Rapid Delineation of Groundwater Enrichment Area in Arid Region of Xinjiang Based on GRSFAI

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Abstract Based on groundwater remote sensing fuzzy assessment index (GRSFAI), a research on groundwater enrichment in the arid gobi region in the southeast of Yanqi basin in Xinjiang was carried out. In consideration of the sources of groundwater, storage space and runoff conditions, remote sensing interpretation and DEM data analysis methods were adopted to extract 6 factors related to the groundwater enrichment, such as lithology, fault, relief, slope, vegetation coverage, flow accumulation. Each factor which was quantified by fuzzy comprehensive method would be calculated by AHP, and the rapid delineation of groundwater enrichment area was finally realized according to the weighted calculation results. On the basis of the research, two wells have been constructed in the groundwater enrichment area, which has water yield of 3500 m$^3$/d and 3800 m$^3$/d respectively. The reliability and applicability of the GRSFAI method to evaluate the groundwater enrichment in research area are also validated.

1. Introduction

Xinjiang is located in central Asia, most of which is gobi desert, and it is scarce in groundwater resources. In order to resolve the difficulty of groundwater exploration, remote sensing technology has been developed to extract the information of groundwater enrichment. Due to the advantages of macro, dynamic, high efficiency and low cost of remote sensing technology (Long F 2014), it can reduce the field work, improve work efficiency and quality, and obtain the hydrogeology information which is difficult to obtain by conventional field investigation. Nowadays, remote sensing technology has been widely studied and applied in arid area.

Groundwater remote sensing assessment is mainly based on the correlation of groundwater and surface water, lithology, landform, vegetation, soil moisture, temperature and other indicators. With the development of remote sensing and GIS technology, assessment of groundwater is gradually developed from qualitative to quantitative (Jha M K et al. 2010; Preeja K R et al. 2011; Jin X M et al. 2011). Using remote sensing interpretation and DEM data analysis, Yan Changhong et al.(2008) evaluated the enrichment degree of groundwater in different locations of a granite site by overlay analysis of 3 factors, such as slope, flow accumulation and fault density. M Vasanthavigar et al.(2011) used GIS and remote sensing approach to extract landform, geomorphology, water network density and fault density to evaluate the tectonic fissure water, which showed that the fault intersection was the groundwater enrichment zone. Yu et al.(2009) extracted 8 factors related to shallow groundwater by remote sensing, and used analytic hierarchy process(AHP)method to predict the groundwater enrichment area of pore water in plain. D Machiwal et al.(2011) selected 7 factors by remote sensing to evaluate the groundwater enrichment in arid areas, which showed that the evaluation results were consistent with the field verification. Deng Zhengdong et al.(2013) quantified 7 factors by fuzzy membership function, including lithology, landform, slope, etc, and for the first time constructed the groundwater remote sensing fuzzy assessment index (GRSFAI) and accurately reflect the degree of
groundwater enrichment. Xu Chunhua et al.(2015) studied on shallow groundwater enrichment in Tibet Ali by GRSFAI, which showed that the index was reliable and applicable for evaluating the groundwater enrichment.

On basis of GRSFAI, this paper studied the groundwater enrichment in arid gobi region of Xinjiang. Several factors of groundwater enrichment were analyzed and extracted according to the supply sources, storage space and runoff conditions of groundwater, and these factors were quantified by the fuzzy comprehensive method. Then the mathematical model of the groundwater enrichment area was constructed and calculated by AHP. By using this model, the characteristics of groundwater distribution were comprehensively mastered, and the aim of the rapid delineation of groundwater enrichment area was finally realized. The result provides a basis for the water source selection and utilization of groundwater resources in this area.

2. Research area and data processing

2.1 General situation of research area
The research area is located in the southeast of Yanqi basin in Xinjiang (Figure 1), which is generally high in the southeast and low in the northwest, with an altitude of 1055~1756m, and a total area of about 1300km². The area is in the transition zone of southern and northern Xinjiang, deep in central Asia. The temperature changes a lot every day, with scarce rainfall and large evaporation of all time. The average annual rainfall is only 107mm, and the amount of evaporation is over 2000mm. The highest temperature in summer can reach 40.5℃, and the minimum temperature in winter can be reduced to -27.6℃. There are only a few springs in the southern mountains, with no perennial river in research area. The groundwater type is mainly pore water, which is stored in Quaternary gravel layer. The Bosten lake is in the northwest of the research area, which is an inland freshwater lake with a total area of 1100km².

