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Principles and Optimization of China's Unconventional Water Management: From a Brand-New Perspective of Responsibility Allocation

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Abstract: Unconventional water includes reclaimed water, harvested rainwater, desalinated seawater, and mine water. Unconventional water use is considered more of a "mandatory responsibility" in China. The initial allocation of unconventional water emphasizes quantity-centered responsibility allocation while the minimum utilization reflects this responsibility. The unconventional water use responsibility (UWUR) should be tailored to the characteristics of each area, moving away from a 'more is better' mindset. However, there is a large research gap in this field. This paper first presented six fundamental principles for unconventional water allocation. Ensuring fairness in allocation involves aligning the allocated amount with urban water usage characteristics. Hence, based on four key features, this paper integrated various socioeconomic and environmental factors to build an initial allocation model. To enhance efficiency, an optimal allocation model was constructed using the zero-sum gains–data envelopment analysis (ZSG-DEA) method. The models were then applied to Jiangsu Province, China, to verify their applicability. The results showed that the projected minimum UWUR allocation (unit: 100 million m^3) for each city in 2025 is 1.482 (Nanjing), 1.501 (Wuxi), 0.919 (Xuzhou), 1.029 (Changzhou), 2.977 (Suzhou), 1.497 (Nantong), 0.818 (Lianyungang), 0.766 (Huai'an), 0.875 (Yancheng), 0.920 (Yangzhou), 0.790 (Zhenjiang), 0.858 (Taizhou), and 0.766 (Suqian). The rational and feasible results indicated that the allocation framework proposed in this paper has a certain practicability. Lastly, this paper considered the differences in unconventional water utilization conditions across 13 cities and proposed corresponding measures to improve the utilization. This paper represents a tentative exploration of unconventional water allocation in China and offers theoretical and practical insights for policy-makers to improve territorial spatial planning and sustainable water management.

Keywords: unconventional water; utilization responsibility; allocation principles; water poverty index; ZSG-DEA; water rights

1. Introduction

The global urban population facing water scarcity is expected to increase to 1.7–2.4 billion in 2050 [1]. Nevertheless, most countries, including sub-Saharan Africa, Thailand, Vietnam, and Armenia, neglect the responsibility of protecting the water environment [2]. It is estimated that over 80% of wastewater flows back into aquatic ecosystems without being treated or recycled [2], leading to 842,000 deaths from unsafe water, poor sanitation and hygiene [3]. Water scarcity and pollution are major pressing concerns and crucial issues for countries across the world. Extensive research and practices have indicated that unconventional water use (UWU) offers a multifaceted solution to these issues [4,5]. For example, in Singapore, the wastewater and desalinated seawater could be recycled to meet 85% of its water demand by 2060, with NEWater accounting for 55% [6,7]. As of the estimate in 2016, in Qatar, approximately 55% of the water resources are sourced from desalination, and 20% from treated sewage effluent [8].

However, in most developing countries with poor water infrastructure, unconventional water resources have not been fully utilized, resulting in little or no economic and environmental benefits [9]. Particularly in East and Southeast Asia, water scarcity intensifies further due to increasing water demand, unsustainable water withdrawal, and insufficient use of wastewater [10]. China, home to a large number of transboundary rivers [11], must combat water pollution and address unconventional water resources to ensure its own high-quality development and contribute to water security in Asia. Therefore, this paper takes China's UWU as the research object.

Drawing from the universal definition of unconventional water [12,13], this paper defines unconventional water as water resources that can only be used after treatment or through technical means, including reclaimed water, harvested rainwater, desalinated seawater, and mine water. Regional unconventional water, as a distinct water resource, is owned by the state [14]. In recent years, China has issued a series of policies integrating unconventional water into its uniform water allocation. In 2022, the dual control goal of the total amount and intensity of water use of the "14th Five-Year Plan" in China stipulated the minimum amount of unconventional water to be used for each province in 2025. In 2023, the Chinese government mandated a comprehensive consideration of the demand, supply capacity, and infrastructure for unconventional water, aiming to determine the minimum allocation amount. It is clear that the allocation of unconventional water, an integral part of water rights, is conducted by the government and local authorities. It should be centered around quantity and is influenced by factors such as the political landscape, water endowment, socioeconomic conditions, and the history of water withdrawal [15,16].

However, as residents in China show low acceptance of UWU [17] due to a lack of sufficient market forces or natural resource demand, the promotion of UWU relies on the government [18], and an established market competition system is yet to be built. In the meanwhile, unlike the "good water" property of conventional water, the low quality and acceptance make it a "mandatory responsibility" to use unconventional water in China. Mandatory responsibility means that all provinces must use unconventional water according to local conditions while maintaining that the amount of unconventional water used by 2025 is not lower than the minimum amount set by the state.

In general, the initial allocation of unconventional water is a quantity-centered use responsibility and should match the regional bearing capacity. On such basis, unconventional water use responsibility (UWUR) is defined as "the minimum utilization of unconventional water in the context of current treatment technology," and "UWUR allocation" as "the minimum amount of unconventional water allocated to cities fairly and efficiently according to regional characteristics like water endowment, socioeconomic conditions, and history of water withdrawal in the context of current treatment technology." Accordingly, two questions arise: "how to determine the UWUR" and "how to ensure that the UWUR matches the regional characteristics such as water endowment, socioeconomic conditions, and history of water withdrawal".

Fairness and efficiency are two major principles of water allocation [19,20]; the former focuses on an equal distribution of resources, while the latter focuses on maximizing economic value and consumer satisfaction [21,22]. UWUR allocation is mainly concerned with water amount. Currently, the matching of allocated water amounts with regional characteristics is mostly explored from the perspective of fairness. The spatial matching of water resources with influencing factors is crucial to ensure the fair allocation of conventional water resources. Influencing factors such as population [23], land resources [24], economic output [25], GDP per capita, and chemical oxygen demand (COD) emission [26] are usually used for conventional water allocation, whereas agricultural irrigation, urban landscape irrigation, and industrial water circulation are often chosen for unconventional water allocation [27]. All the selected influencing factors fall into two categories of human activities and socioeconomic development. Measurement methods of spatial balance include the Gini coefficient [23], the Theil index [28], and the coupling coordination degree (CCD) model [26]. The former two measure the matching of water resources and single indicators

such as population [23,28], land resources [24], the irrigation area of farmer households, and peasant household agricultural population [29], while the latter measures the coordination between the water system and socioeconomic development or the ecological system. In fact, these methods focus on the matching of water resources and a single factor.

The water scarcity measurement and spatial distribution pattern of water resources play a role in the spatial matching of water [30,31]. Water scarcity is a multifaceted challenge that involves water systems and socioeconomic factors [32]. At present, studies on water scarcity measurement are carried out from natural and socioeconomic perspectives. Natural perspective includes the water resource endowment, irrelevant to human activities or economic growth [33], and can be measured by water resources available per capita [34]. From the socioeconomic perspective, economic development and human activities exert a negative influence on water scarcity. Dense populations and rapid economic growth raise the demand for municipal and agricultural water use [35]. Additionally, the poor planning and integrated management of water resources lead to a waste of water resources and a massive discharge of wastewater [1], worsening water scarcity. The Social Water Scarcity Index (SWSI) is proposed to evaluate the impact of economic development and human benefits on water shortages. However, the SWSI does not consider water resource development and utilization or human activities [36]. To evaluate the status of water scarcity from a multidimensional perspective, Sullivan [30,31] created the water poverty index (WPI), which comprises five components: resources, access, capacity, use, and environment. WPI, based on poverty theory, integrates water resource development and management, people's access to water and sanitation, and environmental influence, offering a unique perspective on water scarcity. The WPI has been widely applied in the agricultural sector and in urban/rural areas [34]. However, it has not yet been applied as a new perspective to studies on unconventional water allocation.

