Spatial differences and influencing factors of regional agricultural water use efficiency in Heilongjiang Province, China
Zhang Xiangda and Zhu Shuai

ABSTRACT
Improving the water use efficiency in agriculture is an important way to solve the problem of water shortage in agricultural areas and to improve the efficiency of water resource utilization. An evaluation indicator system of regional agricultural water use efficiency was constructed using data from 13 cities in Heilongjiang Province from 2013 to 2015. In addition, the comprehensive ranking of agricultural water use efficiency in each year was obtained by using an iterative combination method to correct the evaluation of individual models, including the analytic hierarchy process, matter element model and projection pursuit model (PPM). The results showed that the agricultural water use efficiency in Heilongjiang Province exhibited some regional differences in the 3 years evaluated spatially. And then, factors that influenced agricultural water use efficiency were analysed according to various criteria, and the rankings of cities and strategies were proposed to improve the agricultural water use efficiency according to this analysis. The results of the present study will have important theoretical and practical significance for guiding the scientific and rational formulation of agricultural water use strategies and improving the efficiency of agricultural water use in Heilongjiang Province.

Key words | agricultural water use efficiency, Heilongjiang Province, influencing factors, spatial differences

INTRODUCTION
With the rapid socio-economic development and population growth, water consumption is also constantly increasing. The issue of water shortage has become increasingly prominent and a focus of attention worldwide. Although the total amount of water resources in China is abundant, the water resources per capita is only approximately 25% of the world average (Cao et al. 2017). As a major source of water consumption, agriculture accounts for 60% to 80% of the total water consumption. However, the extensive agricultural water use in China is inefficient. The irrigation efficiency in China is only 0.51, which is far below the efficiency in other more advanced countries, resulting in serious waste of agricultural water resources (Yonts et al. 2018). According to statistics, in Shandong Province and Heilongjiang Province, the productivity of agricultural water was only 0.002 and 0.0015 kg per m³ of water in 2015, which was far below the world’s advanced level of 0.004 kg/m³ (Geng et al. 2017). In this context, actively practicing water-saving agriculture to improve the efficiency of agricultural water use is the key to ensuring agricultural production and regional and national food security while achieving sustainable utilization of agricultural water resources.

Many studies have been conducted on agricultural water use efficiency. Liu et al. used the CGE (computable general equilibrium) model to study the pattern of changes in agricultural water use efficiency in Zhangye City. They noted that...
improving the technology could effectively improve the efficiency of agricultural water use (Liu et al. 2017). Mu et al. (2016) adopted the data envelopment analysis (DEA) model to study the time pattern of agricultural water use in Shanxi Province, and the result showed that the agricultural water use efficiency in Xi’an increased from 2004 to 2012. Battese & Coelli (1995) used the SFA model to study the efficiency of agricultural water use in India. Ejaz et al. (2011) studied strategies to improve agricultural water use efficiency in Pakistan from the perspective of the physiological needs of plants. Akram & Mendelsohn (2017) studied a strategy to improve agricultural water use efficiency in Pakistan from the perspective of transport efficiency of water channels. The above studies analysed, from different perspectives, the spatial distribution of agricultural water use and the strategies to improve agricultural water use efficiency. However, most of the studies focused on the DEA model (Wang et al. 2015; Deng et al. 2016; Fu et al. 2017) and placed an emphasis on watershed or national scales (Fishman et al. 2015; Adhikari et al. 2016). Research at the city scale, as well as comparisons and combinations of different methods, is lacking. Meanwhile, the lack of environment-relevant indicators in the evaluation indicator system for characterizing the environment also makes evaluation results less practical and less feasible.

Heilongjiang Province is an important commodity grain production base in China; the total grain output reached 68.4 billion kg, the total amount of water reached 35.3 billion m³ and the total amount of agricultural water was 31.4 billion m³ in 2016, which accounted for 88.99% of the total amount of water. This proportion was far more than the national average of 62.4% of China. Meanwhile, Heilongjiang Province faces serious waste of water in agriculture and the irrigation water use efficiency is low, only about 0.50, which is lower than the national average of 0.53 of China. Therefore, to solve the above problems and in order to improve the irrigation water use efficiency, we proposed an agricultural water use efficiency evaluation indicator system based on environmental constraints imposed by the actual situation of the study region. This environmental-constraint-based, hybrid, evaluation model for regional agricultural water use efficiency was established through comparing and then combining the results of the analytic hierarchy process (AHP), matter element model (MEM) and projection pursuit model (PPM). Then, we analysed the spatial distribution differences and influencing factors of regional agricultural water use efficiency to provide technical support for the improvement of agricultural water use efficiency in the study area.

**MATERIALS AND METHODS**

**Agricultural water use efficiency evaluation indicator system**

Agricultural water resources refer to the water resources required for normal growth and sustenance of the life of crops throughout the agricultural production process. The major water consumption in agriculture is irrigation, accounting for more than 90% of the total agricultural water resources consumption (Song et al. 2018). Therefore, the present study mainly focuses on water use efficiency in agricultural irrigation because irrigation not only involves fields but also links factors such as water conveyance, water distribution and water circulation inside crops. Therefore, the environment-constrained indicator system of regional agricultural water use efficiency evaluations was constructed using scientific, independent, representative and quantifiable principles and considering the data availability and objectivity, as shown in Figure 1.

