

Analysis and predication of urban water security: a case study of Chengdu City, China

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Abstract. To investigate the sustainable state of the water resources in Chengdu, the pressure-state-response model was adopted to establish the index system of the water security, in which the index weights were calculated by the analytic hierarchy process. The comprehensive values of the urban water security in recent years have been calculated. The results showed that the water security level of Chengdu was grade IV from 2005 to 2013, which indicated a safe state. To ensure the coordinated development among the society, economy and environment, several suggestions were proposed. The water-saving consciousness of the public and the water-saving city could be improved through increasing the water-saving facilities and techniques. The environmental investment could be increased for improving the treatment rate of the municipal and industrial wastewater. The management and warning system could be improved to strengthen the ability of coping with the accidental problems relating to the water environment and water resources.

1. Introduction

The urban water security has become increasingly prominent with the urban development. The urban water problems, such as the shortage of water resources, water pollution, water incidents and sustainable security, have aroused the wide concern. The water resources are significant factors in the planning and layout of the city. Thus, it is important to realize the sustainable utilization of water resources and guarantee the water security [1]. The urban water security is not only an important part of the regional water security, but also an essential component of the urban ecological security. The assessment of urban water security is the foundation for establishing the strategy of water security and making decisions in the management [2].



The definition of urban water security has different expressions. Jia [3] explained that the essence of water resources security was whether the water supply could meet the reasonable demand. Han [4] stated that in terms of negative points of the water security, it could be defined as the deterioration and harmful effects of regional water conditions under natural and human factors. Cheng [5] regarded the water security as a social state where everyone had access to the safe and clean water, and the water could meet the demand of life, production and ecological environment. Tong [6] suggested that the urban water security require the adoption of a long view, in order to be able to account for the slow unfolding of some hydrological, ecological and social processes, and the necessary time for waterworks investments to yield their fruits.

The urban water security is a comprehensive system which usually consists of various factors. Many evaluation methods have been proposed for such system with multiple factors, such as the multi-level fuzzy method, system dynamics method, set pair analysis method and pressure-state-response (PSR) structure model [7]. The PSR model has advantages in evaluating the resource utilization and sustainable development. Thus, it is able to reflect the comprehensive relationship among the nature, society, economy, environment and resources [8]. The pressure indexes are used to reflect unsustainable development caused by human activities, consumption patterns and economic system. The state indexes are used to represent the current system status. The response indexes are used to characterize the countermeasures to promote the sustainable development. The PSR model has been widely used for the establishment of evaluation systems, such as the ecological security [9], wetland ecosystem health [10], water environment security [11] and urban water security [2].

In this paper, the concept of urban water security is regarded as the capacity for sustainable development of the city under the influence of water resources, which could ensure the development of society, economy, ecological environment, citizens and humanistic environment. The water security state of Chengdu is evaluated with the quantitative system, which could provide a reference for decision makers. It could also be beneficial for the rational utilization of water resources and promotion of the sustainable urban development.

2. Overview of the study area

Chengdu is the capital of Sichuan province, China. The Chengdu plain is located at the transition zone from the northwest mountains to the basin. The topography around the Chengdu plain is high in the northwest area which is close to the Longmen and Qionglai Mountains, and low in the southeast area which is near to the Longquan Mountain, as shown in figure 1. The city is located at the area with monsoon-influenced humid subtropical climate, which has distinct seasons and abundant rainfall. There are many rivers in Chengdu with a total area of 700 km², which mainly belong to the Minjiang and Tuojiang River. According to the water resources bulletin of Chengdu from 2005 to 2013, the annual amount of surface water resources is 8.12 billion m³ and the annual runoff depth is 668.81 mm.

The demand of water resources, especially the industrial water, has largely increased with the urban development. Thus, the contradiction between the water supply and demand could become serious. In recent years, the deterioration of ecological environment in the upstream of the Minjiang River and the decrease of precipitation have influenced the inflow and the water amount of Chengdu. With the

urbanization of Chengdu moving forward, the water security issues of this city could become more prominent.



