustainably, thereby reducing the need for new drainage systems and lowering costs [56]. Its use of soft engineering solutions reduces reliance on traditional drainage systems, yet implementation costs, including maintenance and reestablishment, can vary due to geographic, climate, and legislative factors, necessitating innovative approaches from policymakers and developers [13].

Research shows that WSUD can enhance property values and provide significant nonmarket benefits. For instance, rain gardens and green roofs positively impact house prices, and WSUD can result in cost savings through better stormwater management and improved local water quality, which can be monetized [4]. The long-term cost savings associated with WSUD, such as the reduced need for expensive grey infrastructure (e.g., stormwater pipes), often offset higher initial implementation costs. However, comprehensive cost–benefit analyses are essential to assess the financial viability of WSUD projects [3].

One of the key goals of WSUD is to minimize the cost of drainage infrastructure systems [2]. In market-driven economies, the sustainability of urban environments often abstracts the relationship between natural and urban systems. However, public perception can be shaped to focus on positive environmental outcomes, as seen with WSUD, which integrates water management into urban planning to support long-term sustainability [57]. WSUD's integrated approach is favored for reducing development costs, minimizing pollution, and safeguarding urban water quality. Still, concerns about high maintenance costs and reduced developable land often hinder the broader adoption of WSUD [2].

Economic assessments of WSUD reveal benefits that are often difficult to quantify due to the multifunctional nature of these systems. Features like rain gardens, green roofs, and bioretention swales offer aesthetic, recreational, health, and biodiversity advantages. Various methods, such as revealed preference techniques (e.g., hedonic pricing) and stated preference methods (e.g., willingness-to-pay surveys), are used to estimate their economic value [4]. Additionally, WSUD can reduce flood risks, lower flood management costs, and improve waterway health by removing pollutants, which can be economically assessed using community willingness-to-pay surveys [58].

Although initial WSUD costs are typically straightforward to estimate, capturing the full range of benefits requires diverse methods that account for social, environmental, and economic impacts. CBA remains the most widely used framework for evaluating WSUD projects, considering factors like timeframe, discount rates, and project scope [58].

WSUD contributes to the circular economy by minimizing resource inputs, reducing emissions, and managing energy efficiently through nature-based solutions (NBS). It can enhance local economies, reduce construction and maintenance costs by using sustainable materials, and improve flood safety and air quality. WSUD initiatives require a variety of stakeholders and careful cost–benefit analysis to ensure ecological, economic, and social sustainability [51]. For instance, the South Australian government invested in stormwater infrastructure to reduce reliance on expensive potable water sources, yielding significant economic savings [59].

Despite the higher upfront costs of WSUD, long-term benefits such as enhanced water security and flood prevention often surpass initial expenses. Moreover, WSUD fosters commercial growth and delivers diverse ecosystem services, increasing the economic value of urban areas [3,60].

Lastly, Vietz and Hawley [61] highlight the unaccounted costs of conventional urban development on downstream waterways. Traditional stormwater systems often lead to biodiversity degradation, increased flooding, and infrastructure damage, with these costs typically borne by the broader community. WSUD practices, such as stormwater harvesting and biofiltration, can mitigate these impacts while delivering local benefits like improved biodiversity and flood reduction, reinforcing the need for a holistic economic approach that includes the monetization of avoided costs from conventional systems.

- Comparative analysis of WSUD versus traditional urban water management systems

Traditional urban water management systems, which predominantly rely on grey infrastructure, may offer lower upfront costs but tend to lead to higher long-term expenses due to environmental degradation, increased flood risks, and costly maintenance. These systems are often designed to remove stormwater quickly from urban areas, which places a heavy burden on municipal water infrastructure, increases the risk of flooding, and exacerbates environmental problems downstream [29].

In contrast, WSUD provides a more sustainable and cost-effective approach in the long term. Unlike traditional systems, WSUD focuses on the retention, infiltration, and reuse of stormwater, reducing the overall demand for potable water and alleviating pressure on urban water systems. The innovative stormwater management techniques employed in WSUD, such as permeable pavements, stormwater harvesting, and biofiltration, not only manage water more sustainably but also protect biodiversity, reduce flooding risks, and promote healthier estuaries [61]. By addressing the root causes of stream degradation rather than merely treating the symptoms, WSUD contributes to significant ecological and economic benefits.

Although WSUD often requires higher initial capital investment and maintenance costs compared to traditional systems, the long-term economic benefits can outweigh these upfront expenses. Economic evaluations, such as cost–benefit analyses, have shown that WSUD can result in substantial savings over time. For instance, Kirshen et al. [62] demonstrated that strategies like sewer separation and LID can be more cost-effective in the long run, particularly under future climate scenarios. Furthermore, innovative WSUD measures like permeable pavements have proven effective at managing stormwater and removing pollutants such as TSS, TN, TP, BOD, and E. coli. Their efficiency can be further enhanced with nanoparticles, which improve pollutant removal and increase the pavement's mechanical strength, making it more durable and effective in stormwater management [13].

However, the economic viability of WSUD can be challenging for local governments, especially without financial incentives or subsidies. Sharma et al. [3] noted that while WSUD offers significant long-term savings through reduced infrastructure needs and lower water consumption, budget constraints may limit its broader adoption, particularly in areas where upfront investment is a critical consideration. In this context, it is essential to assess both short-term and long-term economic impacts, balancing the higher initial costs of WSUD with its potential for reducing expensive downstream rehabilitation, infrastructure damage, and maintenance costs associated with traditional systems.

Comparative economic analyses consistently highlight that, despite the shorter lifespan and potentially higher initial reconstruction needs of BMPs in WSUD, their overall net present value (NPV) can be more favorable over a 30-year lifespan when compared to traditional systems [63]. This makes WSUD a compelling choice for urban planners looking for sustainable, long-term solutions that can adapt to changing climate conditions and urbanization pressures.

In summary, WSUD stands out as a cost-effective and sustainable alternative to traditional urban water management systems. By focusing on stormwater retention, infiltration, and reuse, WSUD not only addresses immediate water management challenges but also contributes to long-term environmental, economic, and social benefits. Its ability to reduce downstream maintenance costs, improve urban resilience, and promote ecological health makes it a key strategy for future urban development and climate adaptation efforts.

3.2.2. Investment and Financing Mechanisms to Promote WSUD

Implementing WSUD requires innovative financing strategies, as traditional funding often proves inadequate. By engaging diverse stakeholders and exploring alternative funding sources, the feasibility of WSUD projects can be enhanced, ultimately promoting sustainable urban development.

- Strategies for financing WSUD projects

Financing WSUD projects often involve a combination of public and private funding sources, including government grants, developer contributions, and public–private partnerships. Due to the higher upfront costs of WSUD compared to traditional infrastructure, securing financing can be a challenge.

One critical aspect in financing WSUD is ensuring equitable access while addressing the higher initial capital costs. Pathirana et al. [64] identified that certain WSUD elements, like green roofs and urban forests, may be more expensive to install and maintain compared to alternatives like rain barrels or rain gardens, which are more cost-effective. However, social preferences and aesthetic values often drive the adoption of more expensive options, like green roofs, even though they may not always offer the best cost/benefit ratio. These costs are based on the case study land area, with runoff reduction calculated for each alternative, assuming a 0% reduction in the existing scenario. The perception of certain WSUD components, such as rain barrels being associated with lower social status, also plays a role in decision-making, highlighting the need for both economic and social considerations when planning WSUD projects.

Innovative pricing mechanisms, such as volumetric water charges, user fees, and environmental taxes, can further incentivize water conservation and help fund WSUD initiatives. However, these must be designed with care to ensure they remain affordable, especially for low-income communities [65]. Additionally, Melbourne Water's life cycle costing tool, developed in 2013, provides a systematic approach for local councils to estimate and plan for the long-term costs of WSUD assets. This tool helps ensure that all phases of WSUD projects—design, construction, maintenance, and renewal—are accounted for, minimizing the risk of underfunding and ensuring the continued provision of environmental and social benefits, such as flood mitigation and water quality improvements [66].

Incorporating real-time monitoring and control systems into WSUD projects can optimize performance and reduce maintenance costs, leading to lower life cycle expenses. However, the initial investment for sensors, data management, and operational components can be substantial. Sweetapple et al. [67] highlight that real-time control retrofits can offer significant long-term savings over passive systems. Demonstrating the economic benefits through pilot projects can build trust in the financial viability of these advanced stormwater management solutions, like WSUD, encouraging broader implementation.

Financial strategies also include the use of penalties for non-compliance, such as those enforced by environmental authorities to deter stormwater pollution. These penalties are part of a broader financing approach that ensures responsible stormwater management [6].

In developing countries, financing WSUD can be particularly challenging due to limited budgets. However, tools like AvDren, introduced by Baptista et al. [63], offer a practical solution by integrating cost and performance indicators, allowing for a detailed comparison of stormwater management alternatives. By visualizing cost-effective solutions through tools like Pareto charts, decision-makers can better balance economic, technical, and environmental considerations, ensuring the long-term success of WSUD projects even in budget-constrained environments. It is notable that the validation of this methodology in Brazilian conditions suggests its applicability to other tropical developing regions [63].

The economic evaluation of Water Sensitive Urban Design (WSUD) reveals a wide range of benefits that can be difficult to quantify due to the multifunctional nature of these systems. WSUD installations, such as rain gardens, green roofs, and bioretention swales, provide not only environmental but also visual, recreational, health, and biodiversity benefits. Leonard et al. [4] suggest three main methods to estimate their economic value.

1. Revealed Preference Methods: These involve analyzing actual market behaviors to determine the value people place on WSUD features. For example, hedonic pricing examines how property values reflect environmental amenities, while the travel cost method assesses the economic value of recreational benefits by analyzing travel expenses to access green spaces.

2. Stated Preference Methods: These involve surveys where respondents are asked about their willingness to pay (WTP) for specific WSUD services. Techniques such as choice

experiments and contingent valuation are used to gauge public preferences and the value that they place on different aspects of WSUD.

3. Benefit Transfer: This method estimates the economic value of WSUD services by applying findings from existing studies to new contexts. It is useful when direct valuation is not feasible and relies on transferring WTP estimates from similar studies.

The Total Economic Value (TEV) framework offers a comprehensive approach for organizing and assessing the full range of ecosystem services provided by WSUD [31]. TEV encompasses direct use values (e.g., water supply), indirect use values (e.g., flood mitigation), and non-use values, including existence and bequest values.

TEV can be represented by the following equation:

$$\text{Total Economic Value} = \text{Direct Use Value} + \text{Indirect Use Value} + \text{Non-Use Value} + \text{Intrinsic Value}$$

According to Weber et al. [68], economic analyses of stormwater impacts often fail to capture these non-use values, which include the option to preserve the environment for future use (option value), the satisfaction of passing it to future generations (bequest value), and the knowledge that the environment exists and is healthy (existence value). Symons et al. [37] reinforce the significance of the TEV framework in quantifying GI and WSUD benefits, using tools like contingent valuation and hedonic pricing to capture the economic impacts. They further highlight that green spaces, especially in urban areas, significantly enhance property values. Tools like i-Tree also demonstrate the economic value of WSUD by quantifying advantages such as improved air quality and energy savings [69]. These approaches support WSUD investments by showing their long-term economic benefits despite challenges in fully capturing all social and environmental gains [37,68].

The NSW Government's Guidelines for Economic Appraisal, Treasury [70] emphasize that economic evaluations of environmental factors are essential for promoting a socially efficient allocation of limited resources. Such appraisals aim to maximize long-term economic welfare by valuing benefits based on what consumers are willing to pay and costs based on what suppliers are willing to accept. In stormwater management, practical approaches, such as evaluating the direct costs of stormwater impacts on environmental assets, can be effective, even when community willingness to pay (WTP) is not directly assessed [68].

Estimating the costs and benefits of WSUD projects is essential for financial justification. Whiteoak [58] outlines that CBA helps determine whether WSUD investments are viable by considering capital expenditures (CAPEX), operational expenses (OPEX), and renewal costs over the lifecycle of the project. While CAPEX covers initial investments, OPEX includes ongoing maintenance, and renewal costs account for replacing aging assets. A well-structured CBA must analyze all costs and benefits over the entire asset lifecycle, using appropriate discount rates to reflect the time value of money. Moreover, the analysis should consider different perspectives—whether from the household level, water business, or local government—and define a base case scenario to compare WSUD against other investment options. Whiteoak also suggests alternative frameworks, such as cost-effectiveness analysis (CEA) and multi-criteria analysis (MCA), when specific outcomes are predefined or non-monetizable benefits need to be evaluated, though CBA remains the preferred tool for its consistency and comprehensive approach [58].

The economic aspect of WSUD also involves addressing maintenance challenges and ensuring cost-effective asset management. Mullaly [71] notes that a lack of detailed cost data can hinder effective budgeting, leading to inadequate maintenance of Stormwater Control Measures (SCMs). Asset management must address both the cost-effectiveness of achieving desired waterway health outcomes and the management of aging infrastructure. New technologies like Zero Additional Maintenance (ZAM) WSUD systems, which integrate with existing urban maintenance routines, are being developed to minimize maintenance costs [71]. Examples such as the Hoyland St bioretention system in Brisbane and low-maintenance bioretention systems in Melbourne have demonstrated reduced upkeep needs over time [71].

Sharma et al. [72] provide an important framework that integrates various analytical tools for comprehensive environmental and economic assessments of water services, including WSUD. This framework combines water balance modeling, contaminant analysis, life cycle costing (LCC), life cycle assessment (LCA) [73], and community cost assessments to provide a holistic evaluation of water-sensitive projects. The inclusion of LCC and LCA in WSUD projects enables a more thorough understanding of both the short and long-term costs (physical system and environmental cost) and benefits, facilitating better decision-making by urban planners and policymakers.

WSUD also aligns with the principles of the circular economy (CE), promoting resource efficiency, waste minimization, and reduced emissions using nature-based solutions (NBS). Pearlmutter et al. [51] explain that WSUD contributes to sustainable urban development by reducing construction and maintenance costs with sustainable materials, improving water quality, and enhancing flood safety. By integrating lifecycle analyses and harmonized criteria, WSUD supports the development of healthier and more competitive urban environments, with long-term economic, social, and environmental benefits.

In addition to the frameworks and tools used for evaluating WSUD projects, decision-makers have access to specialized tools that help determine the most suitable strategies based on site-specific data. The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN), developed by the USEPA, provides a comprehensive framework for evaluating the optimal location, type, and cost of Best Management Practices (BMPs) [74]. Other tools like LIDRA 2.0 [75] and STEPL [76] offer simplified methods for identifying cost-effective BMPs. More advanced techniques, such as NBS (Nature-based Solution) and EBA (Ecosystem-based adaptation) developed by Ahmed et al. [77], combine cost–benefit analysis with multi-criteria approaches, providing economic assessments alongside performance indicators to help select the most effective stormwater management strategies. Lerer et al. [78] developed tools specifically focused on flood risk mitigation, enabling decision-makers to compare the economic benefits of traditional stormwater management with WSUD solutions.

Despite the various tools and frameworks available, Ahammed [13] points out that comprehensive economic evaluations of WSUD technologies are still scarce in the literature. Further research is needed to quantify key financial metrics such as life cycle cost, net present value, benefit/cost ratio, and payback period. Translating indirect benefits into financial gains using models like the UNIDO framework would allow for more robust economic assessments of WSUD projects, ensuring their sustainability both ecologically and economically [13].

