

Evaluation of water resources comprehensive utilization efficiency in the Yellow River Basin

Xin-jian Guan, Sheng-xing Liang and Yu Meng

ABSTRACT

This study investigated appropriate indicators using the trapezoidal fuzzy number method, and constructed an evaluation index system for water resources comprehensive utilization efficiency (WRCUE). A WRCUE evaluation model is applied to areas in the Yellow River Basin in China using a genetic projection pursuit method. Results show that WRCUE is well developed in Shanxi, Shandong, and Henan provinces, moderately developed in Shanxi, Inner Mongolia, and Sichuan provinces, and poorly developed in the Ningxia Autonomous Region, Gansu Province, and Qinghai Province. According to the capacities of provinces, related measures are proposed.

Key words | evaluation index system, projection pursuit method, trapezoidal fuzzy number method, water resources comprehensive utilization efficiency, Yellow River Basin

Xin-jian Guan (corresponding author)

Sheng-xing Liang

Yu Meng

School of Water Conservancy and Environment,

University of Zhengzhou,

No. 97, Wenhua Road,

Zhengzhou City,

Henan Province,

China

E-mail: xinjianguan@sina.cn

INTRODUCTION

Water resources are sources of water that are useful or potentially useful, and the main solution to water resource issues lies in the improvement of water resource utilization efficiency (WRUE). Only if we improve the efficiency of water use can we sustain the constant development of society. Conducting research on water resource use efficiency can help us better understand the balance of water resource use in every area (province). Numerous studies have focused on WRUE, and previous work has included the establishment of an index system and a comprehensive evaluation model. Yang (2009) uses the Delphi method to determine the evaluation index assignment standard, provides an overview of a comprehensive evaluation index system for water resources that includes agricultural, industrial, domestic, and overall WRUE, and is a good reference for basic evaluation index sets. To select appropriate indicators, a number of scholars have adopted the analytic hierarchy process (AHP) (e.g., Wei 2011). Liu *et al.* (2005) used an improved AHP with three scaling methods to obtain weighted indexes, which greatly simplified calculations. Anwandter (2000) applied a data envelopment analysis (DEA) to develop a comprehensive evaluation model for WRUE in Mexico. In addition,

Lilienfeld & Asmild (2007) used a DEA to analyze agricultural WRUE in 43 irrigation areas in the western United States. In the same year, Sun *et al.* (2007) applied a stochastic frontier approach (SFA) together with an error correction model to improve the evaluative precision of industrial WRUE. Liao & Dong (2011a) improved the DEA method by adding the Malmquist index, which objectively measures the relationship between technical efficiency changes, technique changes, and total factor changes (Feng *et al.* 2000; Yang & Liu 2014). Although the DEA and SFA models have been widely employed (e.g., Karagiannis *et al.* 2003; Liao & Dong (2011b)), other comprehensive evaluation models have also been applied. Feng *et al.* (2005) used a genetic algorithm to optimize the projection pursuit model to evaluate the agricultural WRUE of 81 counties in Gansu. The results accurately represent an indicator's size and relationship to comprehensive values. Wang (2010) applied an entropy-weighted model to quantitatively analyze water resources comprehensive utilization efficiency (WRCUE) in an administrative partition of the Song-Liao River Basin, and also studied the causal basis for WRUE differences among counties.

To date, previous research has mainly focused on evaluating a single industry's WRUE, and fewer studies have been conducted on WRCUE for all industries. The establishment of a WRCUE evaluation index system has received little attention, and the establishment of such a system in combination with research on comprehensive evaluation models is urgently needed. In this study, we use data regarding regenerative water resources from the *Yellow River Water Resources Bulletin*, establish a basic evaluation index group by identifying a comprehensive WRUE index for water consumption (water use that does not return to the aquatic environment, which is the water intake quantity from the water source, excluding the loss part during the process of water intake and the part returned to the river after the use of surface and underground water) by agriculture, industry, and domestic sources. We select several indexes from the basic evaluation index group to set up a comprehensive evaluation index system using the trapezoidal fuzzy mathematics method. The selection method is in part quantitative, and hence not fully dependent on experts' subjective opinions. Secondly, the WRCUE of provinces in the Yellow River Basin is evaluated using the trapezoidal fuzzy number method, thus achieving the goal of analyzing the WRUE of every single industry. Last, based on an analysis of the causes of provincial WRCUE differences, we have proposed improved measures to provide the necessary technical support to meet the strict water resource management goals for the Yellow River Basin.

