Evaluation of regional water security using water poverty index

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Abstract: Water security is a widely concerned issue in the world nowadays. A new method, water poverty index (WPI), was applied to evaluate the regional water security. Twelve state farms in Heilongjiang Province, Northeastern China were selected to evaluate water security status based on the data of 2006 using WPI and mean deviation grading method. The method of WPI includes five key indices: resources(*R*), access (*A*), capacity(*C*), utilization (*U*) and environment (*E*). Each key index further consists of several sub-indices. According to the results of WPI, the grade of each farm was calculated by using the method of mean deviation grading. Thus, the radar images can be protracted of each farm. From the radar images, the conclusions can be drawn that the WPI values of Farm 853 and Hongqiling are under very safe status, while that of Farm Raohe is under safe status, those of Farms Youyi, 597, 852, 291 and Jiangchuan are under moderate safe status, that of Farm Beixing is under low safe status and those of Farm Shuangyashan, Shuguang and Baoshan are under unsafe status. The results from this study can provide basic information for decision making on rational utilization of water resources and regulations for regional water safety guarantee system.

Keywords: mean deviation grading method, water poverty index, water security evaluation, weighted average method

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1 Introduction

Recently, the water security problem is a widely concerned issue in the world with the fast economic development and the increased negative effect of human activities. The water security problems such as flooding, drought and pollution have become the bottleneck to hamper the sustainable economic development throughout all counties. Water resources become a strategic problem related to regional subsistence and development, and an important aspect affected national security and international relations[1,2]. The water security problem in China is more serious. The average water volume per capita of water resources in China is less than a quarter of the average value in the world and China is one of the thirteen most deficient countries in water resources. The annual sewage discharge is 5.6×10^{10} ton in China, which results in deteriorated water quality and serious declined water purification function. The human activities and natural disasters lead to the serious deterioration of ecological and environmental systems, which includes surface subsidence caused by groundwater overexploitation seawater intrusion, large-area forest destruction, increased soil and water loss, and frequent occurrence of drought and flooding [3]. Brown and Halweil pointed out that the water shortage problems in China could affect the basis of food security in the world[4]. Therefore, the regional water security problems become an important issue and challenge for researchers in water resources.

The study of water security problems consists of basic fundamental of water security, supporting theory, evaluation system and methods etc.[5], and the water security evaluation is the core of water security system. Many methods were applied to evaluate the regional water security, including semi-structural decision-making method[2, 6], hierarchy fuzzy evaluation method, system dynamics method, set pair analysis method[5] and water

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poverty index[7-14] etc. Water poverty index (WPI) was developed by Caroline et al. from Center for Ecology & Hydrology (CEH) of British Natural Environment Research Council (NERC) in order to monitor the development phases of water industry and to provide decision basis for establishing regional water security guarantee system. The new water management evaluation technique, WPI, is a comprehensive index considering the natural status of regional water resources, water resources acquisition, water environment situation and the utilization capacity and potential of water resources, which is widely applied in different scales[7, 8]. Sun (2006) discussed the origin and meaning of WPI[7]. Cao (2005) introduced the structure, components, and calculation method of WPI and analyzed the function of WPI in the application of water resources development and utilization[8]. Zhang et al. (2005) applied WPI in the water security evaluation of river basins in China and provided a basis to regulate the protection mechanics of water security in river basins[9]. Sullivan et al. (2003) evaluated water security conditions of the various communities in South Africa, Tanzania, and Sri Lanka[10]. Lawrence et al. (2002) compared the water security conditions for 147 countries using WPI[11]. Although WPI is widely applied to evaluate water security problems in river basins, and countries, the application of WPI in food yield area is not yet conducted. Therefore, WPI is employed in this study to evaluate the regional water security conditions in the scale of food yield area and to provide a basis for decision making of regional water security guarantee system.

