Groundwater Source Analysis in Fractured Rock Mass Based On Multi-Source Hydrogeology Information

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Abstract. The recharge source of groundwater is an important part of groundwater circulation. Controlled by geological structures, the distribution of groundwater in bedrock area is complicated. The study on the source of groundwater in bedrock has guiding significance for the evaluation of water source site and groundwater exploitation. By analyzing the model of water-rich zone based on remote sensing information, and according to the groundwater dynamics, major ion concentration, velocity and direction of groundwater flow, pumping and water level data of water source site, this article studies the source of groundwater recharge of Barakan Water Source Site (BWSS) in front of Kuruktag, northwest of China, and analyses the reasons for the abnormal change of the total water yield and the drawdown of the well. The results show that the groundwater of the water source site comes from the Aggregate Reclaiming Plant (ARP) about 6.5 kilometers northwest of BWSS. The ARP water pumping is the main reason of the abnormal change of the total water yield and the drawdown of the well of BWSS. Based on this conclusions, the methods to protect the water source site safety are put forward.

1.INTRODUCTION

Groundwater recharge is an important part of groundwater circulation[1,2]. It is of great practical significance to study the source of groundwater recharge for the evaluation of the water source site, the rational exploitation and utilization of groundwater, and underground engineering drainage. Compared with the groundwater in the unconsolidated sediments, the bedrock fissure water is mainly controlled by the distribution and development of crack in the rock. It has the characteristics of extremely uneven burial and distribution, variety of aquifers, obviously controlled by geological structure and hydrodynamic conditions, etc[2]. Therefore, the source analysis of bedrock fissure water has always been a difficult problem in the study of hydrogeology.

At present, the research on groundwater source is mostly based on hydrogeological data, hydrochemical and isotopic data analysis. Based on the analysis of D, 18O and Cl compositions distribution characteristics of soil water in loess section, Chen Jiansheng, et al. [3] pointed out that the main source of replenishment of Ordos Basin is exogenous water. Through hydrochemistry and environmental isotop tracer technique, Qian Yunping, et al.[4] analyzed the source and circulation characteristics of deep groundwater in Egina Basin. He pointed out that the source of deep groundwater recharge in Heihe Basin is multisource, mainly the old water formed before 1950s, and the water circulation is slow. By analyzing the relationship between hydrochemistry and stable isotope of hydrogen and oxygen, Zhang Qinghuan, et al.[5] studied the groundwater recharge mechanism and hydrochemistry evolution rule in Liyuan River area. By hydrogeochemical information analysis, Sun
Ronglin, et al.[6] pointed out that the groundwater in the dam site of a hydropower station in southwest China is mainly a mixture of the lateral recharge of the granite fissure water and the leakage of the diversion tunnel. The above researches have achieved good results in the analysis of groundwater sources, but the research methods used in these studies are relatively simple and need to accumulate a large amount of hydrochemical and isotopic data. It is not ideal for the application of groundwater sources in some fractured rock masses with complex geological structures.

In view of the abnormal change of total water yield and water level drawdown of Barakan Water Source Site (BWSS) in front of Kuruktag Mountain, the model of groundwater enrichment area based on remote sensing information is established, and the source of groundwater recharge is studied in combination with the abnormal analysis of the multi source hydrogeological information, such as the dynamic data of the groundwater, the main ion concentration, groundwater velocity and direction, water level and quantity of water source. The reasons for abnormal changes of water level and water volume are analyzed in detail, and on this basis, measures for maintaining the safety of BWSS are put forward.

2. Water source profile

The BWSS is located in Gobi in front of Mount Kuruktag, northwest of China, where no perennial river exists (shown in Fig.1). The water source is the only water supply in Kuruktag mining area. It has a typical arid continental climate with a precipitation of 63.7~196.6mm/a and an evaporation of 2200~2700mm/a. The precipitation concentrates mostly in the mountain on the north side of the BWSS, and occurs in the form of rainstorm between July and September. The rock types are mainly migmatite, schist, marble, plagiogranite and granite-gneiss, etc. Influenced by multi-stage tectonic movement and strong physical weathering, these rock masses have developed fractures and laminates with poor filling cementation, forming the main aquifer of the BWSS.

Fig. 1. The sketch of study area.

