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Comprehensive Evaluation on Urban Water Security Based on the Novel DPEBLR Concept Model and the Cloud Matter-Element Model: A Case Study of Chongqing, China

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Abstract: Urban water security problems such as water scarcity, water pollution, and flood disasters have restricted the sustainable development of cities. In order to scientifically evaluate the urban water security situation, this study combined the DPSIR (driver, pressure, state, impact, response) model and HEVD (the hazard of disaster-causing factors, the vulnerability of disaster-affected bodies, the instability of the disaster-pregnant environment, and population loss) model to propose a new conceptual framework for DPEBLR (driver, pressure, environment, insecurity-affected body, loss, response). Based on this conceptual framework, 35 indicators were selected to establish an urban water security evaluation index system. In order to solve the problem of randomness and fuzziness of the boundary values of urban water security classification levels, the cloud matter element model was applied. Chongqing was used as an example for verification, and the results showed that the water security status of Chongqing City improved from 2011 (V) to 2019 (II). This indicates that the water ecology restoration project, centralized water source protection project, centralized water supply project, water-saving society transformation, and flood and drought prevention system construction project implemented in Chongqing has achieved significant results. However, Chongqing still faces the problem that the construction of an urban flood control system cannot meet the speed of urban development. The government should slow down the urbanization and allow the urban flood control system to be ready before the area is occupied. In addition, the awareness of water conservation for industrial use in Chongqing has been formed, and citizens' awareness of water conservation for domestic use should be enhanced in the future.

Keywords: urban water security; DPEBLR model; DPSIR model; cloud matter element model; Chongqing

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Citation: Deng, H.; Song, X.; Li, C.; Li, Y.; Diao, H.; Xu, J. Comprehensive Evaluation on Urban Water Security Based on the Novel DPEBLR Concept Model and the Cloud Matter-Element Model: A Case Study of Chongqing, China. *Water* **2022**, *14*, 3486. https://doi.org/10.3390/w14213486

Academic Editor: Christos Makropoulos

Received: 29 July 2022
Accepted: 18 October 2022
Published: 31 October 2022

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Correction Statement: This article has been republished with a minor change. The change does not affect the scientific content of the article and further details are available within the backmatter of the website version of this article.

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1. Introduction

Since the 21st century, the water security problems faced by cities are a serious constraint to sustainable urban development [1]. Urban water security is the basic condition for the survival and development of a city. Urban water security has become one of the elements that seriously restricts the economic and social development and blue-green areas in cities in China. The changes in the social and natural environment brought about by urbanization have contributed to the increasing frequency of urban water security and the severity of incidents. The city is a complex giant system, and there are many factors affecting the urban water security situation; therefore, the urban water security problem is increasingly hidden and has complex characteristics. For the sustainable development of the city, there is an urgency to ensure continuous improvement of urban water security and to improve the comprehensive treatment of prevention and mitigation of urban water security problems. The term "water security" first appeared at the Stockholm Water Forum in 2000. From the themes of more than 10 meetings of the Stockholm International Water Symposium, it can be seen that with the increasing awareness of the concept of coordinated

and sustainable development of coupled Ec-Re-En (Economy-Resource-Environment) systems in cities, the topics of international water symposiums have gradually developed from water scarcity, water pollution control, water conflicts, and integrated water management to the level of water security [2].

An urban water security assessment is essential to the promotion of sustainable and healthy development with a coupled urban Ec-Re-En (economy-resource-environment) system. The scientific evaluation of urban water security is a prerequisite in the analysis of urban water security issues, and an important basis for urban water policy planning and urban water security decision-making. Constructing an objective and reliable evaluation index system is the basis for the scientific assessment of urban water security. A scientific evaluation framework model is the key to building an objective and reasonable index system. Over the past few years, research on urban water security evaluation frameworks has yielded a wealth of results. For example, Jin Chunling (2009) built a water security evaluation index system in Lanzhou City using an improved PSR (pressure, state, response) model [3]; Tian Tao (2012) used the DPSIR (driver, pressure, state, impact, response) model to create a water security evaluation index system in Guangzhou City [4]. Romero-Lankao (2016) established the SETEG (socio-demographic, economic, technological, ecological, and governance) assessment framework to analyze and quantitatively evaluate urban water security status [5]; Aboelnga (2019) established the DECS (drinking water, ecosystems, climate change and water-related hazards, and socioeconomic) framework and applied it to empirically assess the city of Madaba, a water-stressed city in Jordan [6]; With a deep understanding of the concept of sustainable development, Chang and Zhu (2020) proposed a new framework to assess urban water security over a six-stage process of urban water management paradigm shift and applied it to case evaluations in four Chinese cities (Beijing, Shanghai, Chongqing, and Tianjin) [7,8]. The SETEG assessment framework, the DECS framework, and Chang and Zhu's (2020) urban water security assessment framework are all categorized indicator systems developed through the division of different sectoral areas of urban water security. The advantage of these evaluation frameworks is that they can comprehensively assess the urban water security situation, but the disadvantage is that they cannot dynamically describe the linkages between indicators and cannot sufficiently reveal the evolution mechanism of urban water security events.

The DPSIR model, a framework first proposed in 1993, has been widely used in environment evaluation [9]. The DPSIR model selects evaluation indicators with causal relationships by depicting the causal processes of changes in the state of environmental systems under the action of human activities. The DPSIR model can reveal the complex relationships of various influencing factors in complex environmental systems and conduct a fusion analysis of different sectoral indicators, so it is widely used in the fields of environmental research. Chang and Zhao (2020) used the City Blueprint® Approach to analyze water resources management in major cities in China, pointing out that urban rainfall and flooding is one of the major challenges facing urban water security [10]. The water security assessment should include water resources issues, water ecosystem damage, and water and drought disaster issues [11]. Although the DPSIR framework model can be applied to water resources and water environment assessment, it does not apply not applicable to assessing water disaster issues such as rainfall and flooding, and cannot be targeted to include urban rainfall and flooding disaster issues in the assessment, so the utility of using the DPSIR model for urban water security assessment is questionable. To address the problem that the DPSIR model cannot effectively incorporate the rainfall disaster problems faced by cities into the urban water security assessment system, this paper proposes a conceptual framework of DPEBLR (driver, pressure, environment, insecurity-affected body, loss, response) which is based on the DPSIR model and the rainfall hazard assessment model HEVD (the hazard of disaster-causing factors, the vulnerability of the disaster-affected body, the instability of disaster-pregnant environment, and population loss). The HVED framework model is a conceptual framework of rainstorm flood disaster loss assessment based on the disaster system theory proposed by Chinese scholar Yin Weixia (2016). The

HVED framework model argues that population loss (D) is the result of the combined effect of hazards (H) of disaster-causing factors, the vulnerability of the disaster-affected body (V), and the instability of the disaster-pregnant environment (E) [12].

The results of urban water security evaluation are influenced by a variety of factors, which are constrained and related to each other. Different disciplines have different criteria for judging urban water security, which may lead to contradictions between urban water security evaluation results. The matter-element extension theory transforms the contradictory problem into a compatible problem by transforming the object elements for treatment [13], and establishes the classical domain to quantify the relationship between indicators and evaluation results, and its evaluation results are more accurate [14]. Matter element extension theory is very effective in dealing with the contradictions in the evaluation of urban water security. However, it does not deal well with the randomness and ambiguity of the thresholds for urban water safety classification. The cloud matter element model improves the matter element extension theory by using the uncertain inference property of the cloud model to overcome its randomness and ambiguity problems [15]. The model has a wide range of application areas and has been applied to geological construction risk assessment, cable operation state assessment, system security risk assessment, comprehensive benefit evaluation, etc. [16–18].