Few studies have explored the determination of the minimum amount of unconventional water allocation. Among the two major principles of water allocation—fairness and efficiency (Wang et al., 2008 [26], Yong et al., 2017 [27])—the former emphasizes the spatial matching of the water allocation amount with regional characteristics, while the latter focuses on ensuring that unconventional water allocation delivers economic, environmental, and social benefits. Research on water use efficiency [27,37] has been enriched to include the efficiency of a circulation system that contains both water use and wastewater recycling [38]. The water system consists of two phases of water use and wastewater treatment [39,40], and the system's overall efficiency can be measured using a data envelopment analysis (DEA) model [41,42]. In the context of UWU, current studies concentrate on calculating the efficiency scores of wastewater treatment plants [43–45] and rainwater recycling [46] via the DEA model from the perspective of the circular economy. However, scholars have not reached a consensus on the definition of the efficiency of unconventional water allocation.

The zero-sum gains–data envelopment analysis (ZSG-DEA) model was originally created by Gomes and Lins to address CO_2 emission redistribution [47]. It has become a new approach for resource allocation, extensively applied to allocate energy consumption quotas [48] and air pollutants emission rights [49,50]. In recent years, it has found a useful application in water allocation. However, only a few scholars have applied the model to the allocation of water resources. Zhang et al. [51] constructed the ZSG-DEA model to adjust the water quota of 30 provinces, with water resources as input, and energy production, GDP, and food production as outputs. Through three iterations, the efficiency values of all provinces in China reached a valid boundary of 1.000. Zhao et al. [52] employed a multi-output ZSG-DEA model to estimate the comprehensive allocation efficiency of water pollution and the output efficiency of the production, life, and ecology of 31 provinces in China during 2000–2017 with a fixed sum of water pollutant discharge. Each province's discharge quota of water pollutants in 2017 was adjusted according to the principle of maximum efficiency. However, scholars have yet to apply the ZSG-DEA model to unconventional water allocation.

This paper aims to address two major questions: "how to determine the UWUR" and "how to ensure that the UWUR matches the regional characteristics such as water endowment, socioeconomic conditions, and history of water withdrawal". To fill the gap in the existing research, we first propose six principles of UWUR allocation and then carry out the initial and optimal allocation of UWUR. Compared to previous research, this paper makes the following contributions:

- First, this paper fills the gap in the current studies on the allocation of minimum unconventional water utilization. Based on the principles of fairness and efficiency, we propose four specific principles for unconventional water allocation—respecting the status quo of water scarcity, equal rights and responsibilities, equal capacity and responsibility, and adherence to historical data on unconventional water. We construct an initial model of UWUR allocation accordingly and employ the ZSG-DEA model for optimal UWUR allocation.
- Second, multi-dimensional indicators are employed to allocate unconventional water resources. One single indicator is unable to reveal the complicated relationship between water and socioeconomic systems. Relevant studies focus on the socioeconomic indicators [23,24,28,29] that influence unconventional water allocation, neglecting the physical estimates of water availability. This paper combines both water systems and socioeconomic drivers and calculates the WPI, supply capacity, and utilization capacity to reach a spatially balanced allocation.
- Third, this paper promotes the innovative use of the ZSG-DEA model in unconventional water allocation. The ZSG-DEA model has been widely used in the allocation of energy, pollution discharge rights, and food products, but is rarely employed in studies of unconventional water allocation.

2. Materials and Methods

This paper constructed an initial UWUR allocation model based on allocation principles and methods (Figure 1). First, according to the fairness and efficiency principles, this paper proposed four fundamental principles regarding the process of unconventional water production and use. Next, grounded in four key indexes (water shortage, the supply capacity of unconventional water, the utilization capacity of unconventional water, and the acceptance level of unconventional water), we integrated and quantified the socioeconomic and environmental factors affecting UWU. In doing so, the UWUR for each city is tentatively determined using a proportional method. Lastly, the ZSG-DEA method was employed to ensure allocation efficiency.
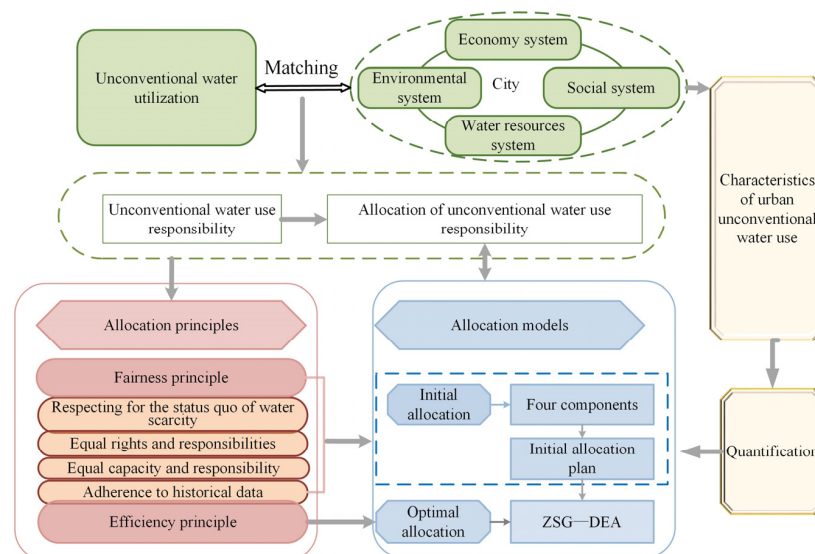

Figure 1. Allocation framework.

2.1. Allocation Principles

The allocation of water resources reveals a conflict between supply and demand dynamics [20], which is intricately influenced by the interactions within the water system, socioeconomic framework, and eco-environment. Also of note is that unconventional water allocation is influenced by the interrelations of socioeconomic and eco-environmental systems. Therefore, the amount of unconventional water allocation should not simply be maximized but should be adapted to the socioeconomic and environmental development characteristics of the city.

As per Water-Saving No. 206 of 2023, UWUR allocation must take the supply and demand into full account. Unconventional water, as a supplementary water source, is developed to alleviate water scarcity. This point extends to unconventional water allocation, where the primary objective should be addressing water scarcity. Moreover, the allocated water amount should be in line with the historical utilization level [53], a criterion to measure the level of consumer acceptance. In addition, due to spatial heterogeneity, factors such as supply capacity and maximum capacity should also be considered to represent the characteristics of urban socioeconomic development. Only by considering urban water scarcity, unconventional water supply capacity, utilization capacity, and the historical utilization level can we ensure the adaptation of unconventional water allocation with regional socioeconomic and environmental characteristics, so as to achieve spatial relative fairness.

At the same time, high-quality development also requires the effective allocation of unconventional water between cities, so as to achieve an increase in the overall production value of the region. Therefore, with reference to the existing framework of water resource allocation principles [54] and combined with the whole process of water resource allocation, this paper determined six principles of responsibility allocation for UWU with fairness and efficiency as the basic principles. Among them, the principles of respecting the status quo of water resources shortage, equal rights and responsibilities, equal capability and responsibility, and adherence to the historical data of UWU are the concrete embodiment of the principle of fairness.

1. The fairness principle. The first principle of UWUR allocation is designed to reach relative equity. A spatial balance should be stricken between water utilization and the socioeconomic and eco-environmental systems [55]. Heterogeneous factor distribution leads to differences in supply capacity, utilization, and the public acceptance of unconventional water. Therefore, the allocated water amount should be consistent with these factors to ensure fair and equal allocation and the coordinated development of unconventional water and socioeconomic and eco-environmental systems.

2. The efficiency principle. Unconventional water allocation is aimed at alleviating water scarcity and pollution [4]. The allocation efficiency of unconventional water involves both economic and ecological benefits. Therefore, to improve the overall regional productivity, unconventional water should be diverted from areas with lower economic and ecological benefits to areas with higher benefits.

3. Respecting the status quo of water scarcity. Equitable and efficient allocation of water resources needs to make clear the spatial distribution and development potential of water in water-scarce areas [30,31].

4. Equal rights and responsibilities. The production of unconventional water is a complex process involving the transfer, integration, and utilization of resource ownership. Notably, the discharge of specific unconventional water sources, like wastewater and mine water, may necessitate pollution discharge rights. Consequently, achieving a balance of water-related rights across regions requires that users with more water rights take on more responsibilities for treating and recycling wastewater.