STUDY AREA

The Yellow River Basin is around 35–40 degrees north latitude. The Yellow River Basin occupies an area of 752,443 km²; the multi-year average annual precipitation and evaporation are 466 and 700–1,800 mm, respectively. The Yellow River flows through nine provinces (Qinghai, Sichuan, Gansu, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces) and its water resources account for 2% of all rivers in China. The river supports 12% of the national population, 15% of the total arable land, and more than 50 large- and medium-sized cities, and the demand for water has surpassed the capacity of the river system. The watershed is located in a typical monsoon

climate area, with runoff contributed mainly by rainfall. The rainfall regime is highly seasonal and its distribution is extremely uneven, both temporally and spatially. While the average water use from 1980 to 2010 and efficiency levels in the Yellow River watershed have significantly improved in recent decades (decreasing from 6,672 m³ per 10,000 yuan GDP in 1990 to 354 m³ per 10,000 yuan GDP in 2010), the efficiency of water use in the Yellow River watershed is generally low, especially in downstream areas.

Under the influence of climate change and human activities, both the quality and quantity of water in the Yellow River Basin have experienced significant declines during the last two decades (Sun *et al.* 2013; Sun *et al.* 2014). In addition, the demand for water has dramatically increased, as has the disparity between supply and demand. Low water-use efficiency and serious water pollution have exacerbated water problems, and the development of prolonged water shortages in the Yellow River Basin will restrict industrialization and contribute to environmental degradation.

EVALUATION INDEX SYSTEM

Basic evaluation index set

More than 200 qualitative and quantitative WRUE indexes are available for various industries, and a systematic analysis of each index (which is necessary for a comprehensive evaluation) is therefore difficult. To construct an evaluative index system for WRUE, expert assessments should be used to prioritize quantitative indexes to expedite the selection of appropriate measures. Priority should be assigned to indexes that demonstrate a broad representation of various industries, and existing statistical and quantitative data should be considered. In this study, we selected three or four indexes for each industry (agricultural, industrial, domestic) as overall WRUE indexes. This set of indexes constitutes the basic evaluation index set for WRUE (see Table 1).

Construction of an evaluation index system

The impacts of different industries on WRCUE vary, and the efficiencies of some industries cannot be generalized by a single index. All indexes in the basic evaluation index set

Table 1 | Basic WRUE evaluation index set

Industries	Indexes	Codes
Overall indexes	Water consumption per unit GDP (m ³ /million dollar)	O ₁
	Comprehensive water use per capita (m ³ /per capita)	O ₂
	The elastic coefficient of total water use	O ₃
	Water resources per capita (m ³ /per capita)	O ₄
Industrial indexes	Water consumption per unit industrial value added (m ³ /million dollar)	I ₁
	The proportion of industrial use of water (%)	I ₂
	Water consumption per unit industrial output value (m ³ /million dollar)	I ₃
Agricultural indexes	Irrigation water per unit area (m ³ /ha)	A ₁
	The proportion of agricultural water (%)	A ₂
	Eliminate the climate effect on WRUE	A ₃
	Grain yield per unit irrigation water (kg/m ³)	A ₄
Domestic indexes	Domestic water use per capita (m ³ /per capita)	L ₁
	The leakage rate of urban water supply network (%)	L ₂
	The proportion of domestic water (%)	L ₃

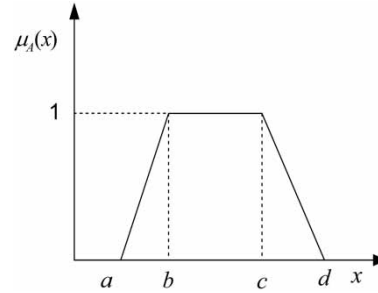


Figure 1 | Trapezoidal membership function.

number, and *a*, *b*, *c*, and *d* define the scope of the trapezoidal fuzzy number function.

$$\mu_A(x) = \begin{cases} \frac{x-a}{b-a} & a < x < b \\ 1 & b \leq x \leq c \\ \frac{d-x}{d-c} & c < x < d \\ 0 & x \leq a \text{ or } x \geq d \end{cases} \quad (1)$$