2 Materials and methods

2.1 Study site

Hongxinglong Land Reclamation Branch Bureau with an area of 8.8×10^5 hm^2 and arable land area of 4×10^5 hm^2 is located at the east of Heilongjiang Province and in the central region of Sanjiang Plain, which covers four cities and seven counties (e.g., Jiamusi City, Shuangyashan City, and Qitaihe City etc.). Hongxinglong Branch Bureau consists of 12 state farms with the main production of wheat, barley, soybean, paddy and corn, which is the important marketable grain base in China with the mechanization degree of 95%. With the adjustment of grain crops planting structure, application of new cultivation techniques for rice in Frigid Zone and economic benefit of paddy, the planting area of paddy in the reclamation region has increased sharply. The paddy planting area of Hongxinglong Branch Bureau increased from 7.7×10^4 hm^2 in 1996 to 1.71×10^5 hm^2 in 2005. And 66% of the paddy field is irrigated with water from wells. Because of the rapid increase of paddy field area, the groundwater level of Hongxinglong Branch Bureau has generally decreased with an annual average drop of 0.5～1.0 m to form the temporary funnel-shape drop. The constant descent of groundwater level has seriously broken the supply and demand balance of local groundwater resources. The water used by industrial, agricultural and domestic sectors has been seriously threatened if the constant increase of paddy area and withdrawal of groundwater level. Thus, it is very necessary to evaluate the water security status of the 12 state farms in Hongxinglong Branch Bureau and further to provide the information for decision making in reasonable exploitation and utilization of regional water resources. WPI was applied in this study to conduct the water security evaluation in Hongxinglong Branch Bureau.

2.2 Water poverty index

2.2.1 Structure of WPI

WPI consists of five key water related components: resource (*R*), access (*A*), capacity (*C*), utilization (*U*) and environment (*E*) [7, 8, 10]. The structure of WPI is shown in Figure 1. The component of Resource (*R*) represents the availability of both surface water and groundwater under the condition of considering the variability, quality and quantity of water resources. The index of Access (*A*) is the approximate degree of water resources utilization including the distance from safe water sources, water travel time to every family, and other important factors. Access not only relates to domestic water use, but also to agricultural irrigation and industrial water use. The Capacity (*C*) is the capability and efficiency of water resources management. Capacity can be interpreted as the purchasing power of clean water resources, education and health condition related to income, which affects the water supply ability. The index of Use (*U*) stands for the mode and efficiency of different water utilization departments, including domestic, agricultural and industrial water use. The Environment (*E*) is the evaluation of environment integrity related to water resources and ecological systems of local aquatic environment.

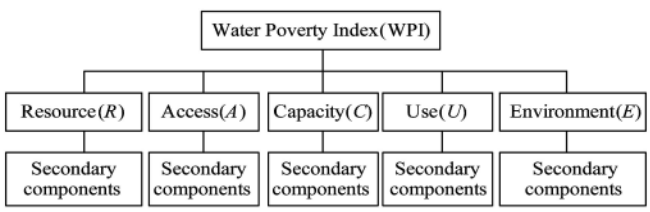

Figure 1 Structural diagram of WPI

2.2.2 Calculation method of WPI

The calculation methods of WPI include weighted average method, difference analysis method and matrix analysis method[11] etc. The weighted average method is the most commonly used one.

The *WPI* calculation using weighted average method can be expressed as[7-11]:

$$WPI = \sum_{i=1}^{N} w_i X_i \Big/ \sum_{i=1}^{N} w_i \tag{1}$$

Where *WPI* is the value of water poverty index in a certain area; X_i is the i^{th} component of WPI structure; and w_i is the weight of each component.

Because each X_i consists of several sub-components, the value of each X_i is necessary to be calculated using the same method. Based on five components of *WPI* discussed above, Equation (1) can be rewritten as:

$$WPI = \frac{w_r R + w_a A + w_c C + w_u U + w_e E}{w_r + w_a + w_c + w_u + w_e} \tag{2}$$

WPI value calculated using Equation (2) is the weighted average of the five components (i.e., resource (*R*), access (*A*), capacity (*C*), utilization (*U*) and environment (*E*). The value of each component is firstly standardized into the range of 0～100 and the range of calculated WPI value is also from 0 to 100. The highest value (100) is considered as the best situation or the smallest probability of water resources scarcity. Reversely, and the lowest value (0) is deemed to be the most unfavorable condition.