In summary, the research objectives of this paper are threefold: first, it addresses the problem of mismatch between the DPSIR model and the evolutionary mechanism of urban water security events; second, it addresses the contradiction problem in urban water security evaluation; and third, it addresses the randomness and fuzziness of the boundaries of urban water security levels.

The following is the organization of the rest of this study. Section 2 describes the research methods: the DPEBLR conceptual model, the construction of the DPEBLR model-based water security evaluation system in Chongqing, and the cloud matter-element model. Section 3 describes the study area and the sources of evaluation data. Section 4 presents the results of the water security evaluation in Chongqing. Section 5 discusses the study results as well as the study limitations and prospects, and gives policy recommendations for the improvement of water security status in Chongqing. Section 6 summarizes the main research findings.

2. Methods

2.1. Presentation of the DPEBLR Conceptual Model

Referring to the DPSIR model and the HEVD rainfall disaster causal chain model, this study proposes the conceptual model of DPEBLR (driver, pressure, environment, insecurity-affected body, loss, response) under the concept of sustainable development and disaster causal chain. Among them, the potential cause of urban water security problems is the driver (D), and the direct cause is the pressure (P). The potential cause driver (D) leads to the direct cause pressure (P), and the direct cause in combination with the environment (E) causes losses (D) to the insecurity-affected body (B), and these losses prompt a direct or indirect human response (R). The specific connotations of the DPEBLR model for urban water security evaluation are as follows:

- Driver (D) refers to the potential causes of urban water security changes, such as population growth, economic growth, and social demands.
- Pressure (P) refers to the direct cause of changes in the state of urban water security, such as integrated water supply capacity, urban water consumption, and urban sewage discharge.
- Environment (E) includes natural factors and human factors. Natural factors such as climate conditions, drinking water quality, water quality, and water resources quantity; Human factors include water supply, water storage, and urban water pollution treatment capacity.
- The insecurity-affected body (B) is the bearer of urban water security problems, including population, housing, transportation, infrastructure, and other water-related objects.

- Loss (L) refers to casualties or economic losses caused by urban water security problems, such as direct economic losses caused by floods, the number of deaths, the number of people suffering from dry drinking water, and the affected area of crops.
- Response (R) refers to the countermeasures taken by human beings for urban water security.

The DPEBLR model is shown in Figure 1.

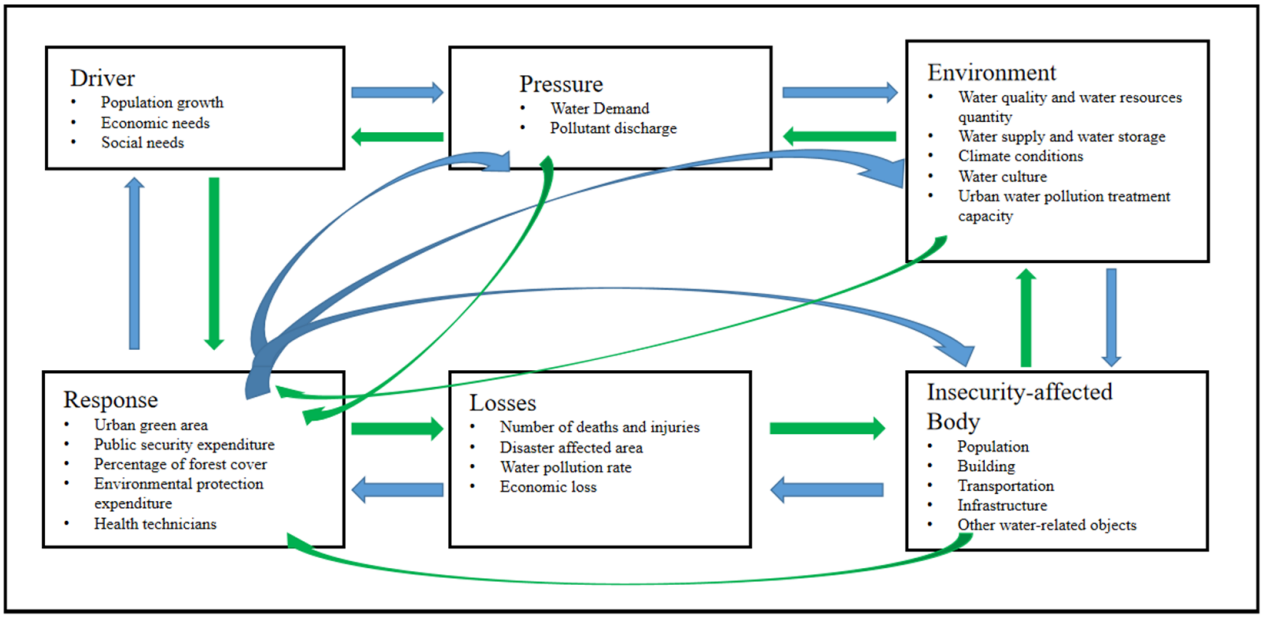


Figure 1. Urban Water Security Evaluation DPEBLR Conceptual Model.

2.2. Building the DPEBLR Evaluation Index System for Urban Water Security

The DPEBLR model framework provides a distinct research viewpoint while also providing a theoretical foundation for the development of an urban water security evaluation index system. With the DPEBLR model as the theoretical basis and the principles of data accessibility, target-oriented, dynamics and completeness as indicator screening, the urban water security evaluation system was created by combining existing studies [1,3,4,6–8,19]. Six subsystems were established in this study: driver (D), pressure (P), insecurity-pregnant environment (E), insecurity-affected body (B), loss (L) and response (R). The index layer includes 35 indicators, which are detailed in Table 1.

Table 1. The DPEBLR evaluation index system for urban water security.

Target Layer	Criterion Layer	Indicator Layer	Type
Urban water security evaluation (A)	Driver (D)	GDP D1 (108 Yuan)	(+)
		The natural growth rate of population D2 (%)	(−)
		Per capita consumption expenditure of all residents D3 (Yuan)	(+)
	Pressure (P)	Water consumption per 10,000 yuan GDP P4 (m^3)	(−)
		Process water consumption P5 (10^8 m^3)	(−)
		Domestic water consumption P6 (10^8 m^3)	(−)
		Water consumption per capital P7 (m^3/person)	(−)
		Wastewater discharge volume P8 (10^8 Tons)	(−)
		Chemical oxygen demand emissions P9 (10^4 Tons)	(−)

