Evaluation of urban water security based on DPSIR model

Sha Shi¹, Xueting Tao², Xiaona Chen², Hao Chen¹, Arniza Fitri³ and Xiaojia Yang²

¹ School of Hydraulic and Ecological Engineering, Nanchang Institute of Technology, Nanchang 330099, China
² School of Yaohu, Nanchang Institute of Technology, Nanchang 330099, China
³ Department of Civil Engineering, Faculty of Engineering and Computer Science, Universitas Teknokrat Indonesia, Bandar Lampung, Indonesia

*Corresponding E-mail: shisha2016@nit.edu.cn

Abstract. Assessment of urban water security is an important scientific basis for the sustainable utilization of urban water resources. This study established an evaluation model for urban water security based on DPSIR model, entropy method and comprehensive index method. The model was applied to Gong Qingcheng City (GQCC) in Jiangxi Province, China. An indicator system is developed based on four aspects including social development, water resources status, water pollution and water resources management, as well as summing up predecessors’ experience. This study analysed per capita domestic water consumption; ratio of ecological water compensation; percentage of water conservancy and public infrastructure investment; and water consumption per ten thousand yuan of industrial output value; where ratio of urban sewage treatment are the main effects on urban water security. The results of single index evaluation show that the change of stress subsystem was most dramatic from 2013 to 2017, while others were relatively stable. This indicates that positive interventions were urgently needed to relieve pressure of the stress subsystem. The results of comprehensive index evaluation show that water security at GQCC was in a critical state. In this paper, the causal relationship between social development and water security was clarified while the main factors and other factors affecting urban water security was identified. Finally, a reference for the formulation of urban development planning based on water resources demand was provided.

Keywords: Comprehensive index method, DPSIR model, Entropy method, Evaluation, Urban water security.

Track Name: Land, Water, Forests and Food Security

1. Introduction

Urban water security includes water shortage, water pollution, water ecological degradation, water management and water disaster [1-10], etc. As a part of urban water space and ecological water environment, lakes are great significance for urban water security [14-15]. The conclusions of the scientific evaluation of urban water security are great scientific significance for urban development planning and improving the relationship between city and lake. However, there is no unified standard
for the evaluation system of the urban water security at present, and the research is changing from qualitative to quantitative, from single evaluation to multi-method and multi-discipline comprehensive evaluation [16]. In this paper, DPSIR model framework and comprehensive evaluation method are used to evaluate the water security of lakeside cities. It has been done in order to solve the problems of difficult index selection and single index system, so that could improve the accuracy of evaluation results. Finally, the evaluation results can achieve multi-angle, objectivity, pertinence and applicability. DPSIR model framework is a conceptual model of evaluation index system widely used in environmental system [17]. It divides the natural system into five criterion layers (driving forces, Pressure, State, Impact and Responses, and under each criterion layer) and many indicators. Based on the interaction chain of "society-economy-nature", the analysis and evaluation are carried out. The DPSIR model framework fully selects evaluation indicators from five criterion layers to build the risk evaluation index database based on the DPSIR model framework. The selection of indicators is more comprehensive and the evaluation index system is more complete [18].

In this paper, Gong Qingcheng City (GQCC) of Jiangxi Province, China, is selected as the study area. By using DPSIR model framework to build index system, comprehensive evaluation method is adopted to obtain comprehensive index of water security. Urban water security of Gong Qingcheng City (GQCC) is then analysed, and therefore can provide reasonable suggestions for urban planning at Gong Qingcheng City.

2. Methods and Data

2.1 Index system construction
The selection of index is particularly important in the process of constructing the index system and it must be objective and reasonable. This study selects and analyses the index system of urban water security by using DPSIR conceptual model. The specific index system is shown in Table 1.