If the weight of each component is difficult to be determined, equal weight was assigned to each component in order to ensure the evaluation transparency. In other words, the weight of each component in this study is set as 1, and then Equation (2) can be rewritten as:

$$WPI = \frac{R + A + C + U + E}{5} \tag{3}$$

3 Results and discussion

The WPI was applied in this study to evaluate the water security status of the 12 state farms in Hongxinglong Branch Bureau. The sub-indices of WPI are firstly selected based on site investigations. Then, the WPI values of the 12 state farms were calculated using the method discussed above and the water safety conditions of the farms could be assessed based on the calculated WPI values.

3.1 Determining sub-indices of WPI

According to the previous research of WPI application through the world and China, we can screen the sub-indices for each component of WPI based on the site investigations. The processes are described as follows:

1) Sub-indices of resource (*R*)

Total volumes of surface water and groundwater resources are considered in this study as two sub-indices of the resource component. Water quality could have important effects on water resources and it is also an important index of the environment component. Thus, water quality index is not included in this part in order to avoid repeated calculation.

2) Sub-indices of access (*A*)

The component of access mainly includes the indices of tap water popularization rate, the ratio of people with drinking water health quality reaching the standard, irrigation rate of arable land etc.

3) Sub-indices of capacity (*C*)

The sub-indices of capacity component include GPD per capita, education level (e.g., high school gross enrollment rate, primary and middle school dropout rate and the ratio of middle school students who enroll in medium or high vocational school), and water conservancy investment.

4) Sub-indices of utilizaiton (*U*)

It mainly includes domestic, agricultural and industrial water use per capita.

5) Sub-indices of environment (*E*)

The sub-indices of the component mainly consists of water quality grade, fertilizer and pesticide use per hectare, soil erosion area and ecological protection area etc.

3.2 Calculation of WPI for each farm in Hongxinglong Branch Bureau

To eliminate the unit influence of each index on calculated WPI value, the sample data set $\{x(i, j)\}$ is needed to be standardized firstly[12-14]. For retaining the variety information of each evaluating index as much as possible, the indices can be standardized using the following formulas.

For the better index with the larger values:

$$r(i, j) = x(i, j) / [x_{\max}(j) + x_{\min}(j)] \tag{4}$$

For the better index with the smaller values:

$$r(i, j) = [x_{\max}(j) + x_{\min}(j) - x(i, j)] / [x_{\max}(j) + x_{\min}(j)] \tag{5}$$

Where $r(i, j)$ is the standardized value of the j^{th} index of the i^{th} sample (i = 1~n and j = 1~m); $x(i, j)$ is the original value of the j^{th} index of the i^{th} sample; $x_{\max}(j)$ and $x_{\min}(j)$ is the maximum and minimum values of the j^{th} index, respectively.

The standardized value $r(i, j)$ should be multiplied by 100 to ensure the values of WPI in the range of 0～100. Based on the calculation methods discussed above, the values of five components and WPI are calculated and the results are listed in Table 1.

According to Table 1, the water security conditions of the 12 farms in 2006 can be ranked and the orders of conditions from good to bad are: Hongqiling, 853, Raohe, Youyi, 579, Jiangchuan, 852, 291, Beixing, Shuangyashan, Shuguang and Baoshan.

Table 1 Values of components and WPI for each farm in Hongxinglong Branch Bureau in 2006

Farm	Component					WPI
	Resource (R)	Access (A)	Capacity (C)	Utilization (U)	Environment (E)	
Youyi	82.46	44.39	46.07	17.12	44.10	46.83
597	42.70	55.51	37.04	20.91	74.70	46.17
852	41.40	45.80	46.45	53.79	37.03	44.89
853	47.88	62.47	47.70	40.03	76.29	54.87
Raohe	58.03	67.82	48.68	34.03	45.91	50.89
291	34.93	43.87	32.48	38.11	50.83	40.04
Shuangyashan	18.78	60.36	26.48	19.06	50.78	35.09
Jiangchuan	25.33	64.03	51.45	41.54	46.97	45.86
Shuguang	6.49	60.97	37.57	18.54	45.80	33.87
Beixing	52.00	31.64	51.90	17.20	41.13	38.77
Hongqiling	17.81	77.28	71.85	58.10	66.18	58.24
Baoshan	8.24	37.69	31.15	35.24	49.41	32.35

Note: The data were adopted from the book of “Statistic Data of Economic and Society Development” and “Water Conservancy Yearbook” of Hongxinglong Branch Bureau in 2006.

