An economic-efficiency analysis of water conservancy investment in Heilongjiang Province based on projection pursuit clustering and DEA models

Qiang Fu, Jia Guo, Song Cui, Tianxiao Li and Dong Liu

ABSTRACT

Water conservancy investment affects economic development. To scientifically analyze its economic efficiency, this paper employs a projection pursuit clustering model based on the real-coded accelerated genetic algorithm to reduce the number of output index systems for each year, and the relative economic efficiency is obtained for 13 cities in Heilongjiang Province during the period 2007–2012 using a data envelopment analysis (DEA) model. The spatial distribution regulation is described based on the average efficiency derived for the period 2007–2012. Finally, the output values are optimized for ineffective cities under the optimization principle according to the 2012 values. The results show that the output index system is different for each year. Most cities exhibit comprehensive effectiveness, and the development of water conservancy is generally good. The spatial distribution regulation of economic efficiency tends to be high in the south and low in the north because it is related to local economic development and water policies. To achieve comprehensive effectiveness, the output indices need to be adjusted. This study assists with the promotion of efficient development plans for water conservancy systems and the economic efficiency of water conservancy investment in Heilongjiang Province.

Key words | DEA, economic efficiency, Heilongjiang, index reduction, projection pursuit clustering, water conservancy investment

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INTRODUCTION

Water conservancy is not only a prerequisite for agricultural production but also a driving force of economic and social development. As a large agricultural province, Heilongjiang needs water conservancy more than many other provinces to provide strong support for its development. However, the economic efficiency of water conservancy among different cities is different due to obvious differences in agricultural production structure, environmental conditions and water and soil resource structure (Liu *et al.* 2006). Therefore, it is important to scientifically analyze the economic efficiency of water conservancy investments to make good use of the limited funds and promote regional development.

Many scholars have researched the economic efficiency of water conservancy investments (Urban *et al.* 2013). The main methods include linear screening models (Cohon & Marks 1973), regression equations (Yang *et al.* 2008), water balance models (Panigrahi *et al.* 2005), real option methods (Michailidis & Mattas 2007), analytic hierarchy process (Zhang 2009), etc. However, previous research has primarily focused on investment incomes (Tica *et al.* 2011; Lee & Kim 2016), with little attention given to optimizing the input–output structure (Isard 1951; Lee & Yoo 2016) of water conservancy to improve low-efficiency problems. Moreover, the scales of these studies have focused on the entire country, a specific city or a special area, with little research on the differences between cities.

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In view of the shortcomings of the above research, this paper presents a new method to analyze the relative economic efficiency of each city from the perspective of the input–output structure (Kashani 2005; Zhang & Jiao 2015). A data envelopment analysis (DEA) model is suited to address the efficiency evaluation problem, which explains the economic impact of water conservancy investment from the perspective of multiple inputs and outputs and can be selected to calculate the efficiency by considering the complexity of water resource systems and output diversity (Puri & Yadav 2015). Moreover, the projection pursuit clustering (PPC) model (Berro *et al.* 2010) is used to reduce the number of output indices of the DEA because the results may become blurred due to many indices (Liu *et al.* 2013). Therefore, a PPC-DEA model is developed to explore a new perspective on economic efficiency analysis for water conservancy investments. This model provides a reference for optimizing the input–output structure of water conservancy investments, improving resource allocation, and increasing the ability of water conservancy to support the economy.

RESEARCH METHODS AND DATA SOURCES

Study area

Heilongjiang Province is located in northeastern China (121°11′–135°05′N, 43°26′–53°33′E; Figure 1) and has a total area of 47.3×10^4 km^2; it has a cold temperate and temperate continental monsoon climate. It is an important commodity grain production base in China and is thus in an important strategic position to protect China's food security. Recently, the country has attached great importance to water conservancy in Heilongjiang. In 2007, the completed investment was 28 billion Yuan, and 140 billion Yuan in 2010. Moreover, it reached 34.8 billion Yuan in 2015, ranking first in China. Although the investment has increased year by year, unbalanced regional development and great differences in economic efficiency always exist because of the lack of correct direction and unreasonable input–output structure, such as outdated water infrastructure and unbalanced temporal–spatial distribution of water and soil resources. In this situation, only a scientific analysis of the economic efficiency of water conservancy investments can result in the complete use of the economic potential of all regions, which relates not only to the economic and social development of Heilongjiang but also to the economic and social development of China.

