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# Optimal Allocation of Water Resources Based on Water Supply Security

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**Abstract:** Under the combined impacts of climate change and human activities, a series of water issues, such as water shortages, have arisen all over the world. According to current studies in *Science* and *Nature*, water security has become a frontier critical topic. Water supply security (WSS), which is the state of water resources and their capacity and their capacity to meet the demand of water users by water supply systems, is an important part of water security. Currently, WSS is affected by the amount of water resources, water supply projects, water quality and water management. Water shortages have also led to water supply insecurity. WSS is now evaluated based on the balance of the supply and demand under a single water resources condition without considering the dynamics of the varying conditions of water resources each year. This paper developed an optimal allocation model for water resources that can realize the optimal allocation of regional water resources and comprehensively evaluate WSS. The objective of this model is to minimize the duration of water shortages in the long term, as characterized by the Water Supply Security Index (WSSI), which is the assessment value of WSS, a larger WSSI value indicates better results. In addition, the simulation results of the model can determine the change process and dynamic evolution of the WSS. Quanzhou, a city in China with serious water shortage problems, was selected as a case study. The allocation results of the current year and target year of planning demonstrated that the level of regional comprehensive WSS was significantly influenced by the capacity of water supply projects and the conditions of the natural water resources. The varying conditions of the water resources allocation results in the same year demonstrated that the allocation results and WSSI were significantly affected by reductions in precipitation, decreases in the water yield coefficient, and changes in the underlying surface.

**Keywords:** water supply security; water supply security index; changing environment; water allocation; Quanzhou

## 1. Introduction

Water resources can be used in different regions or by different groups in a sustainable manner via the optimal allocation of water resources [1]. In a unified framework of the natural water cycle and the societal water cycle, including the total water supply, water consumption and water discharge, the optimal allocation of water resources should achieve a balance between economy, ecology, society and green development of water resources systems. In response to the water demand in regions with different economic and social development trends as well as varying precipitation, an optimal security threshold for water quantity, water quality and water supply continuity must be reached [2,3].

Research on the allocation of water resources has attracted considerable attention over the last few decades. Allocation rapidly developed from a single water source to multiple water sources [4,5], from considering a single objective to multiple objectives, from temporal to spatial [6,7], from demand-oriented to supply-oriented models, and from water quantity and water quality [8] to water quantity-quality coupling [9]. Many computational algorithms, such as genetic algorithms [10], complex adaptive systems [11], fuzzy algorithms [12], ant colony algorithms [13], chaos harmony search algorithms [14], neural networks [15], grey algorithms [16], particle swarm optimization [17], decentralized optimization algorithms and two-stage stochastic programming methods [18], have been introduced. New development theories have also been developed, such as water resources allocation based on sustainable development [19], balanced development [20], low carbon use [21–24] and green development [25]. The allocation of water resources has also been enhanced for cross-disciplinary applications including management science, cybernetics, game theory [26], economics [27], GIS [28] and system dynamics [29]. Rapid progress has been achieved in water resources allocation theories, methods and models.

The demand for water resources has increased with the rapid development of economies and societies. Under the dual impacts of climate change and human activity, water issues, such as water shortage and water pollution, have arisen all over the world [30,31]. In 1977, the United Nations (UN) warned that after the oil crisis, the next crisis would be water related, the UN considered the ten years from 1981 to 1990 as the International Water Supply and Sanitation Decade [32]. In March 2000, the *Hague Declaration of Water Security in the 21st Century* was adopted during the second session of the World Water Forum; this document declared that freshwater, coastal water and related ecosystems must be protected and improved, and that sustainable development and political stability should be enhanced to ensure that everyone has access to adequate safe freshwater to maintain a healthy and rich life at affordable costs and that people are sufficiently far away from water-related disasters. On World Water Day in 2001, Kofi Annan, the former UN Secretary General, noted that sewage may harm human health, hinder social progress and violate human dignity [33]. Currently, there is no uniform definition of water security. However, several international organizations, such as the Global Water Partnership and the World Economic Forum, have continued to research and focus on water security. Other groups identifying the importance of water security include UNESCO's Institute for Water Education, which has made water security one of its research themes, and the Asia-Pacific Water Forum, which held its first summit, entitled "Water Security: Leadership and Commitment" Research, in 2007. Research on water security began in the 1970s and developed rapidly after the 1990s. Water security has become an important issue in recent decades [34,35]. There are many opportunities for addressing the challenges of water security [36].

Water security can be summarized by two aspects: flood control and water supply security (WSS). Both of these issues are concerned with water shortages, which are affected by the amount of water resources, water supply projects, water quality and water management. As an important part of water security, WSS is not only the basis of food security, economic security, ecological security and other water-related security issues but also a factor affecting national security [36,37]. Water security extends beyond basic human rights and social justice, as it impacts the stability and sustainability of economic development. The security of a water supply could be used as a measurement of a region's social welfare. Therefore, it is important that WSS becomes the central task of water management [38] and an important goal of water resources allocation around the world.

Therefore, the optimal allocation of water resources should be based on the reasonable demand of the regional water users [39] and should scientifically allocate the various water sources to users through various water supply systems to ensure regional WSS.

In this study, a method for computing WSS was established using the concept and connotation analysis. Taking regional WSS as the goal, the water resources multi-agent system simulation approach [40] was adopted to form an optimal allocation model for water resources. Then, Quanzhou, a southeastern coastal city experiencing serious water shortage problems in China, was selected as a case study.

## 2. Study Area and Data

### 2.1. Study Area

The city of Quanzhou (Figure 1), China, has a relatively large population and a developed economy with abundant water resources. However, the availability of water per capita is relatively low, and the distribution in time and space is inconsistent. The rapid growth of coastal areas has been restricted by the availability of water resources, particularly during the dry season, and the supply of water resources is an urgent problem. Therefore, Quanzhou was chosen as a typical region to conduct water resources allocation.