Given that the trapezoidal fuzzy number is used to solve a multi-person decision, if the decision-making weight of every decision-maker is the same, a decision is affirmed according to the following method. Given that (*D*₁, *D*₂, ..., *D*_{*n*}) are decision-makers and that (*C*₁, *C*₂, ..., *C*_{*m*}) are fuzzy evaluation indexes, the weight of every decision-maker is *R*_{*i*} = 1/*n*, where *n* is the number of decision-makers. If index *C*_{*j*} (*j* = 1, 2, ..., *m*) is evaluated by expert *D*_{*i*} (*i* = 1, 2, ..., *n*), the result is (*a*_{*ji*}, *b*_{*ji*}, *c*_{*ji*}, *d*_{*ji*}). Thus, the comprehensive fuzzy evaluation of index *C*_{*j*} by the decision-making group is given by:

$$d(C_j) = \left(\sum_{i=1}^n R_i a_{ji}, \sum_{i=1}^n R_i b_{ji}, \sum_{i=1}^n R_i c_{ji}, \sum_{i=1}^n R_i d_{ji} \right) = (a_j, b_j, c_j, d_j) \quad (2)$$

where *d*(*C*_{*j*}) is the comprehensive fuzzy evaluation of index *C*_{*j*}, *R*_{*i*} is the weight of the decision-maker (given that four experts are performing the evaluation in this study, the weight of every decision-maker is *R*_{*i*} = 0.25), and (*a*_{*ji*}, *b*_{*ji*}, *c*_{*ji*}, *d*_{*ji*}) is the fuzzy evaluation of decision-maker *i* of index *C*_{*j*} (Beaumont 2000; Tiwari & Joshi 2012).

The fuzzy weight of *C*_{*j*} is given by:

$$w_j = (a_j + b_j + c_j + d_j)/4 \quad j = 1, 2, \dots, m \quad (3)$$

are important; however, the use of all indexes in the development of an evaluation index system would create an extremely complex system, and would result in inaccuracies in the calculated results (Shchavelev 1970; Wang et al. 2008). Accordingly, we applied systematic methods to select a maximum of nine indexes from the basic evaluation index set (the Yellow River Basin includes nine provinces), and these indexes were used to construct the evaluation index system. According to this approach, the degree of importance of every index in the basic evaluation index was established as a basis for inclusion in the index system (Turayeva 2012).

Selection method

To construct the evaluation index system, a trapezoidal fuzzy number was used to select indexes from the basic evaluation index set. Given that *A* is a fuzzy set in the real number set *R*, and that *a* ≤ *b* ≤ *c* ≤ *d*, the membership function is a trapezoidal fuzzy number (Kaufman & Gupta 2012) as defined in Equation (1). The membership function is illustrated in Figure 1; μ_{*A*}(*x*) is a trapezoidal fuzzy

where w_j is the comprehensive fuzzy weight of index C_j . The fuzzy weight is then unitized, and the weighting vector of the indexes is give as:

$$w = (w'_1, w'_2, \dots, w'_m) \tag{4}$$

where w'_m is the per unit comprehensive fuzzy weight of index m and w is the weighted vector of the index (Faramarzi et al. 2009; Montazar 2013).

Selection of the results

Four experts were invited to evaluate the indexes in the basic evaluation index set using the affirmative decision-making approach based on the trapezoidal fuzzy number set, as explained above. Fuzzy words based on trapezoidal fuzzy numbers can be used to describe the relative importance of

evaluation indexes. Five fuzzy vocabularies are used in this paper, as shown in Table 2. Table 3 lists the evaluations of the four experts, and Table 4 lists the calculation results for every index in the basic evaluation index set.

Six indexes were selected from the WRUE evaluation index set using the trapezoidal fuzzy selection approach: $I_1, O_1, A_3, A_1, L_1, I_2$. Fuzzy weights and unitization weights are given in Table 4. Datasets used in the study were provided by the Yellow River Water Conservancy Commission, and are primarily from the *Water Resource Bulletin of the Yellow River Watershed* and the *Report on a Comprehensive Program for Water Resources for the Yellow River* in 2012. The six indexes can be transformed into one comprehensive index value using the model that is introduced in the next section, which provides a relatively simple approach for analyzing and comparing provincial efficiencies.