In summary, while WSUD investments face challenges in fully capturing their diverse benefits, frameworks such as TEV and CBA, supported by tools like SUSTAIN and LIDRA 2.0, provide a strong foundation for justifying these projects. With their ability to contribute to both urban resilience and the circular economy, WSUD strategies represent sound financial investments, delivering long-term benefits to both society and the environment [4,37,68,70,71].

Overall, effective financing of WSUD requires a multi-faceted approach that combines traditional funding sources with innovative financial tools, strong policy support, and strategic planning. These strategies ensure that WSUD can be implemented sustainably, offering long-term environmental and economic benefits while overcoming the challenges posed by high upfront costs and maintenance requirements.

- Role of public–private partnerships and government subsidies

Public–private partnerships (PPPs) and government subsidies are essential mechanisms for financing and implementing Water Sensitive Urban Design (WSUD) projects. By distributing the risks and benefits between public and private sectors, PPPs can bring together resources and expertise, promoting more effective WSUD implementation. Additionally, government subsidies and incentives can ease the financial burden on developers and municipalities, encouraging broader adoption of WSUD systems.

The economic aspects of WSUD require a balance between cost-effectiveness and sustainable stormwater management. Achieving this balance calls for a paradigm shift in urban planning, where environmental, social, and economic consequences are integrated into decision-making. Cooperation between stakeholders—government, planners, developers, and designers—is essential for ensuring the economic sustainability of WSUD initiatives [79].

WSUD systems, though beneficial, often increase property costs due to their advanced infrastructure and landscaping requirements. Strategies such as incorporating affordable housing or varying plot sizes can help mitigate this issue, fostering economic diversity. Profit-sharing arrangements from affordable housing sales are another approach to maintaining affordability within these developments [4].

Ongoing maintenance of WSUD systems is another financial consideration, typically managed by local councils or community governance bodies. Effective management can reduce maintenance costs, ensuring the economic sustainability of WSUD projects in the long term. For instance, governance bodies can oversee infrastructure, manage funds for community improvements, and negotiate better service contracts, enhancing the viability of WSUD projects [4].

Future Sustainable Construction Management (SCM) designs are likely to integrate Zero Additional Maintenance (ZAM) WSUD principles, which leverage ecological processes to minimize upkeep. Local governments will need to refine planning and design requirements to reduce long-term maintenance costs. Guidelines specifying various bioretention systems and their optimal placement are examples of this approach [71].

Innovative funding and service models are critical for cities transitioning to hybrid infrastructure systems. This requires the development of new institutional frameworks and business models to regulate urban systems and services, along with comprehensive economic tools to quantify the broad benefits of these systems. By integrating economic analysis with urban development models, decision-makers can better assess the distribution of costs and benefits across communities, informing strategies for integrated urban servicing and climate adaptation. Additionally, policy instruments like pricing, regulatory incentives, and innovative finance mechanisms will encourage the adoption of hybrid solutions. Pilot projects and further research will help refine these strategies, exploring markets and business models that promote private financing, manage risks, and ensure social equity in the implementation of hybrid systems [80].

Fam et al. [44] further emphasize the role of PPPs and government subsidies in maintaining urban green spaces, such as parks, gardens, and sports fields. These spaces offer significant economic benefits, not only through income-generating activities like festivals and sporting events but also through societal benefits, including reduced healthcare costs and pollution control. For example, according to the PGA report, in Australia, public investments in irrigation for the golf industry support $2.71 billion sector that employs 23,000 people [81]. Public parks also drive tourism and increase property values, contributing to local tax revenues. These partnerships ensure that urban green spaces continue to provide economic, environmental, and social benefits. Further research is recommended to optimize these collaborations, focusing on health impacts, user needs, and sustainable design.

- Some example case studies on the economic aspects of WSUD

Case studies from various parts of the world provide valuable insights into the economic benefits of Water Sensitive Urban Design (WSUD). A notable example is Canal Park in Washington, D.C., which was transformed from a bus parking lot into a vibrant public space incorporating innovative rainwater management strategies. According to Wang et al. [52], rainwater from surrounding commercial buildings and roads is collected, filtered, and used to support park functions such as fountains and an ice-skating rink during winter. With the capacity to capture approximately 2.84 million gallons of rainwater annually, the park meets 66% of its water needs through collected rainwater, significantly reducing costs associated with piped water supply. This project exemplifies how WSUD can lower operational costs while enhancing public spaces.

In Ahmedabad, India, the Abhishree Ecostead development integrates rainwater harvesting with the creation of an artificial lake for stormwater retention. As RajuAedla [65] explains, this approach not only boosts real estate value but also provides ecological and aesthetic benefits, demonstrating how WSUD can enhance property markets alongside environmental sustainability. Similarly, in Scharnhauser Park, Stuttgart, Germany, stormwater is managed using Sustainable Drainage Systems (SUDS), such as infiltration swales and rainwater harvesting systems. These systems reduce the need for expensive stormwater infrastructure, while the multifunctional green spaces serve as both floodways and community recreational areas, highlighting the dual economic and social benefits of WSUD [65].

A study in Barcelona, Spain, explored rainwater harvesting (RWH) systems and found that while high initial capital costs and low water prices can result in long payback periods, financial subsidies significantly improve the economic viability of these systems. For multi-family buildings, payback periods range from 21 to 30 years for toilet flushing purposes, especially when combined with garden irrigation, making the systems more appealing [82].

In New York City, Montalto et al. [83] evaluated the cost-effectiveness of LID technologies for controlling Combined Sewer Overflows (CSOs) in the Gowanus Canal watershed in Brooklyn. The study found that green roofs, porous pavements, and stormwater treatment wetlands can reduce CSOs significantly, with porous pavement and treatment wetlands being more cost-effective than traditional storage tanks. Public–private partnerships and subsidies for LID installations were recommended as viable approaches for mitigating CSOs, demonstrating the financial benefits of WSUD in dense urban environments.

In Sydney, Australia, Hajani and Rahman [84] analyzed the economic viability of rainwater harvesting systems (RWHS) in peri-urban areas. They found that while a 5 kL rainwater tank offered the highest benefit/cost ratio, water prices would need to increase for the system to become financially viable without government subsidies. The study underlined that the success of WSUD measures like RWHS depends on local demand and the tailored application of solutions rather than a one-size-fits-all approach.

4. Discussion and Recommendations

The successful implementation of Water Sensitive Urban Design (WSUD) is hindered by various obstacles that prevent its full integration. This section discusses these challenges and recommends the necessary steps to promote the integration of WSUD into city planning.

4.1. Discussion on the Barriers to Widespread Adoption of WSUD

Water Sensitive Urban Design (WSUD) has been widely adopted recently, and the key findings from the literature between 2016 and 2024 are listed in Table 1. However, its application also faces several barriers, including high initial costs, limited public awareness, regulatory challenges, and resistance from developers who favor traditional approaches. Overcoming these obstacles necessitates coordinated efforts among policymakers, urban planners, developers, and the community.

Financial costs are a prominent barrier. Both Leonard et al. [4] and Sweetapple et al. [67] highlight that high capital and operational expenses deter investment, particularly for developers and municipalities. Government subsidies and incentives are crucial in offsetting these costs, making WSUD a more attractive option and encouraging broader participation in these initiatives. However, financial incentives alone are insufficient; a lack of public awareness and insufficient policy support further impede WSUD adoption. Leonard et al. [4] stress the importance of increasing education and understanding of WSUD's long-term benefits. Enhancing awareness, alongside stronger policy frameworks, can elevate WSUD as a standard practice in urban planning and development.

Trust in new technologies presents another critical barrier. Stakeholders may hesitate to adopt advanced stormwater management systems due to uncertainty about their effectiveness. Sweetapple et al. [67] note that as IoT and data-driven approaches gain traction and support in gradually building public confidence, demonstrating measurable outcomes in data-rich environments is key to fostering acceptance. Resistance to change, a socio-cultural barrier, complicates the transition to smarter stormwater management solutions. The shift often demands new operational strategies, which can meet resistance from those comfortable with established methods. Sweetapple et al. [67] argue that effective communication and stakeholder engagement are essential for demonstrating the benefits of these newer systems.

Institutional barriers, such as complex regulatory processes and unclear responsibilities, also hinder WSUD adoption. Brown et al. [30] identify these challenges, particularly in regions like Perth, where local contexts vary. Regulatory reforms that streamline approval processes and clarify stakeholder roles are necessary to facilitate smoother implementation and management of WSUD systems.

In summary, addressing the interconnected barriers of financial, educational, technological, cultural, and institutional factors requires a collaborative approach. Financial incentives, public awareness campaigns, trust-building measures, and regulatory reforms must work together to support the transition to WSUD, ensuring its integration into sustainable urban development strategies.

4.2. Recommendations for Policy and Practice to Enhance the Social and Economic Benefits of WSUD

To enhance the social and economic benefits of WSUD, several policy and practice changes are recommended. These include the development of mandatory WSUD targets and policies at the state level, increased investment in capacity building for local government practitioners, and the establishment of dedicated maintenance budgets for WSUD systems. Additionally, the importance of community education and engagement is crucial for building public support for WSUD initiatives, as this support is vital for their long-term success. A community-based approach encourages the development of solutions that align with local values and needs, shifting focus from purely technical issues to social and cultural dynamics [85]. However, one of the primary barriers to WSUD adoption is the perceived complexity and cost of installation, particularly in residential areas. Cook et al. [86] suggested that rebate programs, which effectively reduce the financial burden of adopting rainwater tanks, should be streamlined to simplify the application process. By reducing bureaucratic hurdles, these streamlined rebates can increase public acceptance and facilitate greater household participation in WSUD initiatives. Moreover, providing clear and accessible guidance on installation processes would empower households, boosting their confidence and capability to adopt WSUD technologies.

To maximize the benefits of WSUD, it is crucial to integrate social equity considerations into planning, ensure early public participation, and develop financing mechanisms that prioritize long-term sustainability. Key recommendations include creating supportive policies and clear guidelines for WSUD implementation, increasing public awareness and involvement to align WSUD with community needs, exploring innovative financing options like green bonds and public–private partnerships, and integrating WSUD into broader urban planning to enhance resilience and sustainability. Furthermore, interdisciplinary collaboration among engineers, social scientists, and urban planners is essential to comprehensively address urban water management challenges [31,87].

This review highlights a growing focus on socio-economic dimensions in WSUD but notes inconsistencies in their quantification, such as trade-offs between mental health benefits and initial costs. A unified framework is needed to standardize future research and improve comparability. Xiong et al. [87] conducted a comprehensive assessment aimed at evaluating various WSUD practices using Multi-Criteria Decision Analysis (MCDA), placing significant emphasis on their social and economic aspects alongside technical and environmental performance. Addressing these socio-economic factors is crucial for understanding the broader impacts of WSUD on communities and ensuring the successful implementation and adoption of these practices in urban areas. It is also recommended to focus on increasing public education, improving communication about WSUD features, and fostering community engagement. Implementing supportive policies and exploring innovative financing options can help overcome existing barriers and promote broader adoption of WSUD practices [4].

Kuller et al. [88] highlight that neglecting socio-economic factors in WSUD planning leads to uneven distribution, reducing its potential impact. They advocate for integrated approaches that consider both socio-economic and biophysical factors, underscoring the need for future research to ensure equitable WSUD placement across urban areas. Moreover, addressing these socio-economic barriers is crucial for successfully implementing smarter stormwater management systems. By understanding and systematically overcoming these barriers, effective and sustainable stormwater management that benefits both the built and natural environments can be realized [67].

The Urban Stream Renovation (USR) framework proposes a more flexible, integrated approach that leverages short-term ecological and societal outcomes to achieve long-term ecological improvements [89]. Key aspects include explicitly incorporating societal objectives (e.g., aesthetic, recreational, cultural) alongside ecological goals rather than treating societal benefits as secondary. The framework advocates for an iterative, adaptive process where short-term outcomes generate increased public support for future actions, maintaining long-term public engagement through education and outreach. Importantly, societal objectives must support long-term ecological improvements, not replace them [89]. Implementing this framework requires developing methods to assess societal outcomes, fostering multidisciplinary collaborations, and refining approaches for effective community engagement and education. Overall, the USR framework aims to increase the opportunities for achieving beneficial outcomes for both the stream ecosystem and the surrounding human community.

According to Wong and Eadie [79], the social dimension of WSUD emphasizes a holistic and collaborative approach to urban planning that addresses the environmental imbalances created by conventional practices. This integrated approach promotes cooperation and commitment from all stakeholders, including government agencies, planners, designers, and the development community. Wong and Eadie (2000) [77] also highlight that the social impact of WSUD is rooted in fostering awareness and understanding of the broader environmental, social, and economic implications of urban design choices. By designing stormwater systems to complement other urban infrastructure, WSUD promotes a more ecologically and socially cohesive urban environment, enhancing the quality of life for residents.

Successful implementation requires collaboration across disciplines, including engineering, architecture, and social sciences, to create sustainable urban systems. Engaged communities and innovative water management practices that prioritize social acceptance are key to this transition [5,26]. Additionally, the inequitable distribution of urban green spaces is a significant concern, particularly for disadvantaged communities that often lack access. To address these disparities, it is recommended that policies incorporate green spaces into low-income and public housing developments. This approach not only improves access to nature but also promotes health equity and reduces social exclusion. Fam et al. [44] emphasize that green spaces play a crucial role in facilitating social capital and community cohesion. Encouraging community involvement in activities such as gardening and park restoration can foster social connections and a sense of shared ownership among residents, contributing to overall community safety.

Australia's unique climatic conditions and public ownership of water resources present both challenges and opportunities in becoming water-sensitive cities. Achieving this vision will require distributed leadership, enhanced cross-sectoral collaboration, a culture of innovation, and continuous capacity building—all underpinned by a shared understanding of the critical role of water in supporting liveable, sustainable, and resilient cities [90]. Transitioning to sustainable water provision involves transforming water utilities' organizational culture and overcoming regulatory, technological, and organizational challenges. However, changes to urban water management and infrastructure are often hindered by risk perceptions, the lock-in effects of legacy solutions, vested interests, cost uncertainties, and a fear of transparency among water practitioners. Sustainable water projects typically require significant upfront funding, which can reduce short-term income or operating capital, posing a barrier to change. Additionally, water utilities may lack expertise in areas crucial for sustainability, such as landscape design, renewable energy, social marketing, and financial analysis, necessitating collaboration with external partners.

Schmack et al. [29] emphasize that effective management for sustainability requires an adaptive and flexible approach, with leaders capable of action-oriented learning and reflection. Legislative gaps are a major obstacle to adopting hybrid water systems at both household and communal scales. Addressing this requires a governance framework that enhances trust between stakeholders and clearly defines risk management responsibilities alongside genuine public consultation to ensure that water services align with residents' needs and not just utility perceptions. Brown et al. [30] recommend policy interventions such as capacity-building programs, fostering greater socio-political capital, and developing demonstration projects with training events to help address institutional impediments and accelerate the transition toward more sustainable urban stormwater management practices in Australia.

