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A novel water poverty index model for evaluation of Chinese regional water security

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Abstract. This study proposed an improved Water Poverty Index (WPI) model employed in evaluating Chinese regional water security. Firstly, the Chinese WPI index system was constructed, in which the indicators were obtained according to China River reality. A new mathematical model was then established for WPI values calculation on the basis of Center for Ecology and Hydrology (CEH) model. Furthermore, this new model was applied in Shiyanghe River (located in western China). It turned out that the Chinese index system could clearly reflect the indicators threatening security of river water and the Chinese WPI model is feasible. This work has also developed a Water Security Degree (WSD) standard which is able to be regarded as a scientific basis for further water resources utilization and water security warning mechanism formulation.

1. Introduction

Water security is a water-centered complex huge system, which has a significant influence on social, economic and ecological aspects. To date, the unscientific water utilization and management in many regions resulted in the water shortage and pollution. It leads to not only water imbalance, but also reduction of the water quality. As a result, the water function was being weakened and even lost. Once the water body loses its economic or social value, it leads to water crisis for basic human demands, preventing human economy and society from moving forward [1].

Water security evaluation is the basis to formulate the regional water security planning and strategy for better water management. It is also the premise for regional water security decision-making. At present, researches on regional water security evaluation are still on the preliminary stage, and only some discusses about the qualitative conception, connotation and countermeasures.

For researchers in foreign countries, Falkenmark and Widstrand proposed that per capita water resources can measure regional water resources scarcity level [2]. In moderately developed countries, the thresholds of per capita water resources for arid regions were obtained, shown as follows:

- The water is on the shortage level when the per capita water resource is blow 1700 m^3 but higher than 1000 m^3.
- The water is on the severe shortage level when the per capita water resource is blow 1000 m^3 but higher than 500 m^3.
- The water is on the extreme shortage level when the per capita water resource is below 500 m^3.

Falkenmark and Widstrand improved these indicators to discriminate the water sources scarcity levels and security status in various countries and regions.

In China, Hong Y *et al* [3] suggested that the water security should be analyzed from external environment and conditions. Jia S-F *et al* [4] considered that the water was safe as long as the regional water supply can meet the needs of long-term economy and social progress. Zhang X *et al* [5] defined water security as the non-threatened and controlled influence of water content and activity on economy and society stability and development. Chang M-Q and Huang Q [6] considered that the water security was the status that human existence and development would not be threatened by water problems.

The above discussions show that there were very few quantitative analyses on regional water security evaluation. Therefore, particular emphasis was put on the water security evaluation index system for quantitative processing in this study. It introduced WPI into water security evaluation model, and explored index system in WPI, especially, several components composed of detailed indicators. Meanwhile, it proposed water security evaluation index system adapted to Chinese water. In advanced sustainable use of regional water resources, this study assures the regional water resources security, so it accommodates both theoretical significances and practical significances, and drive sustainable society and economy development.

2. Materials and methods

2.1. WPI

The Water Poverty Index (WPI) method was proposed in 2002 by the researchers in the Center for Ecology and Hydrology (CEH) to monitor the water status [7]. Based on the interdisciplinary theory, the WPI provides a standard framework for evaluation of regional water exploitation and utilization. It particularly evaluates the effects of water scarcity on society and economy. The WPI model has simple calculation, low cost and understandable property. Hence, the WPI has been drawn great concern of the researchers in water resource field all over the world, especially for the 3rd World Water Forum in Kyoto.

The WPI is a standard framework to guide how to rationally manage water. It is appropriate for different regions and countries on different levels. Meanwhile, it is easy to obtain data of the index system in WPI model for a specific region or country. In WPI index system, Resource (R), Access (A), Use (U), Capacity (C) are the five components (indicators of them are shown in table 1), the values of which vary from 0 to 100. The higher the value is, the better the performance is.

Table 1. Indicators in the five WPI components.

WPI components	Indicators
R	Ground water, surface water, water quality value, soil moisture, reliability data.
A	Household water supply, facilities for irrigation, foodstuffs import, state of health.
U	Water usage of agriculture, water usage of industry, water usage of life, water usage of livestock, water utilization efficiency in different industrial sectors, total water usage
C	GDP per capita, levels of household consumption
E	Living species, ecological environment, water pollution, flood, water and soil erosion.