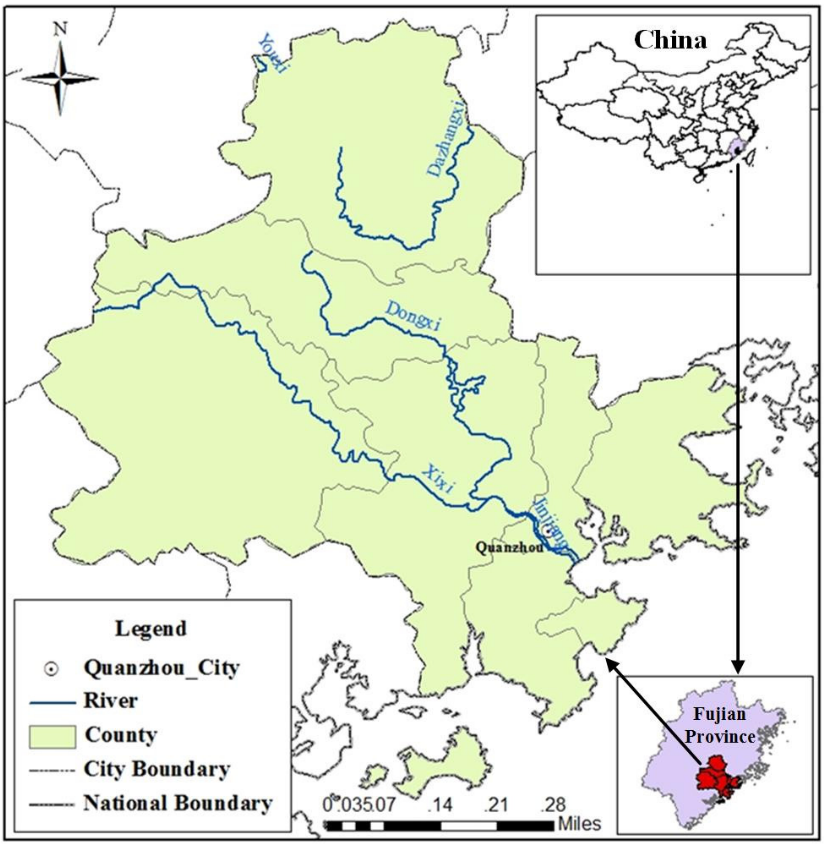

**Figure 1.** Location of Quanzhou in China.

Quanzhou is one of the three central cities in Fujian Province, China, and has jurisdiction over four districts, Licheng, Fengze, Luojiang and Quangang; three county-level cities, Jinjiang, Shishi and Nan’an; and five counties, Hui’an, Anxi, Yongchun, Dehua and Kinmen, with a total land area of 11,015 km$^2$. Due to the limited data available, the study area does not include Kinmen County.

Quanzhou has a subtropical maritime monsoon climate, an annual average temperature of approximately 20 °C, and an annual frost-free period of 310 days or more. The amount of precipitation varies significantly over the region and seasons. Precipitation is greater in the flood season and lower in the dry season as well as greater in the mountainous regions and lower in the coastal areas.

The riverine system in Quanzhou is relatively developed, with several rivers and a high drainage density. The larger rivers are Dongxi, Xixi, and Jinjiang in the Jinjiang Basin, Dazhangxi and Youxi in the Minjiang Basin and Beixi in the Jiulongjiang Basin (Figure 1).

The average annual precipitation in Quanzhou from 1956 to 2011 was 1653.1 mm, and the average annual water resources potential is 9.679 billion $m^3$.

### *2.2. Data*

This paper uses the 1956–2011 hydrological data from the water resources bulletin of Quanzhou to calculate the available water supply potential. Data concerning population growth and economic development from the Five-Year Plan for National Economic and Social Development of Quanzhou were used to anticipate the potential changes in water demand. According to the available data, 2015 was chosen as the base study year and 2020 was chosen as the planning level year.

There were no significant change trends in the annual precipitation (Figure 2a) or the total water resources potential (Figure 2b) in Quanzhou over the time period. The precipitation was closely related to the total water resources potential (Figure 2c), but the water yield coefficient gradually decreased in recent years (Figure 2d) [41]. This reduction was also accounted for in the water conditions of the data by reducing the water resources series by 5% in 2015 and 10% in 2020.

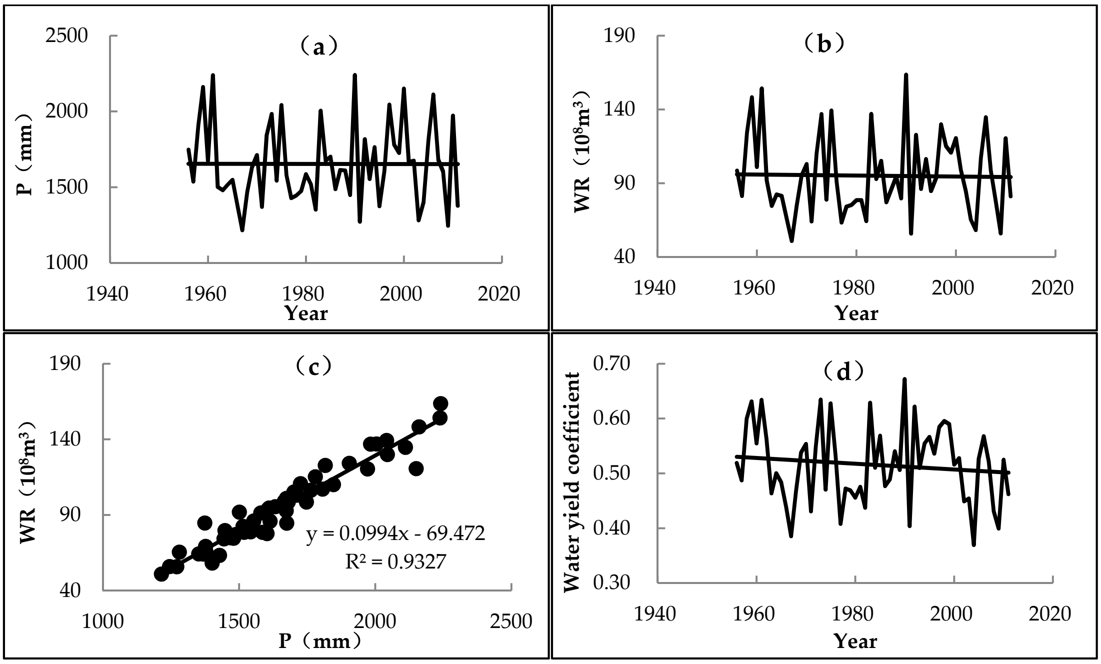

**Figure 2.** Annual precipitation, water resources potential, their relationship and the water yield coefficient in Quanzhou (1956–2011).

## 3. Methods and Model

### *3.1. Concept and Computation of WSS*

A water supply allows for the allocation of natural water resources to different areas and users through artificial water works. Allocation includes three basic elements: taking artificial measures, changing the natural flow of water and satisfying the demands of water users.

High water security implies no danger, threats, or accidents to the water supply. Security has a twofold meaning. One is the description of the objective of the system regarding the system's operational stability and sustainability. The other is a description of the system's response capability, which is the ability of a system to handle events caused by unsecure factors. Therefore, "security" is an overall embodiment of the actual state of the water supply system and its capability to address risks [42].

There have been several studies considering energy supply security in the oil, gas, and electricity fields [43–45]. However, few studies have focused on WSS. The scientific definition and evaluation methods from published works on WSS have not yet achieved a unified understanding, and technical standards and strategic systems have not yet been established [46]. The concept of WSS originates from water security. While research on water security began in the 1970s, a global unified definition of water security has not been established. Although there has been an increase interest in water resources security, the definitions and concepts remain ambiguous [47].

Compared to water security and water resources security, there have been few published works on WSS, and they have primarily focused on urban regions [46]. In terms of safety evaluation, comprehensive evaluations are relatively ample, with a main focus on the water security evaluation index system, the index weight and the choice of the evaluation method. The water security evaluation index was developed from single indexes, such as the Water Stress Index (WSI), the degree of water resources development and utilization, and runoff depth, as well as composite indexes, including the Water Poverty Index (WPI), to create a multi-level index system based on the concept of sustainable development [30,48].

The single index evaluation method is straightforward but not comprehensive, as it focuses primarily on the characteristics of water quantity as opposed to water quality, water environment and social, economic and ecological security issues. Although it has been considered comprehensively, the composite index and index system require more data. The evaluation results are uncertain due to the subjectivity in the weight setting and the selection of the comprehensive evaluation method. Therefore, indicators that are simple and have abundant connotations must be established to characterize the WSS.

At present, WSS evaluation represents the evaluation of the current situation or the completion of water resources allocation. It is simply an evaluation of the balance between supply and demand of the unimodal condition that does not consider the conditions of the different water resources. WSS evaluations are only for water resources under equilibrium supply and demand conditions and do not consider the equilibrium of supply and demand under different water resources conditions.

