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Evaluating Water Resource Assets Based on Fuzzy Comprehensive Evaluation Model: A Case Study of Wuhan City, China

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Abstract: With the rapid development of China’s economy, the demand for water resources continues to sharply increase, which has gradually contributed to serious environmental problems. The Chinese government has proposed establishing a natural resource balance sheet, which is expected to solve this problem by assessing the value of water resources. The main purpose of this study was to assess the value of water resources in Wuhan from 2013 to 2017. Based on a fuzzy mathematical evaluation model, 15 indicators were chosen considering the three main aspects of resources, society, and the environment to construct a water resource evaluation indicator system. In addition, the analytic hierarchy process (AHP) and entropy weight methods were combined to determine the index weight. Based on this, we calculated the value of water resources in Wuhan from 2013 to 2017. The results demonstrated that the values of water resources in Wuhan from 2013 to 2017 were US$2.910 billion, US$5.006 billion, US$9.223 billion, US$14.167 billion, and US$7.189 billion, respectively. Therefore, this paper provides a scientific foundation for the rational establishment of water prices, the assessment of local natural resource assets, and the preparation of natural resource balance sheets.

Keywords: water price; water resource value; fuzzy comprehensive evaluation; Wuhan city

1. Introduction

The Communist Party of China’s report at the 19th National Congress clearly stated that the government should establish a state-owned natural resource asset management supervisory institution [1]. The report emphasizes the importance of accounting for natural resource assets, including their quantity and quality, to promote the construction of an ecological civilization. Nowadays, with the rapid development of agriculture and industry, a large amount of domestic and industrial sewage is unfortunately discharged into rivers and lakes without any treatment, resulting in serious water contamination. Further, there is the problem of water shortages. The unreasonable pricing mechanism of water resources [2] has led to neglecting the importance of water resources [3,4]. Water, an indispensable resource for human life and socioeconomic development, has been degraded and depleted in China [5,6]. The hypothesis of developing the balance sheet of water resources, including their physical quantity and integrated value, has provided support for the innovative management of water resources [7]. The implementation of the approach could be used to determine the properties of water resources assets, promote the construction of ecological civilization, and then ultimately achieve the sustainable development of water resources [8]. Therefore, it is of great significance to explore the accounting of water resource assets as a first step.
Presently, the study of water resources is mainly carried out from two perspectives, namely, technology and management. On the one hand, many studies have concentrated on how to improve water quality from the perspective of technology, including the removal of metal elements such as copper and silver [9,10], as well as eutrophication treatment of water resources, including the important process of removing nitrogen and phosphorus, amongst others [11,12]. On the other hand, some works have focused on water resource management, for example, the sustainable utilization of water resources, the evaluation of water resource carrying capacity, and the assessment of water resource health risks [13–18]. Moreover, the use of economic valuation techniques represents a brand-new perspective for informing water resource management [6]. Early in 2000, the water framework directive 2000/60/EC, proposed by the European Union, aimed to achieve the good qualitative and quantitative status of all waterbodies [6,19]. It set forth the principles of full water cost, including direct cost (DC), environmental cost (EC), and natural resource cost (RC), and full water cost recovery [20,21], which was to be mainly applied in river basin management [22]. However, water resource accounting systems are complex, and are affected not only by natural (including ecological and chemical) factors but also social and economic factors. Therefore, we endeavored to develop a comprehensive water resource asset evaluation system considering the following three aspects: the environment, society, and efficiency.

Many scholars have attempted to study the valuation of water resources. Presently, the commonly used methods of quantifying the value of water resources include the marginal opportunity cost method, the shadow price method, and the pricing method of supply and demand [23–25]. However, the marginal opportunity cost method and the pricing method of supply and demand ignore the impact of water quality on the value of water resources. The shadow price can only reflect the degree of scarcity of water resources and the relationship between water resources and overall economic benefits; it cannot replace the value of water resources [26]. A water resource system is not only affected by natural factors but also social and economic factors [27]. Based on the complexity and fuzziness of water resource systems, we applied a fuzzy mathematical model of water resource value. Fuzzy mathematics was first put forward by Chad, an expert in cybernetics at the University of California, USA, in 1965 [28]. The fuzzy mathematical model was used to solve the problem of water resource valuation to some extent, and the defects in the abovementioned methods were solved to a certain extent. According to the comprehensive consideration of various factors, it is more reasonable to calculate the value of water resources by the fuzzy mathematical model.