3.3 Water security status analysis of each farm in Hongxinglong Branch Bureau

3.3.1 Water security status classification of each farm

Sample mean and standard deviation grading method[15-18] is adopted to classify the water security grade of each farm in Hongxinglong Branch Bureau in 2006 based on the WPI values. Set indices series as x_1, x_2, $\cdots$, x_n, sample mean value as $\bar{x}$ and sample standard deviation as σ_x. If the series is a poor correlated series (the absolute value of correlation coefficient ≤0.2), it can be approximately considered as an independent series with the identical random distributions. On the basis of central limit theorem, we can obtain $P\{\bar{x}-1.5\sigma_x \leqslant x < \bar{x}+1.5\sigma_x\} \approx 0.87$ and $P\{\bar{x}-\sigma_x \leqslant x < \bar{x}+\sigma_x\} \approx 0.68$. Then, the index values are partitioned into five groups based on the ranges of $(-\infty, \bar{x}-1.0\sigma_x)$, $(\bar{x}-1.0\sigma_x, \bar{x}-0.5\sigma_x)$, $(\bar{x}-0.5\sigma_x, \bar{x}+0.5\sigma_x)$, $(\bar{x}+0.5\sigma_x, \bar{x}+1.0\sigma_x)$ and $(\bar{x}+1.0\sigma_x, +\infty)$. In practical application, the ranges of index values are usually expressed as: $(-\infty, \bar{x}-\alpha_1\sigma_x)$, $(\bar{x}-\alpha_1\sigma_x, \bar{x}-\alpha_2\sigma_x)$, $(\bar{x}-\alpha_2\sigma_x, \bar{x}+\alpha_2\sigma_x)$, $(\bar{x}+\alpha_2\sigma_x, \bar{x}+\alpha_1\sigma_x)$ and $(\bar{x}+\alpha_1\sigma_x, +\infty)$ with the range of α_1 between [1.0, 1.5] and α_2 between [0.3, 0.6]. Although the grading method does not consider the effect of physical meaning on the indices, it is easy to handle and has been widely applied.

Based on the method above, the mean value of WPI ($\overline{WPI}$) is 43.9892 with the standard deviation (σ) of 8.2359. The autocorrelation coefficient of each order is within the 95% tolerance limit and the value of $|r_k|$ is mostly less than 0.2. Therefore, the series of WPI values can be considered as an independent identically distributed random series. Table 2 lists the grading results of each farm in Hongxinglong Branch Bureau in 2006.

Table 2 Classification of WPI values for each farm in Hongxinglong Branch Bureau in 2006

Grade	Grading criterion	Grading range	Results
Unsafe	$WPI < \overline{WPI} - 1.0\sigma$	WPI <35.75	Shuangyashan, Shuguang and Baoshan
Lower safe	$\overline{WPI} - 1.0\sigma \le WPI < \overline{WPI} - 0.5\sigma$	35.75≤ WPI <39.87	Beixing
Moderate safe	$\overline{WPI} - 0.5\sigma \le WPI < \overline{WPI} + 0.5\sigma$	39.87≤ WPI <48.11	Youyi, 597, 852, 291 and Jiangchuan
Upper safe	$\overline{WPI} + 0.5\sigma \le WPI < \overline{WPI} + 1.0\sigma$	48.11≤ WPI <52.23	Raohe
Safe	$WPI \geqslant \overline{WPI} + 1.0\sigma$	WPI ≥52.23	853 and Hongqiling

3.3.2 WPI results of each farm in Hongxinglong Branch Bureau

Figure 2 shows the WPI radar chart of each farm in Hongxinglong Branch Bureau.