Integrating economic assessments into urban planning is crucial, as they provide a comprehensive view of the benefits of WSUD, supporting informed decision-making and demonstrating the financial advantages of investing in sustainable urban infrastructure [4]. To effectively implement WSUD systems, Brown et al. [30] suggest that utilities must transform their organizational culture while addressing regulatory, technological, and management challenges that can impede progress. Key obstacles, such as risk perceptions and uncertainties about costs, often complicate this transition, and the significant initial funding required can strain resources and deter adoption. Collaboration with external partners is essential for accessing expertise beyond traditional engineering, while addressing legislative gaps and establishing strong governance will enhance stakeholder trust. Genuine public consultation is vital for fostering community acceptance, while innovative strategies like smart-meter trials [91] and Urban Living Labs [92] can promote water conservation by providing real-time feedback and facilitating the co-development of sustainable practices.

Weber et al. [68] underscore the necessity of incorporating economic considerations into urban planning decisions, calling for further research to fully understand the broader effects of poor water quality on the ecosystem. A major research gap remains in quantifying the economic value of health benefits from urban greening. Although green spaces are linked to better physical and mental health, translating these into economic metrics is challenging due to the need for robust, causative evidence and extensive data. Including realistic failure rates of WSUD investments in economic analyses is crucial to avoid overestimating benefits. The “Benefit Transfer Method” applies economic values from existing studies to new WSUD sites to fill data gaps, with the preferred method using value functions that adjust for differences between sites, enhancing transfer accuracy. However, it requires careful consideration of factors like geographic and socio-economic context to avoid errors, especially when used by less experienced practitioners [58].

Table 1 summarizes key findings from the literature on social and economic aspects of WSUD, including recommendations to address issues for increased adoption of WSUD.

Table 1. Key Findings from the literature between 2016 and 2024.

Aspect	References	Key Findings
Social Aspects	[4,22,27,31,38,39,52,54]	- Enhanced community engagement and cohesion through participatory planning. - Public awareness and education are crucial for WSUD acceptance. - Social benefits include improved urban quality of life, aesthetics, and recreation.
Economic Aspects	[3,4,31,51,56–59,61,64,71]	- Long-term cost savings outweigh the initial investment. - Economic benefits include increased property values and reduced flood risks. - Lifecycle costing tools and public–private partnerships enhance WSUD implementation.
Discussions and Recommendations	[4,26,29,31,58,67,87–90]	- Need for clearer governance frameworks and cross-sector collaboration for increased adoption of WSUD approaches. - Importance of supportive policies, incentives, and capacity building. - Promote interdisciplinary research and community-focused implementation strategies. - Emphasize integrated planning for WSUD in existing urban areas. - Increase funding mechanisms and incentives for WSUD adoption.

5. Conclusions

The implementation of WSUD offers a comprehensive solution to urban water challenges while improving social and economic outcomes. This review highlights the extensive benefits of WSUD beyond its environmental impacts, focusing on its potential to enhance public health, increase property values, reduce infrastructure costs, and strengthen community cohesion. However, achieving these outcomes requires overcoming significant challenges, including high initial costs, limited public awareness, and regulatory hurdles. Addressing these barriers will involve interdisciplinary collaboration, innovative financing strategies, and targeted policy reforms to ensure equitable access and long-term sustainability of WSUD projects.

In addition, the integration of community engagement into WSUD planning and management is critical. Cities can build public trust and foster acceptance by actively involving local populations in the decision-making process, thereby creating socially inclusive and economically viable urban environments. WSUD offers a cost-effective solution to manage stormwater and mitigate flooding in these areas.

Future research and demonstration projects will be essential for assessing the long-term effects of WSUD and identifying strategies to adapt its principles across diverse urban contexts. Emphasis should be placed on quantifying socio-economic benefits, especially in low-income areas where challenging topography often necessitates costly drainage systems, and on developing cost-effective models for scaling WSUD applications. Addressing these areas will enable WSUD to be more supportive of cities to become resilient, inclusive, and sustainable in the face of climate change and urbanization pressures.

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Review

Innovations in Solar-Powered Desalination: A Comprehensive Review of Sustainable Solutions for Water Scarcity in the Middle East and North Africa (MENA) Region

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Abstract: Water scarcity poses significant challenges in arid regions like the Middle East and North Africa (MENA) due to constant population growth, considering the effects of climate change and water management aspects. The desalination technologies face problems like high energy consumption, high investment costs, and significant environmental impacts by brine discharge. This paper researches the relationships among water scarcity, energy-intensive desalination, and the development of renewable energy in MENA, with a particular focus on the Gulf Cooperation Council (GCC) countries. It examines innovations in solar-powered desalination, considering both solar photovoltaic (PV) and solar thermal technologies, in combination with traditional thermal desalination methods such as multi-effect distillation (MED) and multi-stage flash (MSF). The environmental impacts associated with desalination by brine discharge are also discussed, analyzing innovative technological solutions and avoidance strategies. Utilizing bibliometrics, this report provides a comprehensive analysis of scientific literature for the assessment of the research landscape in order to recognize trends in desalination technologies in the MENA region, providing valuable insights into emerging technologies and research priorities. Despite challenges such as high initial investment costs, technical complexities, and limited funding for research and development, the convergence of water scarcity and renewable energy presents significant opportunities for integrated desalination systems in GCC countries. Summarizing, this paper emphasizes the importance of interdisciplinary approaches and international collaboration by addressing the complex challenges of water scarcity and energy sustainability in the MENA region. By leveraging renewable energy sources and advancing desalination technologies, the region can achieve water security while mitigating environmental impacts and promoting economic development.

Keywords: MENA; GCC; reverse osmosis; water resource; renewable energy; solar energy; water sustainability; solar thermal; high energy consumption; membrane fouling; environmental challenges

1. Introduction

Water, a fundamental resource for human life, constitutes approximately 70% of the Earth's surface. Despite this abundance, just 0.015% exists in rivers and lakes, while 96.5% resides in seas and oceans. The worldwide water demand, currently at 4600 km^3 annually, is projected to surge to 5500–6000 km^3 annually by 2050 because of escalating population growth [1,2]. However, this demand is met with challenges such as water scarcity, mismanagement, contamination, and over-extraction, resulting in around 3% of the world's freshwater [3]. Climate change further compounds these issues, leading to extreme weather events that contaminate freshwater resources, disrupt infrastructure, and diminish available water. Approximately 74% of water-related disasters occurred between 2001 and 2018, a trend expected to intensify with climate change [4].

In the MENA region, encompassing a diverse array of countries, water scarcity has already emerged as a pressing issue. The MENA region's unique topography, characterized by deserts, mountains, and coastal regions, contributes to a predominantly arid and semi-arid climate. Annual rainfall in most parts oscillates between 100 and 250 mm, with high variability and low predictability, exacerbating water scarcity [5,6]. Agriculture, the predominant sector consuming water resources, poses a significant challenge to the region's water security. Countries like Syria and Yemen utilize up to 90% and 95% of their water for agriculture, respectively, highlighting the strain on water resources [4,7]. Rapid urbanization and economic expansion further escalate water demands, necessitating strategic interventions to address these challenges [4,8].

The MENA region primarily relies on limited conventional water resources derived from surface and groundwater. Surface water sources, including rivers and dams, face unreliability and scarcity due to the arid climate. Groundwater, accessed through wells, is crucial for irrigation and drinking water but confronts challenges such as over-exploitation, depletion of aquifers, and increased salinity. This situation is clearly shown in the Gulf Cooperation Council countries, Djibouti, Libya, and Jordan, where both surface and groundwater resources are scarce, as shown in Figure 1. As the MENA region grapples with these multi-faceted water challenges, addressing issues of scarcity, pollution, and over-extraction becomes imperative for sustainable water management [9–11].

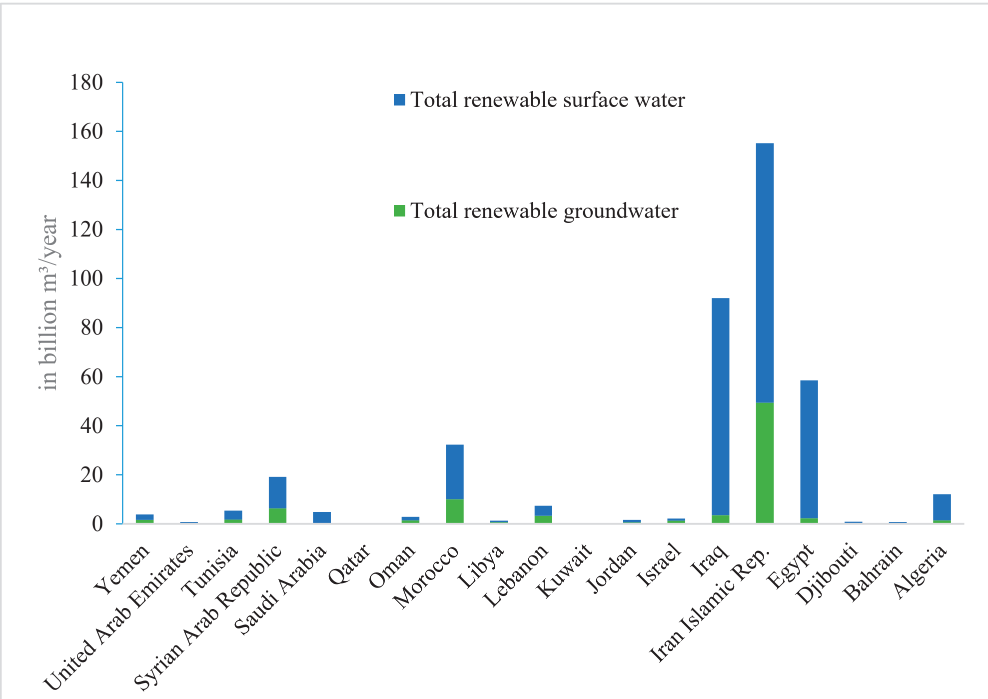

Figure 1. Groundwater and surface water resources in the Middle East and North Africa [9–11].

A decision at UNFCCC COP28 urges all parties of the Paris Agreement to increase adaptation action and support in order to reach a number of climate-resilience targets. The very first of these targets calls for the significant reduction in climate-induced water scarcity, the implementation of a climate-resilient water supply, and ultimately safe and affordable water for all.

Achieving water sustainability demands a multi-faceted approach, encompassing a reliable water supply, sustainable energy sources, and efficient water utilization across domestic, industrial, and agricultural sectors [12,13]. An integral aspect of this strategy is water desalination, presenting itself as a potential solution to augment freshwater resources. The process holds promise in addressing water scarcity concerns, especially in regions like the MENA area, which is abundant in brackish water [12]. Efforts to enhance water sustainability must not only focus on sourcing additional water but also on optimizing the usage of existing resources to ensure resilience in the face of escalating demands and environmental challenges.

The International Desalination Association (IDA) highlights leading contributors to desalinated water production, including some Arabic Gulf countries and the United States. The MENA region holds a substantial 47.5% of global desalination capacity, with 62.3% allocated to municipal applications and 35% for industrial purposes [14,15]. Globally, the installed desalination capacity has reached 97.2 million m^3 annually from 16,876 plants, contributing to a cumulative capacity of 114.9 million m^3 from 20,971 projects [14].

Desalination, a pivotal process for addressing water scarcity, is energy-intensive, consuming an average of 75 TWh yearly and constituting nearly 0.4% of global electrical energy consumption [16]. This energy intensity leads to significant environmental impacts, producing approximately 76 Mt-CO_2 annually, projected to rise to 218 Mt-CO_2 annually by 2040 due to the increased desalination capacities [16]. The intricate relationship between water, energy, and the environment nexus underscores the need for sustainable solutions. Renewable energy (RE), especially solar energy, emerges as a viable tool to reduce the environmental footprint of desalination processes by minimizing fossil energy dependency [17,18].

Desalination processes fall into categories such as thermal, mechanical, electrical, and other processes based on their driving forces and working principles. Thermal processes, like multi-stage flash distillation (MSF), multi-effect distillation (MED), single-effect vapor compression, humidification–dehumidification (HDH) desalination, membrane distillation (MD), solar distillation, and freezing use solar thermal energy for evaporation and condensation, mimic the natural water cycle. Mechanically driven processes, such as RO, nanofiltration (NF), and pressure-assisted osmosis (PAO), use pressure and semi-permeable membranes to separate water molecules from ions. Electrically driven processes, like capacitive deionization (CDI) and electrodialysis (ED), focus on ion separation in saline water [19–21]. The following Table 1 gives an overview of desalination processes and its driving forces.

Table 1. Desalination processes and driving force [19–22].

Desalination Process	Driving Force	Working Principle
MSF	Thermal energy	Evaporation and condensation, natural water cycle
MED	Thermal energy	Evaporation and condensation in multiple stages
HDH	Thermal energy	Evaporation and condensation in separate chambers
MD	Thermal energy	Transfer of vapor molecules through a microporous hydrophobic membrane
Solar Distillation	Solar thermal energy	Evaporation and condensation, relying on natural solar radiation
Freezing	Thermal energy	Freezing and separation of water from salt in saline solutions

Table 1. *Cont.*

Desalination Process	Driving Force	Working Principle
RO	Mechanical (pressure)	Separation of water molecules from salts through semi-permeable membranes
NF	Mechanical (pressure)	Similar to RO but with slightly larger pore sizes in the membrane for partial salt removal
PAO	Mechanical (pressure difference)	Separation of water from salts across a semi-permeable membrane using osmotic pressure
CDI	Electrical (potential difference)	Attraction and removal of ions from saline water using electrical potential
ED	Electrical (ion-selective membranes)	Separation of ions from saline water using electrical potential gradients

Notably, RO dominates both the global and MENA desalination markets, constituting 69% of desalination capacity and 84.5% of the overall plants [14,23]. Figure 2 illustrates the prevalence of RO technologies, depicting their respective capacities measured in Mm^3/day across various countries in the MENA region. Furthermore, Figure 3 highlights the trends in desalination technologies, presenting (a) the total number and capacity of desalination units alongside their operational counterparts, and (b) the operational capacity distributed across different desalination technologies [14].

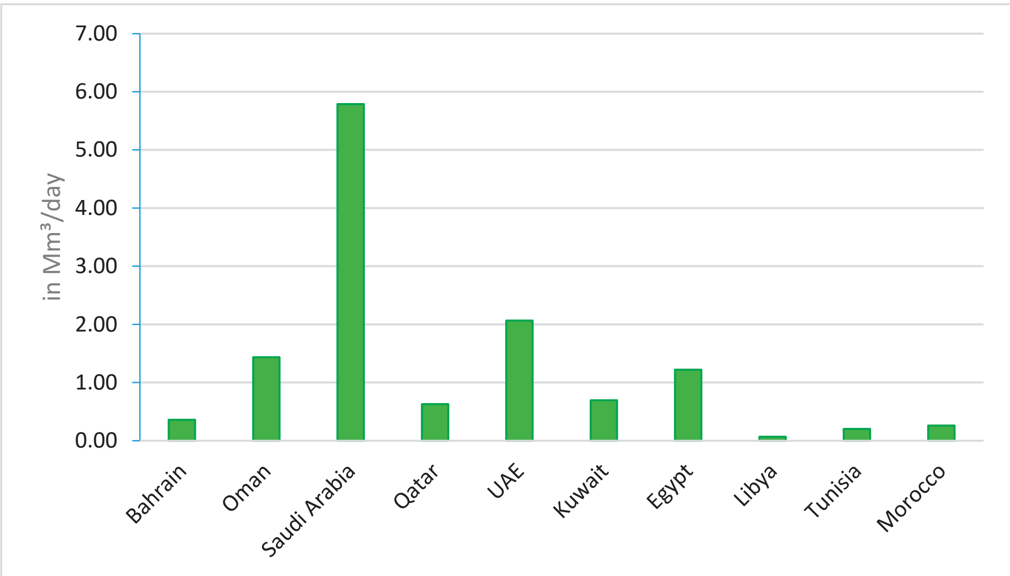

Figure 2. RO capacity in different countries in the MENA region [23,24].