Wuhan is the capital city of Hubei Province and the core city of the central region in China. Wuhan is rich in freshwater resources and possesses the largest water area among the large cities in China. As of 2017, Wuhan, with its 166 lakes, is known as the “city of a hundred lakes” and has a surface area of 803.17 km² at normal water levels, which ranks first among Chinese cities [29]. Wuhan has taken the lead in the capitalization of natural resources, providing significant contributions and guidance to the process of promoting natural resource capitalization in the central region. In order to determine the value of water resources in Wuhan from 2013 to 2017, we conducted our research considering the following four aspects: (1) to establish the water resource stock and flow accounts in Wuhan from 2013 to 2017; (2) to establish the fuzzy comprehensive evaluation system of water resources in Wuhan; (3) to evaluate Wuhan water resources according to the evaluation index system and calculate the unit water resource price of Wuhan city from 2013 to 2017; and (4) to calculate the total value of Wuhan water resources according to their stock and flow in Wuhan city from 2013 to 2017.

2. Materials and Methods

2.1. Study Area

Located in the middle part of China in the Yangtze River Basin, Wuhan is the core city in the central region and has a total area of 8494.41 km². In 2017, Wuhan had a permanent population of 10,914,000 people and a regional gross domestic product of US$198.47 billion. Due to the subtropical monsoon climate, rainfall in Wuhan is abundant all year. It is the most influential area in the middle
reaches of the Yangtze River Basin in terms of socioeconomic development and water resource utilization. The Yangtze River and its largest tributary, the Han River, traverse the center of the city and divide the central city of Wuhan into three parts, forming the three towns of Wuhan, Hankou, and Hanyang across the river. The rivers in the city are longitudinal and horizontal, and the lakes and ports are intertwined. The total water area of the whole city is 2217.6 km², accounting for 26.1% of the land area of the whole city (Figure 1). As of 2017, Wuhan, with its 166 lakes, is known as the “city of a hundred lakes” and has a surface area of 803.17 km² at normal water levels, which ranks first among Chinese cities [29]. Wuhan is rich in freshwater resources and possesses the largest water area among large cities in China. The per capita water resources in Wuhan are about 40 times that of the national average level and 10 times that of the global per capita level.

Figure 1. Location and distribution map of water resource in Wuhan city.

2.2. Data Acquisition

According to the Wuhan Statistical Yearbook 2013–2017 and the Wuhan Water Resource Bulletin 2013–2017, standards for water quality grades were established according to the pollution degree of the National Standard for Surface Water Environmental Quality (GB3838-2002). The comprehensive evaluation index system of water resources in Wuhan was constructed by selecting 15 criteria considering the following three dimensions: resources, society, and the environment [30].

2.3. Software for Data Processing

Microsoft Excel 2016 is a powerful tool that can be used for data analysis, model simulation, matrix operation, and more [31–33]. In this study, the dataset consisted of time panel data from 2013 to 2017 including 15 indicators and a total of 75 actual values. Using Excel to import and analyze the data was very simple and easy to operate. Here, Microsoft Excel 2016 was used for data processing, including the calculation of subjective and objective weights, table drawing, the calculation of water resource price and value, and matrix operations.

2.4. Comprehensive Evaluation Model of Water Resource Value

Due to the complexity and fuzziness of water resource valuation, Jiang Wenlai put forward the fuzzy mathematical model of water resource values in 1995, consisting of water resource evaluation and water price calculation models [34].
2.4.1. Water Resource Evaluation Model

In order to calculate the value of water resources, we prioritized conducting a comprehensive evaluation of water resources. Considering the actual situation of the research area and referring to research done by previous scholars [8,35], we selected 15 indexes considering the aspects of resources, society, and the environment to set up the water resource evaluation index system and establish the water resource evaluation model. The specific steps are as follows:

\[ V = f(§_1, §_2, §_3, \ldots, §_n). \]  

where \( V \) represents the value of water resources and \( §_1, §_2, §_3, \ldots, §_n \) are factors that influence the value of water resources, such as water quality, quantity of water resources, population density, economic structure, technological influence, production cost, and normal profit for water resources. The specific methods are as follows: setting the domain \( U \) as the value element of water resources, \( w \) denotes the evaluation vector, and the comprehensive evaluation of water resource value can be expressed as

\[ V = A \cdot R, \]  

\[ U = [§_1, §_2, §_3, \ldots, §_n], \]  

\[ W = [High, Relatively high, Middle, Relatively low, Low]. \]

In Formula (2), \( A \) denotes the weight value of the evaluation elements, is the compound operation symbol of the fuzzy matrix, \( V \) is the comprehensive evaluation vector of water resource value, and \( R \) is the comprehensive evaluation matrix consisting of a single-factor evaluation matrix which can be expressed as

\[
R = \begin{bmatrix}
R_1 & \cdots & R_{15} \\
R_{21} & \cdots & R_{25} \\
R_{31} & \cdots & R_{35} \\
\vdots & \ddots & \vdots \\
R_{n1} & \cdots & R_{n5}
\end{bmatrix},
\]

where \( R_i \) (\( i = 1, 2, 3, \ldots, n \)) is the evaluation matrix that represents a single-factor resource (society), and the environment, \( R_{ij} \), is defined as

\[ R_i = \omega \cdot \mu, \]

where \( \omega \) represents the weight of each evaluation factor in a single factor, \( \mu \) is the membership matrix of each evaluation factor determined by their respective membership functions, and \( R_{nj} = (n = 1, 2, 3, \ldots, n; j = 1, 2, 3, 4, 5) \) denotes the evaluation value of the \( n \)-th influence factor at the \( j \) evaluation level.

