Establishment of the Performance Evaluation Model of Integrated Water Resources Management and Empirical Study

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Abstract

Based on the socioeconomic development goals of water resources management in a typical river basin of China, this paper puts forward a performance evaluation index model of integrated water resources management (IWRM), classifies the model into four evaluation dimensions by the hierarchical structure of AHP, such as environment sustainability, social fairness, economy benefit and organization energy efficiency, and further divides the four evaluation dimensions into 18 evaluation indices. Besides, this paper establishes a theoretical evaluation system of IWRM performance in different basins on the basis of binary comparison, entropy weighting and linear superposition, and effectively reveals the change trend of IWRM performance in different basins. The results show that the key to IWRM lies in sustainable development of water resources environment, the utilization ratio of water resources and the corresponding economic benefits, and that the rational utilization of water resources is conducive to rapid economic development. From 2003 to 2014, the IWRM performance index in the five basins increased gradually, and the growth rate of the performance indices increased first and then decreased. The change trend of IWRM performance in the five basins is basically the same with that of the performance index.

Keywords: water resources management performance; evaluation indices; AHP.

1. INTRODUCTION

The sustainable utilization of water resources is of great significance to socioeconomic development. To ensure the effective operation of water resources management mechanism, it is of great necessity to establish and improve water resources management system, realize sustainable and efficient water resources management and strictly control the major influencing factors of water resources management.

A number of studies have been done on the integrated water resources management (IWRM) and IWRM system construction (Brown et al, 1999; Savenije and Zaag, 2008; Manoj and Ashim Das Gupta, 2003; Partnership, 2004). In the practice of water resources management, evaluation is an important link, which mainly consists of process evaluation, impact evaluation and performance evaluation. Among them, IWRM performance evaluation is a useful tool to examine the rationality of water resources management system and realize the sustainable and efficient utilization of water resources. The performance evaluation target system of IWRM can be divided into three aspects: social performance, economic performance and ecological environmental performance (Partnership, 2014; Partnership and Carriger, 2006; Zaag, 2007). So far, several kinds of models have been developed to describe IWRM performance evaluation, namely AHP (Takahasi and Uitto, 2004), multi-criteria decision-making (Gallego-Ayala and Juízo, 2011), WEAP model (Purkey, 2005),PGMS model (Hu et al, 2007), water security evaluation model based on narrow and broad sense water management (Cook and Bakker, 2012), multi-objective optimization model (Kuby et al, 2005),and emergency water supply assessment model (Loo et al, 2012).
Currently, most research on IWRM performance index system focuses on the IWRM performance evaluation of a specific basin (Karagiannis et al, 2003; Nill et al, 2001; York et al, 2003; Thanassoulis, 2000), while little research has been done on dynamic evaluation and comparative analysis of IWRM performance in different basins. Based on the above analysis, puts forward an IWRM performance evaluation index model according to the socioeconomic development goals of water resources management in a typical basin in China, classifies the model into four evaluation dimensions by the hierarchical structure of AHP, and further divides each of the evaluation dimension into evaluation indices. Besides, this paper establishes a theoretical evaluation system of IWRM performance in different basins on the basis of binary comparison, entropy weighting and linear superposition, and effectively reveals the change trend of IWRM performance in different basins. The results effectively reveal the existing problems of water resources management mechanism in the basins and provide basis for decision-making on improving IWRM performance.

2. IWRM QUANTITATIVE EVALUATION MODEL

2.1 IWRM Performance Evaluation Index System

The IWRM evaluation involves multiple objects, multiple regions and multiple criteria. Generally speaking, the IWRM performance evaluation should be based on the following principles:

(1) The principle of comprehensiveness: the evaluation system needs to take into account social, economic and environmental and other factors;

(2) The principle of representation: the selected evaluation index should be typical and universal, which can effectively reflect the state of every factor of water resources.

(3) The principle of operability: the selected evaluation indices should have practical significance, and can be calculated according to the corresponding system.