Figure 1. The location and topography of Chengdu: (a) Schematic map of the city location. (b) A snapshot of the topography at the Chengdu plain.

3. Evaluation index system

3.1. Establishment of index system

With the consideration of regional conditions in Chengdu, the index system of urban water security is established on the basis of improved PSR model, which could be divided into 3 subsystems and 3 levels, as shown in table 1.

3.2. Weight calculation

The analytic hierarchy process (AHP) is used to calculate the index weight. A complex system could be decomposed into sequential and hierarchical structure with the AHP method, in which qualitative judgments are quantified through the rank of decision schemes. Thus, it is a decision assessment method combined of qualitative and quantitative analyses, which is suitable for the system evaluation with multiple criteria [16]. The analysis process of the AHP method generally consists of the following 4 steps:

- Analyze the relationship between factors of the system and establish a hierarchical structure.
- Compare the importance of items on the current level based on the same criterion on the previous level and construct the judgment matrix of pairwise comparison.
- Calculate the relative weights of the items to the criterion through the judgment matrix.
- Calculate the synthetic weight of the items to the overall system and sort the weights.

Thus, the index weights could be obtained by the process of the expert scoring, calculation and consistency judgment, as illustrated in table 1.

4. Calculation of standardization

The principle of diminishing marginal benefit [13] is used to evaluate the effect of index variation. Assuming the short term production and other conditions unchanged, such as the technology level, the benefit could start to decrease when the input amount of the production factor has reached a certain degree.

Under the principle of diminishing marginal benefit, the index system of urban water security could

Table 1. Index weights in the PSR model of the urban water security.

Criteria level	Item level	Index level	Weight （‰）	
Pressure index	Water resources	Daily water consumption per capita (L)	22.64	
		Water resource amount per capita (m³)	68.54	
		Utilization ratio of water resources (%)	22.64	
	Water environment	Discharge amount of specific pollutants in industrial wastewater (mg/L)	107.09	
		Discharge amount of domestic wastewater (104 m3)	43.43	
	Social economy	Industrial water demand per 10,000 RMB output (m³)	68.54	
		Population density (people / square kilometers)	12.17	
	Flood and drought	Disaster probability (time/year)	9.31	
		Ratio of economic loss to gross domestic product (GDP) (%)	22.64	
	State index	Environment	Water quality of drinking water source (%)	24.41
Public green space per capita (m2)			43.01	
Social economy		GDP per capita (10,000 RMB)	60.87	
		Engel coefficient (%)	24.41	
		Urbanization rate (%)	34.12	
Resources		Surface water resources (10 ⁸ m³)	60.87	
		Green coverage rate (%)	84.31	
Response index		Environmental protection and control	City sewage treatment rate (%)	31.53
			Ratio of investment in treatment of industrial wastewater to GDP (%)	95.22
		Management	Discharge attainment rate of industrial waste water (%)	66.30
	Reuse ratio of industrial water (%)		17.50	
	Per capita net income of rural residents (RMB)		17.50	
	Management	Disaster prevention and emergency response capability	10.09	
		Water saving consciousness of citizens	7.04	
		Laws, regulations and management in water environment	45.82	

be divided into three categories, namely the bigger with the better index, the smaller with the better index and linear variation index [14]. Then, the calculation models are chosen for three categories. The model of the bigger with the better index is the power function: $y = a + bx^{1/2}$ ($y \in [0,1]$). Similarly, the model of the smaller with the better index adopts the power function: $y = a + bx^2$ ($y \in [0,1]$). The model of linear variation index uses the linear function: $y = a + bx$ ($y \in [0,1]$).

Taking into account the relevance of society, economy and water resources, the calculation range of indexes are assigned and the index calculating functions are determined after obtaining the coefficient a and b , as shown in table 2.

5. Water security assessment of Chengdu

5.1. Classification of water security level

Considering the current social and economic development in China, the range of different levels of urban water security could be determined on the basis of the national standards, international standards, urban planning and critical values of specific indexes. Thus, the water security standard could be divided into 5 levels, namely I, II, III, IV and V, as shown in table 3.

