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# Management decision of optimal recharge water in groundwater artificial recharge conditions- A case study in an artificial recharge test site

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**Abstract.** The city conducted groundwater artificial recharge test which was taken a typical site as an example, and the purpose is to prevent and control land subsidence, increase the amount of groundwater resources. To protect groundwater environmental quality and safety, the city chose tap water as recharge water, however, the high cost makes it not conducive to the optimal allocation of water resources and not suitable to popularize widely. To solve this, the city selects two major surface water of River A and B as the proposed recharge water, to explore its feasibility. According to a comprehensive analysis of the cost of recharge, the distance of the water transport, the quality of recharge water and others. Entropy weight Fuzzy Comprehensive Evaluation Method is used to prefer tap water and water of River A and B. Evaluation results show that water of River B is the optimal recharge water, if used; recharge cost will be from \$0.4724/m<sup>3</sup> to \$0.3696/m<sup>3</sup>. Using Entropy weight Fuzzy Comprehensive Evaluation Method to confirm water of River B as optimal water is scientific and reasonable. The optimal water management decisions can provide technical support for the city to carry out overall groundwater artificial recharge engineering in deep aquifer.

## 1. Introduction

In many developing countries, groundwater plays a major life support to mankind, as it is the major source to support domestic needs and irrigation purposes. Groundwater occurs in a wide range of rock types and usually requires little or no treatment; therefore it is often the cheapest and simplest water supply option. However, the rising demand for water worldwide, mostly for production and irrigation, can lead to problems of over exploitation of these resources and conflicts with competing demands [1]. With the irrational development and utilization of groundwater resource, it makes a series of environmental and geological problems, such as groundwater resource depletion, land subsidence, etc [2].

Artificial recharge is one of the effective means to increase the amount of groundwater recharge, prevent and control of land subsidence, prevent seawater intrusion and storage energy [3]. In the nineteenth century, the United States and Europe had been carrying out research of artificial recharge [4], and after the 1930s, it had been widely used in more than 30 countries and regions in the world [5].



Now, the technique of artificial recharge is very mature, and more widely applied.

With the rapid economic growth, the over-exploitation of groundwater resources has existed for a long time, which leads to the serious land subsidence and groundwater resources depletion in the city. To solve the above environmental geology problems, the city conducted groundwater artificial recharge test which was taken a typical site as an example, because of water quality of the target aquifer is good, and the aquifer will be a reserve after recharge, therefore, tap water with good water quality and easily recharged is used to be the first choice of recharge water. However, the high cost makes it not conducive to the optimal allocation of water resources and not suitable to popularize widely. To solve this, the city selects two major surface water of River A and B as the proposed recharge water, to explore its feasibility.

In order to prefer tap water and water of River A and B, it should be a comprehensive analysis a variety of factors, such as the cost of recharge, the distance of the water transport, the quality of recharge water and others, the factors is independent that is difficult to determine which factors play a leading role. Therefore, it needs to carry out a multi-criteria decision-making to evaluate the optimal water, so that the result of evaluation will be more objective and reasonable. Domestic and foreign experts and scholars made numerous studies on multi-criteria decision-making evaluation; fuzzy theory is most widely applied, the weights of indicators are to measure their impact on the final decision, and they are of great importance [6]. Obviously the greater the weight of an indicator is, the greater its impact is on the decision [7]. However, they have many limitations of the method to calculate the definition of weights, such as tedious calculation, heavy workload, and no considering the link between multiple indicators, and so on [8]. Fuzzy Clustering Method, Analytic Hierarchy Process (AHP), and Fuzzy Comprehensive Evaluation Method are common and traditional analysis methods in the fuzzy theory; especially Fuzzy Comprehensive Evaluation Method is widely used in optimal allocation of water resources, groundwater resource management decisions [9-12], etc. Subjective methods of determining the weight, such as Fuzzy Comprehensive Evaluation Method, are also in use, but this may cause the bias of evaluation results because of subjective factors [13]. To solve the problems above, Zou, *et al* [14] proposed a new weight evaluation process using entropy method. It is based on actual data of indicators which reflects the changes of objective information [15]. Thus it is an objective method, and can reduce effects of subjective factors. It is a simple calculation, which simplifies fuzzy evaluation process greatly. The workload can be reduced evidently. Another remarkable character is to avoid equalization of weights distribution [16]. By using the fuzzy mathematics and entropy theory, the evaluation results of the fuzzy synthetic evaluation would be more scientific and reasonable than the normal methods.