Table 1 shows that the index system includes not only water and environment indicators, but also economic and social indictors. Water security problems in the early human civilization are exhibited by natural disasters, such as arid, flood, river diversion. With the human civilization progress development, the contents of water security in economy and society are enriched and extended.

The equation of the WPI model given by CEH is shown as follow:

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$$WPI = \frac{\sum_{i=1}^{N} w_{x,i} X}{\sum_{i=1}^{N} X_{x,i}} \quad (1)$$

Equation (1) shows WPI value for a certain region. N denotes the number of WPI components. X is the components values in this region, including R, A, U, C or E. $w_{x,i}$ denotes weights of the i^{th} indicator in the components X . It is obvious that the WPI is obtained by the weighted average value of all five components. The following is the rearranged equation:

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

2.2. Chinese WPI index system
In general, the WPI index system could reflect the water and water industry state in different regions. So WPI theory was spread to 147 countries by the Center for Ecology & Hydrology (CEH), while WPI value varied from 48 to 55.9 in China. However, the 5 components in the WPI index system were determined according to Europe realities. In other regions or countries, some indicators of the 5 components are difficult to be obtained. For instance, the indicators related to household water and household welfare are important in water management decision making in Europe and America. While some of them are hard to collect because of large population. Meanwhile, it is lack of some indicators which could better reflect the Chinese water situation in the index system.

Typically, this study firstly proposed the Chinese indicators of the 5 components in the WPI index system on basis of the CEH [7] and realities in China, which is shown in table 2. On account of the natural attribute, social attribute and humanity attribute of the water security, the related indicators should be considered in the WPI index system. Besides the regional water conditions, the factors related to environment, society and economy in China are also included.

In order to get the indicator values, a large number of reliable data were obtained from the relevant agencies and departments termed as step one. After that, the data were processed in different ways. There is no doubt that it was a complicated and time-consuming process. For the qualitative description, it is necessary to consult experts to get much more accurate results. For indictors in different regions, the calculation bases are different. So how to choose suitable variables to establish the mathematical model is an important work.

The WPI index system in China was formed according to situation of China, related economic development, social insurance, and water supply. It could be better to reflect the water shortage on influencing human life. The Chinese WPI system provides conveniences for water managers to check the water availability and social economic factors changes. It provides comprehensive information about water resources and social economic status to further establish the water security system.

2.2.1. Resource (R) in China. The Resource is the component showing physical availability of water resources in the study area. The larger the component value is, the more the water availability is considering internal-annual and seasonal variability. It includes 4 indicators:

- Surface water amount.
- Overdraft rate of groundwater.
- Water supply / demand ratio.
- Quality compliance rate of drinking water.

Table 2. Chinese WPI index system.

WPI components	General indicators	Indicators in China	Dimension	Nature
R	Evaluation of surface water with hydrological technology	Surface water amount	m^3	↑
	Evaluation of ground water evaluation with hydrogeological technology	Groundwater overdraft rate	%	↓
	Resource reliability evaluation about quantitative and qualitative evaluation	Supply/demand ratio of water	%	↑
	Water quality reliability values evaluation about quantitative and qualitative	Drinking water quality compliance rate	%	↑
A	Acquisition approaches of clean water	Percentage of running water users	%	↑
	Proportion of human with health facilities	Urbanization rate	%	↑
	Water collection time, including waiting time	Water resources utilization ratio	%	↑
	Irrigation way	Irrigated area ratio	%	↑
U	Industrial water consumption per capita	Water consumption based on industrial output ($/10^4$Yuan)	$m^3/10^4$Yuan	↓
	Household water consumption per capita	Daily per capita water consumption	/ day	↑
	Agricultural water consumption per capita	Agricultural water consumption per unit area	m^3/ha.	↓
C	GDP per capita	GDP water consumption per 10,000 Yuan	$m^3/10^4$Yuan	↓
	Education level	Number of university students per 10,000 persons	$/10^4$ persons	↑
	Household consumption level	Farmers' annual net income	Yuan/ year	↑
	Drink coefficient	Town Engel coefficient	Dimensionless	↓
	Child under 5 mortality rate (Health Indicators)	Mortality of infant and child	%	↓
E	Observations of water quality	Integrated pollution index of surface drinking water	Dimensionless	↓
	Environmental management and governance	Urban sewage treatment rate	%	↑
	Water pollution load	Industrial wastewater specific pollutants emissions	Kg	↓
	Biodiversity	Green coverage	%	↑

Notes: "↑"denotes the performance increases with the increase of the value.
"↓"denotes performance decreases with decreasing value.