**Hybrid evaluation of agricultural water use efficiency with iterative correction**

When evaluating agricultural water use efficiency, different methods could generate different results. To effectively reduce the error among evaluation methods and generate consistent results for the same object regardless of the method used, different evaluation results can be combined and sorted using Spearman’s rank correlation coefficient (Hui-Mean et al. 2018) and using methods such as the mean value method (Liu 2007), Copeland method (van den Brink & Robert 2003) and Board method (Walter et al. 2017) until the standard deviation (SD) of results from the different evaluation methods converges to 0. The specific steps are indicated as follows.

**Step 1**: Use an individual evaluation method to evaluate the agricultural water use efficiency in Heilongjiang Province. In this paper, we use the AHP (Sun et al. 2017), MEM (Bin
et al. 2012) and PPM (Liu et al. 2018) to obtain different
evaluation results and rankings.

Step 2: Calculate the correlation coefficient of the evaluation results from different methods and test the significance of the correlation coefficient. If significant, then the results of the three methods are consistent with one another and can be corrected iteratively.

Step 3: Use the mean value method, Copeland method and Board method to comprehensively assess the evaluation results of the above three methods and rank them.

Step 4: Repeat Step 2, and if the test for significance is passed and the SD among the different evaluation results is close to 0 or less than a given minimum, then the result is final; otherwise, repeat Step 3.

Data sources

The data of the agricultural water use efficiency evaluation indicator system were collected for 13 cities in Heilongjiang Province from 2013 to 2015. The data sources mainly included Bulletin of Water Resources of Heilongjiang Province (2013–2015), Comprehensive Statistics of Water Conservancy of Heilongjiang Province, 2014–2016 Statistical Yearbook of Heilongjiang Province, Annual Report on Environmental Statistics of Heilongjiang Province (2013–2015), and survey data of municipal water authorities from various cities. To eliminate the effect of dimensional differences among the different data, the original data were initialized before the evaluation using the following formula.

For indicators that optimize towards greater value:

\[ x(i, j) = \frac{x'(i, j) - x_{\text{min}}(j)}{x_{\text{max}}(j) - x_{\text{min}}(j)} \]

For indicators that optimize towards lower value:

\[ x(i, j) = \frac{x_{\text{max}}(i, j) - x'(i, j)}{x_{\text{max}}(j) - x_{\text{min}}(j)} \]

where, \( x_{\text{max}}(j) \) and \( x_{\text{min}}(j) \) are the maximum and minimum values of the \( j \)th indicator, and \( x(i, j) \) is the normalized indicator value sequence.

RESULTS AND ANALYSIS

Analysis of evaluation results by individual methods

The agricultural water use efficiency of 13 cities in Heilongjiang Province from 2013 to 2015 were evaluated using
AHP, MEM and PPM. The scores and evaluation results are shown in Table 1.

Table 1 shows that differences exist in the evaluation results among the different years and different evaluation methods. For example, for Suihua City, the rankings of year 2013, when evaluated by three different methods, were No. 8, No. 9 and No. 4. Therefore, the different evaluation results need to be unified, and the correlation coefficients between the three methods for the 3 years should be calculated.

\[
R_{2013} = \begin{pmatrix}
1.000 & 0.9989 & 0.8681 \\
0.9890 & 1.0000 & 0.8407 \\
0.8681 & 0.8407 & 1.0000
\end{pmatrix}
\]

\[
R_{2014} = \begin{pmatrix}
1.000 & 0.7143 & 0.6923 \\
0.7143 & 1.0000 & 0.9725 \\
0.6923 & 0.9725 & 1.0000
\end{pmatrix}
\]

\[
R_{2015} = \begin{pmatrix}
1.000 & 0.7088 & 0.9066 \\
0.7088 & 1.0000 & 0.7637 \\
0.9066 & 0.7637 & 1.0000
\end{pmatrix}
\]

For a significance level of 0.01, the correlation coefficient significance threshold table shows \( R_{0.01} = 0.6410 \). This result indicates that the evaluation results obtained by the three methods were well correlated with one another; that is, the evaluations of the different methods were consistent with one another and could be combined using the iterative correction method.

**Iterative correction and spatial distribution of agricultural water use efficiency**

After the calculation, analysis and two iterations of correction, the SD of each year converged to zero. The evaluation results of the different methods were the same. The specific results are shown in Table 2.

According to the above evaluation results, the rankings were divided into five categories: 1–2 as high, 3–5 as medium high, 6–7 as medium, 8–10 as medium low and 11–13 as low. The map of the agricultural water use efficiency evaluation (2013–2015) of Heilongjiang Province was plotted and is shown in Figure 2.