Dry gullies around the study area are well developed. Rainstorms often form ravine currents in summer, providing temporary recharge for groundwater. According to the relevant data, the groundwater in the study area mainly receives the infiltration of precipitation and flood in the northern mountainous areas, which is transported from the west to the southeast, and is ultimately drained through submersible surface evaporation (including plant transpiration), spillover of spring and recharge of downstream aquifer [7~9]. There are a number of sand dunes in the BWSS, with reeds and camel thorn growing on them, and scattered shrubs around them. There is a spring in the vicinity which has a flux of about 100m³/d. According to the hydrogeological exploration, there is a groundwater enrichment zone of about 700×200m in the BWSS. The groundwater depth in this zone is 2~7m, and the water inflow of a single well is about 1000m³/d with a drawdown of 5m. The groundwater depth outside of this zone is generally greater than 10m, and the water inflow of the single well is less than 100m³/d.
3. Analysis of groundwater source

3.1 Analysis of the model of groundwater enrichment area

The rainfall in the study area is mainly topographic rain. As stated previously, the rainfall is mainly concentrated in the mountains in the northern part of the BWSS, and recharge groundwater by infiltration as well as flood. Influenced by topographic landforms, lithology and geological structure, the groundwater flows from the north to the south and forms a point or strip of groundwater enrichment area where conditions of water enrichment are favorable, and the vegetation is well developed.

Three hydrogeological boreholes (located at the top, middle and middle-lower part of the alluvial fan) are constructed on the alluvial fan on the northwest of the BWSS. Water inflow of each well is less than 100m$^3$/d, indicating that the water of the alluvial fan is poor, and the groundwater in the BWSS is not mainly supplied by the alluvial fan. In order to analyze the possible source of groundwater, remote sensing images are used to extract the information of terrain, geomorphology, geological structure, lithology, vegetation, and flow accumulation. By analytic hierarchy process, a model of groundwater enrichment zone is established. The related methods [10] were used to quantify different impact factors. According to the hydrogeological conditions of the study area, the weight of each influence factor is determined by expert scoring. The specific value is shown in Table 1.

| Geological Condition Types     | Weight |
|--------------------------------|--------|
| Vegetation                    | 2      |
| Confluence accumulation       | 1.5    |
| Geological structure          | 2      |
| Formation lithology           | 2      |
| Topographic slope             | 1.5    |
| Landform                      | 1      |

According to the above method, the model of groundwater enrichment zone in the study area is obtained. As shown in Fig.2, there are two main groundwater enrichment zones in the study area, one for the fractured rock mass of the piedmont in the northern part of the study area, the other near the BWSS. In order to verify the correctness of the model, a pumping test was carried out in the study area, and the water inflow from a single well with drawdown of 5m was obtained, as shown in Fig.2. It can be seen the high yield borehole is located at the water-rich zone, and the model is credible.

According to the fact of the water rich in the east-west fault zone in the northern part of the study area and the water scarcity of the alluvial fan in the north side of the BWSS, we conclude that the groundwater in the northern mountainous area is moved from the north to the south. Due to the water resistance in vertical fault direction and the water guide along the fault direction, the groundwater is enriched at the fault and migrated along the fault, and the lateral recharge of the groundwater enrichment zone to the southern aquifer is relatively weak in the study area.

The groundwater enrichment zone near the BWSS is in the southern part of Fig.2. Combined with the abundant water volume in the aggregate reclaiming plant(ARP) in northwest side of the BWSS, it can be inferred that the groundwater in the BWSS may have a certain connection with the groundwater enrichment zone.
3.2 Dynamic characteristics of groundwater
The interannual variation curve of the water table of 3 hydrogeological boreholes was collected. As shown in Fig.3a, the groundwater level of the BWSS was found to reach the annual lowest level in July–October, and the maximum was in February–June, and the interannual variation was about 20 to 50cm. This does not coincide with the rainy season in the region (generally in July–September of the year), while the rise of the groundwater level in the surrounding boreholes is generally consistent with the annual rainfall time (Fig.3b). With the arrival of the rainy season, the water level begins to rise in July, and to fall in September to the lowest level in the following July, and annual variations reach 20cm ~ 2m. It can be seen that the time of groundwater depth variation of the BWSS is not coincide with local rainy season, and the value of variation is also small, which indicates that the groundwater in the BWSS is not mainly from the infiltration of the local rainfall.

