

The spatial and temporal variation of water use efficiency in the Huai River Basin using a comprehensive indicator

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ABSTRACT

A comprehensive indicator of water use efficiency (WUE) to promote coordinated development between socio-economic and environmental systems was developed. A comprehensive consideration of the social, economic and environmental benefits of water was made in the evaluation index system of WUE and the projection pursuit model combined with chaotic particle swarm optimization was adopted to calculate the comprehensive indicator of WUE. The Huai River Basin (HRB) was selected as a case study area. The temporal change of WUE showed that the annual WUE of the HRB from 2007 to 2013 increased obviously because of the enhanced emphasis on environmental protection by the government. The spatial results showed that the spatial WUE of each province in 2013 was significantly higher than in 2007. In 2013, Anhui with the lowest WUE was selected as representative to reveal the problems of water use in the HRB. The main reasons were that the government paid more attention to the high water consumption industries and ignored the small-scale water users, and wastewater treatment was still weak in the HRB. The research can provide the foundation for improving WUE and solving the problem of water shortages.

Key words | chaotic particle swarm optimization, evaluation index system, projection pursuit model, temporal and spatial changes, water management

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INTRODUCTION

Due to changed climate conditions and intensified anthropogenic activity, water consumption continuously increases nowadays, and therefore has seriously influenced socio-economic development and the ecological environment (Haddeland *et al.* 2014). Increasing water consumption, combined with widely existing water problems such as the irrational utilization of water resources, is believed to aggravate water shortages and could finally result in many other water-related problems. As a result, the concern of water management has turned to how to use existing water resources more effectively. Therefore, the improvement of water use efficiency (WUE) becomes an important way to support the sustainable utilization of water resources (Zoehl 2006).

How to quantitatively evaluate WUE is considered as the preliminary step of efficient water resources management. The existing methods of WUE evaluation can be broadly divided

into two classes: the single industry evaluation method and the comprehensive evaluation method considering multiple industries. In the first method, more attention has been paid to agricultural WUE. Some evaluation indexes, such as the irrigation efficiency index (Lankford 2006; Perry 2007) and the water productivity index (Ali & Talukder 2008), have been proposed. Furthermore, with the development of industrialization in recent years, industrial water consumption has increased, and the evaluation of industrial WUE has focused on the water consumption of industrial output (Guo & Fu 2010) and industrial wastewater reclamation (Vourch *et al.* 2008; Yi *et al.* 2011) has attracted more interest.

Molden & Sakthivadivel (1999) indicated that the estimation of WUE should consider multiple industries, which could reflect water consumption in various ways such as water for production, living and also the

ecosystem. The comprehensive evaluation methods of WUE can be generally grouped into three classes: data envelopment analysis (DEA), stochastic frontier analysis (SFA), and the evaluation index system method. The DEA method is a frontier estimation technique developed by Charnes *et al.* (1985), which is based on the mathematical procedure of using linear programming dealing with multiple inputs and outputs to determine the efficiency scores of decision-making units (Hu *et al.* 2006). DEA is simple in operation and does not need massive sample data; however, this method applies with the assumption that no random errors exist in the samples, and the computational accuracy will be seriously affected when random errors exist. SFA is a non-radial, input-oriented measure of input-specific technical efficiency (Karagiannis *et al.* 2003). The production function is established to reflect the relationship between the input resources and output return, and mathematical methods are used to estimate the parameters in the function. SFA explicitly recognizes that each system could be technically inefficient for several reasons that can be explored through statistical methods (Alsharif *et al.* 2008). However, this measure assumes that the production function and the error term will reduce the effectiveness of parameter estimation. DEA and SFA have been widely used in the evaluation of WUE in China (Hu *et al.* 2006), South Africa (Stijn *et al.* 2008), Pakistan (Alsharif *et al.* 2008), Tunisia (Dhehibi *et al.* 2007), etc.

The evaluation index system method consists of two steps: the determination of the evaluation index system and the computation of the comprehensive indicator. The evaluation index system method is flexible because the evaluation index system can be structured according to different requirements. Yang (2009) suggested that a comprehensive evaluation index system should contain all of the indicators related to the WUE, including the agricultural, industrial, domestic, and environmental indexes. However, in most cases, the environmental indexes are rarely used because of the difficulty in collecting the corresponding data.