The MENA region's desalination landscape primarily features RO, MSF, and MED technologies. While thermal processes like MSF and MED are suitable for large capacities, RO plants offer flexibility and modularity [24]. RO, being cost-effective compared to technologies like MSF and multiple-effect evaporation (MEE), has become the preferred choice, constituting 85% of operational desalination plants and 91% of under-construction plants worldwide [4]. The Middle East, representing 39% of global desalination capacity, heavily relies on fossil fuel-based thermal desalination, especially in the Persian Gulf region [20]. However, the MENA region's solar and wind energy potential, particularly solar energy, presents opportunities for sustainable water production through solar-assisted desalination [4].

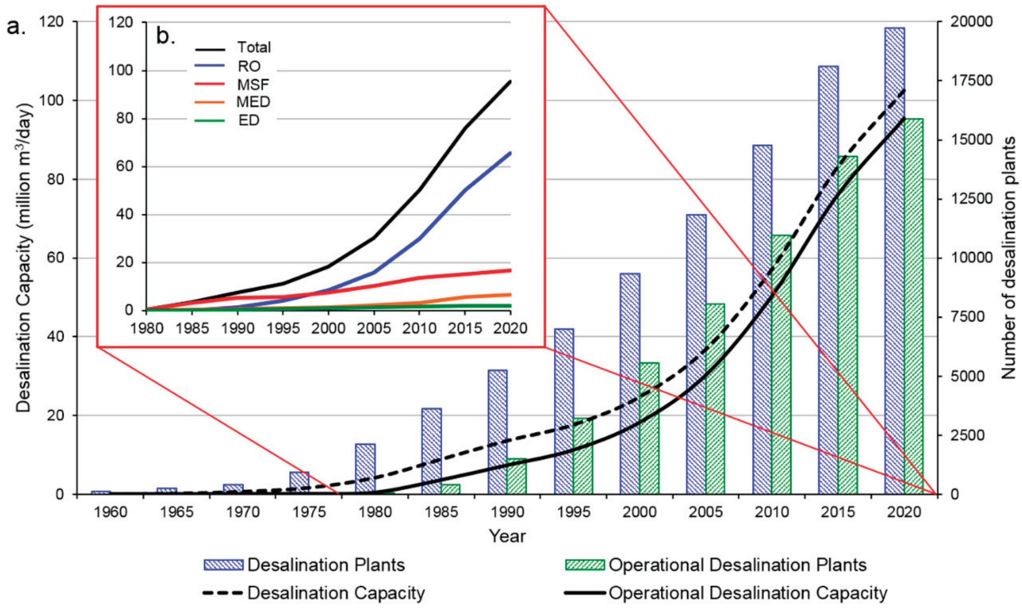

Figure 3. Global desalination trends: analysis of facility numbers, capacities, and technology operationalities: (**a**) the total number and capacity of desalination units alongside their operational counterparts, and (**b**) the operational capacity distributed across different desalination technologies [14].

Integrating solar energy into desalination processes offers a promising solution to address both water scarcity and environmental concerns. Direct and indirect solar desalination methods, utilizing PV and concentrated solar power (CSP), emerge as attractive energy sources. PV-solar-based desalination, which provides electricity for membrane-based desalination processes, is suitable for treating brackish water. In contrast, CSP, offering backup energy and extended working hours, is connected with RO systems. While PV has no limitations and is suitable for densely populated areas, CSP's ability to operate after sunset makes it an advantageous choice [4,25].

Traditional desalination methods such as RO, MED, and MSF require significant amounts of energy, mostly from fossil fuels. This reliance results in higher operating costs and increased environmental impact due to carbon emissions. For instance, desalinating seawater using RO consumes about 2.5 to 4 kWh/m^3 of energy, with production costs ranging from 0.5 to 3 USD/m^3 [26]. In comparison, MSF and MED methods have even higher energy consumption, with MSF varying from 13.5 to 25.5 kWh/m^3 and MED from 6.5 to 28 kWh/m^3, with associated costs ranging from 0.84 to 1.56 USD/m^3 [27]. Incorporating solar power into desalination technologies offers the benefit of reducing reliance on fossil fuels and minimizing greenhouse gas emissions, leading to a smaller environmental impact. Solar-powered desalination processes also tend to have lower operational costs due to minimal energy input requirements once the solar infrastructure is installed. However, the initial capital investment for solar panels and related equipment can be substantial, and the efficiency of solar-powered systems can be influenced by geographical and climatic conditions. For example, when using PVRO for seawater desalination, the energy demand ranges between 2.5 and 6.6 kWh/m^3, with costs ranging from 0.89 to 1.8 USD/m^3 [28]. Therefore, the choice between solar-powered desalination and traditional methods depends on various factors, including the specific regional energy landscape, environmental priorities, and economic considerations.

With the MENA region hosting approximately half of the global desalination capacity, the adoption of solar-powered desalination technologies is gaining traction, particularly in countries like Saudi Arabia, the UAE, and Qatar. Investments in solar desalination, despite higher initial costs, indicate a shift toward sustainable practices. For example, the construction of the world's largest PV-RO plant in Saudi Arabia and plans for a significant PV-RO project in the UAE underscore the region's commitment to solar-powered desalination [29,30].

Although challenges such as brine disposal and high upfront costs persist, advancements in solar-driven desalination technologies and the increasing demand for water in the MENA region suggest a promising future for sustainable desalination practices. Ongoing research aims to optimize reverse osmosis plants, coupled with renewable energy sources, to improve the efficiency and economic viability of these processes. The integration of solar energy into RO desalination not only addresses water scarcity but also aligns with global efforts to transition toward sustainable and eco-friendly solutions. This paper delves into the feasibility and potential of implementing solar-driven reverse osmosis (RO) desalination plants within the MENA region. It offers a comprehensive examination of the reverse osmosis membrane process, detailing the fundamental processes within RO plants, while also addressing the challenges inherent to RO technology. These challenges encompass high energy consumption, membrane fouling, environmental challenges, and boron removal. Furthermore, the paper delves into the realm of renewable energies, particularly focusing on solar photovoltaics and solar thermal energy, and their abundant presence within the MENA region. By highlighting the solar energy potential in this region, the discussion extends to advancements in the deployment of solar energy-driven RO technology. Both solar photovoltaic-powered and solar thermal-powered RO systems are explored, showcasing the strides made in integrating renewable energy sources into desalination processes. Through a comprehensive review, this paper sheds light on the current landscape of solar-powered RO desalination, emphasizing the ongoing endeavors aimed at surmounting technical barriers and commercializing these sustainable technologies. Ultimately, the overarching aim is to foster the development of economically viable and ecologically sound RO desalination systems, capable of mitigating the escalating water scarcity challenges prevalent in the MENA region.

2. Background

2.1. Overview of Membrane-Based Processes

Membrane separation technology, a cornerstone for various fluid separations, offers advantages such as low running energy requirements, easy upscaling, simplicity, and no need for additional chemicals. The classification of membrane technology processes is organized based on different driving forces, including pressure, electrical, thermal, and concentration-driven processes. Figure 4 displays different types of pressure-driven membrane processes, which are categorized based on the pore size, applied pressure, and removing target [31]. Microfiltration (MF) membranes, which have the largest pores (0.1–1 μm), operate at low pressures (below 1 bar) to remove larger particles. Ultrafiltration (UF) membranes have smaller pores (2–100 nm) and slightly higher pressures (1–6 bars), which help to eliminate suspended solids and macromolecules. Nanofiltration (NF) membranes have even tighter pores (below 1 nm) and operate at moderate pressures (5–15 bars) to separate smaller molecules and multi-valent ions. Reverse osmosis (RO) membranes have a dense structure and operate under high pressure up to 70 bars for seawater desalination.

Reverse osmosis is a water purification method employing a semi-permeable membrane to remove ions, molecules, and larger particles, producing clean drinking water. In the RO process, applied pressure overcomes osmotic pressure, a collative property driven by the chemical potential difference between the solute and solvent. This technique, widely used for water treatment, effectively eliminates dissolved and suspended species, including bacteria, from water in both industrial and potable water production applications. During reverse osmosis, the pressurized membrane retains solutes on one side, allowing only the pure solvent to pass through. Mass transport across RO membranes is believed to adhere to a solution–diffusion mechanism [32]. This implies that water dissolves on the feed surface, moves through the active layer via diffusion, and then releases from the surface on the permeate side. The process involves the solvent moving from a region with lower solute concentration to a higher concentrated solute region, driven by a decrease in the free energy of the system. Reverse osmosis essentially reverses this natural solvent flow by applying external pressure [33].

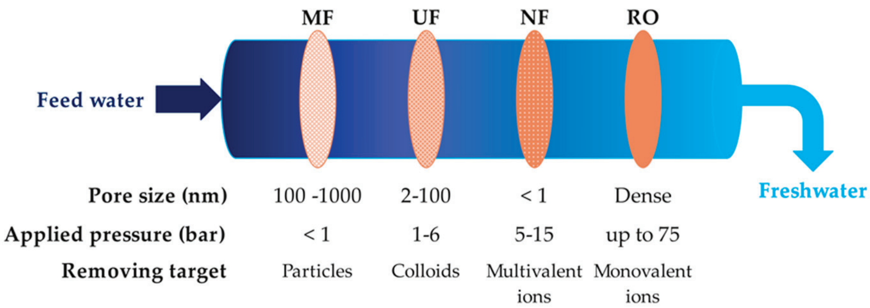

Figure 4. Main pressure-driven membrane technologies.

The present market for RO membranes is primarily dominated by thin-film composite (TFC) polyamide membranes characterized by a three-layer structure. This design comprises a robust polyester support layer (120–150 μm) that provides essential mechanical stability. A middle microporous layer (~40 μm) acts as a bridge between the support and the top layer. Finally, an ultrathin top barrier layer (~0.2 μm) selectively allows water molecules to pass through, making it the central part of the desalination process [34]. The spiral-wound membrane module configuration is the famous type used in RO desalination, mainly because of its many advantages. This configuration provides a large specific membrane surface area, making it easy to scale up. It also allows for interchangeability, and the cost of replacing the modules is low. Additionally, it is the most cost-effective module configuration when using flat-sheet TFC membrane material [34].

RO, recognized by the IDA as the fastest-growing technology, has witnessed increasing adoption in the MENA region, outpacing traditional thermal desalination methods. This shift is attributed to lower energy needs and advancements in membrane technologies, rendering RO suitable for high-salinity feed waters. The specific energy consumption (SEC) of SWRO has significantly decreased from 20 kWh/m^3 in the 1980s to less than 3–4 kWh/m^3 in recent years [35].

RO processes are divided into two main categories based on the quality of the input water. Brackish water RO plants (BWRO) handle water with salinity levels ranging from 1 g/L to 10 g/L [36], while seawater RO plants (SWRO) are designed for water with salinity levels ranging from 25 g/L to 45 g/L [37]. The efficiency of the reverse osmosis process is dependent on a range of operational parameters, the selection of the membrane, and the characteristics of the feed water. The BWRO process is capable of achieving 70–90% water recovery at pressures of 15–25 bar, while the SWRO process achieves 40–55% recovery at pressures of 55–70 bar and 2–4 kWh/m^3 of specific energy consumption [2,37,38].

In addressing the global water scarcity crisis, RO systems play a crucial role in providing clean drinking water. The advantages of employing RO systems include ease of design, lower maintenance needs, modularity, removal of contaminants, lower energy requirements, reclamation and recycling of waste process streams, operation at ambient temperatures, modular structure for increased flexibility, lower specific energy requirements, and a significant decrease in waste stream volume, resulting in more efficient and cost-effective water treatment.

However, despite their advantages, RO systems also face some challenges, especially when it comes to handling the concentrated brine produced during SWRO. The quantity and concentration of the brine depend on the desalination recovery rate. When operating at a 50% recovery rate, the brine concentration can become twice as high as the feed seawater. This highlights the importance of implementing responsible brine management strategies. Furthermore, RO systems strip away most of the minerals from water, resulting in an acidic pH, which some may view as undesirable due to the removal of essential minerals. Additionally, the initial cost of installing RO systems is high, and they necessitate regular filter replacements and maintenance. Moreover, they consume energy, emit greenhouse gases, and encounter limitations such as restricted recovery rates, membrane fouling, and the production of waste brine. The process is also slow, particularly for household purposes, as it operates under very low pressure. Finally, RO systems are ineffective at removing dissolved molecules of similar size to water molecules, potentially leading to system clogging [39].

2.2. Components of Seawater Desalination with RO Process

The SWRO desalination process typically includes three main stages: pre-treatment, the RO desalination unit, and post-treatment. The process starts with seawater intake, which is a significant aspect of desalination plants. The intake aims to maintain a consistent and ample supply of high-quality feed water throughout the plant's operational lifespan while mitigating environmental impacts. There are two common types of seawater intakes: open water intakes and subsurface intakes. After the intake, seawater is conveyed through intake pumps for pre-treatment. Pre-treatment of the feed water is important to reduce turbidity and concentrations of microorganisms, colloids, and total dissolved solids (TDS). It also minimizes the silt density index (SDI) to acceptable levels for subsequent processing. This is achieved through screening, disinfection, coagulation–flocculation, filtration, dichlorination, pH adjustment, and antiscalant addition to solving fouling and scaling issues. The choice of pre-treatment process relies on feed water quality, space availability, and RO membrane requirements.

The RO unit typically consists of high-pressure pumps (HPP), energy recovery devices (ERD), and RO membranes. HPPs are used to pump the pre-treated water and forcing it to pass through the membrane. The required pressure depends on the type of feed water being treated. ERDs are used to recover energy from the high-pressure reject brine generated during the desalination process [40]. This process involves transferring hydraulic pressure from the concentrated brine stream to the incoming feed water, thereby reducing the overall energy consumption of the desalination plant. Membrane unit, the crux of the RO-based separation process, involves a semi-permeable membrane that selectively allows pure water to pass while rejecting salts, ions, and organic molecules present in the feed water. Commonly employed membrane module configurations for large-scale applications include spiral wound and hollow fiber modules.

Post-treatment follows membrane separation, wherein the permeated water undergoes stabilization and preparation for distribution. The post-treatment strategy depends on the intended application of the product water. Although the membrane effectively removes most dissolved solids from the feed water, a small percentage of salt may permeate through, necessitating post-treatment. This stage involves pH adjustment, degasification of carbon dioxide, lime addition, disinfection using sodium hypochlorite, and remineralization [41–43].

2.3. Challenges Associated with the RO Process

2.3.1. High Energy Consumption

Desalination is a promising technology for producing freshwater as there is an abundance of seawater available. Although the RO process consumes less energy compared to thermal-based technologies, it still has a relatively high energy demand, highlighting the need for further reductions. Over the past decades, the energy required for desalination in SWRO plants has sharply decreased, owing to continuous advancements in technology, such as more efficient pumps, energy recovery devices, high-performance membranes, and membrane module designs. However, there is still potential for reducing the energy demand in the SWRO process. The theoretical minimum energy requirement (SECth) for desalinating seawater with a salinity of 35 g/L is approximately 1.06 kWh/m^3 at a recovery rate of 50% [44]. The specific energy consumption (SEC) of the SWRO has significantly decreased from 8.5 kWh/m^3 in 1990 to below 3 kWh/m^3 by 2009 [45]. However, the

SEC is much higher than SECth due to non-reversible thermodynamic processes, pump constraints, and system losses.