2.2 Remote sensing data processing
SPOT 5 satellite images, with a full color resolution of 2.5m and a multispectral resolution of 10m, were selected to carry out remote sensing interpretation for this research. The ERDAS was used for remote sensing image registration, and the base map with scale and measurement function was formed. By means of image fusion, ortho-rectification and image enhancement, we eventually obtained the 2.5m color digital orthogonal projection image.

DEM data is based on a basic scale of 1:50000, which is provided by the national bureau of surveying and mapping, with a horizontal resolution of 25m and an elevation resolution of 5m.
3. Analysis method

Due to the relativity and fuzziness of groundwater enrichment, there is no absolute good or bad, and the fuzzy mathematics method can objectively evaluate the degree of groundwater enrichment (Yang LB et al. 2003). Through the combination of remote sensing interpretation and DEM data analysis, 6 factors related to the groundwater enrichment were extracted with the field investigation, such as lithology, fault, relief, slope, vegetation coverage and flow accumulation. Then the membership function of various factors and groundwater enrichment was established by fuzzy mathematics, which was quantified into the 0-1 interval (Equation (1)), with 0 representing the worst groundwater enrichment and 1 representing the best.

\[ P_i = f(x_i) \in [0,1] \]  

(1)

Where \( x_i \) is the evaluation factor, \( f \) is the membership function, \( P_i \) is the fuzzy membership of each factor.

After the quantification of evaluation factors, the quantified raster graphs of each factor were weighted to obtain GRSFAI (Equation (2)) with ArcGIS.

\[ \text{GRSFAI} = \sum_{i=1}^{n} P_i \times \omega_i \]  

(2)

Where \( P_i \) is the fuzzy membership of each factor, \( \omega_i \) is the weight of each factor, \( \text{GRSFAI} \) is the groundwater remote sensing fuzzy assessment index.

4. Extraction and quantification of evaluation index

The evaluation factors should be normalized before GRSFAI is used to evaluate groundwater enrichment, in order that the factors can be compared and evaluated directly. In this paper, the fuzzy comprehensive evaluation method is adopted, and the membership function of each factor is established with the trig function of linear segment.
4.1 Lithology
The pore in the stratum is the basis of groundwater storage, which plays a decisive role in the occurrence and migration of groundwater. Through the artificial visual interpretation of the SPOT image by means of ERDAS and MAPGIS, referring to research area 1:200000 geological map, the lithology of the research area was divided, and the water-rich of the stratum was distinguished by the porosity of the formation. As a result, there are five types of lithology in the research area, namely, the middle Pleistocene proluvium (Q2pl), the Holocene proluvium (Q3-4pl), the Holocene eolian sediments (Q3-4eol), the Holocene lacustrine sediments (Q3-4l), the Sinian clastic rock (Z). According to the properties of water-rich, membership degree of each type of lithology was given a value of 0.4, 1.0, 0.8, 0.6 and 0.2 respectively, and the quantitative lithology thematic map was obtained by ArcGIS (Figure 2a).

4.2 Fault
Fault is a controlling factor of the occurrence of groundwater. The larger fault scale and wider influence zone will result in higher fracture development and better groundwater enrichment. Meanwhile, the fracture development degree of fault influence zone is also related to rock hardness. Fracture development in hard brittle stratum makes the stratum rich in water, and the water in soft-plastics stratum is poor with few fractures in it. Therefore, the membership of the fault influence zone is assigned by overlay analysis of the fault influence zone and the stratum. The influence zone widths of different levels of faults in the research area are presented in Table 1.

| Fault level       | Classification standard | Influence zone width/m |
|-------------------|-------------------------|------------------------|
| Lithosphere fault | I                       | 500                    |
| Regional fault    | II                      | 300                    |
| General fault     | III                     | 100                    |