Table 1. *Cont.*

Target Layer	Criterion Layer	Indicator Layer	Type
Urban water security evaluation (A)	Environment (E)	Surface water resources E10 (10^8 m^3)	(+)
		Quantity of groundwater resources E11 (10^8 m^3)	(+)
		Per capita water resources E12 (m^3/person)	(+)
		Water production modulus E13 (10^4 m^3/km^2)	(+)
		Total water supply quantity E14 (10^8 m^3)	(+)
		Total volume of water storage E15 (10^8 m^3)	(+)
		Water consumption rate E16 (%)	(−)
		Average annual rainfall E17 (mm)	(−)
		Comprehensive production capacity of water supply E18 (10^4 m^3/Day)	(+)
		City daily sewage treatment capacity E19 (10^4 m^3)	(+)
		Drinking water quality compliance rate E20 (%)	(+)
	Insecurity-affected Body (B)	Urban population density B21 (person/km^2)	(−)
		Built-up area B22 (km^2)	(−)
		Length of pipes B23 (km)	(+)
		Length of urban drainage pipeline B24 (10^4 km)	(+)
		The total length of bus lines B25 (km)	(+)
	Loss (L)	The direct economic loss of flood disaster L26 (10^8 Yuan)	(−)
		The death toll of flood disaster L27 (person)	(−)
		Population in drinking water access difficulties because of drought L28 (10^4 person)	(−)
		Areas affected by drought crops L29 (10^3 hm^2)	(−)
	Response (R)	Urban green area R30 (10^4 hm^2)	(+)
		Public security expenditure R31 (10^4 Yuan)	(+)
		Ecological and environmental water supplement R32 (10^8 m^3)	(+)
		Percentage of forest cover R33 (%)	(+)
		Environmental protection expenditure R34 (10^8 Yuan)	(+)
		Health technicians per 10,000 population R35 (person)	(+)

Notes: "+" indicated as a positive indicator; "−" indicated as a negative indicator.

2.3. Comprehensive Evaluation Method of the Cloud Matter Element Model

The matter element extension evaluation theory is mainly used to study the contradiction in dealing with problems, but there are inevitably problems of fuzziness and randomness of quantitative values in the analysis and evaluation process [20]. By assigning random degrees of certainty to sample points, the cloud model facilitates the merging of qualitative concepts and quantitative representations, thus integrating the portrayal of randomness, ambiguity, and relevance in concepts [21]. The extension of matter element evaluation improved by the cloud model will effectively solve the shortcomings of the traditional matter-element model in randomness and fuzziness and make the evaluation conclusion more reliable.

2.3.1. Urban Water Security Evaluation Index Weights Acquisition

The combination weighing approach avoids the subjective arbitrariness of subjective weights while also overcoming the drawback of objective weights that ignore the decision-maker's intent. In this paper, game theory is chosen for determining the combined weights of each indicator.

AHP Method to Obtain Subjective Weights

First, based on the urban water security evaluation index system proposed in Table 1, experts compared the indicators two-by-two according to the 1–9 scale method [22] to construct a judgment matrix and normalize.

$$M_i = \prod_{j=1}^{n} a_{ij} \tag{1}$$

$$\overline{W_i} = \sqrt[n]{M_i} \tag{2}$$

Second, the weight vector was calculated.

$$W_i = \overline{W_i} / \sum_{i=1}^{n} W_i \tag{3}$$

Third, the eigenvectors and the maximum eigenroots of the decision matrix A were calculated.

$$AW = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} \\ a_{21} & a_{22} & \cdots & a_{2j} \\ \vdots & \vdots & & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} = \lambda\omega \tag{4}$$

$$\lambda_{max} = \sum_{i=1}^{n} \frac{(AW)_i}{nW_i} \tag{5}$$

Fourth, consistency tests were performed on the judgment matrix ($CR < 0.1$).

$$CR = CI/RI \tag{6}$$

$$CI = \frac{1}{n-1}(\lambda_{max} - n) \tag{7}$$

Entropy Weighting Method to Obtain Subjective Weights

First, the judgment matrix is constructed with the raw data. The original data are normalized using Equation (8), and the information entropy value is calculated using Equations (9) and (10) [15]:

$$\begin{cases} Y_{ij} = \frac{X_{ij} - X_{min}}{X_{max} - X_{min}}, \ positive\ indexes \\ Y_{ij} = \frac{X_{max} - X_{ij}}{X_{max} - X_{min}}, \ negative\ indexes \end{cases} \tag{8}$$

$$P_{ij} = \frac{1 + Y_{ij}}{\sum_{i=1}^{n}(1 + Y_{ij})} \tag{9}$$

$$H_i = -\frac{1}{ln\ n} \sum_{i=1}^{n} P_{ij} ln\ P_{ij} \tag{10}$$

Second, the objective weight values of the indicator layer are calculated using Equation (11), and the objective weights of the criterion layer are calculated using Equation (12) [18]:

$$\omega_i = \frac{1 - H_i}{\sum_{i=1}^{n}(1 - H_i)} \tag{11}$$

$$W_k = \frac{\sum_{i=1}^{n}(1 - H_i)}{\sum_{k=1}^{N}\sum_{i=1}^{n}(1 - H_i)} \tag{12}$$

Game Theory to Obtain Combination Weights

Firstly, the fundamental weight vector set is structured based on the subjective weight values calculated by the AHP method 1 and the objective weight values calculated by the Entropy Weighting Method [23,24]. $\omega_k = \{\omega_{k1}, \omega_{k2}, \cdots, \omega_{kn}\}(k = 1, 2, \cdots k)$, n is 35, and k is 2 in this study. Introducing a linear combination of weight coefficients, the stochastic linear combination of combined weight vectors is shown in Equation (13).

$$\omega = \sum_{k=1}^{n} \alpha_k \omega_k^T \tag{13}$$

Secondly, the best combination coefficient α_k is calculated by using the objective function ($min \| \sum_{k=1}^{n} \alpha_k \omega_k^T - \omega_k \|$), and normalizing it by Equation (14)

$$\alpha_k^* = \alpha_k / \sum_{k=1}^{n} \alpha_k \tag{14}$$

Finally, we get the combined weight of urban water security indicators according to Equation (15).

$$\omega^* = \sum_{k=1}^{n} \alpha_k^* \omega_k^T \tag{15}$$

2.3.2. The Cloud Matter-Element Model

Evaluation Criterion

Evaluation criteria are the basis of the Cloud Matter-Element Model. Evaluation criteria for urban water security vary from region to region. In this study, concerning the existing literature on urban water security criteria, the evaluation criteria for urban water security are classified into five levels: safer, safe, critical safe, unsafe, and extremely unsafe, taking into account the critical values of water pollution security indicators, water disaster classification criteria, and other nationally promulgated standards as well as the planning targets of local governments [1,3–8,19].

The classification criteria of urban water security indicators are shown in Table 2.

Table 2. Urban water security evaluation criteria.

Indicator	I (Safer)	II (Safe)	III (Critical Safe)	IV (Unsafe)	V (Extremely Unsafe)
D1	>25,000	[20,000, 25,000)	[15,000, 20,000)	[10,000, 15,000)	<10,000
D2	<2	[2, 3)	[3, 4)	[4, 5)	>5
D3	>30,000	(25,000, 30,000]	(20,000, 15,000]	(15,000, 10,000]	<10,000
P4	<30	[30, 40)	[40, 70)	[70, 100]	>100
P5	<50	[50, 60)	[60, 70)	[70, 80)	>80
P6	<13	[13, 14)	[14, 15)	[15, 16)	>16
P7	<200	[200, 230)	[230, 260)	[260, 290)	>290
P8	<20	[20, 22)	[22, 24)	[24, 26)	>26
P9	<5	[5, 10)	[10, 20)	[20, 30)	>30
E10	>700	[600, 700)	[500, 600)	[400, 500)	<400
E11	>120	(110, 120]	(100, 110]	(90, 100]	<90
E12	>2000	(1800, 2000]	(1600, 1800]	(1400, 1600]	<1400
E13	>90	(80, 90]	(70, 80]	(60, 70]	<60
E14	>85	(82, 85]	(76, 82]	(70, 76]	<70
E15	>55	(50, 55]	(45, 50]	(40, 45]	<40
E16	<45	[45, 50)	[50, 55)	[55, 60)	>60
E17	<500	[500, 1000)	[1000, 1500)	[1500, 2000)	>2000
E18	>700	(600, 700]	(500, 600]	(400, 500]	<400
E19	>400	(350, 400]	(300, 350]	(250, 300]	<250
E20	>98	(96, 98]	(94, 96]	(92, 94]	(92, 80]
B21	<1000	(1000, 1500]	(1500, 2000]	(2000, 2500]	>2500
B22	<1200	(1200, 1500]	(1500, 1800]	(1800, 2100]	>2100