Research method

PPC model

A PPC model is a dimension reduction processing technology. It can transform a multidimensional analysis problem into a one-dimensional problem using the optimal projection direction. Specifically, the multi-factor index of the influencing problem is transformed into the projection eigenvalue, which reflects the comprehensive index characteristics based on PPC analysis.

Step 1: Equal frequency discretization and output index classification (Zhang *et al.* 2008)
Step 2: The structure of the index function $Q(a)$
Step 3: Optimization of the projection index function
Step 4: Classification
Step 5: Reduction of the output index system

Further details are shown in the supplementary material (available with the online version of this paper).

Data envelopment analysis

In this study, the CCR and BCC models (Liu *et al.* 2014) from the DEA are selected to calculate the economic efficiency of water conservancy investments. The CCR model is used to measure the comprehensive efficiency θ. It indicates that the existing portfolio is not the optimal combination when $\theta < 1$, which may be due to technical factors or scale factors. The pure technical efficiency δ can be evaluated using the BCC model. The pure technical efficiency is effective when $\delta = 1$ and inefficient when $\delta < 1$. Moreover, γ is the scale efficiency, where $\gamma = \theta/\delta$. The scale efficiency is effective when $\gamma = 1$ and is inefficient when $\gamma < 1$. Using a combination of the CCR and BCC models, the comprehensive efficiency θ, pure technical efficiency δ and scale efficiency γ can be evaluated for each city. Further details are shown in the supplementary material.

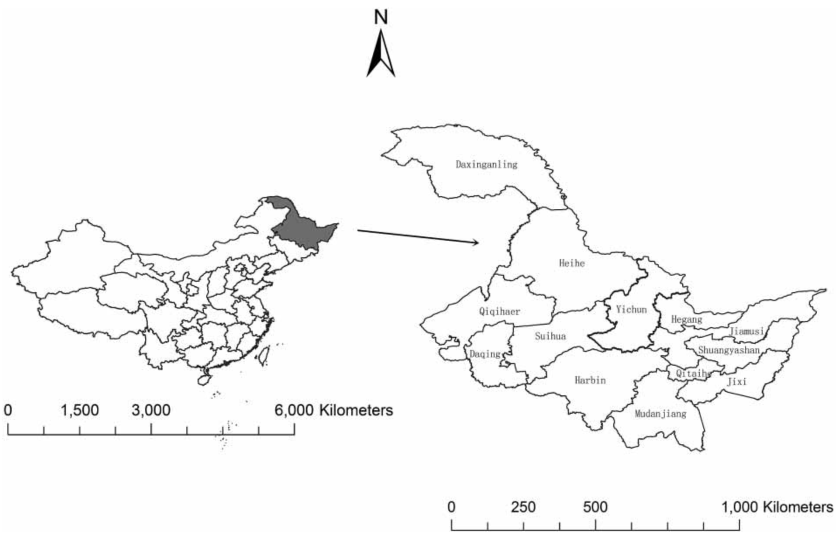

Figure 1 | Sketch map of the administrative divisions in Heilongjiang Province.

PPC-DEA model

Based on the above theory, the number of output indices is reduced using the PPC model. Then, the economic efficiencies of water conservancy investments are calculated and analyzed via DEA. Divisions are made according to the comprehensive efficiency (You *et al.* 2011), and solutions are given to solve the problem of low efficiency (Zhang *et al.* 2013) in 13 cities in Heilongjiang. The specific steps are as follows:

Step 1: Determine the input and output indices
Step 2: Reduce the number of output indices using the PPC model
Step 3: Determine the new output index system for each year
Step 4: Calculate the economic efficiency using DEA
Step 5: Conduct the economic efficiency analysis of water conservancy investments

Data sources

The data related to water conservancy investments, effective irrigation area, hydropower generation, drainage area, number of reservoirs, levee protection population, water and soil erosion control areas and annual water supply are obtained from the 'Heilongjiang Province Statistical Yearbook of Water Conservancy Construction' for the period 2007–2012. The gross regional product and grain yields are obtained from the 'Heilongjiang Province Statistical Yearbook' for the period 2007–2012.