3.3 Principal ion concentration ratio analysis
In the process of groundwater migration, the concentration of the main ions of groundwater changes continuously with the influence of lithology, evaporation and recharge, forming a unique hydrochemical field with certain connections. Therefore, the ratio coefficients of various ions in groundwater are the effective indexes to study the evolution law of underground water. In general, Cl⁻/Ca²⁺ mainly reflects the hydrodynamic conditions, while Mg²⁺/Ca²⁺ and Na⁺/Mg²⁺ reveal the intensity...
of mineralization, and $\text{SO}_4^{2-}/\text{Cl}^-$ gives the strength of evaporation and concentration, and $\text{Cl}^-/\text{HCO}_3^-$ can be used as the parameters of anionic evolution process and the component distribution of hydrogeochemical[5,11].

The main ion concentrations of four places (the northern mountain area, the northern alluvium fan, the BWSS and the ARP) are obtained. According to the location of the sampling points, 4 groups are divided and the average value of the main ion mole concentration in each water sample is analyzed. The results are shown in Table 2. Following conclusions can be made from Table 2 along the northern mountain alluvial fan to the BWSS:

1) The TDS value of groundwater is increasing gradually, while $\text{Cl}^-/\text{Ca}^{2+}$, $\text{Mg}^{2+}/\text{Ca}^{2+}$ and $\text{Na}^+/\text{Mg}^{2+}$ increases first and then decreases. It indicates that the hydrodynamic conditions along the northern mountain area and the alluvial fan are gradually weaken, $\text{Cl}^-$ gradually enriches, $\text{Ca}^{2+}$ gradually decreases, and the mineralization is enhanced. On the contrary, the BWSS has good hydrodynamic conditions and weak mineralization.

2) The value of $\text{SO}_4^{2-}/\text{Cl}^-$ increases gradually, mainly for the reason that the rainfall decrease gradually. Furthermore the groundwater depth decrease, and the evaporation and concentration of groundwater increases gradually.

We can also find from Table 2 that the TDS and main ion concentration increases along ARP to BWSS, indicating that the hydrodynamic conditions gradually weaken, and the mineralization, evaporation and concentration are enhanced. It can be concluded that groundwater in the BWSS may be come from the direction of ARP.

| Position     | $\text{Cl}^-/\text{Ca}^{2+}$ | $\text{Mg}^{2+}/\text{Ca}^{2+}$ | $\text{Na}^+/\text{Mg}^{2+}$ | $\text{SO}_4^{2-}/\text{Cl}^-$ | TDS (mg/L) |
|--------------|--------------------------------|---------------------------------|----------------------------|-----------------------------|-------------|
| Mountain area| 3.25                           | 1.16                            | 3.95                       | 0.68                        | 841.28      |
| alluvial fan  | 3.29                           | 1.17                            | 4.95                       | 0.80                        | 902.23      |
| ARP          | 2.52                           | 1.02                            | 3.87                       | 0.79                        | 1237.25     |
| BWSS         | 3.05                           | 1.22                            | 4.36                       | 1.24                        | 1338.87     |

3.4 Principal ion concentration ratio analysis

According to the direction and velocity of the groundwater of three wells (namely SK1, SK2 and SK3) in the BWSS, the flow directions are 135°, 132° and 136° respectively, and the flow velocities are 3.67m/d, 8.16m/d and 2.88m/d respectively. It indicates that the groundwater in the BWSS flows from the northwest to the southeast, and the velocities vary greatly due to the influence of the lithology and structure of the strata. Fig.4 shows the groundwater level contour of the BWSS, which shows that the groundwater level in the BWSS is high in the northwest and low in the southeast, and the groundwater flows from the northwest to the southeast. Thus, it can be seen that the velocities of groundwater in the BWSS flows coincident with that of above wells.