The concept and calculation method of the WSS are presented below to lay the foundation for the water resources allocation of the time series data.

### 3.1.1. Connotation Analysis and Definition

The major factors affecting the WSS include the inflow condition, the design scale of the water supply project, changes in the demand and influences from other users. The WSS mainly includes the following three basic conditions [49]:

(1) The reasonable demand of water use. Because the WSS is the representation of the balance status and the capability of the water supply and demand, the analysis of the WSS must be based on the precondition that the water demand is authentic and relatively reasonable, *i.e.*, the WSS is based on the reasonable water demand under the current specific technological and economic levels. A water demand standard that exceeds or is below the reservoir level cannot invert the authentic supply-demand balance situation. However, achieving a reasonable demand standard is often a technical challenge [39].

(2) Security in four aspects: water quantity, water quality, sustainability and economic efficiency. Based on an examination of water demand factors, the WSS is a four-dimensional vector relating the satisfaction rate of the water supply to the actual demand in the four dimensions (quantity, quality, time and economy) under the current conditions or a future scenario.

$$S = f\left(a, q, d, e\right) \tag{1}$$

where $S$ (*security*) represents the degree or capability of the WSS, $a$ (*amount*) represents the water quantity, $q$ (*quality*) represents the water quality, $d$ (*duration*) represents the duration of the water supply and $e$ (*economy*) represents the cost of the water supply.

Accordingly, the WSS consists of four basic factors: (a) A certain amount of water yield, *i.e.*, the water supply can meet the actual water demand under the relevant standards. For example, the household water supply can satisfy the water demand of certain regions under the water quota standard; the irrigation water supply can satisfy the water demand of effective irrigation regions under sufficient irrigation or economical irrigation quotas; or the industry water supply can satisfy the water demand for the daily operation of enterprises; (b) Standard water quality, *i.e.*, the water yield supplied achieves the prescribed water quality standard for the target water consumption, including standards for drinking-water quality, agricultural irrigation water quality, industrial water quality and ecological environment water quality. (c) A stable water supply, which is used to represent the continuity of the water supply. This includes two aspects, the security reliability of the water supply source and the reliability of the water supply engineering system. (d) The bearable economic efficiency including economic factors, such as the cost and price; the use of unconventional measures, such as seawater desalination, rainwater storage and water transfer from out of the region, are primarily results of restricted economic efficiency [46].

(3) The inclusion of both general and emergency statuses. The WSS has two security statuses, general and emergency. The WSS under the general status means maintaining a stable water supply under the given WSS reliability and normal operation, represented as the effectiveness of the target water supply and the stability of the water supply system. Under this status, the water supply should satisfy the normal water demand of users or development (*i.e.*, a larger water supply can encourage an increase in the number of water users). The WSS under the emergency status means that the water supply system avoids or reduces impact via emergent measures to maintain the standard water supply to meet the basic needs of users under extreme situations when the preset WSS reliability is overly high or natural/ or man-made accidents occur.

Based on the above analysis, this paper attempts to define the WSS with a clear physical meaning. Under the current economic and technical conditions with respect to the actual water demand, the regional water supply system should meet the required satisfaction degree in terms of water quantity, quality, continuity and economic efficiency as well as the ability to control the damage risk and the impacts of special circumstances under the acceptable range.

### 3.1.2. Basic Properties of the WSS

Five basic properties of WSS can be established: relativity, systematism, limitedness, dynamism, and economy.

1. Relativity. The WSS represents the balance between supply and demand and is thus a relative concept. The WSS depends on not only the supply capacity but also the size of the users' demand. As a result, the WSS must regulate both the supply and demand sides.
2. Systematism. The water supply system has three subsections: the water source, water supply project and water user. The WSS is the cooperative security of the three subsystems. A high overall WSS can only be achieved when the three subsystems are secured individually and collaboratively. Therefore, improving the WSS of a water supply system involves performing a system analysis and addressing the weaknesses of the system.
3. Limitedness. The WSS has a limited security, and the performance is limited by two aspects. (a) Under the general status, the WSS is based on the specific scope of planning, the corresponding water supply guarantee rate of each user and certain water use standards; (b) Under the emergency status, the WSS is the special security based on specific objectives, specific standards such as the occurrence of severe drought, and unmet agricultural irrigation demand. The industrial and domestic water use standards may also be reduced.

4. Dynamism. Under the influence of environmental changes, economic development and social progress, both the water supply and demand are dynamic. The WSS presents clear dynamic characteristics, such as for rural drinking-water security issues in China, with the cyclic operation of supply projects and improvements in water use standards.
5. Economy. With the development of engineering technologies, there is an increasing number of methods for ensuring WSS. However, WSS is closely related to the economic characteristics of the supply route selection. Utilization of seawater resources to resolve the water shortage problem in China is one possible supply route. Although seawater is abundant and the technology is mature, under the restriction of economic costs and benefits, new concepts, such as the East-to-West Seawater Transfer and Leading Bo Seawater to Xinjiang Province in China, do not currently offer maneuverability.

#### 3.1.3. Computation of the WSS

The Water Supply Security Index (WSSI) can be used to measure WSS. The WSSI indicates the level of satisfaction of the benefited subjects (water users) regarding the water supply service provided by the water supply project or department. The WSSI also indicates the level of water consumption security. A larger WSSI indicates a higher level of satisfaction of the water users and a higher WSS.

WSS is the integrated security of three subsystems, the water source, water supply project and water user. The three subsystems should be comprehensively considered when computing the WSSI. Due to the different requirements of each user regarding the water source, quality, and duration, the safety standards for different groups of users are also different. The allocation of water resources is the process of supplying different water sources through different projects to different users. Therefore, through the process of water resources allocation, the WSSI can be calculated for each group of users and the regional WSSI can be obtained.

The empirical frequency formula (mathematical expectation formula) [50] was adopted to compute the WSSI as follows:

$$P_i = \frac{m}{n+1} \times 100\% \tag{2}$$

where $P_i$ is the long-series WSSI for a single water user, $i$ is a subscript representing different water users or regions, $m$ is the duration of normal operation of the supply system (e.g., year, month, or day), which is computed according to the duration for which the water supply meets the water demand, and $n$ is the total computation period.

For example, 5 years of hydrological data are available; thus, the water supply and demand series of 60 months were determined through water resources allocation. If water demand is met in a period of 49 months, then there are 11 months of water shortage. The WSSI of this group of users is 80.3%. The calculation diagram is shown in Figure 3.

Considering the comprehensive WSS in each region or basin, the weighted average of each water user can be determined in the computation as follows:

$$P = \sum_{i=1}^{k} P_i \times \alpha_i = \sum_{i=1}^{k} P_i \times \frac{W_i}{W} \tag{3}$$

where $P$ is the comprehensive WSSI, $k$ is the total number of water users, $W_i$. is the total amount of water supply for the water user $i$, $W$ is the total amount of water supply for all users, $\alpha_i$ represents the weight coefficients and the remaining variables are as previously defined.

