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Performance Evaluation of Groundwater Overdraft Recovery Units in North and Coastal China Based on DEA Models

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ABSTRACT

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Groundwater overdraft has affected sustainable development, especially in North and Coastal China, since the 1960s. The Chinese government instituted the Pilot Project of Groundwater Overexploitation Control (PPGOC) in Hebei Province during 2014 to 2016. This project introduced a set of hydrological, agricultural and administrative activities to recover the aquifer in the pilot area. In order to evaluate the effects of these activities on the groundwater status, a series of Data Envelopment Analysis (DEA) models are assembled as a model group and applied to calculate the relative performance of groundwater recovery units, i.e. the recovery efficiency in 49 counties or Decision-Making Units (DMUs). It is shown that the DEA model group can be used to evaluate the recovery efficiency, improve the performance of units not on the DEA frontier via radial and slack movement, and study the possibility of cost reduction. The result shows that 20 DMUs formed the frontier, which is the collective of the efficient DMUs, and that another 29 DMUs require efficiency improvement. The high efficiency of certain DMUs is related to the location and farmers' responses, which indicates that groundwater overdraft recovery is a technical problem that also has something to do with social and economic development and comprehensive governance. The model group can be used as a reference in the forthcoming implementation of aquifer recovery in groundwater overdraft zones in North and Coastal China.

ADDITIONAL INDEX WORDS: *Groundwater, overdraft, DEA models, control units, recovery efficiency, North China Plain, PPGOC.*

INTRODUCTION

As a valuable and stable natural resource, groundwater plays an important role in human society and economic development. According to statistics, groundwater accounts for over 97% of the available fresh water and more than half of the drinking water (Jakeman *et al.*, 2016).

In both quantity and quality, groundwater presents greater stability than other water resources. With the rapid development of high-efficiency pumps and power supply networks, the groundwater draft on this planet increased from 312 km^3a^{-1} in the 1960s to 743 km^3a^{-1} in 2000, with more than 70% of it used for irrigation (Wada *et al.*, 2010). In 2009, India drafted the largest quantity of groundwater - 190 km^3 of water from aquifers - in the world, whereas the USA was second to India and extracted 110 km^3 of groundwater. Other countries that extracted more than 50 km^3 of groundwater were Pakistan, China and Iran (Giordano, 2009).

In recent decades, groundwater has been over-exploited in many countries. In India, 20,000 km^2 of farmland is irrigated by surface water, while 45,000 km^2 is irrigated by groundwater, with 70% of the agricultural output value produced from groundwater-irrigated farmland (Vörösmarty *et al.*, 2000).

In the USA, approximately 60% of irrigation water is from underground sources and the High Plains (HP). Groundwater utilization in the HP accounts for one third of the total groundwater development and provides drinking water to 2.3 million residents. Scanlon analyzed the data from 3600 monitoring wells and the GRACE satellite and found that groundwater overdraft cumulated to 330 km^3 and that the decline in groundwater storage in the HP was approximately 36% of the total groundwater depleted in the USA during 1900–2008 (Scanlon *et al.*, 2012).

China has experiencing groundwater overdraft since the 1960s, when the central government encouraged farmers to build tube wells for irrigation. Over the past decades, the overexploitation in the North China Plain (NCP) has already caused a decline in the groundwater tables in both confined and unconfined aquifers (Liu, Yu, and Kendy, 2001).

To recover depleted aquifers threatened by overexploitation, the Chinese government implemented the Pilot Project of Groundwater Overexploitation Control (PPGOC) in the Hebei Province during 2014 to 2016. Investment in that period reached 24.6 billion RMB (approx. 3.6 billion US dollar) and covered an area that encompassed 49 counties in 2014 and 115 counties in 2016. Now the pilot period has ended and the groundwater table has been fundamentally altered by inte-

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*Corresponding author: panzenghui@hotmail.com grated measures taken in Hebei, which proves that the measures implemented by the PPGOC are useful and the positive experience of recovering over-exploited aquifers can be spread as persuasive precedent. However, although a series of measures and experiences have been summarized, a performance evaluation has not been done for the pilot counties.

This study aims to answer the following two questions for areas planning to implement groundwater overdraft recovery projects in the future. (1) What is the performance of every pilot county – treated and modelled as a decision making unit (DMU) – in groundwater recovery, and which counties viz. DMUs are more efficient? (2) How can the performance of inefficient units be improved? A series of DEA models are used to answer these questions.

