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Water Resources Compound Systems: A Macro Approach to Analysing Water Resource Issues under Changing Situations

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Abstract: Water resource crises are an increasing threat to human survival and development. To reveal the nature of water resource issues under changing situations, the water resources system needs to be studied from a macro and systematic perspective. This report develops a water resources system into a water resources compound system that is constantly evolving under the combined action of the development, resistant, and coordination mechanisms. Additionally, the water quotient is defined as a quantitative representation of the sustainable development state of the water resources compound system. Four cities in China, Beijing, Fuzhou, Urumqi, and Lhasa, were selected as the study areas. The differences in the three types of mechanisms and the water quotient of the water resources compound system of each city in 2013 were compared. The results indicate that the different subsystems that comprise the compound system of a given area have different development mechanisms and resistant mechanisms. There are clear differences in the mechanisms and the water quotients for the water resources compound systems of different regions. Pertinent measures should be taken into account during integrated water resource management to improve the sustainable development status of regional water resources compound systems.

Keywords: water resources; compound system; water quotient; sustainable development; atmosphere system; mechanism

1. Introduction

Water resources provide human beings with clean drinking water, irrigation water, and industrial water. The hydrological cycle has changed profoundly due to climate change and increasing population [1]. The quantity and quality of available freshwater in several regions has become severely restricted [2,3]. Because of the differences within the time-space of water resource distribution, some of the population on Earth is experiencing a severe strain on its water resources [4]. Hence, there is an emerging water resource crisis [5–7].

The World Commission on Environment and Development (1987) is responsible for defining the idea of sustainable development. This definition states that water resources should be managed such that neither the present nor the future needs are compromised [8]. Water resources influence several international borders [9] because their management involves different stakeholders. The management pattern, which is led by a single goal, has encountered numerous difficulties in practice. The cooperation of regions and water basins must be strengthened to become the basis for managing integrated water resources and achieving its sustainable development [10–12]. The study on water resources is gradually expanded to focus on the entire system. The economic-engineering optimization model used for the optimization of the water resources system enriched the evaluation method of the macro-system, which considered data related to surface water, groundwater, water infrastructure, and water demand [13]. Inexact Multistage Stochastic Integer Programming integrated the fixed-charge cost functions to reflect the complexity and the dynamic characteristics of the system [14]. The system dynamics method established a communication platform between the public and the decision makers to lead a discussion on the interpretation and the strategic intent of this resource [15]. Water resource management policies and their sustainability can be evaluated by the Water Sustainability Index, which also determines whether a policy can be promoted to achieve its targets [16]. Because the water resources system data is extremely extensive, building a web of information that integrates all aspects of the information can improve the comprehensive level of its management and its flexibility [17]. In recent years, the methods used for water resource management and the sustainable development of water resources under changing environments have been constantly pursued through interdisciplinary studies [18]. To manage the rising challenges [19–21], a mutual cooperation between research, management, and policy measures should be formed [22]. By using a suitable model to evaluate the status of regional water resources against the background of climate change, the environment adaptability of the vulnerable water resources system can be improved [23].

The above methods, which selected the water resources system as the research objective, have improved the level of the integrated water resource management. However, along with social and economic developments, the attributes and functions of the water resources become more diversified [24]. The relationship between the water resources systems and the outside systems, such as social, economic, and ecological environment systems, has become more complex and interlinked [25,26]. It is necessary to consider the comprehensive connection between the different systems when studying integrated water resource management. This study aims to establish a macro and systemic method that reveals the nature of water resource issues under changing situations and provides a decision-making basis for integrated water resource management. In this report, the water resources system is developed into a water resources compound system, which uses the water resources system as a link through close contact with the atmospheric system, social economic system, and ecological environment system to constitute a macrocosm. The complexity of the structure of this compound system leads into its complex mechanisms. These mechanisms are generalized into a development mechanism, resistant mechanism, and coordination mechanism, which represent the factors that promote the development of the water resources compound system, factors that cause the recession of the compound system, and feedback that coordinates the above two functions, respectively. Because the water resources compound system has feedback characteristics and is based on the concepts of intelligence quotient, emotion quotient, and spiritual quotient [27] as well as the characteristics of the three types of mechanisms, the water quotient can be defined as a quantitative representation of the sustainable development condition of the compound system. Initially, the connotations and the mechanisms of the water resources compound system are discussed, and the calculation method of the water quotient is then introduced. Four cities in China, Beijing, Fuzhou, Urumqi, and Lhasa, were selected as the study areas to use this method to compare the sustainable development status of the compound system in each city.