Table 2 | Fuzzy words and fuzzy numbers

Fuzzy words	Fuzzy numbers
Very low	(0, 0, 0, 3)
Low	(0, 3, 3, 5)
Medium	(3, 5, 5, 7)
High	(5, 7, 7, 10)
Very high	(7, 10, 10, 10)

EVALUATION OF WRCUE

Genetic projection pursuit model

A projection pursuit model can be used to analyze high-dimensional data. In this approach, high-dimensional data are projected into a low-dimensional subspace, and the projection values are used to represent the structure or characteristics of the high-dimensional data (Fu & Zhao 2006; Cao et al. 2010).

Table 3 | Fuzzy evaluation of the basic evaluation index set

Index (C_j)	Code	The fuzzy evaluations of experts			
		D_1	D_2	D_3	D_4
Industry	O_1	(5, 7, 7, 10)	(7, 10, 10, 10)	(5, 7, 7, 10)	(7, 10, 10, 10)
	O_2	(3, 5, 5, 7)	(3, 5, 5, 7)	(0, 0, 0, 3)	(5, 7, 7, 10)
	O_3	(3, 5, 5, 7)	(0, 3, 3, 5)	(0, 3, 3, 5)	(7, 10, 10, 10)
	O_4	(0, 0, 0, 3)	(5, 7, 7, 10)	(0, 0, 0, 3)	(5, 7, 7, 10)
Industrial indexes	I_1	(5, 7, 7, 10)	(7, 10, 10, 10)	(7, 10, 10, 10)	(7, 10, 10, 10)
	I_2	(5, 7, 7, 10)	(3, 5, 5, 7)	(0, 3, 3, 5)	(5, 7, 7, 10)
	I_3	(3, 5, 5, 7)	(5, 7, 7, 10)	(0, 3, 3, 5)	(0, 0, 0, 3)
Agricultural indexes	A_1	(5, 7, 7, 10)	(3, 5, 5, 7)	(5, 7, 7, 10)	(5, 7, 7, 10)
	A_2	(3, 5, 5, 7)	(3, 5, 5, 7)	(5, 7, 7, 10)	(3, 5, 5, 7)
	A_3	(5, 7, 7, 10)	(5, 7, 7, 10)	(7, 10, 10, 10)	(5, 7, 7, 10)
	A_4	(3, 5, 5, 7)	(3, 5, 5, 7)	(3, 5, 5, 7)	(3, 5, 5, 7)
Domestic indexes	L_1	(5, 7, 7, 10)	(7, 10, 10, 10)	(3, 5, 5, 7)	(3, 5, 5, 7)
	L_2	(0, 3, 3, 5)	(3, 5, 5, 7)	(3, 5, 5, 7)	(0, 0, 0, 3)
	L_3	(3, 5, 5, 7)	(5, 7, 7, 10)	(0, 3, 3, 5)	(0, 3, 3, 5)

Table 4 | Fuzziness and unitization results sorted by weight

No.	Index (C_j)	Fuzzy weight	Unitization weight	No.	Index (C_j)	Fuzzy weight	Unitization weight
1	I_1	8.75	0.1105	8	A_4	5.00	0.0631
2	O_1	8.25	0.1042	9	O_3	4.81	0.0608
3	A_3	7.75	0.0979	10	O_2	4.5	0.0568
4	A_1	6.69	0.0845	11	L_5	4.44	0.056
5	L_1	6.63	0.0837	12	O_4	4.00	0.0505
6	I_2	5.56	0.0702	13	I_3	3.94	0.0497
7	A_2	5.50	0.0695	14	L_2	3.38	0.0426

The projection pursuit method has been successfully applied to calculate the integrated indexes of several index systems (Wouter 1992; Howell 2000; Kotas 2006; Naim 2011). The projection pursuit method has significant advantages over other methods. We can obtain the weight based on the spatial structure of the data themselves not dependent on the subjective opinions of specialists, and the evaluation result is real-value, which is helpful to comprehensively evaluate the value and direction of every index in comprehensive evaluation. The projection pursuit model flow chart is shown in Figure 2. The modeling process consists of two steps; in the first step, the structure of the projection index function is determined, and in the second step, the projection index function is optimized (Pereira et al. 1996).