In summary, Entropy weight Fuzzy Comprehensive Evaluation Method will be used to determine the optimal recharge water in the paper.

## 2. Materials and methods

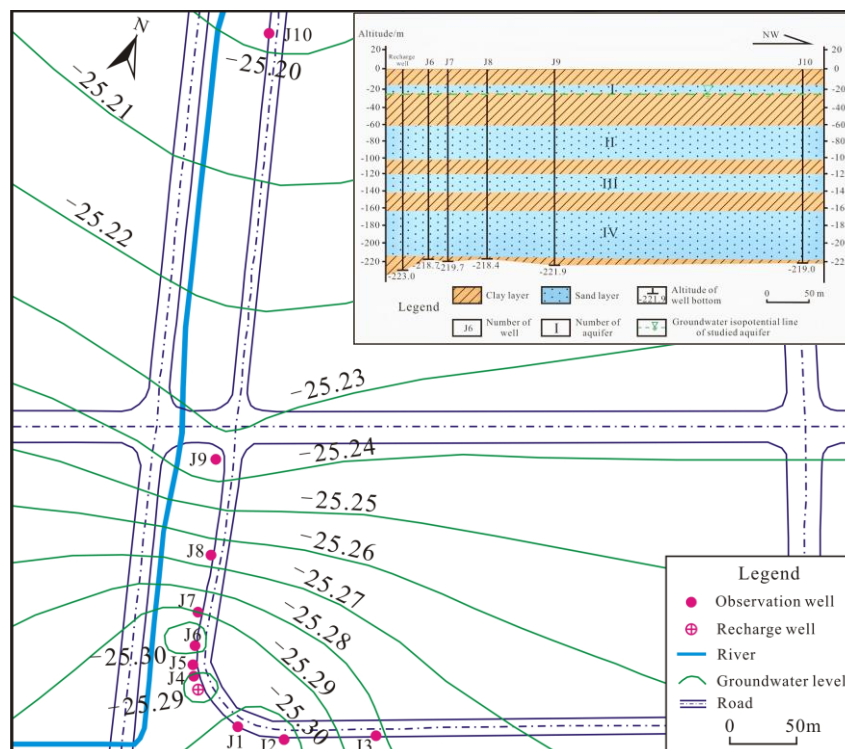
### 2.1. Study area

The study area is located in the city; north-east China, as a result of the rapid development of the city's economy, the 1st to 4th aquifers were exploited with a large number while water quality of 1st to 3rd aquifers were contaminated by human activity. In order to control land subsidence and save water resources, the 4th aquifer is used as a backwater source for the city after recharge. The city chooses the artificial recharge test site as typical, if successful, it will be fully promoted in the city. The target aquifer is the fourth confined aquifer which will be the city's water reserves after recharge in figures 1 and 2 (the maps were obtained from Shanghai Institute of Geological Survey). The key aquifer is the 4th confined aquifer, a homogeneous isotropic aquifer, about 50 m thick. Lithology is mainly gray gravel with the fine sand and the coarse sand. Aquifer elevation and hydraulic conductivity are -170 m and 50 m/d respectively, and the hydraulic gradient along the flow direction is about 0.3‰. The city has two major rivers with plenty of water, taking River A and B as the proposed recharge water. Water points of River A and B were selected as the nearest water intake, the distance from the water intake of

River A and River B to water treatment plant are separately 14.4 km and 13.8 km, water treatment plant is 2.4 km away from recharge test site. Test results of water of River A and B show that components of concentration in excess are total iron, manganese and TOC. According to the most stringent specifications, if the two alternative water will be recharged, water of River A and B must be transferred to water purification plant, the quality of the water is up to the standard (GB/T14848-2007), the recharge water was selected with the lowest cost, according to the cost of water taken and treatment, and then be recharged to the target aquifer.