2. Materials and Methods

2.1. Water Resources Compound System

Water resources form the core of the entire water resources system. The global atmospheric system is involved in the production, transformation, and consumption of the water resources on

Earth. Furthermore, the water resources act as a medium for water to become a part of the global atmospheric system. These water resources and the atmospheric system are interdependent and inseparable. Therefore, the atmospheric system and the water resources system have an equally important status and function.

To achieve a sustainable development of the water resources, it is necessary to study water resources from the perspective of system research. The regional water resources system is affected by itself and the atmospheric system and has a close link with the regional economic and social development, human water activity, and regional ecological environment. In this study, the regional water resources systems have been used as the basis and the link of the systems. The closely connected atmospheric system, social economic system, and ecological environment system are regarded as separate systems that have their own characteristics but the same subject position as that of the water resources system. The water resources compound system is comprised of the above four subsystems (Figure 1). The operation and change in the compound system is affected by the subsystems simultaneously. The compound system's structure is a combination of these four subsystems, and its function follows the characteristics of each subsystem but with its own unique characteristics.

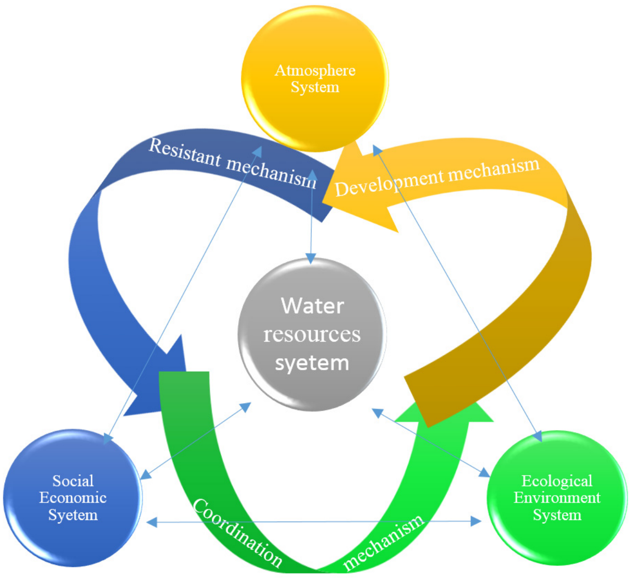

Figure 1. Five subsystems and three mechanisms of the water resources compound system.

2.2. Mechanisms of Water Resources Compound System

The water resources compound system has a connection with the external factors. There is an interaction between each subsystem as well as an interaction between the elements of each subsystem. The elements of the water resources compound system connect with each other and play a role through several mechanisms as well as contribute to the evolution of the entire compound system. This study summarizes the mechanisms of the water resources compound system as the development mechanism, resistant mechanism, and coordination mechanism.

There are factors that exist in the water resources compound system that maintain its existence and promote its evolution. These factors accelerate the change in the compound system from a normal state to a sustainable development state. Their role drives the development mechanism of the water resources compound system. The water resources compound system meets the resistant factors, which restrict its development and cause its decline in different stages of development. These factors prevent and restrict the normal operation of the water resources compound system, thus forming the resistant mechanism. The factors and subsystems of the water resources compound system are affected by the common influence of the development and resistant mechanisms and feed back to this influence. These effects encourage the compound system to overcome the resistant barriers and achieve sustainable development. This coordination function constitutes the coordination mechanism of the water resources compound system.

2.3. Calculating the Water Quotient

The development mechanism, resistant mechanism, and coordination mechanism of the water resources compound system are mutually connected and restricted, hence allowing the compound system to be a complex system of self-organization and self-correction. The water quotient is introduced to indicate the sustainable development status of the water resources compound system, and it is a comprehensive quantification of the above three mechanisms.