MATERIALS AND METHODS

Study Area and Pilot Project

Water shortage represents a serious problem in the NCP. Since the 1960s, this region has been suffering from constant water shortage and pollution due to the expansion of irrigated farmland, growing population, social and economic development and decreasing precipitation caused by climate change (Liu and Xia, 2004). However, the regional groundwater table is continuously decreasing at a rate of up to 1 m a^{-1} because of groundwater exploitation (Zheng *et al*., 2010).

Hebei Province is particularly short in water resources, with a water resources per capita of only 307 m^3. Since the 1980s, the groundwater table has been declining (Luo *et al*., 2017).

By the end of 2016, the Chinese central government and Hebei provincial government had invested more than 3.5 billion USD on this pilot project, and the groundwater overdraft had been preliminarily controlled. The annual reduction of groundwater overdraft in the pilot areas for agriculture has reached 500 million m^3, and the groundwater tables in both confined and unconfined aquifers have begun to rise in most pilot areas.

The measures taken are agricultural water-saving, hydraulic engineering and governance measures, specifically including:

- Water resource replacement: The South-to-North Water Transfer Project for urban water supply and the water diversion projects from the Yellow River to Hebei have been implemented to replace groundwater. In addition, reclaimed water and seawater will also be used as alternative sources of water.
- Plant pattern adjustment: The winter wheat acreages have been diminished. In order to decline the groundwater consume
- Farmland replacement by forests: Land for agricultural use has been changed from water-consuming crop land to water-saving forest.
- Water-saving irrigation technologies: Sprinkle irrigation, drip irrigation have been applied to improve the water use efficiency.
- Economical leverage: water tariff and water resources tax have been used as leverage to encourage farmers and other users to adopt water-saving technologies.
- Well control: certain tube wells have been sealed to stop groundwater draft in groundwater overdraft areas.

Evaluation Method Selection

Policy simulation seems useful for the performance evaluation of different units. The Computable General Equilibrium (CGE) model, which was proposed by Léon Walras in 1874 (Walras, 1874), is the most popular policy simulation model. It has been widely applied to solve water resources issues since its establishment (Calzadilla *et al*., 2017).

However, the CGE model is not suitable for analyzing the unit performance: First, the CGE model views the whole social and economic system as its subject and thus requires massive data from different industries and departments, which are difficult to obtain and not useful for the groundwater overdraft control project; second, the CGE model relies heavily on data in I/O tables and the last version of the I/O table for China was updated in 2007, which obviously cannot be used to evaluate the performance between 2014 and 2016.

The MOP is found to be unsuitable because it considers both the efficient and inefficient units with the same weight, and obtains statistics from the Production Possibility Set (PPS) without considering the impacts of inefficient units.

The Data Envelopment Analysis (DEA). As a relative efficiency evaluation or balanced benchmarking method, DEA can be used to analyze the input and output efficiency of a group of decision-making units (DMUs – in our case represented by county-level administrative units). The DEA model can produce a best-practice frontier, which is the collective of all efficient DMUs. Within the frontier, all the units are inefficient. In this model, one can project the inefficient DMUs to the frontier, and then identify the methods to improve their relative efficiency. This model only requires input and output data for the DMUs and thus can avoid collecting excessive information, which is a problem of the CGE model.

DEA Models

Farrel proposed the concept of technical efficiency (TE) in 1957 and described TE as the ratio of output to input, which can be used to evaluate a unit's performance. The DEA models may be input-oriented or output-oriented.

Suppose that there are n DMUs. Each DMU$_j$, $j = 1, 2, ..., n$, produces q different outputs, y_{rj} $(r = 1, 2, ..., q)$, with m different inputs, x_{ij} (i = 1, 2, ..., m). The input-oriented CRS model (CCR) can be expressed as:

$$\theta = min\theta, s.t. \sum_{j=1}^{n} \lambda_j x_{ij} \leq \theta_{x_{ik}}, \sum_{j=1}^{n} \lambda_j y_{rj} \geq y_{rk}$$

$$\lambda \geq 0, i = 1, 2, \ldots, m; r = 1, 2, \ldots, q; j = 1, 2, \ldots, n \qquad (1)$$

where, θ is the efficiency, with θ; and λ is the weight multiplier of each DMU. The CCR model can be used to obtain TE and the weights of inputs and outputs.