CONSTRUCTION AND REDUCTION OF THE INDEX SYSTEM

Construction of the index system

Input and output index systems are the basis for evaluating the economic efficiency of water conservancy investments. After selecting 13 cities from Heilongjiang as decision-making units (DMUs), input and output indices are required to support them. This paper selects one input index and nine output indices based on the agricultural production structure, the pattern of water and soil resources and the direction of recent water conservancy investments, and the basic types of water conservancy investments (Zheng 2004) and the availability of data are also considered (see Figure 2).

Index reduction

The DMUs from each output index are listed in ascending order and divided into four grades according to the theory

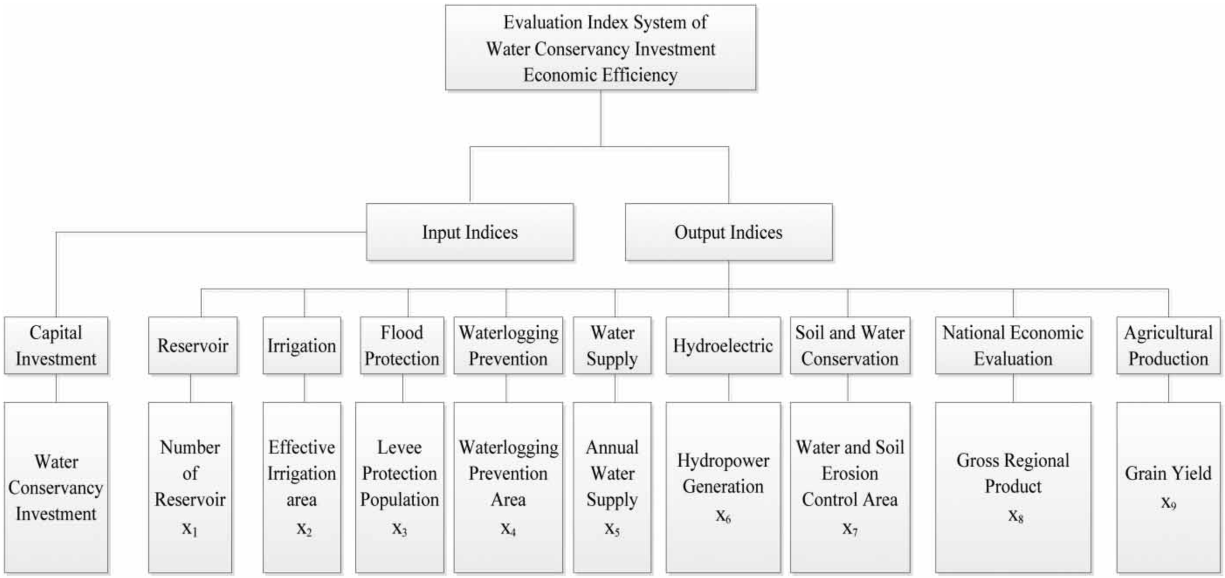

Figure 2 | The index system for the economic efficiency of water conservancy investments in Heilongjiang Province.

discussed above: the value is 1 when the DMU ranking is 1–3, 2 when the DMU ranking is 4–6, 3 when the DMU ranking is 7–9, and 4 when the DMU ranking is 10–13. The projection direction in the PPC model is optimized using a real-coded accelerated genetic algorithm with MATLAB 2013a. The best projection values for the initial output index system and the new output index system when each index is removed in order are obtained. This paper defines that the index should be deleted when the sum of the level-changes exceeds 5. Results are shown in the supplementary material for 2010 as an example (available with the online version of this paper). Then, the final output index system for each year is obtained (see Table 1).

RESULTS AND ANALYSIS

Comprehensive efficiency analysis of water conservancy investments

The CCR model calculates the comprehensive effectiveness of 13 cities in Heilongjiang Province using the above input and output index systems. Then, the comprehensive efficiency of the cities' water conservancy investments is obtained for the period 2007–2012 (see Table 2).

There are 32 DMUs (accounting for 41%) of 78 that exhibit comprehensive effectiveness during the 6 years.