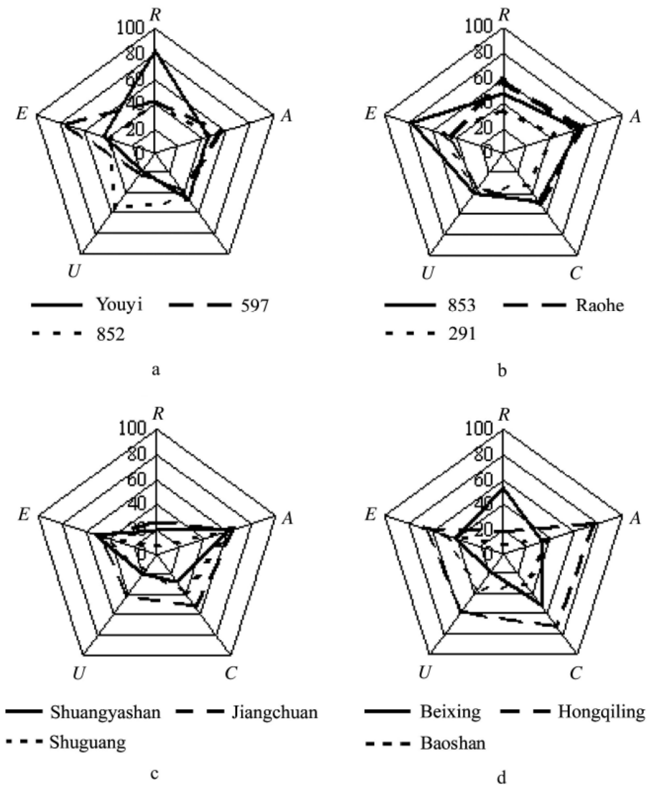

Figure 2 WPI radar charts of each farm in Hongxinglong Branch Bureau in 2006

One can see from Figure 2a that the *U* value of Youyi Farm is low, indicating that the water utilization needs to be improved. However, the WPI value of Youyi Farm can be evaluated as moderate safe status because of sufficient surface water and groundwater resources, good environmental condition, high water conservancy investment, higher levels of tap water popularization rate, the ratio of people with drinking water health quality reaching the standard, and GDP per capita on the Youyi Farm. Therefore, the important measures can be taken to establish water security guarantee system on the Youyi Farm, including further investing water conservancy, strengthening hydraulic engineering construction and enhancing water resources (especially groundwater resources) exploitation and utilization ratio. One can also see from Figure 2a that the *C* and *U* values of Farm 597 are also low, indicating the capacity and utilization are in unsafe condition for Farm 597. But some positive effects also make WPI value of Farm 597 in moderate safe status, which are sufficient groundwater resources, good environmental condition and higher levels of the ratio of people with drinking water health quality reaching the standard, tap water popularization rate and arable land irrigation rate. The main measurements such as controlling primary and middle school dropout rate, enhancing evaluation level, intensifying government water resources management capacity, further investing water conservancy, strengthening hydraulic engineering construction and enhancing water resources (especially groundwater resources) exploitation and utilization ratio can be taken to establish water security guarantee system of Farm 597. The *E* value of Farm 852 is low too, indicating the environment of Farm 852 is not very good. But sufficient surface water resources and high levels of per capita GDP, water resources exploitation and utilization degree, the ratio of people with drinking water health quality reaching the standard, tap water popularization rate and water conservancy investment could make the WPI value of Farm 852 in moderate safe status. For Farm 852, the measures are effective for establishing its water security guarantee system to control fertilizer and pesticide input and soil erosion area, and to restore ecological environment.

Figure 2b shows that the WPI values of all components on the Farm 853 are greater than 40, indicating the WPI value of Farm 853 is in safe status. The values of A and E are very high because of the high level of tap water popularization rate, the ratio of people with drinking water health quality reaching the standard and arable land irrigation rate, small soil erosion area and large ecological protection area. Though the *U* value of Farm Raohe shown in Figure 2b is low. The WPI value of Farm Raohe is in high safe status because there are sufficient surface water and groundwater resources, good environmental condition, high water conservancy investment and higher levels of tap water popularization rate, the ratio of people with drinking water health quality reaching the standard, arable land irrigation rate, GDP per capita in Farm Raohe. Further investing water conservancy input, strengthening hydraulic engineering construction and enhancing water resources (especially surface water resources) exploitation and utilization ratio are the important measures to establish water security guarantee system of Farm Raohe. One can also see from Figure 2b that the *R*, *C* and *U* values of Farm 291 are very low, indicating the resource, capacity, and utilization on the Farm 291 are in unsafe status. However, the WPI value of Farm 291 is still in moderate safe status because of high levels of tap water popularization rate and arable land irrigation rate, and small pesticide input and soil erosion areas on the farm. The important measures (e.g., maximally utilizing the runoff, reducing the stress of water resources shortage, enhancing education level, intensifying government water resources management capacity, further investing water conservancy, strengthening hydraulic engineering construction and enhancing the capacity and efficiency of all water utilization departments) can be taken to establish water security guarantee system of Farm 291.