Based on the regional characteristics and research requirements as well as the principles of systematicness and hierarchy selection indicators, an evaluation index system was constructed (Table 1).

Table 1. Evaluation index system.

Subsystem	Indicator	Indicator Type
Water Resources System	Volume of sewage emission per capita (L/people day)	cost
	Water consumption per 10,000 Yuan RMB in GDP (m^3/10,000Yuan)	cost
	Total volume of water resources (m^3)	efficiency
	Volume of water resources per capita (m^3/people)	efficiency
Atmosphere System	Aridity Index	cost
	High temperature days (day)	cost
	Annual precipitation (mm)	efficiency
	Annually average relative humidity (%)	efficiency
Social Economic System	Population growth rate (%)	cost
	Population density (people/km^2)	cost
	Investment in wastewater treatment (10,000 Yuan)	efficiency
	Per capita GDP (Yuan)	efficiency
Ecological Environment System	Average concentration of ammonia nitrogen in water (mg/L)	cost
	Annual concentration of PM2.5 (μg/m^3)	cost
	Ecological Index	efficiency
	Eco-environmental water consumption rate (%)	efficiency

Notes: (1) Calculation of the Ecological Index references [28]; and (2) High temperature days: days throughout the year in which the highest temperature is no less than 35 °C; (3) Total volume of water resources is the volume of freshwater in an existing water body.

Each subsystem contains two types of indicators: one with a category value as small as possible, known as the type cost index, and the second with an index value as large as possible, known as the efficiency index [29]. Equations (1) and (2) can be used to standardize the two types of indicators as follows:

$$x_{iC} = \frac{I_{\max} - I_i}{I_{\max} - I_{\min}} \tag{1}$$

$$x_{iE} = \frac{I_i - I_{\min}}{I_{\max} - I_{\min}} \tag{2}$$

where x_{iC} and x_{iE} are the two types of indicator values after standardization; I_i represents the raw value, and $I_{\min}$ and $I_{\max}$ are the lower limit and the upper limit of the raw indicator, respectively.

The development mechanisms of each subsystem and the water resources compound system can be calculated using Equations (3) and (4) as follows:

$$D_n = \sum_{i=1}^{m} \alpha_i x_i \tag{3}$$

$$D = \sum_{n=1}^{4} \beta_n D_n \tag{4}$$

where m is the number of indicators in each subsystem ($m = 4$); x_i is the standardized indicator; α_i is the index weight, $\sum_{i=1}^{m} \alpha_i = 1$; β_n is the weight of each D_n when calculating the value of D; and $n = 1, 2, 3, 4$ represents the water resources system, atmospheric system, social economic system, and ecological environment system, respectively.

The resistant mechanism of each subsystem and the water resources compound system can be calculated using Equations (5) and (6) as follows:

$$R_n = 1 - \frac{\sum x_{iN}}{2} \tag{5}$$

$$R = \frac{1}{4} \cdot \sum_{n=1}^{4} R_n \tag{6}$$

where x_{iN} is the value of the standardization indicator for the type cost indicators of each subsystem; R_n is the resistant mechanism of each subsystem; and $n = 1, 2, 3, 4$ corresponds to the water resources system, atmospheric system, social economic system, and ecological environment system, respectively. The coordination state of the compound system is associated with the development mechanism of each subsystem and the coupling condition between each subsystem. The coupling degree is calculated to reflect the degree of coupling between the subsystems. Because the water resource subsystem is the core of the compound system, Equation (7) can be used to calculate the coupling degree (C_0) between the subsystems as follows:

$$C_0 = 2 \cdot \sum_{j=2}^{4} \gamma_j \frac{\sqrt{D_1 \cdot D_j}}{D_1 + D_j} \tag{7}$$

where γ_j represents the weight of cohesion between the water resources system and the atmospheric system, social economic system, and ecological environment system. When calculating the coupling degree, $j = 2, 3, 4$ corresponds to the above three types of coupling relationships.