Table 1 | Reduction results of the output index system for each year

Year	Effective irrigation area	Hydropower generation	Drainage area	Number of reservoirs	Levee protection population	Water and soil erosion control areas	Annual water supply of water conservancy project	Gross regional product	Grain yield
2007		√	√	√		√		√	
2008	√	√			√			√	√
2009		√		√			√	√	√
2010	√	√	√				√		√
2011	√			√		√		√	√
2012	√					√	√	√	√

Table 2 | Comprehensive efficiency of water conservancy investments in Heilongjiang Province during the period 2007–2012

DMU	2007	2008	2009	2010	2011	2012	Average	Sort
Suihua	0.894	0.820	1.000	1.000	1.000	1.000	0.976	1
Harbin	1.000	1.000	1.000	0.827	0.859	1.000	0.974	2
Qiqihar	1.000	0.911	0.856	0.885	1.000	1.000	0.971	3
Jixi	0.760	0.850	1.000	1.000	1.000	1.000	0.968	4
Daqing	1.000	0.807	0.943	0.841	1.000	1.000	0.966	5
Shuangyashan	0.700	1.000	0.559	1.000	0.805	1.000	0.922	6
Mudanjiang	1.000	1.000	0.254	0.544	0.800	1.000	0.883	7
Qitaihe	1.000	0.934	0.410	0.666	1.000	0.800	0.801	8
Jiamusi	0.694	0.873	0.795	0.636	1.000	0.800	0.800	9
Hegang	0.422	0.774	0.413	1.000	0.833	0.840	0.777	10
Heihe	0.530	1.000	1.000	1.000	0.574	0.674	0.735	11
Daxing'anling	0.337	1.000	0.287	0.332	0.215	0.392	0.410	12
Yichun	0.132	0.531	0.272	0.254	0.266	0.353	0.327	13

This means these 32 DMUs made full use of water investments and obtained ideal output. Moreover, 65% of the 78 DMUs have a comprehensive efficiency exceeding 0.800, showing that the comprehensive efficiency of the water conservancy investments is relatively high. Thus, the input and output structure of the water conservancy investments is reasonable in Heilongjiang. The average comprehensive efficiency for each city during the 6 years is sorted as follows: Suihua > Harbin > Qiqihar > Jixi > Daqing > Shuangyashan > Mudanjing > Qitaihe > Jiamusi > Hegang > Heihe > Daxing'anling > Yichun. Suihua, which has the highest comprehensive efficiency, has a comprehensive efficiency that is three times that of Yichun. Therefore, there are large differences among the studied cities in Heilongjiang Province. In Yichun, which exhibits comprehensive ineffectiveness for all 6 years, water conservancy began late and the infrastructure is very poor, although the intention was good.

In summary, water conservancy investments exhibit a prosperous developing trend in Heilongjiang, although the differences between cities are large, and the efficiency of some cities is very low, which is related to the degree of local water conservancy infrastructure construction.

Pure technical efficiency and scale efficiency analysis of water conservancy investments

Combined with the CCR model, comprehensive efficiency is further decomposed into pure technical efficiency and scale efficiency using the BCC model, and the results are shown in Table 3.

There are 51 DMUs (accounting for 71%) exhibiting pure technology effectiveness, which indicates that water conservancy investments have reached a relatively optimal output with current technology. Suihua and Harbin exhibit pure technology effectiveness for all 6 years because these cities attach importance to investing in water conservancy science and technology and promote advanced production technology, leading to a higher level of economic development. Suihua and Harbin are the most invested cities in water-saving and grain-increasing activities, giving them an advantage.

Furthermore, 19 of the 51 DMUs fail to achieve scale effectiveness, such as Jiamusi in 2007, which had an incomplete flood control system and lacked large-scale control projects, and Qitaihe in 2008, which had serious problems in improving support facilities for water conservancy and reforming old buildings. Therefore, the focus for

Table 3 | Pure technical efficiency and scale efficiency of water conservancy investments in Heilongjiang Province during the period 2007–2012