Table 2. *Cont.*

Indicator	I (Safer)	II (Safe)	III (Critical Safe)	IV (Unsafe)	V (Extremely Unsafe)
B23	>25,000	(20,000, 25,000]	(15,000, 20,000]	(10,000, 15,000]	<10,000
B24	>2	(1.8, 2]	(1.6, 1.8]	(1.4, 1.6]	<1.4
B25	>25,000	(20,000, 25,000]	(15,000, 20,000]	(10,000, 15,000]	<10,000
L26	<10	[10, 30)	[30, 50]	[50, 100)	>100
L27	<3	[3, 10)	[10, 30)	[30, 50)	>50 (150)
L28	<10	[10, 50)	[50, 100)	[100, 150)	>150 (300)
L29	<10	[10, 50)	[50, 100)	[100, 150)	>150 (400)
R30	>7	(6, 7]	(5, 6]	(4, 5]	<4
R31	>240	(200, 240]	(160, 200]	(120, 160]	<120
R32	>1.5	(1.2, 1.5]	(0.9, 1.2]	(0.6, 0.9]	<0.6
R33	>50	(48, 50]	(46, 48]	(44, 46]	<44
R34	>170	(150, 170]	(130, 150]	(110, 130]	<110
R35	>70	(60, 70]	(50, 60]	(40, 50]	<40

The Cloud Matter Element Model Evaluation Process

The Cloud Matter-Element Model can be expressed by Formula (16):

$$R = \begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix} = \begin{bmatrix} N & C_1 & V_1 \\ & C_2 & V_2 \\ & \vdots & \vdots \\ & C_n & V_n \end{bmatrix} = \begin{bmatrix} N & C_1 & (E_{x_1}, E_{n_1} H_{e_1}) \\ & C_2 & (E_{x_2}, E_{n_2} H_{e_2}) \\ & \vdots & \vdots \\ & C_n & (E_{x_n}, E_{n_n} H_{e_n}) \end{bmatrix} \quad (16)$$

In the formula, R is the matter element, Ex is an expectation, En is entropy, and He is super entropy. In the Cloud Matter-Element Model, with the different grades of the evaluation index as the reference, the urban water security level is represented by the fixed interval $[C_{min}, C_{max}]$. We converted the interval values to cloud parameters according to the "3En" rule of the cloud model (Ex, En, He).

$$Ex = \frac{C_{max} + C_{min}}{2} \quad (17)$$

$$En = \frac{C_{max} - C_{min}}{2.5348} \quad (18)$$

$$He = s \quad (19)$$

In the formula, s is a constant. This study is determined by a trial algorithm.

The steps of the trial algorithm are as follows (taking GDP in the urban water security evaluation index system as an example):

Firstly, based on Table 2, according to Equations (17) and (18), Ex and En are calculated, respectively, and the cloud map of GDP water security level under different He is drawn by MATLAB software.

Secondly, according to the basic requirements of fuzziness and randomness of the cloud model, the cloud maps under different He in Figure 2 are compared. When He = 200, the part of the membership degree greater than 50% in the cloud model is clear, and the part of the membership degree less than 50% is fuzzy and crossed. The fuzziness is moderate, which is conducive to obtaining a more accurate membership degree. Therefore, He = 200 was chosen as the evaluation parameter for the urban water security level of GDP, and the cloud matter element models of the urban water security level of GDP are obtained. Similarly, the cloud matter element models of different water security levels in urban water security index systems are obtained. The final results are shown in Table 3.

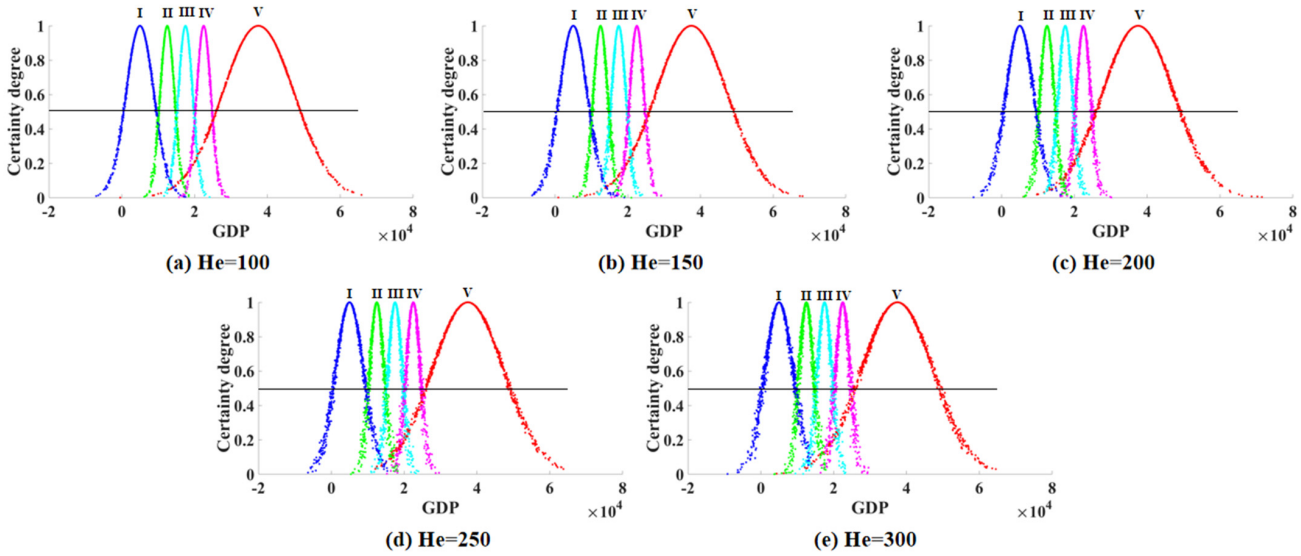


Figure 2. Cloud model map of GDP.

Table 3. The Cloud Matter element Parameters of Urban Water Security Evaluation Standard.