The coordination mechanism of the compound system can be calculated using Equation (8) as follows:

$$C = \sqrt{D \cdot C_0} \tag{8}$$

Equation (9) can be used to calculate the water quotient as follows:

$$WQ = \frac{C \cdot D}{R} \tag{9}$$

The threshold values of the standardized indices, the three mechanisms, the coupling degree and the water quotient are (0,1). If the value is nearer to 1, it means the sustainability status is better; on the contrary, the sustainability status is worse when the value is nearer to 0. The weights of the above formulas are calculated using the Analytic Network Process method [30].

2.4. Case Study

There are several complex and diverse climate types within the six climactic zones in China. In this report, the 200 mm, 400 mm, and 800 mm isohyetal lines in China were selected as the boundary, with the four selected study areas of Beijing, Fuzhou, Urumqi, and Lhasa situated on different sides of these boundaries (Figure 2). The color in Figure 2 indicate the provinces of China. The data used in this study is obtained from these four cities in 2013. The water quotient of each area was compared to reveal the mechanisms of the water resources compound system of the four cities and reflect the similarities and differences of their respective sustainable development conditions.

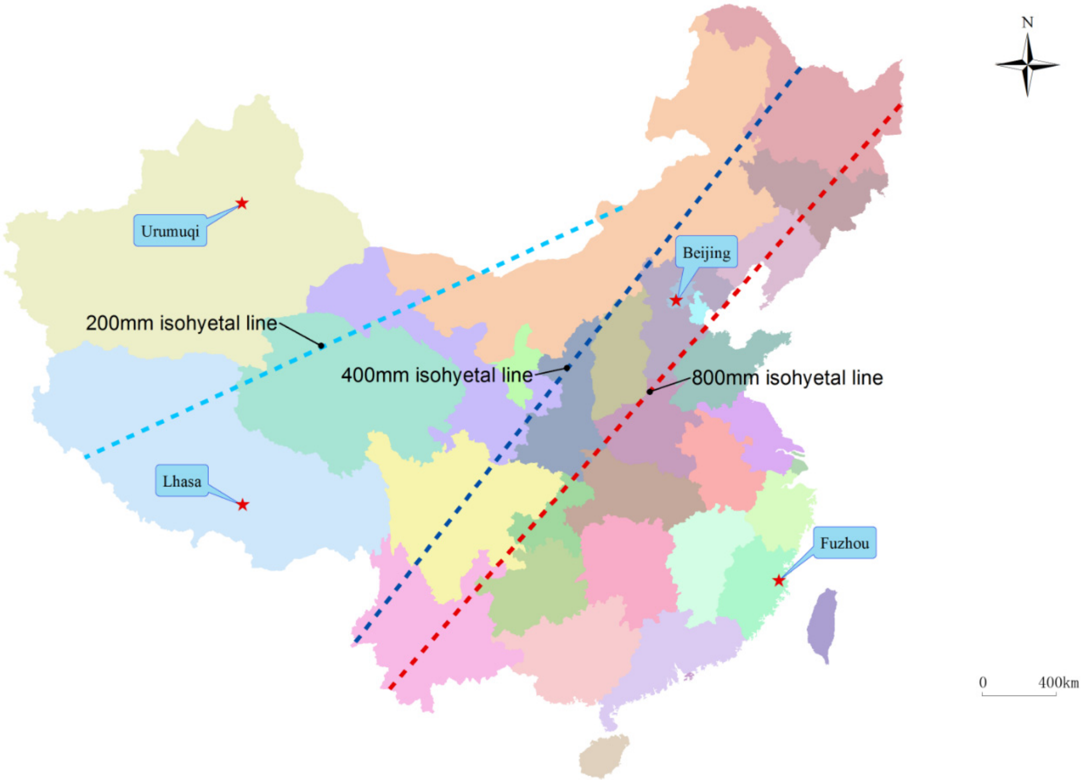

Figure 2. Location map of the study areas.