Influencing Factors of Water Resource Value

Water resources are used in all aspects of daily human life, from bottles of drinking water to the water used for agriculture and industry. The value of water resources relies, first and foremost, on the quantity and quality. Moreover, we should note that the value of water resources is also affected by social factors. Without the involvement of human activities, water resources would not have been exploited, which indicates that social factors play a significant role in the water resource value assessment. In this study, the influence of water quality on the value of water resources was reflected in the criterion layer of environment. In terms of resources, we selected three indexes—water resources per capita, water resources per unit area, and total water supply—to reflect the abundance of water resources in the study area. However, the value of water resources is not only related to the quantity of water resources but is also closely related to water quality, which reflects the health status of waterbodies. Thus, we chose four indexes of environmental factors—ammonia nitrogen, chemical oxygen demand (COD), sewage treatment rate, water functional area water quality compliance rate—to evaluate the influence of water quality. In addition, the socioeconomic value of water resources should
not be ignored. Therefore, the population density, per capita GDP, utilization rate of water resources, water consumption per ten thousand yuan GDP, agricultural water consumption, and eight other indicators of socioeconomic aspects were selected to reflect the influence of socioeconomic factors on the value of water resources.

Weight of Water Resource Value Influence Factors

The analytic hierarchy process (AHP) is a mature method for determining index weight, especially for a multilevel and multifactor index system, with high reliability and accuracy [36,37]. After several rounds of discussion, we selected and determined 15 indexes considering the three aspects of resources, society, and the environment to establish an evaluation index system for the comprehensive evaluation of water resources. In this process, AHP was applied to determine the weight of influence factors. Firstly, 16 experts in the fields of environmental ecology, water resource management, government, and environmentalism were invited to take a water resource assessment as the target layer, and resources, society, the environment were the criterion layer. Secondly, based on AHP, we established a scoring table, and the 16 experts were invited to rate the relative importance between two indicators and score them based on their knowledge and experience. In this way, we obtained a judgment matrix between the indexes. Eventually, by the AHP method was used to obtain the weights of the criterion layer of resources, society, the environment, and the subjective weights of the 15 indicators.

Entropy Method

Considering the subjectivity of weight determination by AHP, it was combined with the entropy method to determine the index weight in order to reduce the possible deviation of a single weighting method and enhance the objectivity, scientific rigor, and accuracy of the comprehensive measurement of the evaluation index system. The entropy method is an objective weighting method which determines the weight of the index according to the information provided by the observed value of each index [38]. The specific steps are as follows.

Calculate the entropy value of the index $H_j$:

$$ P_{ij} = \frac{X_{ij}}{\sum_{i=1}^{n} X_{ij}}, $$

$$ H_j = -k \sum_{i=1}^{n} P_{ij} \ln(P_{ij}) = -\frac{1}{\ln(n)} \sum_{i=1}^{n} P_{ij} \ln(P_{ij}), $$

$$ k > 0, \quad k = \frac{1}{\ln(n)}, \quad H_j \geq 0, $$

where $P_{ij}$ is the proportion of a certain index in all similar indexes, $X_{ij}$ denotes the initial data value of the index, and $\sum_{j=1}^{n} (H_j)$ represents the sum of all the data of the number $j$ index.

Calculate the weight of the evaluation indicators:

$$ \omega_j = \frac{1 - H_j}{n - \sum_{j=1}^{n} (H_j)}, $$

which satisfies $\sum_{j=1}^{n} \omega_j = 1, \quad 0 < \omega_j < 1$.

After calculating the weight of the evaluation factors by the AHP and entropy methods, the subjective and objective weights were linearly weighted to determine the comprehensive weight of each evaluation index in order to avoid any deviation caused by the subjective weight method and the absolutization of the objective weight method. The selected indicators and their weights are shown in Table 1.
Table 1. Indexes of water resources evaluation system and weights of indexes.