Despite the recent advancements in SWRO desalination, its energy consumption (3 kWh/m^3) remains relatively high compared to conventional sources of drinking water supply, such as surface or groundwater treatment (<0.5 kWh/m^3). Consequently, this higher energy demand contributes to increased operational expenditures and greater dependency on fossil fuels, resulting in adverse environmental impacts. Moreover, the substantial energy demand of SWRO systems can also lead to the emission of greenhouse gases, thereby exacerbating the effects of climate change [16]. The estimated energy consumption of SWRO plants is 100 TWh/year, leading to 60–100 Mt-CO_2 emissions annually [29]. As SWRO is a highly energy-intensive technology, reducing energy demand would have a tremendous impact. Moreover, the current global energy crisis has made low-energy seawater desalination a pressing issue. To address this challenge, researchers and engineers are actively seeking innovative methods to decrease the energy demand of SWRO desalination.

The energy consumption breakdown in SWRO plants, estimated by [46], is shown in Figure 5. The total energy demand is estimated to be 3.57 kWh/m^3, constituting 25 to 40% of the water production cost. The RO system consumes the highest amount of energy at 71.15% (2.54 kWh/m^3) of the entire RO plant. The remaining energy is distributed across pre-treatment (0.39 kWh/m^3, 10.8%), seawater intake (0.19 kWh/m^3, 5.3%), post-treatment, and freshwater distribution (0.18 kWh/m^3, 5%), and other facilities like storage and brine disposal (0.19 kWh/m^3, 5.3%). This breakdown highlights the pivotal role of the RO system in the overall energy consumption of SWRO plants, emphasizing the need for continuous development of energy-efficient technologies throughout the entire desalination process.

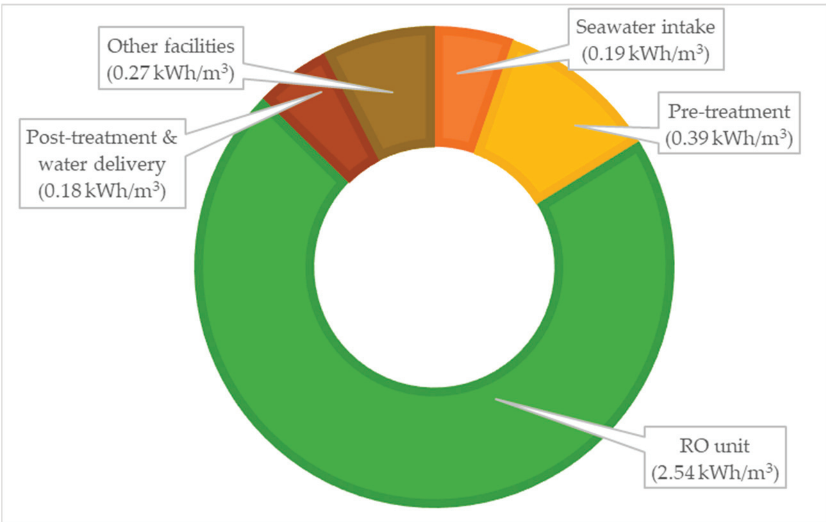

Figure 5. Distribution of energy consumption in SWRO desalination plants.

2.3.2. Membrane Fouling

The RO process faces a significant challenge associated with fouling, which leads to a decline in membrane performance and an increase in operational costs. Fouling occurs due to the accumulation of suspended or dissolved substances on the external surfaces of the membrane, at the pore openings, or within the pores. It can result in reduced water permeation, salt rejection, and membrane lifespan, and increased energy consumption, and the need for more frequent membrane cleaning, replacement, and pre-treatment [47,48]. Fouling can be either reversible or irreversible, with the latter resulting in a long-term reduction in the flow rate [49,50]. It is classified into organic (from organic matter accumulation such as humic substances), inorganic (inorganic substances such as from mineral scales), colloidal (deposition of colloids or fine suspended particles), and biofouling (resulting from microbial attachment), each of which can be mitigated to some extent through pre-treatment processes [48,49,51].

Furthermore, the occurrence of fouling mechanisms can give rise to the formation of scale, cake, and biofilm, thereby adversely affecting membrane performance. Colloidal matter, whether organic, inorganic, or biological, contributes to the formation of cake, while scaling occurs due to the heterogeneous crystallization of soluble mineral salts on the membrane surface. Biofilm formation is a consequence of the colonization of deposited microorganisms. To address these challenges, a clear understanding of fouling mechanisms, types, and factors affecting fouling is crucial [52–55].

The occurrence of different types of fouling may be simultaneous, while fouling mechanisms may be initiated in different phases of the operational process. For instance, scaling and silica fouling typically occur in the final membrane stage, whereas colloidal fouling deposits at an early phase when drag forces are elevated [53,54]. Furthermore, surface fouling is more common in RO membranes due to their non-porous structure, but it can be controlled by manipulating the hydrodynamics or performing chemical cleaning [52].

To prevent membrane fouling, it is essential to consider factors such as membrane selection, system design, and regular cleaning routines. Membrane fouling can lead to a decrease in production, increased energy consumption, and even damage to the membranes. Therefore, implementing preventative measures and understanding the causes and types of fouling are crucial for maintaining the efficiency of the RO process [56].

2.3.3. Environmental Challenges

Although SWRO desalination is an effective solution to water scarcity in coastal areas, it also poses several environmental challenges. The process of desalination has significant interactions with various environmental subsystems, which include the water (hydrosphere), land (geosphere), living organisms (biosphere), air (atmosphere), and human-made processes (technosphere) [57]. The desalination process requires substantial energy consumption, which is often generated from fossil fuels and results in air pollution and greenhouse gas emissions that contribute to climate change. The extraction and processing of materials for desalination infrastructure can also worsen environmental degradation. The extensive land footprint of desalination plants may impact local ecosystems and land use patterns. Additionally, the intake of seawater and discharge of concentrated brine can disrupt coastal habitats and affect the biodiversity of marine life within the biosphere.

Brine disposal, a concentrated saline by-product generated during desalination processes, poses significant challenges and environmental concerns. One of the most critical environmental issues associated with desalination is the intake of seawater and the discharge of concentrated brine, which can disrupt coastal habitats and affect the biodiversity of marine life within the biosphere. Intake systems can cause marine species such as fish, plankton, algae, and seagrass to become trapped against suction racks, resulting in injury or death [58]. The harmful effects of brine on the environment are attributed to its salinity, turbidity, temperature, and chemical composition. The salinity of brine is 1.6–2 times higher than that of seawater, and its temperature depends on the desalination process employed. Various chemicals employed in pre-treatment and membrane cleaning, including copper, ferrous, nickel, molybdenum, and chromium further contribute to the potential environmental impact [59]. Studies have shown that even a slight increase in salinity can disrupt the osmotic balance of marine species, leading to irreversible dehydration of their cells and potential extinction in the long term. While brine from a single desalination plant may not cause significant harm, the cumulative effects of brine from multiple plants operating in the same area over an extended period could adversely affect marine life [60–62]. Therefore, careful management practices and innovative solutions are essential to minimize the environmental impacts of brine disposal. Besides ongoing research to limit the environmental effects of brine discharge, full scale plants implemented various process optimizations in new installations. Careful engineering of mixing and diffusion in brine discharge locations helps to limit the local effect of salinity. Alternative pre-treatments like ultrafiltration (UF) [63] lower the amount of chemicals added in the process. And effective heat recovery in thermal desalination systems limits the temperature change in receiving waters while it improves the overall and economic efficiency of the system.

The increasing public awareness of the adverse environmental impacts of brine disposal has led to the development of stricter regulations, potentially limiting conventional disposal methods. In response to these challenges, minimal and zero-liquid discharge (MLD and ZLD) has gained attention. MLD/ZLD systems aim to recover high-quality freshwater with the near complete elimination of liquid waste from desalination plants, achieving water recovery rates of more than 95%. The compressed solid waste generated can be disposed of in an eco-friendly manner or repurposed as high-value-added compounds [64,65].

ZLD/MLD systems comprise a pre-concentration stage (membrane-based technologies) and successive evaporation and crystallization stages (thermal-based technologies), exhibiting variations in design, arrangement, and operation. As shown in Figure 6, membrane-based technologies encompass reverse osmosis (RO), high-pressure reverse osmosis (HPRO), forward osmosis (FO), osmotically assisted reverse osmosis (OARO), nanofiltration (NF), membrane distillation (MD), membrane crystallization (MCr), electrodialysis (ED) and electrodialysis reversal (EDR), and electrodialysis metathesis (EDM). In contrast, thermal-based technologies include multi-stage flash distillation (MSF) and multi-effect distillation (MED), brine concentration (BC), crystallizer (BCr), spray drying (SD), eutectic freeze crystallization (EFC), and wind-aided intensified evaporation (WAIV) [66,67].

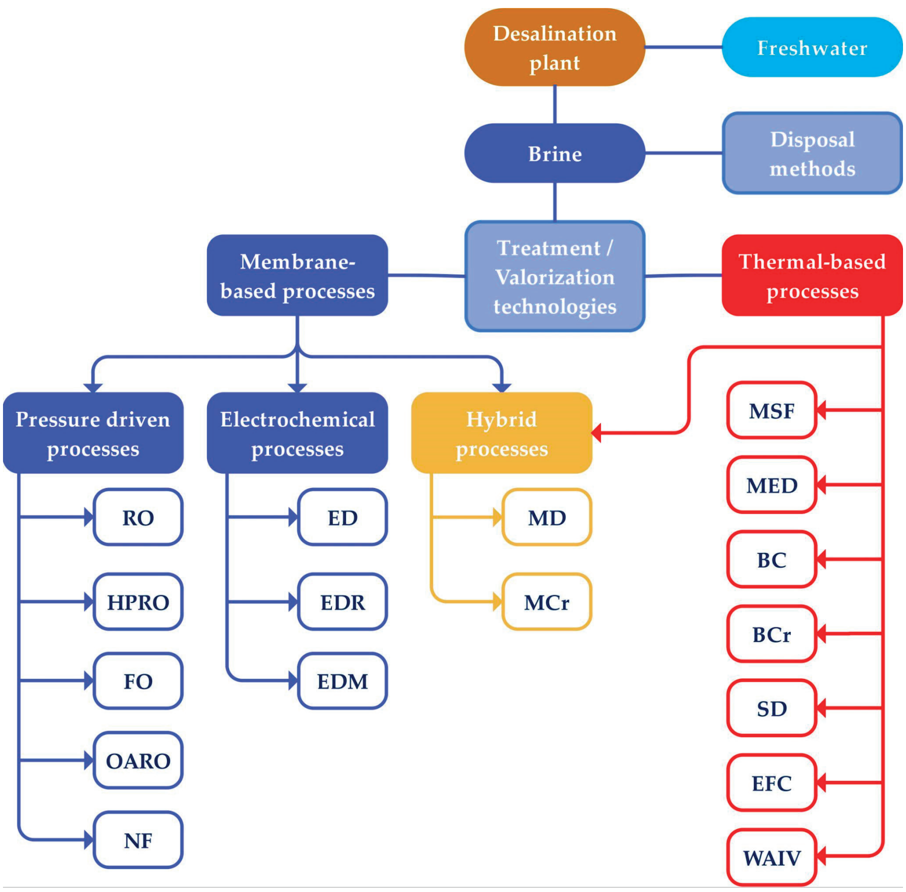

Figure 6. Main technologies used for the treatment and valorization of desalination brine.

Recently, numerous studies have addressed the challenge of managing brines from SWRO with innovative methods aimed at reducing environmental impacts and enhancing resource recovery. C. Morgante et al. [68] proposed a novel MLD system that includes a nanofiltration (NF), crystallizer, and MED hybrid process. Their findings demonstrate that this MLD system not only helps alleviate environmental concerns but also produces high-purity minerals and salts at lower costs compared to current market prices. Similarly, J. Zuo [69] focused on treating real SWRO brines using a hybrid BC and MD process. They achieved a water recovery rate exceeding 95% and generated salt slurries with around 10–20% moisture from the crystallizer. This approach highlights the potential of the proposed system to achieve ZLD, providing an eco-friendly solution to brine management by maximizing water recovery and generating economically valuable salt by-products.

2.3.4. Boron Removal

Boron removal remains a major challenge in SWRO desalination. The World Health Organization (WHO) recommends a maximum boron concentration of 2.4 mg/L in drinking water [70]. However, seawater naturally contains a much higher concentration of boron (between 4.5–9 mg/L) mainly in the form of uncharged boric acid ($B(OH)_3$). The small size of boric acid molecules allows them to pass through RO membranes due to size exclusion limitations. Furthermore, the absence of electrostatic interactions between the non-dissociated boric acid and the membrane surface facilitates their passage. As a result, boron rejection rates generally range from 40% to 60% within a pH range of 5 to 9 in a single-pass RO system [71]. However, at higher pH levels (pH > 9), borate anions ($B(OH)_4{}^-$) are formed, which have a negative charge that improves their rejection by RO membranes through size exclusion and Donnan repulsion mechanisms. This leads to rejection rates of up to 99%.

Recent advancements have led to new methods to enhance boron removal from seawater under neutral pH conditions. One of the most effective methods is the double-pass RO system, where a portion of the initial permeate water undergoes a second pass through RO without requiring any pH adjustment [72]. However, this method may increase energy consumption and require additional infrastructure. Other less conventional approaches involve adjusting the pH above 9 to convert boric acid into more readily rejected borate ions. One promising strategy for enhancing boron removal involves surface modification techniques. These modifications can target either steric hindrance or adjust the surface chemistry to optimize the affinity between membrane materials and boric acid [73]. Various technologies and integrated processes are being explored to improve the efficiency of boron removal in RO systems, including electrochemical methods [74], using cellulose fiber-carbon nanotube nanocomposite polyamide membranes [75], combining RO processes with other techniques such as adsorption, coagulation, and complexing membrane filtration [72,74], using ion exchange methods with boron-selective resins (BSRs) [76], and hybrid processes based on adsorption membrane filtration and the chemical oxidation precipitation (COP) method [72,76,77]. Emerging membrane-based technologies such as membrane distillation (MD) [70], forward osmosis (FO) [78], and capacitive deionization (CDI) [79] are also being explored either integrated with RO or as standalone solutions. Optimizing these strategies is essential to produce high-quality drinking water with limited boron concentration that meets WHO guidelines.

3. Reverse Osmosis Technology Dominance in the MENA Region

Reverse osmosis technology has emerged as the primary method for desalination in the MENA region, commanding over 90% of total desalinated water production, as reported by Desal Data [80]. This shift marks a significant departure from traditional thermal methods such as MSF and MED, which now contribute less than 10% to the region's desalination output. Notably, countries like Syria, Morocco, Djibouti, and Palestine have embraced RO exclusively for their desalination needs [81].

MENA's pivotal role in global desalination is underscored by contributions from nations like Saudi Arabia and the UAE, which boast some of the largest desalination plants worldwide. Recent trends point to a definitive transition toward RO-based plants, exemplified by the decommissioning of thermal capacity in key locations such as Jeddah, Oman, and Abu Dhabi. Plans by the UAE's Department of Energy to replace thermal capacity with large-scale seawater reverse osmosis (SWRO) plants further emphasize this shift [82].