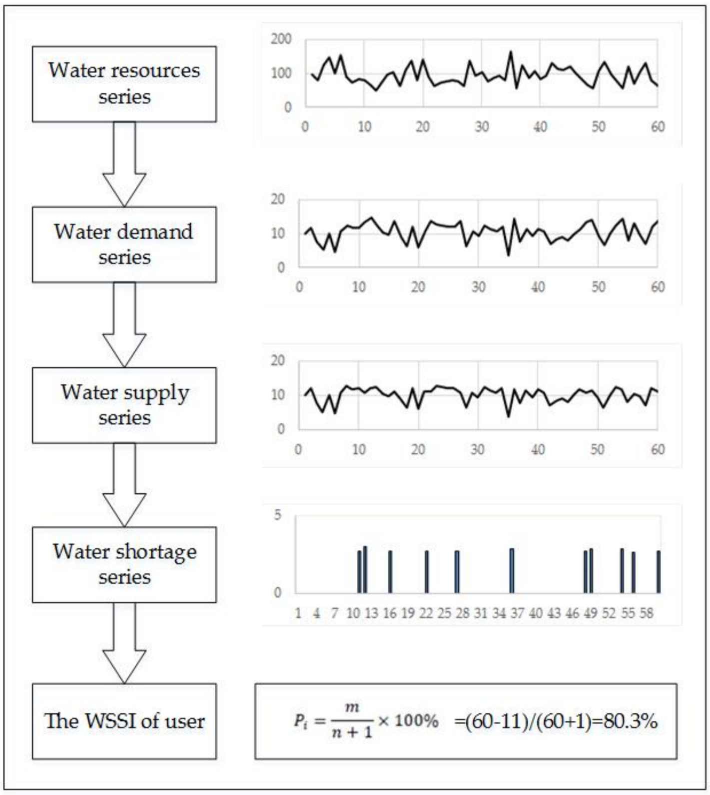

**Figure 3.** Calculation diagram for the Water Supply Security Index (WSSI).

### *3.2. Establishment of the Optimal Allocation Model for Water Resources Based on WRMASSM*

The optimal allocation of water resources involves establishing a mathematical programming model by setting targets and constraints to obtain the allocation results. The optimal model can acquire a satisfactory result when the system target and constraints are both clear and the scale is not overly large. However, because the water resources system itself is extremely complex, it is difficult to adopt the objective function and constraints to build the complete programming model. In addition, the excessive scale of the model may increase the difficulty of converging to a solution; thus, the optimized results may not correspond to the actual situation. Given the complex adaption of the water resources system [51], the Water Resources Multi-Agent System Simulation Model (WRMASSM) based on the Complex Adaptive System (CAS) [52] can be used to compensate for the inadequacy of traditional theory methods in the modeling and simulation of water resources systems. This provides a tool for the optimal allocation of water resources and provides an optimal solution for the scientific utilization of water resources [11].

The WRMASSM was used to simulate the process of water resources allocation to determine the optimal allocation solution, allowing the maximum comprehensive benefits of limited water resources. The construction of the optimal allocation model included the following important steps [11]:

1. Analysis of the water resources systems. The theory and methods of the system engineering were adopted according to the characteristics of the water resources system. Based on the conceptualization of the water resources system, focus should be placed on studying the organization of the water resources system, the system environment, and the inputs and outputs of the system.
2. Determination of the optimal simulation target. The major target was set as the maximum regional comprehensive WSS using Equations (2) and (3). The WSS can also determine several sub-targets according to needs.

3. The construction of the water resources system is divided and the organization structure is determined according to the elements of the water resources system and the function of each element.
4. Based on the determined organization structure, the agent is further divided and the conceptual model for each of the agents is obtained. The construction of the agent model mainly includes studying the behavior mode of each agent in the water resources multi-agent system and the interactive model for each agent and the surrounding environment. On this basis, the water resources demand of each agent can be analyzed under different development requirements.
5. Determination of the requirements and constraints of the water resources allocation. Under the region or basin water resources management system, some requirements and constraints in the water resources allocation should be determined in advance.
6. Design of the model program and operation until the requirements are met. The model results are then rationally analyzed.

### *3.3. Model Construction for Quanzhou*

After generalizing the water resources system network for Quanzhou (Figure 4), the WRMASSM was adopted to establish the optimal allocation model for the water resources. The model considers the strictest water resources regulation system and the "Three Red-Line" control indicators of Quanzhou and follows the strictest assessment requirements of the water resources management to predict the water demand [38]. Based on the set water level year and different inflow conditions, the optimal allocation of water resources in Quanzhou was determined with the aim of maximizing the comprehensive WSSI.

The agents of the water resources system in Quanzhou can be divided into government agents (hereinafter referred to as GovAgents) and User Agents. The GovAgents include the Quanzhou Agent, Lichen Agent, Fengze Agent, Luojiang Agent, Quangang Agent, Jinjiang Agent, Shishi Agent, Nan'an Agent, Hui'an Agent, Anxi Agent, Yongchun Agent and Dehua Agent. The User Agents can be divided into the Domestic Agent, Primary Industry Agent, Secondary Industry Agent, Tertiary Industry Agent and Ecotope Agent. The Domestic Agent can be divided into the Urban Domestic Agent and the Rural Domestic Agent. The Primary Industry Agent can be divided into the Agricultural Agent and Forestry Animal Husbandry and Fishery Agent. The Secondary Industry Agent can be divided into the Industry Agent and Construction Industry Agent. Because the industry in Quanzhou is quite developed and its water consumption is the largest component of the total water consumption, the Industry Agent can be divided into the Thermal and Nuclear Power Industry Agent, High Water Consumption Industrial Agent and General Industrial Agent. The Tertiary Industry Agent can be divided into the Catering Industry Agent and Other Services Industry Agent. The Ecotope Agent can be divided into the Ecotope Function Agent and Ecotope Construction Agent. Each agent can be further divided into other agents in accordance with the river basin or region; however, further dividing of agents increases the complexity of the model and makes it more difficult to control the simulation precision. To achieve the optimal allocation of water resources in Quanzhou, the GovAgents are divided into one City Agent and 11 County Agents, the User Agents are divided into 25 Agents by county and the Industry Agents are divided into 3 Agents in one county. Finally, the Water Resources Agents in Quanzhou are divided into 123 Agents.