The AHP (Analytic Hierarchy Process) method is widely used in the calculation of index weight because it can transform the subjective qualitative analysis into quantitative analysis in an accurate manner. According to the basic principles mentioned above, and the theoretical analysis, literature reference and frequency statistics, AHP-based hierarchical structure is used to divide the quantitative evaluation model into four categories: Environment Sustainability (M1), Social Fairness (M2), Economy Benefit (M3), and Organization Energy Efficiency (M4) (See Table 1). Specifically, the Environment Sustainability mainly includes 3 evaluation indices like woodland coverage ($I_1$), water resources development coefficient ($I_2$), etc.; the Social Fairness mainly includes 5 evaluation indices like tap water access rate ($I_4$), drinking water dispute ($I_6$), etc.; the Economy Benefit mainly includes 6 evaluation indices like water consumption/person ($I_{10}$), GDP/cubic meter water ($I_{14}$), etc.; the Organization Energy Efficiency mainly includes 6 evaluation indices like water charges collection ($I_{15}$), dissension processing ($I_{16}$), etc. $I_2$, $I_3$, $I_5$, $I_6$, $I_{11}$ and $I_{14}$ are negative evaluation indices, while other indices are positive evaluation indices. The higher the value of negative evaluation indices, the poorer the performance is; the higher the value of positive evaluation indices, the better the performance is.
Table 1 The Evaluation Index System for Water Resources Management

<table>
<thead>
<tr>
<th>Evaluation Dimensions</th>
<th>Code</th>
<th>Evaluation Index</th>
<th>Index Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environment Sustainability (M1)</td>
<td>$I_1$</td>
<td>Woodland coverage</td>
<td>Woodland coverage area/Total area</td>
</tr>
<tr>
<td></td>
<td>$I_2$</td>
<td>Water resources development coefficient</td>
<td>Area water intake quantity/Area total water quantity</td>
</tr>
<tr>
<td></td>
<td>$I_3$</td>
<td>Sewagediameter rate</td>
<td>Sewageemission/Surfacercrunoff</td>
</tr>
<tr>
<td>Social Fairness (M2)</td>
<td>$I_4$</td>
<td>Tap water access rate</td>
<td>Household accessing the tap water/Total household</td>
</tr>
<tr>
<td></td>
<td>$I_5$</td>
<td>Standard-reaching rate</td>
<td>Drinking water standard-reaching population/Total people</td>
</tr>
<tr>
<td></td>
<td>$I_6$</td>
<td>Drinking water dispute</td>
<td>Frequency of drinking water dispute</td>
</tr>
<tr>
<td></td>
<td>$I_7$</td>
<td>Conference participation</td>
<td>The proportion of water resources conference the populace had participated</td>
</tr>
<tr>
<td></td>
<td>$I_8$</td>
<td>Suggestion adoption rate</td>
<td>Adopted suggestion/Total suggestion</td>
</tr>
<tr>
<td>Economy Benefit (M3)</td>
<td>$I_9$</td>
<td>Water consumption/mu</td>
<td>Irrigation water consumption/Irrigation area</td>
</tr>
<tr>
<td></td>
<td>$I_{10}$</td>
<td>Water consumption/person</td>
<td>Living water consumption/Total populace</td>
</tr>
<tr>
<td></td>
<td>$I_{11}$</td>
<td>Industrial water utilization</td>
<td>Industrial water reuse amount/Industrial water amount</td>
</tr>
<tr>
<td></td>
<td>$I_{12}$</td>
<td>Agriculture output value per cubic meter water</td>
<td>Total agriculture output value/Total water consumption</td>
</tr>
<tr>
<td></td>
<td>$I_{13}$</td>
<td>Industrial output value per cubic meter water</td>
<td>Total industrial output value/Total water consumption</td>
</tr>
<tr>
<td></td>
<td>$I_{14}$</td>
<td>GDP /cubic meter water</td>
<td>Total GDP/consumption of different industries</td>
</tr>
<tr>
<td>Organization Energy Efficiency(M4)</td>
<td>$I_{15}$</td>
<td>Water charges collection</td>
<td>Hand in water charges/ water charges should be paid</td>
</tr>
<tr>
<td></td>
<td>$I_{16}$</td>
<td>Dissension processing</td>
<td>Dissension processing times/Total dissension amount</td>
</tr>
<tr>
<td></td>
<td>$I_{17}$</td>
<td>Lining intact ratio</td>
<td>Lining length/ditch length</td>
</tr>
<tr>
<td></td>
<td>$I_{18}$</td>
<td>Maintain intact ratio</td>
<td>Maintain length/ditch length</td>
</tr>
</tbody>
</table>

2.2 IWRM Performance and Evaluation Indices

Since the importance of evaluation indices vary from index to index and from dimension to dimension, the author decides to calculate the weights of IWRM dimensions and of the different indices in each dimension by AHP, and then determine the importance of each evaluation index in the IWRM performance system according to the weights.