After the determination of the evaluation index system, the next step is the estimation of the weight of each index to quantify its effect on the WUE. Many weight estimation models have been used such as analysis hierarchy process,

entropy weight, and projection pursuit. However, the projection pursuit (PP) model is regarded as one of the most effective methods. In general, an optimization algorithm should be used along with the PP model provided that the solution of the PP model is a complex nonlinear programming problem. The genetic algorithm is a common way to solve the PP model (PP-GA model). The PP-GA model has been successfully applied to estimate the comprehensive indicator in various areas (Montanari & Lizzani 2001; Fu *et al.* 2002; Zhang & Dong 2009). Feng *et al.* (2005) considered that this model could give an appropriate assessment of WUE and they were the first to apply the PP-GA model in the evaluation of WUE. Gao *et al.* (2013) also used the PP-GA model to evaluate China's WUE, and found that the WUE in China revealed obvious territorial characteristics and regional differences. Water was used more efficiently in regions with higher water shortage stress or an advanced economy.

To the best of our knowledge, previous research on WUE has mainly focused on the evaluation of a single industry's WUE, and only a few studies have been conducted on comprehensive WUE with the consideration of several industries. Furthermore, few studies have been concerned with the evaluation of WUE in the Huai River Basin (HRB) (Ji & Zhang 2009; Zhang *et al.* 2013), and the existing studies have mainly concentrated on evaluating a single industry or have not considered comprehensively various industries. In addition, although the social and economic benefits of water resources were often considered in the previous evaluation index system, the environmental benefits were usually ignored. However, the environment and ecology are affected by the exploitation and utilization of water and also closely related to the water cycle and regeneration, so the environmental benefits of water cannot be simply ignored in the WUE evaluation (Chen & Du 2008). In this study, the evaluation index system method was adopted. We proposed a comprehensive indicator which was a comprehensive evaluation result of overall, agricultural, industrial, domestic, and environmental WUE. The evaluation index system that we established considered not only the social and economic benefits but also the environmental benefits of water. Then, the comprehensive indicator was computed using the PP model. The common way to solve the PP model was by particle swarm algorithm. In

order to prevent the particles' premature phenomenon, we added a chaos optimization to the particle swarm algorithm. The HRB was selected as a case study. The temporal and spatial changes of WUE in the HRB were analyzed in our study to better understand the variations of WUE.

METHODS

Structure of the evaluation index system

In this study, the evaluation index system of WUE was determined with a comprehensive consideration of the social, economic and environmental benefits of water. In detail, the social and economic benefits of water contained four index categories that were commonly used in the previous studies, including the overall, agricultural, industrial and domestic indexes.

On the other hand, four environmental indexes were also selected. Chemical oxygen demand (COD) and $\text{NH}_3\text{-N}$ are the major water quality assessment indexes in the HRB recommended by the Chinese government (Zhai *et al.* 2014; Xia & Chen 2015). So the two indexes, the Ratio of COD Discharges and Its National Discharges Standard (E1) and the Ratio of $\text{NH}_3\text{-N}$ Discharges and Its National Discharges Standard (E2), were selected. In 2005, 'the Suggestion to Limit the Total Pollutant Discharges in the HRB' given by the Huai River Commission of the Ministry of Water Resources published the policy that the discharge standards of COD and $\text{NH}_3\text{-N}$ were 382 and 27×10^3 ton/yr. It was important to consider not only the major pollutants, but also the overall

pollution situation. The two indexes, Dilution Ratio (E3) and Qualified Ratio of Water Functional Areas (E4), could reflect that. E3 was a ratio of sewage discharges to runoff. The water functional area is a typical concept defined by the Ministry of Water Resources of the People's Republic of China and frequently used in Chinese water resource management. Generally speaking, it refers to a specific area with the consideration of the water resources to satisfy the requirement of socioeconomic development and eco-environment in the aspect of considering both water quantity and quality. According to water quality conditions, rivers and lakes were classified in four broad categories (protection water areas, storage water areas, development and utilization water areas, and water areas at the junction of provinces) for different usage purposes. Each broad category was also classified into several minor sorts. All of the waters in a basin were divided into many water functional areas. Different water functional areas corresponded to different water quality requirements. If the water quality of a water functional area fell short of the requirements, the water functional area was unqualified. E4 was a ratio of the number of qualified water functional areas to the total number of water functional areas in a region.