<table>
<thead>
<tr>
<th>Criterion Layer</th>
<th>Weight</th>
<th>Abbreviation</th>
<th>Index Layer</th>
<th>Subjective Weight</th>
<th>Objective Weight</th>
<th>Comprehensive Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resources</td>
<td>0.4096</td>
<td>N1</td>
<td>Per capita water resources (m³/people)</td>
<td>0.4627</td>
<td>0.4756</td>
<td>0.4691</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N2</td>
<td>Water resources per unit area (10,000 m³/km²)</td>
<td>0.2903</td>
<td>0.5084</td>
<td>0.3993</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N3</td>
<td>The amount of water supply (10⁸ m³)</td>
<td>0.2470</td>
<td>0.0160</td>
<td>0.1315</td>
</tr>
<tr>
<td>Society</td>
<td>0.2486</td>
<td>N4</td>
<td>Population density (people/hm²)</td>
<td>0.1039</td>
<td>0.0023</td>
<td>0.0531</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N5</td>
<td>Per capita water consumption (m³/person)</td>
<td>0.2101</td>
<td>0.0352</td>
<td>0.1226</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N6</td>
<td>Per capita gross domestic product (GDP; 10,000 yuan/people)</td>
<td>0.0820</td>
<td>0.1006</td>
<td>0.0913</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N7</td>
<td>GDP water consumption (m³/10,000 yuan)</td>
<td>0.1249</td>
<td>0.2070</td>
<td>0.1660</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N8</td>
<td>Water resource development and utilization rate (%)</td>
<td>0.1334</td>
<td>0.4210</td>
<td>0.2772</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N9</td>
<td>Industrial added value of water consumption (m³/10,000 yuan)</td>
<td>0.1048</td>
<td>0.2321</td>
<td>0.1685</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N10</td>
<td>Industrial water reuse rate (%)</td>
<td>0.0983</td>
<td>0.0002</td>
<td>0.0492</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N11</td>
<td>Agricultural irrigation water utilization factor</td>
<td>0.1426</td>
<td>0.0016</td>
<td>0.0721</td>
</tr>
<tr>
<td>Environment</td>
<td>0.3418</td>
<td>N12</td>
<td>Ammonia nitrogen (mg/L)</td>
<td>0.2425</td>
<td>0.9063</td>
<td>0.5744</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N13</td>
<td>Chemical oxygen demand (COD; mg/L)</td>
<td>0.2710</td>
<td>0.0402</td>
<td>0.1556</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N14</td>
<td>Sewage treatment rate (%)</td>
<td>0.2012</td>
<td>0.0096</td>
<td>0.1054</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N15</td>
<td>Water functional area compliance rate (%)</td>
<td>0.2854</td>
<td>0.0439</td>
<td>0.1647</td>
</tr>
</tbody>
</table>
Membership Function

In order to determine the value of $R_{nj}$, it is necessary to confirm the membership function of each index. There are many ways to do this, and the usual method is an ascending or descending semi-trapezoidal distribution. Here, we chose the descending semi-trapezoidal distribution and established a one-dimensional linear membership function [8].

When $j = 1$,

$$
\mu_i(x) = \begin{cases} 
1 & x \leq x_{i1} \\
\frac{x-x_{i1}}{x_{i2}-x_{i1}} & x_{i1} < x < x_{i2} \\
0 & x \geq x_{i2}
\end{cases}
$$

When $j = 2, 3, 4$,

$$
\mu_j(x) = \begin{cases} 
\frac{x-x_{ij-1}}{x_{ij}-x_{ij-1}} & x_{i,j-1} \leq x \leq x_{ij} \\
\frac{x-x_{ij}}{x_{ij+1}-x_{ij}} & x_{ij} < x < x_{i,j+1} \\
0 & x \leq x_{i,j-1}, x \geq x_{i,j+1}
\end{cases}
$$

When $j = 5$,

$$
\mu_n(x) = \begin{cases} 
1 & x \geq x_{in} \\
\frac{x-x_{in-1}}{x_{in}-x_{in-1}} & x_{in-1} < x < x_{in} \\
0 & x \leq x_{in-1}
\end{cases}
$$

2.5. Price Calculation Model of Water Resources

What is obtained above is the comprehensive evaluation vector of water resource value, which is a dimensionless vector. In order to convert this dimensionless vector into the scalar value of water resource price, according to the transformation formula put forward by Jiang Wenlai in the monograph “Theory of Water Resource Value”, we utilized the price vector [39, 40]:

$$W_LJ = V \times S^T,$$

where $V$ is the comprehensive evaluation vector and $S^T$ is the transfer of the water resource price vector.

2.5.1. Tolerance of Water Fees

In this study, the tolerance of water fees was applied to determine the price vector of water resources. The tolerance of water fees is an index which reflects the ability of users to afford water fees for water resources. According to international standards of affordability in developing countries, water expenses generally account for less than 3% of disposable income [41]:

$$QI = \frac{F}{TI},$$

where $QI$ is the tolerance of water fees, $F$ represents water expenses, and $TI$ is the real household income.

2.5.2. Price Cap of Water Resources

Reasonable water resources should include the intrinsic value of water resources and the production costs and profits. Therefore, when calculating water prices, production costs and profits should be taken into account [35]. The price cap of water resources, namely, the prices of water resources when the maximum tolerance for water fees is reached, is expressed by the following formula:

$$P = M QI \times \frac{T^T}{\bar{f}_W} - C,$$
where \( P \) is the price cap of water resources, \( MQI \) is the maximum tolerance of water fees, \( TI \) is annual disposable income, \( AW \) is annual water consumption, and \( C \) is water production cost and profit.