| Criteria | Alternatives | Unit | Attribute | Description |
|----------|--------------|------|-----------|-------------|
| Drive    | Annual growth rate of GDP | % | Positive | Represents the level of regional economic development |
|          | Natural population growth rate | % | Negative | Represents the increase of population with the increase of water demand |
|          | Water resources per unit area | $10^4 \text{m}^3/\text{km}^2$ | Positive | Represents the finiteness of water resources |
| Pressure | Water consumption per 10,000 yuan of industrial output value | m$^3/(10^4\text{yuan})$ | Negative | Represents the pressure of regional socio-economic development on water resource consumption |
|          | Agricultural water consumption rate | % | Negative | Represents the demand for water resources in agriculture |
|          | Ratio of ecological water compensation | % | Negative | Represents the amount of water resources needed to maintain the ecological environment |
|          | Per capita domestic water consumption | L/d | Negative | Represents the pressure of water pollution |
|          | Discharge of wastewater of 10,000 yuan of output value | m$^3/(10^4\text{yuan})$ | Negative | Represents the content of organic substances in water |
|          | COD concentration in wastewater | mg/L | Negative | |
| State    | Per capita water resources | m$^3/cap$ | Positive | Represents the consumption of water resources |
|          | Utilization rate of water | % | Negative | Represents the consumption and |
resources

| Criteria | Alternatives | 2013  | 2014  | 2015  | 2016  | 2017  |
|----------|--------------|-------|-------|-------|-------|-------|
| Drive    | Annual growth rate of GDP | 10.50  | 10.50 | 9.90  | 9.60  | 9.20  |
|          | Natural population growth rate | 6.72   | 6.82  | 6.79  | 6.93  | 7.76  |
|          | Water resources per unit area | 71.15  | 81.02 | 100.24| 111.18| 115.47|
| Pressure | Water consumption per 10,000 yuan of | | | | | |

2.2 Study area and data sources

Administrative Region of Gong Qingcheng City (GQCC) in Jiangxi Province is shown in Figure 1. The original data of water security evaluation in GQCC, Jiangxi Province from 2013 to 2017 are shown in Table 2. Data sources are Jiangxi Statistical Yearbook (2014-2018), Jiujiang Statistical Yearbook (2014-2018) and Jiangxi Water Resources Bulletin (2014-2018).
industrial output value
Agricultural water consumption rate 54.46 52.32 47.15 48.97 48.16
Ratio of ecological water compensation 0.72 0.70 0.81 0.83 0.83
Per capita domestic water consumption 158 158 158 158 157
Discharge of wastewater of 10,000 yuan of output value 36.00 25.00 57.00 60.96 76.08
COD concentration in wastewater 3.85 4.04 2.5 4.5 5.26

State
Per capita water resources 2796 3173 3910 4317 4460
Utilization rate of water resources 19.59 16.97 12.46 10.91 10.49
Full factor water quality compliance rate 68.90 63.80 80.40 80.40 87.50
GDP per capita 8.01 8.89 9.32 7.58 8.85

Impact
Rate of urbanization 67.54 69.29 70.81 63.63 65.18
Green coverage rate in built-up areas 49.52 48.74 47.84 47.65 42.29

Response
Ratio of urban sewage treatment 82.76 82.59 96.89 113.49 125.93
Comprehensive utilization rate of industrial solid waste 47.93 100.00 100.00 100.97 125.93
Percentage of water conservancy and public infrastructure investment 6.47 4.71 3.93 3.90 3.54
Number of College Students per 10,000 166 173 184 191 190

### 2.3 Evaluation criteria
The key of evaluation work is the establishment of the standard value which directly affects the quality of evaluation results. There are 3 criteria to determine the standard value: (1) the standard value of the existing international or national standards, (2) the standard value is determined based on the development plans of the study areas or condition of environmental protection, (3) indicators without any standard reference should be determined according to previous experience, average value or peak value of the research area. On this basis, this study selects standard values based on the specific situation in GQCC, Jiangxi province as shown in Table 3.

