Technique of the rapid detection of groundwater based on multidimensional space

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ABSTRACT

The ability to detect groundwater quickly and accurately is critical to the work of drought resistance. However, conventional groundwater detection methods are inefficient and costly. To solve the difficulties of using water in water-deficient areas, the method of rapid groundwater detection based on multidimensional space was presented. First, using satellite remote sensing (RS) technology, factors related to the occurrence of groundwater, such as lithology, structure, and landforms, were obtained. Then, through quantitative inversion of aeromagnetic data, the lithology and structure were improved. Using geographic information system (GIS) as an information analysis platform, the water storage conditions of various lithologies, structures, and landforms were comprehensively studied; and a water-rich target area was delineated. Based on the above-mentioned achievements, the ground geophysical prospecting work was carried out, the optimum well-position determined, and the target area accuracy verified by drilling data. The method integrates many technical means, such as satellite RS, airborne RS, ground physical exploration, and exploration drilling to detect groundwater, incorporating the advantages of each method. Through the preliminary application in the city of Beipiao, China, the well completion rate is 72.73%. High-quality groundwater resources were exploited in this area, proving it to be an effective method for accurately detecting groundwater.

Key words | groundwater, multidimensional space, rapid detection, remote sensing, water-deficient area

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INTRODUCTION

As we all know, groundwater is the largest available fresh water resource in the world and is distributed ubiquitously in nature (Agarwal & Garg 2016). The rapid increase in human population has increased the need to use groundwater for drinking, agriculture, and industry. Especially in arid and water-scarce areas, the surface runoff is less, so groundwater is particularly important. The Chaoyang district in northeast China has a serious water shortage. Cong *et al.* (2017) indicated that the drought in Chaoyang has become more serious, and drought resistance and disaster reduction are urgent. In the work of drought resistance, the timeliness of groundwater detection is very important. Therefore, rapid detection of groundwater has become an urgent need.

The detection of groundwater by means of ground geophysical prospecting and drilling technology has higher accuracy (Afshar *et al.* 2015; Akinrinade & Adesina 2016; Anomohanran *et al.* 2017; Liu *et al.* 2017), but it has the disadvantages of high workload, low efficiency, and limitations imposed by topography and geomorphology, meaning that it has difficulty in meeting the demand in water-deficient areas. Remote sensing (RS) is considered to be a fast and efficient groundwater detection method (Yu *et al.* 2009; Khodabakhshi *et al.* 2015; Tahmassebipoor *et al.* 2016;

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Xu *et al.* 2018); however, because of the limited resolution of RS data, it has relatively low accuracy, can only reach the requirements of hydrogeological survey, and cannot determine the optimal parameters for well mining. Therefore, some scholars have tried integrated groundwater detection methods, such as the combination of RS and geological data (Yousif *et al.* 2018), the combination of RS and geographic information system (GIS) (Gebre *et al.* 2018; Gnanachandrasamy *et al.* 2018; Thakur *et al.* 2018), and the combination of RS and ground physical prospecting (Magaia *et al.* 2018), with varying results. RS is nevertheless not effective in detecting hidden faults. Aerial RS, such as aeromagnetic data, has great advantages in this respect (Ndikilar *et al.* 2019), but the accuracy of these methods cannot meet the requirements of groundwater exploitation.

Therefore, to improve the groundwater detection speed and enhance the well completion rate, rapid groundwater detection technology based on multidimensional space, which applies the '3S(RS,GIS,GPS)' technology, is proposed to establish the 3D-space rapid detection mode for groundwater, gathering space, aerial, and ground data as a whole.

METHODS

Study area

The study area (Figure 1), Beipiao city, located in the western Liaoning province, belongs to the Chaoyang district, with geographical coordinates of 41°40′–42°00′N and 120°20′–121°00′E, and a total area of 1,840 km^2. The Jurassic and Cretaceous strata are exposed largely in the study area, and the lithology is sandstone, conglomerate, and shale. The recharge source of underground water in the study area is mainly rainfall recharge, followed by surface runoff replenishment. It occurs mainly in loose rock and pores, fissures, and fissure caves of all kinds of rocks. Beipiao city is a water-deficient area in northeast China, with unstable precipitation and a serious shortage of domestic, industrial, and agricultural water.