	2007		2008		2009		2010		2011		2012	
DMU	**Pure technology efficiency**	**Scale efficiency**	**Pure technology efficiency**	**Scale efficiency**	**Pure technology efficiency**	**Scale efficiency**	**Pure technology efficiency**	**Scale efficiency**	**Pure technology efficiency**	**Scale efficiency**	**Pure technology efficiency**	**Scale efficiency**
Daxing'anling	1.000	0.337	1.000	1.000	1.000	0.287	1.000	0.332	0.795	0.270	0.431	0.911
Heihe	1.000	0.530	1.000	1.000	1.000	1.000	1.000	1.000	0.599	0.958	0.757	0.891
Yichun	0.220	0.599	0.568	0.934	0.528	0.516	0.454	0.560	0.417	0.639	0.412	0.856
Hegang	0.552	0.764	0.892	0.868	0.696	0.593	1.000	1.000	0.900	0.926	0.879	0.955
Jiamusi	1.000	0.694	0.924	0.945	0.832	0.955	1.000	0.636	1.000	1.000	1.000	0.800
Shuangyashan	1.000	0.700	1.000	1.000	0.739	0.756	1.000	1.000	0.992	0.812	1.000	1.000
Qitaihe	1.000	1.000	1.000	0.934	0.721	0.568	0.431	1.547	1.000	1.000	0.813	0.984
Jixi	0.904	0.841	1.000	0.850	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Mudanjiang	1.000	1.000	1.000	1.000	0.274	0.924	0.345	1.576	1.000	0.800	1.000	1.000
Harbin	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.827	1.000	0.859	1.000	1.000
Qiqihar	1.000	1.000	1.000	0.911	0.860	0.995	1.000	0.885	1.000	1.000	1.000	1.000
Daqing	1.000	1.000	1.000	0.807	0.989	0.954	1.000	0.841	1.000	1.000	1.000	1.000
Suihua	1.000	0.894	1.000	0.820	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000

these cities is to adjust and expand the production scale of water conservancy. Moreover, 27 of the 78 DMUs fail to demonstrate both pure technology and scale effectiveness during the 6 years, such as Daxing'anling, Heihe, Hegang and Yichun in 2011 and 2012. Yichun performs ineffectively for both pure technology and scale during all 6 years. As a forest resource city, it is particularly important for Yichun to improve both production technology innovation and expand the production scale with the decrease in forest resources. Thus, these cities must make appropriate adjustments in water conservancy production technology and production scale to achieve comprehensive effectiveness.

Spatial distribution of the economic efficiency of water conservancy investments

To further investigate the spatial distribution of the economic efficiency of water conservancy investments in Heilongjiang Province, partition sets are made for 13 cities according to the average comprehensive efficiency during the 6 years. The standard partition sets are as follows: [0.009 1.000] for the high economic efficiency area of water conservancy investments; [0.800 0.900] for the sub-high economic efficiency area of water conservancy investments; [0.500 0.800] for the middle economic efficiency area of water conservancy investments; and [0 0.500] for the low economic efficiency area of water conservancy investments. The results are shown in Figure 3.

The economic efficiency of water conservancy investments is generally high in the south and low in the north. High economic efficiency areas are found in western and eastern Heilongjiang Province, including the six cities of Qiqihar, Suihua, Harbin, Daqing, Jixi and Shuangyashan. Among them, three cities, i.e., Harbin, Daqing and Qiqihar, form the 'Ha-Da-Qi Industrial Corridor'. This is the area with the strongest economy, the highest level of industrialization and the most obvious advantage in