Beijing is located in the north temperate zone with a moist, semi-arid monsoon climate, a hot and rainy summer, and a cold and dry winter. Fuzhou is located in the southeast coast of China facing the Pacific Ocean to the east with a typical subtropical monsoon climate. Urumqi is located in the middle of the north western province of Xinjiang. It is the farthest city from the sea in the world and is located in the intermediate continental dry climate zone. Lhasa is located in the central part of the Tibetan Plateau, which is north of the Himalayas, in a temperate zone with a semi-arid monsoon climate.

The indicators in this study were primarily selected from original statistical data or calculated based on the original statistical data. The original statistical data from 2013 was obtained from the following sources: Beijing Statistical Yearbook, Beijing Water Resources Bulletin, Beijing Environment Statement, Fuzhou Statistical Yearbook, Fuzhou Water Resources Bulletin, Fuzhou Environment Statement, Urumqi Statistical Yearbook, Urumqi Water Resources Bulletin, Lhasa Statistical Yearbook, Lhasa Water Resources Bulletin, as well as the meteorological data from the four cities. To compensate for the lack of data in the information above, three experts were selected from each of the four cities and provided with four rounds of anonymous questionnaires to complete using the Delphi method [31].

3. Results and Discussion

Table 2 represents the indicator data value of the four cities in 2013. The results of the development mechanism, resistant mechanism, coordination mechanism, coupling degree, and water quotient are presented in Table 3. It can be observed that Fuzhou has the highest water quotient, with a value of 0.9983. The water quotient of Beijing is the lowest of the four cities studied, *i.e.*, 0.4292, which is less than half the value of that in Fuzhou. The water quotients of Urumqi and Lhasa are 0.8433 and 0.5449, respectively.

Table 2. Indicator values of the water resources compound system of the study areas in 2013.

Subsystem	Indicator	Beijing	Fuzhou	Urumqi	Lhasa
Water Resources System	Volume of sewage emission per capita (L/people·day)	201	164	124	131
	Water consumption per 10,000 Yuan RMB in GDP (m^3/10,000Yuan)	18.67	66.35	17.80	101.36
	Total volume of water resources (m^3)	24.81	86.04	13.22	82.03
	Volume of water resources per capita (m^3/people)	118.60	1240	502.80	2367.73
Atmosphere System	Aridity Index	1.40	0.50	1.60	2.40
	High temperature days (day)	10	41	7	0
	Annual precipitation (mm)	501	1393.90	294	565.20
	Annually average relative humidity (%)	53.33	75.67	60.67	37.25
Social Economic System	Population growth rate (%)	2.19	1.56	1.99	1.53
	Population density (people/km^2)	1289	556	188	20
	Investment in wastewater treatment (10,000 Yuan)	613.08	127.79	31.07	28.69
	Per capita GDP (Yuan)	93,213	70,302	83,781	9006
Ecological Environment System	Average concentration of ammonia nitrogen in water (mg/L)	10.10	5.30	8.90	1.70
	Annual concentration of PM2.5 (μg/m^3)	88.30	31.40	87	23.60
	Ecological Index	66	73	59	63
	Eco-environmental water consumption rate (%)	1.80	4.20	0.90	1.20

Notes: (1) Total volume of water resources is the volume of freshwater in existing a water body.

Table 3. Development mechanism, resistant mechanism, coordination mechanism, coupling degree, and water quotient of the study areas in 2013.

City	Beijing	Fuzhou	Urumqi	Lhasa
Development Mechanism	0.4114	0.6005	0.4089	0.5057
Resistant Mechanism	0.6049	0.4644	0.4779	0.4191
Coordination Mechanism	0.6309	0.7719	0.6369	0.6989
Coupling Degree	0.9676	0.9923	0.9919	0.9660
Water Quotient	0.4292	0.9983	0.5449	0.8433

The development mechanism of each city is under the influence of the development situation of the four subsystems simultaneously. The development mechanism is a combination of the performance of the development levels of the four subsystems. The status of certain subsystems that belong to the water resources compound system of a city is superior whilst other subsystems are in a state of relative inferiority. Figure 3 reflects the difference in the development mechanisms of different subsystems, which is a component of the water resources compound system of each city. Furthermore, the resistant mechanism of the water resources compound system is influenced by the resistant factors of the four subsystems. It is also a comprehensive reflection of the restricted situation of each subsystem. Figure 4 depicts the difference between the resistant mechanisms of the different subsystems, which are a component of the water resources compound system of a particular city. Figure 5 reflects the differences in the mechanisms and the water quotient of the water resources compound system in the four cities.