Despite RO's dominance, significant disparities exist in desalination capacities among MENA countries, primarily influenced by capital costs and ongoing operational expenses. Saudi Arabia and the UAE lead in capacity, with noteworthy projects like Algeria's Magtaa plant demonstrating relatively low costs per cubic meter of water produced. Table 2 illustrates the prevalence of RO technology across the region, reflecting its efficiency and cost-effectiveness.

Table 2. Major planned RO plants in the MENA: focus on KSA and the UAE [81].

Location	Capacity (m^3/d)	Feedwater	Operation Year	Cost (USD)
Umm al Quwain IWP, UAE	681,900	Seawater	2020	250 M
Rabigh 3 IWP, KSA	600,000	Seawater	2021	-
Khobar 2 replacement SWRO, KSA	600,000	Seawater	2021	650 M
Taweelah IWP, UAE	909,200	Seawater	2022	840.5 M
Rabigh, KSA	600,000	Seawater	2022	-
Jubail 3b IWP, KSA	600,000	Seawater	2022	3 bn
Jubail 3a IWP, KSA	600,000	Seawater	2022	3 bn
Shoaiba 6 IWP, KSA	600,000	Seawater	2029	-
Hassyan SWRO, UAE	545,520	Seawater	Planned	-
Haradh BWRO, KSA	800,000	Brackish water or inland water	Planned	-

However, widespread adoption of desalination, particularly RO, presents energy challenges in MENA. The International Energy Agency (IEA) estimates desalination's substantial energy consumption, ranging from 2.4% in Algeria to a staggering 30% in Bahrain. This reliance on energy, predominantly from fossil fuels, raises sustainability concerns, notably in countries like Saudi Arabia, where desalination and electricity generation heavily rely on crude oil.

In GCC countries, RO is gradually supplanting thermal methods, with Saudi Arabia, Oman, and Bahrain leading this transition. Conversely, North African countries predominantly utilize RO for desalination, except for Libya, where MED technology remains prevalent. Algeria boasts the region's largest desalination capacity.

Desalination in MENA primarily caters to domestic (municipal) needs, especially in GCC countries, where reliance on desalinated water is paramount due to limited alternative sources. Cities such as Muscat, Doha, and Dubai rely entirely on desalination for municipal supply. Moreover, desalinated water finds application across various sectors, including industry, tourism, power generation, military, and agriculture, albeit to a lesser extent compared to municipal use [81].

4. Contribution of MENA Countries to Solar-Driven RO Desalination Research

To gain a deeper understanding of the research landscape in the MENA region concerning solar-powered desalination, a bibliometric analysis was conducted. This method provides valuable insights into publication trends, prominent countries, institutions, researchers, and collaborations in this important field. To conduct this study, data were collected from the Web of Science (WoS) core collection, a comprehensive database for scholarly publications. An advanced search function was employed to identify relevant articles using the search query: Topic: (desalination AND (solar OR photovoltaic OR "renewable energ*")). This ensured that the retrieved articles included these terms within their title, abstract, and keywords. Only articles and reviews published in English were considered for analysis to maintain consistency and accessibility within the global research community. The analysis covered the period from 2004 to 2024 (data collection completed on 11 June 2024). To ensure a regional focus, the search query limited the retrieved publications to those affiliated with research institutions located within the MENA region. The recorded data were analyzed using VOSviewer software (version 1.6.20), which is specifically designed for bibliometric mapping and visualization.

The analysis revealed a significant contribution from the MENA region to the field of solar-powered desalination. Notably, 391 out of 1262 articles identified globally originated from institutions within the MENA region. This translates to a percentage contribution of 30.1%. Furthermore, co-authorship analysis identified strong collaborative relationships among MENA region countries. Figure 7 visually depicts these collaborations, with larger nodes representing more productive countries (in terms of publication output) and the thickness and length of connecting lines indicating the strength of cooperation. The analysis identified Egypt as the leading contributor within the MENA region, with 144 published documents and a total link strength of 122. This is followed by Saudi Arabia with 129 documents and a total link strength of 173. Tunisia ranks third with 45 documents and a total link strength of 32. Jordan and the United Arab Emirates also emerged as significant contributors, with 32 and 31 documents and total link strengths of 36 and 38, respectively. These findings highlight the MENA region's expertise and commitment to addressing water scarcity challenges. The strong publication output and collaborative research efforts demonstrate their active involvement and substantial contributions to advancements in solar-driven reverse osmosis desalination technology.

The bibliometric analysis not only revealed the substantial contribution of the MENA region to research on solar-powered desalination but also shed light on collaboration patterns. Figure 8 focuses on the countries of the corresponding authors to visualize these patterns. It differentiates between articles with a single corresponding author affiliated with a MENA country (single country publications—SCP) and those with corresponding authors from multiple countries (multiple country publications—MCP). The analysis identified Saudi Arabia as a leader in international collaboration within the MENA region. Notably, 42 out of 69 articles with a corresponding author affiliated with a Saudi institution involved collaboration with researchers from other countries. This translates to a significant percentage (60.1%) of their research output involving international partnerships. This is followed by Egypt with 29 MCPs out of 93 articles and the United Arab Emirates with 15 MCPs out of 22 articles. These findings highlight that MENA countries can position themselves at the forefront of solar-powered desalination advancements, contributing to a more secure and sustainable water future for the region.

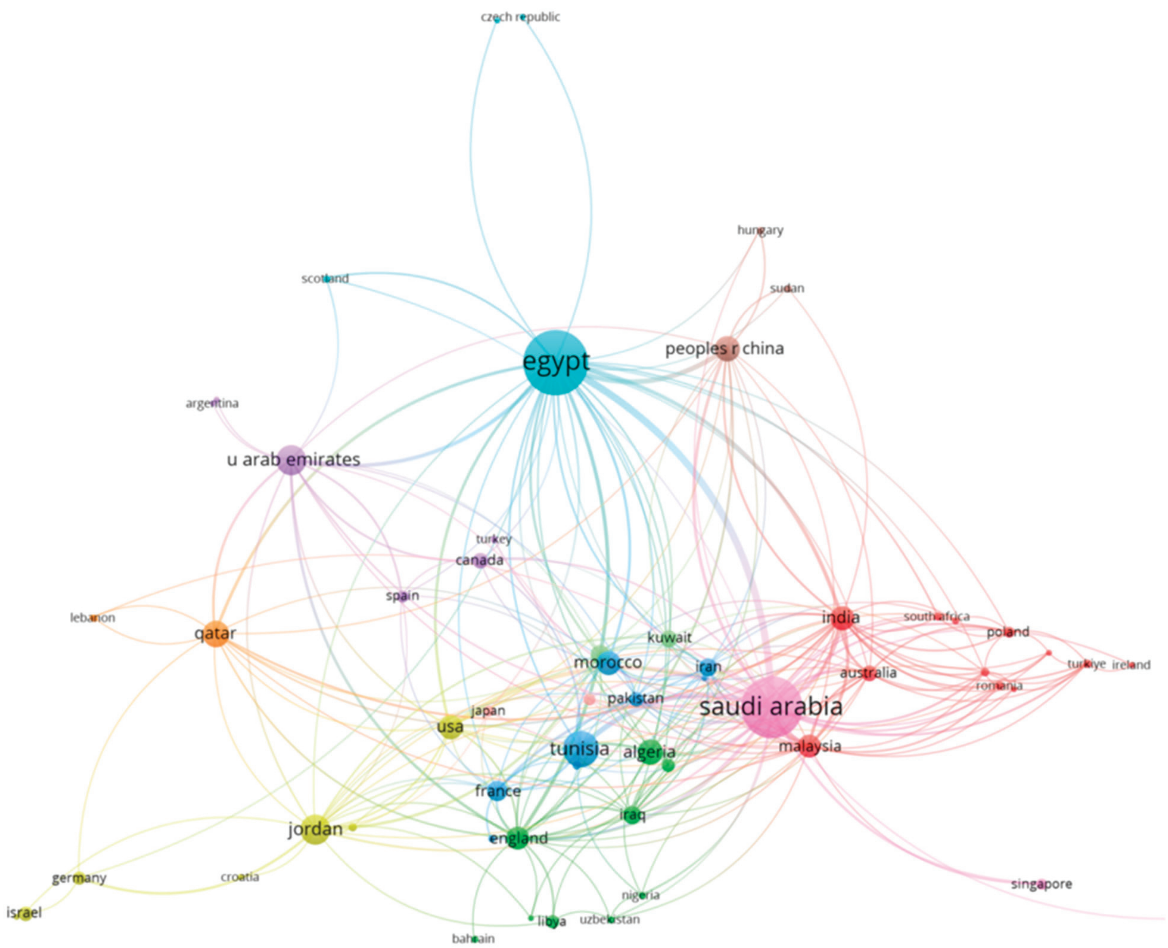

Figure 7. The collaboration map of country co-authorship regarding solar-driven RO desalination.

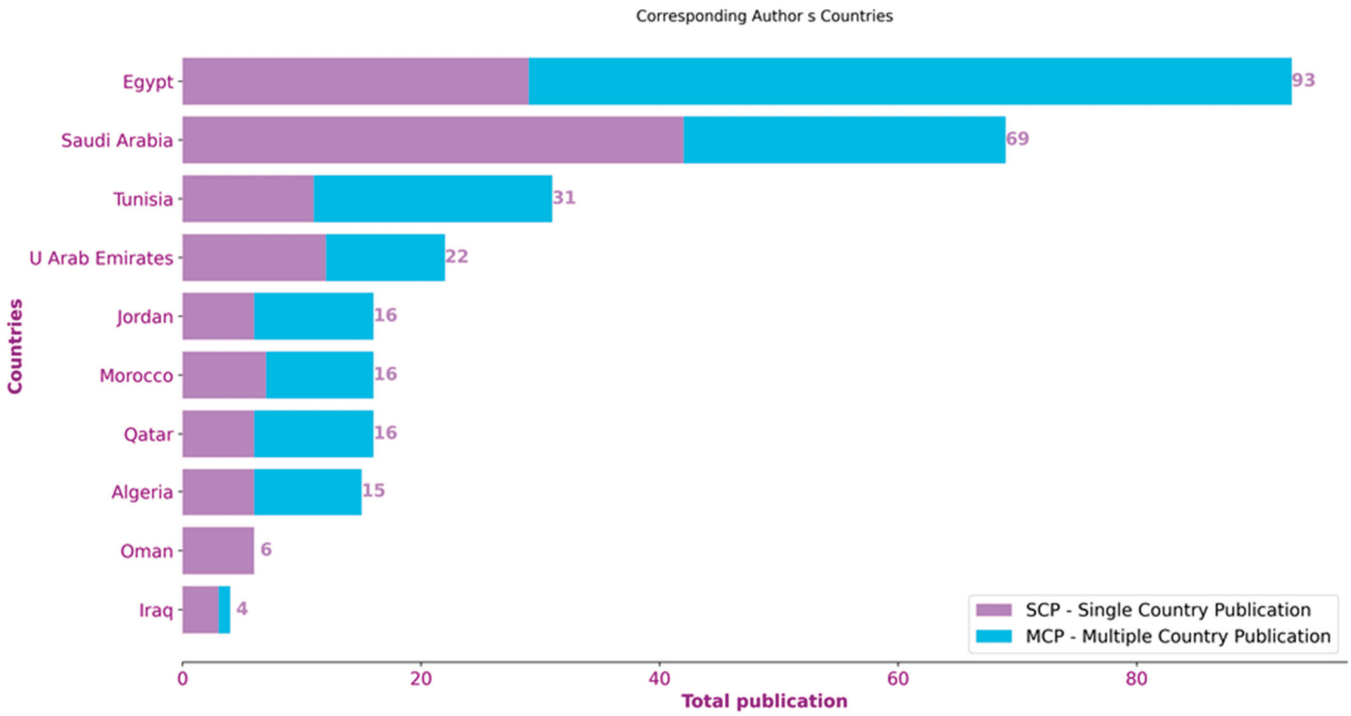

Figure 8. Collaborative patterns of MENA countries.

Overlay analysis is an effective bibliometric technique for tracking the evolution of research topics and identifying emerging trends over time. By examining the occurrences and average publication years (APY) of keywords, we can gain insights into the current focus and predict future directions in the field of solar-powered desalination. To capture the most recent advancements, we focused on the period between 2016 and 2023. Figure 9 depicts these temporal trends using an overlay visualization, where keywords are color-coded by publication year: navy blue indicates earlier appearances, while yellow highlights the most recent publications. Based on the overlay analysis, several promising trends in solar-powered desalination in the MENA region can be anticipated:

- Advancements in materials: Keywords such as "nanofluid" (4 occurrences, APY = 2021.25) and "phase change materials" (6 occurrences, APY = 2021.33) indicate ongoing research aimed at enhancing thermal efficiency and energy storage capabilities. This could lead to more viable and cost-effective solar desalination systems.
- Integration of CSP and solar chimney: Keywords like "concentrated solar power" (5 occurrences, APY = 2021.4) and "solar chimney" (4 occurrences, APY = 2021.5) suggest that these technologies will likely see increased integration into desalination systems. These technologies efficiently convert solar energy into thermal energy, thereby improving overall system efficiency.
- Increased use of artificial intelligence (AI): Keywords such as "artificial intelligence" (5 occurrences, APY = 2023) and "decision making" (4 occurrences, APY = 2021) indicate a growing focus on developing intelligent systems for predictive maintenance, process optimization, and real-time decision-making in solar-powered desalination plants. For example, AI could optimize energy consumption based on variable solar irradiance.

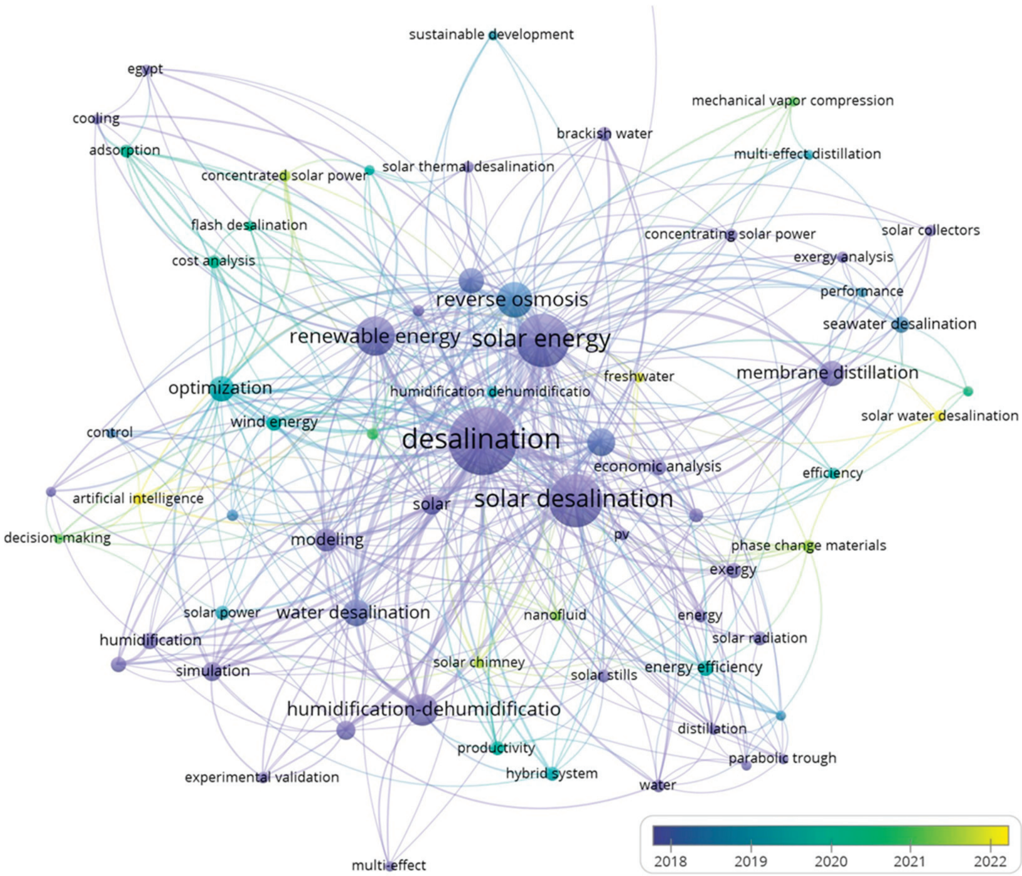

Figure 9. Overlay visualization of keyword trends.