2.5.3. Price Vector of Water Resources

The upper limit of water price is \( P \); thus, the price of water resources should be less than or equal to \( P \). The water price from \( P \) to 0 is divided into five levels according to the method of equal intervals, which is expressed in the form of a price vector:

\[
\] (17)

The water resource price can be calculated by substituting the price vector \( S^T \) into the formula \( WLJ = V \times S^T \).

3. Results

3.1. Physical Accounting of Water Resources in Wuhan City

Water balance refers to the two main parts of water resources: consumption and recharge of water resources [7,42,43]. Based on this, a water balance sheet or stock account of water resources needs to be established to account for the stocks of water resources and their changes in order to comprehensively record the possession, use, consumption, restoration, and increase of water resources caused by natural and economic entities in the current period (from the beginning to the end of the period) [44]. Hence, we should use clear definitions of stocks and flows to perform the water balance of total water resources within an area [45]. From this perspective, it is necessary to establish a water resource physical account consisting of stocks and flows of water resources. Considering some previous studies [8,46], we finally established the stock account of the water resources of Wuhan city from 2013 to 2017 in order to conduct the water balance of the total water resources of the area. According to Wuhan Water Resource Bulletin (2013–2017), the physical accounting of water resources in Wuhan city has been established and is divided into two parts. One part is the increase in stock, which includes precipitation, inflows, and the water return of society. The other part is the decrease in stock, which considers water intake, outflows, water evaporation, and ecological water consumption of rivers and lakes. The accounting table for the physical stock of water resources in Wuhan is shown in Table 2.

Table 2. Stock accounting of the water resources of Wuhan city from 2013 to 2017 (100 million m\(^3\)).

<table>
<thead>
<tr>
<th>Item</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year—beginning stock</td>
<td>47.92</td>
<td>41.03</td>
<td>39.29</td>
<td>57.46</td>
<td>99.79</td>
</tr>
<tr>
<td>Increase in stock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water resources from precipitation</td>
<td>100.25</td>
<td>98.27</td>
<td>119.02</td>
<td>154.03</td>
<td>98.32</td>
</tr>
<tr>
<td>Inflows</td>
<td>6387</td>
<td>7237</td>
<td>6811</td>
<td>7598</td>
<td>7437</td>
</tr>
<tr>
<td>Water return of society</td>
<td>0.62</td>
<td>1.2</td>
<td>0.68</td>
<td>0.44</td>
<td>0.36</td>
</tr>
<tr>
<td>Decrease in stock</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Water intake</td>
<td>40.13</td>
<td>39.52</td>
<td>37.59</td>
<td>34.02</td>
<td>34.61</td>
</tr>
<tr>
<td>Evaporation</td>
<td>96.46</td>
<td>98.51</td>
<td>122.69</td>
<td>188.71</td>
<td>188.36</td>
</tr>
<tr>
<td>Outflows</td>
<td>6358</td>
<td>7200</td>
<td>6752</td>
<td>7487</td>
<td>7373</td>
</tr>
<tr>
<td>Ecological water consumption of rivers and lakes</td>
<td>0.17</td>
<td>0.18</td>
<td>0.25</td>
<td>0.41</td>
<td>0.39</td>
</tr>
<tr>
<td>Year—end stock</td>
<td>41.03</td>
<td>39.29</td>
<td>57.46</td>
<td>99.79</td>
<td>39.11</td>
</tr>
</tbody>
</table>
3.2. Calculation of Water Resource Price

According to Formula (14), the water resource price ($\text{WLJ} = V \times S^T$) is necessary to carry out the comprehensive evaluation of water resources by obtaining the vector $V$.

3.2.1. Fuzzy Evaluation of Water Resource Quantity

The total amount of water resources refers to the surface and underground water formed by precipitation, that is, the sum of river runoff and precipitation infiltration recharge. In this work, water resources per capita, water resources per unit area, and total water supply were selected to represent the abundance of water resources in the study area. Water resources per capita is the average amount of water resources per person in a period within a region or basin, namely, the ratio of the total water resources to the total population. The amount of water resources per unit area is the ratio of total water resources to the research area. The total amount of water supply refers to the total amount of water supplied by public water plans and social units with self-provided water sources for the whole year, including the effective water supply and the loss of water. Taking 2016 as an example, the total amount of water resources in Wuhan was 3.911 billion m$^3$, the per capita water resources was 926.88 m$^3$, and the total amount of water supply for the whole year was 3.402 billion m$^3$ (data source: Wuhan Water Resource Bulletin 2016). The water quality grading standard was formulated according to the population-level classification table of the “National Surface Water Environmental Quality Standard (GB3838-2002)” [47]. In addition, based on relevant research [48–50] and according to the water resource development and control program proposed in the “13th Five-Year Plan of Water Conservancy Reform and Development” [51], we carried out a classification of the indicators. As shown in Table 3, the per capita water resources in Wuhan city is at the middle level, while water resources per unit area is at a relatively high level. When it comes to the total amount of water supply, the total amount of water supply for the whole year is quite large, and Wuhan city is relatively rich in water resources. However, the per capita water resources are relatively low due to the large population.