Indicator	I (Safer)	II (Safe)	III (Critical Safe)	IV (Unsafe)	V (Extremely Unsafe)
D1	(37,500, 9862.7, 200)	(22,500, 1972.54, 200)	(17,500, 1972.54, 200)	(12,500, 1972.54, 200)	(5000, 3845.08, 200)
D2	(0, 1.578, 0.1)	(2.5, 0.395, 0.1)	(3.5, 0.395, 0.1)	(4.5, 0.395, 0.1)	(7.5, 1.973, 0.1)
D3	(45,000, 11835.25, 200)	(27,500, 1972.54, 200)	(22,500, 1972.54, 200)	(17,500, 1972.54, 200)	(7500, 5917.63, 600)
P4	(15, 11.835, 1)	(35, 3.945, 1)	(55, 11.835, 1)	(85, 11.835, 1)	(150, 39.451, 1)
P5	(25, 19.725, 0.4)	(55, 3.945, 0.4)	(65, 3.945, 0.4)	(75, 3.945, 0.4)	(120, 31.561, 1.5)
P6	(6.5, 5.129, 0.01)	(13.5, 0.395, 0.01)	(14.5, 0.395, 0.01)	(15.5, 0.395, 0.01)	(24, 6.312, 0.01)
P7	(100, 78.902, 1.5)	(215, 11.835, 1.5)	(245, 11.835, 1.5)	(275, 11.835, 1.5)	(435, 114.407, 1.5)
P8	(10, 7.890, 0.01)	(21, 0.789, 0.01)	(23, 0.789, 0.01)	(25, 0.789, 0.01)	(39, 10.257, 0.01)
P9	(2.5, 1.973, 0.2)	(7.5, 1.973, 0.2)	(15, 3.945, 0.2)	(25, 3.945, 0.2)	(45, 11.835, 0.2)
E10	(1050, 276.156, 5)	(650, 39.451, 5)	(550, 39.451, 5)	(450, 39.451, 5)	(200, 157.803, 5)
E11	(180, 47.341, 0.5)	(115, 3.945, 0.5)	(105, 3.945, 0.5)	(95, 3.945, 0.5)	(45, 35.505, 0.5)
E12	(3000, 788.989, 5)	(1900, 78.899, 5)	(1700, 78.899, 5)	(1500, 78.899, 5)	(700, 276.1559, 5)
E13	(135, 35.505, 0.5)	(85, 3.945, 0.5)	(75, 3.945, 0.5)	(65, 3.945, 0.5)	(30, 23.669, 0.5)
E14	(127.5, 33.533, 0.01)	(83.5, 1.1835, 0.01)	(79, 2.3671, 0.01)	(73, 2.3671, 0.01)	(35, 27.6156, 0.01)
E15	(82.5, 21.698, 0.2)	(52.5, 1.9725, 0.2)	(47.5, 1.9725, 0.2)	(42.5, 1.9725, 0.2)	(20, 15.7803, 0.2)
E16	(22.5, 17.7529, 0.3)	(47.5, 1.9725, 0.3)	(52.5, 1.9725, 0.3)	(57.5, 1.9725, 0.3)	(90, 23.6705, 0.3)
E17	(250, 197.2542, 30)	(750, 197.2542, 30)	(1250, 197.2542, 30)	(1750, 197.2542, 30)	(3000, 789.0169, 30)
E18	(1050, 276.1559, 6)	(650, 39.451, 6)	(550, 39.451, 6)	(450, 39.451, 6)	(200, 157.803, 6)
E19	(600, 157.8034, 2)	(375, 19.7254, 2)	(325, 19.7254, 2)	(275, 19.7254, 2)	(125, 98.6271, 2)
E20	(99, 0.789, 0.05)	(97, 0.789, 0.05)	(95, 0.789, 0.05)	(93, 0.789, 0.05)	(86, 4.7341, 0.05)
B21	(500, 394.5084, 30)	(1250, 97.2542, 30)	(1750, 97.2542, 30)	(2250, 97.2542, 30)	(3750, 986.2711, 30)
B22	(600, 473.4101, 20)	(1350, 118.3525, 20)	(1650, 118.3525, 20)	(1950, 118.3525, 20)	(3150, 828.4677, 20)
B23	(37,500, 9862.7, 300)	(22,500, 1972.5, 300)	(17,500, 1972.5, 300)	(12,500, 1972.5, 300)	(5000, 3945.1, 300)
B24	(3, 0.789, 0.01)	(1.9, 0.0789, 0.01)	(1.7, 0.0789, 0.01)	(1.5, 0.0789, 0.01)	(0.7, 0.5523, 0.01)
B25	(37,500, 9862.7, 300)	(22,500, 1972.5, 300)	(17,500, 1972.5, 300)	(12,500, 1972.5, 300)	(5000, 3945.1, 300)
L26	(5, 1.9725, 0.5)	(20, 7.8902, 0.5)	(40, 7.8902, 0.5)	(75, 19.7254, 0.5)	(150, 39.4508, 0.5)
L27	(1.5, 1.1835, 0.1)	(6.5, 2.7616, 0.1)	(20, 7.8902, 0.1)	(40, 7.8902, 0.1)	(100, 39.4508, 0.1)
L28	(5, 1.9725, 0.5)	(30, 15.7803, 0.5)	(75, 19.7254, 0.5)	(125, 19.7254, 0.5)	(225, 59.1763, 0.5)
L29	(5, 1.9725, 0.5)	(30, 15.7803, 0.5)	(75, 19.7254, 0.5)	(125, 19.7254, 0.5)	(275, 98.6271, 0.5)
R30	(10.5, 2.7616, 0.05)	(6.5, 0.3945, 0.05)	(5.5, 0.3945, 0.05)	(4.5, 0.3945, 0.05)	(2, 0.789, 0.05)
R31	(360, 94.6820, 2)	(220, 15.7803, 2)	(180, 15.7803, 2)	(140, 15.7803, 2)	(60, 47.341, 2)
R32	(2.25, 0.5918, 0.01)	(1.35, 0.1184, 0.01)	(1.05, 0.1184, 0.01)	(0.75, 0.1184, 0.01)	(0.3, 0.2368, 0.01)
R33	(75, 19.7254, 0.01)	(49, 0.789, 0.01)	(47, 0.789, 0.01)	(45, 0.789, 0.01)	(22, 17.3584, 0.01)
R34	(255, 67.0664, 1)	(160, 7.8902, 1)	(140, 7.8902, 1)	(120, 7.8902, 1)	(55, 43.3959, 1)
R35	(105, 27.6156, 0.5)	(65, 3.945, 0.5)	(55, 3.945, 0.5)	(45, 3.945, 0.5)	(20, 15.7803, 0.5)

According to Table 3, the degree of membership of the cloud for different urban water security levels is calculated according to Equations (20) and (21).

$$\mu(x) = exp\left[\frac{-(x-Ex)^2}{2(En')^2}\right] \tag{20}$$

$$En' = r + H_e + En \tag{21}$$

Considering the introduction of random number r, the calculation results have great randomness. Therefore, in this study, the median of 1000 iterations of the calculation was taken as the membership of each evaluation index for different urban water security levels.

The degree of membership of each criterion in the criteria layer for different urban water security levels is calculated according to Equation (22):

$$\mu_j(B_i) = \sum_{s=1}^{n} W_{is}\mu_j(I_{is}) \tag{22}$$

In Formula (22), $\mu_j(B_i)$ is the membership degree of the matter element of the ith criterion layer to different urban water security grades j, W_{is} is the combined weight of the sth index to the ith criterion layer, and $\mu_j(I_{is})$ is the membership degree of the matter element of the s index layer to different urban water security grades j. The calculation method of membership degree of the target layer to different urban water security grades is the same as above. According to Equation (23), the urban water security level L of different matter elements is determined.

$$L = \max\mu_j(B); j \in \{I, II, III, IV, V\} \tag{23}$$

2.3.3. The Comprehensive Urban Water Security Evaluation Process

Integrated with the contents described in the previous sections, the process of comprehensive evaluation of urban water security is shown in Figure 3.