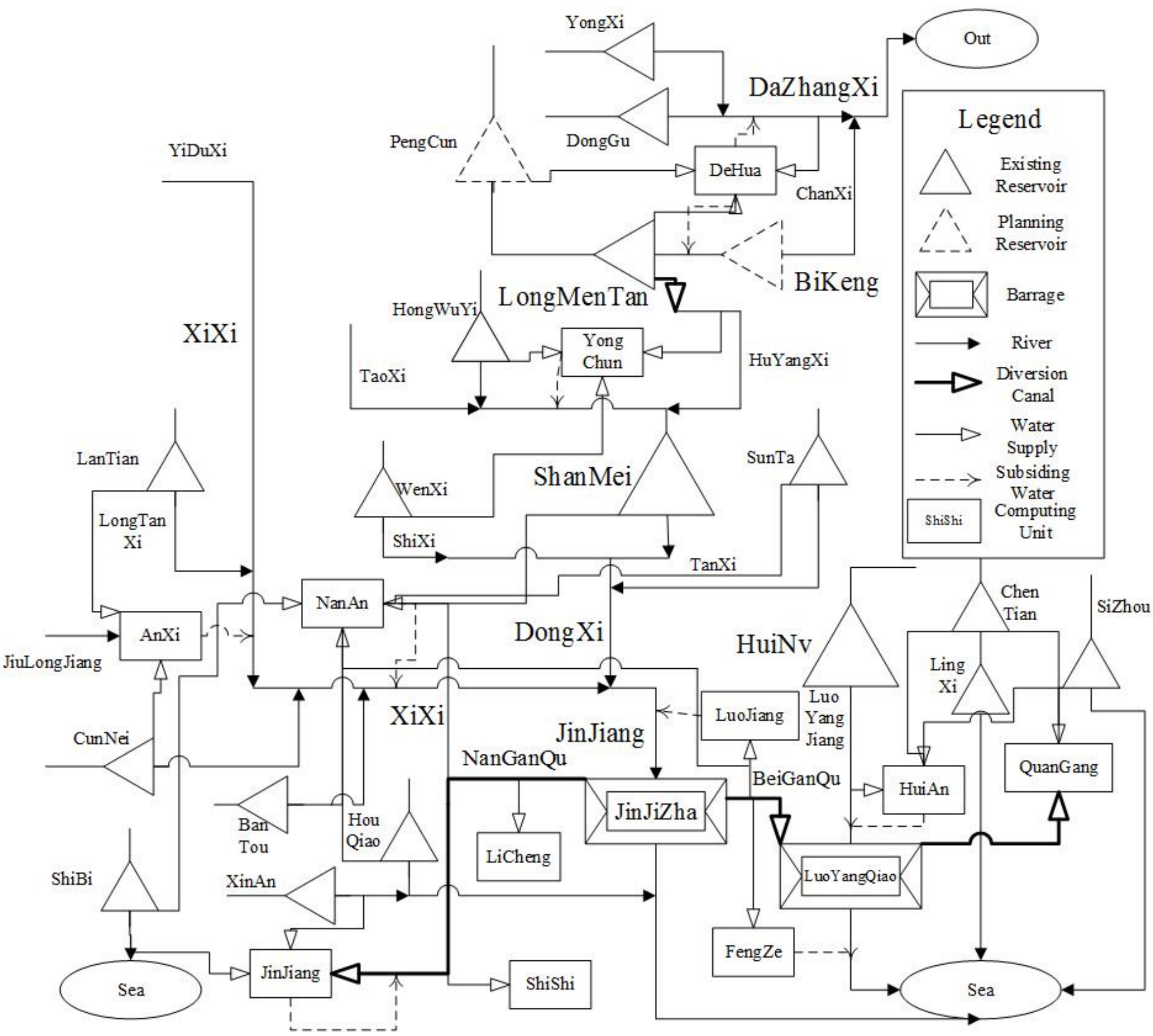

**Figure 4.** Water resources system of the generalized network for Quanzhou.

The optimization targets of the Quanzhou Agents can be expressed by the following mathematical formulas:

$$y = f(x) = (f_1(x), f_2(x), f_3(x), f_4(x), f_5(x)) \tag{4}$$

$$f_1(x) \Rightarrow maxPG = max\frac{1}{n}\sum_{k=1}^{n} PC_k \tag{5}$$

$$f_2(x) \Rightarrow maxENIG = max\sum_{k=1}^{n} ENIC_k \tag{6}$$

$$f_3(x) \Rightarrow maxSFWG = max\frac{1}{n}\sum_{k=1}^{n} SFWC_k \tag{7}$$

$$f_4(x) \Rightarrow minWEQG = min\sum_{k=1}^{n} WEQC_k \tag{8}$$

$$f_5(x) \Rightarrow maxENWG = max\sum_{k=1}^{n} ENWC_k \tag{9}$$

where $PG$, $ENIG$, $SFWG$, $WEQG$, and $ENWG$ are the comprehensive WSSI, regional economic benefit, satisfaction of the domestic water consumption, wastewater effluent and the ecotope water consumption of the Quanzhou Agents, respectively. $PC_k$, $ENIC_k$, $SFWC_k$, $WEQC_k$, and $ENWC_k$ are the comprehensive WSSI, regional economy, satisfaction of the domestic water consumption, wastewater effluent and ecotope water consumption of the County Agents, respectively. $k$ is the number of counties, $n$ is the total number of agents, $x$ is the decision variable and "⇒" represents the regulation and feedback between the agents.

The optimization targets of the County Agents are the same as those of the Quanzhou Agents and represent the regulation and feedback between the County Agents and the User Agents. The mathematical formulas are as follows:

$$z = g(x) = (g_1(x), g_2(x), g_3(x), g_4(x), g_5(x)) \tag{10}$$

$$g_1(x) \Rightarrow maxPC_k = max \sum_{i=1}^{m} P_i \times \frac{W_i}{W} \tag{11}$$

$$g_2(x) \Rightarrow maxENIC_k = max \sum_{i=1}^{m} ENI_i \tag{12}$$

$$g_4(x) \Rightarrow minWEQC_k = min \sum_{i=1}^{m} WEQ_i \tag{13}$$

where $P_i$, $ENI_i$, and $WEQ_i$ are the WSSI, regional economic benefit and wastewater effluent of the User Agents, respectively. $W_i$ is the amount of water supply of each User Agent, $W$ is the total water supply of the County Agent, $i$ is the number of users, $m$ is the total number and $g_3(x)$ and $g_5(x)$ are the behavior patterns of the Domestic Agent and Ecotope Agent, respectively.

The following formula can represent the relationship between the satisfaction of the domestic water consumption and the amount of domestic water consumption (Zhao, 2003):

$$g_3(x) \Rightarrow maxF = \max\{0.5qt - 0.14\left(\frac{Inc}{Pr} - 100\right)^{0.5} \times qt\} \tag{14}$$

where $F$ is the satisfaction of the domestic water supply, $qt$ is the quota of the domestic water consumption ($m^3/capita/month$), $Inc$ is the income of per capita ($yuan/month$) and $Pr$ is the price of water ($yuan/m^3$).

Currently, the concept of sustainable development has become increasingly popular, and governments in China are starting to focus on establishing an ecological civilization. As a result, scientists are conducting an increasing amount of research on ecotope water supplies. The Ecotope Agent cannot initiate interactions with other Agents or the environment. It can only passively respond to the behavior of the other agents; thus, its self-regulation ability is limited.

The water supply of the Ecotope Agent is determined by the GovAgent. The economic benefit of the Ecotope Agent is not calculated, but because it is part of the total water supply under certain conditions, larger values yield overall better results.

$$g_5(x) \Rightarrow maxW_{eco} \tag{15}$$

where $W_{eco}$ is the ecotope water supply.

The design philosophy of the optimal allocation model based on the WRMASSM is illustrated in Figure 5. First, the primary allocation of water resources under the long-series inflow condition was tentatively determined by the parameters (see Table 1) and calculated by the comprehensive WSSI for 2015. On this basis, the optimal allocation of different typical Multi-Agent system simulations is conducted for 2015 and 2020. The sub-targets are to achieve a relatively optimal status of the regional economy as well as societal and environmental benefits to achieve the optimization targets.