### Table 3. Evaluation standard values.

| Criteria   | Alternatives                        | Attribute | Standard value | Source                                      |
|------------|-------------------------------------|-----------|----------------|---------------------------------------------|
| Drive      | Annual growth rate of GDP           | Positive  | 9.9            | Five-year average value of Gongqingcheng    |
|            | Natural population growth rate      | Negative  | 8              | Refer to leading domestic cities            |
|            | Water resources per unit area       | Positive  | 95.8           | Five-year average value of Gongqingcheng    |
|            | Water consumption per 10,000 yuan of industrial output value | Negative | 100            | Five-year average value of Gongqingcheng |
|            | Agricultural water consumption rate | Negative  | 55             | The critical value                          |
|            | Ratio of ecological water compensation | Negative   | 0.83           | The highest value of Gongqingcheng in 5 years |
| Pressure   | Per capita domestic water consumption | Negative | 220            | The highest value of Gongqingcheng in 5 years |
|            | Discharge of wastewater of 10,000 yuan of output value | Negative | 51             | The highest value of Gongqingcheng in 5 years |
|            | COD concentration in wastewater     | Negative  | 4.3            | The highest value of Gongqingcheng in 5 years |
| State      | Per capita water resources          | Positive  | 3700           | Five-year average value of Gongqingcheng   |
|            | Utilization rate of water resources | Negative  | 40             | Internationally recognized values           |
|            | Full factor water quality compliance rate | Positive  | 76.2           | Five-year average value of Gongqingcheng   |
| Impact  | GDP per capita | Positive | 8.5 | Gongqingcheng Five-year average value of Gongqingcheng |
|---------|----------------|----------|-----|------------------------------------------------------|
|         | Rate of urbanization | Negative | 65  | Fifth census                                        |
|         | Green coverage rate in built-up areas | Positive | 45  | National ecological assessment standards            |

| Response | Ratio of urban sewage treatment | Positive | 95  | National environmental protection model city assessment standards |
|----------|--------------------------------|----------|-----|---------------------------------------------------------------|
|          | Comprehensive utilization rate of industrial solid waste | Positive | 89.5 | Energy conservation and emission reduction targets          |
|          | Percentage of water conservancy and public infrastructure investment | Positive | 3   | Extrapolating from developed countries                       |
|          | Number of College Students per 10,000 | Positive | 100 | Extrapolating from developed countries                       |

2.4 Calculation of index weight

2.4.1 Standardization

Range method is used to standardize the primary data in order to avoid the impact caused by the difference of index in unit and dimension. Specifically, the indexes are divided into positive index and negative index. The formula is as follows:

**Positive index:**

\[ A_{ij} = \frac{x_{ij} - \min (x_{ij})}{\max (x_{ij}) - \min (x_{ij})} \]  

(1)

**Negative index:**

\[ A_{ij} = \frac{\max (x_{ij}) - x_{ij}}{\max (x_{ij}) - \min (x_{ij})} \]  

(2)

Where, \( x_{ij} \) is the original data of the \( i \)-th evaluation object on the \( j \)-th evaluation index, \( A_{ij} \) is the standardized value of the \( i \)-th evaluation object on the \( j \)-th evaluation index, \( A_{ij} \in [0,1] \).

2.4.2 Entropy method

Entropy method is a commonly weighting method. It analyses the weight according to the influence of the index on the system. For example, the smaller entropy of the indicator, the greater amount of information and the degree of variation to the system, which can play a greater role in the overall comprehensive evaluation.

First, formula (3) was used to determine the index proportion \( R_{ij} \):

\[ R_{ij} = A_{ij} / \sum_{j=1}^{m} A_{ij} \]  

(3)

Then, calculate the entropy of the \( i \)-th index \( e_i \):

\[ e_i = -\frac{1}{\ln n} \sum_{j=1}^{n} (R_{ij} - \ln R_{ij}) \]  

(4)

Further, calculate the difference coefficient of the \( i \)-th index \( g_i \):
Finally, calculate the weight of i-th index \( \omega_{ij} \):

\[
\omega_{ij} = g_i / \sum_{j=1}^{m} g_i
\]  

Where, \( i = 1, 2, 3, \ldots, n \), \( j = 1, 2, 3, \ldots, m \), \( R_{ij} \) is the proportion of the index value in all objects of the same index, \( e_i \) is the index j entropy value in the evaluation problem of m evaluation indicators and n evaluation objects, \( g_i \) is the difference coefficient of the i-th index, \( \omega_{ij} \) is the entropy value of the j-th index.