5. Equal capacity and responsibility. UWUR allocation amount shall not exceed the maximum capacity at which a region can responsibly and sustainably utilize its untraditional water resources. Maximum capacity involves considerations of water availability, infrastructure capacity, environmental sustainability, and the ability to

meet the diverse needs of various sectors such as agriculture, industry, and households, which is a crucial consideration to ensure fair allocation.

6. Adherence to historical data. Adhering to the historical data of UWU is an essential principle of water allocation [53]. Historical data reflect trends related to unconventional water acceptance over a certain period of time. Public acceptance is the key to the promotion of unconventional water [56]. Excessive allocation amounts may exceed the maximum capacity or be unacceptable for users, while inadequate allocation amounts may fail to achieve an equitable allocation.

2.2. Initial Allocation Model

Following the principle of fairness, we selected four indicators—water shortage, the supply capacity of unconventional water, the utilization capacity of unconventional water, and the total amount of UWU during the sample period—to ensure the adaptability of UWUR to urban development characteristics such as water endowment, socioeconomic conditions, and the history of water withdrawal. The four indicators correspond to the four principles, respectively: respecting the status quo of water resource shortages, equal rights and responsibilities, equal capability and responsibility, and adherence to the historical data of UWU. Then, we constructed the initial allocation model accordingly as follows:

$$W_j = \left(w_{ws} \frac{WS_j}{\sum\limits_{j=1}^{n} WS_j} + w_s \frac{S_j}{\sum\limits_{j=1}^{n} S_j} + w_d \frac{D_j}{\sum\limits_{j=1}^{n} D_j} + w_h \frac{H_j}{\sum\limits_{j=1}^{n} H_j} \right) \times W_p \tag{1}$$

where W_j represents the minimum utilization amount of unconventional water allocated to city j; W_p represents the minimum utilization amount of unconventional water at the provincial level, denoted as per relevant national development planning; WS_j, S_j, D_j, and H_j stand for water scarcity, the supply capacity of unconventional water, the maximum capacity of UWU, and the cumulative UWU during the sample period of city j, respectively; w_{ws}, w_s, w_d, and w_h stand for weights, denoted as per the method of Wu and Xiang [53].

2.2.1. Water Poverty Index

Water scarcity, a global concern, arises from a combination of the water system and the socioeconomic system. Apart from insufficient water endowment and water quality, the issue is further compounded by socioeconomic and political factors that influence water allocation and distribution. The water poverty index (WPI) is a multidimensional tool designed to assess and measure the degree of water stress and scarcity in a particular region. It aims to provide a comprehensive evaluation of water-related conditions and challenges, considering both the physical availability of water and the socioeconomic factors like engineering, management, economy, social welfare, and the environment [34]. According to Sullivan [30], the WPI comprises five components: resources (R), access (A), capacity (C), use (U), and environment (E). In this paper, due to data availability, some variables (Table 1) were adjusted in alignment with the current WPI in China [34,57] to make data analysis more accurate. Specifically, resources refers to water resource endowment; the better the endowment, the lower the risk of water scarcity. Access refers to people's access to clean and safe water, represented by the facilities of water supply, drainage, and wastewater treatment. Capacity refers to resource management—the influence of socioeconomic development on the water system, represented by the level of water infrastructure, the education of science and technology, and economic growth. Use refers to water use intensity, represented by the status quo of water use for living and production. Environment refers to the pressure of socioeconomic development on the eco-environment, including pollution of the water, soil, and air.

Table 1. WPI components and variables.

Components	Resources (R)	Access (A)	Capacity (C)	Use (U)	Environment (E)
Sub-components (Variables)	R1: Multi-year average of rainfall in each city (+)	A1: Lost water of urban public water supply (−)	C1: Investment in construction of urban water-saving facilities (+)	U1: Contribution of each city to provincial GDP (−)	E1: Municipal wastewater discharge (−)
	R2: Per capita annual water resources (+)	A2: Density of sewers in built-up area (+)	C2: Average number of students in colleges and universities per 10,000 people (+)	U2: Water consumption for livelihood per capita (−)	E2: Rural chemical fertilizer application (−)
		A3: Sewage treatment rate (+)	C3: Engel coefficients of urban residents (−)	U3: Industrial structure (−)	E3: Concentration of PM2.5 (−)
				U4: Agricultural water consumption (−)	

Note: The indicator of "U3: Industrial structure" was calculated by the proportion (%) of water-consuming and car-intensive enterprises in all local industrial enterprises above the designated size. The higher its value, the more the city depends on water-consuming and pollution-intensive enterprises. "+" and "−" represent the positive and negative indicators, respectively.

The final value of WPI is calculated as follows:

$$WPI_i = \sum_{k=1}^{n} 100 \times w_{ik} v_{ik} \tag{2}$$

$$WPI = w_R \times WPI_R + w_A \times WPI_A + w_C \times WPI_C + w_U \times WPI_U + w_E \times WPI_E \tag{3}$$

where WPI_i is the score of the sub-component i; w_{ik} is the variable k of subcomponent i; v_{ik} is the standardized value of the variable by using min-max normalization; w_R, w_A, w_C, w_U, and w_E represent the weight applied to each of the five components R, A, C, U, and E, respectively. Each of the components is normalized so that the value of WPI falls between 0 and 100 (0 is most water-poor while 100 is least water-poor). The weights in Equations (2) and (3) were determined as per the method proposed by Liu et al. [58] and Song et al. [59] to access the WPI based on principal component analysis (PCA).

The WPI is negatively correlated with water scarcity, so we used the reciprocal of the WPI for measurement:

$$WS = 1/WPI \tag{4}$$

where WS stands for water scarcity; the higher the value, the scarcer the water.

2.2.2. Supply Capacity of Unconventional Water

In this paper, the supply capacity of unconventional water refers to the total amount of reclaimed water, harvested rainwater, desalinated seawater, and mine water, considering the current technological development. The supply capacity of unconventional water is calculated based on the total amount as follows:

$$S_j = \varphi_j \times (\rho_j WD_j) + \varsigma_j W_j^{ra} + \psi_j P_j^{mi} + W_j^{de} \tag{5}$$

where S_j represents the supply capacity of unconventional water; $\rho_j WD_j$ is the amount of wastewater discharge of city j; ρ_j is the coefficient of integrated wastewater discharge; WD_j is the total amount of water consumption of city j in the planning year; W_j^{ra}, P_j^{mi}, and W_j^{de}, respectively, represent the rainfall, coal-mining output, and seawater desalination of city j in the planning year; and φ_j, ς_j, and ψ_j, respectively, stand for the wastewater treatment

rate, maximum rainwater harvesting rate, and water yield per ton of coal of city j in the planning year.

2.2.3. Maximum Utilization Capacity of Unconventional Water

As per the regulations concerning UWU in cities and provinces of China, the main six users of unconventional water include urban road washing, public toilet washing, green space watering, construction, vehicle washing, and once-through cooling systems in thermoelectric power plants. The utilization amounts of six users were totaled as the maximum utilization capacity of each city. Then the quota method was employed to calculate each user's utilization capacity of unconventional water, namely, the maximum demand:

$$D_j = \sum_{q=1}^{6} \phi^q Q_j^q \tag{6}$$

where D_j stands for the maximum utilization capacity (maximum demand) of unconventional water in city j; $q = 1, 2, \ldots, 6$, respectively, stand for the six users—road washing, public toilet washing, green space watering, construction, vehicle washing, and once-through cooling system; ϕ^q is the water use quota of user q, determined by the provincial water quota; and Q_j^q represents the number of user q in the planning year.

2.2.4. Accumulated Utilization of Unconventional Water

The historical level of UWU in this paper refers to the cumulative utilization of unconventional water during the sample period, reflecting both the level of utilization and public acceptance. The equation is as follows:

$$H_j = \sum_{t=1}^{T} H_j^t \tag{7}$$

where H_j represents the accumulated value of UWU of city j during the sample period; $t = 1, 2, 3, \ldots, T$ represent the sample years; and H_j^t is the UWU of city j in year t.