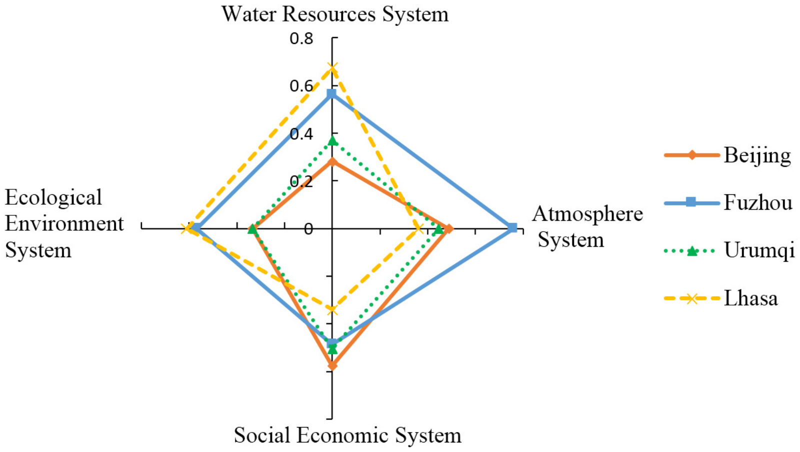

Figure 3. Radar chart of the development mechanism of the water resources compound system in the four cities in 2013.

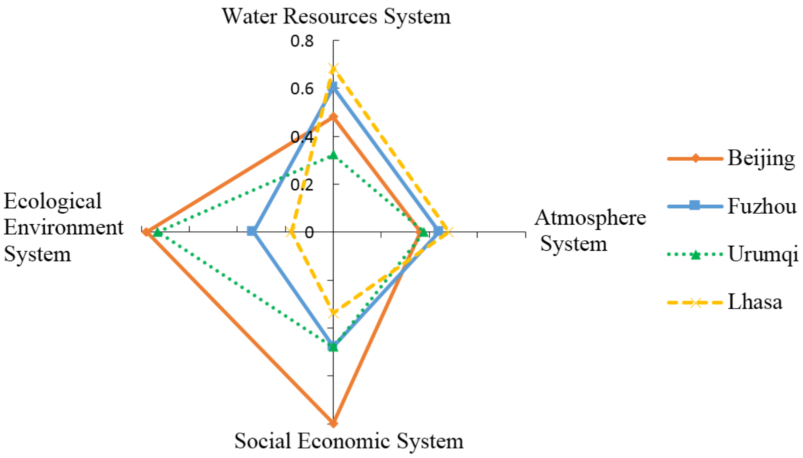

Figure 4. Radar chart of the resistant mechanism of the water resources compound system in the four cities in 2013.

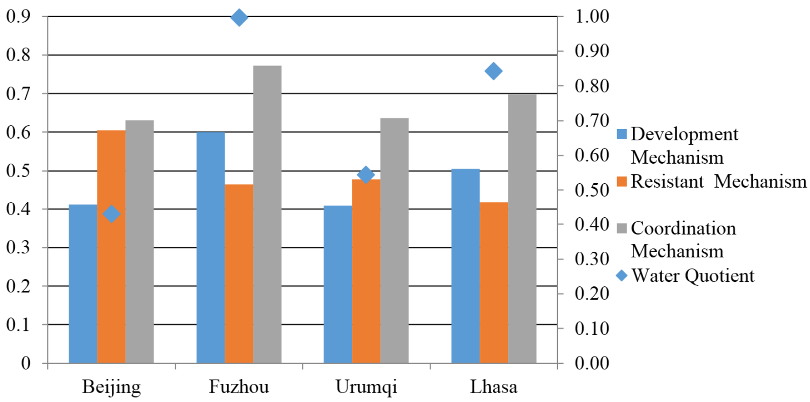

Figure 5. Comparison chart of development mechanism, resistant mechanism, coordination mechanism, and water quotient of the study areas in 2013.