The weight which is obtained from entropy method is shown in Table 4.

| Criteria     | Alternatives                                      | Entropy  | Difference coefficient | Weight  |
|--------------|---------------------------------------------------|----------|------------------------|---------|
| Drive        | Annual growth rate of GDP                         | 0.8141   | 0.1859                 | 0.0392  |
|              | Natural population growth rate                    | 0.8688   | 0.1312                 | 0.0277  |
|              | Water resources per unit area                     | 0.8041   | 0.1959                 | 0.0413  |
| Pressure     | Water consumption per 10,000 yuan of industrial output value | 0.6737   | 0.3263                 | 0.0688  |
|              | Agricultural water consumption rate               | 0.8239   | 0.1761                 | 0.0371  |
|              | Ratio of ecological water compensation            | 0.5952   | 0.4048                 | 0.0854  |
|              | Per capita domestic water consumption             | 0.1344   | 0.8656                 | 0.1826  |
|              | Discharge of wastewater of 10,000 yuan of output value | 0.8040   | 0.1960                 | 0.0413  |
|              | COD concentration in wastewater                   | 0.8015   | 0.1985                 | 0.0419  |
| State        | Per capita water resources                        | 0.8068   | 0.1932                 | 0.0407  |
|              | Utilization rate of water resources               | 0.8216   | 0.1784                 | 0.0376  |
|              | Full factor water quality compliance rate          | 0.8084   | 0.1916                 | 0.0404  |
|              | GDP per capita                                    | 0.8163   | 0.1837                 | 0.0387  |
| Impact       | Rate of urbanization                              | 0.7929   | 0.2071                 | 0.0437  |
|              | Green coverage rate in built-up areas             | 0.8668   | 0.1332                 | 0.0281  |
| Response     | Ratio of urban sewage treatment                   | 0.6820   | 0.3180                 | 0.0671  |
|              | Comprehensive utilization rate of industrial solid waste | 0.8621   | 0.1379                 | 0.0291  |
|              | Percentage of water conservancy and public infrastructure investment | 0.6638   | 0.3362                 | 0.0709  |
|              | Number of College Students per 10,000             | 0.8182   | 0.1818                 | 0.0383  |

2.5 The method of water security evaluation
Based on the single factor evaluation method, the comprehensive index method divides the evaluation object into multiple measurable indexes. After selecting the corresponding evaluation criteria for the indexes, the weighted evaluation of each index is carried out. Finally, the comprehensive score of the evaluation object is obtained, which is the water security index in this paper.
Let $x_i$ be the actual value of the evaluation index, $p_i$ be the safety index of index $i$, $s_i$ be the standard index of index $i$, and $0 \leq p_i \leq 1$.

For the positive index, the safety value is the standard value:

$$ p_i = \begin{cases} 
1 & x_i \geq s_i \\
\frac{x_i}{s_i} & x_i < s_i 
\end{cases} \quad (7) $$

For the negative index, the unsafe value is the standard value:

$$ p_i = \begin{cases} 
0 & x_i \geq s_i \\
1 - \frac{x_i}{s_i} & x_i < s_i 
\end{cases} \quad (8) $$

The comprehensive index model is shown in the following formula:

$$ E = \sum_{i=1}^{n} W_i \cdot P(x_i) \quad (9) $$

Where, $E$ is the comprehensive index of urban water security evaluation, $n$ is the total number of indicators, $W_i$ is the weight of each index, and $P(x_i)$ is the security index of each index.

3. Results and Discussion

3.1 Results

According to the previous research, the status of water safety in GQCC, Jiangxi province can be evaluated by the value of $E$ and ranked as corresponding five levels, as presented in Table 5. Table 6 presents the safety index in GQCC.

| Safety class | Range | Gradient ramp |
|--------------|-------|---------------|
| safe         | $0.8 \leq E \leq 1$ |               |
|              | $0.6 \leq E < 0.8$ |               |
| critical     | $0.4 \leq E < 0.6$ |               |
|              | $0.2 \leq E < 0.4$ |               |
| dangerous    | $0 \leq E < 0.2$ |               |