The detailed description of the selected ten indexes is given in Table 1. In the fourth column of Table 1, the symbol '+/-' means a positive/negative correlation between the index value and the WUE.

PP model with chaotic particle swarm optimization

The basic idea of the PP model is to project data from high-dimensions to low-dimensions according to the projection

Table 1 | The evaluation index system of WUE

Criterion layer	Categories	Index layer	Property	Code
Social and economic benefits	Overall	Water Consumption per Unit GDP ($\text{m}^3/\text{million dollars}$)	-	O1
		Irrigation Water per Unit Area (m^3/m^2)	-	A1
		Grain Output per Unit Water (kg/m^3)	+	A2
	Industrial	Water Consumption per Unit Industrial Added Value ($\text{m}^3/\text{million dollars}$)	-	I1
		Domestic	Urban Domestic Water Consumption per Capita ($\text{m}^3/\text{per capita}$)	-
	Rural Domestic Water Consumption per Capita ($\text{m}^3/\text{per capita}$)		-	D2
Environmental benefits	Environmental	Ratio of COD Discharges and Its National Discharges Standard	-	E1
		Ratio of $\text{NH}_3\text{-N}$ Discharges and Its National Discharges Standard	-	E2
		Dilution Ratio (%)	-	E3
		Qualified Rate of Water Functional Areas (%)	+	E4

directions with regard to the projection indicator function and projection objective function, and to find out the best group of projection directions by optimizing the projection objective function. Because there are many groups of projection directions during the course of mapping from high-dimensional space to low-dimensional space, the group of projection directions which can make the projection objective function reach the maximal value is the best. Solving the PP model is a complex nonlinear programming problem, so chaotic particle swarm optimization (CPSO) is used to solve this problem (Liu et al. 2005; Hong 2009). The computational process of the PP-CPSO model is shown in Figure 1.

The main steps of the PP-CPSO model are as follows (Fu et al. 2002; Zhang & Dong 2009):

(i) Structure the projection indicator function

Assume that $x^{*(j,i)}$ is the standardized value of the index j of sample i ($i = 1 \sim n, j = 1 \sim p$), where n is the number of samples and p is the number of indexes, as the input values of the PP-CPSO model. Suppose $a = [a(1), a(2), \dots, a(p)]$ are p -dimensional projection directions. In order to convert the p -dimensional $x^{*(j,i)}$ onto a 1-dimensional projection value $z(i)$ with $a = [a(1), a(2), \dots, a(p)]$ as the projection directions, the following formula should be used:

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

(ii) Structure the projection objective function

In order to find the structural characteristics of n groups of indexes, numerous groups of projection directions are randomly generated, and we can get the best group of projection directions through a number of updates by the CPSO method. The optimal projection directions were equivalent to the weights of indexes. The projection objective function is the optimization target. The projection value $z(i)$ must extract the greatest possible variance information from $x^{*(j,i)}$; thus, both the standard deviation S_z of $z(i)$ and the correlation coefficient between $z(i)$ and the experience evaluation levels $y(i)$ should be as large as possible. Therefore, the projection objective function is given by Equation (2) and the restricted condition of Formula (3) should be as close to 1 as possible:

$$\text{Objective function: } \max Q(a) = S_z |R_{zy}| \tag{2}$$

$$\text{Restricted condition: } \sum_{j=1}^p a^2(j) \rightarrow 1 \tag{3}$$

(iii) Optimize the projection objective function

The best group of projection directions (weights) is obtained by optimizing the projection objective function. This is a complex nonlinear programming problem, so the CPSO method is used to solve it. Firstly, the projection directions are randomly generated and optimized by the particle swarm algorithm and the fitness values of the particles are