**Figure 1.** Location of the study area.



**Figure 2.** Schematic diagram of the groundwater isopotential line in the 4th confined aquifer in the test field.

## 2.2. Methods

How much information obtained from the evaluation and decision-making is one of the decisive factors about the accuracy and reliability of evaluation [17]. In information theory, entropy is the measure of the disorder degree to the system, it can also measure the data provided by the information effectively. Therefore, entropy can be used to determine the weight [18]. When value of the evaluation objects on an index is larger, the entropy value is smaller, shows that the larger amount of effective information provided by the index, the bigger weight, otherwise, if the difference between the values is smaller, the entropy value is larger, means that the index provides a smaller amount of information, the weight is smaller [19]. Therefore, the entropy theory is a kind of objective weighting method.

*2.2.1. Normalization of the original evaluating matrix.* Suppose there are evaluating indicators counted  $m$ , evaluating objects counted  $n$ , then forms an original indicators value matrix  $U = (u_{ij})_{m \times n}$

$$U = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ u_{m1} & u_{m2} & \cdots & u_{mn} \end{bmatrix} \quad (1)$$

The selection of the optimal recharge water is a comprehensive evaluation result. According to the principle of the evaluation index of the testability, reliability and adequacy, therefore,  $U$  contains indicators of economic cost, technical feasibility and water quality. All calculations were done by computing platform which is spss18.0.

Normalization this matrix to get equation (2):

$$R = (r_{ij})_{m \times n} \quad (2)$$

where,  $r_{ij}$  means the data of the  $j$ th evaluating object on the indicator, and  $r_{ij} \in [0,1]$ . Among these indicators, to which the bigger the better, there are

$$r_{i,j} = \frac{x_{i,j} - \min\{x_{i,j}\}}{\max\{x_{i,j}\} - \min\{x_{i,j}\}} \quad (3)$$

while, the smaller the better, there are

$$r_{i,j} = \frac{\max\{x_{i,j}\} - x_{i,j}}{\max\{x_{i,j}\} - \min\{x_{i,j}\}} \quad (4)$$

Normalization matrix is

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \cdots & r_{mn} \end{bmatrix} \quad (5)$$

Initial parameters is obtained by the factual research and test data. Since each element is composed of different dimensions, they cannot be directly compared, and it is necessary to normalize, the assumptions are that all the different parameters can be normalized. The key of the fuzzy evaluation model is that parameters must be normalized.

*2.2.2. Definition of the entropy.* In the  $m$  indicators,  $n$  evaluating objects evaluation problem, the entropy of  $j$ th indicator is defined as



$$H_j = -k \sum_{i=1}^n f_{ij} \ln f_{ij} \quad (i=1,2,\dots,m) \quad (6)$$

In the equation:  $f_{ij} = r_{i,j} / \sum_{j=1}^n r_{i,j}$ ,  $k = 1/\ln n$ , when  $f_{ij} = 0$ ,  $\ln f_{ij}$  has no mathematical sense, therefore need to be revised to the  $f_{ij}$ ,  $f_{ij} = (1 + r_{i,j}) / \sum_{j=1}^n (1 + r_{i,j})$ .

The coefficient of  $H$  indicates that the larger the value, the greater influence. According to the aim, the optimal water is determined by the minimizing economic cost, maximizing technical feasibility, and optimizing water quality.

**2.2.3. Definition of the weight of entropy.** Weight of entropy is a method of determining the weight based on the degree of discretization, which can avoid subjective human disturbance. The effect of different evaluation indexes on optimal water source selection is different. Therefore, in order to make the evaluation results more objective and true, this paper uses the weight of entropy to determine the index weight.