Rapid detection technology of groundwater based on multidimensional space

The so-called rapid groundwater detection technology based on multidimensional space is the 3D-space rapid groundwater detection mode gathering space, aerial, and ground data as a whole, which is the process of taking GIS as the platform and using target theory to determine the optimal target area by narrowing the target area layer by layer. Its workflow is as follows.

Firstly, at the space level, reconnaissance by space satellites is used to understand the situation of water sources across a large range of the region, i.e., at the macro-scale, and then to extract information on water sources for the preliminary delineation of the water-rich target area. Secondly, at the aerial level, a key investigation is carried out for the delineated water-rich target area by using aeromagnetic detection to narrow the scope. Thirdly, at the ground level, by using hydrogeological and tectonic geological methods in combination with ground geophysical prospecting, the area with anomalous information on groundwater in the delineated water-rich target area is identified as the final target, and then the optimal mining of the well is determined. Fourthly, based on the above three steps, drilling prospection and drilling are carried out, which can finally achieve the purpose of sifting true from false information through narrowing layer upon layer with the use of target theory.

Target theory

The so-called target theory involves taking a highly anomalous field as the background and successively narrowing the target area down, layer upon layer, to a smaller area with larger potential by the integration of technological means; therefore, it is the process of determining the optimal target area by the gradual focus from region to block and then to point. The first layer of the target area of rich groundwater is delineated by using space satellite RS; then, the target area of rich groundwater is further narrowed by using aeromagnetic detecting means; subsequently, the optimal mining of the well is determined by using hydrological and geological methods combined with ground geophysical prospecting technology; finally, the groundwater is prospected through drilling.

Ring theory

A variety of methods may be involved in the process of extracting RS information for the enrichment index of a