![Fig. 4. Equal water level map of water source site groundwater](image)

3.5 Abnormal characteristic analysis
During the operation of the BWSS, the total water yield decreased and the drawdown of groundwater depth increased abnormally in September 2016. In order to analyze the causes and ensure water safety, field investigations were carried out, and it was found that a temporary ARP was built at about 6.5km northwest of the BWSS. The ARP began to run in August 20, 2016, with a pumping water of about 1100m³ and a returning water of about 600m³ every day, which means is, the consumption of water was about 500m³/d. Accordingly, it was concluded that the abnormal changes of water level of the BWSS were related to the pumping of ARP. In order to confirm the inference, the monitoring data of pumping and water level of the 3 wells in the BWSS were analyzed. As the pumping amount is not fixed, the water amount per day is taken according to an monthly average amount, and the drawdown taken the monthly lowest. The yield per day and the maximum drawdown of monthly are drawn respectively, as shown in Fig.5 and Fig.6.

As can be seen from Fig.5, from July to November 2016, March to November 2017, March to April 2018, the water consumption is relatively larger because of the construction of the project. From December 2016 to February 2017 and December 2017 to February 2018, the water consumption is relatively smaller due to the suspension of engineering construction. To a certain extent, pumping of the ARP has resulted in a decrease of total yield in BWSS. As can be seen from Fig.6, from July to November 2016 and March to November 2017, with the increase of water consumption for project construction and ARP running, the monthly maximum drawdown increased significantly. From December 2016 to February 2017 and December 2017 to February 2018, with the suspension of project construction and the halt of ARP, the monthly maximum drawdown decreased significantly. It is worth noting that from the beginning of the project construction in March 2018, the water level have increased obviously, and the ARP has been in a stop state at this time, which shows that the pumping of the ARP is directly related to the decline of the groundwater table and total yield of the BWSS. In order to clarify this problem, the amount of yield per meter is calculated by dividing the monthly average amount with the largest drawdown of the monthly as shown in Fig.7. From July to September 2016, it can be seen that the yield of water per meter is large, mainly because the BWSS has just started running, the depression cone is still unstable, and the pumping amount mainly comes from the recharge of the groundwater near the water source. After September 2016, the amount of water per meter decreases obviously and get stable subsequently, mainly due to the extension of the pumping time with the pumping amount mainly coming from a distant area. However, it is clear that the amount of water of the two periods (November 2016 to March 2017 and November 2017 to April 2018) is higher than that of the other two periods (September to October 2016 and March 2017 to April 2018), indicating that the decline of the groundwater table and total yield are related to the water use of ARP. It also indicates that the main source of groundwater supply comes from the direction of ARP. In addition, from Fig.5 and Fig.6, it can be seen that there is a lag time about 20~30 days between the start or the halt of the ARP and emergence of abnormality the groundwater depth or total yield in the BWSS.
3.6 Groundwater age analysis
In order to further analyze the characteristics of groundwater recharge in water source, the tritium concentration of groundwater in BWSS are obtained, as shown in Table 3. Based on the data of the tritium concentration of groundwater in BWSS from 1976 to 2014, the age of groundwater in BWSS is calculated using the piston flow model and the full mixing model respectively. And precipitation data between 1960 and 2009 are directly quoted from the literature[12]. The atmospheric precipitation concentration data between 2010 and 2014 were measured in this study. The tritium concentration-time curves between 1976 and 2014 using total mixed model (shown in Fig.8) and groundwater tritium concentration - the average retention time curve(shown in Fig.9) using piston flow model were drawn.

| Location | 1976 | 2014 |
|----------|------|------|
| SK1      | 129  | 29.80|
| SK2      | 132  | 30.65|
| SK3      | 118  | 28.18|
| average  | 126.33 | 29.54|

Table 3. The concentration tritium concentration of water source site(TU)
Using the established model and the output curve of tritium concentration, the age of groundwater in BWSS was calculated based on the average tritium concentration data between 1976 and 2014, as shown in Table 4. It can be seen from the table that the ages of groundwater in BWSS calculated by the piston flow model are 6~93 years in 1976 and 1 year in 2014 respectively. The groundwater age of BWSS calculated by the total mixed model are 1~9 years in 1976 and 2~84 years in 2014 respectively. The age of groundwater calculated by the piston flow model is small in 1976 and is larger in 2014, and the result calculated by the full mixing model is just the opposite. This is mainly due to the high tritium concentration in the precipitation in 1976, while the tritium concentration in the precipitation in 2014 is greatly reduced. Nevertheless, the piston flow model and the full mixing model are the two extremes of groundwater mixing. Therefore, the residence time of groundwater should be in between. In the absence of remarkable changes in geological conditions, the groundwater age obtained by the tritium concentration in the 1976 and 2014 should be the same, that is to say the average residence time of groundwater in BWSS is about several decades, which means the groundwater is young and close to the recharge area.