The weight of entropy of  $j$ th indicator could be defined as:

$$w_j = \frac{1 - H_j}{n - \sum_{j=1}^n H_j} \quad (7)$$

in which  $0 \leq w_j \leq 1$ ,  $\sum_{j=1}^n w_j = 1$ . Weight of entropy matrix is

$$W = (w_1 \quad w_2 \quad \dots \quad w_n) \quad (8)$$

**2.2.4. Entropy weight fuzzy comprehensive evaluation method.** The entropy weight and fuzzy normalization matrix are combined to Entropy weight Fuzzy Comprehensive Evaluation Method. The influence factors of the optimal water source were determined and judged, the judgment matrix is equation (9):

$$Q = W \otimes R = (w_1 \quad w_2 \quad \dots \quad w_n) \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \quad (9)$$

According to the calculation result of the judgment matrix, combining the principles of minimizing economic costs, maximizing technical feasibility, and optimizing water quality, and then the optimal recharge water source is selected to recharge to the 4th confined aquifer to control land subsidence and save water resources. After the successfully field test, the optimal recharge water will be fully promoted in the city, and a comprehensive artificial recharge program and requirements will be put forward.

### 3. Results and discussion

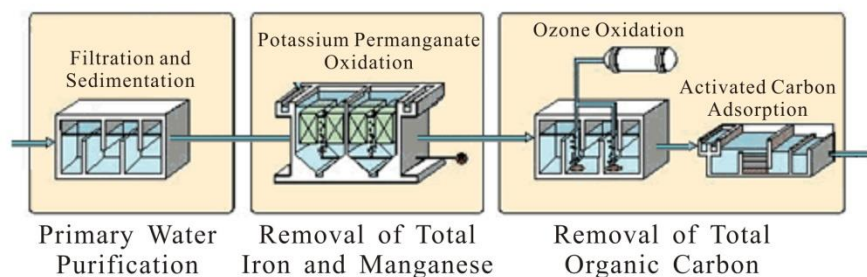
According to a comprehensive analysis feasibility of tap water and water of River A and B as recharge water, three indicators of recharge water management are identified, indicators of economic cost, technical feasibility, water quality, respectively. According to the actual situation and combining the local water policies, the indicator of economic cost can be disassembled to treatment cost, transportation cost and additional cost of recharge water. Water from river to aquifer need to be transported and purified, the indicator of technical feasibility consists of three parts, ease of water treatment; the distance of water transport and water storage condition. According to the test reports of

water of River A and B, components of concentration in excess are total iron; manganese and TOC, so, the indicator of water quality consist of total iron, manganese and TOC.

### 3.1. Economic cost

The tap water price for administrative business in the city is  $\$0.3258/\text{m}^3$ , treatment and operating cost are  $\$0.1955/\text{m}^3$  and  $\$0.1303/\text{m}^3$ , municipal water recharge needs to pay the recycled water fee which is  $\$0.1466/\text{m}^3$ , and additional cost is  $\$0.2769/\text{m}^3$  which is the sum of operating and recycled water fee.

As recharge water, water of River A and B need to remove iron, manganese and TOC, water treatment process is determined in the water purification test field as figure 3:



**Figure 3.** Water treatment process flow diagram.

The treatment cost of water of River A and B is consist of the primary treatment cost and removing iron, manganese and TOC cost, the sum are separately  $\$0.1565/\text{m}^3$  and  $\$0.1583/\text{m}^3$ . Additional cost is operating cost which is the same to tap water that contains equipment cost, maintenance cost, management cost, etc. The transportation cost of water of River A and B are separately about  $\$0.08438/\text{m}^3$  and  $\$0.08096/\text{m}^3$  [20].

### 3.2. Technical feasibility

Technical feasibility index cannot be used to evaluate the superiority of index through quantitative assignment, thus, the subset assignment need to use theory and method of dealing with fuzzy system regularity, it takes only two values of ordinary set theory which are 0 and 1, the variable relationship is “one or the other” [21].

Tap water was recharged to aquifer without any treatment, the process is the simplest, assignment is as curtained as 0; the above-mentioned treatment technology which is used to purify water of River A and B is more complicated than tap water, thus the assignment of the two water source is 1. The distance from the water intake of River A and River B to the test site are separately 14.4 km and 13.8 km (figure 1). Tap water was recharged without storage, the assignment of the distance is 0. After removing iron, manganese and TOC, water of River A and B need to be stored separately rather than drinking water, the storage condition is more complex than tap water; thus, the assignment is 1.