In this paper, a typical basin in China is selected as the research object. The author gathers the water utilization data and relevant socioeconomic data in the 12-year period from 2003 to 2014, and calculates the index weights. See Figure 1 for the distribution of evaluation indices and index weights in each dimension. As shown in the figure, water resources development coefficient ($I_2$) weighs the heaviest in Environment Sustainability, tap water access rate ($I_4$) and standard-reaching rate ($I_5$) have relatively higher weights in Social Fairness, agriculture output value per cubic meter water ($I_{12}$) and GDP /cubic meter water weigh heavier than other indices in Economy Benefit, while the four evaluation indices have similar weights in Organization Energy Efficiency with dissension processing ($I_{16}$) accounting for the largest proportion. The above statistical results indicate the importance of these indices in the whole performance evaluation system. As
A result, the processing efficiency and success rate in these particular aspects should be treated with great care.

Figure 1 Evaluation Index Weights of Different Evaluation Dimensions

Figure 2 illustrates the distribution of each evaluation dimension and index in the overall performance evaluation system. The weight distribution of evaluation dimensions demonstrates that M1>M3>M2>M4, that is, Environment Sustainability has the greatest impact on the evaluation system, followed by the Economy Benefit of water resources, while the Organization Energy Efficiency has the lowest impact. Hence, more importance should be attached to the environmental governance in the surroundings of the basin than to the promotion of regional economy and the improvement of economic benefits.

To make the case easily observable, the weight of each evaluation index in Figure 2 is normalized. All values of an index are divided by the max value. The red dotted line stands for the critical line. All evaluation indices above the line play an importance role in the whole performance evaluation system. According to the figure, water resources development (I2) weighs heavier than any other indices in the performance evaluation system, indicating that putting emphasis on sustainable development of the surrounding environment can significantly improve the value of the index in the overall evaluation system, a byword for high efficient and sustainable utilization of the basin and a guarantee of good water quality. Woodland coverage (I1) also weighs heavily, making afforestation an effective way to curb water quality degradation. In the Social Fairness dimension, only the tap water access rate manages to reach 0.81, suggesting that urban and rural residents are treated more fairly for water management becomes more democratic when tap water is available to more people, effectively reducing adverse impacts like civil disputes over water consumption. In Economy Benefit, water consumption/mu (I9), agriculture output value per cubic meter water (I12), and GDP/cubic meter water (I14) have relatively high normalized weights, showcasing the positive effect of rational utilization of water resources on rapid economic development. In Organization Energy Efficiency, all index weights are relatively small.
### 3. IWRM PERFORMANCE EVALUATION MODEL IN DIFFERENT BASINS

#### 3.1 IWRM Performance Evaluation Method in Different Basins

The analysis in the preceding section mostly focuses on the IWRM performance evaluation of a specific basin, while few methods have been proposed for IWRM performance evaluation in different basins. In light of the quantitative IWRM performance evaluation model mentioned in the preceding section, the author establishes a theoretical evaluation system of IWRM performance in different basins on the basis of binary comparison, entropy weighting and linear superposition. The index weights can be expressed as:

\[
I_i = \left( \lambda_i + h_i \right) / 2
\]  

(1)

The weight of each index is 1. \( \lambda_i \) is the index weight calculated by binary comparison; \( h_i \) is the index weight calculated by entropy weighting, and

\[
h_i = (1 - E_i) / \sum_{i=1}^{n} (1 - E_i)
\]  

(2)

\( n \) is the number of indicators proposed; \( E_i \) is the entropy of any index.

\[
E_i = -1 / \ln \beta \sum_{j=1}^{q} \frac{d_{ij}}{d_{ij} + \sum_{j=1}^{q} d_{ij}} \left( \ln \frac{d_{ij}}{\sum_{j=1}^{q} d_{ij}} \right)
\]  

(3)

\( \beta \) is the number of basins; \( d_{ij} \) is the normalized representation of \( D_{ij} \); \( D_{ij} \) stands for the approximation of any index \( I_i \) and the optimal value \( \max(I_i) \) in all basins to the worst value.