Banker *et al*. added an additional convex constraint of $\sum_{j=1}^{n} \lambda_j = 1$ into equation (1) and obtained an input-oriented Variable Return to Scale (VRS) model, This VRS model is called the BCC model, named after the first letters of the three authors' names.

$$\theta = min\theta, s.t. \sum_{j=1}^{n} \lambda_j x_{ij} \le \theta_{x_{ik}}, \sum_{j=1}^{n} \lambda_j y_{rj} \ge y_{rk}$$

$$\sum_{j=1}^{n} \lambda_j = 1, \lambda \ge 0, i = 1, 2, \ldots, m;\ r = 1, 2, \ldots, q;\ j = 1, 2, \ldots, n \qquad (2)$$

Because the BCC model takes the influence of scale into account, the efficiency obtained by this model is the Pure Technical Efficiency (PTE), and the Scale Efficiency can be obtained by the ratio of TE to PTE.

$$SE = \frac{TE}{PTE} \qquad (3)$$

The CCR and BCC models can distinguish efficient DMUs from inefficient ones but cannot compare the efficiency of efficient ones because they have the same efficiency of 1 due to the definition of the model.

The new constraints j≠k for the CRS model and $\sum_{j=1,j\neq k}^{n} \lambda_j = 1$ for VRS are added to obtain the super efficiency in the two types of models. The resulting super efficiency models can distinguish the efficiency among efficient DMUs, although the efficiency values of inefficient one remain the same as in the CRS or VRS DEA models.

For inefficient DMUs, two popular improvement methods are applied in DEAs: radial and slack movement. The former can improve the performance of an inefficient DMU by proportionally improving relevant factors (inputs/outputs) to make the evaluated DMU reach the frontier. The latter can improve the performance of an inefficient DMU by maximizing the average improvement of relevant factors (inputs/outputs) to make the evaluated DMU reach the frontier (Tone, 2001). The target (projected point) determined by this method is a strong efficient point on the frontier that is the closest to the evaluated DMU.

Input and Output Data

The investments in the seven major measures taken in 2014 are selected as input data, including:

1. Cancellation of winter wheat planting;
2. Replacement of farmland with forest;
3. Water-saving seed planting;
4. Reduced tillage technology;
5. Integrated irrigation with fertilizer;
6. Water-saving irrigation;
7. water source replacement which includes seawater use.

The investments for input 1 through input 5 are functionally equivalent in the project year, although the investments in input 6 and input 7 are different because the engineering investments will be used for more than 1 year and the amount of water used in seawater varies from year to year. Considering that the lifetime of water-saving irrigation and water source replacement engineering is 10 and 30 years, respectively, we use the input data for input 1 to input 5 as the original data and the input data for input 6 and input 7 as the investment divided by 10 and 30, respectively. Figure 2 shows both the total investments made per county and with inputs 6 and 7 adjusted for comparison; As can be seen from the maps in Figure 2, investments were largely concentrated in the Hengshui Prefecture.

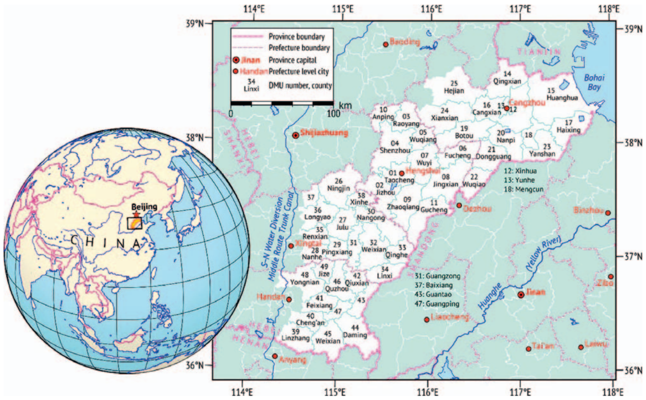

Figure 1. Location of the 49 pilot counties in 2014.

Considering the lack of direct and rapid impacts on groundwater recovery from such measures like water rightsidentification, water price reform, regulation system and construction institution reformation, the investments in these activities are not included as inputs.