2.3. Optimal Allocation Model

Another integral principle to guarantee an adequate allocation is efficiency. For that, we employed the ZSG-DEA model to adjust the input of each decision-making unit (DMU) with a constant total amount, to increase the DMU efficiency. On such a basis, we constructed an optimal allocation model of UWUR to improve the efficiency of unconventional water allocation of each city grounded in a spatially balanced allocation.

2.3.1. ZSG—DEA BCC Model

In this paper, cities are deemed DMUs, so there are $N(j = 1, 2, 3, \ldots, n)$ DMUs. Suppose there are $m + 1$ input indicators, of which x_j is the amount of unconventional water allocation, and other input indicators are denoted as $X_j = (x_j^1, x_j^2, \ldots, x_j^m)^T$; there are z output indicators; and the output matrix is denoted as $Y_j = (y_j^1, y_j^2, \ldots y_j^z)^T$. Cities vary greatly in input, output, and efficiency, inconsistent with the assumption of constant returns to

scale (CRS). Hence, drawing from the method of Zeng et al. [60], we built an input-oriented Banker–Charnes–Cooper (BCC) model.

$$\min\theta_d$$
$$s.t. \begin{cases} \sum_{j=1}^{n} \lambda_j X_j \leq X_d \\ \sum_{j=1}^{n} \lambda_j x_j \leq \theta_d x_d \\ \sum_{j=1}^{n} \lambda_j Y_j \geq Y_d \\ \sum_{j=1}^{n} \lambda_j = 1 \\ \lambda_j \geq 0, \theta_d > 0 \\ j = 1, 2, 3 \ldots, n; d = 1, 2, 3, \ldots, n \end{cases} \tag{8}$$

The DMU with low input efficiency is denoted as DMU_0 with the efficiency as θ_0. To increase this efficiency, unconventional water utilization must be lowered by

$$\Delta x_0 = x_0(1 - \theta_0) \tag{9}$$

As per the scale-up method, the unconventional water utilization deducted from DMU_0 is allocated to the other $n - 1$ $DMU_j(j \neq 0)$ according to the input ratio of x_j. So, $DMU_j(j \neq 0)$ obtains the following inputs from DMU_0:

$$\frac{x_j}{\sum\limits_{j \neq 0} x_j} x_0(1 - \theta_0) \tag{10}$$

After the adjustment of all DMUs, the input of $DMU_j(j \neq 0)$ turns into

$$x_j^* = \sum_{0 \neq j} \left[\frac{x_j}{\sum\limits_{j \neq 0} x_j} x_0(1 - \theta_0) \right] + x_j \theta_j \tag{11}$$

The constraint in Equation (8) turns into

$$\sum_{j=1}^{n} \lambda_j x_j [1 + \frac{x_0(1 - \theta_0)}{\sum\limits_{j \neq 0} x_j}] \leq \theta_0 x_0 \tag{12}$$

The input-oriented ZSG-DEA BCC model was constructed as follows—the optimal UWUR allocation model:

$$\min\theta_d$$
$$s.t. \begin{cases} \sum_{j=1}^{n} \lambda_j X_j \leq X_d \\ \sum_{j=1}^{n} \lambda_j x_j [1 + \frac{x_d(1 - \theta_d)}{\sum\limits_{j \neq d} x_j}] \leq \theta_d x_d \\ \sum_{j=1}^{n} \lambda_j Y_j \geq Y_d \\ \sum_{j=1}^{n} \lambda_j = 1 \\ \lambda_j \geq 0, \theta_d > 0 \\ j = 1, 2, 3 \ldots, n; d = 1, 2, 3 \ldots, n \end{cases} \tag{13}$$

DMUs with low initial efficiency scores need to obtain extra unconventional water in proportional terms to improve efficiency. Even so, however, certain DMUs cannot reach the efficient frontier. So, we kept adjusting low-efficiency DMUs via iteration until all DMUs reached the efficient frontier.

2.3.2. Input and Output Indicators

Now, unconventional water is predominantly produced for industrial purposes in both the primary and secondary sectors, as well as for ecological applications. In this paper, two input indicators (unconventional water allocation and total investment in water-saving facilities), as well as three output indicators (food production per capita, the value added of the secondary sector, and green space in urban built-up areas), were carefully selected to assess the efficiency of UWUR allocation. On the input side, the allocation of unconventional water and investment in water-saving facilities are essential components, reflecting the efforts to optimize water use and enhance water use efficiency. The selection of output indicators is driven by economic and ecological considerations. Specifically, the indicator of food production per capita is chosen due to the critical role of unconventional water resources in sustaining agricultural activities. Second, the value added of the secondary sector is considered, given the rapid industrial progress in China. Once-through cooling water systems in power plants and construction projects require a lot of water. In this case, reclaimed water is a more cost-effective alternative compared to treating and using conventional freshwater. Third, due to data availability, the green space in urban built-up areas in the planning year is included as an output indicator from the ecological dimension. Using treated wastewater can reduce the discharge of pollutants into natural water bodies. In addition, unconventional water offers a sustainable alternative for green space irrigation, promoting ecological governance and conservation, and contributing to overall ecological resilience. Additionally, we defined the efficiency of UWUR allocation as follows: with the unconventional water allocation remaining constant, a DMU is higher in efficiency if it produces more food production or value added of the secondary sector or larger green space. The details are shown in Table 2.

Table 2. The inputs and outputs of unconventional water in the planning year.

Input	Output	Description
x_j: Unconventional water allocation (100 million m^3)	y_j^1: Food production per capita (kg)	The higher the unconventional water quality and water use efficiency for agricultural irrigation, the more the food production.
x_j^1: Total investment in water-saving facilities (10,000 RMB)	y_j^2: Value added of the secondary sector (100 million yuan)	The cheaper the unconventional water used in the industrial sector, the lower the production cost is with more profits.
	y_j^3: Green space in an urban built-up area (hectare)	Using more water for ecological governance and protection can improve ecological resilience.

2.4. Empirical Study

2.4.1. Study Area

Boasting China's largest manufacturing cluster, Jiangsu Province emerges as China's premier economic performer. According to the National Bureau of Statistics of China, the province achieved a noteworthy GDP of RMB 12.287 trillion in 2022, ranking second in the country. Notably, the value added of the local secondary sector amounted to RMB 5.588 trillion, ranking first across the country. However, the province grapples with sig-