According to the rock hardness, the membership of the fault influence zone is assigned by Equation (3).

\[ C_F = \begin{cases} 
1 & \text{brittle stratum} \\
0.5 & \text{transitional stratum} \\
0 & \text{plastic stratum} 
\end{cases} \]  

(3)

Yanqi fault is the regional fault in the research area (Xu X F et al. 2014), which controls the division of the stratum and groundwater. Other faults in this area are general. Through the image transformation of multispectral remote sensing image, the feature of faults were highlighted (Wang Q J et al. 2009), and the results of fault interpretation in the research area were obtained. The membership of fault was given according to fault level and rock hardness of fault influence zone. The thematic map of fault was obtained using ArcGIS(Figure 2b).

4.3 Relief
The extent of groundwater enrichment is often determined by geomorphic types. According to the form, origin and topographic relief, it can be classified into 3 types as follows: plain, hill and mountain, with a topographic relief of less than 30m, 30~70m and more than 200m respectively. The richness of groundwater decreases as the topographic relief increases. Therefore, it is considered that the water-rich in the plain is the best, the second in the hills, and the worst in the mountains. The fuzzy comprehensive evaluation method was used to establish the membership function (Equation (4)) with linear trig function, and thematic map of relief was obtained (Figure 2c).
Where $x$ is relief.

4.4 Slope
Learning from the research of Tang Guoan (2006), and referring to the classification basis of soil and water conservation norms, it is more beneficial to groundwater enrichment in flat area (slope value is less than 3 degrees). On the contrary, it is unfavorable to groundwater enrichment, when the ground is relatively steep (slope value is greater than 20 degrees). The slope analysis of the research area was carried out with ArcGIS based on DEM data. The fuzzy comprehensive evaluation method was used to establish the membership function (Equation (5)) with linear trig function, and the thematic map of slope was obtained (Figure 2d).

$$C_S = \begin{cases} 
1 & x \leq 3 \\
\frac{20 - x}{17} & 3 < x < 20 \\
0 & x \geq 20
\end{cases}$$

(5)

Where $x$ is slope.

4.5 Vegetation coverage
Vegetation is a direct instruction factor of groundwater in arid areas. Its growth is directly controlled by climate, lithology, landform and hydrology geology conditions, especially the shallow groundwater in the region. Vegetation can reflect the buried depth, chemical types and TDS of groundwater. The shallow groundwater is abundant in areas with large vegetation coverage, and it is scarce in areas with low vegetation coverage. Based on remote sensing technology, the vegetation information was extracted by pixel decomposition model (Purevdor J et al. 1998). The study shows that when the vegetation coverage is less than 60%, the surface is mainly rock, bare soil and desert, where the groundwater enrichment is poor, and when the vegetation coverage is greater than 90%, the groundwater enrichment is better. Similarly, the thematic map of vegetation coverage (Figure 2e) was obtained after the establishment of the membership function (Equation (6)).

$$C_{VC} = \begin{cases} 
1 & x \geq 90 \\
x - 60 & 60 < x < 90 \\
30 & x \leq 60
\end{cases}$$

(6)

Where $x$ is vegetation coverage.

4.6 Flow accumulation
As is well known, the larger the flow accumulation is, the more easily the surface runoff is formed. Shallow groundwater is often rich where there is a higher accumulation volume. However, when the flow accumulation is too large that the surface runoff is formed, it is not conducive to exploit groundwater. Therefore, the hydrologic analysis was carried out with the DEM data of the research area, and the flow accumulation was divided by the auxiliary data, including topographic maps, drainage maps, and so on. The study indicated that surface runoff formed when the flow accumulation exceeded 80,000. Accordingly, the fuzzy membership function (Equation (7)) was established and the flow accumulation thematic map (Figure 2f) was obtained based on the relationship between flow accumulation and groundwater enrichment.

$$C_R = \begin{cases} 
1 & x \leq 30 \\
\frac{200 - x}{170} & 30 < x < 200 \\
0 & x \geq 200
\end{cases}$$

(4)
\[ C_{FA} = \begin{cases} 
0.0002x & 0 \leq x \leq 1000 \\
1 & 1001 < x < 12000 \\
-2.94 \times 10^{-6}x + 1.0353 & 12001 \leq x \leq 80000 \\
3.408 \times 10^8x^{-1.76} & x > 80000 
\end{cases} \] (7)

Where \( x \) is flow accumulation.