Table 2. Calculating standards and models of the index system of urban water security.^a

Index	Worst	Middle	Best	Function
Daily water consumption per capita (L)	60		200	$Y=(-1.21103)+(0.15634)X^{0.5}$
Water resource amount per capita (m ³)	50		1000	$Y=(-0.288)+(0.041)X^{0.5}$
Utilization ratio of water resources (%)	60		10	$Y=1.02857-(0.0002857)X^2$
Discharge of COD in industrial wastewater (mg/L)	1000		100	$Y=1.01010-(0.000001010)X^2$
Discharge of A-N in industrial wastewater (mg/L)		50	15	$Y=1.04945-(0.00022)X^2$
Discharge amount of domestic wastewater (10 ⁴ m ³)	50000		15000	$Y=1.0989-(0.00000000043956)X^2$
Industrial water demand per 10,000 RMB output (m ³)	300		6	$Y=1.0004-(0.000011116)X^2$
Population density (people / square kilometers)	1300		500	$Y=1.17361-(0.0000006944)X^2$
Disaster probability (time/year)	5		0	$Y=1-(0.2)X$
Ratio of economic loss of disaster to GDP (%)	2	1	0	$Y=1-(0.5)X$
Water quality of drinking water source (%)	0		100	$Y=(0.01)X$
Public green space per capita (m ²)	0		16	$Y=(0.25)X^{0.5}$
GDP per capita (10,000 RMB)	1.3		5.3	$Y=(-0.98122)+(0.86059)X^{0.5}$
Engel coefficient (%)	60		30	$Y=1.33333-(0.00037)X^2$
Urbanization rate (%)	0		85	$Y=(0.10847)X^{0.5}$
Surface water resources (10 ⁸ m ³)	5		100	$Y=(-0.28801)+(0.128801)X^{0.5}$
Green coverage rate (%)		30	60	$Y=(-0.786)+(0.231)X^{0.5}$
City sewage treatment rate (%)	0		100	$Y=(0.01)X$
Ratio of investment in treatment of industrial wastewater to GDP (%)	0		0.2	$Y=(2.2361)X^{0.5}$
Discharge attainment rate of industrial waste water (%)	0		100	$Y=(0.01)X$
Reuse ratio of industrial water (%)	0		100	$Y=(0.01)X$
Per capita net income of rural residents (RMB)	0		8000	$Y=(0.01118)X^{0.5}$
Disaster prevention and emergency response capability	0		1	$Y=X$
Water saving consciousness of citizens	0		1	$Y=X$
Laws, regulations and management in water environment	0		1	$Y=X$

^a The index range refer to relevant industrial standards and index values of developed cities.

Table 3. Levels of urban water security.

Water security level	Very dangerous	Dangerous	Generally safe	Safe	Very safe
Range of comprehensive index	[0, 0.2)	[0.2, 0.5)	[0.5, 0.7)	[0.7, 0.9)	[0.9, 1]

- Level I: the water security state is very dangerous. With the full deterioration of water resources, as well as the water shortage, drought, flood and severe water pollution, the water environment function is disabled. The social and economic sustainability of the city is seriously hindered. Thus, the first level and most important alert would be suggested for the government.
- Level II: the water security state is dangerous. With the influence of water shortage, serious water pollution and degradation of water environment function, the water resources and water environment system could threaten the social and economic sustainability of the city. Thus, the second level alert would be suggested for the government.
- Level III: the water security state is generally safe. The water resources and water environment system are able to coordinate with the city development, and the satisfaction degree of urban social and economic sustainability is ordinary. The water supply is maintained at the critical state and the water environment function still has the certain recoverability under the water pollution. Thus, strengthening the management of water security would be suggested for the government.
- Level IV: the water security state is safe. The water resources and water environment system are able to coordinate with the city development, and the satisfaction degree of urban social and economic sustainability is moderate. The water amount could meet the demand and the water is slightly polluted. The water environment function has the sufficient recoverability. Thus, maintaining the current management of water security would be suggested for the government.
- Level V: the water security state is very safe. The water resources and water environment system are able to coordinate efficiently with the city development, and the satisfaction degree of urban social and economic sustainability is high. The water amount is abundant and the water quality is good. The water environment function has the strong recoverability and is not susceptible to external pollutions. Thus, maintaining the current management of water security would be suggested for the government.