Table 5. The range of safety class

| Alternatives                               | Safety index |
|--------------------------------------------|--------------|
|                                            | 2013 | 2014 | 2015 | 2016 | 2017 |
| Annual growth rate of GDP                  | 1 | 1 | 1 | 0.97 | 0.93 |
| Natural population growth rate             | 0.16 | 0.15 | 0.15 | 0.13 | 0.03 |
| Water resources per unit area              | 0.74 | 0.85 | 1 | 1 | 1 |
| Water consumption per 10,000 yuan of industrial output value | 0 | 0 | 0 | 0.18 | 0.26 |
| Agricultural water consumption rate        | 0.01 | 0.05 | 0.14 | 0.11 | 0.12 |
| Ratio of ecological water compensation     | 0.13 | 0.16 | 0.02 | 0 | 0 |
| Per capita domestic water consumption      | 0.28 | 0.28 | 0.28 | 0.28 | 0.29 |
| Discharge of wastewater of 10,000 yuan of output value | 0.29 | 0.51 | 0 | 0 | 0 |

Table 6. The safety index in GQCC
The values of water security index in GQCC, Jiangxi province are determined by using entropy weight method (EWM). There are 5 indicators with the weighted value of over 0.05, including water consumption per capita, ecological water replenishment ratio, proportion of investment in water conservancy and other infrastructure, industrial water consumption amount per unit output value of 10,000 yuan and urban disposal rate of sewage. It suggests that these 5 indicators pose a more significant impact on urban water security when other weighted indicators value are mostly around 0.04. The percentage of industrial solid wastes utilized, coverage rate of afforestation in developed area and the rate of natural increase (RNI) stay at the bottom of the list, with the weight values of 0.0291, 0.0281 and 0.0277 respectively, having a moderate impact on water security.

### 3.3 Trends of Criterion Layer
Based on the analysis of five subsystems in the evaluation criterion layer of urban water security, comparatively significant fluctuation can be detected in pressure and situation subsystem while driving force, response and influence subsystem remained stable.

As shown in Figure 2, during the five-year period, the weighted values of the driving force system were fluctuated between 0.07 and 0.08, similarly, the value for impact system stayed almost unchanged at 0.028. In addition, the response system was the most efficient in view of its gentle upward trend, reflecting that GQCC has made continuous efforts to improve and maintain the water security environment as well as popularize relevant knowledge. More dramatically, the weighted value of pressure system changed in the shape of “S”, the data of state subsystem declined after the highest point at 2015 but shown an upward trend in general. In a conclusion, the evaluation value of response subsystem occupied the highest point, followed by the state, pressure driving force and influence system respectively.
3.4 Trends of Water Security
According to the formula (9), the comprehensive evaluation index of water security in GQCC from 2013 to 2017 can be calculated (see figure 3). During this five-year period, the trend of index values changed in the shape of “S”, reaching the highest point at 2015, that is 0.543. To sum up, the water security index in GQCC is at a critical safety state, suggesting that water security situation is still not promising.

4. Conclusion
By the analysis of index values, some conclusions can be made that: (1) there are five main factors to urban water security which are water consumption per capita, ecological water replenishment ratio, proportion of investment in water conservancy and other infrastructure, industrial water consumption amount per unit output value of 10,000 yuan and urban disposal rate of sewage; (2) from 2013 to 2017, the change in pressure system was the most prominent while other systems were relatively stable, indicating that intervention measures are urgently needed to alleviate the pressure subsystem; (3) the water security index of GQCC is in a critical safety state. According to the above evaluation results, it can be known that the water security of GQCC requires more indicators to support the response subsystem for alleviating the threat of pressure subsystem and promoting the sustainable urban water security development.

Hence, we put forward some suggestions as following: (1) fully use the lakes in GQCC, strengthen the implementation of the water system connection project, improve the storage network system of unified and coordinated water resources allocation, and alleviate the water pressure of industry and
residents; (2) strictly implement the management of water resources and promote the formulation and implementation of water-saving standards and water quotas in various fields, especially in the industrial sector; (3) By speeding up the construction of information infrastructure for water monitoring, especially paying attention to the standards of "quality" and "quantity" of industrial pollution discharge, we can minimize the harm of water pollution to the water environment and promote the transformation of water environment management guided by environmental quality; (4) GQCC need to optimize the spatial pattern and improve usage efficiency of urban space, and land, scientifically plan and construct new and old urban areas, reduce the shortage of water resources caused by excessive population density, and optimize the allocation of water resources.

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