5. Evaluation of groundwater enrichment based on GRSFAI and verification

According to the hydrogeological characteristics of the research area, the contribution of each factor to the enrichment of groundwater was analyzed comprehensively, and the weight (\( \omega_i \), a total of 10) of each factor was determined by using the method of expert grading, the values of \( \omega_L \), \( \omega_F \), \( \omega_R \), \( \omega_S \), \( \omega_{VC} \), \( \omega_{FA} \) are 2.5, 1.0, 2.0, 1.5, 1.0, 2.0. The GRSFAI and the map of groundwater enrichment target area were obtained according to Equation (2) with ArcGIS (Figure 3). According to the map, the areas with higher scores in the groundwater enrichment are better than those with lower scores.
As is shown in Figure 3, the primary groundwater enrichment area is mainly in the central and north-central part of the research area, covering a total area of 161km², accounting for 12.3% of the total area. The distribution of groundwater enrichment areas is controlled by surface drainage, landform and lithology, which are characterized by low-lying terrain, good supply conditions and well-developed pores.

The secondary groundwater enrichment area is in the front of the alluvial-proluvial plain in central research area, which is mainly distributed on the periphery of the primary groundwater enrichment areas, covering an area of about 210km², accounting for 16.5% of the total area. The terrain is relatively flat, the surface gully is developed, and the surface runoff is slow in this area. The stratum is mainly composed of alluvial-proluvial gravel layer and well-developed pores, where the groundwater is well preserved, and the burial depth of groundwater is shallow.
The tertiary groundwater enrichment area is in the alluvial fan in the south and north of the research area. These areas have great topographic relief, strong surface runoff, poor supply conditions and a large burial depth of groundwater.

The poor groundwater area is mainly distributed in the mountains in the south, east and northeast of the research area. This area covers an area of 231km², accounting for 17.8% of the total area. In addition, the groundwater of the hilly areas in the Midwest of the research area is also poor. These areas have great topographic relief, good surface runoff conditions, and the stratum is mainly composed of bedrock and cementation gravel layer, which is unfavorable to groundwater enrichment.

According to the result map of groundwater enrichment target area and field hydrogeology survey, the No.4 and No.5 wells were built to meet the needs of actual engineering (Figure 4). The water yield of each well reached 3500m³/d and 3800m³/d respectively. The drilling data shows that there are two aquifers in this area, the upper aquifer is composed of breccias and gravel sand, and the lower aquifer is composed of gravel sand. The results confirm that the groundwater in this area is abundant.

In order to further verify the effectiveness and applicability of GRSFAI in arid area, data of some wells and hydrological exploration borehole in the research area have been collected to draw the contour map of water yield. Figure 4 shows that the groundwater enrichment area based on GRSFAI is consistent with the actual survey results.

![Figure 4. The contour map of water yield in the research area](image)

6. Conclusion
This paper studied on the groundwater enrichment in arid gobi region in the southeast of Yanqi basin in Xinjiang based on GRSFAI, and the research area was divided into four levels of groundwater enrichment area. Then the No.4 and No.5 wells were built to meet the needs of actual engineering, and the water yield of each well has reached 3500m³/d and 3800m³/d respectively. The results verified the effectiveness and applicability of GRSFAI in arid areas.

The research shows that GRSFAI can be used for groundwater exploration in arid area, and it has the advantages of rapidity, quantification, synthesis, accuracy and good applicability. Different from traditional hydrogeological survey method, remote sensing interpretation and DEM analysis were used as the main research methods, which is amended by hydrogeological survey appropriately. The method finally realizes the goal of reducing the field work and the rapid delineation of the groundwater enrichment target area.

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