On the basis of determining the weight of each index, linear weighting is used to get \( WI \), the static index of IWRM, of basins of different conditions.
\[ WI(t) = \sum_{i=1}^{m} (\omega_i \cdot x(t)) \]  

(4)

Where, \( \omega_i \) is the index weight of the \( i \)-th index in the selected basin at time \( t \); \( x(t) \) is the corresponding dimensionless index value; and

\[
x(t) = \begin{cases} 
\frac{a(t)}{\max\{a(t)\} + \min\{a(t)\}} & a(t) \text{ 为效益型} \\
1 - \frac{a(t)}{\max\{a(t)\} + \min\{a(t)\}} & a(t) \text{ 为成本型}
\end{cases}
\]

(5)

\( t = 1, 2, ..., n \). \( \max\{a(t)\} \) refers to the ideal value of the \( i \)-th index in the \( j \)-th basin; \( \min\{a(t)\} \) refers to the negative ideal value.

To obtain the change of performance indices in different regions, the author constructs the time-series multi-index evaluation matrix \( Z \), i.e.:

\[
\begin{align*}
Z(t) &= \alpha WI(t) + \beta H(t) \\
\alpha + \beta &= 1
\end{align*}
\]

(6)

\( H(t) \) is the increase of IWRM index in a certain period.

\[ H(t) = \frac{WI(t) - WI(t-1)}{WI(t-1)} \]

(7)

\( \alpha \) and \( \beta \) respectively refers to the correlation coefficient of \( WI \) and \( H(t) \). Based on Equations 1-7, the author compares the level of IWRM in different basins. The level of IWRM performance in any basin \( P_j \) is expressed by:

\[ P_j = S_{j2}/(S_{j1} + S_{j2}) \]

(8)

\( S_{j1} \) and \( S_{j2} \) respectively refers to the distance between the multi-index evaluation value \( z(t) \) to the corresponding ideal point and the negative ideal point.

Integrating binary comparison, entropy weighting and linear superposition, a new IWRM evaluation method is formed, which is capable of making comparative analysis and evaluation of the IWRM in different basins.

### 3.2 Case Study

The author analyzes the statistics of 5 typical basins in China over the 12 years from 2003 to 2014, and explores the current IWRM in each basin. The basins are named basin 1, basin 2, and the like. Because the statistics of some evaluation indices lack continuity, the author only chooses the following out of the 18 evaluation indices mentioned in the preceding section, namely \( I_1, I_2, I_4, I_5, I_9, I_{10}, I_{12}, I_{13}, I_{14}, \) and \( I_{16} \), expands the weights of indices on the same level in the same scale, obtains index weight matrix \( I_i \) by binary comparison and entropy weighting, and thereby calculates the IWRM indices of the 5 basins from 2003 to 2014 (See Figure 3).
As shown in Figure 3, with the increase of supervision and the requirement of sustainable development of water resources, the overall IWRM performance index of the 5 basins in the past 12 years shows an increasing trend. The performance index of basin 5 grows the fastest, with an average annual growth rate of 4.49%. The performance index of the basin 4 grows relatively slowly, with an annual growth rate of only 1.68%. Overall, the IWMI performance indices of basin 2 and basin 5 are generally high.

![Figure 3 IWMR Performance Indices of Different Basins](image)

Table 2 illustrates the growth rates of IWRM performance indices of the 5 basins over different periods. According to the table, the overall growth rate of the performance indices of the 5 basins increased first and then decreased. Except for that of basin 5, the performance indices of all the other 4 basins grew slightly from 2003 to 2006, mainly because of the frequent environmental accidents in early years, and the heavy comprehensive water consumption and wastewater discharge. Fortunately, the industrial and agricultural water consumption in the basins was further regulated as the nation stepped up its monitoring efforts, resulting in substantial increase in the growth rates of IWRM performance indices between 2007 and 2010. When it comes to 2011-2014, with the rapid development of the national economy, the per capita water consumption, the comprehensive water consumption, the proportion of agricultural water consumption and the development of water resources all increased greatly. Thus, the IWRM performance indices are relatively low. It can also be seen from the table that the IWMI performance in basin 3 has the lowest annual growth rate.