### 3.3. Water quality

According to the test data of total iron, total manganese and TOC of three kinds of water which were tested by the Lab of Shanghai Institute of Geological Survey, the total iron concentration of tap water, water of River A and B are separately 0.14, 2.33 and 2.18 mg/L; the total manganese concentration are separately 0.005, 0.32 and 0.26 mg/L; and the TOC concentration are separately 1.885, 5.9 and 6.7 mg/L.

### 3.4. Discussion

Entropy weight Fuzzy Comprehensive Evaluation Method is built according to the factual research and test data, proper order of the matrix is tap water and water of River A and B.

$$U = \begin{bmatrix} 0.1955 & 0 & 0.2769 & 0 & 0 & 0 & 0.14 & 0.005 & 1.885 \\ 0.1565 & 0.08438 & 0.1303 & 1 & 14.4 & 1 & 2.33 & 0.32 & 5.9 \\ 0.1583 & 0.08096 & 0.1303 & 1 & 13.8 & 1 & 2.18 & 0.26 & 6.7 \end{bmatrix}$$

First of all, normalize the original matrix by equations (2)-(5). The entropy and its weight could be calculated according to equations (6) and (7), the calculated results of entropy and its weight as below:

$$H = (0.2408 \quad 0.3155 \quad 0.4530 \quad 0.4507 \quad 0.4531 \quad 0.4507 \quad 0.4624 \quad 0.4616 \quad 0.4619)$$

$$W = (0.1446 \quad 0.1302 \quad 0.1044 \quad 0.1046 \quad 0.1042 \quad 0.1046 \quad 0.1024 \quad 0.1026 \quad 0.1025)$$

It can be observed from the calculated value of entropy and its weight that the difference between each index is large, especially the first two indicators which are treatment cost and transportation cost. Among the results, the two smallest value of entropy are 0.2408 and 0.3155, and the largest value of weight are 0.1446 and 0.1302, according to the theory of entropy and its weight, it points out that the two indexes occupy the most important position and have the largest impact for selecting optimal water source. It means that economic cost factors also play the decisive role.

Through adding the results of entropy weight into fuzzy normalization matrix, judgment result is made to be more precise to show the impact of each indicator for selecting optimal water source. According to equation (8), the calculation as below:

$$Q = (0.249 \quad 0.734 \quad 0.8215)$$

The calculated results show the comprehensive score of tap water, water of River A and B are separately 0.249, 0.734 and 0.8215. Fuzzy comprehensive judgment model take the rule that the water with the larger management indicator is the better selection. Therefore, the optimal water is water of River B. The results of entropy and its weight indicate that, if water treatment technology is feasible and quality of water is up to standards, economic cost index is the main factor to decide whether recharge water is optimal. Taking the distance of getting water, water treatment cost, water transportation cost, additional cost and other factors into comprehensive consideration, the cost of water of River B is much less than tap water, the distance of River B is shorter than River A, so, selecting water of River B as the optimal water is truthful. If water of River B is used as recharge water, the cost will decline from \$0.4724/m<sup>3</sup> to \$0.3696/m<sup>3</sup>, it will save \$0.1028 every ton. In the present quantity of recharge water (35 m<sup>3</sup>/h), after recharging five years, recharge cost of \$157.57 thousand can be saved. When the city starts to carry out the artificial recharge engineering in deep aquifer, the saving of recharge cost will be more considerable. Thus, using Entropy weight Fuzzy Comprehensive Evaluation Method to confirm water of River B as optimal water is correct and reliable. The optimal water management decisions can provide technical support for the city to carry out overall groundwater artificial recharge engineering in deep aquifer.

#### 4. Conclusions

Using Entropy weight Fuzzy Comprehensive Evaluation Method to confirm water of River B as optimal water, the optimal water is not only a technical feasible but also the lowest cost, the cost will decline from \$0.4724/m<sup>3</sup> to \$0.3696/m<sup>3</sup>. By using the fuzzy mathematics and entropy theory, the evaluation results would be scientific and reasonable. The optimal water management decisions can provide technical support for the city to carry out overall groundwater artificial recharge engineering in deep aquifer.

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