The water quotient of Beijing is the lowest of the four cities, and its sustainable development status of the water resources compound system is the worst. The compound system encounters severe problems. Beijing is located in the Haihe river basin and experiences a semi-arid, continental monsoon climate. The total volume of the water resource and precipitation is generally low (Table 2). Over the years, the daily life of residents, economy, and society have produced a high dependence on the exploitation of groundwater. The region has significantly exploited its groundwater resources above its quota, thus resulting in a crisis situation [32]. Additionally, Beijing, which is the capital of China, has a high population density that is growing rapidly every year. This increase in population causes the per capita water resource level to be extremely low. In 2013, the volume of water resources per capita was only 5% of that of Lhasa. These are the reasons behind the shortage of developing power of the water resources system, and because of this shortage, it is hard to contribute to the development mechanism of the compound system.

Furthermore, the survival and development of the large population in Beijing is highly dependent on the support of the regional social economic system. The continuous growth of the population results in an enormous pressure on the social economic system in Beijing. In recent decades, pollutants discharged into the water and air by the industrial and agricultural production and the urban expansion of Beijing severely damaged the ecological environment of Beijing. In 2013, in the Beijing area, the annual average concentration of ammonia nitrogen in water and the annual average concentration of PM2.5 reached their highest levels amongst the four cities [33]. Beijing's ecological environment system is facing greater pressure than that of other cities. The resistant mechanism of the water resources compound system in Beijing is also significantly greater than that in other cities.

Unlike Beijing, Fuzhou experiences a subtropical monsoon climate. It is humid and rainy, with an annual precipitation level in 2013 of 1393.9 mm, which is 4.7 times that of Urumqi. The superior climate condition in Fuzhou is the reason that the development mechanism of the atmospheric system gave Fuzhou first place out of the four cities in this study. These climate conditions guarantee the sustainable development of the water resources compound system in Fuzhou and further enhance the development mechanism of the compound system of Fuzhou, resulting in its development mechanism being superior to that of other cities.

In Fuzhou, the development situation of the water resources system, social economic system, and the ecological environment system are in good condition, and their levels are similar. The coordination degree of the compound system is the highest of the four cities. Specific details demonstrate the following: the population density of Fuzhou is 50% less than that of Beijing, and its economic strength and social structure are in line with the regional population size. The volume of water resources per capita is more than 10 times that of Beijing. The water resources system of Fuzhou has great development potential. Fuzhou relies on its abundant regional natural resources, optimizing the structure of its water utilization. The eco-environmental water consumption rate in 2013 was as high as 4.2%. Through investments, the threat to water security can be reduced and biodiversity can be improved [34]. Fuzhou provides great importance to the protection of its ecological environment in the process of urbanization with considerable investments in engineering, which could protect and restore the local environment. The Ecological Index reached a value of 73, indicating that the ecological environment is extremely suitable for human survival and development. The strong power of the compound system along with a high level of coordination between the subsystems in Fuzhou promotes the sustainable development of the compound system and indicates that the water quotient of Fuzhou ranked first.

Using Figure 3, it is clear that the development of the water resources system in Urumqi has certain advantages over that in Beijing. This is due to several factors. The population and population density of Urumqi is far lower than that of Beijing, and the volume of water resources per capita is greater than that of Beijing. For several years, due to a lack of adequate water supply, Urumqi has given greater importance to the efficient utilization of water resources, especially for daily residential life and industrial and agricultural production. The water consumption per 10,000 Yuan RMB GDP in 2013 was the lowest of the four cities; however, its development mechanism of the water resources system was still at a lower level.

Urumqi is located in the innermost part of the Asian-European continent, *i.e.*, it is in an intermediate zone with a continental dry climate. Rainfall is sparse; thus, the development mechanism of its atmospheric system is just above the level of Lhasa. The ecological environment in the Urumqi region is extremely fragile: the value of its environment index was only 59 in 2013. The ecological environment system cannot promote the development of the water resources compound system. Due to the inferiority of its climate, water resources, and ecological environment, the development mechanism of the compound system in Urumqi was the lowest of the four cities, reaching only 68% of the level of Fuzhou. Additionally, the development of the social economic system does not match the regional water resource, climate, and ecological environment conditions. Therefore, the coordination mechanism of the compound system is at a lower level, causing the water quotient of the compound system in Urumqi to be third out of the four cities.