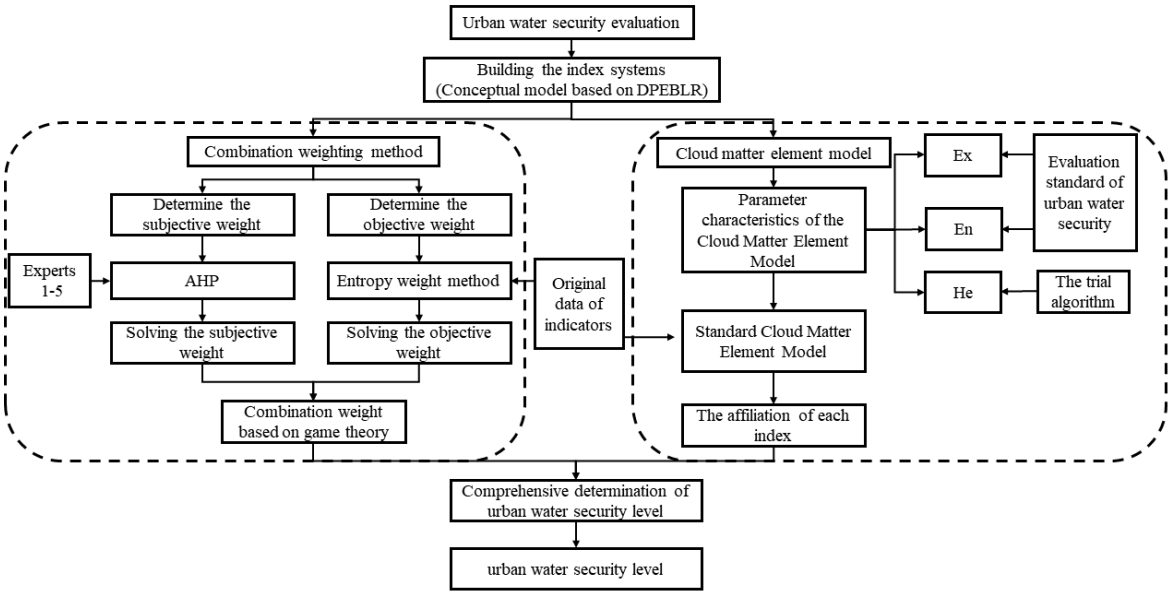


Figure 3. Urban water security assessment process based on DPEBLR conceptual model and combined weight cloud matter-element model.

3. Instance Validation

3.1. Research Area

Chongqing (105°17′~110°11′ E,28°10′~32°13′ S), located in southwestern China (as shown in Figure 4), is an important bridge for the inland area of the national "Belt and Road" strategy and the western center of the Yangtze River Economic Belt, covering an area of 82,400 km^2. The Yangtze River runs from southwest to northeast across the city, with the Jialing River in the north and the Wu River in the south, forming a centripetal, asymmetrical network of water systems. There are 274 rivers with a watershed area greater than 100 km^2, including 42 rivers with a watershed area greater than 1000 km^2 (Chongqing Water Resources Bulletin, 2020). By the end of 2020, Chongqing's GDP was 78,294 yuan. Chongqing's resident population is about 32.1 million, the urbanization rate was 69.5%, the per capita water resources was 2397.7 m^3/person, and the water consumption population was 15,246,000 [25]. The annual rainfall in Chongqing is 1000–1450 mm, with uneven distribution of precipitation and more frequent droughts and floods. The flood control standard in the main city of Chongqing is not up to one in 10 years. The city's 1388 reservoirs cannot safely through the flood season.

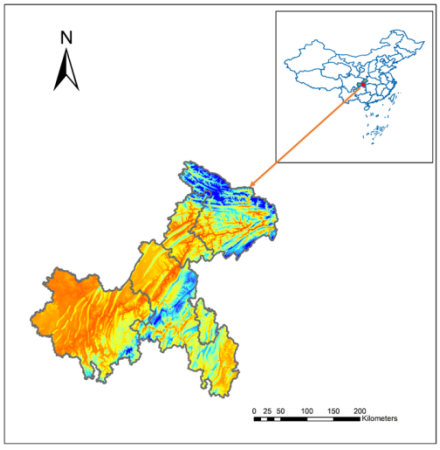


Figure 4. The geographical location of Chongqing.

3.2. Data

The original data of the indicators are derived from the China Statistical Yearbook (2010–2020) [26], China Flood and Drought Prevention Bulletin (2010–2020) [27], Chongqing Statistical Yearbook (2010–2020) [28], and Chongqing Water Resources Bulletin (2010–2020) [29]. The original data are shown in Table 4:

Table 4. The raw data of Chongqing water urban water security evaluation index (2011–2019).

Indicator	2019	2018	2017	2016	2015	2014	2013	2012	2011
D1	23,605.8	21,588.8	20,066.3	18,023	16,040.5	14,623.8	13,027.6	11,595.4	10,161.2
D2	2.91	3.48	3.91	4.53	3.86	3.62	3.6	4	3.17
D3	20,774	19,248	17,898	16,385	15,140	13,811	12,600	11,468	10,263
P4	32	38	40	44	50	56	66	72	87
P5	59.2982	66.3301	61.1187	61.3079	63.2056	65.103	69.2068	68.7287	72.7787
P6	15.9199	15.6567	15.2374	15.1086	14.8025	14.4369	13.8573	13.4439	13.3031
P7	245	249	252	254	262	269	283	282	297
P8	24.2073	24.5195	25.0693	24.8829	24.7178	24.977	24.2642	24.7039	25.2102
P9	5.15	5.36	5.57	6.49	37.98	38.64	39.18	40.28	41.68
E10	498.1	524.2	656.1	604.9	456.2	642.6	474.3	476.9	514.6
E11	98.5	104	116.1	112.3	103.3	121.8	96.4	97.8	98.3
E12	1600.1	1697.2	2142.9	1994.7	1518.7	2155.9	1603.9	1626.5	1773.3