Structure of the projection index function

The index of the experience level of WRUE is given as $y(i)$, ($i = 1, 2, \dots, m$), and the standardized water resource use efficiency is given as $\{x^*(j, i) | j = 1 \text{ to } p\}$, where m is the number of samples and p is the number of indexes. The comprehensive evaluation model is developed to connect $y(i)$ and $\{x^*(j, i) | j = 1 \text{ to } p\}$, and the projection index function is given as:

$$z(i) = \sum_{j=1}^p a(j)x(j, i) \tag{5}$$

where $z(i)$ is the projection value of sample i in one dimension, $a(j)$ is the projection direction of index j , and $x(j, i)$ is the standardized $x^*(j, i)$ value. It should be noted that $z(i)$ is a one-dimensional projection value based on a p -dimensional array, $\{x^*(j, i) | j = 1 \text{ to } p\}$, with $a = [a(1) \ a(2) \ \dots \ a(p)]$ as the

projection direction (Dono et al. 2012; Chen et al. 2014). The process of calculating is the process of optimizing. We can get the best projection direction through a number of iterations and updates. That is a^* , and then putting a^* into Equation (5) again, we get the result of Table 5.

Optimization of the projection index function

The projection value $z(i)$ must extract the greatest possible variance information from $x(j, i)$; thus, the standard deviation S_z of $z(i)$ should be as large as possible (Demin 2005; Mukhammadiev 2014). At the same time, the correlation coefficient describing the relationship between $z(i)$ and $y(i)$ should be as large as possible. The optimal conditions for the solution of the projection pursuit model are given by Equations (6) and (7):

$$\max Q(a) = S_z |R_{zy}| \tag{6}$$

$$s.t \sum_{j=1}^m a^2(j) = 1 \tag{7}$$

where

$$S_z = \left\{ \frac{\sum_{i=1}^k [z(i) - E(z)]^2}{k - 1} \right\}^{0.5} \tag{8}$$

$$R_{zy} = \frac{\sum_{i=1}^k [z(i) - E(z)][y(i) - E(y)]}{\left\{ \sum_{i=1}^k [z(i) - E(z)]^2 \sum_{i=1}^k [y(i) - E(y)]^2 \right\}^{0.5}} \tag{9}$$

and where $Q(a)$ is the projection objective function of the projection pursuit model, S_z is the standard deviation of $z(i)$, R_{zy} is