nificant water sensitivity. From 2017 to 2021, Jiangsu exhibited an annual average water use per capita of only 668.4 m^3 (Figure 2). This figure underscores an acute water scarcity challenge, creating a pronounced conflict between water scarcity and sustained economic growth. This predicament prompted some cities in Jiangsu to be the first pilots of reclaimed water use initiatives. Nonetheless, despite these efforts, in 2021, the unconventional water substitution rate of Jiangsu stood at 2.10%, even lower than the national average of 2.34% (Figure 2). Moreover, the total amount of UWU still falls significantly below the target stipulated by Water-Saving No. 113 of 2022, which mandates a utilization threshold of no less than 1.52 billion m^3.
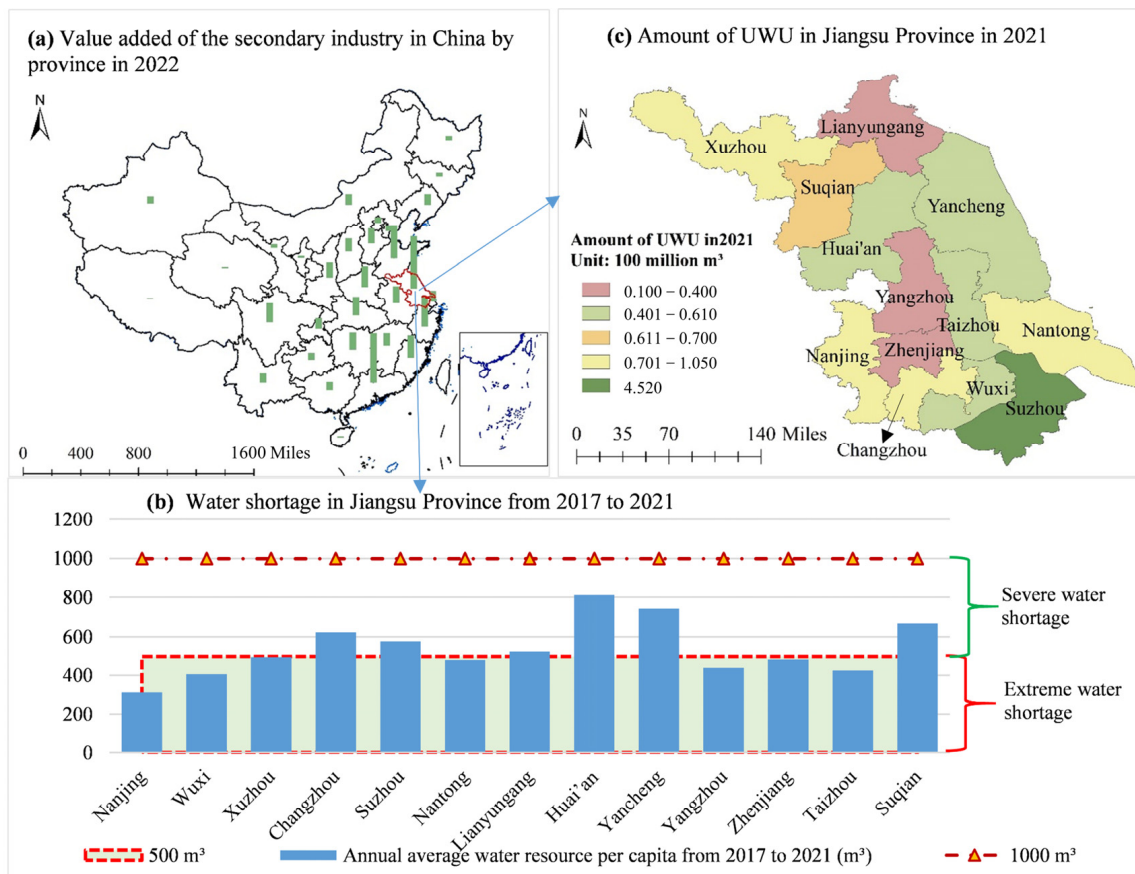

Figure 2. Economic development and water resources of Jiangsu Province.

2.4.2. Data Sources

China was a latecomer of UWU in 2012. Therefore, due to data availability, we collected data from 13 cities in Jiangsu Province from 2012 to 2021, with the year 2025 (the end of China's 14th Five-Year Plan) as the planning year. The data in this paper include statistical data, planning data, and quota data, and were mostly collected from statistical yearbooks, water resources bulletins, planning, and water quotas:

(1) Statistical yearbooks were from the China Urban-Rural Construction Statistical Year-book (2012–2021), statistical yearbooks of cities in Jiangsu Province, such as the Statistical Yearbook of Nanjing (2013–2022), water resources bulletins of each city, such as the 2012 Suzhou Water Resources Bulletin, and environmental state bulletins of each city.

(2) Planning came from the eco-environment planning of each city, Xuzhou Overall Plan-ning of Mineral Resources (2020–2025), and Overall Planning of Mineral Resources of Jiangsu Province.

(3) Quotas were sourced from Water Use Quota for Forestry, Animal Husbandry, Fishery, Industry, Service, and Domestic Use of Jiangsu Province (Revised in 2019), and Sanitary Fixture for Water Saving (GB/T 31436-2015).

3. Results

3.1. Results of WPI and UWUR Allocation

Estimating the values of relevant indicators in the planning year is a prerequisite for unconventional water allocation. In this paper, we drew from the established GM (1,1) [61] and the year-on-year growth rate [62] and used the SPSS for the estimation. The results are shown in Tables S1–S3. In light of Table 1 and Table S1, we ran a principal component analysis (PCA) using SPSSAU, a web-based application that performs data analysis, to obtain the weights (Table S4) and values (Table S5) of the WPI variables. According to Lawrence et al. [63] and Jafari Shalamzari and Zhang [64], we divided the WPI into five levels: severe (WPI < 48), high (48–56), medium (56–62), medium–low (62–68), and low (WPI > 68). It can be seen that in Jiangsu Province, only Changzhou (73.051) and Wuxi (62.694) will be at the lower level of water scarcity; most of the other cities will be at a higher level of water scarcity with a WPI < 62, and Lianyungang (47.548) will even face extreme water scarcity (Figure 3a).
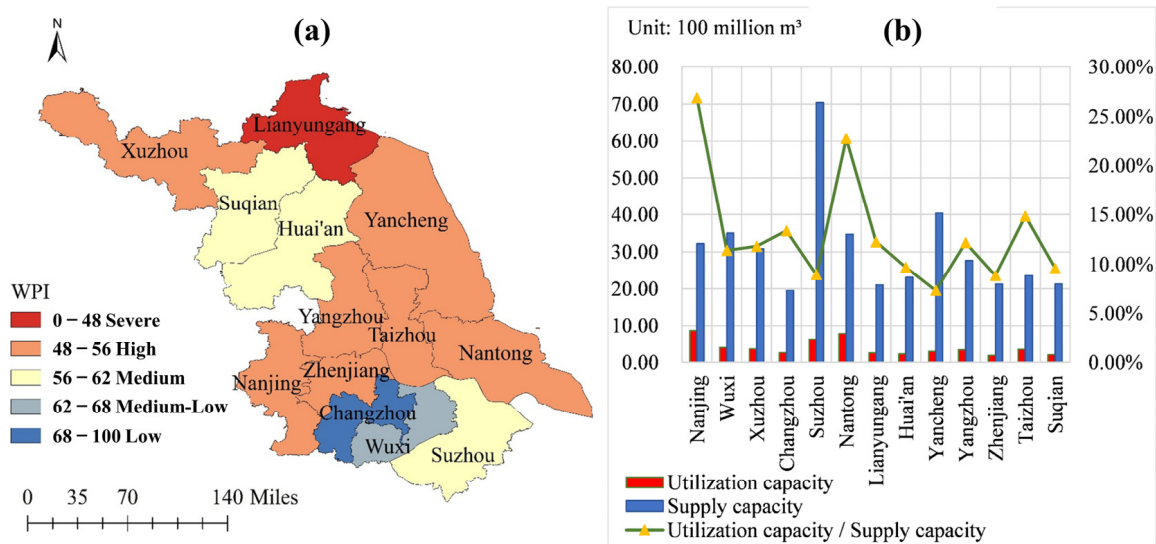

Figure 3. Estimation of main indicators in initial model: (**a**) water scarcity measured by WPI for each city in Jiangsu Province in 2025; (**b**) supply and utilization capacity of each city in 2025.

Next, from Tables S2 and S3 and Equations (5) and (6), we obtained each city's unconventional water supply and utilization capacities, as shown in Figure 3b. Regarding utilization capacity, Nanjing, Nantong, and Suzhou are much higher than other cities, while Zhenjiang, Suqian, and Huai'an rank the lowest. In terms of supply capacity, Suzhou, Yancheng, and Wuxi are the strongest, while Changhzhou, Lianyungang, and Zhenjiang are the weakest. The results show the mismatch between the production capacity and utilization capacity of cities, indicating that cities differ in the water-cycle economy. In addition, the amount of unconventional water consumed accounts for only around 13% of the unconventional water produced province-wide in 2025. Except for Nanjing and Nantong, the other cities can only consume 12% of the produced unconventional water, far away from the example of Singapore—meeting about 40% of its national water demand only through the reuse of reclaimed water [7].

In line with the practice of equal weighting [53], combined with the status quo of UWU in Jiangsu, we proportionally assigned 25% of the weights to each of the indicators in Equation (1), to show that the four principles of UWU share equal significance. Next,

from Tables S2–S5, we attained the indicators for the initial allocation of UWUR in each city of Jiangsu via Equation (1), as shown in Table 3.

Table 3. Indicators of the initial allocation of UWUR in Jiangsu Province in 2025.