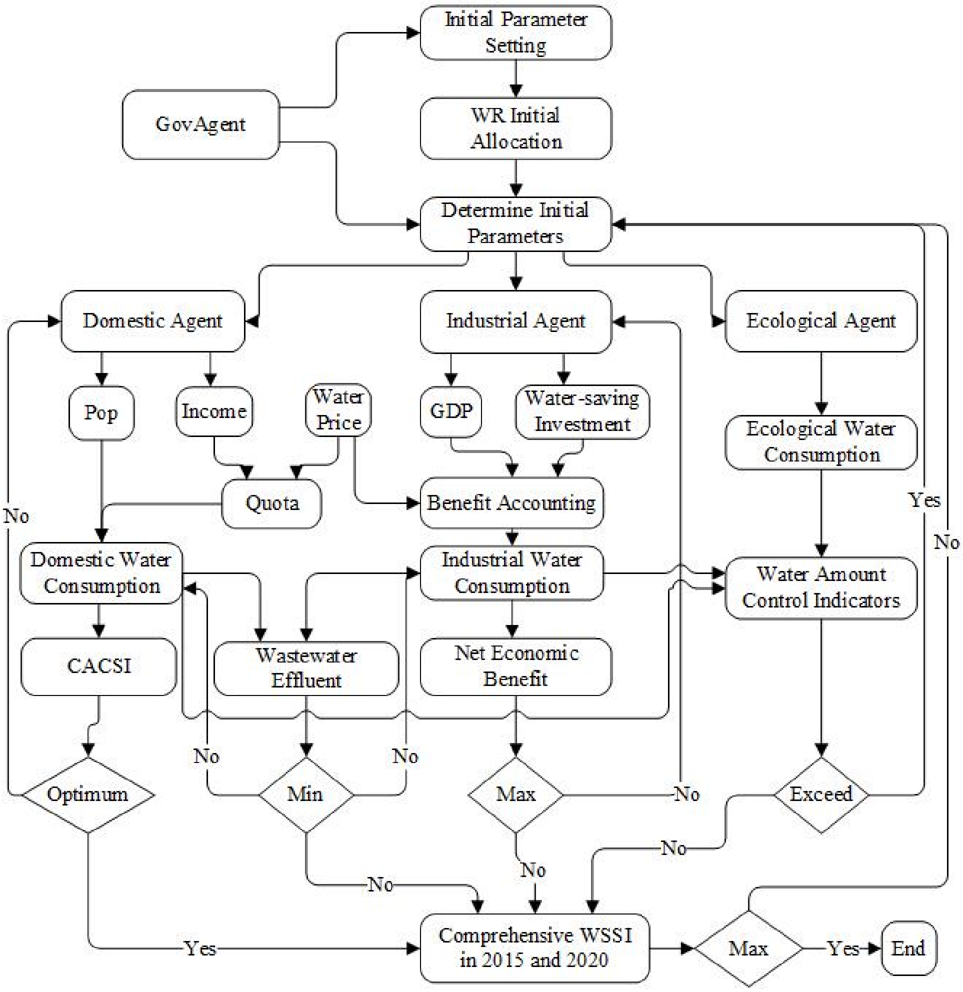

**Figure 5.** Process for calculating the optimal allocation model for water resources.

**Table 1.** Initial values of water efficiency indexes in 2015 and 2020 in Quanzhou.

| NO. | Category | Indexes | 2015 | 2020 |
|---|---|---|---|---|
| 1 | Comprehensive | Water consumption per 10,000 GDP ($m^3$/10,000 yuan) | 52 | 33 |
| 2 | | Comprehensive water consumption per capita ($m^3$/per capita) | 400 | 415 |
| 3 | Agricultural Water Conservation | Area ratio of water-saving irrigation projects (%) | 67 | 70 |
| 4 | | Effective coefficient of irrigative water utilization | 0.55 | 0.60 |
| 5 | Industry Water Conservation | Water consumption per 10,000 yuan of value-added by industry ($m^3$/10,000 yuan) | 48 | 35 |
| 6 | | Repetitive water use rate of industry (%) | 85 | 88 |
| 7 | Domestic Water Conservation | Penetration rate of urban water-saving appliances (%) | 92 | 95 |
| 8 | | Leakage rate of the urban water supply pipe network (%) | 9 | 8 |
| 9 | Construction Industry and Tertiary Industry Water Conservation | Water consumption per unit of building area ($m^3$/$m^2$) | 0.7 | 0.5 |
| 10 | | Water consumption per 10,000 yuan of value-added by tertiary industry ($m^3$/10,000 yuan) | 7 | 5 |

The water supply sequences of different users set in the model are as follows. The ecological base flow was reserved first and then the domestic water demand was met, followed by the water demands of the second and third industries. Then the water demand of the first industry was met, followed by the urban environment water demand and finally the ecotope water demand. The water demand values were predicted by the methods in reference [53] with the parameters listed in Table 1.

The step time of the model was months, and there are 684 months during the 1956–2011 period. However, the duration period of the WSSI computation is in years. Therefore, the total computation period $n$ was 56.

Some important constraint equations in the model are as follows:

1. Control of the total water consumption. The average value of the water supply under the long-series hydrological condition should not exceed the amount determined by the superior government.

$$\overline{W} \leqslant W_{Ctl} \tag{16}$$

where $\overline{W}$ is the average value of water supply in the allocation and $W_{Ctl}$ is the maximum total water consumption determined by Fujian Province, which was 3.433 billion m$^3$ for 2015 and 3.637 billion m$^3$ for 2020.

2. The water quality standard. Different users have different standards of water quality in China. The water supply should meet the lowest standards of water quality.

$$R \leqslant R_{Std} \tag{17}$$

where $R$ is the rank of the water supply quality in the allocation and $R_{Std}$ is the rank of the water quality in the national standard of China. There are five ranks (I-V) for $R_{Std}$. The national standard for both surface water and groundwater is organized such that a higher rank indicates poorer water quality. The rank of the domestic water supply quality should be smaller than III.

Some other constraint equations can be found in reference [14].

## 4. Results

### 4.1. Allocation Results for Quanzhou

According to the long-series optimal allocation (see Table 2), the average water supply of Quanzhou in 2015 was 3.433 billion m$^3$, but the average water demand was 3.486 billion m$^3$. The average water supply in 2020 was estimated to be 3.673 billion m$^3$, but the average water demand will be 3.712 billion m$^3$. Neither year exceeds the controlling indicators for total water consumption. From the perspective of the water supply sources, surface water still occupies the primary position, accounting for 91.6% of the total water supply; groundwater accounts for 7.3%, and non-traditional water sources account for 1.1% in 2015. The proportion structure in 2020 is nearly identical.

**Table 2.** Average water supply and WSSI of User Agents after the long-series optimal allocation.

| User Agents | 2015 | | 2015 (5% Reduction) | | 2020 | | 2020 (10% Reduction) | |
|---|---|---|---|---|---|---|---|---|
| | Supply | WSSI | Supply | WSSI | Supply | WSSI | Supply | WSSI |
| Domestic | 4.80 | 94.7% | 4.79 | 93.0% | 5.14 | 98.2% | 5.10 | 96.5% |
| Primary Industry | 10.72 | 75.4% | 10.67 | 70.2% | 11.50 | 89.5% | 11.50 | 80.7% |
| Secondary Industry | 15.40 | 93.0% | 15.39 | 91.2% | 16.44 | 94.7% | 16.28 | 91.2% |
| Tertiary Industry | 1.37 | 91.2% | 1.37 | 89.5% | 1.47 | 96.5% | 1.45 | 93.0% |
| Ecotope | 2.04 | 82.5% | 2.04 | 78.9% | 2.18 | 91.2% | 2.16 | 86.0% |
| Quanzhou | 34.33 | 87.1% | 34.26 | 84.1% | 36.73 | 93.4% | 36.50 | 88.4% |

Note: The water supply is in units of 10$^8$ m$^3$.

The annual comprehensive WSSI in 2015 was 87.1%. In the inflow conditions of 1967, 1971, 1982, 1991, 2004, and several other years, the water supply is insufficient and a water shortage occurs in the primary industry and environmental water supply. Due to the construction of the planned water supply, the comprehensive WSSI of Quanzhou will be improved in 2020, reaching 93.4% (Figure 6).