<table>
<thead>
<tr>
<th>Water Resources Value Grade</th>
<th>High</th>
<th>Relatively High</th>
<th>Medium</th>
<th>Relatively Low</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population density</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(people/hm$^2$)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Per capita water consumption(m$^3$/person)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.08</td>
<td>0.92</td>
</tr>
<tr>
<td>Per capita gross domestic product (GDP; 10,000 yuan/people)</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GDP water consumption (m$^3$/10,000 yuan)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Water resource development and utilization rate (%)</td>
<td>0</td>
<td>0</td>
<td>0.591</td>
<td>0.405</td>
<td>0</td>
</tr>
<tr>
<td>Industrial added value of water consumption (m$^3$/10,000 yuan)</td>
<td>0</td>
<td>0</td>
<td>0.2125</td>
<td>0.7875</td>
<td>0</td>
</tr>
<tr>
<td>Industrial water reuse rate (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Agricultural irrigation water utilization factor</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

According to the standard and actual values of water resources per capita, water resources per unit area, and total water supply in Wuhan in 2016, the evaluation vectors obtained by the membership function were [0, 0.6828, 0.3172, 0, 0, 0, 0, 0, 0.8355, 0.1645], and [0, 0.598, 0.402, 0, 0, 0], respectively.
As shown in Table 2, the comprehensive weights for resources were 0.47, 0.40, and 0.13. According to Formula (6), the evaluation vector of water resources can be obtained, which are expressed by $R_1$:

$$R_1 = \begin{pmatrix} 0.47 & 0.40 & 0.13 \end{pmatrix} = \begin{pmatrix} 0 & 0.6828 & 0.3172 \ 0 & 0 & 0.8355 \ 0 & 0.598 & 0.402 \end{pmatrix} \begin{pmatrix} 0.4 & 0.20 & 0.33 & 0.07 \end{pmatrix}.$$

The evaluation vector result suggests that, in terms of water resource stocks in Wuhan, the membership degrees that belong to relatively low, moderate, and relatively high grades were 0.4, 0.2, and 0.33, respectively. Due to the heavy rainfall in Wuhan in 2016—the second-most heavy year of rainfall since 1956—the water supply was quite adequate, and the subordinate degree of the higher grade was 0.33. Nevertheless, Wuhan city has a large population and demand for water resources, so the per capita water resources were still relatively low. As a result, the subordinate degree of water resources belonged to a relatively low level of 0.4. According to market laws for water resources, the value of water resources will be lower when the evaluation grade of water resources is high. On the contrary, the value of water resources becomes higher when there is a low grade.

### 3.2.2. Evaluation of Social Value of Water Resources

As for the fuzzy evaluation of social and economic factors, we chose eight indicators—population density, per capita water consumption, per capita gross domestic product, water consumption per ten thousand yuan GDP, water resource development and utilization rate, industrial added value of water consumption, industrial water reuse rate, and the agricultural irrigation water utilization coefficient—to carry out the fuzzy evaluation of water resources from the social aspect.

As shown in Table 3, the membership degree of the eight indicators of the social category corresponding to the evaluation grade in 2016 was calculated. The weighting matrix of the above eight indicators was $[0.053 \ 0.123 \ 0.091 \ 0.166 \ 0.277 \ 0.168 \ 0.049 \ 0.072]$. The fuzzy evaluation vector of the social factors of Wuhan water resources, $[0.2165, 0, 0.1996, 0.2559, 0.3280]$, was obtained by multiplying the matrix composed of the weights of the above eight indexes and the membership degree of each index to get the fuzzy evaluation vector of the social factors of water resources in Wuhan. Judging from the comprehensive evaluation results of the eight indexes, the social value of water resources in Wuhan belonging to the high, middle, relatively low, and low levels were 0.2165, 0.1996, 0.2559, and 0.3280, respectively. The value of water resources belongs to the high level, accounting for about 20%, indicating that the selection of indicators was more comprehensive and the evaluation of water resources was more reasonable. Overall, the social value of water resources probably belongs more to the relatively low and low grades.