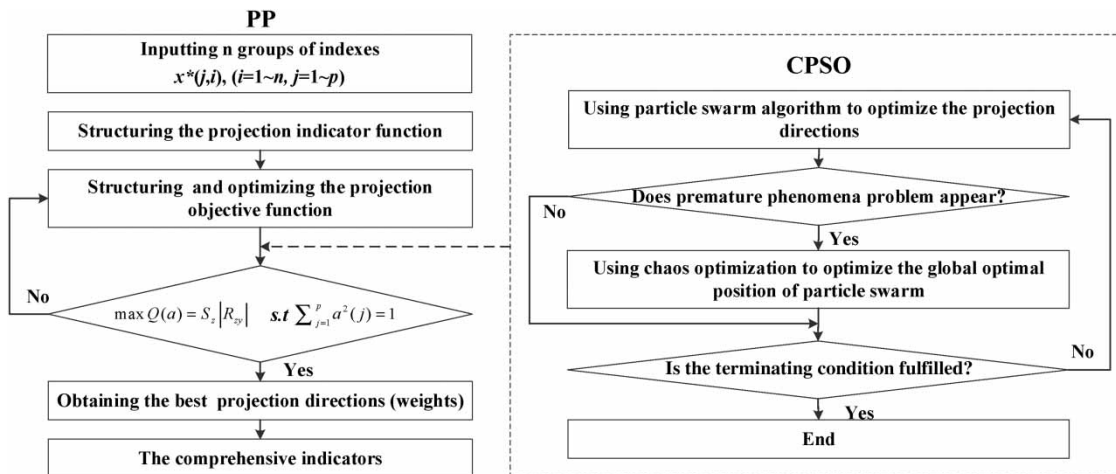


Figure 1 | The flowchart of the PP-CPSO model.

calculated. Then, the fitness variances are judged whether or not the particle cluster appears. If the premature phenomenon appears, the chaos algorithm is used to update the global optimal position. The best group of projection directions is obtained by massive iterations using particle swarm optimization. With the best group of projection directions (weights), Function (1) is used to calculate each sample's comprehensive indicator. The higher the comprehensive indicator is, the higher the WUE is.

STUDY AREA AND DATA

The Huai River, located in eastern China between $30^{\circ}55' - 36^{\circ}36'N$ and $111^{\circ}55' - 121^{\circ}25'E$, flows through five provinces (Hubei, Henan, Anhui, Jiangsu, and Shandong) in China with a total length of about 1,000 km and a drainage area of about 270,000 km² (Figure 2) (She et al. 2016). Due to rapid population growth and economic development, the Huai River has become a highly developed and polluted river. From Table 2, four provinces had the similar land-use situation in that cultivated land was the main land-use type (about 70%) and the unused

land was almost 0%. There was little difference between 2005 and 2010 in that the percentage of cultivated land had a bit of decline and the rural and urban settlements expanded unceasingly. Since 1949, more than 11,000 dams and floodgates have been constructed. Although these dams and floodgates have contributed to flood control and water supply, heavy development of water resources has caused serious water pollution. The HRB has become the most heavily polluted basin in China. The water quality in more than 83% of rivers in the basin cannot reach the national standard. The water quality in the main stream is relatively better than that in the tributaries. The water pollution of the northern tributaries in the densely populated areas or the areas agricultural concentration is very serious, especially in the Shaying and Wo Rivers. Therefore, the improvement of the WUE is regarded as an important approach to solving the water problem in this area.

In this study, the evaluation of the WUE during the time period of 2007 to 2013 is considered in the HRB. The social and economic data used were collected from the Water Resources Bulletin of the HRB and the Provincial Statistical Yearbook of Henan, Jiangsu, Anhui, and Shandong. The