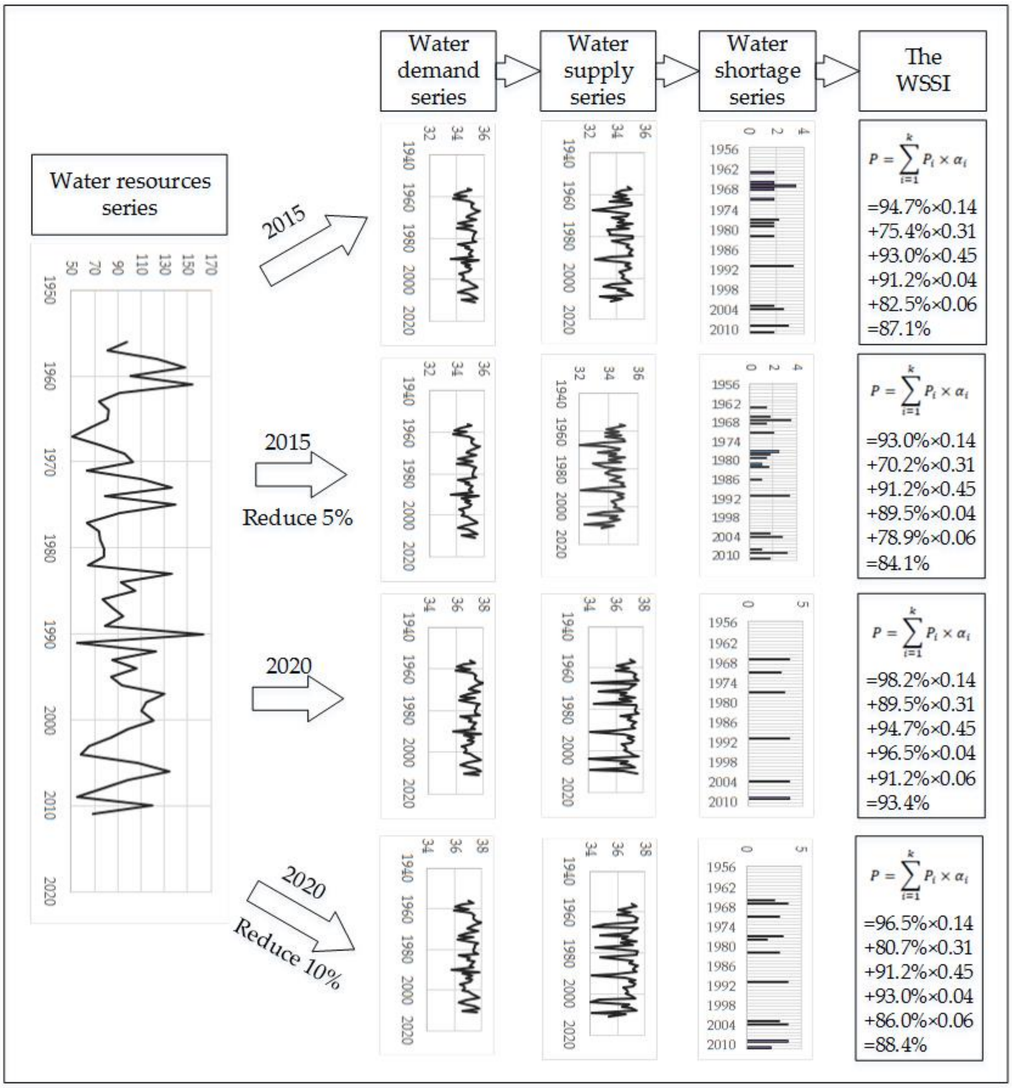

**Figure 6.** Allocation results and WSSI in Quanzhou. Note: The units for water resources, water demand, water supply, and water shortage are $10^8$ $m^3$.

In our former scenario, the total water resources will be reduced under the influence of climate change and human activities, and after the optimal allocation, the average water supplies in 2015 and 2020 are 3.426 and 3.650 billion $m^3$, respectively. The comprehensive WSSI will decrease significantly in 2015 and 2020, reaching 84.1% and 88.4%, respectively (Figure 6).

### *4.2. Allocation Results for the Counties*

The allocation results are given in Table 3 for each of the counties. The WSSI values were higher for the counties located in the upper reaches, such as Anxi County, Yongchun County and Dehua County. For those counties under the constraint of total water control, the WSSI in 2015 were above 96% and in 2020 more than 98%. However, in Hui'an County (Quanzhou Taiwanese Investment Zone included), due to the rapid development of the industrial economy, the amount of water demand increased rapidly and the regional comprehensive WSSI was relatively lower at 84.2% in 2015 and 79.5% in 2020. The counties located downstream of Quanzhou (Licheng District, Fengze District, Luojiang District), due to the shortage of water resources, and the increase of environmental water demand, the comprehensive WSSI values were relatively lower, under 93% in 2015 and 2020. Because the water diversion from the Jinjiang River increased significantly, the water supply met almost all of the water demands and the comprehensive WSSI reached 96.2% in 2015 and 97.8% in 2020.

**Table 3.** Average water supply and WSSI of counties after the long-series optimal allocation.

| **County** | **2015** | | **2015 (5% Reduction)** | | **2020** | | **2020 (10% Reduction)** | |
|---|---|---|---|---|---|---|---|---|
| | **Supply** | **WSSI** | **Supply** | **WSSI** | **Supply** | **WSSI** | **Supply** | **WSSI** |
| Lichen | 1.62 | 90.2% | 1.60 | 82.8% | 1.97 | 92.2% | 1.95 | 90.5% |
| Fengze | 2.32 | 89.5% | 2.30 | 82.5% | 2.71 | 91.5% | 2.71 | 90.7% |
| Luojiang | 0.70 | 88.4% | 0.70 | 88.4% | 0.74 | 92.4% | 0.73 | 91.1% |
| Quangang | 2.51 | 90.3% | 2.50 | 81.2% | 3.02 | 91.3% | 3.02 | 91.3% |
| Jinjiang | 2.23 | 96.2% | 2.23 | 96.2% | 2.44 | 97.8% | 2.44 | 97.8% |
| Shishi | 6.41 | 86.6% | 6.41 | 86.6% | 6.55 | 93.4% | 6.55 | 93.4% |
| Nan’an | 5.56 | 85.8% | 5.56 | 85.8% | 5.69 | 89.5% | 5.60 | 88.2% |
| Hui’an | 3.61 | 84.2% | 3.60 | 81.3% | 3.78 | 79.5% | 3.66 | 74.2% |
| Anxi | 4.07 | 96.5% | 4.07 | 96.5% | 4.13 | 98.2% | 4.13 | 98.2% |
| Yongchun | 2.81 | 96.2% | 2.81 | 96.2% | 3.08 | 98.1% | 3.08 | 98.1% |
| Dehua | 2.47 | 96.6% | 2.47 | 96.6% | 2.63 | 98.3% | 2.63 | 98.3% |

Note: The water supply is in units of $10^8$ $m^3$.

For the reduction of the long series water conditions, the comprehensive WSSI in Licheng District, Fengze District, Luojiang District, Quangang District and Hui’an County decreased accordingly and distinctly.