Indicators	Nanjing	Wuxi	Xuzhou	Chang zhou	Suzhou	Nan tong	Lianyun gang	Huai'an	Yan cheng	Yang zhou	Zhen jiang	Taizhou	Suqian
Water scarcity (WS)	0.019	0.016	0.018	0.014	0.018	0.018	0.021	0.018	0.019	0.019	0.018	0.018	0.017
Supply capacity (100 million m^3)	32.268	35.012	30.892	19.500	70.466	34.704	21.063	23.123	40.418	27.663	21.251	23.668	21.319
Maximum utilization capacity (100 million m^3)	8.675	3.995	3.649	2.609	6.305	7.901	2.583	2.241	2.967	3.368	1.884	3.514	2.046
Accumulated utilization (100 million m^3)	3.800	12.004	6.619	8.377	31.069	5.105	1.160	1.405	2.329	2.727	2.677	1.090	3.230
Initial allocation plan (100 million m^3)	1.427	1.445	1.170	0.991	2.867	1.442	0.788	0.738	1.016	0.942	0.761	0.826	0.787

To guarantee the efficiency of unconventional water allocation, we used the optimal allocation model to calculate the efficiency scores of the initial allocation (Table 3) via Matlab R2023a. According to Table 4, the initial allocation is high in efficiency in general, with only four cities failing to reach the efficient frontier. After four iterations, we increased the efficiency score of every city to 1.0000.

Table 4. Optimization of UWUR allocation of Jiangsu Province in 2025.

City	Initial Allocation Efficiency		First Adjustment		Second Adjustment		Third Adjustment		Forth Adjustment	
	Allocation Amount	Efficiency	Allocation Amount	Efficiency	Allocation Amount	Efficiency	Allocation Amount	Efficiency	Allocation Amount	Efficiency
Nanjing	1.4267	1.0000	1.4803	1.0000	1.4813	1.0000	1.4816	1.0000	1.4816	1.0000
Wuxi	1.4453	1.0000	1.4996	1.0000	1.5006	1.0000	1.5009	1.0000	1.5009	1.0000
Xuzhou	1.1698	0.7710	0.9236	0.9946	0.9189	1.0000	0.9190	1.0000	0.9191	1.0000
Changzhou	0.9907	1.0000	1.0279	1.0000	1.0286	1.0000	1.0288	1.0000	1.0288	1.0000
Suzhou	2.8669	1.0000	2.9746	1.0000	2.9766	1.0000	2.9772	1.0000	2.9773	1.0000
Nantong	1.4419	1.0000	1.4961	1.0000	1.4971	1.0000	1.4974	1.0000	1.4974	1.0000
Lianyungang	0.7877	1.0000	0.8173	1.0000	0.8178	1.0000	0.8180	1.0000	0.8180	1.0000
Huai'an	0.7380	1.0000	0.7657	1.0000	0.7662	1.0000	0.7664	1.0000	0.7664	1.0000
Yancheng	1.0160	0.8394	0.8793	0.9951	0.8754	1.0000	0.8755	0.9999	0.8755	1.0000
Yangzhou	0.9425	0.9438	0.9214	0.9998	0.9219	0.9982	0.9203	0.9999	0.9203	1.0000
Zhenjiang	0.7607	1.0000	0.7893	1.0000	0.7898	1.0000	0.7900	1.0000	0.7900	1.0000
Taizhou	0.8265	1.0000	0.8575	1.0000	0.8581	1.0000	0.8583	1.0000	0.8583	1.0000
Suqian	0.7873	0.9404	0.7674	0.9998	0.7678	0.9982	0.7665	0.9999	0.7664	1.0000

Note: unit of "Allocation Amount" is "100 million m^3".

3.2. Rationality Analysis of the Optimal UWUR Allocation Results

Table 4 reveals that after four times of adjustments, the optimal UWUR allocation (unit: 100 million m^3) in Jiangsu Province in 2025 is 148.2 (Nanjing), 150.1 (Wuxi), 091.9 (Xuzhou), 102.9 (Changzhou), 297.7 (Suzhou), 149.7 (Nantong), 81.8 (Lianyungang), 76.6 (Huaian), 87.5 (Yancheng), 92.0 (Yangzhou), 79.0 (Zhenjiang), 85.8 (Taizhou), and 76.6 (Suqian). As Figure 4a shows, in 2025, the optimal UWUR allocation of each city falls within their supply and maximum capacity of UWU (maximum demand), proving basic feasibility.

Specifically, according to Figure 4b, the optimal allocation amount in 2025 is less than the maximum historic data of UWU from 2012 to 2021 in five cities (Nanjing, Wuxi, Xuzhou, Changzhou, and Suzhou), while the situation is the opposite in the remaining seven cities. It can be seen that the optimal allocation is feasible for the five cities. Furthermore, according to Figure 4c, unconventional water substitution rates for the remaining seven cities in 2025 range from 2 to 3%, less than the targeted goal of 3%, indicating the potential for improvement. Meanwhile, Figure 4d shows that in Yancheng and Taizhou, the yearly growth of UWU in 2025 compared to 2021 is nearly consistent with that observed in 2021 compared to 2020. In contrast, in Huai'an and Suqian, the yearly growth in 2025 is significantly lower than the figure in 2021, proving the feasibility of the optimal allocation for Yancheng, Taizhou, Huai'an, and Suqian.
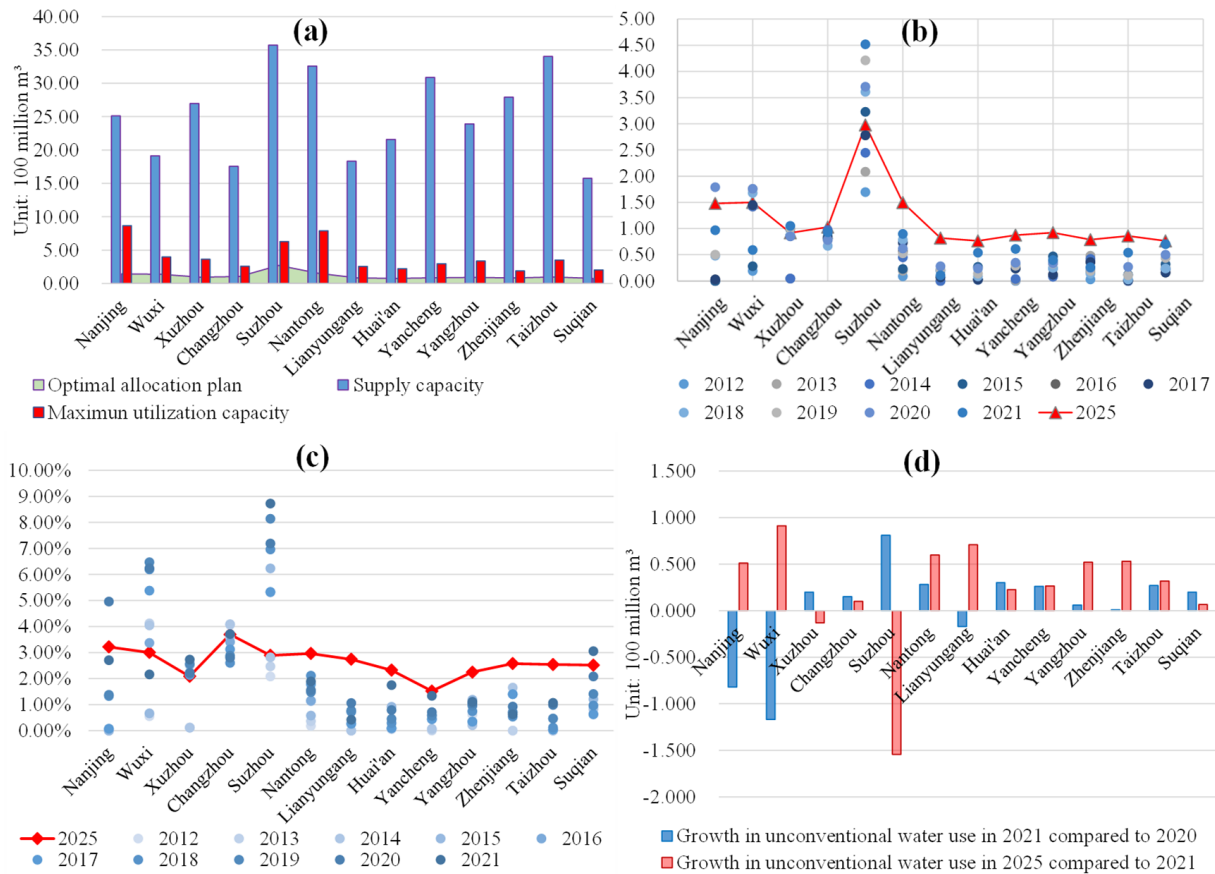
Figure 4. Comparative analysis for the 4th optimization: (**a**) comparison of the 4th optimization results with supply and demand in 2025; (**b**) comparison of optimal allocation in 2025 with the historical data of unconventional water use during the sample period for each city; (**c**) comparison of unconventional water substitution rate in 2025 with that during the sample period; (**d**) comparison of yearly unconventional water use growth.