5. Potential for Renewable Energies and Resources in the MENA Region

Renewable energies have gained significant attention globally as alternatives to conventional fossil energy sources due to their efficiency, environmental friendliness, emission-free nature, local availability, and recent cost-effectiveness. This shift is reflected in the steady rise of the global energy supply sourced from REs, nearly doubling from 1.125 to 1.976 gigatons of oil equivalent (Gtoe) over the past thirty years. The MENA region, rich in fossil energy resources, has traditionally relied on conventional fuels. However, with growing environmental and economic concerns, several countries in the region are now embracing ambitious plans to expand their renewable energy capacity [83].

Solar energy harnessed through PV and solar thermal energy technologies, stands out as a prominent renewable resource in the MENA region. The region benefits from abundant sunlight, making it an ideal candidate for large-scale solar power projects. The study conducted by the International Renewable Energy Agency (IRENA) illustrates the evolution of REs electricity capacity worldwide and in the MENA area from 2000 to 2021. During this period, the capacity increased almost four times, with solar and wind REs dominating the growth, accounting for 60% of global RE capacity in 2021 [84].

The MENA region receives 22–26% of the planet's solar rays, and the achieved solar energy is equivalent to 1–2 million barrels of oil, a source that can supply half of the world's electrical consumption [85]. Despite this potential, the utilization of solar energy in the MENA region has been relatively low, with around 1% of the global renewable electricity capacity being dominated by solar energy [85]. This can be attributed to the region's historically low-cost access to fossil energy resources. However, recognizing the environmental and economic benefits, many countries in the MENA area have set ambitious goals to increase their REs capacity [86].

For instance, Saudi Arabia, as part of its 2030 vision, aims to meet 50% of the kingdom's local energy demand through REs, displacing approximately 1 million barrels of liquid fuel per day and reducing carbon emissions by 175 million tons/year. The UAE's "Energy Strategy 2050" aims to raise the share of renewable energies to 50% of the energy mix, up from 7% in 2020, while enhancing energy efficiency by 40% and reducing the carbon footprint by 70% [87,88]. Egypt has outlined plans for renewable energies to meet 20% and 42% of its electricity demand by 2022 and 2035, respectively, compared to 10% in 2020 [87,88].

In the MENA region, several renewable energy resources like solar, wind, hydro and tidal power, geothermal, and biomass present viable substitutes to conventional fossil fuels. However, these resources are not yet fully established as primary energy sources, with fossil fuels still dominating the power supply [83,89]. However, the region's strategies to diversifying its energy mix and reducing carbon emissions indicates a promising shift toward harnessing the untapped potential of solar and other renewable resources. As these nations continue to implement their renewable energy plans, the MENA region is poised to play a crucial role in the global transition toward sustainable and eco-friendly energy solutions.

5.1. Solar Photovoltaics

The integration of renewable energy with desalination presents a significant challenge due to the disparity between the steady-state operation of desalination technologies and the intermittent nature of renewable energy sources. While renewable energy generation requires adjustments for continuous supply through energy storage, desalination technologies can adapt to variable operations.

Moreover, the implementation of renewable desalination solutions is further complicated by challenges related to land cost and size. Nevertheless, there is considerable potential for the advancement of solar desalination technologies, particularly in regions like the MENA, where solar energy is abundant and the cost of PV systems is declining.

Previously deemed less cost-competitive compared to conventionally powered methods, PV-powered desalination has experienced a shift in perception due to the decreasing costs of PV technology in recent years, as shown in Figure 10. Solar photovoltaic technologies, commonly known as solar panels, are instrumental in harnessing sunlight to generate electricity.

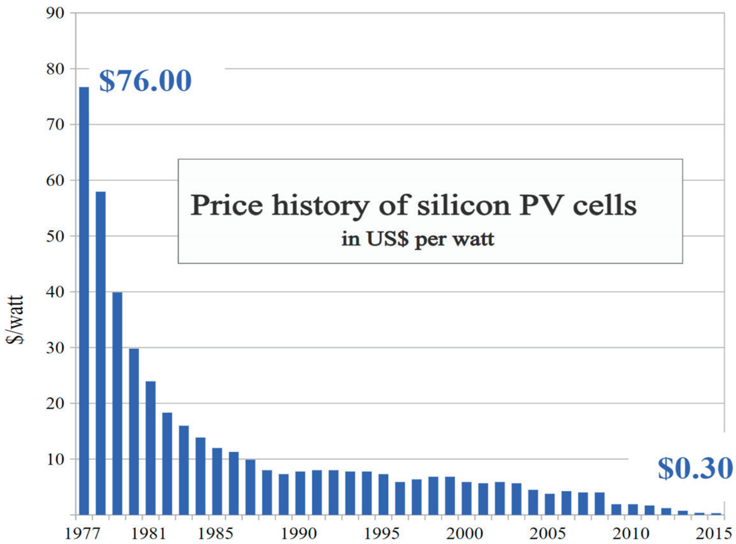

Figure 10. Evolution of crystalline silicon PV module prices: 1977–2015 (USD/Watt) [81].

The U.S. Department of Energy (DOE) is actively involved in efforts to enhance the competitiveness of solar energy by reducing its levelized cost, targeting a goal of $0.02 per kilowatt-hour for utility-scale solar projects [90].

The efficiency of PV cells varies based on the semi-conductor material employed, with silicon being the most commonly used material. However, alternative technologies, such as thin-film solar cells, also contribute to the diversity of solar PV systems. PV cells exhibit efficiencies ranging from 15% for commercial panels to as high as 25% for state-of-the-art modules [91].

PV systems can be configured by connecting multiple solar cells to form modules or panels. These modules, in turn, can be grouped into larger arrays, ranging from small-scale applications like calculators to utility-scale electricity generation. The flexibility of PV systems allows them to function in various environments, including remote areas where conventional electricity distribution infrastructure is unavailable [92,93].

Solar PV technology employs P-N junctions to directly convert solar energy into electrical energy in the form of direct current (DC). Since its inception in 1954, solar PV technology has undergone significant advancements in terms of efficiency and applications. The efficiency of different PV technologies has improved from 2–22% in the 1975–2020 period to recent achievements of up to 48% [89,94,95].

The DC power from PV panels can be utilized in several ways, including storage in batteries for future use, direct powering of DC loads, or conversion to AC power using inverters to supply electricity to AC loads. Additionally, solar PV systems can drive RO system for desalination [89].

In the context of the MENA region, which boasts abundant solar irradiance resources, solar PV is considered as a promising technology for sustainable energy generation. The geographic advantage of MENA countries, with their high solar irradiance, positions solar PV as a valuable primary energy source. This solar potential can be harnessed for power generation, addressing the energy needs of the region. Countries like Algeria, Egypt, Libya, Saudi Arabia, and Yemen exhibit significant photovoltaic potential, as indicated by specific yields in the range of 4.6 to 5.4 kWh/kWp/day and 1680 to 1972 kWh/kWp/year. This underscores the potential of solar PV as a key player in the sustainable energy landscape of the MENA region [96].

Studies have extensively explored the optimization of PV-RO systems, demonstrating that adjustments in flow rate and pressure can enhance recovery ratios. The integration of buffer tanks has been shown to substantially boost productivity. Furthermore, the economic viability of PV-powered RO systems for various applications, including agriculture and small-scale usage, has been analyzed in regions such as Jordan and Iran. Larger systems employing low-energy membranes and grid-powered setups were found to be more economically viable, with on-grid PV systems proving more cost-effective than off-grid alternatives [30,97–100].

PV-RO desalination plants have exhibited cost-effectiveness and environmental sustainability compared to conventional grid-powered systems in various contexts. From small-scale units in Beirut to large-scale plants in Morocco and the Jordan Valley, PV-powered RO systems have demonstrated promise as viable alternatives. Additionally, standalone hybrid systems combining renewable systems and RO technologies have been identified as cost-effective solutions, particularly in regions like Iran [101–105]. The integration of photovoltaic and reverse osmosis systems for water desalination is becoming an increasingly sustainable approach to mitigate water scarcity issues.

Despite the efficiency challenges encountered by PV systems, innovations such as water evaporation cooling aim to enhance performance. Comparisons with other solar technologies like CSP underscore the cost-effectiveness of PV for desalination. System configurations and energy recovery mechanisms, in addition to economic analyses, contribute to improving overall efficiency and viability.

The PV-RO technology integration presents a promising approach for sustainable water desalination. However, ongoing efforts are important to optimize the system, evaluate its economic feasibility, and modify its design to fully solve its potential across various settings.

5.2. Solar Thermal Energy

Solar thermal energy harnesses the power of solar irradiance to generate usable energy, primarily in the form of heat. This renewable energy technology capitalizes on the sun's radiant energy by absorbing it through various solar collector designs, including concentrating, flat-plate, and evacuated collectors. These collectors facilitate the absorption of solar irradiance, converting it into thermal energy, typically using water as a heat transfer fluid. Vapor is produced by heating water to drive the steam turbine, leading an electrical generator as an application [106,107]. Concentrated solar power emerges as an appealing choice for sustainable and renewable energy, gaining traction for desalination applications. A key distinction between the two prevalent systems, the steam cycle and organic Rankine cycle (ORC), lies in their respective working fluids: water for the steam cycle and organic fluids for ORC. The primary aim of the ORC is to power the RO unit and to pre-heat the input water for the RO system utilizing the condensation heat of the working fluid in the condenser [108].

One notable application of solar thermal energy involves its integration into desalination processes. Two distinct methods can be employed for this purpose. The first method involves utilizing the work produced by the turbine to generate electricity. This electricity, in turn, powers an electrically driven desalination process, exemplified by the solar thermal–RO desalination plant. The second method entails using thermal energy directly as a heat source for thermal-driven desalination processes, such as MED and MSF [24,109].

Moving on to the evaluation of solar thermal systems, there are two main types. The first type absorbs all incident radiations, irrespective of their direction (horizontal or vertical), exemplified by flat-plate solar collectors. The global horizontal irradiance (GHI) is a crucial parameter to assess a location's suitability for such systems. GHI, a measure of solar potential, is used to compare different locations. Observations across the MENA region reveal that GHI increases for regions closer to the equator, particularly in the southern parts of the MENA region [96,110].

The second type of solar thermal technology focuses on absorbing only the direct normal irradiance (DNI)—the solar irradiance coming directly from the sun. Concentrated solar power (CSP) technology is an example designed specifically for this purpose. The MENA region exhibits varying DNI values, with countries like Algeria, Egypt, Jordan, Libya, Morocco, Saudi Arabia, Syria, and Yemen displaying the highest DNI values [24,96].

Numerous studies have explored the optimization of CSP systems integrated with RO desalination, focusing on environmental impacts and cost-effectiveness. These investigations have revealed promising outcomes, such as a 27.6% reduction in CO_2 emissions and the identification of the most cost-effective design when combining RO with solar energy. Additionally, ORC-SWRO designs have been highlighted as superior for medium-range capacities, while dish concentrators paired with microgas turbines show viability in rural areas with low freshwater demand. For intermediate water production, systems like RO with parabolic trough collectors (PTC) or linear Fresnel collectors (LFC) combined with ORC have been identified as preferred options [2,111]. In their study published in 2010, Delgado-Torres and García-Rodríguez examined the operational characteristics of solar ORC-powered seawater (SWRO) and brackish water (BWRO) systems. They observed variations in production per square meter of aperture area, depending on collector type and working fluid. Linear concentrators like PTC or LFC were recommended for maximum overall efficiency due to their high temperatures [112].

There is an increasing interest in the utilization of renewable energy sources for desalination. A variety of technologies, including those utilizing renewable energy and internal combustion engines, are currently under investigation. These studies have explored a variety of factors, including the choice of working fluids, the availability of heat sources, the necessity for pre-heating and cooling, and the tracking of the process, with the objective of enhancing the cost-effectiveness and overall performance of desalination systems.

Overall, coupling renewable energy sources with desalination processes has shown the potential to significantly reduce environmental impact and freshwater production costs. However, further research is necessary to optimize these systems, improve their efficiency, and minimize exergy destruction to enhance their competitiveness against traditional desalination technologies [2,113,114].

6. Advancements in Solar Energy-Driven RO Technology Deployment in the MENA Region

The MENA region has long been recognized for its abundant solar resources and increasing water scarcity, making it a prime candidate for the deployment of solar energy-driven RO technology. In recent years, significant advancements have been made in harnessing solar power to drive RO systems, revolutionizing the desalination and water purification industries in the region. These advancements not only offer a sustainable solution to the pressing water challenges but also contribute to the region's commitment to renewable energy adoption and reducing dependence on fossil fuels. Nearly one-third of the total installed capacity of renewable energy-driven desalination systems worldwide is attributed to solar PV-RO, with abundant solar resources present in all MENA countries, particularly Egypt, Jordan, Libya, Saudi Arabia, and Yemen. Additionally, solar thermal technology also holds promise, with its abundance in MENA countries [110,115]. The low energy consumption of the RO desalination, coupled with both solar electrical and solar thermal resources, enables their efficient utilization in driving the desalination process, further enhancing the region's sustainable development goals.

6.1. Solar Photovoltaic-Powered RO Systems

Advancements in PV-RO systems in the MENA region have demonstrated their potential to provide sustainable and cost-effective water solutions. The unstable nature of solar radiation presents challenges for PV-RO plants, which can be addressed by coupling PV systems with energy storage systems or by directly connecting to the power grid. Grid-tied PV-RO systems require fewer PV panels and eliminate the need for batteries, reducing capital and operating costs [116].

Morocco has been a leader in adopting PV-RE desalination plants, with the Khenifra plant producing 36,290 m^3/day of freshwater. RO systems using solar energy have been reported as the best alternative, as they are low-cost and sustainable for treating brackish water [116]. RO systems powered by PV are more cost-effective than wind-powered vapor compression systems, with water costs of 1 USD/m^3 in Morocco. In Morocco, where water scarcity is a pressing issue, the adoption of membrane-based desalination systems, particularly RO, has gained momentum. Studies by [117–119] have highlighted the effectiveness of solar-powered RO plants in treating brackish water, offering a low-cost and sustainable solution to meet freshwater demands. Furthermore, the integration of PV renewable energy sources in desalination plants, as observed in the works of [118], has contributed to reducing energy costs and carbon emissions in the region.