Although the impact assessment report evaluated changes both in the groundwater quantity and in the water table, only the water table changes are considered output data because changes in the former are estimated data instead of observed ones, e.g. the data estimated based on the correlation between the electricity used by the pump and the water exploited by the well.Water table changes are monitored data and thus are more objective. Furthermore, quantitative changes are reflected in the water table changes. Output 1 and output 2 are the water table changes in confined and unconfined aquifers, respectively.

Figure 3 shows the overall water table changes in confined and unconfined aquifers.

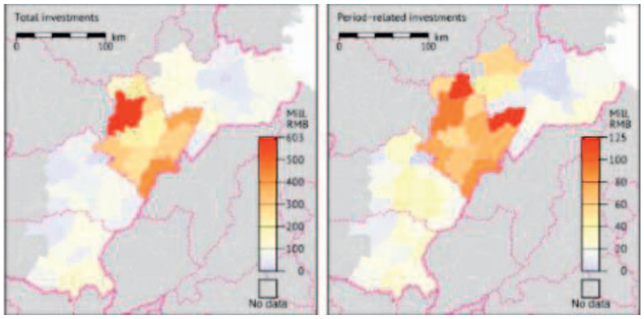

Figure 2. DMU-specific allocation of total investments efficiently made in 2014 (left) and long-term investments (irrigation and water source replacement) adjusted to period related use (right).

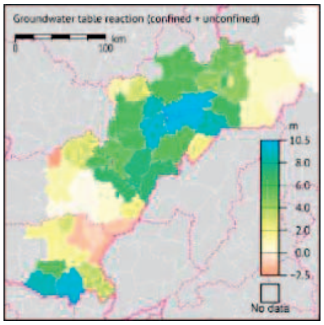

Figure 3. Overall relative groundwater table changes in confined and unconfined aquifers in the year 2015 vs. those in 2010.

RESULTS

The input and output information is input to the software MaxDEA to solve the problems, the results of which are further analyzed.

TE, PET, SE and RTS from BCC and CCR Models

TE and PTE are obtained using the models CCR and BCC based on equations (1) and (2), respectively, and the SE can then be calculated based on equation (3).

Figures 4 and 5 show the model results. Here, TE means the real groundwater overdraft control efficiency of every pilot county, PTE the ideal groundwater overdraft control efficiency of every pilot county, SE the groundwater overdraft control efficiency status of every pilot county and RTS the Return to Scale of every pilot county.

The result shows that there are 20 DMUs in the DEA frontier: 01, 05–07, 12–14, 19, 20, 23, 26, 30, 33, 35, 36, 38, 39, 45, 48, and 49; Therefore, 40.81% of the pilot counties are efficient. However, these 20 efficient DMUs present different RTS values. Only two efficient DMUs present an increasing scale: 23 and 33. 11 ones a constant scale: 01, 12, 13, 19, 20, 26, 30, 36, 38, 48, and 49, and the other DMUs of partial coastal area present a decreasing scale. In contrast, many inefficient DMUs present an increasing scale. This shows that there are no direct relations between efficiency status and RTS status and it should be very carefully analyzed to determine whether a specific DMU should get more investment or not.

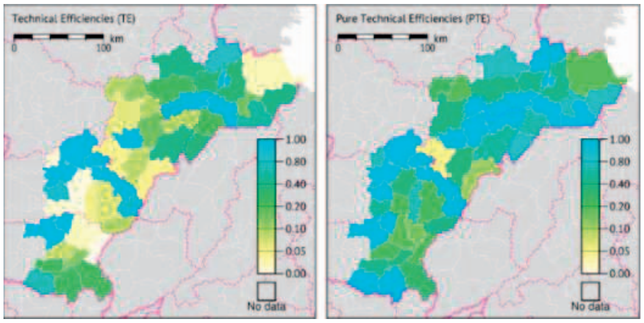

Figure 4. Spatial distributions of TE (left) and PTE (right).

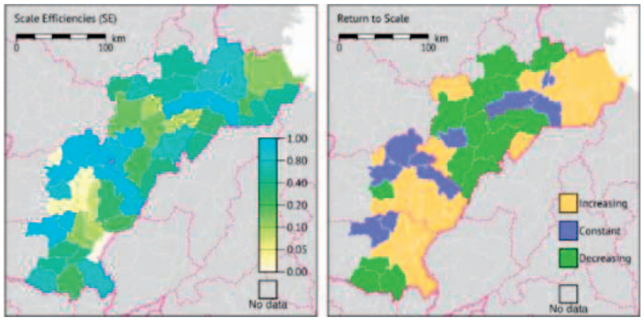

Figure 5. Spatial distributions of SE (left) and RTS (right).