Lhasa is located in the Tibetan Plateau, which has a temperate zone and a semi-arid monsoon climate. In 2013, despite the annual precipitation being only approximately 40.5% of that of Fuzhou, it was more abundant than that in Beijing and Urumqi. The Lhasa River runs through the city, resulting in a sizeable total volume of water resources in Lhasa. Due to its sparse population density, the volume of water resources per capita is considerably better than those in the other three cities. The development mechanism of the water resources system in Lhasa ranked first out of the four cities.

The total population of Lhasa is relatively low for a city in China, *i.e.*, the population density is only 1.6% of that of Beijing, and it has a population growth rate that is the lowest out of the four cities. Thus, the resistant mechanism of the social economic system in Lhasa is minimal compared to the other three cities. Because the Lhasa region has not experienced large-scale industrial production, the regional water and air quality are better than that in any of the other cities, resulting in the resistant mechanism of the ecological environment system in Lhasa to be clearly lower than that of the other cities. At the same time, the water resources compound system in Lhasa has a higher coordination mechanism. The comprehensive effect of the above factors indicates that the water quotient of the water resources compound system in Lhasa is higher, and its value is second only to Fuzhou.

Overall, the development mechanism of the compound system in Beijing is lacking, resulting in a maximum resistant mechanism and its water quotient being the lowest out of the four cities. The development mechanism of the compound system is strongest in Fuzhou, and its coordination mechanism is the best; furthermore, it has the highest water quotient. The development mechanism of the compound system in Urumqi is the weakest, and its coordination mechanism is extremely low, with its water quotient coming in third place. The water resources compound system in Lhasa has a minimum resistant mechanism. The compound system is relatively coordinated, and its water quotient is second only to Fuzhou. These results indicate that the water resources compound system of every city is composed of the water resources system, atmospheric system, social economic system, and ecological environment system. However, each subsystem is influenced by several factors, and these factors indicated great variation in each of the different areas studied. This result led directly to different strengths and weaknesses within the four cities in terms of the development mechanism, resistant mechanism, and coordination mechanism. Hence, the water quotient of the water resources compound system within the four cities appears to be clearly different.

4. Conclusions

To reveal the characteristics and the changes in the water resources system under the influence of complex internal and external factors, it has been expanded to become a water resources compound system. The compound system is composed of the water resources system, atmospheric system, social economic system, and ecological environment system, all of which have the same subject status. The elements of the compound system are involved in its evolution through the development mechanism, resistant mechanism, and coordination mechanism. The water quotient is defined to represent the sustainable development status of the compound system.

The four Chinese cities of Beijing, Fuzhou, Urumqi, and Lhasa were selected as study areas to analyze the water resources compound system of the four cities in 2013. The results indicate that each subsystem of the water resources compound system is composed of different elements. A region may have certain elements that are superior yet have other elements that are inferior, causing the different subsystems of a region to have different development mechanisms and resistant mechanisms. Of the four cities in this study, Fuzhou had the highest water quotient while Beijing had the lowest. The water quotients of Urumqi and Lhasa were between those of Fuzhou and Beijing. This is due to the varying nature of water resources in the different regions and the differences in the characteristics of each subsystem. A result of these differences is that the development mechanism, resistant mechanism, and coordination mechanism of the compound system were not the same in the four different regions, resulting in different sustainable development statuses of the water resources compound system with different strengths and weaknesses in the four different cities.

Based on the specific features of the three mechanisms for the regional water resources compound system, pertinent measures should be taken to improve the water quotient of the compound system and the sustainable development status of the regional compound system, thus improving the level and efficiency of the regional integrated water resource management. Hereafter, further research on the performance of the water resources compound system over a long period of time should be considered to comprehensively reflect the effects of atmospheric factors and enhance the concept of the water quotient.

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