The pioneering work of [120] in Saudi Arabia set the stage for PV-RO integration, with the commissioning of the first commercial PV-RO pilot plant in Jeddah in 1981. This pilot plant, powered by an 8 kWp PV system, demonstrated the feasibility of coupling PV technology with RO for freshwater production. Subsequent studies, such as those by [121] in the UAE and Abdallah et al. [122] in Jordan, have further validated the viability of PV-RO systems across the MENA region. However, more studies, economic analyses, and a review of the country's policy regarding renewables are required to fully assess the economic and technical feasibility of the PV-RO systems. Al Suleimani and Nair studied a PV-BWRO system in Oman with a 3.25 kWp PV module and a 200 Ah battery. With a 20-year lifespan and 5 m^3/day output, it costs 25% less than diesel-powered RO systems. Their findings highlight the economic benefits of PV-RO systems in remote areas [123]. A number of alternative storage solutions for PV-RO systems, including fuel cells (FCs), are available. Research conducted on a PV-RO/FC system with a 150 m^3/day capacity indicated that the system is economically viable with a reasonable cost of electricity (COE) [124]. The implementation of PV-RO systems in the MENA region has demonstrated their capacity to provide sustainable and cost-effective solutions to water management challenges. These systems exhibit clear economic and technical viability through the integration of high-efficiency PV power generation with the low-energy demands of the RO desalination process.

6.2. Solar Thermal-Powered RO Systems

The MENA region stands out for its abundant direct solar radiation, making it a prime location for CSP technology. Trieb et al. [125] noted that the Middle East alone receives solar energy equivalent to 1.5 billion barrels of crude oil annually. They emphasized the potential of CSP-powered desalination as a promising alternative to traditional methods, providing a sustainable and dependable freshwater supply. Furthermore, CSP desalination plants can both generate electricity and produce freshwater at competitive prices [126,127]. Shatat et al. [128] explored the global opportunities and challenges of solar seawater desalination, concluding that harnessing solar energy in the MENA region could significantly alleviate water scarcity.

In the United Arab Emirates, particularly in Abu Dhabi, there is a notable adoption of solar thermal-powered RO systems. Palenzuela et al. [129] conducted thorough simulations and assessments of various CSP configurations for desalination plants in Abu Dhabi. Among these configurations, coupling a parabolic trough collector (PTC) field with RO systems employing MED and low-temperature MED (LT-MED) emerged prominently. Their findings highlighted the thermodynamic superiority of the LT-MED configuration over CSP-RO setups, requiring smaller solar field footprints while maintaining comparable power and water yields [129].

In Saudi Arabia, cities like Yanbu, Al Jubail, and Jeddah host large-scale RO desalination plants boasting substantial production capacities ranging from 56,800 to 128,000 cubic meters per day. Although many of these plants currently rely on conventional energy sources, there is a growing inclination toward integrating solar thermal technology to curtail operational expenses and environmental impact [130].

Moreover, research endeavors have concentrated on augmenting the efficiency and cost-effectiveness of solar thermal-powered RO systems through innovative methodologies such as hybrid ORC-RO systems. Manolakos et al.'s (2009) pioneering experimental work on a low-temperature solar ORC system coupled with RO desalination demonstrated continuous operation despite fluctuating solar inputs [131]. Despite initial efficiency hurdles, such hybrid systems present promising prospects for leveraging low-grade thermal energy to economically and sustainably produce freshwater [132].

Advancements in membrane technology and system optimization have further propelled the performance of solar thermal-powered RO units. Studies by Nafey and Sharaf [133] as well as Li et al. [134] delved into energy and exergy analyses of large-scale solar desalination systems under varying operating conditions, aiming to enhance overall system efficiency. Furthermore, efforts to optimize system design and operation for part-load performance have been pursued to accurately predict water production under diverse conditions.

The application of solar thermal energy for desalination in MENA and GCC countries often involves integrating an ORC with seawater reverse osmosis (ORC-RO) systems. This configuration capitalizes on seawater's role as a heat sink for the ORC condenser, simultaneously pre-heating the seawater to enhance RO membrane permeability and reduce power consumption. The research underscores the socio-economic and environmental advantages of solar PV and solar ORC-operated RO units over diesel generator-operated units [111,133].

While solar thermal-powered RO systems offer promising solutions to address water scarcity, challenges such as intermittency and system efficiency persist. Further research and development endeavors are imperative to optimize these systems, enhancing their scalability and cost-effectiveness.

7. Solar Desalination Challenges and Opportunities in MENA

The MENA region faces a critical water scarcity predicament, necessitating innovative solutions for sustainable freshwater provision. Solar-powered RO desalination plants emerge as a promising avenue to address this pressing challenge. However, while these plants offer considerable potential, they also encounter formidable hurdles that demand strategic navigation and proactive measures. This comprehensive review delves into the multi-faceted landscape of solar-powered RO desalination in MENA, analyzing both the challenges encountered and the opportunities ripe for exploration.

7.1. Challenges in Solar-Powered RO Desalination in MENA

7.1.1. High Initial Investment Cost

Solar-powered RO desalination plants are a sustainable solution to the freshwater scarcity problem in the MENA region. However, the high initial investment costs of these plants pose a significant challenge.

While the investment can be significantly higher in contrast to desalination with conventional energy supplies, site specific factors, like distance to the grid, can make solar-powered systems more economically feasible. At the same time, the permanent cost of conventional energy supply is high and strongly market dependent. To lower these operational expenditures, Morocco and other MENA countries adopt solar-powered desalination systems.

Desalination with RO and PV is considered the best non-conventional solution in Morocco. It is widely deployed as a relatively inexpensive and sustainable solution for brackish water desalination [135]. The cost of water at 1 USD per cubic meter is still double the average for an RO-produced cubic meter in the MENA region, but again site and application specific factors are important. It still is competitive with the average price per cubic meter produced by MED or MSF [135,136].

The most extensive plants in the MENA region are situated in Saudi Arabia, with the United Arab Emirates following closely. The primary facility, Al Shuaiba, boasts a notably low water cost of $0.56/m^3$, surpassing even the largest Moroccan plant, the Chtouka desalination plant, which incurs a cost of 1 USD/m^3. However, Al Shuaiba's cost aligns closely with that of the Magtaa plant in Algeria [135,136].

Most important for the economics of a solar-powered desalination system is the scale of the plant. Research indicates that solar MED systems become competitive for capacities above 1.000 m^3/day [30]. For smaller systems, PV-RO has the advantage of better scalability and therefore higher cost saving potentials. This is accompanied by the constant decrease in investment cost for PV modules through the wide adoption of PV systems in recent decades. The flexibility of the PV-RO approach and the decreasing cost for PV modules and RO membranes, initial investments become less prohibitive than a decade ago. Additionally, the site-specific integration of different energy sources for desalination can further increase the overall energy efficiency and lower the cost of investments and operations [4,30]. Leveraging these developments and approaches, desalination with renewable energy, the MENA region, with its high average solar potential, has unique opportunities to widely adopt technologies for sustainable water supply.

7.1.2. Technical Complexities

Integrating solar power with desalination technologies presents several technical complexities that necessitate expertise in both domains. These challenges include the following considerations:

- Optimizing energy capture and utilization: Developing systems capable of efficiently converting solar energy into electricity for desalination purposes is essential.
- Energy storage solutions: Implementing robust and efficient energy storage methods is critical for addressing fluctuations in solar radiation and meeting peak demand during periods of low sunlight.
- Reliability and durability: Equipment must be designed to function reliably and maintain its integrity under harsh environmental conditions, including extreme temperatures, humidity, dust, and salt corrosion.
- Variability in solar irradiance and weather patterns: System design and operation must account for variations in solar radiation levels and weather patterns, which influence the availability and intensity of solar energy.

In Morocco, the complexity of constructing high-voltage transmission lines from the desert for CSP contributes to increased costs compared to PV energy, rendering PV more financially practical and affordable [104,137]. In contrast, countries like Jordan face challenges due to heavily subsidized water tariffs of up to 80%, which decrease the economic feasibility of solar-powered RO plants [125,138]. If subsidies were removed, solar-powered RO installations could become more economically viable and encourage wider adoption.

7.1.3. Limited Funding for Research and Development

Limited funding for research and development poses challenges for solar-powered reverse osmosis desalination plants in the MENA region. This limitation hinders the advancement of technology and innovation in this field, impacting the efficiency and sustainability of such plants. One example illustrating this challenge is the Al Khafji solar seawater reverse osmosis desalination plant in Saudi Arabia [24]. Despite the potential of solar-powered desalination as a sustainable solution, the high costs associated with research and development hinder widespread adoption in the region. Countries like Egypt, Morocco, and Tunisia have initiated projects to harness solar energy for desalination, showcasing efforts to overcome these challenges [139]. These endeavors highlight the importance of addressing limited funding to drive innovation and enhance the viability of solar-powered reverse osmosis desalination plants in the MENA region.

7.1.4. Lack of Expertise

Developing and operating solar-powered RO desalination plants necessitates specialized expertise encompassing solar energy systems, desalination technology, and system integration. However, there may be a scarcity of qualified professionals possessing the requisite skills and knowledge in the MENA region, potentially hindering the widespread adoption of solar-powered desalination. Countries with established proficiency in renewable energy technologies, such as solar power, may enjoy a comparative advantage in executing solar-powered desalination projects.

For instance, in the UAE, substantial investments have been made in renewable energy infrastructure and expertise, potentially resulting in a larger pool of skilled professionals available for such projects compared to other regional countries. Additionally, Egypt, Morocco, and Tunisia have initiated significant projects involving CSP plants. Moreover, in Qatar, the Monson Group has announced a new, low-energy-consumption, automated, renewable energy-powered desalination plant [24,135,139]. These endeavors underscore the region's growing commitment to investing in sustainable desalination solutions, notwithstanding challenges related to expertise and operational stability.

7.2. Opportunities for Navigating the Challenges of RO Desalination Plants in the MENA Region

7.2.1. Technology Optimization and Innovation

Encourage research and development initiatives focused on optimizing solar energy capture and utilization, energy storage solutions, and improving the reliability and durability of equipment. Investing in innovation can lead to advancements that enhance the efficiency and cost-effectiveness of solar-powered desalination plants.

On the other hand, exploring small-scale technologies offers potential solutions to water scarcity challenges in remote areas or for individual households. These include small-scale desalination systems such as small-scale RO, as well as emerging technologies like adsorption desalination (AD) and humidification–dehumidification (HDH) desalination systems. Unlike traditional thermal and membrane-based technologies, AD can utilize renewable energy sources such as solar, geothermal, or low-grade waste heat [140]. HDH desalination systems can use a variety of energy sources, including geothermal, solar, wind, waste heat, and biomass [141]. Both AD and HDH have demonstrated reliability, energy efficiency, and sustainability in producing freshwater for decentralized and small-scale applications.

Research efforts should focus on improving the energy efficiency, cost-effectiveness, and scalability of these small-scale technologies. Developing advanced materials and innovative designs can further enhance their performance and broaden their applicability. By addressing these aspects, small-scale RO and emerging thermal desalination systems can become viable options to complement large-scale desalination efforts, contributing significantly to alleviating water scarcity in the MENA region and beyond.

7.2.2. Government Support, Financial Incentives, and Investment

Develop comprehensive regulatory frameworks and policies that support the deployment of solar-powered desalination plants. This may include setting targets for renewable energy usage in desalination projects, streamlining permitting processes, and establishing standards for environmental sustainability and performance.

Implement financial incentives and investment schemes to mitigate the high initial investment costs associated with solar-powered RO desalination plants. This could include subsidies, tax breaks, or financing options to encourage private sector involvement and reduce the burden on governments.

7.2.3. Regional Collaboration and Knowledge Sharing

Facilitate regional collaboration and knowledge exchange through initiatives such as the proposed regional observatory for desalination technologies. This platform can promote best practices, facilitate technology transfer, and provide advisory support to governments and stakeholders in the MENA region.

7.2.4. Investment in Education, Training, and Capacity Building

Expand technical and vocational training programs in desalination and renewable energy technologies to address the lack of expertise in the region. This could involve partnerships with educational institutions, industry associations, and international organizations to develop specialized curricula and certification programs tailored to the needs of the desalination sector.

Foster public–private partnerships to leverage expertise from both sectors in addressing technical complexities and expanding the pool of qualified professionals. This could involve joint research projects, training programs, and knowledge transfer initiatives aimed at building local capacity in solar energy and desalination technologies.

7.2.5. Promotion of Local Manufacturing and Innovation

Encourage local manufacturing of critical components for desalination plants through incentives and support for domestic businesses. This can contribute to economic sustainability, create employment opportunities, and foster innovation in the region.

Despite formidable challenges, solar-powered RO desalination systems hold immense promise for addressing water scarcity in the MENA region. By capitalizing on the outlined opportunities and implementing proactive measures, stakeholders can navigate the complexities and unlock the full potential of these sustainable water solutions. Through collaborative efforts, strategic investments, and policy support, MENA countries can chart a path toward water security and sustainable development in the face of mounting challenges.

8. Conclusions

The pursuit of sustainable solutions for water scarcity in the MENA region demands a multi-faceted approach that integrates renewable energy sources with innovative desalination technologies. As highlighted throughout this paper, solar-powered reverse osmosis (RO) desalination plants offer a promising pathway toward addressing the pressing water challenges faced by the region. When local policies implement a stronger focus on sustainable plant operations, for example, with suitable key performance indicators (KPI) in public tenders, a self-accelerating trend toward renewable energy desalination seems to be achievable.

The MENA region's abundant solar resources, coupled with advancements in solar photovoltaic (PV) and solar thermal technologies, emphasize the transformative potential of solar energy-driven RO desalination systems. Despite initial challenges such as high investment costs and technical complexities, concerted efforts toward research, development, and capacity building are underway to overcome these hurdles. Notably, the last 10 years solved many challenges of membrane and PV technology alike. These advances allow for better integrated plant performance, reduced environmental challenges, and longer plant life at considerably lower investment cost.

Strategic investments in renewable energy infrastructure and expertise, coupled with collaborative partnerships between governments, private sectors, and international entities, are crucial for realizing the full benefits of solar energy in addressing water scarcity challenges. Initiatives such as the construction of large-scale PV-RO plants in countries like Saudi Arabia and the UAE signify a paradigm shift toward sustainable desalination practices in the region. The best practice examples of these technology leaders can serve as a baseline for policy makers in other MENA countries.

Furthermore, ongoing research endeavors aim to optimize the efficiency and economic viability of solar-powered RO desalination systems while addressing challenges such as high energy consumption, membrane fouling, environmental challenges, and boron removal. By leveraging renewable energy sources, the MENA region can not only meet its growing water demands but also contribute to global efforts to transition toward environmentally friendly and resilient water management practices. At the same time, timely design of action plans for a systematic, economically feasible transition will help to avoid overspending, when the demand or supply of energy and water is impacted by disruptive events like extended droughts, political tensions, or humanitarian crises.

In essence, by embracing solar-powered RO desalination as a cornerstone of water sustainability strategies, the MENA region can lead the way toward a future characterized by clean, sustainable, and accessible water resources for generations to come. Through continued innovation, collaboration, and strategic planning, the vision of a water-secure MENA region powered by renewable energy can be realized, offering hope and resilience in the face of mounting environmental challenges.

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