### 3.2.3. Evaluation of Water Resource Quality

The environmental indicators of water quality reflect health status factors, such as ammonia nitrogen, chemical oxygen demand, the rate of sewage treatment, and the water functional area water quality compliance rate. According to the above weight-calculating method, the weight of the four indicators for judging water quality was represented in the form of the matrix $[0.574 \ 0.1556 \ 0.1054 \ 0.225]$. In the year 2016, according to the Wuhan Environmental Quality Bulletin, the ammonia nitrogen in the waterbody was 0.791 mg/L, and the chemical oxygen demand was 24 mg/L. Referring to the surface water environmental quality standard GB3838-2002, the membership sets of ammonia nitrogen and chemical oxygen demand were written as the vectors $[0, 0.6, 0.4, 0, 0]$ and $[0, 0, 0.6, 0.4, 0.4, 0]$, respectively. According to the statistical yearbook of Wuhan city, the sewage treatment rate was 95% and the water functional area water quality compliance rate was 50.9%. Using the membership function, the membership sets of the sewage treatment rate and the water functional area water quality compliance rate were written as the vectors $[0, 0, 0, 0, 1]$ and $[0.91, 0.09, 0, 0, 0]$, respectively.
According to the index of ammonia nitrogen, the membership degrees of grades 2 and 3 were 0.6 and 0.4, respectively. Eventually, we obtained the fuzzy evaluation vector of water quality:

\[
R_3 = (0.574 \ 0.1556 \ 0.1054 \ 0.225) \begin{pmatrix}
0 & 0 & 0.6 & 0.4 & 0 & 0 \\
0 & 0 & 0.6 & 0.4 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0.91 & 0.09 & 0 & 0 & 0 & 0
\end{pmatrix}
= (0.2048, 0.3649, 0.3231, 0.0622, 0.1054).
\]

From the vector results of the fuzzy evaluation of water quality, the probability that the water resource value belongs to the middle level or worse was 0.8928, which indicates that the overall water quality was poor, suggesting a low value of water resources in Wuhan city in 2016.

### 3.2.4. Price Vector of Water Resources

The price vector of water resources was calculated using Formula (16). According to the international standard of affordability in developing countries, the value of this coefficient should be less than or equal to 0.03, and the value depends on specific studies in the research area [27,35,52,53]. The water price of Wuhan city in 2016 was 0.474 USD/m³ (data from China Water Network) [54], the per capita disposable income of Wuhan in 2016 was US$53.279 hundred (data from Wuhan Statistical Yearbook 2016), and the average annual water consumption of households was 48.3114 m³ (data from Wuhan Statistical Yearbook 2016):

\[
P = 0.03 \times 35383 / 48.3114 - 3.155 = 2.749 \text{ USD/m}^3,
\]

\[
S^T = P \cdot \begin{pmatrix} 3/4P, 1/2P, 1/4P, 0 \end{pmatrix} = [18.257, 13.6928, 9.1285, 4.5643, 0].
\]

### 3.2.5. Calculation of Water Resource Price

According to the AHP, the weights of the factors considering the three aspects of resources, society, and the environment were 0.4096, 0.2486, and 0.3418, respectively. Based on the above calculation, the comprehensive evaluation matrix \( R \) of water resources were obtained as follows:

\[
R = \begin{pmatrix} R_1 \\ R_2 \\ R_3 \end{pmatrix} = \begin{pmatrix}
0 & 0.4 & 0.2 & 0.23 & 0.07 \\
0.2165 & 0 & 0.1996 & 0.2559 & 0.3280 \\
0.2048 & 0.3649 & 0.3231 & 0.0622 & 0.1054
\end{pmatrix}
\]

\[
V = AR \begin{pmatrix} 0.4096 & 0.2486 & 0.3418 \end{pmatrix} \begin{pmatrix}
0 & 0.4 & 0.2 & 0.23 & 0.07 \\
0.2165 & 0 & 0.1996 & 0.2559 & 0.3280 \\
0.2048 & 0.3649 & 0.3231 & 0.0622 & 0.1054
\end{pmatrix}
= \begin{pmatrix} 0.123812 & 0.28813 & 0.242669 & 0.22154 & 0.144483 \end{pmatrix}
\]

According to Formula (14), the price of water resources in Wuhan 2016 was

\[
WLJ = V \times S^T = \begin{pmatrix} 18.257 \\ 13.6928 \\ 9.1285 \\ 4.5643 \\ 0 \end{pmatrix}
= 1.42\text{ USD/m}^3.
\]
3.3. Stock Value of Water Resources in Wuhan

On the basis of multiplying the price of water resources and the stocks of water resources in Wuhan city, the values of water resource stocks from 2013 to 2017 are summarized in Table 4.

Table 4. The stock value of water resources in Wuhan city from 2013 to 2017.