As shown in Figure 2, in 2013, the agricultural water use efficiency of Heilongjiang Province showed some regional...
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differences, certain degrees of clustering in small areas and no significant overall clustering. Greater Khingan and Yichun, where agricultural water use efficiency was high, showed no direct spatial linkage between them and seemed to be isolated in the distribution map. Jiamusi City, Hegang City and Shuangyashan City, where agricultural water use efficiency was at the medium high level, were spatially adjacent. Jixi City and Heihe City, where agricultural water use efficiency was at the medium level, were spatially isolated. Suihua and Daqing, areas with medium-low agricultural water use efficiency, were adjacent to each other, whereas Qitaihe was isolated. For low agricultural water use efficiency cities, Harbin and Mudanjiang City were spatially adjacent to each other, whereas Qiqihar was spatially isolated. These results show that the spatial association of areas with various agricultural water use efficiency levels was weak. In addition, the spatial distribution of agricultural water use efficiency showed a certain degree of zonal characteristics. The agricultural water use efficiency was low in the south but high in the north. The agricultural water use efficiency in Heilongjiang Province in 2014 was different from that in 2013. However, the water use efficiency showed some clustering at a smaller scale; Shuangyashan City, Jixi City and Mudanjiang City had low water use efficiency, whereas the overall clustering characteristics were not significant. From a regional perspective, Daqing’s water use efficiency changed from the medium-low level in 2013 to the high level in 2014, while Hegang changed from the medium-high level in 2013 to the medium-low level in 2014; Suihua also changed from the medium-low level in 2013 to the medium-high level in 2014. For the rest, only Harbin’s agricultural water use efficiency remained at a low level. In addition, the spatial distribution of agricultural water use efficiency in Heilongjiang Province also showed a certain degree of zonal characteristics in 2014, with lower efficiency in the east and higher efficiency in the west. Compared with 2014, overall, there was little change in the 2015 agricultural water use efficiency in Heilongjiang Province, and the agricultural water use efficiency was still lower in the east and higher in the west. However, some local differences were observed: Harbin changed from low efficiency in 2014 to medium-low efficiency in 2015, Suihua City changed from medium-high efficiency in 2014 to low efficiency in 2015, and Jixi City changed from medium-low efficiency in 2014 to medium efficiency in 2015. Although some differences were observed when the efficiencies in 2013 and 2014 were compared, these differences were characterized by small-scale clustering, and no overall clustering remained. These differences were mainly due to the differences of the evaluation index of agricultural water efficiency in different years. For example, the effective irrigation area of Qiqihar city was 624.2 million hm² in 2013, but was 675.1 million hm² in 2014.

Influencing factors of agricultural water use efficiency

Taking 2015 as an example, we use the above-mentioned agricultural water use efficiency evaluation method to sort and analyse water distribution efficiency, agricultural water use efficiency, production efficiency and environmental constraints. The specific results are shown in Table 3.

According to Table 3, agricultural water use efficiency was high in the Daxinganling area and in Daqing City, ranked No. 6 and No. 8, respectively, in water distribution efficiency. Therefore, these areas should increase their investment in water conservancy to improve water transmission and distribution infrastructures. The agricultural water use efficiency was at the medium high level in Yichun, Heihe and Qiqihar. However, Yichun City ranked No. 8 in production efficiency and, therefore, should focus on measures to improve production efficiency, such as
adjusting planting structure and improving the agricultural yield per unit area. Qiqihar City was low in both water distribution efficiency and water use efficiency. Therefore, it should take measures to improve both water transmission/distribution and water use processes in the field. Most other cities ranked low in all four criteria layers. For example, Hegang, Shuangyashan, Jiamusi, and Suihua City should take corresponding measures to improve the water transmission, field water use, water use efficiency in production and other aspects while taking into account the impact of environmental changes and farmland pollutant emissions on agricultural water use efficiency. For example, although Harbin ranked high in water distribution efficiency, its overall ranking was low due to environmental constraints. Therefore, Harbin should step up efforts in environmental protection to improve agricultural water use efficiency.

CONCLUSIONS

We reviewed previous field research and propose an evaluation indicator system of agricultural water use efficiency, based on environmental constraints and on evaluations of the agricultural water use efficiency in Heilongjiang Province from 2013 to 2015, using a hybrid iteratively corrected evaluation method. The main conclusions are as follows:

(1) An indicator system of agricultural water use efficiency evaluation with four criteria (water distribution efficiency, water use efficiency, productivity, and environmental constraints) and nine indicators (utilization coefficient of canal water, effective irrigation area, utilization coefficient of field water, irrigation water per unit area, proportion of food crops, crop yields per cubic meter of water, agricultural output value per cubic meter of water, proportion of ecologial water use in agricultural water, and agricultural ammonia emissions) was established that considers the entire process of agricultural water use and the impact of the environment.

(2) Evaluations of multiple methods were combined to resolve the differences among the evaluation results of the different individual methods, and the agricultural water use efficiency in various regions in Heilongjiang Province from 2013 to 2015 were evaluated. The method could
give comparatively precise results and has good computational stability and provide reference for the evaluation of the agricultural water use efficiency in other areas.

(3) Spatially, the agricultural water use efficiency in Heilongjiang Province showed some regional differences in the 3 years evaluated. While clustering was observed at a small scale, no significant clustering occurred in the overall pattern. The agricultural water use efficiency was lower in the east and higher in the west.

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