Figure 4 shows that 20 efficient DMUs have the same PTE value (1.0). Despite all of these DMUs being in the frontier, certain DMUs present better performance than the others. Thus, the super-efficiency model is introduced.

Efficient DMU Evaluation by the Super-efficiency Model

The super-efficiency DEA model is used to evaluate the performance of the efficient DMUs, as the results, presented in Figure 7, show that the 20 efficient DMUs have the same efficiency values in the BCC model as mentioned in 2.3. Now, with the super-efficiency values, the efficient DMUs can be classified into two groups: 9 DMUs have an efficiency value of higher than 1 while the other 11 have a value of 1, among which, DMU20 has the highest efficiency value of 7.195.

Figure 7 clearly demonstrates the differences in the performance value between the super-efficiency model and the VRS model: they differ only in the nine cases with super-efficiencies above 1.0; cf. the maps in Figure 4 (right) and Figure 6. Unfortunately, although the super-efficiency model can be used to show that certain DMUs have a higher efficiency than the others, it does not present satisfactory performance for ranking efficient observations according to the research of Banker and Chang (2006).

Radial and Slack Movement

The radial and slack movements are obtained via the input-oriented models. All 29 inefficient DMUs can reach the efficient frontier through proportionate and slack movements (Thomas *et al.*, 2017).

According to the radial movement and slack variable values, the investment of seven inputs in 29 DMUs can be lowered without decreasing the outputs.

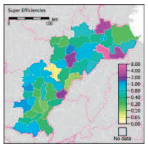

Figure 6. Spatial distribution of the super-efficiencies.

Table 1. *Inefficient DMU movement (10^4 RMB).*

Movement	Input 1	Input 2	Input 3	Input 4	Input 5	Input 6	Total movement	Total investment	Movement proportion
Proportionate Movement	−18019	−6092	−17370	−797	−16860	−6016	−65154	616790.5	10.56 %
Slack Movement	−6295	−984	−7446	−363	−4737	−2314	−20052	616790.5	3.25 %

However, input 7, water source replacement which includes seawater use, is very different from the other six because it is more closely connected to the location. Water source replacement investment is used to construct the channels for the water transfer project to transfer water from the Yangtze or Yellow River and cannot be cancelled or downscaled in the middle of the route without affecting the whole project and downstream units. Therefore, the proportionate and slack movement for water source replacement cannot be considered for individual improvements; instead, it must be considered for the whole project.

Table 1 shows the proportionate and slack movement values for the other 6 inputs. According to the results, the total radial movement and slack movement can reach 651 million RMB and 201 million RMB, occupying 10.56% and 3.25% of the total investment made in 2014, respectively. If we consider the 29 inefficient DMUs only, the ratio of radial movement and slack movement to the total investment will reach 16.02% and 4.93%, respectively, which means that 20.95% of the investments in inefficient counties may be used at a very low efficiency.

DISCUSSION AND CONCLUSIONS

The DEA models show that the best-practice frontier is composed of 20 efficient DMUs. The 9 highest-efficiency DMUs out of the 20 efficient ones are identified through the super-efficiency model, and the 29 inefficient DMUs are analyzed to identify the best-practice frontier via radial and slack movement.

The analysis of the PPGOC provides a number of results that should facilitate future implementation of groundwater overdraft control and recovery.

First, the outputs of these DEA models are the monitoring data of water table changes in the pilot area. However, the density of monitoring wells is not sufficient to reflect the real situation. Based on the data from the GRACE satellite and the calibration with the monitoring data, the changes in groundwater water at large scales should be easier to obtain, which can help improve water governance in the future. These solutions should be studied in future research.

Second, policies for improving groundwater recovery should be designed very carefully. The balance between government targets and farmers' interests should be considered simultaneously because farmers are the most vulnerable water users in Hebei. A procedure for investigation and negotiation among stakeholders should be designed before implementing policies.

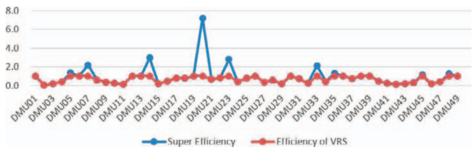

Figure 7. Super efficiency and VRS efficiency of the DMUs.

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