5.2. Water security assessment

The score of each index y_{ij} can be obtained by substituting the index value into the corresponding calculation function, as illustrated in table 4.

With the index weights (table 1) and scores (table 4), the comprehensive value of water security could be obtained as follows:

$$S_j = \sum_{i=1}^n w_i y_{ij} \quad (1)$$

where S_j is the comprehensive value of water security, w_i is the index weight and y_{ij} is the index score after the standardization of the index datum. Thus, the comprehensive value of water security of Chengdu could be obtained from 2005 to 2013, as listed in table 5. The results show that the water security states of Chengdu from 2005 to 2013 reach the safe level IV, in which the water amount could meet the demand and the water environment function has the sufficient recoverability with slight pollution.

6. Prediction of urban water security

To predict the future water security state of Chengdu, the index data of GDP per capita from 2008 to 2013 are analyzed and the fitting function is obtained with the correlation coefficient of 0.984. Thus, the calculated value of GDP per capita in 2014 is 82,900 RMB, which is close to the real value of 83,064 RMB. Meanwhile, the predicted value of GDP per capita in 2015, 2016 and 2017 are 88,300, 93,200 and 97,700 RMB, respectively.

Table 4. Scores of each index of urban water security from 2005 to 2013 in Chengdu.^b

Index	2005	2006	2007	2008	2009	2010	2011	2012	2013
Daily water consumption per capita	1.000	1.000	1.000	0.678	0.697	0.926	0.821	0.875	1
Water resource amount per capita	0.801	0.676	0.718	0.875	0.679	0.911	0.942	0.796	0.911
Utilization ratio of water resources	0.000	0.000	0.000	0.010	0.000	0.000	0.084	0.000	0.220
Discharge amount of specific pollutants in industrial wastewater	0.868	0.829	0.825	0.788	0.955	0.429	0.673	0.871	0.774
Discharge amount of domestic wastewater	0.996	1.000	0.991	0.509	0.519	0.000	0.000	0.000	0.000
Industrial water demand per 10,000 RMB output	0.786	0.851	0.903	0.912	0.957	0.963	0.975	0.983	0.991
Population density	0.644	0.623	0.614	0.582	0.568	0.550	0.534	0.523	0.507
Disaster probability	0.000	0.800	0.800	0.400	0.600	0.800	0.400	0.800	0.400
Ratio of economic loss of disaster to GDP	0.966	0.924	0.999	0.982	0.990	0.996	0.985	0.992	0.989
Water quality of drinking water source	0.997	0.999	0.977	0.977	0.992	1.000	1.000	1.000	1.000
Public green space per capita	0.740	0.759	0.818	0.815	0.824	0.909	0.917	0.924	0.917
GDP per capita	0.298	0.382	0.420	0.532	0.729	0.910	1.000	1.000	1.000
Engel coefficient	0.872	0.908	0.771	0.816	0.827	0.827	0.827	0.870	0.877
Urbanization rate	0.840	0.858	0.858	0.861	0.874	0.878	0.888	0.897	0.904
Surface water resources	0.811	0.698	0.758	0.929	0.729	0.972	1.000	0.873	1.000
Green coverage rate	0.547	0.609	0.629	0.638	0.657	0.665	0.660	0.664	0.678
City sewage treatment rate	0.798	0.793	0.822	0.795	0.885	0.907	0.967	0.951	0.917
Ratio of investment in treatment of industrial wastewater to GDP	0.548	0.625	0.632	0.707	0.592	0.866	0.583	0.592	0.600
Discharge attainment rate of industrial waste water	0.962	0.842	0.964	0.987	0.997	0.998	1.000	1.000	1.000
Reuse ratio of industrial water	0.813	0.822	0.837	0.874	0.880	0.880	0.876	0.823	0.897
Per capita net income of rural residents	0.749	0.783	0.824	0.900	0.944	1.000	1.000	1.000	1.000
Disaster prevention and emergency response capability	0.600	0.630	0.680	0.700	0.750	0.800	0.820	0.850	0.880

Index	2005	2006	2007	2008	2009	2010	2011	2012	2013
Water saving consciousness of citizens	0.600	0.630	0.650	0.680	0.700	0.720	0.750	0.760	0.780
Laws, regulations and management in water environment	0.700	0.800	0.850	0.870	0.900	0.910	0.920	0.940	0.950

^b The data refer to the water resources bulletin and statistical yearbook of Chengdu [15, 16].