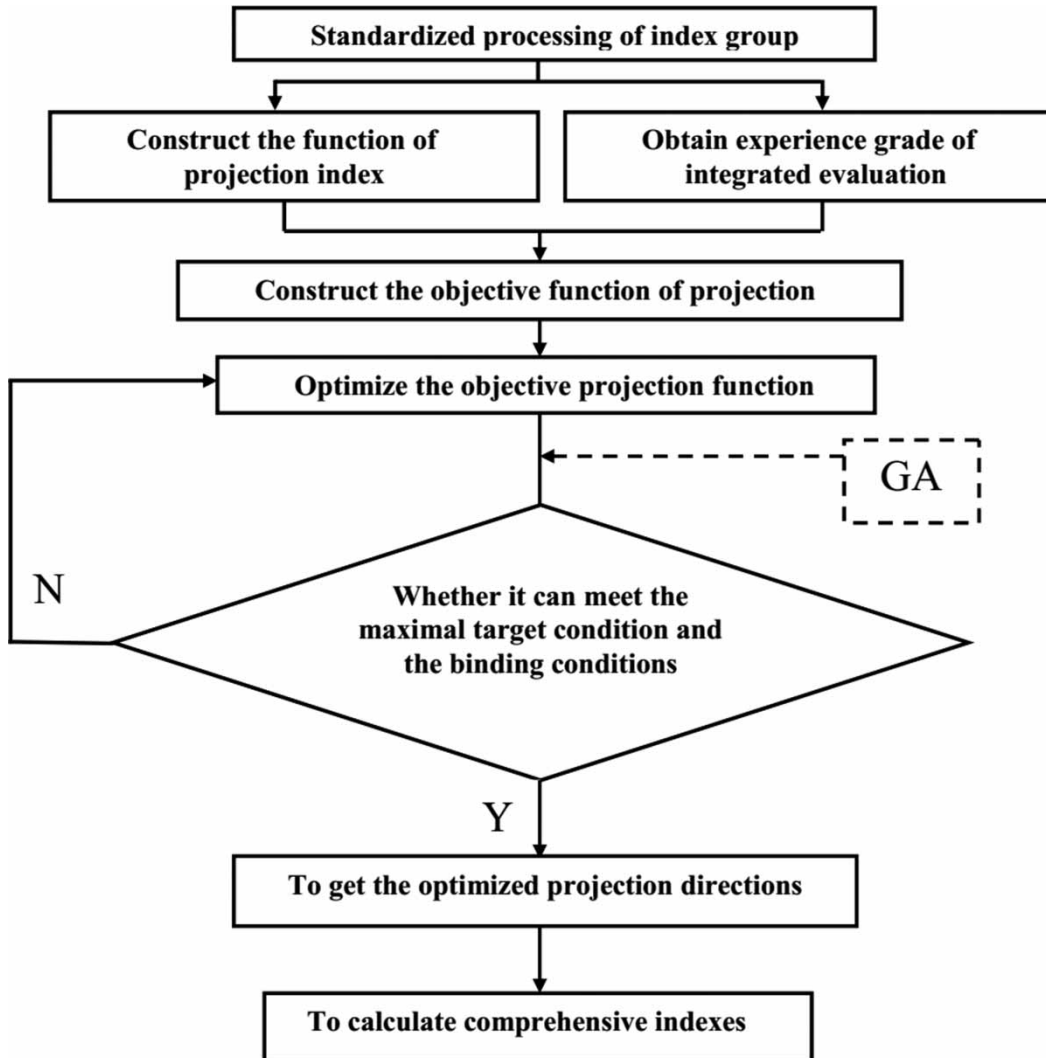


Figure 2 | Flow chart of the projection pursuit model.

the relevance coefficient of $z(i)$ and $y(i)$, $E(z)$ is the expectancy of $\{z(i), i = 1, \dots, k\}$, and $E(y)$ is the expectancy of $\{E(i), i = 1, \dots, k\}$. The solution of Equations (6) and (7) is a complex nonlinear optimization problem, which is solved using a genetic algorithm (Bo *et al.* 2000; Zeng 2005).

Evaluation of comprehensive index values for provinces of the Yellow River Basin

Cluster analysis

A comprehensive WRUE evaluation requires the empirical levels of the genetic projection pursuit model. For this

purpose, we adopted a cluster analysis method (Li 2006; Mwitondi 2012), performed using Statistical Analysis System software. Hierarchical clustering results were achieved using a group-averaging method, and the squared sum of the deviations of clusters. In Figure 3 higher levels of clustering represent lower WRUEs.

Calculation of the WRCUE

A projection pursuit model was used to calculate the index values selected from the comprehensive evaluation index system developed above. In the genetic algorithm used to optimize the model, the nonlinear function

Table 5 | The WRUE index system

Province	O_1 (m ³ /million dollar)	I_1 (m ³ /million dollar)	I_2 (%)	A_3	A_1 (m ³ /hm ²)	L_1 (m ³ per capita)
Qinghai	1,316.29	462.77	12.09	0.65	7,561.95	60.81
Sichuan	785.06	220.24	9.68	0.56	3,130.80	78.79
Gansu	1,171.39	730.87	22.46	0.79	6,649.80	45.52
Ningxia	3,038.17	487.45	6.33	0.55	14,751.15	53.01
Inner Mongolia	1,035.13	157.41	8.18	0.83	7,903.95	88.56
Shanxi	708.93	235.41	17.58	0.91	3,694.20	41.71
Shaanxi	341.90	140.29	19.82	1.08	3,497.85	42.15
Henan	564.54	250.62	26.96	0.94	3,640.05	39.06
Shandong	463.64	237.00	27.91	0.93	2,757.75	46.33
Basin average	798.74	238.71	15.18	0.84	5,925.45	47.28

**Figure 3** | Hierarchical clustering results indicating relative WRUEs at the provincial level.

$s.t \sum_{j=1}^p a^2(j) = 1$ is maximized by satisfying the nonlinear constraint $s.t \sum_{j=1}^p a^2(j) = 1$. When the projection direction is $a^* = (-0.283 -0.576 0.402 0.639 0.121 0.087)$, the maximum value of the objective function is $Q(a^*) = 0.416$.

The value of the climate effect on the WRUE elimination index (0.639) is greater than that of all the other indexes; thus, this index controls the results and direction of the projection pursuit model. The provincial WRCUEs

are shown in descending order in Table 6, with larger comprehensive values representing higher efficiencies.

The model is dependent on the numerical value to determine the weighed proportion, which avoids the error brought by subjective judgment. This model considers different indexes in which weights + means the bigger the better and in which weights - means the lower the better. The last composite index after calculation is bigger and better.