2.2.2. Access (A) in China. The access is the component that considers population with reasonable access to sanitation for health and much well-being, and to adequate safe drinking water. It includes 4 indicators:

- Percentage of running water users.
- Urbanization rate.
- Water resources utilization ratio.
- Irrigated area ratio.

2.2.3. Use (U) in China. Water use is one of the most important things in human activity, and the water consumption increases with the society and economic development. Therefore, Use is the component that indicates the ability of human use water effectively and the water to be contributed to society and economy. It includes 3 indicators:

- Daily per capita water consumption.
- Water consumption based on industrial output (/104Yuan).
- Agricultural water consumption per unit area.

2.2.4. Capacity (C) in China. The Capacity is the components that refer to the current potential to manage water. It includes 5 indicators:

- GDP water consumption per 10,000 Yuan.
- Famers' annual net income.
- Town Engel coefficient.
- Number of university students per 10,000 persons.
- Infant and child mortality.

2.2.5. Environment (E) in China. The environment is the component that shows the ability that the ecosystem continuously provides benefits to society and the environment influence water quantity and quantity. It includes 4 indicators:

- Integrated pollution index of surface drinking water.
- Urban sewage treatment rate.
- Industrial wastewater with specific pollutants emissions.
- Green coverage.

2.2.6. WPI Mathematical model in this study. Take Capacity(C) for example, its calculation steps were shown as follows:

- Divide each of the indicators of Capacity (C) in a certain region by its corresponding national average value to get the ratios. For Capacity (C), the indicators are GDP water consumption per 104 Yuan (C1), urban worker wage level (C2), number of university students per 104 persons (C3), Town Engel coefficient (C4), infant and child mortality (C5).
- Average all of these ratios. The result reflects Capacity (C) of this region compared to the national level.
- Obtain the Capacity(C) value by multiplying the above average value with Chinese Capacity(C) value given by the CEH. Thus, the component value and WPI reflect the relative level of the region in one country.

Based on the CEH model and the above steps, the WPI mathematical model given by this study is concluded as follow:

$$X = \frac{\sum_{1}^{N} \frac{X_i}{X_{i-CN}}}{N} \times X_{CEH} \tag{3}$$

Suppose X_i denotes the i^{th} indicator in the WPI component X . X_{i-CN} denotes the indicator's national average value. N denotes the indicator numbers in the component. X_{CEH} is the component value given by CEH. Then the component value can be calculated as follow:

In situations where it is difficult to obtain the components weights, the equal weighted method was adopted to ensure the evaluation transparency. The WPI value can be calculated by equation (4) and all of the components weights to 1.

$$WPI = \frac{R + A + C + U + E}{5} \tag{4}$$

2.3. *Water security degree (WSD)*

The study firstly proposed the Water Security Degree (WSD) in China in order to give direct water security levels. So the thresholds and ranges of each degree should be confirmed. With the purpose of getting accurate thresholds, 20 indicators which can better describe water security status [8] are chosen, and all of the indicators values are quantized and classified. After that, the international standards, and the standards and development plan in China were collected as the basis and standards. The WSD thresholds and ranges were obtained by Expert Consultation Method. 5 degrees of WSD are shown as follows:

- WSD1 - *Very Safe* degree (WPI > 62): Development of society and economy is **highly satisfied** with the water resources and water environment.
- WSD2 - *Safe* degree (62 > WPI > 56): The society and economy development is **satisfied** with the water resources and water environment.
- *WSD3*- *Generally Safe* degree (56 > WPI > 48): The society and economy development is **generally satisfied** with the water resources and water environment.
- *WSD4*- *Unsafe* degree (48 > WPI > 35): The society and economy development is **dissatisfied** with the water resources and water environment.
- *WSD5*- *Extremely Unsafe* degree (WPI < 35): Entirely degraded water and water environment which seriously hinder the society and economy sustainable development.