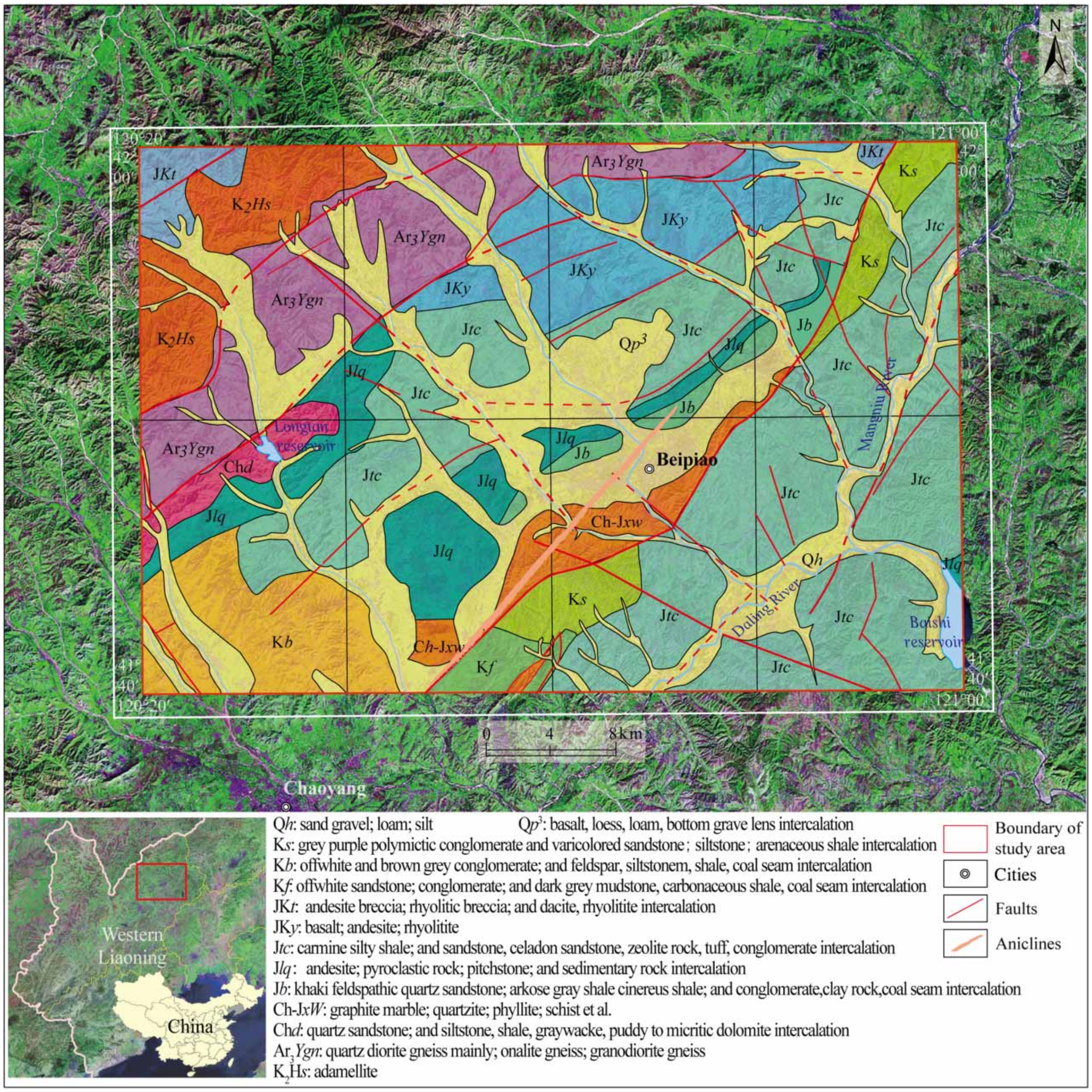

Figure 1 | Location of the study area.

groundwater source. To improve interpretation accuracy, multiple rings theory is adopted to determine the groundwater enrichment index. The so-called ring theory is the process of establishing the subset information of each set of information to confirm each other one, based on set theory (intersection) in mathematics (Hornell 1972). The mathematical meaning of ring theory is the intersection of sets. Its simple mathematical expression is:

$$M = A \cap B \cap C \cap D$$
$$= \{x{:}x \in A \text{ and } x \in B \text{ and } x \in C \text{ and } x \in D\}$$

The so-called 'multiple rings' are simply the 'ring' within the 'ring', namely: M is the degrees of groundwater enrichment determined by the stratum lithology A, geological structure B, terrain C, and landform D, while A is the intersection of the groundwater enrichment obtained by stratum A_1, lithologic A_2, and genetic type of rock A_3, and so on, and B is the intersection of the groundwater enrichment obtained by fault strike B_1, mechanical and strength properties of fracture B_2, and so on, which can be followed by analogy. The purpose of sifting true information from false can be achieved through narrowing layer upon layer with the multiple rings, to obtain the more accurate enrichment index of the groundwater.

RESULTS AND DISCUSSION

Target area of groundwater productivity based on space satellite remote sensing

In the context of the Beipiao district, the comprehensive extraction of RS information on the stratum lithology, geological structures, terrain, and landform of the research area was carried out, with Landsat ETM and SRTM DEM as the data source, the interpretation by space satellite RS imagery, and the geographic information system as the platform, according to the occurrence properties, hydraulic properties, and water physical properties of the groundwater.

The occurrence of groundwater is mainly related to formation lithology and geological structure. Its recharge conditions are mainly affected by topography and landform. Based on the principle of the hydrogeological method, the water-rich conditions of different formation lithologies were scored by an expert scoring method. According to the idea that stratum lithology is the foundation, geological structure is the condition, and topography and geomorphology are the basis for groundwater storage (Long 2010), the groundwater evaluation model was constructed by considering the influence of geological structure on groundwater occurrence and the influence of topographic gradient and topographic elevation difference on groundwater storage conditions. Based on the 'ring theory', groundwater occurrence was determined by combining quantitative analysis with qualitative analysis. Then, the enrichment area of groundwater was deduced. There are four types of groundwater in the research area: loose rock pore water, clastic rock fissure pore water, carbonate fractured karst water, and bedrock fissure water.

Research shows that among the many factors, geological and topographic information are important factors that reflect the existence and the dynamic changes of groundwater. Whether it is fissure pore water, fractured karst water, or bedrock fissure water, the enrichment of groundwater is not only influenced by lithology, but is also influenced by geological structure.

To improve the accuracy of using stratum lithology and geological structure, further RS information extraction needs to be done in the next step, based on airborne RS.