Table 4. Groundwater Age of water source site calculated use tritium concentration

| Year | Result of Piston flow model/a | Result of All mixed model/a |
|------|------------------------------|-----------------------------|
| 1976 | 1~9                          | 6~93                        |
| 2014 | 2~84                         | 1                           |

4. Analysis of groundwater recharging and discharging
The model of groundwater enrichment zone based on analytic hierarchy process shows that the groundwater in the northern mountains area mainly accepts the rainfall infiltration and moves southward. With the influence of the fault in front of the mountain, the flow direction changed, and mainly moves along the fault, and therefore the recharge of the groundwater to the south side is weak, resulting in the alluvial fan in front of the mountain water-lacking. It also means that the mountain area on the northern recharge BWSS weakly. The dynamic characteristics of groundwater shows that the rise of water level of groundwater in BWSS has a certain delay with the local rainy season, which indicates that the groundwater in BWSS is not recharged from local rainfall infiltration. The analysis of the concentration of main ions in BWSS and surrounding groundwater shows that groundwater in BWSS is more likely to come from the northwest direction. The analysis of flow velocities and directions of groundwater in BWSS indicates that the groundwater flows mainly from northwest to southeast in the local area of BWSS. The analysis of the water level data shows that the water intake of the ARP has a significant influence on the water yield and the groundwater table of BWSS, and there is a strong hydraulic connection between the ARP and BWSS. It shows that the groundwater of BWSS is recharged from the ARP mainly.

Combined with further analysis of geological structure (Fig.1) and relevant literature in the study area (Xinjiang Bureau of Geology and mineral resources second hydrogeology and Engineering Geological Brigade, 1996; Zhao Zhenhua, 2011; Wang Dongqing, 2016), it can be deduced that infiltration of atmospheric rainfall is the main source of groundwater supply in the study area. The recharge of groundwater is mainly influenced by topography, and lithology. Groundwater generally moves along the direction of terrain reduction, and is greatly influenced by the fault structure. Groundwater is enriched in the water supply side of the structure, and migrates along the fault fracture zone, and eventually excrete through transpiration and evaporation. For BWSS, the characteristic of groundwater recharge, runoff and discharge are as follows:

The recharge: the recharge area, which borders the ridge line of the Kuruktag mountain in the north, the western edge of the alluvial fan in the east, and the local groundwater ridge in the west, recharge the groundwater by rainfall direct infiltration or flood infiltration, which is the main recharge source of the groundwater in BWSS.

The runoff: groundwater is transported southward after receiving rainfall infiltration, which is enriched by the f2 fault near the ARP, and moves along f3 fault to BWSS.

The discharge: f3 thining out in BWSS, which is relatively low-lying. The main discharge way of groundwater in BWSS is spring overflowing and recharging the downstream aquifer, which finally evaporates and transpires in downstream.

According to the above analysis, the average distance between the recharge area and BWSS is about 30km, and the average flow velocity of the groundwater should be 1 to 8m/d, which is close to the velocity of the groundwater flow measured in BWSS.

5. Conclusion
Based on the model of groundwater enrichment area, and the dynamic characteristics, the main ion concentrations, the flow velocity and directions, the water table and the water yield of the groundwater, it is concluded that the groundwater of BWSS is mainly from the direction of the ARP. The characteristics of groundwater recharge, runoff and discharge are as follows. Atmospheric precipitation infiltrates and flows southward to the ARP, which is enriched by the f2 fault and moved along f3 fault to BWSS. The groundwater discharge in the form of spring and recharging the downstream aquifers.

The recharge, runoff and discharge of groundwater in BWSS are synthetically influenced by the surrounding topography, geological structure and lithology. On a regional scale, the topography dominate, and the flow direction of groundwater is from north to south. As the geological structure is dominant on the scale of water source site, the groundwater mainly distributes near the fault structure, and moves along the fault.
Groundwater recharge from the direction of ARP is the main source of BWSS groundwater, and the water intake of ARP directly affects the yield of BWSS. BWSS is the only drinking water source in the Kuruketug mining area. In order to maintaining the safety of mining area production and living water supply, the ARP should be closed or the site should be reselected.

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