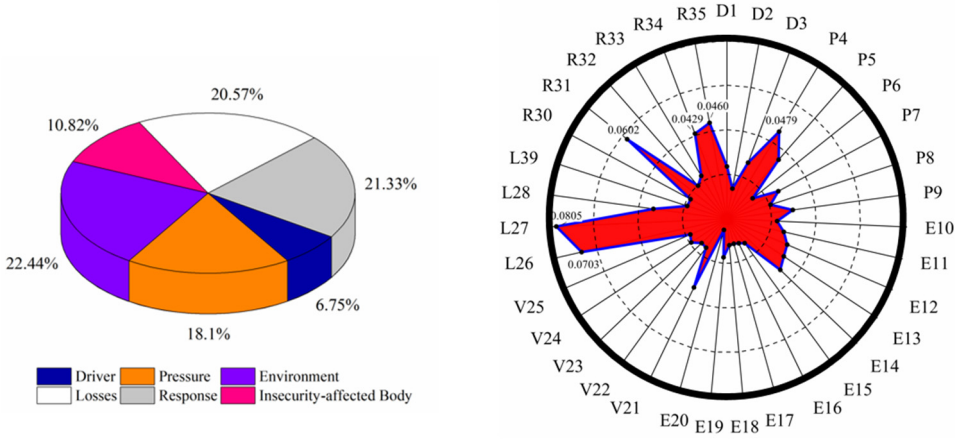
Table 4. *Cont.*

Indicator	2019	2018	2017	2016	2015	2014	2013	2012	2011
E13	60.45	63.62	79.63	73.41	55.36	77.98	57.57	57.87	62.45
E14	76.4719	77.1959	77.4408	77.483	78.9802	80.4687	83.9066	82.936	86.7976
E15	53.4793	55.8578	59.7778	54.8246	50.3225	60.5885	49.4209	51.4615	38.4217
E16	55.88	55.79	55.37	54.93	54.01	51.18	49.49	50.08	47.66
E17	1106.8	1134.8	1275.3	1236.8	1048.3	1270	1063.6	1080.6	1091.8
E18	627.76	616.99	599.87	566.12	529.92	506.89	491.22	447.83	429.27
E19	394.1	367.1	319	289.7	273.8	257.8	253.8	238.4	219.7
E20	100	100	100	100	100	97.3	100	100	100
B21	2012	2026	2017	1953	1904	1872	1847	1832	1830
B22	1515	1497	1423	1351	1329	1231	1115	1052	1035
B23	20,159	19,078	17,789	16,629	15,054	11,601	10,619	9534	8914
B24	2.08	1.89	1.73	1.56	1.3	1.11	0.95	0.89	0.82
B25	27,105	16,394	16,164	14,352	13,342	11,989	16,972	8828	8880
L26	14.0	12.57	15.94	41.23	22.7	96.02	23.06	53.04	38.99
L27	25	0	8	30	20	103	7	17	19
L28	23.32	3.85	10.39	15.89	6.39	51.00	228.99	58.70	104.17
L29	42.45	28.95	79.57	47.2	2.37	7.60	64.97	61.93	387.6
R30	6.77	6.48	6.16	5.98	5.59	5.25	4.81	4.72	4.39
R31	268.66	259.31	235.91	226.17	203.29	159.56	141.22	134.03	124.93
R32	1.2538	1.2901	1.0847	1.0665	0.9721	0.9288	0.8425	0.7634	0.7158
R33	50.1	48.3	45.4	46.5	45	43.1	42.1	41	39
R34	172.95	160.19	154.95	136.2	140.73	105.51	114.55	128.69	100.81
R35	72	67	62	59	55	52	42	45	36

4. Results

4.1. Weight Calculation Results

The weight calculation results are shown in Table 5. The weight value of each combination of urban water security evaluation systems can be seen Figure 5. The top six weights are the number of flood deaths, direct economic losses of flood disasters, public security expenditure, health and technical personnel per ten thousand people, environmental protection expenditure, and water consumption per 10,000 yuan GDP. These indicators have a great impact on water security in Chongqing.



(a) Weights of the criterion Layer (b) Weights of the indicator layer

Figure 5. Chart of calculation results of Chongqing water security evaluation index weights.

Table 5. The weight calculation results of Chongqing water security evaluation indicators (2011–2019).

Indicator	AHP	Entropy Weight Method	Combination Weight	Criterion	Combination Weight
D1	0.0232	0.028	0.0247	D	0.0674
D2	0.0129	0.018	0.0145		
D3	0.0284	0.028	0.0283		
P4	0.0604	0.019	0.0479	P	0.1808
P5	0.0444	0.02	0.0370		
P6	0.0097	0.029	0.0155		
P7	0.0307	0.02	0.0275		
P8	0.0193	0.027	0.0216		
P9	0.0205	0.056	0.0313		
E10	0.0167	0.04	0.0237	E	0.2242
E11	0.0186	0.048	0.0275		
E12	0.0278	0.038	0.0309		
E13	0.0286	0.04	0.0321		
E14	0.0308	0.044	0.0348		
E15	0.0138	0.015	0.0142		
E16	0.0075	0.025	0.0128		
E17	0.0041	0.031	0.0122		
E18	0.0061	0.027	0.0125		
E19	0.0118	0.033	0.0182		
E20	0.0025	0.012	0.0054		
B21	0.0358	0.036	0.0359	B	0.1081
B22	0.0093	0.034	0.0168		
B23	0.0089	0.034	0.0165		
B24	0.0130	0.037	0.0202		
B25	0.0100	0.039	0.0188		
L26	0.0948	0.014	0.0703	L	0.2055
L27	0.1101	0.012	0.0805		
L28	0.0445	0.013	0.0350		
L29	0.0231	0.012	0.0197		
R30	0.0163	0.027	0.0195	R	0.2131
R31	0.0712	0.035	0.0602		
R32	0.0172	0.029	0.0207		
R33	0.0239	0.023	0.0236		
R34	0.0485	0.03	0.0429		
R35	0.0556	0.024	0.0460		

4.2. Comprehensive Evaluation Results of Water Security in Chongqing

The cloud matter element code and calculations were written using MATLAB2016b software. The comprehensive determination results of the urban water security status are detailed in Table 6.

According to Table 6, Chongqing's water security situation showed a ladder-like rise from 2011 to 2019. This shows that the issue of insufficient water supply, water ecological deterioration, water environment damage, and flood and drought disasters in Chongqing have been improved significantly.

Due to the special geographical location of Chongqing (located in the upper reaches of the Yangtze River), Chongqing has undertaken heavy social responsibility for ecological environment maintenance and restoration. The government has been committed to environmental protection and the construction of ecological civilization cities. It can be seen from the original data of being seen that wastewater discharge volume and chemical oxygen demand emissions in Chongqing are declining year by year, and the City's daily sewage treatment capacity, urban green area, ecological environment water supplement, forest cover rate, and environmental protection expenditure are increasing year by year. This shows that the construction of a water ecological restoration project in Chongqing has achieved good results.

Table 6. Chongqing's assessment results (2011–2019) of water security based on DPEBLR.

Year	Comprehensive Membership Degree					Evaluation Result
	I (Safer)	II (Safe)	III (Critical Safe)	IV (Unsafe)	V (Extremely Unsafe)	
2019	0.0470	0.0585	0.0440	0.0259	0.0213	II
2018	0.0539	0.0660	0.0513	0.0209	0.0194	II
2017	0.0403	0.0835	0.0581	0.0182	0.0183	II
2016	0.0332	0.0470	0.0915	0.0318	0.0237	III
2015	0.0313	0.0304	0.0929	0.0380	0.0320	III
2014	0.0290	0.0162	0.0632	0.0384	0.0547	III
2013	0.0194	0.0430	0.0397	0.0667	0.0510	IV
2012	0.0197	0.0164	0.0555	0.0760	0.0474	IV
2011	0.0183	0.0091	0.0498	0.0598	0.0606	V

In terms of water resources security, Chongqing's centralized water source protection project construction, centralized water supply project construction, and water-saving social construction has also made significant achievements. The comprehensive production capacity of the water supply increased from $429.27 * 10^4$ m^3/day in 2011 to 627.76×10^4 m^3/day in 2019. The drinking water source water quality standards rate was maintained at 100% year-round. The length of the water supply pipeline also increased from 8914 km in 2011 to 20,159 km in 2019. The water consumption per 10,000 yuan GDP decreased from 87 cubic meters in 2011 to 32 cubic meters per year in 2019.

In terms of water disaster prevention, the construction of flood control and drought resistance systems in Chongqing has also made great improvements. The total volume of water storage increased from 384.217 billion cubic meters in 2011 to 534.793 billion cubic meters in 2019. The length of the drainage pipeline, public security expenditure and health technicians per million people are increasing year by year. In addition to individual years, the losses caused by floods and droughts are also declining year by year.

5. Discussion and Policy Suggestions

5.1. Discussion

Urban water security is the foundation of urban sustainable development [30]. Scientific assessment of urban water security is a foundation for water policy formulation and the prevention of urban water security problems and is valuable for building environmentally friendly cities.