Target area of groundwater productivity based on aeromagnetic survey

In terms of aeromagnetic interpretation of formation lithology, the formation lithology was interpreted artificially by aeromagnetic data pretreatment and upward/downward continuation (Wang *et al.* 2015), aeromagnetic derivation (Fnais *et al.* 2016), directional filtering (Badmus *et al.* 2013), and so forth. It can be seen from the preliminary results that some lithologic boundaries can be well inverted, especially with obvious effect for the Jurassic and Cretaceous lithology and intrusive rocks, and the interpretation accuracy of formation lithology was effectively improved.

The result shows that the interpretation results for the data after aeromagnetic processing can reflect the distribution of the fracture zone, especially several NNE-trending deep fractures. And a total of 41 geological boundaries and six geological structures have been modified to effectively improve the interpretation accuracy of the fracture and stratum lithology.

Figure 2 shows a modified water-rich target area based on aeromagnetic surveys. The water-rich target area was consistent with the Chaoyang hydrogeological map. The evaluation results show that the areas with good groundwater enrichment are mainly distributed in the Quaternary loose deposits, such as valley plains, mountain valleys, proluvial fans, and so on. Clastic rock fracture pore water aquifer formations are composed of Jurassic sandstone, sandy conglomerate, and sandy shale, and their enrichment is controlled by structure. Carbonate fractured karst water aquifer formations are mostly developed in marble and ferromanganese limestone, and near tectonic fracture zones. Results also show that landform and tectonic conditions have a great influence on groundwater enrichment. Generally, groundwater enrichment is better in areas with gentle terrain or tectonic development. Otherwise, groundwater enrichment is worse.

The enrichment area of groundwater was delineated and the scope of the workspace was reduced, as benefitted by using the satellite RS method and airborne RS method.