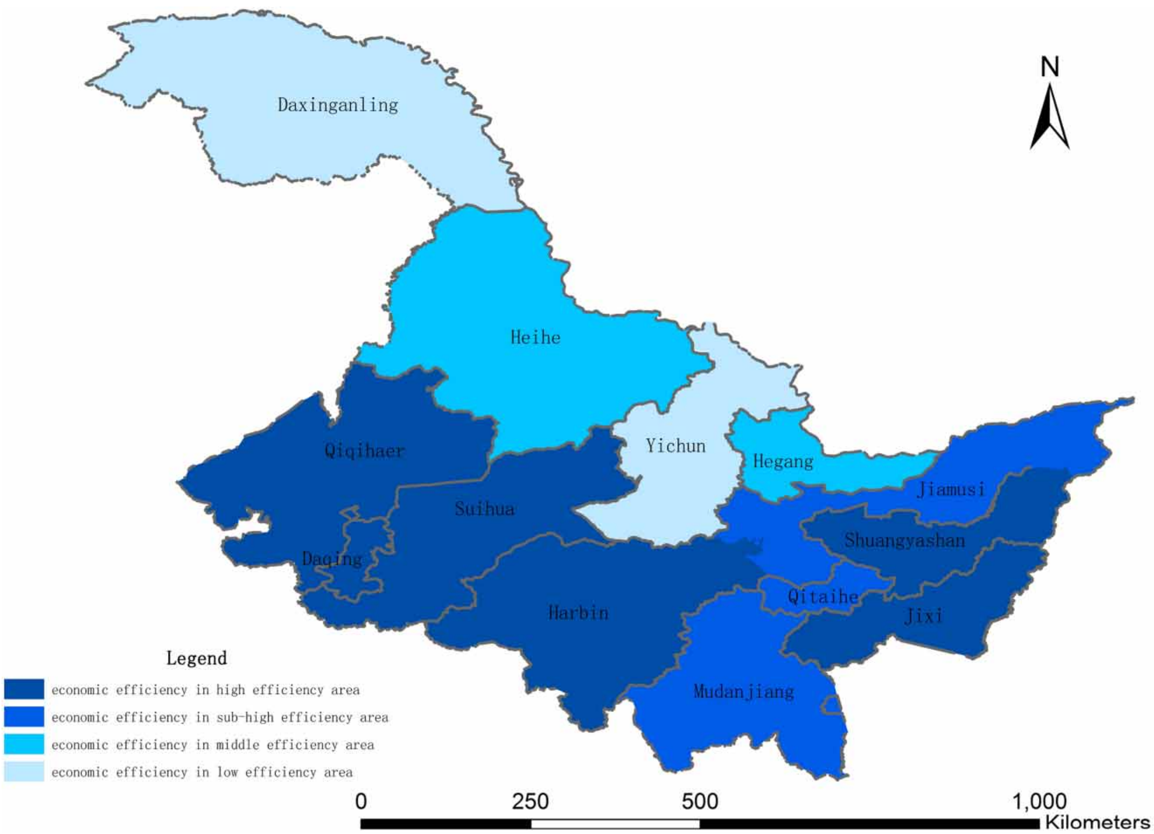

Figure 3 | Spatial distribution of the economic efficiency of water conservancy investments.

terms of talent in Heilongjiang Province. The intensity of water conservancy investments is high and has had good results. Suihua's total grain output accounts for 1/4 that of Heilongjiang Province and ranks first in the growth of the major economic indicators. Jixi and Shuangyashan are cities in the eastern part of the northeast's old industrial base. With the implementation of 'The Plan of the Development of the East of the Northeast Economic Zone', the infrastructure has improved; industrial transformation and upgrading have been strongly supported by the local government. It seems that most developed cities in Heilongjiang enjoy high economic efficiency.

Sub-high economic efficiency areas are located in southeastern Heilongjiang Province, including Qitaihe, Mudanjiang and Jiamusi, whose economic development is in the middle and upper levels. Recently, Jiamusi's economy has declined due to the unsatisfactory development of the industrial chain. However, it remains a grain base in Heilongjiang and the center of the eastern region. Qitaihe, as an economically restructuring pilot city, was identified as the second of the national resource-exhausted cities. Thus, the city must engage urgently in the task of sustainable development. Mudanjiang is relatively rich in local resources and has a good industrial base; it was voted into 'China's top-ten developing cities with the most potential'. However, during the 'Twelfth Five Year Plan', the city experienced problems, such as improper adjustment in industrial structure and shortage of funds. Although these three cities are located in the sub-high economic efficiency area, they have enormous potential in human resources, natural resources and social resources, which may allow them to join the high economic efficiency area with proper adjustments to output structure.

The middle and low economic efficiency areas are dispersed across northern Heilongjiang. The middle area includes Heihe and Hegang, whose economic efficiencies vary little from the sub-high economic efficiency area. The border trade economy of Heihe and the coal economy of Hegang dominate development, leading to structural contradictions and limited economic growth. The low economic efficiency areas include Yichun and Daxing'anling, which are resource-based cities relying on forestry. With the decrease in forest resources, the economic development of these cities has been severely constrained, making them the most underdeveloped economic region. They urgently need economic transformation.

Optimization design of the economic efficiency of water conservancy investments

Table 2 shows that there are six cities, i.e., Daxinganling, Heihe, Yichun, Hegang, Jiamusi and Qitaihe, that exhibited comprehensive ineffectiveness in 2012. They must increase output to achieve comprehensive effectiveness. According to the results of the CCR model, the optimization results are shown in Table 4.