Based on the natural disaster chain theory, the DPEBLR conceptual model provides a new perspective and index system construction method for urban water security evaluation which can fully evaluate urban water security that integrates water resources security, water environment security, water ecological security and water disaster security. The DPEBLR conceptual model also provides an effective system analysis approach for identifying the cause of urban water security problems, predicting the possible adverse consequences of urban water security problems, as well as developing reasonable countermeasures. The cloud matter element model provides a useful tool for the quantitative evaluation of urban water security. The cloud matter element model effectively solves the contradiction problem in urban water security evaluation through the matter element extension theory, and effectively solves the problem of fuzziness and randomness of the boundary threshold of water security level through the cloud model. In addition to urban water security evaluation, the cloud matter element comprehensive evaluation model can also work in the fields of environmental carrying capacity, ecological safety assessment, environmental health assessment, etc.

However, there are still limitations to the model. Firstly, due to the unavailability of data, there are some relevant but unavailable indicators in the urban water security evaluation system that are not used (e.g., water pollution loss and water ecological loss), which may lead to biased evaluation results. Therefore, future research should consider the use of urban big data to analyze and mine out the above types of indicator data to improve

the urban water security evaluation system. Secondly, this study is a long-term evaluation with an annual cycle, and the influence of seasonal factors on urban water security status cannot be reflected in this study, but the influence of seasonality on urban water security status is obvious [31,32].

5.2. Policy Suggestions

Urban water security is an essential component of sustainable urban development, as it is the cornerstone of urban development. Scientific management and effective governance remain an important means of achieving sustainable improvements in urban water security. The regional environment, economic development level, science and technology level, and strategic position of different cities are different. Therefore, the evaluation of urban water security should be combined with the historical evolution and actual situation of the city to make a reasonable evaluation. Taking Chongqing as an example, this research proposes the following policy recommendations to address the urban water security issues facing Chongqing:

(1) Chongqing has special natural geographical characteristics. Although water resources are abundant, it is located in a karst landscape, which makes groundwater utilization difficult, and coupled with the fact of insufficient supporting water conservancy infrastructure, the engineering water shortage is serious. In the future, we should increase the investment in water conservancy infrastructure construction and explore new technologies and methods for sustainable utilization of water resources in karst landscapes to reduce the problem of engineering water shortage.

(2) Chongqing is characterized by a well-developed surface water system and abundant precipitation with uneven seasonal distribution. While the population and social economy of Chongqing are developing rapidly, the urban water disaster defense system has started late and developed slowly, resulting in serious losses from water and drought disasters. From the raw data of two indicators, public security expenditure and health technicians per 10,000 population, it can be seen that the construction of the current urban water disaster defense system is not coordinated with the current development of urban water security. In the future, Chongqing should slow down urbanization, improve the resilience of the insecurity-affected body of urban water security issues, increase investment in water disaster defense infrastructure, improve water disaster defense infrastructure support facilities, enhance the rapid response capability of water disasters, establish mature flood prevention and mitigation system, coordinate the speed of urban development with water disaster defense capability, and guarantee urban water disaster security.

(3) In terms of building a comprehensive awareness of water conservation, the amount of water used for production in Chongqing is decreasing year by year, but the amount of water used for domestic purposes is increasing year by year. This indicates that the city of Chongqing has had remarkable results in industrial water conservation over the past few years, and the development of laws and regulations at the enterprise level has had significant results and achieved noticeable results in easing the water tension. However, the awareness of water conservation among citizens in the area of domestic water use is not yet in place, and public participation is poor. Therefore, the government should allocate some of its resources in the future to the promotion of water conservation concepts and knowledge to the public [10].

(4) Urban water security management is a complex mega-system management project that involves multi-disciplinary and multi-sectoral cooperation. In the future, the city of Chongqing needs to combine urban water security management with urban big data work to achieve urban water security information perception, analysis and prediction, intelligent decision-making, etc., in addition to the implementation of the four links of closed-loop operation in order to achieve "smart water security city", to help the sustainable development of the city.

6. Conclusions

Urban water security evaluation is the basic work of urban water security. In response to the challenge that the environmental assessment framework DPSIR model does not fit the water security issues faced by cities such as rain and drought hazards, this study improves and enriches the DPSIR model by incorporating the HEVD rain and flood hazard model to achieve a scientific assessment of urban water security status. To solve the contradictory problems among the indicators in urban water security evaluation and the randomness and fuzziness of the boundaries of urban water security evaluation levels, the cloud matter element model was applied. The DPEBLR conceptual framework and cloud matter element model proposed in this study were applied to the water security evaluation in Chongqing and proved their validity and rationality. This study made the following conclusions.

(1) To solve the problem of mismatch between the DPSIR model and the inner mechanism of an urban water security evaluation, the DPEBLR conceptual model was constructed. Based on this conceptual model, 35 indicators are selected from six aspects: driver, pressure, insecurity-pregnant environment, insecurity-affected body, loss, and response to develop a water security evaluation system. The cloud matter element model was applied to make a comprehensive evaluation of the water security status. The results prove that the evaluation results are consistent with the current situation of water security in Chongqing city and have strong practicality. Also, this study found that the DPEBLR conceptual model can be an effective approach to the systematic analysis of urban water security issues.

(2) During the period of 2011 to 2019, Chongqing's water security status showed a gradual improvement. It gradually changes from 2011 from an extremely unsafe (v) to a safe level (II) in 2019. Among them, the death toll of flood disasters, direct economic losses from flooding, public security expenditures, health technicians per 10,000 population, environmental protection expenditures, and water consumption per 10,000 Yuan GDP are the top six indicators affecting the current water security situation in Chongqing.

(3) Chongqing's water security situation gradually improved. However, Chongqing still faces the following problems: (a) Engineering water shortages due to low groundwater utilization in karst landscapes; (b) The construction of an urban water disaster defense system lags behind the current urban development resulting in water and drought disaster problems; and (c) Industrial water conservation has achieved significant results, effectively alleviating the problem of water stress, but citizens' awareness of water conservation in life is weak. Therefore, in driving the development of urban ecological civilization in the future, the government should, firstly, pay attention to increasing investment in science and technology and innovating technologies for the efficient use and development of water resources in karst landscapes to alleviate engineering water shortages; Secondly, while the city is developing rapidly, it should improve its urban flood and drought disaster defense capacity as soon as possible and accelerate the construction of flood and drought disaster defense infrastructure. Thirdly, it should increase the awareness of water conservation for domestic use and promote the construction of a culture of water conservation for all people; Fourthly, Chongqing should continue to implement the requirement of "putting the restoration of the Yangtze River ecological environment in an overriding position, grasping great protection together and not engaging in great development" [29].

Author Contributions: Conceptualization, H.D. (Hongwei Deng) and X.S.; methodology, C.L.; software, X.S.; formal analysis, C.L. and Y.L.; resources, H.D. (Hongwei Deng); data curation, J.X. and Y.L.; writing—original draft preparation, X.S.; writing—review and editing, H.D. (Hongwei Deng); visualization, X.S., Y.L. and H.D. (Hu Diao); funding acquisition, H.D. (Hongwei Deng), J.X. and H.D. (Hu Diao). All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China (Grant No. 51874352), the Postgraduate Research Innovation Project of Central South University (University-Enterprise Joint) (Grant No. 1053320200344) and the Independent Exploration and Innovation Project for Graduate Students at Central South University (Grant No. 2021zzts0879).

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

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