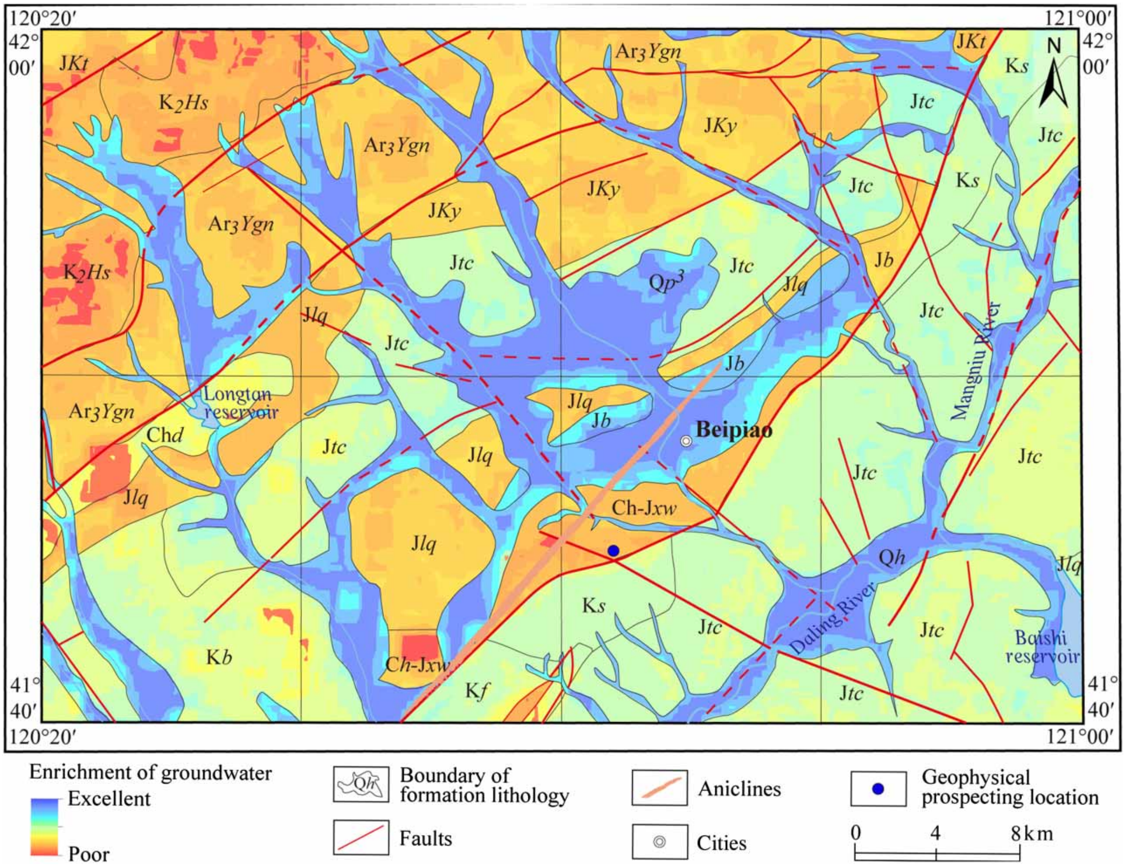

Figure 2 | The modified water-productive target area based on aeromagnetic survey.

However, for the exploration of underground water, the work is still not sufficient; the optimal mining of the well and mining depth need to be further confirmed.

Determination of the optimal mining of the well based on ground physical exploration

The geophysical prospecting adopts the DZD-6A multifunctional direct current electric instrument. The geophysical prospecting work was carried out for a total of 32 places, of which there are 16 places for the unconsolidated pore water, 10 places for the clastic rock fracture pore water, and six places for the carbonate fractured karst water. Because of the limited space of the paper, only a group of the geophysical prospecting results is shown, as follows:

a. Geophysical prospecting location: shown in Figure 2.
b. Geophysical prospecting method: induced polarization sounding.
c. The geographical coordinates of the verifying points: Point 1, 41°45′39.7″N, 120°42′26.4″E; Point 2, 41°45′42.6″N, 120°42′26.9″E; Point 3, 41°45′44.9″N, 120°42′27″E.
d. Stratum lithology: the stratum lithology in this area is Ch-JxW and the lithology of the Weijiagou rock group is mainly graphite marble, quartzite, phyllite, schist, and so on.
e. Occurring types of groundwater: carbonate fractured karst water.

The results of the apparent resistivity testing are shown in Figure 3. The apparent resistivity reflects the distribution and tendency of the bedrock, the high resistivity layer in the deep part reflects the electrical characteristics of the marble, and it is the nonwater storage stratum encountered when the apparent resistivity is greater than 300 Ω•m. The shallow part reflects the Quaternary alluvial and pluvial deposits and the shallow buried sand gravel, and the low resistivity

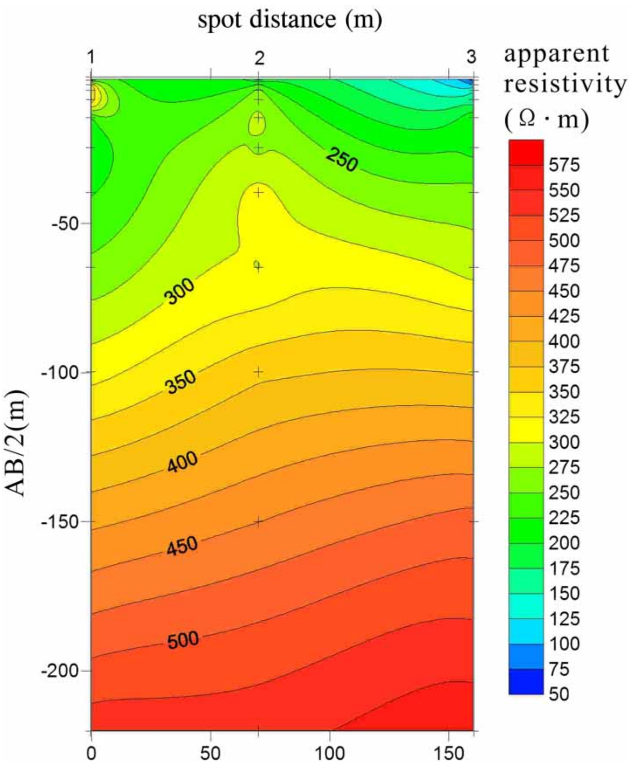

Figure 3 | The results of apparent resistivity testing.

layer in the central part reflects the weathered marble, which is the main water storage stratum in this area. According to the bedrock distribution and tendency, the thickness of the weathering crust at point 1 is larger, so it is determined as the optimal well location.