Table 4 shows that these six cities must increase their output values by different degrees in output optimization. Yichun has improved the most in the output effective irrigation area, followed by Daxing'anling and Heihe. These three cities are located in the northern part of Heilongjiang Province and belong to the Daxing'anling Forest Region. They have a lot of land and few people, resulting in high per

Table 4 | Output index for the comprehensive ineffectiveness of the studied cities

DMU	Effective irrigation area/khm^2	Levee protection population/10 thousand persons	Water and soil erosion control area/khm^2	Annual water supply of water conservancy project/10 thousand cu.m	Gross regional product/100 million Yuan
Daxing'anling	98	0	96	129,599	259
Heihe	99	35	0	180,014	239
Yichun	167	0	186	218,954	536
Hegang	0	34	115	60,953	205
Jiamusi	0	11	330	209,276	1,123
Qitaihe	59	23	3	78,461	0

capita arable land. Thus, improving the effective irrigation area would promote economic development. Heihe, Hegang, Jiamusi and Qitaihe all exhibit different degrees of improvement in the value of output levee protection per population. With the exception of Heihe, the other three cities are located in the eastern part of Heilongjiang Province and belong to the agricultural and pastoral areas of the Sanjiang plain. The serious flood disasters in this area make the construction of levees particularly important. Daxing'anling, Yichun, Hegang, Jiamusi and Qitaihe all exhibit different degrees of improvement in the area of output water and soil erosion control. Obviously, water and soil erosion has become a common problem affecting economic efficiency. The six cities have all experienced large increases in the value of output annual water supply of water conservancy projects. Groundwater is the main water supply source in Heilongjiang Province, resulting in an unreasonable structure of water supply. Thus, the water supply has become an important factor restricting economic development and affecting economic efficiency. With the exception of Qitaihe, the other five cities have shown different degrees of improvement in the value of gross regional product. Their gross regional product has been affected by lower population density, sparse distribution of labor and weak water infrastructure. Simultaneously, in the key areas of agricultural production, economic efficiency is restricted by the development of agriculture. Therefore, the structure of agricultural production should be adjusted, the level of mechanization should be improved, and the high and stable yield of crops should be ensured.

CONCLUSIONS AND SUGGESTIONS

(1) This paper presents a new method based on the PPC and DEA models to obtain a characteristic perspective and analyze the economic efficiency of water conservancy investments. Using the PPC model's strong multidimensional analysis ability, the input–output structure of DEA is simplified. This resolves the problem of fuzzy efficiency judgment caused by traditional DEA with a complex input–output structure. Compared with the previous analysis methods, it is simple and applicable, which greatly improves the analysis method.

(2) Through the establishment of the new model, 13 cities in Heilongjiang Province are selected and empirically studied. The results show that the economic efficiency of water conservancy investments is generally high during the period 2007–2012, and the input–output structure is reasonable. However, there are still large differences among the cities. Suihua and Harbin have paid great attention to the development of science and technology, obtaining pure technology effectiveness for all 6 years. However, Yichun fails to achieve pure technology effectiveness or scale effectiveness for all 6 years because of its technology and scale of water conservancy.

(3) In terms of the spatial distribution of the economic efficiency, it is high in the south and low in the north. The high economic efficiency areas are located in regions with a relatively high level of economic development. Most cities are in the high or sub-high condition. The distribution is highly correlated with the level of local economic development and water conservancy policies.

(4) Under the existing technology and scale of water conservancy production, the output values in comprehensively ineffective cities must be adjusted. To achieve comprehensive effectiveness, the optimization scheme is calculated based on the outputs in 2012, which are taken as the initial values. The results show that each city's adjustment values are different, and the output index of the annual water supply of water conservancy projects should be the focus of future efforts. Therefore, these six cities must make varying adjustments. Heilongjiang is under a severe water supply condition that affects economic development. The adjustment values provide theoretical support for increasing the economic efficiency of water conservancy investments and achieving comprehensive effectiveness.

(5) This paper selects only one index, which is the water conservancy investment value, as the input index. It does not use the consumption of water resources and water conservancy labor because the relevant data are difficult to obtain. Meanwhile, the limited number of DMUs in the DEA model leads to certain shortcomings in the index selection. However, the selection of input and output indices will affect the economic efficiency. Thus, this analysis has some shortcomings that are difficult to overcome but may be improved in future research.

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