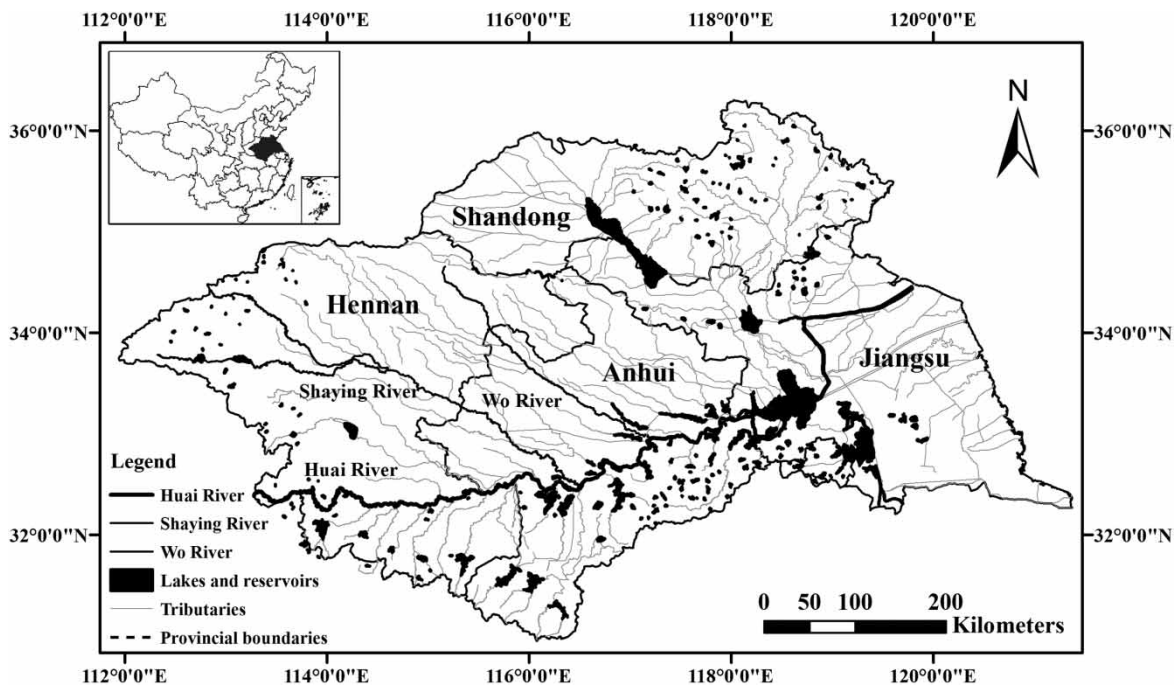


Figure 2 | Map of the HRB.

Table 2 | The percentages taken by corresponding land-use types in 2005 and 2010 (unit: %)

Land-use types	Henan		Anhui		Jiangsu		Shandong	
	2005	2010	2005	2010	2005	2010	2005	2010
Cultivated land	76.0	75.5	74.6	74.4	73.9	73.1	70.5	69.5
Forested land	10.0	10.1	7.5	7.6	2.1	2.1	5.4	5.3
Grass land	2.1	2.0	4.6	4.5	1.1	1.0	9.3	9.2
Water body	1.9	2.1	3.4	3.4	9.8	9.9	4.2	4.4
Rural and urban settlements	10.0	10.3	9.9	10.1	13.1	13.8	10.3	11.2
Unused land	0.0	0.0	0.0	0.0	0.0	0.0	0.4	0.4

sewage discharge data for Shandong, Henan, Anhui and Jiangsu provinces was also collected from the Water Resources Bulletin of the HRB. In addition, the water quality data including $\text{NH}_3\text{-N}$ and COD was provided by the monitoring center of the Huai River Water Resources Protection Bureau through long-term monitoring. The 1:100,000 digital land-use data was obtained from the Institute of Geographic Sciences and Natural Resources Research, the Chinese Academy of Sciences.

RESULTS AND DISCUSSION

Temporal change of the comprehensive WUE indicators of the HRB

The PP-CPSO model was used to calculate the annual comprehensive WUE indicators of the whole basin from 2007 to 2013. The comprehensive indicator of WUE was a relative

value. An annual comprehensive indicator that was greater than the average of many years meant a higher WUE. The annual comprehensive indicators could reflect the trend of WUE change as well. Table 3 provides the values and calculated weights of ten indexes in the evaluation index system. The variation of the annual WUE is shown in Figure 3.

From Figure 3, it can be found that the annual WUE increased obviously from 2007 to 2013, and it was more sensitive to E2 (with weight of -0.643) and I1 (with weight of -0.369) provided that the two indexes had higher absolute weights. The reasons for the change were analyzed to support river basin management. Both E2 and I1 showed a decreasing trend, which means that the $\text{NH}_3\text{-N}$ discharge has decreased and the industrial WUE has increased. Firstly, the control of pollutant discharges has become more and more strict. The discharge standards of COD and $\text{NH}_3\text{-N}$ had been reduced from 466×10^3 and 91×10^3 ton/yr in 2003 to 382×10^3 and 27×10^3 ton/yr in 2005, respectively,

Table 3 | The values and weights of indexes in the evaluation index system of temporal change