<table>
<thead>
<tr>
<th>Years</th>
<th>Basin 1</th>
<th>Basin 2</th>
<th>Basin 3</th>
<th>Basin 4</th>
<th>Basin 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2006</td>
<td>3.1</td>
<td>4.5</td>
<td>1.1</td>
<td>2.4</td>
<td>4.1</td>
</tr>
<tr>
<td>2007-2010</td>
<td>7.3</td>
<td>7.6</td>
<td>8.2</td>
<td>6.2</td>
<td>4.9</td>
</tr>
<tr>
<td>2011-2014</td>
<td>1.6</td>
<td>2.1</td>
<td>1.4</td>
<td>2.3</td>
<td>6.0</td>
</tr>
<tr>
<td>2003-2014</td>
<td>4.1</td>
<td>4.7</td>
<td>3.4</td>
<td>3.7</td>
<td>4.9</td>
</tr>
</tbody>
</table>

Table 3 Performance Levels and Grades of IWRM in Different Basins in 2003-2014

<table>
<thead>
<tr>
<th>Years</th>
<th>Basin 1</th>
<th>Basin 2</th>
<th>Basin 3</th>
<th>Basin 4</th>
<th>Basin 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2006</td>
<td>0.413</td>
<td>0.397</td>
<td>0.194</td>
<td>0.393</td>
<td>0.498</td>
</tr>
<tr>
<td>2007-2010</td>
<td>0.692</td>
<td>0.791</td>
<td>0.659</td>
<td>0.555</td>
<td>0.543</td>
</tr>
<tr>
<td>2011-2014</td>
<td>0.435</td>
<td>0.428</td>
<td>0.327</td>
<td>0.336</td>
<td>0.699</td>
</tr>
<tr>
<td>2003-2014</td>
<td>0.532</td>
<td>0.545</td>
<td>0.386</td>
<td>0.455</td>
<td>0.598</td>
</tr>
</tbody>
</table>

Performance Level
Performance Grade

Table 3 Performance Levels and Grades of IWRM in Different Basins in 2003-2014

<table>
<thead>
<tr>
<th>Years</th>
<th>Basin 1</th>
<th>Basin 2</th>
<th>Basin 3</th>
<th>Basin 4</th>
<th>Basin 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-2006</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>2007-2010</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
<tr>
<td>2011-2014</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>
Table 3 shows the performance levels and grades of IWRM in the 5 basins in different periods. The change trend of IWRM performance in the 5 basins is basically the same with that of the performance index growth. Basin 5 has the highest IWRM performance in 2003-2006 and 2011-2014, while basin 2 comes top of the list in 2007-2010. Generally speaking, only basin 3 has low grade IWRM performance, while other basins all fall to the medium grade, indicating that the management of basin 3 hinders the sustainable development of the basin and should be rectified in a timely manner. Boasting the highest management performance, basin 5 has adopted proper protection measures, which improves the conditions of the basin and promotes sustainable development of the basin.

4. CONCLUSION

(1) Based on the IWRM model and the socioeconomic development goals of water resources management in a typical river basin of China, this paper puts forward a performance evaluation index model of IWRM, classifies the model into four evaluation dimensions by the hierarchical structure of AHP, such as environment sustainability, social fairness, economy benefit and organization energy efficiency, and further divides the four evaluation dimensions into 18 evaluation indices, providing a new quantitative tool for IWRM performance evaluation.

(2) The IWRM performance and evaluation indices show that the key to IWRM lies in sustainable development of water resources environment, the utilization ratio of water resources and the corresponding economic benefits, that putting emphasis on sustainable development of the surrounding environment can significantly improve the value of the index in the overall evaluation system, and that the rational utilization of water resources is conducive to rapid economic development. Further restricting water consumption and optimizing water resources allocation are the important directions for the strategic adjustment of sustainable water resources management.

(3) Besides, this paper establishes a theoretical evaluation system of IWRM performance in different basins on the basis of binary comparison, entropy weighting and linear superposition. The results show that, from 2003 to 2014, the IWRM performance index in the five basins increased gradually, and the growth rate of the performance indices increased first and then decreased. The change trend of IWRM performance in the five basins is basically the same with that of the performance index. The IWRM performance evaluation can effectively detect loopholes in basin management, and call for timely rectification.

5. REFERENCES


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