Drilling and well drilling prospection

By using this technique, the drilling and drilling prospection work at 11 places was carried out in Beipiao district, and eight wells were successfully drilled, which found a large amount of high-quality groundwater for the Beipiao area (Table 1 J01–J08), with a well completion rate of up to 72.73%. In addition, fitting analysis was made on the water yield and groundwater enrichment of 15 drilling wells (including seven collected; Table 1 J09–J15) in the study area. The results show that there is a good exponential correlation between the water yield and enrichment of groundwater, with a coefficient of determination of 0.763, and the relationship is $y = 2.676e^{7.935x}$.

Table 1 | Drilling wells data table

Number	Water yield/ $t{\cdot}d^{-1}$	Enrichment of groundwater	Types of groundwater
J01	110.82	0.47	III
J02	1,431.85	0.84	I
J03	668.22	0.58	II
J04	2,016.28	0.82	I
J05	1,038.83	0.68	I
J06	3.31	0.35	IV
J07	339.16	0.61	I
J08	173.15	0.55	I
J09	2,147.94	0.91	I
J10	1,054.18	0.72	I
J11	1,431.39	0.76	I
J12	1,434.24	0.79	I
J13	604.81	0.72	II
J14	304.31	0.53	III
J15	43.72	0.21	IV

I is loose rock pore water, II is clastic rock fissure pore water, III is carbonate fractured karst water, and IV is bedrock fissure water.

CONCLUSIONS

In the multidimensional space-based groundwater detection method proposed in this paper, the satellite RS technology is not limited by time and region, and the application of this technology can quickly obtain the geological and topographic factors in the study area, and also elucidate the pattern of groundwater occurrence in the study area macroscopically. The aerial RS technology is expensive, but the detection accuracy is very high. Targeted aerial RS exploration based on satellite RS can greatly improve the accuracy of RS interpretation. The outstanding advantage of the surface geophysical prospecting method is the high precision of groundwater detection, and it can provide technical data for further groundwater exploitation and determination of the optimum well location. Compared with the traditional method of geological prospecting, the technology has the characteristics of being macro-scale, comprehensive, dynamic, efficient, all-weather, real-time updating, and low-cost, which can effectively improve the rapidity, accuracy, and timeliness of groundwater detection.

(1) From satellite RS technology to aerial RS technology to surface geophysical prospecting and drilling, the process

uses 'target theory' to gradually narrow down the groundwater-rich area. The results show that this method incorporates the advantages of the four technologies mentioned above. And through the preliminary application in Beipiao city, western Liaoning province, China, it has been proven to be an effective method for accurately detecting groundwater.

(2) The results also indicate that the interpretation accuracy of stratum lithology has been improved by the application of aeromagnetic data and that the insufficiency of satellite RS in the interpretation of buried faults has also been compensated.

(3) The combination of RS and surface geophysical prospecting not only overcomes the difficulty of the low precision of water prospecting by satellite RS technology, but also overcomes the difficulty of the high cost and low efficiency of surface geophysical prospecting. Therefore, this method effectively improves the detection accuracy and efficiency of groundwater and reduces the detection cost. At the same time, it can also determine the optimum mining well location to provide data support for the further exploitation of groundwater.

(4) The method has been applied only in semiarid and hilly areas, and the application effect is good. For high and cold plateau areas, surface work is greatly affected by the harsh environment, thus this method may have more advantages in detecting groundwater. However, for the arid desert area, it is difficult to use RS technology to interpret stratum lithology and terrain in the arid desert area is relatively gentle, so it is still difficult to use this method to detect groundwater.

In addition, the research deficiencies and recommendations are as follows.

(1) In the result verification, geophysical prospecting and drilling points are mainly carried out according to the needs of engineering drilling. According to the preliminary application in Beipiao city, the expected effect has been achieved. In order to obtain more reasonable evaluation results in a later study, systematic sampling should be used to verify the results.

(2) The application of aeromagnetic data in aerial RS data is not satisfactory. Because aeromagnetic data can only be valid for some lithology and geological structures with magnetic anomalies, aeromagnetic data sources need to be further enriched. For example, the use of the airborne electromagnetic method may be better for detecting groundwater.

(3) Satellite RS technology plays an important role in grasping and analyzing the pattern of groundwater occurrence through a macro view. However, the process of using satellite RS technology to determine areas of groundwater potential needs professional hydrogeological knowledge, which is greatly affected by human factors.

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