Table 5. Comprehensive value of water security from 2005 to 2013 in Chengdu.

Time	2005	2006	2007	2008	2009	2010	2011	2012	2013
Comprehensive value	0.7257	0.7348	0.7622	0.7672	0.7755	0.7794	0.7871	0.7969	0.7995

Through the correlation analysis between the index of GDP per capita and comprehensive value of water security from 2008 to 2013, the corresponding exponential function could be fitted as $y = 0.74e^{0.01x} - 10.21e^{-2.53x}$ with the correlation coefficient of 0.953. Thus, the comprehensive value of water security from 2014 to 2017 could be predicted, as shown in table 6.

Table 6. Predicted values of water security in Chengdu.

Time	2014	2015	2016	2017
Comprehensive value	0.8040	0.8083	0.8122	0.8159

The results show that the comprehensive value of water security is 0.8040 in 2014 and the predicted values are 0.8083, 0.8122 and 0.8159 in 2015, 2016 and 2017, respectively. The water security state is safe, and the comprehensive values show a steadily rising trend, as illustrated in figure 2. Thus, the water resources and water environment system are able to coordinate with the city development, and the satisfaction degree of urban social and economic sustainability is moderate.

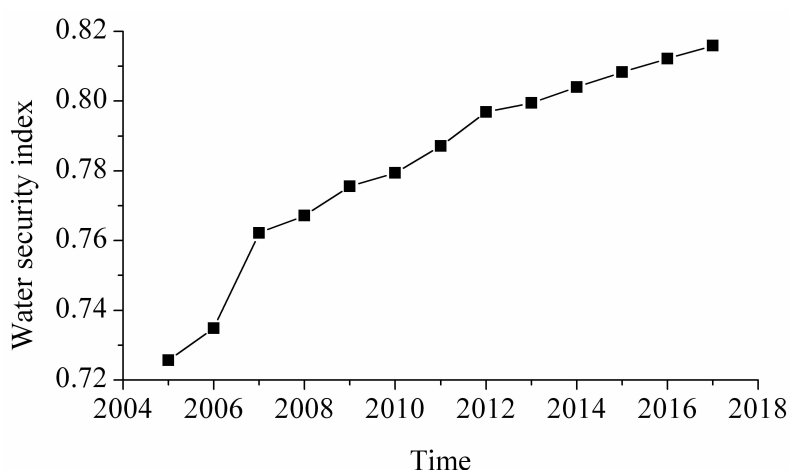


Figure 2. Comprehensive values of water security in Chengdu.

7. Conclusion

Based on the improved PSR model and AHP method, the urban water security of Chengdu is evaluated. The water security states are safe from 2005 to 2013, which is consistent with the actual situation. However, the index values of public green space per capita and ratio of investment in treatment of industrial wastewater to GDP are slightly low, which need more improvements. With the urban development, the index value of discharge amount of domestic wastewater is bad and the sewage treatments need to be improved. Through the correlation analysis, the water security states are predicted to be safe from 2014 to 2017 with a steadily rising trend. Thus, the overall water security state of Chengdu is safe and optimistic.

With the development of the city, the scale of society, economy and urbanization need to be planned in the existing bearing capacity of the water environment, and the water resources should be regarded as an important strategic resource. To ensure the coordinated development among society, economy, and environment, several suggestions are proposed. The water-saving consciousness of the public and the water-saving city could be improved through increasing the water-saving facilities and techniques. The environmental investment could be increased to improve the treatment rate of municipal and industrial wastewater. The management and warning system could be improved to strengthen the ability of coping with the accidental problems relating to the water environment and water resources.

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