As for Nantong, Lianyungang, Yangzhou, and Zhenjiang, their UWUR allocation greatly exceeds the historic data in the sample period. We compared the initial allocation plan with the optimal plan and found that the optimal plan makes little adjustment to the initial allocation of the four cities (Figure 5a). This indicates that the significant factors influencing the allocation plan in these cities lie within elements that make up the initial allocation model. Therefore, based on Figure 5b–e, this paper analyzed why the optimal allocation amount for these cities significantly exceeds their historical unconventional water utilization levels from the perspectives of water scarcity, supply capacity, and the utilization capacity of unconventional water.

(1) Nantong's strong maximum capacity of unconventional water plays a role in UWUR allocation, as suggested by Figure 5b. In light of the China Urban Construction Statistical Yearbook (2012–2021), Nantong's floor space of buildings under construction occupied 35% of the provincial total during the sample period. The real estate industry has become one of the strongest industries in Nantong [65,66], affirming the city's huge potential for UWU. Despite an overall upward trend in unconventional water substitution rate, it currently hovers below 2% (Figure 4c). According to our allocation plan, Nantong's unconventional water substitution rate is expected to reach 2.96%, mostly consistent with the 3% target outlined in the Nantong Municipal Plan on Building a Water-Saving Society during the 14th Five-Year Plan Period. Therefore, the proposed UWUR allocation of 149.7 million m^3 in Nantong in this paper is reliable and feasible.
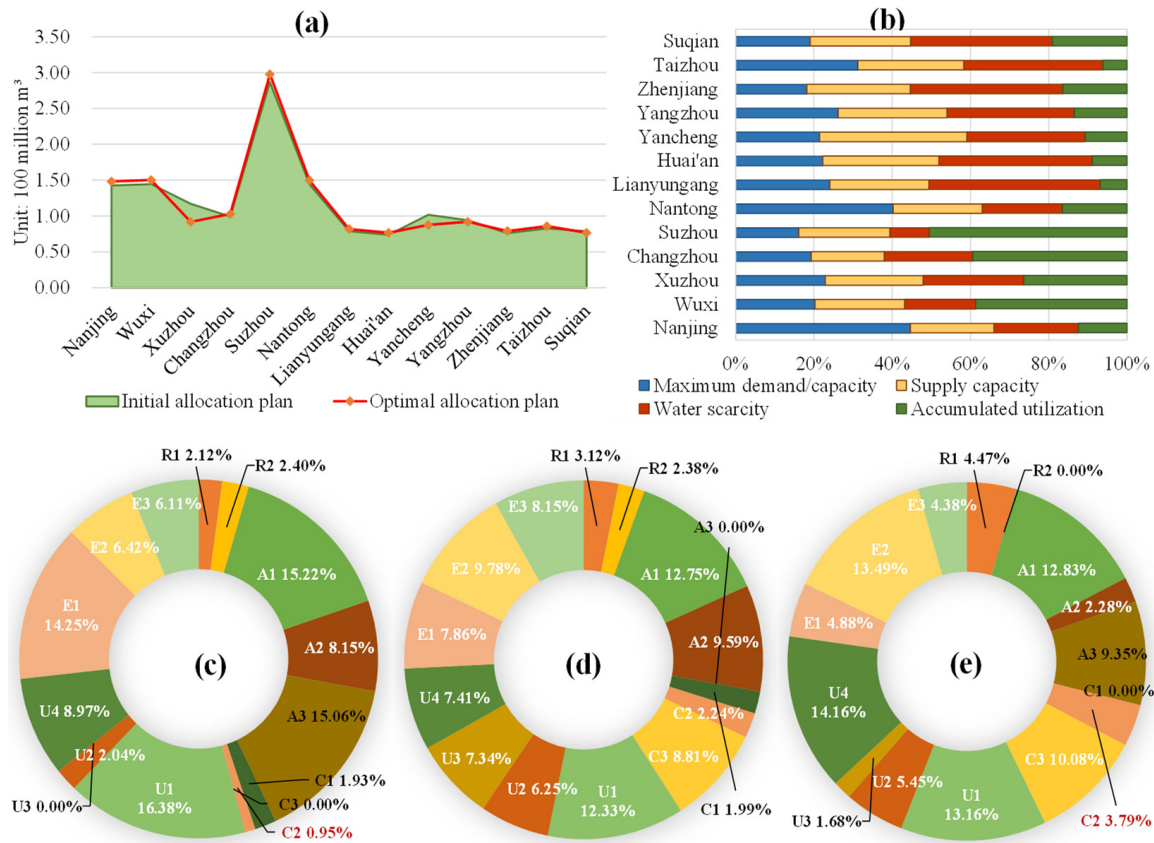
Figure 5. Analysis of optimal allocation of Nantong, Lianyungang, Yangzhou, and Zhenjiang: (**a**) comparison of initial allocation plan with optimal allocation plan; (**b**) contribution of each component to the initial allocation plan; (**c**) proportion of WPI variables in Lianyungang; (**d**) proportion of WPI variables in Yangzhou; (**e**) proportion of WPI variables in Zhenjiang.

(2) In Lianyungang, severe water supply shortages and deteriorating water quality are evident [67]. In accordance with the Lianyungang Statistical Yearbook (2013–2022), the city ranked second to last in annual average water availability per capita during the sample period, reaching a meager 461.499 m^3. Nevertheless, in this situation, Lianyungang's water intensity once reached the highest in the province. The proportion of output from water-intensive and pollution-intensive enterprises among those above the designated size consistently remained around 60%, far exceeding other cities. Challenges are further exacerbated by point source pollution from a high-density chemical industry park [67]. In addressing these issues, strategic utilization of unconventional water is crucial.

(3) Yangzhou exhibits resilience in unconventional water supply yet faces pronounced water scarcity in 2025. Low investment in environmental protection and a large amount of wastewater discharge lead to a huge ecological carrying capacity in Yangzhou [68]. The total amount of water use stimulated by the Yangzhou Water Conservancy Development Planning of the "14th Five-Year Plan" is 4.097 billion m^3, the seventh in the province. In the meantime, the China Urban Construction Statistical Yearbook (2012–2021) reveals that Yangzhou also ranked seventh in urban wastewater discharge during the sample period. In this paper, the city's UWUR allocation in 2025 is 92 million m^3, significantly higher than the figure in 2021 (40 million m^3), ranking sixth in the province. In summary, the UWUR allocation of Yangzhou in 2025 is broadly in line with the total amount of water use and wastewater discharge of Yangzhou.

(4) Zhenjiang struggles with severe water scarcity, a significant factor driving its UWUR allocation. The city's dependence on water-consuming and pollution-intensive industries, coupled with poor water-saving management (Figure 5e), leads to a relatively

lower WPI value. According to the Zhenjiang Municipal Statistical Yearbook (2013–2022), the proportion of water-consuming and pollution-intensive enterprises among all local industrial enterprises above the designated size was 43.67% in the sample period, second only to Lianyungang. The Zhenjiang Water Resources Bulletin (2012–2021) further reveals that in 2021, the city's secondary industry used up to 3.109 billion m^3 of water, accounting for 78.4% of the total water consumption. In addition, Zhenjiang's water availability per capita reached 800 m^3 per year, ranking first in the province. In short, severe water scarcity persists due to a low utilization efficiency of water resources, severe water scarcity, and serious water pollution [69]. It is imperative to utilize unconventional water to address the acute water scarcity challenges in Zhenjiang.