Indexes	2007	2008	2009	2010	2011	2012	2013	Weights
O1 ($\text{m}^3/\text{million dollars}$)	16.19	13.45	12.53	10.03	8.64	7.25	6.23	-0.109
A1 (m^3/m^2)	0.38	0.40	0.40	0.44	0.42	0.39	0.41	-0.09
A2 (kg/m^3)	5.48	4.93	4.74	4.91	4.99	5.49	5.70	0.287
I1 ($\text{m}^3/\text{million dollars}$)	7.13	4.77	4.26	3.24	2.88	2.37	2.20	-0.369
D1 ($\text{m}^3/\text{per capita}$)	42.81	43.00	43.14	41.10	42.56	43.03	43.22	-0.115
D2 ($\text{m}^3/\text{per capita}$)	23.24	23.00	23.55	24.69	42.81	42.81	25.19	-0.316
E1	1.92	1.38	1.44	1.31	1.27	1.27	1.13	-0.263
E2	3.00	2.49	2.63	2.50	2.09	1.70	1.55	-0.643
E3 (%)	4.68	4.49	5.06	5.40	5.38	5.41	5.45	-0.214
E4 (%)	36.30	42.40	46.70	49.22	50.00	52.87	54.60	0.349

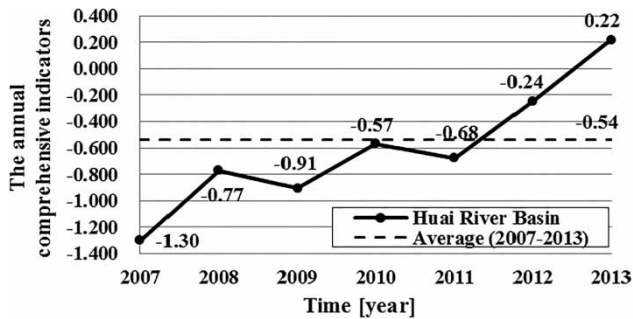


Figure 3 | The temporal change of the annual comprehensive indicators of WUE of the whole basin.

in the HRB. Because of the mandatory requirements of the policies, the COD and $\text{NH}_3\text{-N}$ discharges in the HRB had been effectively controlled. Secondly, the concept of ‘harmony between human and water’ has been enhanced. For the sustainable use of water resources and the virtuous circle of aquatic ecosystems, the state departments, basin management organizations, scientific institutes, and enterprises have done a lot of work including optimizing water allocation, strengthening ecological construction, improving the technologies of water use and so on. The improvement of WUE in the HRB depends on the efforts of all industries. Especially, the industrial WUE has been improved significantly by increasing investment in water-saving technology for the treatment of wastewater.

Spatial change of the comprehensive indicators of the provinces in 2007 and 2013

The years of 2007 and 2013 were selected to reveal the spatial variations. It should be noted that the spatial results could not be compared with the annual results because the samples for

spatial calculation were provinces in 2007 and 2013, and the results could only reflect the spatial differences. The spatial comprehensive indicator of each province greater than the whole basin level meant a more efficient WUE. The spatial comprehensive indicators of the provinces in 2007 and 2013 are shown in Figure 4. The results shows that the WUE of each province in 2013 was significantly higher than in 2007, and the I1 (with the weight of -0.509) and E4 (with the weight of 0.401) had the greatest influence on the spatial WUE (Table 4). In 2007 and 2013, the WUE of Shandong was the highest, followed by Henan. In 2007 Jiangsu was the smallest, but in 2013 Anhui was the worst and only Anhui was less than the whole basin level. Although the WUE of Anhui had been increased from 2007 to 2013, the increase of WUE in Anhui was slower than other provinces.

The reasons why the WUE of Anhui was lower were analyzed to reveal the problems of water use in the whole basin. Although the industrial WUE of Anhui was increasing significantly (in Figure 5, the I1 of Anhui shows a significant decrease), the I1 of Anhui was about 59% higher than the whole basin level in 2013, which shows that the industrial WUE of Anhui was still at a lower level. After years of development, a complete industrial system with a reasonable management system, advanced technologies, and good collaborations among departments and enterprises had been basically constructed in Anhui, but heavy industry was still the predominant part of industrial structure (about 59% in 2013), which consumed large amounts of water and produced more wastewater. Moreover, there were many medium and small industrial enterprises (the percentage of medium and small enterprises was higher than 60% in Anhui), but their distribution was scattered and it was hard to produce scale benefit.