2.4. *Calculation examples*

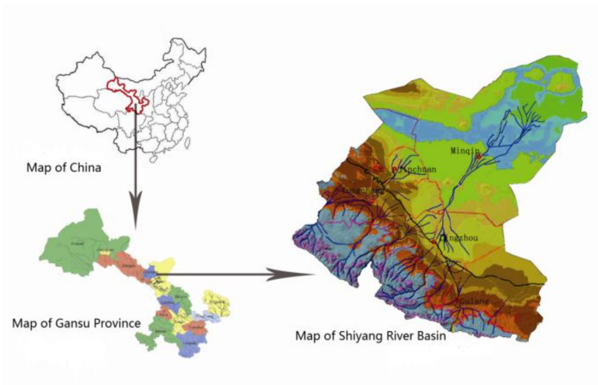

Figure 1. Shiyanghe River Basin.

The Shiyanghe river basin lies to the eastern of the Hexi Corridor, which is on the western of Wushaoling Mountain and the northern of Qilian Mountain. It encompasses 41,600 km^2 area, lying between 101°41′ to 104°16′ E and 36°29′ to 39°27′ N. The Shiyanghe River is in China hinterland with the continental temperate arid climate. The characteristics are abundant sunshine, large temperature difference, strong solar radiation, rapid evaporation, less rainfalls and the dry air. The river basin from south to north is divided to 3 climatic regions. The southern part is along Qilian Mountain with climate of alpine, semi-arid and semi-humid. The middle part along the Hexi corridor plain is the cool and arid climate. The southern part is the warm and arid area. The Shiyanghe River is composed of 8 rivers and many streams. The 8 rivers are Dajing River, Gulang River, Huangyang River, Zamu River, Jinta River, Xiying River, Dong River and Xi River from south to north. The river is feed by snow melt water in the mountain and atmospheric precipitation. The Shiyanghe River runoff area is 11,100 km^3 and average annual runoff is 1.56 trillion m^3 [9, 10]. The Shiyanghe River is shown in figure 1. The statistical data of Jinchang City, Wuwei City and Minqin County in Gansu province of China were used in the calculation examples.

3. Results

Based on the Chinese WPI index system, the WPI values, components values and the water security levels of Jinchang City, Wuwei City, Minqin County and Gansu Province in Shiyanghe River Basin were calculated, the results are shown as follows.

Table 3. WPI and components values of the Shiyanghe River.

River secondary region	R	A	U	C	E	WPI value	Degree of Water Security
Jinchang (J)	21.5	78.1	55.2	59.7	23.0	49.1	WSD3
Wuwei (W)	25.3	44.1	39.5	45.1	22.3	35.3	WSD4
Minqin (M)	2.7	14.3	15.1	13.4	3.1	9.7	WSD5
Gansu Province (G)	45.9	42.1	53.8	50.1	54.6	49.3	WSD3

Table 3 shows that the highest WPI value is in Jinchang City, while the lowest one is in Minqin County. Overall, the water resource in Shiyanghe River is on WSD4- *Unsafe* degree. It seemed that the security level in Jinchang City is on WSD3- *Generally Safe* degree, while its WPI value 49.1 was close to 48 which is the marginal value of WSD4. Wuwei City is on WSD4 with the WPI value of 35.3, which is close to the marginal value of WSD5- *Extremely Unsafe* degree. The WPI value of Minqin County is 9.7, indicating water and water environment system were degraded entirely, which had seriously hindered the society and economy sustainable development.

4. Discussion

The Radar Chart is usually applied to describe WPI value. Figures 2-5 are the Radar Charts showing the WPI and its components values in regions of Shiyanghe River. Jinchang City lacks water resources and good environment. While it has good performances in urbanization, resident income and water use,

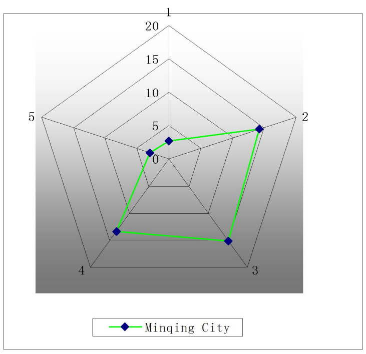

Figure 2. Radar chart- WPI values in Minqin: WPI (M) =9.7.