To sum up, the allocation plan after four times optimization is reasonable and feasible to be the minimum unconventional water allocation of each city in Jiangsu Province in 2025 (Table 5). Specifically, Nanjing, Wuxi, Xuzhou, Changzhou, Suzhou, and Nantong account for a larger proportion of the total allocation amount, while the remaining cities have a smaller share. The rationality of the empirical results also indicates that the framework proposed in this paper for the allocation of UWUR has a certain degree of validity.

Table 5. Minimum unconventional water allocation of each city in Jiangsu Province in 2025 (unit: 100 million m^3).

City	Minimum Amount	City	Minimum Amount
Nanjing	1.4816	Huai'an	0.7664
Wuxi	1.5009	Yancheng	0.8755
Xuzhou	0.9191	Yangzhou	0.9203
Changzhou	1.0288	Zhenjiang	0.7900
Suzhou	2.9773	Taizhou	0.8583
Nantong	1.4974	Suqian	0.7664
Lianyungang	0.818	The whole province	15.2

4. Discussion

4.1. Recommendations

Promotion policies regarding UWU should be tailored to the specific circumstances of each city. Cities with a solid foundation in terms of economic growth, well-established unconventional water infrastructure, and high levels of public acceptance, such as Nanjing, Wuxi, Xuzhou, Changzhou, Suzhou, and Nantong, are well positioned to scale up the use of unconventional water. These cities should assume greater UWURs and implement market-oriented measures:

First, increased subsidies should be provided to wastewater treatment plants that process larger volumes of wastewater while delivering higher-quality treated water. This strategic approach aims to lower the processing costs for these plants, incentivizing user demand for reclaimed water. By facilitating financial support in this manner, authorities can foster a more robust and sustainable framework for UWU in economically advanced and infrastructure-ready cities.

Second, comprehensive market research is a must. Governments must make clear the water use gap among coastal cities and leverage local renewable energy sources to their full potential, which can lower the cost of water supply and stimulate the demand for seawater desalination. By analyzing market dynamics and understanding the challenges and opportunities in each coastal city, tailored policies can be developed to optimize the utilization of unconventional water sources.

Cities that lag in UWU should improve their infrastructure. In the central and northern parts of Jiangsu Province, these cities often grapple with inadequate water infrastructure, heightened reliance on water-consuming and pollution-intensive industries, and low-level water management. To bolster unconventional water allocation, we need to incentivize local enterprises to optimize the use of unconventional water and facilitate market access:

First, municipal governments should align the policies with local water resource endowments and socioeconomic development, adjust industrial and agricultural structures, and curtail the construction of water-consuming services and extensive agricultural irrigation. Additionally, stringent access thresholds should be implemented for industrial parks, especially in terms of water use. Enterprises operating within these parks are mandated to prioritize the use of recycled and reclaimed water over conventional tap water.

Second, financial support is strongly encouraged. It is crucial to structure contracts carefully, ensuring alignment with the goal of unconventional water projects, and providing sufficient incentives for all stakeholders. Leveraging contracts for pollution control and water-saving initiatives can raise funds for unconventional water projects, thereby facilitating progress and alleviating the financial burden on local governments. To incentivize enterprises to use reclaimed water, mine water, or desalinated seawater, tax exemption is recommended.

Third, environmental liability insurance can be implemented to boost sustainable water management. Insurance can serve as a safety net for enterprises and projects involved in utilizing reclaimed water, mine water, or desalinated seawater. Financially responsible for potential environmental liabilities, companies are incentivized to implement advanced technologies, adhere to best practices, and prioritize water pollution control and treatment measures. Additionally, local government requires businesses, particularly those engaged in industries with potential environmental impact, to carry environmental liability insurance as part of regulatory compliance. By doing this, authorities can ensure that enterprises prioritize environmentally responsible practices.

4.2. Comparison with Other Studies

The water resource system interacts with the social, economic, and environmental systems [70]. Therefore, the amount of unconventional water allocation should not be the more the better but should be matched with the characteristics of economic, social, and environmental development. The attention of academia to the contribution of unconventional water resources to water security has increased due to water scarcity and food production security in arid and extremely arid regions [71]. It can be said that water scarcity is the primary driver for unconventional water utilization and management. In addition, social and hydrological factors [72,73], water supply and demand gap [14], and demand for water quality and quantity [74] have been proposed to determine the allocation of recycled water. Whether the allocated amount of regional water resources matches historical utilization values is also an important criterion for evaluating the satisfaction of allocation results [53,72]. However, existing research on unconventional water allocation frameworks has not yet focused on the importance of historical utilization levels. Furthermore, given that public acceptance willingness is also a key factor in the success of water recycling plans [56,75], and historical utilization data can reflect the characteristics of the entire society's willingness to accept unconventional water, this paper uses historical utilization data to gauge local acceptance willingness. Based on existing research, a new allocation pattern of "water scarcity status—supply capacity—utilization capacity—acceptance willingness" is proposed, expanding the content of the unconventional water allocation framework.

Existing research has guaranteed the allocation fairness of water resources through multi-criteria decision-making [72], goal programming [70,74], interval numeral–hierarchical planning models [76], and multi-agent models [77]. Allocation efficiency is also an important principle [25]. In recent years, studies on water use efficiency [27,37] have expanded to include the efficiency of a system that involves both water use and wastewater recycling [41,42]. However, there is still a significant gap in the research on the efficiency of unconventional water allocation. This paper, based on the current state of unconventional water utilization in China, introduces the concept of unconventional water allocation efficiency and expands the application of the ZSG-DEA model in the field of unconventional water allocation. Additionally, in selecting output indicators, this study aligns with Hussain

et al. [78] by considering agricultural water use, industrial recycled cooling water, and ecological replenishment water as primary allocation targets.

4.3. Limitations

This paper has the following limitations: First, due to data availability, the recent initiation of UWU practices in China in 2012 restricted our study period to ten years. This constraint may impact the comprehensiveness and accuracy of our indicators and predictions. This limitation can be addressed in future research as additional data and materials become more accessible. Second, the construction of the WPI relied on only fifteen variables, and the ZSG-DEA model utilized five input and output indicators. Future endeavors will aim to enhance the scope of our measurement by integrating both desirable and undesirable environmental outputs associated with UWU. This will enable a more comprehensive assessment, accompanied by the inclusion of more data and research subjects. Last, the principles affecting unconventional water allocation may be of different significance, so our future research will determine the degrees of importance as per expert interviews.

5. Conclusions

Based on China's need to specify the minimum allocation of unconventional water sources, this paper established the allocation principles and models for the minimum utilization of unconventional water from the perspective of responsibility. Six principles of UWU based on the whole process of water allocation were presented first, and then an initial allocation model was constructed. The initial allocation mode is composed of four parts. Part 1 uses water shortage to reflect the demand of regional UWU; Part 2 assesses the regional unconventional water supply capacity in four aspects—reclaimed water, harvested rainwater, mine water, and desalinated seawater; Part 3 evaluates the regional unconventional water supply capacity based on data from major industries that promote and use unconventional water; and Part 4 considers the regional history of UWU to show the willingness and acceptance of local residents. In a word, the initial allocation model fully considers the interplay among the water resources, and socioeconomic and ecological environment systems, forming a pattern of "realistic requirements—supply capacity—utilization capacity—acceptance willingness," in line with China's policies. Lastly, the ZSG-DEA model was used to ensure the effective allocation of the minimum utilization of unconventional water in each city, expanding the application of ZSG-DEA in unconventional water allocation.

We applied the allocation model proposed in this paper to Jiangsu Province of China in 2025. The results proved the practical feasibility and validity of the model. Generally speaking, the results of this paper are of great significance to China's construction of integrating unconventional water into the unified allocation pattern of water resources. In addition, by considering the adaptability of the UWU to the characteristics of urban socioeconomic and environmental development, this paper can provide some references for decision-makers to make territorial spatial planning and sustainable resource management programs.

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

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