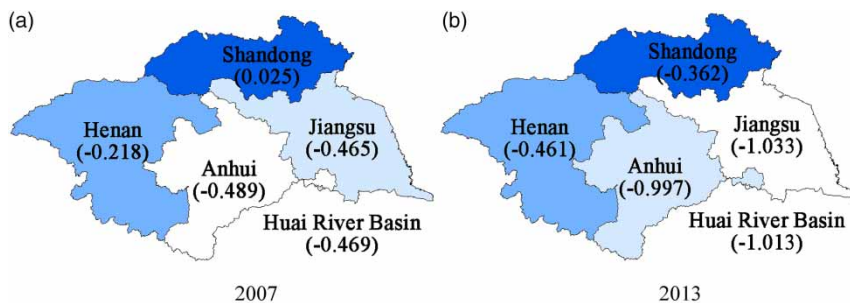
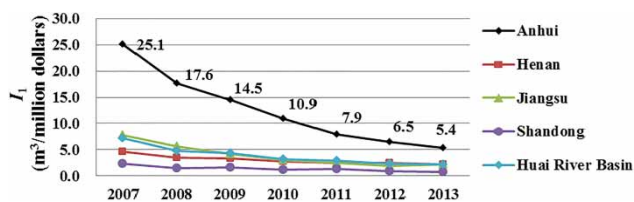


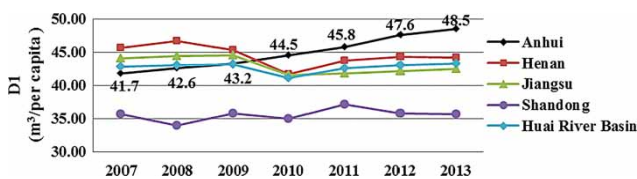
Figure 4 | The spatial comprehensive indicators of the provinces in 2007 and 2013.

Table 4 | The weights of indexes in the evaluation index system of spatial change in 2007 and 2013

Indexes	Weights	Indexes	Weights
O1 (m ³ /million dollars)	-0.297	D2 (m ³ /per capita)	-0.255
A1 (m ³ /m ²)	-0.158	E1	-0.197
A2 (kg/m ³)	0.287	E2	-0.243
I1 (m ³ /million dollars)	-0.509	E3 (%)	-0.264
D1 (m ³ /per capita)	-0.398	E4 (%)	0.401

**Figure 5** | The change trends of the I1 index of the HRB and its provinces from 2007 to 2013.

On the other hand, the D1 of Anhui continued to increase (Figure 6), which showed that the government of Anhui did not give enough support for domestic WUE. In 2009, the leakage rate of the urban water supply network of Anhui reached 23%, and was much higher than the national average (15%). The phenomenon was not just for Anhui, but for the whole HRB. The government paid more attention to the high water consumption industries, such as the agricultural irrigation system and large-scale industrial enterprises. However, the management of low water consuming sectors has been largely ignored, such as urban or rural domestic water supply systems. Additionally, compared with developed countries, the construction of wastewater treatment plants has lagged far behind and many technologies of wastewater treatment are still not advanced. According to the notice of the state council, in 2010 the national average wastewater treatment ratio was 77.5%, but the usage of reclaimed water was less than

**Figure 6** | The change trends of the D1 index of the HRB and its provinces from 2007 to 2013.

10% (The Central People's Government of the People's Republic of China 2012), because the quality of wastewater after treatment was still poor and could not be drunk or used. Although domestic water was a lower percentage of total water consumption, it could not be ignored.

CONCLUSIONS

This paper structured the evaluation index system of WUE including the overall, agricultural, industrial, domestic and environmental index categories. The evaluation index system not only considered the social and economic benefits, but also the environmental benefits of water. The PP model with CPSO algorithm was used to calculate the weights of the indexes and obtain the annual and spatial comprehensive indicators. In the temporal change analysis, the annual comprehensive indicators of the whole basin increased from -1.30 in 2007 to 0.22 in 2013. More emphasis on environmental protection by the state was the main reason for the increase in WUE. In spatial difference analysis, the PP-CPSO model was used to calculate the spatial comprehensive indicators of the provinces in 2007 and 2013. The WUE of each province in 2013 was significantly higher than in 2007. In 2013, Anhui was the worst, and only Anhui was less than the whole basin level. Anhui was selected as representative for analysis to reveal the problems of water use for the whole basin. There were two main reasons: (1) the government paid more attention to the industries that use lots of water, while ignored the management of small-scale water users; and (2) compared with developed countries, the construction of wastewater treatment plants has lagged far behind and the quality of wastewater after treatment has still been poor because many technologies are not advanced. In the future, the government and enterprises should perfect the management of and improve the technologies for the sustainable utilization of water resources.

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