Table 6 | Provincial projection values

Rank	Province	Score	Rank	Province	Score
1	Shanxi	0.903	6	Basin average	0.417
2	Shandong	0.766	7	Sichuan	0.024
3	Henan	0.733	8	Gansu	-0.023
4	Shaanxi	0.527	9	Qinghai	-0.102
5	Inner Mongolia	0.422	10	Ningxia	-0.476

After calculation, comprehensive indexes are obtained, the bigger the better. If the fundamental databases are all the same, then we may get the wrong experience rank, which plays an important role in the projection pursuit model. In addition, the projection pursuit model is a kind of method of data compression and data feature extraction, aiming to put higher-dimensional array projections onto the low-dimensional space. If the higher-dimensional data are totally the same, it will not have difference characteristics, and the projection is insignificant.

ANALYSIS OF WRCUE DIFFERENCES AND IMPROVEMENT MEASURES

WRCUE results were divided into grade levels prior to analyzing their differences. No unified standard of classification is available for WRCUE measures, and the classification thus provides a reference for (i) the planning of water conservancy projects, (ii) water resource comprehensive programs, (iii) the development of evaluation indexes of water consumption in various provinces in the Yellow River watershed, and (iv) current national water consumption indexes in various industries. The WRCUE of provinces in the Yellow River Basin were divided into three levels based on the results in Table 6.

First-level WRCUE provinces

The WRCUE values in first-level Yellow River Basin provinces, including Shanxi, Shandong, and Henan provinces, are higher than average (i.e., greater than 0.6).

Although water efficiencies in first-level provinces are high, water-saving measures cannot be ignored. For

example, water prices can be appropriately adjusted to improve awareness of the importance of water conservation. Furthermore, industrial water-saving measures must be strengthened by reforming technologies involved in agricultural and industrial water diversion and consumption, and by appropriately introducing these technologies into these sectors.

Second-level WRCUE provinces

Second-level WRCUE provinces in the Yellow River Basin, including Shaanxi, Inner Mongolia, and Sichuan, have WRCUE values close to basin-wide averages (values greater than 0).

Second-level provinces possess rich water resources, so that water-saving measures are not heeded. Awareness of water-saving measures in these provinces should be improved, by increased publicity and adjusting industrial structures such that water sources are more reasonably allocated. Leakage rates from tap-water pipelines should be reduced and water-saving standards for water facilities should be implemented, including the addition of measures such as water taps, flush toilets, and low-flow shower heads.

Third-level WRCUE provinces

The WRCUE values in the third-level WRCUE provinces of the Yellow River Basin, including Gansu, Ningxia, and Qinghai provinces, are low (less than 0), and the potential for improvement is also low.

The above-mentioned difficulties occur throughout the western region of China, in which natural water resources are scarce and relatively undeveloped due to economic obstacles and poor management of water resources, thus leading to very low WRUEs. The management of water resources in these provinces is rudimentary, leading to the inefficient use of water resources. Effective measures must therefore be proposed and adopted in these areas. First, industrial structures must be adjusted and low productivity must be eliminated. Industries with high water consumption must be limited in these areas, and regional approval of such industries should be restricted. Second, implementation of water resource laws must be strengthened, and the laws and regulations concerning water resources should be

formulated in detail to support effective enforcement. In addition, the implementation of water resource laws and regulations must be supported by public scrutiny; the public should be granted rights to monitor and track illegal abuse of water resources.

CONCLUSION

The trapezoidal fuzzy number approach was used to select WRCUE indexes, including those for the agricultural, industrial, and domestic sectors, and for overall WRUE. The indexes were then used to construct an evaluation index system using an established basic evaluation index. The WRCUE evaluation model then identified the WRUE characteristics of provinces in the Yellow River Basin using a genetic projection pursuit method. The main conclusions are as follows:

1. According to the calculations and analysis, large discrepancies exist among the WRCUEs of different watershed provinces. The WRCUEs of Shanxi, Shandong, and Henan provinces are greater than the basin average; those of Shaanxi, Inner Mongolia, and Sichuan provinces are close to the basin average; and those of Ningxia, Gansu, and Qinghai provinces are below the average, representing very poor efficiencies in these areas.
2. Based on the causes of the different levels of efficiency in the different provinces, we have proposed targeted measures to improve WRCUEs in provinces of the Yellow River Basin, and to narrow the gap among provinces. The results of the study are of utmost importance for promoting regional economic development, water resource management, and the development of water-conservation practices in the Yellow River Basin. The study is also a driving force for a water resource development strategy and for the promotion of sustainable development in China.

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