<table>
<thead>
<tr>
<th>Year</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per capita disposable income/USD</td>
<td>4344.93</td>
<td>4823.04</td>
<td>5214.5</td>
<td>5326.92</td>
<td>5723.21</td>
</tr>
<tr>
<td>The yearly household water consumption/m³</td>
<td>49.77</td>
<td>48.76</td>
<td>48.31</td>
<td>49.56</td>
<td>51.11</td>
</tr>
<tr>
<td>Tolerance of water fee/%</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Water supply cost and the norm profit/USD</td>
<td>0.396</td>
<td>0.526</td>
<td>0.543</td>
<td>0.474</td>
<td>0.467</td>
</tr>
<tr>
<td>Price of water resources (USD/m³)</td>
<td>0.709</td>
<td>1.275</td>
<td>1.604</td>
<td>1.420</td>
<td>1.838</td>
</tr>
<tr>
<td>Stock of water resources/100 million m³</td>
<td>41.03</td>
<td>39.29</td>
<td>57.46</td>
<td>99.79</td>
<td>39.11</td>
</tr>
<tr>
<td>Stock value of water resources/billion USD</td>
<td>2.910</td>
<td>5.006</td>
<td>9.223</td>
<td>14.167</td>
<td>7.189</td>
</tr>
</tbody>
</table>

4. Discussion

According to the Wuhan Water Resource Bulletin 2013–2017, the water function compliance rates of Wuhan city, which has 166 lakes, were 51.1%, 45.4%, 48.1%, 50.9%, and 46.8%, respectively. However, the water function compliance rates of Nanjing, another beautiful city rich in water resources along the Yangtze River, reached 44.6%, 53.6%, 62.5%, 68.1%, and 58.4% from 2011 to 2015 [35]. It has been suggested that the waterbodies in Wuhan city are seriously polluted as the water quality of some lakes belong to Class V and grades even more inferior than Class V. In the face of such severe water contamination, it is necessary for the public to realize the great value of water resources and to reasonably exploit and utilize them. Thus, calculating the value of water resources in Wuhan is an urgent matter.

Taking Wuhan city as the study area, this research established a physical account of water resources from 2013 to 2017 and evaluated water resource values based on a fuzzy comprehensive evaluation model. The entropy and the AHP methods were combined to determine the comprehensive weight of the evaluation index. In addition, the membership function was introduced to evaluate the water resources in Wuhan city, which further reduced the uncertainty and enhanced the credibility of the conclusion. Compared with the opportunity cost method, shadow price method, and pricing method of supply and demand, the fuzzy comprehensive evaluation method adopted here made the assessment more objective and comprehensive by considering water quality, water quantity, and the social factors that affect the value of water resources. However, the manner by which a unified and reliable model can be established to study the value of water resources is a significant topic requiring further research.

As for the unit price, stocks, and value of water resources in Wuhan city from 2013 to 2017, these showed that the surge of water resource stocks in 2016 (up nearly 74% from the end of 2015) led to a slight decline in the price of water resources. Except for 2016, the unit price of water resources increased sharply. Nevertheless, the value of water resources in the year 2016 was at its highest in five years, which indicated that the abundance of water resources occupied a dominant position in their asset evaluation. However, it is undeniable that water quality is also an essential part of calculating the value of water resources. After comprehensive consideration of factors, such as water quality and quantity, it was concluded that the real-life price of water resources in Wuhan city is on the low side and can still increase significantly irrespective of the macro-control of Chinese government.
5. Conclusions

Based on a fuzzy comprehensive evaluation method, 15 indicators considering water resources, society, and the environment were chosen to construct an evaluation index system of water resource value in Wuhan city. The AHP was applied to acquire the weights of water resources, society, and the environment, which were 0.4096, 0.2486, and 0.3418, respectively. For the purpose of reducing uncertainty, the membership degree function was introduced and the membership degree of each index corresponding to the standard was obtained using descending semi-trapezoidal distribution. Utilizing the value conversion model put forward by Jiang Wenlai, the unit prices of water resources in Wuhan city from 2013 to 2017 were calculated to be 0.709, 1.275, 1.604, 1.420, and 1.838 USD/m$^3$, respectively. Subsequently, according to the stocks of water resources in Wuhan, the values of water resources in Wuhan city from 2013 to 2017 were calculated to be US$2.910 billion, US$5.006 billion, US$9.223 billion, US$14.167 billion, and US$7.189 billion, respectively. Eventually, the local government needs to guide the public to develop and utilize water resources more rationally and to ensure the sustainable utilization and development of water resources. Thus, this research on the evaluation of water resources has provided a scientific basis for the capitalization of natural resources and the compilation of a natural resource balance sheet.

Author Contributions: J.Z. contributed to organize study, prepared datasets, performed the statistical analysis and revised the manuscript. C.L. organized this study, conducted study design, performed the statistical analysis and revised the manuscript. J.F. contributed to prepared datasets, performed the statistical analysis and drafted the manuscript. Z.Q. contributed to study design, interpretation of analysis, and revision of the manuscript. Y.L. contributed to study design and datasets prepare. E.L., Z.Y. and L.J. contributed to datasets prepare and revision of the manuscript. All read and approved the final manuscript.

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

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