### *4.3. Allocation Results of the Users*

For the Quanzhou users’ WSSI, due to the water supply sequences set in the model, after optimization the WSSI values of the Domestic Agent, Tertiary Industry Agent and Secondary Industry Agent reached nearly 100% in 2015 and 2020 with and without reductions in the long-series inflow, with the exception of Hui’an County. The WSSI values of the Primary Industry Agent in Jinjiang County, Anxi County, Yongchun County and Dehua County exceeded 80% in 2015 and 2020, but in the urban district, the WSSIs values were relatively low at approximately 50%. Due to the developed industrial economy of the Quanzhou Taiwanese Investment Zone in 2020 in Hui’an County and in the absence of water rights transactions under the premise, there were some water shortages in the Secondary Industry Agent, and the WSSI decreased from 95.1% in 2015 to 88.3% in 2020.

For the Thermal and Nuclear Power Industry Agent, the High Water Consumption Industrial Agent and the General Industrial Agent of the Secondary Industry Agent, due to the allocation order, in addition to Hui’an County, the WSSI values of the other counties all achieved 97%+ in 2015 or 2020. The WSSI of all the Secondary Industry Agents in Hui’an County were 95%+ in 2015, but in 2020 the WSSI of the High Water Consumption Industrial Agent decreased to 90.1%, of the General Industrial Agent decreased to 85.7% and only the Thermal and Nuclear Power Industry Agent reached 95.2%.

## 5. Discussion

### *5.1. Allocation of Water Resources with the Long Series Can Enable a Comprehensive Evaluation of WSS*

Hydrological time series have a certain periodicity and randomness due to the effects of natural and random factors. A typical year of hydrological data with the long series can be determined based on the calculated frequency. For the majority of the traditional water resources allocations, the allocation processes were computed using the typical year method due to the simplified calculation procedure and reduced data requirements. However, the typical year method, which calculates the allocation process of one year, only reflects the condition of precipitation, water resources and water demands in that year. Although the optimal allocation of water resources in one typical year was performed, water resources in other years have a similar frequency but different allocation processes. The results cannot represent the change process and dynamic evolution of water resources. In recent years, the development of technologies for allocating water resources has led to long-series allocation technology becoming the primary method used [9].

There are several variations in precipitation and irrigation water demand in the planning years. Because the hydrological time series occurred in the past few decades, nearly all possibilities of precipitation in the planning year could be considered. Water resources allocation with the long series data could consider all of the water supply and demand scenarios. The data also contains water allocation results for all of the states regardless of whether WSS has been achieved. Based on the explanations above, the WSS evaluation could be conducted in a more comprehensive manner.

Static WSS evaluation represents a type of water supply status determined by rainfall and future water supply potential and is only one possibility. However, there are a variety of possibilities for precipitation and water demand in the future.

In addition, the value of WSSI in this study indicated that security was not established and that this threshold was determined subjectively. The WSS should be an expression of an objective condition, that continuously changes with economic and social development and advances in science and technology. The current state of security may become unsafe in the future with future increases in demand.

### *5.2. Changes in the Environment Can Affect the Allocation Results and WSS*

Changes in the environment, including climate change and human activities, have a significant impact on the allocation of water resources and WSS [54,55]. Environmental changes may lead to decreases in the quantity of natural water, increased water demands [39], and reduced reliability in the water allocation [55]. In contrast, the water supply will increase with advancements in project construction and operation and improvements in the water resources management level [56].

For Quanzhou, a city affected by environmental changes, the results of the water resources allocation indicated that the average water demand increased from 3.486 billion m$^3$ in 2015 to 3.712 billion m$^3$ in 2020, representing a 6.5% increase. If there were no reduction in water resources, the average water supply would increase from 3.433 billion m$^3$ in 2015 to 3.673 billion m$^3$ in 2020 with a growth rate of 7.0%. However, if any worsening in the condition of water resources occurs, the average water supply will increase from 3.426 billion m$^3$ in 2015 to 3.650 billion m$^3$ in 2020 with a growth rate of 6.6%.

According to the WSSI values obtained, the WSS in 2020 is significantly higher than that in 2015 (increasing from 87.1% to 93.4%, or 6.4%). In the case of increased water demand, the status of the water supply is safer, which indicates that the regional WSS could be measurably improved via project construction and operation and improvements in the water resources management level. However, in terms of whether the time series were shortened, the natural water resources decreased, leading to water shortages in certain years, which was a threat to WSS. The WSSI values in 2015 and 2020 decreased by 2.9% and 5.0%, respectively.

### *5.3. Applicability of This Model*

This model has extensive applicability. The model was applied to the water resources allocation of the Sanjiang Plain in Northeast China and achieved satisfactory results.

The Sanjiang Plain is the confluence area of the Heilong River, Songhua River and Wusuli River, located in the region of 43°49′55″ N–48°27′40″ N, 129°11′20″ E–135°05′26″ E, where 23 counties cover a gross area of 108,900 km$^2$. The availability of local water resources is limited, but the transit water resources of the three rivers are rich. After years of development and construction, the Sanjiang Plain has become an important grain production base and energy base and has made important contributions to China's social and economic development. According to China's general development requirements and its local characteristics and natural advantages, the Sanjiang Plain will develop into a nationally important rice-based grain production base, with coal, electricity and chemical developments as well as ecological demonstration zones as the core of natural wetland protection in the future. Under the guidance of the basic state policy of ensuring food security and the policy of revitalizing the old northeast industrial base, a study on the optimal allocation of water resources was conducted based on ensuring WSS in the Sanjiang Plain. After the allocation was optimized, the regional water demands were 20.870 billion $m^3$ in 2020 and 21.408 billion $m^3$ in 2030. The water demands increased significantly compared with 2015. Assuming that local water resources are fully utilized, with the new diversion of water resources of 6.779 billion $m^3$ in 2020 and 7.503 billion $m^3$ in 2030 from three rivers, the regional water demand can be met and the regional WSS can be ensured. The WSSI increased from 70.2% in 2015 to 75.4% in 2020 and 80.1% in 2030.

The WSSI values in the Sanjiang Plain were smaller than those in Quanzhou City, primarily because the agricultural water demand in the Sanjiang Plain was the largest and the degree of agricultural WSS was considerably smaller than the industrial portion. Future research should focus on methods to improve the WSS in Sanjiang Plain.

## 6. Conclusions

Water is the source of life, the foundation of production, and the basis of ecology. By accounting for water security, the water conservancy department guarantees the economic and societal development and environmental safety. However, water shortages are a serious problem, and enforced water management is needed, requiring the strictest water resources management in every aspect. Therefore, with the function of flood control as a priority, water resource allocation should also ensure the WSS of users in accordance with the strictest water resources management.

1. WSS means that under current economic and technical conditions, considering the actual water demand, the regional water supply system should achieve the acquired satisfactory level in terms of water quantity, quality, continuity and economic efficiency, and possess the ability to respond to risks and impacts of special circumstances within an acceptable range. There are five basic properties of WSS: relativity, systematism, limitedness, dynamism and economy. The WSSI can be used to measure the degree of WSS and can be computed by adopting the empirical frequency formula.
2. The WRMASSM based on the CAS can be used to allocate water resources. With the target of maximizing the comprehensive WSSI in Quanzhou, the model has achieved the optimal allocation of regional water resources and ensured the security of the regional water supply.
3. The allocation results of Quanzhou indicated that the level of regional comprehensive WSS was significantly influenced by the capacity of water supply projects and the conditions of natural water resources. The allocation results and the WSSI were significantly affected by reductions in precipitation, decreases in the water yield coefficient, and changes in the underlying surface.

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