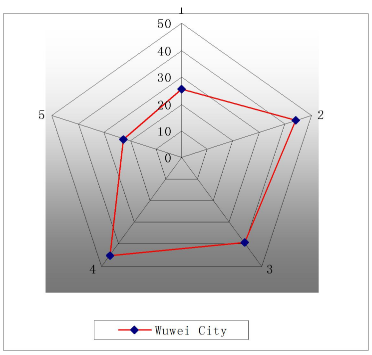

Figure 3. Radar chart- WPI values in Wuwei: WPI (W) =35.3.

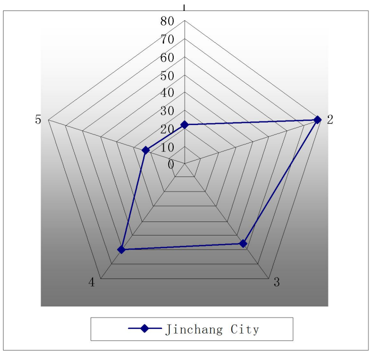

Figure 4. Radar chart- WPI components values in Jinchang: WPI (J) = 49.1.

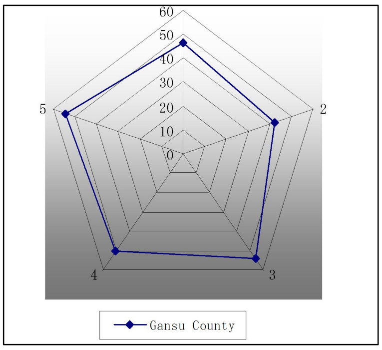

Figure 5. Radar chart- WPI components values in Gansu: WPI (G) =49.3.

making the WPI value in the lower-middle level. So Jinchang City is on WSD3- *Generally Safe* degree. Wuwei City has scarce water resource and degraded environment. Meanwhile, most social indicators in the index system were below the national level in China, causing the WPI value lower than average. So Wuwei City is on WSD4- *Unsafe* degree.

The extremely low WPI value shows that the water security in Minqin County is on WSD5- *Extremely Unsafe* degree. In the upper and middle reaches of Minqin, the water resource use increases, so the surface water amount flowing in Minqin County has declined from the 590 million m^3 in 1950s to less than 100 million m^3 in 2005. With the increasing of the water requirement, the ground water exploitation for Minqin Basin has been up to 520 million m^3, overexploiting 300 million m^3. The ecological deterioration of Minqin County was very serious. The serious overexploitation of water resource and the environmental degradation have formed a vicious circle. With conditions going out of control, Minqin County would probably become the second Lop Nor, which not only threatens the local livelihoods, but also brings bad effect on development of the entire region.

The composite WPI value of cities in Gansu Province was 49.3, which was on WSD3- *Generally Safe* degree, close to WSD4- *Unsafe* degree. It should be paid more attentions to increase water utilization efficiency and improve water security situation.

5. Conclusions

- WPI model was proposed to construct river water security index system in China, on the basis of its traditional applications on different environments and ecologies comprehensive evaluation. It indicates the path to establish universal river water security index system.
- The Chinese WPI index system was applied in the water security evaluation of Jinchang City, Wuwei City, Minqin County and Gansu Province. By analyzing the 5 components in the Chinese WPI system, the main factors affecting water security in this region. The result shows that the system provides theoretic basis for coordination between regional water security and economic development.
- Certain indicators in the WPI index system can be appropriately adjusted for different regions. Therefore, the evaluation results could objectively reflect the water security characteristics in different regions. It is because the complex water types and different water security problems in different regions.
- The application of the Chinese WPI index system in Shiyanghe River proved that this system could clearly indicate the factors threatening water security. The Water Security Degree (WSD) proposed in this study provides evidence for security warning mechanism of water resources.

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