Although the *A* and *E* values of Farm Shuangyashan and Shuguang shown in Figure 2c are very high, their R, C, and U values are low because of deficient surface water and groundwater resources, low levels of GDP per capita, education, water conservancy investment and water utilization efficiency in all related departments. Thus, it leads to the WPI values of the two farms in unsafe status. The problems can be solved using the measures of maximally utilizing the runoff, decreasing water resources deficiency, enhancing living and education level, further investing water conservancy and strengthening hydraulic engineering construction. One can see from Figure 2c that the *R* value of Farm Jiangchuan is low, indicating the resource of Farm is in unsafe status. But the WPI value of Farm Jiangchuan is still in moderate safe status because there are high arable land irrigation rate, good environmental condition, higher levels of tap water popularization rate, the ratio of people with drinking water health quality reaching the criterion, GDP per capita, evaluation and water conservancy input, and high water utilization efficiency in the farm. The good measures can be taken to establishing water security guarantee system for Farm Jiangchuan, which include further investing water conservancy, strengthening hydraulic engineering construction, enhancing the utilization of runoff.

One can see from Figure 2d that the *R*, *C* and *E* values of Farm Beixing are high but the A and U values are very low because of low levels of the ratio of people with drinking water health quality reaching the standard, arable land irrigation rate and water utilization efficiency in all related departments. Thus, the WPI value of Farm Beixing is in lower safe status. The measures such as financing, enhancement of drinking water security construction for residents and hydraulic engineering construction, further investment of water conservancy, improvement of arable land irrigation rate and water use efficiency are useful to establish water security guarantee system of Farm Beixing. The *R* value of Farm Hongqiling shown in Figure 2d is low, but high levels of tap water popularization rate, GDP per capita, water conservancy investment, water utilization efficiency, the ratio of people with drinking water health quality reaching the standard, arable land irrigation rate and education, and good environmental condition can make the *A*, *C*, *U* and *E* values higher. Thus, the WPI value of Farm Hongqiling is in safe status. The water security status will be better if Farm Hongqiling could further increase water conservancy investment, strengthen hydraulic engineering construction and enhance water utilization efficiency of runoff. The *E* value of Farm Baoshan in Fig.2d is high and the R, A, C, and U values are very low because of water resources shortage, low levels of tap water popularization rate, the ratio of people with drinking water health quality reaching the standard, education, water conservancy investment and water utilization efficiency. Thus, the WPI value of Farm Baoshan is in unsafe status. The unsafe status in Farm Baoshan can be improved if increase the utilization of runoff, remit water resources shortage, enhance living and education level, increase the financing, enhance drinking water security engineering construction for residents and hydraulic engineering construction, further increase water conservancy investment and water utilization capacity and efficiency.

4 Conclusions

1) WPI is an effective tool to evaluate the regional water security condition by combining various information of water problem. The sub-indices of WPI were selected based on site investigation in Hongxinglong Branch Bureau. The water security assessment in this study comprehensively reflects the water security management level under the scale of food production area in China.

2) The regional water security status was evaluated and graded based on the calculation of WPI of the 12 farms in Hongxinglong Branch Bureau in 2006, which can provide decision-making basis for rational exploitation and utilization of regional water resources.

3) Although the equal weight adopted in the calculation of WPI is not very reasonable, it is an effective way to calculate WPI with only limited information from different domains by five indexes. Therefore, the future study can be focused on how to determine the weights of five sub-indices of WPI to improve its evaluation accuracy.

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